HiPER

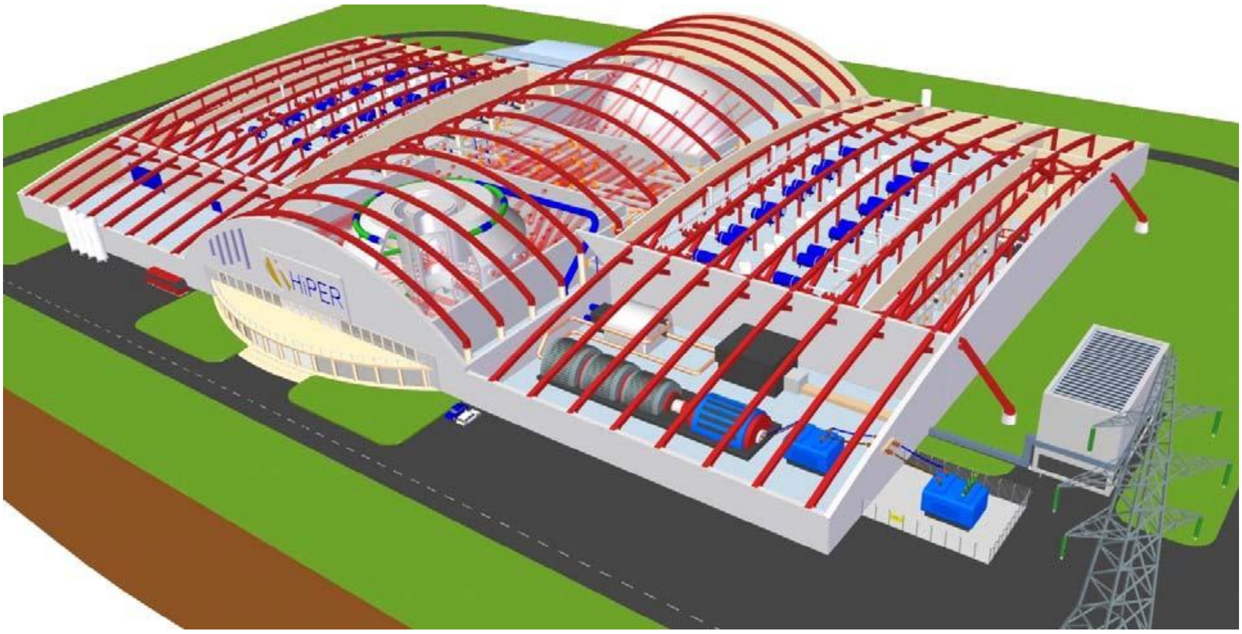
Preparatory Phase Study

Grant Agreement Number 211737

Final Report

HiPER Project Team

1st December 2013



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1 Executive Summary

HiPER is an ambitious, European "ESFRI" Roadmap project seeking to develop commercial power production based on laser-driven fusion of deuterium and tritium.

The Preparatory Phase Project commenced in April 2008 and concluded in April 2013. It was co-ordinated in the UK by the Science and Technology Facilities Council of the Department of Business, Innovation and Skills. The project management, co-ordination and governance of the project was financed by the European Commission under Grant Agreement 211737. Research and technical development was funded jointly by STFC and by MSMT, the Ministry for Education Youth and Sports of the Czech Republic. Other partners made extremely valuable "contributions in kind", including laser beam time at national facility assets in France, Czech Republic and UK and computational resources in Italy, Spain and Greece.

Key outputs from the project include over 100 peer reviewed publications in the scientific literature covering all aspects of the technology of laser-driven fusion; many high profile invited lectures at international conferences in Europe, North America, Canada, Japan and Russia; events including exhibitions and visits to companies to encourage industrial participation in future phases of the project and a campaign to raise public awareness of the growing energy challenge and the potential contribution of laser-driven fusion with public lectures and visits to schools and universities.

Much of this Final Report is devoted to the work conducted during the final two years of the Preparatory Phase, particularly the identification and costing of a phased delivery strategy for the construction of the HiPER facility itself and the identification of opportunities for exploitation of the technology in the short and medium term. Further information concerning the project and its outputs to date are available from the HiPER website, http://www.hiper-laser.org.

Proof of principle of the laser-driven fusion scheme at the National Ignition Facility (NIF) in US is an important pre-cursor to substantial public or private funding for HiPER. Recent results are extremely encouraging and there is a growing consensus that ignition will be achieved within the next few years.

European prospects for taking laser-driven fusion energy forward to the construction phase of HiPER were given an important boost in 2010 when President Sarcozy of France announced that beam time at the Laser Mégajoule (LMJ) and the co-located PETAL facility would be made available to develop "new forms of energy". This important policy decision by the French Government gives researchers throughout Europe the opportunity to conduct key "proof of principle" laser-driven fusion experiments at full scale. This enables HiPER to devise a strategy whereby construction of a single, large scale plant can bridge the facility gap between existing "single shot" machines such as LMJ and NIF and a demonstration power plant. Considering the time required to fund, design, construct and commission such large scale facilities, this strategy is essential if laser-driven fusion is to make a contribution to power production on a timescale relevant to national and world energy needs. The HiPER community must now develop a robust case for beam time for submission to the LMJ Access Panel in 2015, supported by detailed numerical simulations and experiments conducted at existing, "intermediate scale" facilities.

In addition to development of the science and related technologies, HiPER must ensure that its stakeholders are well positioned to exploit opportunities arising in the immediate "post-ignition" era. This includes broadening its stakeholder community within industry, Governments, funding agencies and potential partners as well as identifying the key commercial drivers.

Finally, I wish to thank the HiPER Executive Board, members of the HiPER Project Management Committee all HiPER partners and participants for their enthusiasm, support and hard work which has enabled the project to make such encouraging progress.

Prof. John L Collier
on behalf of the Project Coordinator,
Science and Technology Facilities Council
1st December 2013

2 Introduction

Achievement of "first ignition" of a Deuterium - Tritium plasma at the National Ignition Facility (NIF), laser facility at the Lawrence Livermore National Laboratory (LLNL), California or at LMJ in France is expected to transform the prospect of Laser Energy from a distant aspiration to a credible proposition on a 30 year timescale. The ESFRI HiPER Project has been developed as Europe's response to the opportunity of developing the potential of Laser Energy to the stage of an operational demonstrator plant on a timescale consistent with meeting the global demands for environmentally responsible energy.

During the Preparatory Phase Project of HiPER, April 2008 to April 2013, project partners have been working on a plan to produce energy from laser driven fusion based on a "shock ignition" scheme that offers high net energy gain. An essential advantage of shock ignition is that it is amenable to demonstration, albeit on a single shot basis, using the Laser MégaJoule (LMJ) facility due to be commissioned at CESTA, Bordeaux at the end of 2014. Following success at LMJ, a global programme of technology development will deliver the advances necessary to present a project to construct a "first of type" demonstration facility based on a technological risk mitigation proposition.

This Preparatory Phase Final Report identifies the route to fielding a successful shock ignition campaign on LMJ, the technology development which will underpin the repetitive operation of a Laser Energy power plant and the concept engineering needed to construct a fusion chamber and energy absorbing blanket able to harness the fusion reaction for power production.

A three phase strategy to HiPER construction has been devised to minimise the cost of the project in advance of ignition at LMJ while the scientific risks are relatively high. Financial risk during this phase is reduced by the exploitation potential of intellectual property which arises from the technology development programme.

The work to build high level political support for the project has already met with some success at a national level in UK, Greece and Spain. Achievement of first ignition at NIF and LMJ should provide the necessary justification for governments in Europe, US and beyond, to transform this support into funding for delivery of Laser Energy.

The HiPER Laser Energy Strategy provides a high value science and technology program which maintains Europe's status in the field and enables options for wider collaboration strategies in the future whilst protecting the option for Europe to proceed independently should this be required.

The investment will be economically beneficial to European industry in the short and medium terms in the field of Laser Technology and will enhance the potential for longer term economic returns as a supplier of Laser Energy technologies to world markets.

3 Overview of the HiPER project

With increasing dependence upon fossil fuel based energy resources becoming less viable, the world is seeking new strategies and new technologies to meet the energy challenge. This is made more pressing by ageing power generation and distribution infrastructure in developed nations, rising demand from developing nations, anticipated electrification of transport and security concerns over the wider exploitation of nuclear fission. It opens a perspective for fusion energy to be part of the energy mix required for future generations. The magnetic fusion program is already on a programmatic route while laser energy fusion has not been strongly investigated because of lack of proof of principle in reaching fusion via laser energy. Ignition at NIF and / or LMJ over the next few years will mark a fundamental change in this position.

A transformation in the energy market is required to meet the need for low carbon, sustainable, affordable, base load energy, matched with security of supply.

In the short term, an increasing contribution from renewable energy sources may provide a solution in some locations. In the medium term, low carbon, sustainable solutions must be developed which are environmentally acceptable and match base load energy demand to avoid the threat of an energy gap and the political instabilities this would bring.

Laser Energy is one potential candidate for meeting this challenge, with research work approaching Proof of Principle on the world's most powerful High Energy Facilities, NIF and LMJ.

Though the concept of fusion investigated in priority on these facilities (called indirect drive) is different from the one aimed for laser energy fusion (called direct drive - shock ignition) - "First Ignition" of Laser Fusion at the National Ignition Facility in California will open the way for a programme of physics and technology development before construction of a prototype plant to demonstrate power production through Laser Energy.

3.1 HiPER International Context

The ESFRI "HiPER" project has defined a path to a prototype European Laser Energy facility to demonstrate the entire process and to prove the feasibility of repeated fusion of DT pellets, the neutron heat conversion scheme and the sustainability of the process on long run. In a second step the facility can be converted to prove that economic viability can be achieved in a commercial environment.

The HiPER Project can be regarded as an "opportunity program". Based on dual use facilities (high energy lasers, material testing facilities under high neutron flux, etc.), this program requires only a small level of investment from the European partners until the proof of concept is obtained. This makes a fundamental difference compared to other fusion programs and allows us to propose a parallel pathway to magnetic fusion at almost no investment cost during the preliminary phases of the project. Moreover, many technical and scientific advances driven by HiPER will serve other programs of general interest (ELI high intensity lasers, laboratory astrophysics, medical application of lasers, etc.).

During the Preparatory Phase Project (HiPER PPP), careful attention has been paid to developing the expertise of the HiPER partners in the various areas of technological development required either to contribute to a wider international program on Laser Energy or, if required, to enable Europe to proceed on a "go it alone" basis. This expertise includes the physics of ignition under direct drive conditions, the development of new generation laser technology (high energy efficiency, high repetition rate, high energy), high gain direct drive target design and mass production of cryogenic targets, high speed injection, tracking and firing of targets in the chamber, advanced material development and testing under extreme conditions of fusion reactors, fusion chamber design and integration of the complete system from ignition physics through to a functioning demonstrator facility including tritium handling and cycling. Many shorter term technology exploitation opportunities of these technologies also exist in high-tech manufacturing, new medical treatments, advanced imaging techniques and fundamental science.

In an international context, the HiPER partnership positions Europe advantageously as laser driven fusion ignition approaches, with attractive options following that key event, to embrace strategically valuable partnerships with the US and Japan.

Activities proposed for the HiPER consortium in the post – "first ignition" era have been chosen to be complementary to work which is being undertaken in US and elsewhere. This protects a range of options for Europe after Proof of Principle has been achieved as competition intensifies for commercial exploitation of the new possibilities. At that stage, a range of possible collaborations can be assessed.

Enhanced collaboration has already been achieved with US, through Memoranda of Understanding between Spain and Lawrence Livermore National Laboratory (LLNL), and between STFC, AWE and LLNL to facilitate joint working and free exchange of information.

These MoU's have the potential to develop into inter-governmental agreements to pursue Laser Energy on an international basis. It is important that the HiPER partners can make sure that Intellectual Property is adequately protected in spite of bilateral agreements as stated above.

3.2 Phases of the proposed HiPER Laser Energy Programme

This Outline Business Case identifies a high level, three phase approach for HiPER, to be delivered by partners within the EU.

The phasing strategy is shown in Figure 1 below.

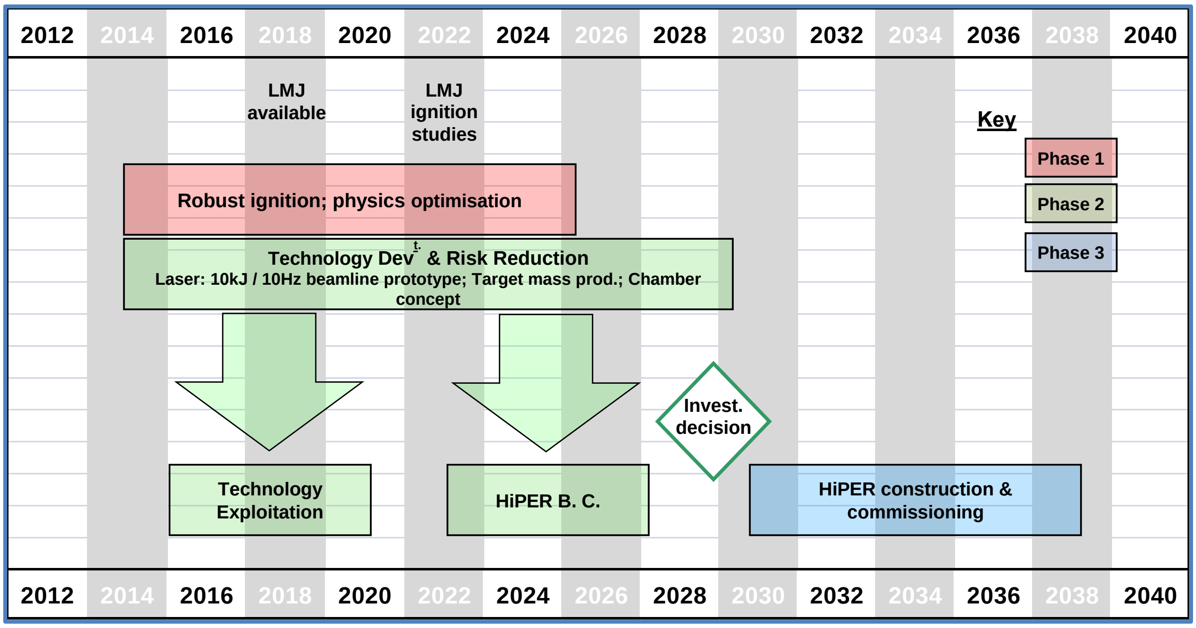


Figure 1: Timeline for the 3-phase HiPER Laser Energy Programme

Phase 1: Ignition programme on LMJ

Planning for underpinning experiments and modelling commences in 2013. Phase 1 commences with an ignition campaign including sub- ignition experiments on existing EU and possibly US facilities (e.g. LULI 2000, Orion, VULCAN, Petal, and Omega) and ultimately ignition at LMJ in the 2020 – 2025 timeframe. This is followed by gain optimisation experiments as required for commercial viability of Laser Energy

Access to LMJ beam time is available to HiPER, but will be in competition with other proposals and will be subject to scientific peer review. The pre-cursor experiments at intermediate facilities, computational modelling of the physics and detailed planning for each LMJ shot will be crucial to securing the necessary LMJ access.

The detailed programme and cost are currently under development

Source of funding: Potentially national with EU contribution

Facility access: Existing facilities until 2016, followed by programmatic access to Laser MégaJoule subject to programme approval (see above)

Phase 2: Technology Development

Technology Development commenced in 2014 with nationally funded programmes with possible future EC support in areas of short term high commercial potential. It includes next generation laser development (France & UK), advanced materials and fusion chamber concepts (France, Spain), community building (Greece) and target design (UK, Italy, France), etc.

The main development programme commences in 2022 with the funding being tapered to increase as risks reduce

Cost: Estimated at ~ 500 MEuro (+50% -50%)

Duration: 12 - 13 years

Source of funding: National with possible EU / investment contribution

Phase 3: Plant prototype development; investment appraisal and construction

Commences: circa. 2022 with a target investment decision in 2027

Potential start of 12 year construction phase in 2027 – 2028, commissioned around 2040 Estimated at 7BEuro to 12BEuro

Source of funding: Private investment or public / private partnership

3.3 Phase 1

Phase 1 develops and extends the existing links already established within the HiPER Preparatory Phase Project (HiPER PPP) with industry, academia and other partners and potential funding agencies.

A programme of experiments and numerical simulations will be conducted in support of the shock ignition physics roadmap, culminating in full-scale ignition experiments at Laser Mégajoule (LMJ) circa 2021. Following successful demonstration of ignition, a five year period of optimisation is envisaged in order to demonstrate the high energy gain required for commercial exploitation of Laser Energy.

LMJ is currently under construction and, prior to its availability to the User Community, underpinning experiments and associated numerical modelling will be conducted using existing intermediate scale facilities. These include the LULI facility at École Polytechnique, VULCAN and Orion in UK and the Omega facility at LLE Rochester where members of the HiPER physics community are already conducting “proof of principle” experiments under existing national agreements. The programme within Phase 1 will address physics issues using modest laser energy to give confidence in the physics and to inform the subsequent programme of experiments at LMJ.

The details of the Phase 1 campaign, including the requirement for beam time at existing facilities, the number of shots required at LMJ to demonstrate ignition and the costing model for those shots will be fully developed in partnership with facility operators.

It is also possible on the timescale of LMJ availability, that the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, LLNL, will be configured for shock ignition experiments in order to achieve high gain in support of the fundamental science and energy research elements of the NIF programme. In this case, collaboration between the two Laser Energy programmes is likely to accelerate progress, bringing forward the demonstration of high energy gain using an advanced ignition scheme.

3.4 Phase 2

In **Phase 2**, activity is divided into three main areas of development as shown in Figure 1.

In the first, work is focused on the development of technologies to remove the technological barriers limiting the exploitation of Laser Energy. T his includes developing a of "next-generation" laser technology capable of operation at the repetition rate and energy efficiency necessary for commercial viability of Laser Energy. In the second low cost techniques are pursued for mass production of fuel capsules. These are areas with short and medium term exploitation potential outside the Laser Energy arena, giving associated economic impact. Patent protection will be sought where appropriate, as well as identification of exploitation and spin-out opportunities.

In the third area, the activity will concentrate on development of systems engineering concepts for the fusion chamber capable of withstanding the environment of fusion reactions at high repetition rate, followed by concept designs required to underpin the Construction Phase Business Case. This will include advanced first wall material development and testing; reactor design; blanket design; tritium breeding schemes and tritium management; energy extraction; safety and licensing. At this stage it seems likely that these activities will yield exploitation potential outside of Laser Energy. Consequently the resource profile will be arranged to peak after the ignition physics has been demonstrated at LMJ (c. 2021). By this means, the overall financial risk of this activity will be minimized.

As Phases 1 and 2 progress, understanding of the balance of risk and opportunity for the future options of the Laser Energy programme will grow to the point at which strategic decisions can be taken. Options would include prototype demonstrator facility construction in partnership with International partners or proceeding alone within Europe. The option would also remain to exit from the programme, minimising the net cost by capitalising the arising intellectual property at that point. The decision would be made by the governments of the day, with advice from the HiPER Project Steering Committee and other stakeholders.

Making reasonable assumptions of progress during the Technology Development Phase, it is anticipated that the project to construct the "First of Type" Laser Energy demonstrator facility will be funded largely by private sector investment in return for a share of the intellectual property earned. Activity is included within Phases 1 and 2 to identify potential industrial and investment partners and economic analysis will be conducted at the required level to inform investment decisions.

3.5 Phase 3

Phase 3 covers development of the HiPER Construction Phase Business Case, investment appraisal and then the construction, commissioning and operation of the "First of Type" Laser Energy demonstrator facility. With the major technological risks mitigated during Phases 1 and 2 , the mission of Phase 3 is to demonstrate the commercial viability of the Laser Energy concept to the point at which utility companies would be convinced that Laser Energy represents an attractive commercial proposition and commit to the roll-out of first generation power plants. Phase 3 will focus on the overall systems integration including blanket operation, fusion chamber management, mass production of targets, tritium fuel cycle and continuous operation to demonstrate system reliability and availability as required by the power utilities.

4 The Laser Energy concept

Laser Energy is based on the conversion of isotopes of Hydrogen into Helium through the process of fusion, using powerful laser pulses to drive the reaction. This technology can provide an energy solution in line with the Fusion energy roadmap, with the potential to supply a significant proportion of world energy needs in the second half of this century.

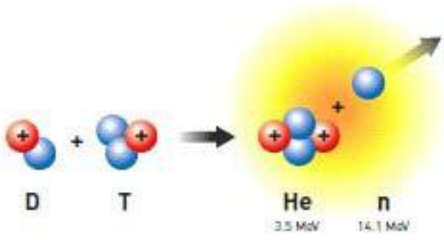


Figure 2: The Deuterium - Tritium fusion reaction

The principle is to use high energy laser beams to compress and heat small fuel pellets containing Deuterium and Tritium to the temperature and pressure at which the atoms of the fuel fuse to form Helium, each liberating a highly energetic neutron. The reaction releases more than a million times the amount of energy associated with a typical chemical combustion reaction.

The reaction takes place in an evacuated "fusion chamber" surrounded by a "blanket" containing lithium. As each pellet is ignited by the laser pulse, the escaping energetic neutrons are captured in the blanket, where their energy is converted to heat, used to drive conventional, high efficiency electricity generating plant. The neutrons also interact with the lithium blanket to produce helium and tritium. The tritium is re-cycled into the fuel.

For economic viability, analysis shows that the cycle of target injection, fusion by the laser pulses and energy capture must run at a rate of at least 10 pulses per second. The process is analogous to a petrol engine with its familiar cycle of fuel injection, ignition, exhaust and energy extraction.

'Inertial' fusion (the basis of Laser Energy) has already been demonstrated by UK and US teams, exploiting underground nuclear tests. Duplication of these results, but initiating the reaction with lasers, to produce fusion ignition with net energy gain from a fuel pellet, is anticipated within the next 2 years at the National Ignition Facility in the USA. 'First Ignition' will be a powerful demonstration that the physics of laser-driven fusion has been transformed from an elusive scientific phenomenon to a predictable, controllable process, ready to be optimised for commercial energy production.

The HiPER Project has been Europe's response to the opportunity to develop the potential of Laser Energy to the stage of an operational demonstrator plant.

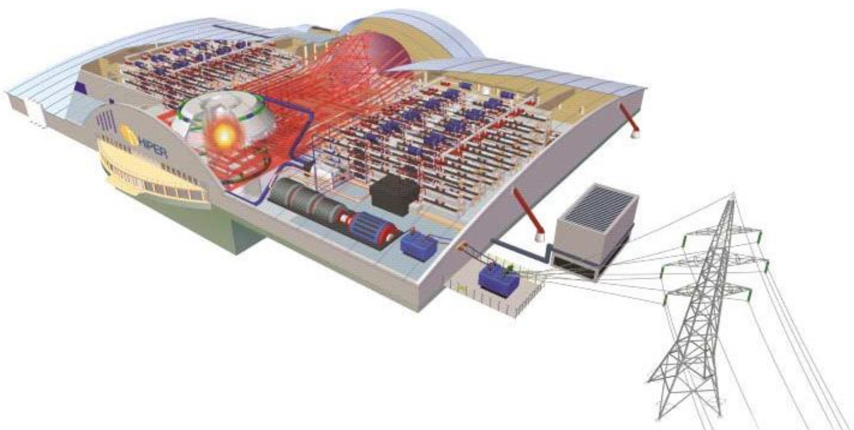


Figure 3: Visualisation of HiPER prototype power plant

Fusion energy, in particular Laser Energy, meets European energy generation requirements, providing a sustainable, low carbon, environmentally acceptable, safe and secure commercial energy source without the long-lived radioactive waste associated with conventional nuclear power plants.

Sustainable

Sustainability assessments of key fuels, construction materials and the rare earth supplies required to produce Laser Energy plants show that sufficient materials are available for power production at the 1 TW(e) level for more than 1,000 years.

Low Carbon

A Laser Energy plant produces no CO_2 during electricity generation. The only carbon footprint would be associated with construction, maintenance and decommissioning of plant, as is the case for all forms of energy generation.

Low Waste

Any radioactive material generated from a fusion energy plant due to neutron activation of fusion chamber components will be short lived, allowing recycling within 100 years through appropriate choice of materials. This contributes to simplification of essential regulatory processes needed for Laser Energy.

Safe

Electricity production from fusion is intrinsically a much safer process than conventional fission. Under fault conditions energy production will simply stop and the plant will stabilise. Fuel is consumed at the same rate at which it is injected into the fusion chamber, allowing no possibility of a “runaway reaction”, as has been an enduring concern in fission plants. Primary safety focus in nuclear terms would be on neutron shielding, tritium containment and safe storage of activated chamber materials. These challenges already have appropriate solutions.

Commercially viable

Financial modelling for both the European HiPER and US LIFE projects shows that, to be commercially viable, the fusion cycle must run at a repetition rate of at least 10 cycles per second, with a “target gain” (laser energy input divided by fusion energy output) of 60 – 70. Other key technical and economic performance criteria identified are overall laser efficiency greater than 7% and cost of the targets less than €0.5.

Reasonable assumptions for technical progress over the next few years and economies associated with volume production indicate that Laser Energy will be cost competitive with other low carbon sources.

5 The Energy Landscape

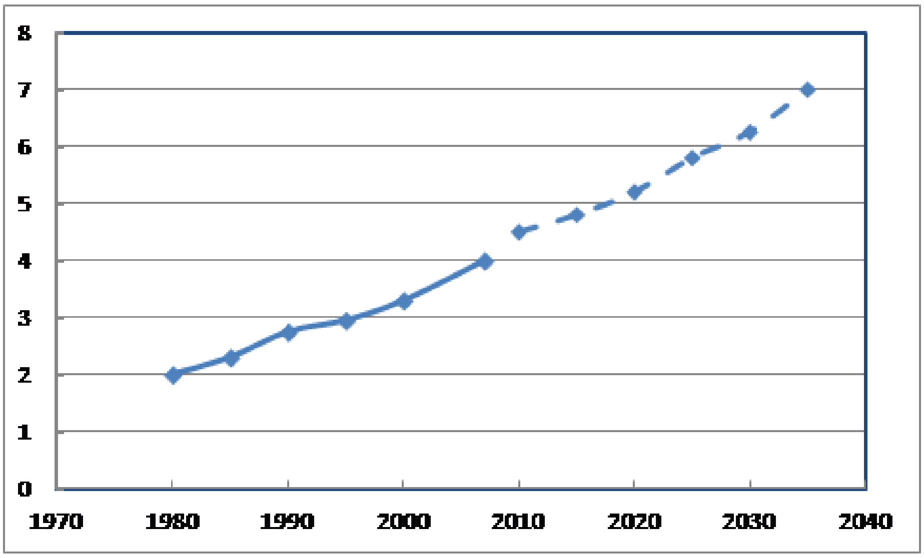
5.1 World Energy Demand

The International Energy Agency’s reference scenario predicts global energy demand to grow by 70% between 2000 and 2030. To meet this demand, at least 4800 GW(e) of additional electrical generating capacity will be required by 2030, equivalent to 5 times the existing generating capacity of the USA.

Anticipated world energy demand is shown below in Figure 4.

Although leading nations have recognised the imperative to move away from dependence upon them, fossil fuels will inevitably remain the main source of energy worldwide over this period. Petroleum's share will decline, boosting the share of coal and renewable sources. The capital market associated with meeting this projected energy demand by 2030 is in excess of $10T and is certain to grow substantially in subsequent years.

Figure 4: Anticipated world energy demand (US Energy Information Administration)



5.2 Energy and the Environment

It is widely accepted that if the rising demand for energy is met by expanding the use of fossil fuels within this century, the world will be facing a damaging and possibly irreversible global temperature rise of up to 6°C. To avoid this catastrophic eventuality the International Panel on Climate Change (IPCC) has recommended that greenhouse gas (GHG) emissions be reduced by 70% by 2050.

Transforming the energy market to generate sufficient "clean-energy" to meet these targets will require technological advancement and a radical shift to the use of low-carbon energy sources of all types. Availability of industrial scale energy at affordable prices is a prerequisite for economic growth and to reverse the spiralling trend of increased emissions represents a major challenge to all nations. Commercialisation of Laser Energy could provide a major component of the response to this challenge.

5.3 The Energy Mix

Renewable energy currently makes a relatively small contribution to meeting global energy demands. This contribution will increase over the next 25 years, but cannot match the shortfall arising from closure of fossil fuel stations, the demands of increasing populations and of developing nations for energy to drive their economies forward.

Carbon reduction commitments require a move away from burning fossil fuels for base-load electricity generation. Carbon capture and storage (CCS) may delay the end of the fossil fuel burning era, but is expensive and has yet to be proven at large scale. The energy demands of CCS technology, as yet unproven on an industrial scale, are expected to increase the cost of electricity by 25% -40% beyond 2030.

Security of supply will become a significant concern, requiring modification of electricity infrastructure and additional storage to achieve diversity of supply.

An increased contribution from nuclear fission will inevitably be required to meet Europe's energy needs in the short and medium term. Greater reliance upon nuclear fission plants and other zero-carbon approaches to electricity generation is therefore likely between 2030 and 2050, potentially to offset the operating and capital costs of CCS and also in recognition of the limited longevity and political risks associated with reliance on gas as a sustainable fuel source.

A new solution for base-load energy generation is therefore urgently required in the longer term.

Fusion energy is an attractive option. The magnetic fusion approach is being approached with the ITER facility. Its timescale is such that the facility will be commissioned with Tritium in 2028. Next the DEMO facility is to be build, then a commercial demonstration reactor in the second half of the century. T he inertial (or laser) fusion energy is another route of interest to energy production.

6 Progress to date and likelihood of success

'Inertial' fusion, the basis of Laser Energy, was demonstrated by UK and USA teams in a series of underground tests. Duplication of these results on a small scale, using lasers to compress and heat the fusion fuel to ignition to produce net energy gain, is anticipated within ~2 years at the National Ignition Facility in the USA. This so-called 'First Ignition' will be a powerful demonstration that the physics of laser-driven fusion has been transformed from an elusive scientific phenomenon to a predictable, controllable process, ready to be optimised for commercial energy production. NIF ignition will be a seminal moment which will spark the interest of governments, national policy makers and industry.

Following the commissioning of the NIF facility in March 2009, the National Ignition Campaign, (NIC) to achieve single shot "first ignition" was initiated with the ambitious goal of demonstrating energy breakeven and then fusion gain by the end of this US fiscal year '12-'13. NIC has been extremely successful and many technical challenges have been overcome. The ignition campaign has, though, yet to reach its primary goal of demonstrating significant burn of the D-T fuel. This is largely because the computer models which are being used to guide the experimental campaign have proven less accurate than expected when extrapolated to the regime of the NIC experiments. Consequently, homing in on the precise configuration of fuel capsule and laser beam parameters requires a greater number of laser shots than was at first predicted.

Recent international reviews of the NIC campaign, with membership including UK, French and Italian experts, have reconfirmed confidence that ignition will be achieved at NIF, though the precise timescale is not certain. In addition to the number of laser shots required, there are other "customers" for laser time, including the academic access programmes.

Scientific break-even (energy produced = energy absorbed by the fuel hot-spot) was achieved in September 2013 and subsequent results have already demonstrated a further factor two enhancement. Fusion reactions are beginning to dominate the process, with "self heating" from alpha particles and fusion neutrons now depositing more than twice as much energy in the fuel as the laser itself. The system is now very close to full ignition which is expected within 2-3 years.

The most recent information from Livermore suggests that ignition within 24 months is a reasonable assumption.

International Context

Europe has been at the forefront of Laser Energy development in Europe since 2005 when the concept of the HiPER (High Power Laser Energy Research) project was formed in the Central Laser Facility, Rutherford Appleton laboratory. Recognising the prospect of this technology, the need to prepare for ignition at NIF and the subsequent strategy, the CLF led the formation of a European consortium through an initial informal 'concept design' phase and the successful inclusion of HiPER on the ESFRI roadmap. In 2007, the consortium (26 partners from 10 nations) was successful in obtaining FP7 funding for co-ordination and moved to a formal 'Preparatory Phase' with STFC appointed co-ordinator. Funding of the Preparatory Phase was augmented by STFC and MSMT (Ministry of Education, Youth and Sports) of the Czech Republic through the provision of £5M and 2.4MEuro respectively for technical work. The Preparatory Phase has been successful in establishing a project approach to the development of this field and has, for the first time, brought about the alignment of participating institutions.

The success of HiPER was instrumental in developing the US strategy beyond "First Ignition" at NIF, with creation of the analogous project called LIFE (Laser Inertial Fusion Engine) hosted at the Lawrence Livermore National Laboratory (LLNL). This ambitious project seeks to exploit the current US capability surrounding NIF to deliver a Laser Energy prototype plant on an aggressive timescale.

The form of the Laser Energy delivery strategy will develop and participation will broaden as the HiPER project moves into the Technology Development phases. This will be shaped by the political interest which will follow "First Ignition" at NIF and the commissioning of LMJ in France in 2015.

The Livermore approach: "LIFE"

The NIF facility is designed to achieve ignition using an ignition scheme known as indirect drive. In this scheme, the laser drive beams are converted to X-rays in a gold cavity, known as a "Hohlraum" which surrounds the fuel capsule. The X-rays create an intermediate energy stage, smoothing any non-uniformities of drive arising from the finite number of laser beams (192 in the case of NIF).

Planning on the success of NIF and prompted by European preparations, LLNL established the 'LIFE' project to develop a delivery strategy for Laser Energy. LIFE is based on indirect drive, thereby capitalising on existing investment in NIF, and seeks to demonstrate a full system solution as early as possible, based on using existing materials, proven physics and known technologies.

The European approach: "HiPER"

The European HiPER project is based on the concept of advanced ignition and in particular, shock ignition, a direct drive scheme which offers the prospect of higher gain than indirect drive since it avoids the intermediate step of X-ray generation. In this scheme, the fuel capsule is first compressed to moderately high density by firing a long laser pulse directly onto the surface of the fuel capsule.

Synchronous with maximum compression, a convergent spherical shock wave is launched into the compressed fuel using a high intensity "spike" in the laser pulse. The shock wave converges on the high density core and collides with the rebounding shock wave, resulting in pressure amplification. Simulations predict that with appropriate target design, the temperature of the fuel can be raised to the ignition point for fusion. This direct drive approach gives the scheme some important commercial benefits including reduced laser drive and fuel capsule simplicity.

HiPER identified a delivery strategy based primarily on shock ignition, with construction of a prototype plant in the 2030 timeframe. This schedule reflects the requirement to validate the ignition scheme experimentally on the CEA Laser MégaJoule (LMJ) facility at Bordeaux, France, or at NIF in the US. Construction of LMJ is due to complete in ~2016, when beam time will become available for user-driven science experiments including shock ignition studies. The experimental and computational programmes which are required to underpin a shock ignition campaign using LMJ at the end of the decade are described in Appendix II (Roadmap to Shock Ignition at LMJ); a preliminary assessment of the requirements for the ignition campaign itself is given in Appendix III (Shock Ignition Campaigns at LMJ).

While indirect drive at NIF may to provide the quickest route to a prototype plant, Europe has an opportunity through access to the LMJ facility to develop the higher gain shock ignition scheme which may ultimately prove to be the optimum solution from a commercial perspective.

7 Timescale for delivery

Laser energy benefits from important advantages which make the delivery timescale relevant to the challenge of a low carbon solution on the 2040 – 2050 timescale.

7.1 Demonstration power plant

The HiPER team has identified a "single build" demonstration power plant strategy which takes the concept from first ignition to commercial deployment with just one large scale construction project. This arises because ignition and the campaign of optimisation experiments which will follow represent a demonstration of the necessary physics at full commercial scale. The mission of this subsequent facility will be to demonstrate the commercial potential of a pilot plant through integration of the new generation high repetition rate laser driver technology with suitable target injection systems, a neutron-absorbing lithium blanket and heat extraction and electricity generating capability.

The facility will be used to optimise tritium production, minimise the local tritium inventory, develop the heat extraction systems and meet the levels of reliability and availability demanded by utility operators. In short, its purpose is to demonstrate to investors that the technology is sufficiently mature to justify roll-out of a first-of-type fleet of power stations underpinned by the required level of commercial and regulatory confidence.

This "single facility build" strategy enables Laser Energy to be delivered on an appropriate timescale to meet the challenge of the energy gap. The time required to plan, fund, design, construct and commission a pilot plant of this scale is estimated at 20 – 30 years.

7.2 Separable technology

An important advantage of Laser Energy is that the laser driver is located remotely from the fusion chamber, with the laser beam energy relayed by optics to the pellet interaction point. This is advantageous for a number of reasons :-

- The laser, a high value capital asset, is isolated from the neutron flux and is therefore not subject to this potential source of damage.
- By incorporating redundancy into the laser driver, which consists of a large number of identical beam lines, maintenance can be carried out "live", without interrupting power generation. This increases the availability of the system for operations and simplifies maintenance, - two crucial requirements of utility operators.
- The driver design and performance can embrace further improvements, demonstrated on a single prototype beam line, and then implemented via a rolling installation programme in operating plants. In the context of the single facility pilot plant strategy, incorporation of new laser drivers does not require construction of a new facility.

Similarly, new blanket designs, improved target manufacturing techniques and new first wall materials can be incorporated into the existing facility without the need for major reconfiguration or shut-down.

These advantages are intrinsic to the Laser Energy concept and, together, enable accelerated delivery of both the pilot demonstration plant and the subsequent roll-out of first generation power plants at acceptable cost.

7.3 HiPER twin chamber strategy

The strategy for HiPER construction is to proceed in two steps, 4a and 4b, taking advantage of the separable technology (see 6.2 above).

In **Phase 3a**, HiPER is constructed with the inclusion of a target chamber able to withstand fusion shots at full repetition rate in a “burst mode”. This is envisaged as a burst of 50 zero, or low yield shots interspersed with 5 full yield shots. This configuration would test the integration of the laser systems, target injection and tracking, diagnostic control systems. The chamber would not be equipped with a full blanket and targets for each run could be manufactured on a “one off” basis.

When the system is fully commissioned and running reliably in burst mode, and when target mass production is available, **Phase 3b** would commence. In this phase, a second fusion chamber will be constructed equipped with a full blanket and designed to operate with fusion shots at 10Hz for an extended period. This will enable the blanket to be optimized and the long term reliability of the whole system to be proven as required by potential commercial operators. Balance of plant would be added to demonstrate electrical power generation at a modest level.

By employing this strategy, the Phase 3a chamber could be operated to de-risk many aspects of the systems integration without the need for target mass production or a fully developed first wall concept.

7.4 Deliverable with existing materials

The approach taken by the LIFE team in the US is to use a low pressure gas fill within the fusion chamber to protect the plasma-facing “first wall” from damage induced by high energy ions and X-rays that are produced in the fusion reaction. At the same time, the separation of the laser driver from the chamber leads to a mechanically simple design in which the first wall is neither the vacuum barrier nor a structural component.

The shock ignition scheme adopted by HiPER could be amenable to the gas fill solution provided that a suitable high mass heat shield is integrated with the fuel capsule. Studies will be conducted into the effects of such an atmosphere on the positioning accuracy of the fuel pellet during Phase 2.

This being the case it is possible that existing materials could be used for the first wall of a shock ignition reactor. These would be replaced when neutron impact damage reduces the material strength to a pre-calculated minimum acceptable level. In an operating plant, it would be possible to incorporate multiple fusion chambers. A mirror system would offer a convenient way to switch driver beams between fusion chambers, would allow the first wall change-out to occur “off-line”, reducing interruption of the power production cycle.

An alternative to gas protection would be the physical separation of the first wall, breeder blanket assembly and chamber containment pressure vessel. Consequently the pressure vessel is isolated from the flux of neutrons and can be constructed using existing qualified materials. It is highly likely that this approach would gain regulatory consent.

The only optics exposed to fusion neutrons are the final beam focusing systems. Optical materials are already available which are self-annealing under neutron bombardment, while the chamber gas fill protects against X-ray and ion damage.

Thus commercial-scale Laser Energy is deliverable using currently qualified materials, while improvements in material resistance to neutron damage will enable the time between first wall changes to be extended, improving plant availability, reducing operating costs and increasing profitability.

8 Shock ignition for HiPER

There are two principal schemes for ignition of a fuel capsule using laser drivers; direct drive (DD) as adopted for HiPER and indirect drive (IDD) as adopted for LIFE, in which laser light is converted to X-rays which then compress and heat the fuel capsule. Both schemes involve compression of a thin-shelled capsule containing deuterium (D) and tritium (T) to very high density and then heating a very small region of the D-T fuel to very high temperature, producing ignition, with a burn wave propagating through the compressed fuel. The schemes differ in the way in which the energy is delivered to the fuel capsule. Each approach faces challenges related primarily to target design and laser/plasma interaction physics and, where facilities exist to test hypotheses, experimentation is underway to explore optimum solutions.

Current programmatic emphasis for HiPER is upon “shock ignition”, but advanced schemes including “fast ignition”, also based on direct drive, have been proposed. These cannot currently be pursued at full scale due to the non-availability of appropriate facilities but, while the current focus is on shock ignition for which suitable experimental facilities are available.

In the shock ignition scheme, the fuel capsule is first compressed to moderately high density by firing a long laser pulse directly onto the surface of the fuel capsule. At the end of the compression, as stagnation is reached, a convergent spherical shock wave is launched into the compressed fuel using a high intensity laser “spike”. The shock wave converges on the high density core and collides with the rebounding shock wave. Both the shock convergence and the shock collision result in pressure amplification and, with appropriate target design, simulations predict that the temperature of the fuel can be raised to the ignition point.

There are important advantages of the shock ignition scheme over conventional “indirect drive” ignition. The thicker fuel capsule shell and lower implosion velocity lead to reduced hydrodynamic instability; the energy required for the initial compression is reduced; the shock ignition pulse requires less energy to ignite, since only the hot spot is raised to ignition pressure compared to conventional central hotspot ignition which requires that the whole mass is raised to ignition pressure. The direct drive scheme also avoids the inefficiency of X-ray conversion associated with the indirect drive scheme and the energy gain of the target is increased.

8.1 Shock ignition “roadmap”

The main disadvantage of the shock ignition scheme is that it is comparatively less well developed than the indirect drive approach. To demonstrate repetitive operation as required for commercial energy production, systems engineering issues must be addressed regarding survival of the fuel capsule once injected into the fusion chamber.

The Shock Ignition Roadmap, currently under development, will identify the programme of experiments, numerical simulations and systems engineering studies required to develop shock ignition to the point at which it can be demonstrated in single shot ignition events at Laser Méga Joule (LMJ) and developed into a credible ignition platform.

The experimental, computational and engineering programmes, including underpinning experiments on sub-ignition scale facilities and fielding of a full scale “scale 1” ignition campaign on LMJ, represent a substantial challenge for the European community. The funding, scheduling and resourcing requirements are currently under development and will form a major element of the Phase 1 HiPER Business Case.

Important aspects of the shock ignition scheme which require development are identified below.

Drive uniformity

In every ignition scheme, it is necessary to deliver uniform drive on the fuel capsule in order to reduce the growth of hydrodynamic instabilities. In the case of indirect drive, this is achieved through conversion of the laser drive to X-rays within a Hohlraum which bathe the fuel capsule uniformly in radiation. In direct drive schemes such as shock ignition, drive uniformity must be achieved through the disposition of beams around the capsule. Ideally this would be achieved by arranging distribution of many drive beams over the entire capsule surface. This arrangement is not available for the foreseeable future at the NIF or LMJ facilities, which are configured for indirect drive with beams distributed around two (LMJ) or three (NIF) axial cones. A promising solution to this issue is a hybrid "polar direct drive" (PDD) arrangement whereby some of the beams from the higher angle cones are re-pointed towards the equator of the fuel capsule.

The advantage of the PDD arrangement is that it can be fielded on NIF and LMJ facilities in their "Day 1" configuration (i.e. no modifications to the facility are required beyond re-pointing the beams). Further enhancements are available at modest cost by changes to the phase plates which modify the energy distribution of each beam on the target surface.

Calculations suggest that the PDD arrangement produces sufficient drive uniformity to achieve the required level of compression without driving hydrodynamic instabilities. Experimental verification on existing sub-ignition facilities is required before a compelling case can be made for full scale compression experiments at LMJ or NIF. A series of experiments is being planned using existing intermediate scale facilities such as Orion (UK), PETAL (France) and Omega (US).

Laser plasma interaction physics

There is a high level of confidence in the hydrodynamic performance of relatively large targets (>1.5mg) with correspondingly high laser drive energy (~ 1MJ). Smaller targets, with laser drive energies within the reach of existing facilities configured for polar direct drive, are less well understood. Furthermore, preliminary experiments performed to date have not achieved the ablation pressures in the 300Mbar regime that are required for shock launch. Equally, the role of hot electrons generated in the interaction of the laser spike and the compressed fuel is unclear. In the traditional central hot spot ignition scheme, hot electrons lead to target pre-heat and lower compression for given laser drive; in shock ignition hot electrons are potentially beneficial as they may contribute to enhanced energy transport and improved shock uniformity.

A comprehensive series of experiments is therefore required to explore the regimes of importance and to increase the fidelity of the numerical models needed to design full-scale ignition experiments. These experiments are being specified as part of the shock ignition roadmap.

Systems engineering and reactor modelling

Provided that the experimental and simulation programmes identified within the Shock Ignition Roadmap are favourable, ignition and burn of a fuel capsule at high energy gain by shock ignition using the "Day 1" configuration of either LMJ or NIF is a real possibility. This will be a vital demonstration but important systems engineering issues must be addressed in order to progress to commercial power production.

Currently the most important systems consideration is the technical strategy for delivery of the shock ignition fuel capsule to the ignition point in the fusion chamber. The first shock ignition demonstration experiments at LMJ or NIF will be conducted in an ambient temperature (20 deg C), evacuated target chamber with the cryogenically cooled target mounted in a fixed position. This is far removed from conditions which will be encountered in a power plant environment, which is likely to be running at temperatures exceeding 600 deg C. Targets will be accelerated to 100's $m.sec^{-1}$ before injection into the fusion chamber.

All of these environmental factors impact upon survival of the target prior to engagement by laser beams. For example, to maintain the target at the D-T triple point requires the shortest possible exposure time to the hot chamber environment. This demands high injection velocity and associated high acceleration. Survival of the target under such acceleration and its travel at high velocity through the chamber gas will impose constraints on the target's mechanical design which in turn may affect its ignition performance.

To satisfy the above requirements, and others which will emerge as understanding of the issues improve, requires a comprehensive systems engineering approach. The full extent of the systems engineering effort required for the next phase of the project is being developed and cost schedule will form part of the business case for the next phase.

8.2 Timeline for LMJ shock ignition demonstration

An indicative timeline for first demonstration of shock ignition at LMJ is shown in Figure 5.

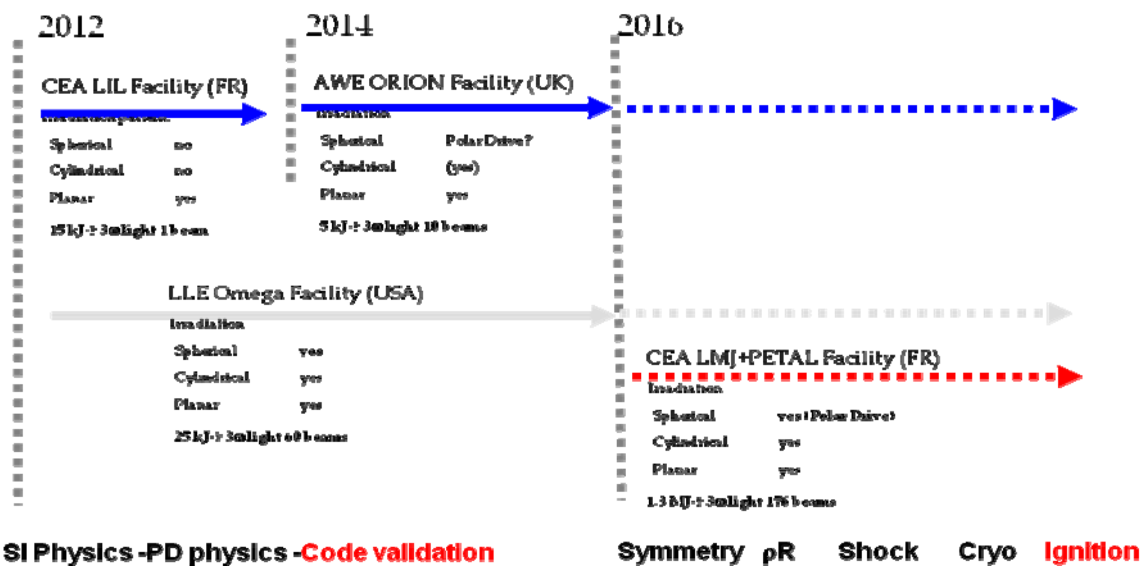


Figure 5: Indicative timeline for shock ignition demonstration on LMJ

In the period to 2016, existing sub-ignition facilities including LIL (France), Omega (US) and Orion (UK) are used in a series of experiments to improve fidelity of the numerical simulations and to study outstanding aspects of shock ignition physics.

In the 2016_2020 time period, a programme of experiments would be conducted using the LMJ facility to prepare the shock ignition platform. This includes validation of the hydrodynamics using the polar direct drive arrangement, compression experiments to demonstrate that high density conditions can be created and studies of shock generation propagation. These experiments will be conducted initially using warm (non-cryo) targets. The cryogenic D-T campaign will commence by 2020 and, given sufficient beamtime at the facility to perform the necessary tuning and optimisation, ignition is expected around 2022.

The cost of the experimental programme at LMJ will depend on many factors, including the negotiation of beam time costs and charges for experimental support, target manufacture, diagnostics provision. These costs will be identified following negotiations with the facility operators which will be included within the Business Case.

9 Current Status of the Technology for Laser Energy

Demonstration of ignition and burn of a cryogenic D-T target, on a single shot basis, is an essential step towards demonstrating the commercial viability of power production from Laser Energy. Translation of that single shot event to a repetitive process, mass production of targets at low cost, energy capture and plant lifetime are equally important to commercial power production. For Laser Energy to make a significant contribution to meeting world energy needs on a relevant timescale, these aspects must be addressed in parallel with the campaign to demonstrate single shot ignition.

9.1 Laser Driver

The present conceptual design for the Laser Energy pilot plant is based upon 10kJ laser beamline units, replicated to deliver the required total laser energy uniformly to the fuel pellet target. Commercial viability requires an overall energy efficiency of ~10% and a pulse repetition frequency (prf) of 10 – 15Hz. These requirements imply the need for a new laser architecture. The most cost effective solution identified for this is based on advanced solid state laser gain materials pumped by diode lasers.

A small-scale (10J) system (DiPOLE) is currently under development at the Centre for Advanced Laser Technology and Applications (CALTA), STFC Rutherford Appleton Laboratory. A similar system, LUCIA, is already operating at the LULI laboratory in Paris. Results from both systems are very encouraging.

The DiPOLE architecture is intrinsically scalable and a development path to 100J and 1kJ has been identified. When scalability is proven at the 1kJ level, construction of a 10kJ demonstrator would represent low technological risk, implemented as an array of 1 kJ units. Similarly encouraging results have been obtained from the LUCIA laser at École Polytechnique, Paris.

A detailed discussion of the laser technology for HiPER is available in Appendix I.

A strong market is foreseen for laser systems operating in the 1kJ – 10 kJ, 10Hz regime. In industry, applications will be developed for materials processing; in medicine for advanced beam therapies, in advanced imaging for security and inspection applications and in fundamental science, where the high repetition rate enables signal averaging, detection will be possible of phenomena many orders of magnitude below the threshold of current diagnostics.

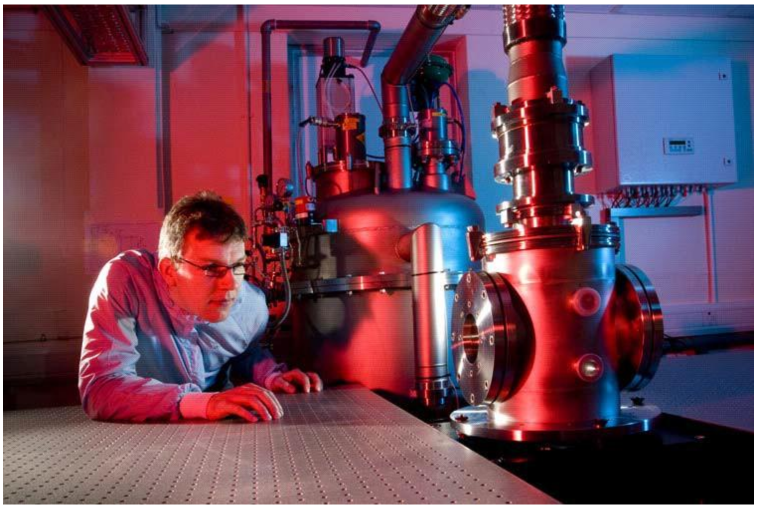


Figure 6: The DiPOLE prototype laser

The demands of such an ambitious "next generation" laser development programme are an excellent match to the expertise of the HiPER partners.

9.2 Fusion Chamber Design

Europe has extensive industrial capability in fission reactor design vested in companies such as EDF, AREVA, CEA, Rolls Royce, AMEC, etc. The design requirements of a repetitively pulsed fusion chamber are similar to those of several fission reactor variants including liquid metal cooling systems, remote and robotic handling, materials activation, waste minimisation, high process availability and low maintenance. These similarities make the commercialisation of Laser Energy an attractive proposition to all these companies. For some, being in both fission reactor design and energy supply, the attraction of this new technology is two-fold.

Within the European academic community much work is being done on production and assessment of new materials for fusion chamber design. Spain is leading studies into fusion chamber, blanket and energy extraction, including modelling and thermodynamics. UK has a leading fusion materials centre within Culham Centre for Fusion Energy, whose work could be extended from its current remit, magnetic fusion, to incorporate aspects of inertial fusion. In France, CEA forms a central hub for laboratories involved in assessing materials for Generation IV fission, many of which could be considered for inertial fusion applications.

Obvious synergies exist between the requirements of Laser Energy and magnetic fusion (ITER). These include neutron resistant materials, tritium breeding and recovery, energy extraction and waste management. The broad spectrum of development work undertaken by the magnetic community in Europe and elsewhere should be harnessed to assist in the future development of fusion plant design. Capture and use of this valuable knowledge by the Laser Energy engineering community is an important element of the European programme.

Technology developments for the HiPER fusion reactor must be undertaken in a measured and progressive manner, focused on continuous risk reduction for the future construction phase. Wherever possible, existing qualified materials will be used. These are likely to satisfy all but the chamber first wall requirements. The first wall is subject to high heat loading, fast neutrons, helium nuclei (alpha particles), ions and X-rays. This is an environment which will cause significant damage over time and reduce the life of first wall materials. New materials more suited to this environment are being developed. Examples are nano-structured tungsten and carbon nano-tubes, both of which permit surface exfoliation of helium gas derived from alpha deposition and accommodate very high heat loadings. These materials show considerable promise for a reactor first wall but much remains to be done on testing capabilities. This work will continue in the early years of technology development, with significant investment occurring after ignition on LMJ, when conceptual design and prototyping of the first wall will be undertaken.

From a regulatory perspective, segregation of the first wall and breeder blanket from the fusion chamber containment (pressure wall) and design of the containment using known and qualified materials would increase the probability of regulatory endorsement for a fusion chamber of this type.

9.3 Target Design and Physics Modelling

The design of the target employed in the first shock ignition experiments at LMJ must be optimised for robustness of ignition rather than for high gain and efficient burn. Once ignition has been demonstrated and the ignition platform characterised, the target design must be re-optimised for high net energy gain, insensitivity to laser drive variations, substitution of preferred materials, and low unit cost. Through expertise and modelling tools available within the UK and links with theacademic community via the Centre for Inertial Fusion Studies (CIFS), and in France (CEA and CELIA), HiPER is well positioned to make significant contributions to this work.

Substantial intellectual property opportunities are available in this area, as future commercial viability of the Laser Energy scheme will ultimately reside in design and development of high energy gain fuel pellets. Protection of intellectual property will be critical to gaining maximum return on this investment.

9.4 High Volume Target Manufacture

Each Laser Energy plant will require approximately one million fuel pellet targets per day. Commercial modelling from the HiPER Preparatory Phase indicates a maximum acceptable unit cost for targets of approximately 0.5 Euro. The current cost of NIF targets, which are made individually and require many manual assembly steps, is more than four orders of magnitude higher than this. Commercial viability of Laser Energy plants therefore requires a step change in manufacturing techniques to increase production rates and reduce cost.

Potential process solutions have been identified but all need development to meet the systems requirement for commercial Laser Energy. Again, intellectual property is a key factor and the UK and France have the potential to reap substantial benefits in this area.

The technologies required for mass production of Laser Energy fuel pellets have very significant commercial potential. Examples include advanced coating and polishing, micro electro-mechanical systems (MEMS), microfluidics and dielectro-phoresis. Investment in new capability and capacity in these areas will produce commercial spin-off opportunities.

9.5 Target Injection and Tracking

The fuel pellet or "target" must be injected into the fusion chamber at high velocity, as its survival time in this hostile environment is limited to 10's of ms. Precise timing, tracking and laser aiming systems are required to ensure that multiple laser pulses strike the target symmetrically as it reaches the centre of the fusion chamber.

The requirements for injection and tracking, derived from target design and reactor modelling, are comparable with those of military systems, though they require development for adaption to the environment of a Laser Energy fusion chamber. This development is assumed to be specific to Laser Energy, although it is likely that exploitation opportunities will be identified.

The Institute of Physics (IoP) in Czech Republic has funded development work on target injection and position sensing within the HiPER Preparatory Phase Project and this programme is set to continue within the Technology Development phase.

9.6 Control Systems

The control system hardware technology already exists for a Laser Energy plant. The high operating speed of some systems requires development of bespoke software to achieve the necessary performance parameters. This will require detailed definition, extensive software development and testing prior to construction. It is not necessary to commence this work until Phase 3.

9.7 Supporting Plant and Machinery

The technology for other plant is already available. This includes cryogenic cooling, radioactive materials management, tritium handling, Heating, Ventilation and Air Conditioning (HVAC), building services and power generation. No further development of these technologies is needed at this stage.

9.8 Building

Building technology already meets the requirements of a Laser Energy plant and no further development is needed. Evolving best practice associated with low carbon footprint construction, operation and decommissioning of large scale infrastructure will be incorporated in the design during the next phase through normal planning permission processes.

10 Existing partner capabilities

A European Laser Energy Programme will build on existing capabilities and exploit strategic international partnerships, avoiding duplication while maintaining the strategic option to proceed with future construction on a European basis should this become necessary. It will exploit previous investment in the technical work of the HiPER Project and give best advantage for Europe in the short, medium and long term.

European capabilities for technology development and risk reduction (Phases 2 & 3) have been identified during the HiPER Preparatory Phase Project and are summarised below.

10.1 United Kingdom (HiPER Coordinator)

The Science and Technology Facilities Council (STFC)

STFC is recognised as a world leader in advanced, large-scale laser development and associated technology, including the concept development of ultra-high peak power DPSSL laser systems, diagnostics, and micro-target design and fabrication. The wide ranging capability of STFC gives access to comprehensive in-house engineering services including precision mechanics, nano-technology, cryogenics and high-bandwidth electronics. STFC has recently delivered a number of large scale development projects including the Diamond Light Source synchrotron and ISIS Target Station 2.

STFC Centre for Advanced Laser Technology (CALTA)

High power laser technology is now on the threshold of an evolutionary step with the development of high peak power, high average power high repetition rate lasers, based on Diode Pumped Solid State Laser (DPSSL) technology. This will pave the way to new industrial processes and products. These are likely to include enhanced scanning and imaging techniques, table-top accelerators, defence and homeland security applications, advanced industrial materials processes and advanced cancer treatments. The technology may also deliver the laser drivers required for the European ELI project and, ultimately, the 10kJ 10Hz laser modules needed for Laser Energy itself.

The STFC has seed-funded CALTA with a mission to develop these laser technologies, harnessing the intellectual property from the designs. The Centre will provide laser platforms, upgrading them as the technology progresses and providing industry with access to the technology for application and product development, while also providing science with access for experimentation.

AWE Aldermaston

AWE's new high power laser system, **Orion**, comes on line in 2012 as one of the most powerful research lasers operating in Europe. To deliver this facility AWE has built new capabilities and skills in partnership with industry in areas including advanced optics, engineering design, specialist manufacturing, project delivery and large facility commissioning, management and operations. AWE is also managing the delivery of other major capital schemes as part of its capability sustainment programme and is well placed to play a key role in the next phase of HiPER.

The company’s expertise in high performance computing, modelling and simulation of laser/plasma interactions places AWE at the forefront of work to optimise fuel pellet performance, while its longstanding working relationship with the Lawrence Livermore National Laboratory in the USA will enhance collaboration as Laser Energy develops internationally.

AWE is also making an important contribution to work on the mass production of fuel pellets, underpinning the commercial credibility of Laser Energy. Its world leading capability in micro-scale target production supports scientific programmes on both sides of the Atlantic. Synergy with the physics design capability will allow AWE to join other HiPER partners to make a unique contribution to fuel pellet design and production.

UK Industry

Ultimately, industry must play a leading role in the Technology Development Phase and the subsequent implementation of Laser Energy.

A key activity of the Technology Development phase will be to encourage industry to engage and invest in the development of mass production techniques for the components and systems required. Laser diode manufacture is a notable example of the potential for investment in automated production to bring substantial rewards in intellectual property and exploitation rights, both in the intermediate and longer term, with proven market appetite for enhanced capability and applications for diodes. This benefit will be realised independently of large scale uptake of Laser Energy.

Engagement with industry is already an important element in the HiPER Preparatory Phase project. The R&D Society event "Laser Energy, an opportunity for UK industry", held at the Royal Society in September 2011, was well received by participants. MoU's continue to be negotiated with major companies which can support future steps towards delivering Laser Energy.

Academic Community

Establishment of the Centre for Inertial Fusion Studies (CIFS) at Imperial College in 2009 provides an important interface between the academic and AWE communities. CIFS provides the ideal vehicle for growth of the academic and engineering groups which will be essential to deliver future phases of Laser Energy.

It is widely accepted that large projects with strong societal missions are significant attractors of skilled people. A Laser Energy programme will trigger a demand for expertise, requiring growth of the academic community in laser physics, plasma and experimental physics, micro fabrication, engineering and robotics. Such growth demands an increase in the training available through UK academic courses and apprenticeships.

10.2 France

The capabilities of France in the domain of Laser Energy include a large set of equipment and expertise distributed in National Laboratories, in the academic community and in industry.

National laboratories

France develops and operates several large-scale laser facilities relevant to Laser Energy, in Paris (LULI, École Polytechnique) for CNRS and in Aquitaine (PETAL & LMJ) for CEA.

LULI is the national academic large-scale infrastructure dedicated to high-power high-energy lasers for the study of laser-generated plasmas and their applications. It operates LULI2000 and ELFIE, two multi-beam laser facilities coupling nanosecond and picosecond laser chains at maximum energies of respectively 1 kJ and 100 J for LULI2000, and 100 J and 30 J for ELFIE. These facilities are fully open for access to the national and European scientific community and to the international community through collaborations.

LULI also develops a diode-pumped solid-state laser LUCIA that will help design the next generation of high-power lasers, one of the prerequisites for a future reactor based on Laser Energy.

In Aquitaine, CEA is commissioning a MJ-scale laser system, **LMJ**, which will enable European researchers to study the physics of laser-driven inertial fusion at full scale, including advanced schemes such as shock ignition. This facility will be partially open to the academic community for basic science and inertial fusion energy research.

PETAL is a multi-PW multi-kJ picosecond chain that will be coupled to LMJ. Funded by the academic community, it will both add unique diagnostic capabilities on LMJ and allow exploring the physics of fast-ignition in relevant conditions.

While LMJ is progressively commissioned, CEA continues to operate its **LIL** facility, a 30 kJ nanosecond laser, also partially open for access to the academic community.

In addition to these unique facilities, CNRS and CEA have acquired a large body of expertise on all aspects of laser-generated plasmas, on experimental, theoretical and numerical aspects, as well as technologies associated with these programs, up to the realisation of MJ-scale ignition experiments.

Academic community

In France, the "Institut Laser Plasma" gathers the academic community working on high-power lasers and laser-generated plasmas. More than 200 scientists develop research programs on the physics of laser-generated hot plasmas, most often in the context of national and international collaborations.

In so-called "Grandes Écoles" and universities, training in the domains of laser, optics, plasmas and their applications is very active at the Engineer level and in various Master degrees as well as PhD and post-docs in the research laboratories.

Industry

In France, a program like HiPER can clearly be supported by a wide panorama of industries in the domains of lasers and optics, but also in the design and construction of large infrastructures such as LMJ and nuclear power plants.

Several events have already been organised with industrial companies in order to present the project and the perspectives regarding the design and the construction of a HiPER infrastructure, as well as the R&D work to be pursued in the next years.

10.3 Greece

National laboratories

Greece actively participates in the HiPER project at governmental level. Greece via the General Secretariat for Research & Technology (GSRT) has funded the establishment of a national network for HiPER, the so called HiPER – GR (http://www.hiper-hellas.teicrete.gr/). A feasibility study for the establishment of the network and the way for the participation of the country in the HiPER project has been performed and was the main deliverable of the HiPER-GR project. The study was set up to test the feasibility of a national shared service (Network) for HiPER. This would build on existing investment and good practice, fill gaps and develop capacity for the long term. A successful National HiPER-GR Network will:

- Co-ordinate research performed in Greece related to HiPER (by establishing a Hellenic research agenda and implementation plan)
- Enable high quality scientific research related to HiPER
- Provide access to tools and expertise
- Be a focus for the development of policies and standards
- Provide access to effective training services and materials
- Engage existing facilities and expertise
- Be more cost effective as a shared service than institutions acting independently
- Give the opportunities to Hellenic SMEs to participate to tenders and procurement related to HiPER

This study describes in detail the high capabilities of the HiPER-GR network. The case study work involved consultation with groups representing approximately 50 researchers and academics, identified a number of issues (key findings):

- An increasing number of disciplines and research activities from the Hellenic Higher Education and Research Centres Sector that can be involved with HiPER scientific program
- There is an acknowledged interest for researchers and academics to be involved with research done at HiPER
- Most researchers and academics believe that there is a need for a regional small scale national facility in Greece
- Most researchers and academics use a national or international facility in other projects
- Most researchers are interconnected and share related data
- Those who did not have access to an established facility were particularly keen on a regional small scale facility.

The engagement with stakeholders and desk studies indicated that there is substantial expertise and infrastructure available in Greece related to the science of HiPER.

The study showed that for a way forward a Co-operative Service with one facilitator is the best option. Under this option, the HiPER-GR network will act as an enabling service (Facilitator) working with the many Hellenic stakeholders. Such a service will be well placed to act as a catalyst for new services and partnerships, as a centre of excellence, as a standards-guiding body and as a source of expertise and information about data management and repositories, building on current best practice and facilities. The Centre for Plasma Physics & Lasers (CPPL) of TEI of Crete is the central facilitator of the service. CPPL is an internationally renewed centre pursuing cutting edge research in plasma physics and laser matter interactions (http://www.cppl.teicrete.gr).

The following summarises the structure of the established Hellenic HiPER Network

12 Academic Institutions:

- TEI of Crete, Centre for Plasma Physics and Laser (CPPL) – Coordinator - regional HiPER facility
- TUC, Technical University of Crete, Laboratory of Matter Structure and Laser Physics, (MSLP -Sciences Department)
- UoI, University of Ioannina, Laboratory of Atomic and Molecular Physics and Central Laser Facility (Department of Physics)
- NTUA, National Technical University of Athens, Physics Department (School of Applied Mathematical and Physical Sciences)
- NKUA, National and Kapodestrian University of Athens, Group of Electrical Characterization of Electronic Devices (Physics Department)
- ICEHT-FORTH, Institute of Chemical Engineering and High Temperature Chemical Processes (ICEHTCP), Foundation for Research and Technology Hellas (FORTH)
- Academy of Athens
- UPAT, University of Patras, Laboratory of Photonic Materials, Structures and Applications (Department of Materials Science)
- DUTH, Democritus University of Thrace, Laboratory of Electromagnetism and Space Research (Department of Electrical and Computer Engineering)
- NCSR “D”, National Centre for Scientific Research "Demokritos", Institute of Nuclear Technology and Radiation Protection (INTRP)
- NHRF, National Hellenic Research Foundation, Theoretical and Physical Chemistry Institute (TPCI), Photonics for Nano-applications Laboratory and the Applied Spectroscopy Laboratory

- IESL-FORTH, Institute of Electronic Structure and Laser (IESL), Foundation for Research and Technology Hellas (FORTH)

2 Energy related Companies

- PPC, Public Power Corporation S.A.
- Tropical, Tropical S.A.

The creation of this interdisciplinary HiPER network in Greece is supporting the demanding task of HiPER but also is incorporating and utilizing the output of new knowledge, while scientific sectors of the project covering several areas of Sciences and Technology. The conclusion is that Greece has a sound basis on which joined the HiPER infrastructure and reinforced its current infrastructure. Lately, GSRT has announced the further financial support for HiPER with 2MEuros to support the national regional HiPER infrastructure at TEI Crete/CPPL.

Academic community

The HiPER project is certainly an attractor for the academic community in Greece. Its dual mission (energy, fundamental science) is attractive and has led to the expression of interest of 12 Universities and research centres within Greece. The establishment of the Hellenic HiPER network (HiPER-GR) and the national regional infrastructure in Crete (CPPL) is the result of the high interest of the Hellenic academic community for HiPER. This network and the regional HiPER facility is a top-level academic capability of Greece in relation to the HiPER project. The growth of the academic community in Greece but also in Europe is a key issue for HiPER. TEI of Crete/CPPL has put significant efforts in the development of training programmes relevant to HiPER such as 1) Erasmus funded Intensive Programmes, 2) Erasmus funded new Curriculums for European Master Degrees on HiPER related Physics & Technology and 3) further networking for training at the PhD and Postdoctoral training.

Industry

Industry must play a leading role in the Technology Development Phase of the HiPER infrastructure. Two distinct industry groupings have been identified as stakeholders from the Hellenic industry.

'Early adopters' will form the initial core skills and capability. Early adopters may grow in scale over time, but their efforts will be focused initially on areas of most pressing need (i.e. optoelectronic technology, automation systems etc). It is likely that at the detailed planning stage early adopters will be further qualified in the light of practical priorities.

'Later adopters' may be added subsequently. Later adopters may start to come on board roughly two years after the launch of HiPER facility and, as for early adopters, may also be scaled-up over time.

10.4 Italy

Academic and Government Research institutions

After the significant involvement in the early stage of Inertial Confinement Fusion (ICF), with activities at the ENEA Research Centre in Frascati, Italy has played a key role in the European endeavour towards the establishment of scientific grounds of Inertial Fusion Energy (IFE). Key academic and research institutions the Universities of Rome, Pisa and Milano, under the CNISM consortium, and CNR, with groups now belonging to the CNR Institute of Optics in Pisa, and have been building expertise in a range of ICF related areas, including theory and numerical modelling of hydrodynamics, laser and laser-plasma diagnostics, fusion materials and radiation safety. Over the past decade, these activities were funded under competitive schemes including the so-called FIRB, PRIN and FISSR which enabled the national community to establish itself and grow significantly.

This process culminated in 2007 in the endorsement by the Ministry of University and Research (MIUR) of the participation of ENEA, CNR, CNISM and INFN in the HiPER preparatory phase (FP7). Italian groups belonging to these institutions were involved directly, often with leading roles, in key areas concerning the definition of the basic HiPER point design, the overall facility design and layout and the experimental physics programme at existing small and medium laser facilities. More institutions and academic groups are also working on related topics and collaborations are being developed also in view of future engagement in the next Phases of HiPER.

From the theory viewpoint, contribution comes from the academic community at different Universities nation-wide. Major role is played by the Group for Advanced Plasma Studies (GAPS) at the University of Rome “La Sapienza”, internationally regarded as a reference for the point design of HiPER. The GAPS has developed a range of numerical codes, including the 2D Lagrangian nuclear- radiative hydrocode DUED for plasma studies especially related to Inertial Confinement Fusion. The publication record of the group in this area includes many of the most cited papers that represent milestones in the ICF hydrodynamic modelling. The group currently coordinates the HiPER related national PRIN project funded by the MIUR for investigation of Shock-Ignition related physics that also involves groups from the University of Bologna, the University of Tor Vergata, the University of Milano-Bicocca and the ILIL group of INO-CNR. This follows other similar grants for studying other advanced ICF ignition schemes, including the fast-ignition scheme. The theory groups at the University of Pisa and more recently from the Politecnico di Milano also provide key contribution to the theoretical and numerical modelling of laser-plasma interactions at high intensities for fusion and laser-driven ion acceleration.

From an experimental perspective, the group currently running the Intense Laser Irradiation Laboratory (http://ilil.ino.it) of the CNR-INO in Pisa has been actively working in laser plasma interactions since the late ‘80s, with special attention to laser induced instabilities in long scale-length plasmas and X-ray time resolved spectroscopy. Based on this background and thanks to a close collaboration with several groups across EU, the ILIL group has been involved in ICF activity at Large Laser Facilities in EU, including the Central Laser Facility at RAL, the LULI facility at École Polytechnique and PALS in Prague. The laboratory features a full range of techniques for laser-plasma interaction studies, based upon multi-TW femtosecond and nanosecond lasers and a range of plasma diagnostics, from the optical to the X-ray range. Recently, the ILIL lab has also been leading the construction of a new laser installation at LNF-Frascati (INFN) aimed at the development of laser-driven radiation sources.

These activities on radiation sources are also included in the wider participation, funded by the MIUR of INFN, CNR and Sincrotrone di Trieste to the Extreme Light Infrastructure (ELI), another laser-based ESFRI Research Infrastructure currently under development in the Czech Republic, Hungary and Romania. The experience gained by this participation and resulting R&D is expected to be a major contribution to the progress of several HiPER related fields.

Figure 7: The ABC laser facility at Frascati, Italy

The ABC facility in Frascati is operating a 2-beam-100J nanosecond, Nd:YAG laser coupled with a fully equipped experimental target area, with a main target chamber, frequency doubling capability and a range of diagnostics from the optical to the X-ray. This installation is currently hosting experiments from external users on a collaborative basis.

With its major involvement in the magnetic fusion ITER project, ENEA is also able to make an important contribution to in the area of materials, fusion technology and safety. ENEA also features expertise in thermo-mechanical modelling and characterization of the first wall, Tritium extraction from Pb/Li breeder, remote handling, metrology, cryogenics and superconductivity, neutron detection and advanced plasma diagnostics.

ENEA was among the first to launch, in the early '90s, the concept of diode pumped lasers for IFE. Diode-pumped laser concepts for future high-repetition rate IFE installations are being explored in a wider collaboration that includes groups at the CNR Institute of Optics in Florence with established expertise in diode pumped lasers, the CNR Istitute of Ceramic Materials in Faenza, the ENEA research centre in Frascati and the ILIL Lab. This is an important example of the activity that is expected to benefit from the synergy between HiPER and other laser-related large initiatives (e.g. ELI).

R&D and spin-off activities

Following successful academic research carried out also within the HiPER preparatory phase, a range of activities are ready to spin-off to participate to the prototyping and construction of the HiPER facility. These include custom laser plasma diagnostics for ultra-high intensity interactions, prototyping and characterization of optical components (INO-CNR). Of particular importance are the in-house capabilities for R&D on new lasing ceramic materials on their way to become competitive with world leader industries (Konoshima Chem. Co.) (ISTEC-CNR).

Key nuclear physics and technology capabilities are also accessible through the INFN Laboratori del Sud (LNS), where established expertise exists in the construction, commissioning and operation of large nuclear installations. LNS also has strong collaboration with ST-Microelettronics, FBK-Trento, CAEN, Hitec2000, for the development of detectors, inclusing front-end electronics, acquisition and control and general infrastructures. Examples of these collaborations are the SINPHOS-SINngle PHOton Spectrometer, developed by INFN in collaboration with ST-Microelectronics, for the development of SPAD-Single Photon avalanche Diodes, and the TRIS-Time Resolved Imaging Sensors developed by INFN in collaboration FBK-Trento for the development SPAD arrays.

Industry and SME

The major involvement of ENEA in ITER and in the development of next generation fission reactors has yielded a growth of the industrial activities in the large vessels and vacuum mechanics (Ansaldo Nucleare, Mangiarotti, SIMIC, Fantini Sud) electrical engineering (OCEM). Moreover, based upon established joint participation to large infrastructures with CNR, well established links exist with leading industry including Finmeccanica Group, involving Alenia Aeronautica, Galileo Avionica, Selex Sistemi Integrati, STMicroelectronics, Carlo Gavazzi Space, El.En, just to cite a few.

Of particular relevance for the development of new laser technologies is the well established cooperation relation existing between INO-CNR and El.En., a relation that brought to the development of new industrial Laser sources in the past decades. El.En. is a relatively young Company (established in 1981 as a University spin-off) with laser sources and systems production as its core business. It is now listed at the Italian Stock Exchange and controls a group of Companies including Cynosure (USA), Asclepion (D) and others in USA, France, Spain, Belgium, Brazil and China.

CNR, being the largest research institution in Italy with a distributed network of institutes, can also facilitate links with SME in the country to cover High vacuum components (vacuum vessels, accessories, sensors etc), Fine mechanics and opto-mechanics for custom components, Personal Safety and environment protection, Electronics and control (design, construction, assembly).

Training at higher level education and engineering

Within the range of expertise required for HiPER, Italy offers experience in academic and research training at graduate, PhD and post-doc levels. Training at engineer level can be provided via stages at research centers including nuclear safety, mechanics, electronics and control systems.

10.5 Czech Republic

The HiPER project is amongst priority projects at the Czech National Roadmap of large infrastructures (Chapter 2.4 “Energy” of the National Roadmap). The Institute of Physics v.v.i. (FZU) is in charge of national coordination of R & D activities related to HiPER.

Funding 2013-15: The PP project was funded on national level by MSMT until April 2013. Negotiations are underway to obtain “keep in touch” funding for the period until 2015. Likely level of this funding will be a few thousand (6,000 to 8,000) Euro per year.

Outlook for co-funding of the implementation phase (2015 -): Good. The issue of “energy” is high on R & D politics in the Czech Republic, so there is a chance for obtaining contribution in tens of M€. The best strategy for obtaining the funding is, besides highlighting the strategic dimension, to emphasize the technology development for HiPER, as well as opportunities for partnership with the private sector.

Development of technology:

- Contribution to development of high energy / high repetition rate Yb:YAG laser technology for fusion, harnessing synergy with ELI-Beamlines and HiLASE
- Development of gain material for kilojoule Yb:YAG lasers. The private sector (Crytur) is very interested and is making its own investment in growing monocrystals that can be available, in about two year term, as gain media for multi-100-J rep rate lasers
- Ingoing injector development by private sector (Delong). The effort will continue using its own resources after 2013, with the aim to obtain detailed understanding of the phenomena involved in the acceleration and guiding. Application for national grant for 2013-2016 from the Czech Technology Agency is considered.

10.6 Spain

In the potential case of starting an industrial initiative for looking the realistic possibilities to obtain energy using the alternative of Laser Inertial Fusion, that could conclude with the decision to build an engineering demonstration facility, prototype or demonstration power plant, Spain is prepared according with previous and present expertise to contribute with the following Institutions and tools:

Electrical Utilities

Spanish ENDESA, IBERDROLA, UNION FENOSA utilities have been involved in the design and construction of many of the present fission reactors. They can prepare and they have experience in the management of such large projects. Their contributions in pushing (if demonstration appear) the structure of an Industrial Team for Energy Generation could be perfectly prepared.

Engineering Groups

There are many engineering groups in Spain that among have been extensively involved in large projects in nuclear engineering and, in particular, some in fusion in general. They may well be prepared to engage in the technology development for Laser Energy. In particular, IDOM, TECNATOM, EMPRESARIOS AGRUPADOS, IBERINCO, ABENGOA and TECNALIA should be highlighted.

They have been involved in calls for proposals in the ITER Euratom Fusion Program. Their teams have also participated in the follow-up of design and problems of present nuclear facilities for energy, including their interests in the G IV fission reactors.

Regulatory Bodies and Ministerial Initiatives

The Consejo de Segguridad Nuclear (CSN), the nuclear regulator of Spain has the main responsibility for nuclear safety in Spain. It has also an efficient and very large team of technical staff with experience in procedures for managing the regulatory and safety aspects of Laser Energy.

The Ministry of Industry and Energy of Spain has started very recently an important initiative, INDUCIENCIA, that will enable closer engagement between the industry and research centres and universities in the context of energy.

Other key institutions with interest in energy and fusion, with extensive programs for funding in the industrial phase, is the Centro Para el Desarrollo Technologico Industrial (CDTI) that reports to the Ministry of Economy and Competitiveness. It has the responsibility of coordinating initiatives that join industry and research & development in areas of potential interest such as energy, space and others. T his institution can contribute to the funding of specific connections aimed at the advancement of industrial quality. The Laser Energy goal matches the objectives of this organisation.

Research Centres

The Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT) of Spain is a research institution that reports to the Ministry of Economy and Competitiveness (previously in former Ministry of Science and Innovation). It is the main research centre in fusion and fission. Though currently focused on magnetic fusion, much of its research could be of benefit to Laser Energy in areas such as materials, systems, diagnosis, components, remote handling and others. With a large group in magnetic confinement plasmas, it operates the large Stellarator TJ-II facility in collaboration with universities within the EFDA and F4E communities.

The Consejo Superior de Investigaciones Científicas (CSIC) [National Research Council] is the main Spanish centre for pure and applied research with a large portfolio of activities. While currently not specifically involved in energy, there are inter-disciplinary groups that are engaged in research in lasers, optics, robotics and materials physics, and could be perfectly involved in large research projects for Laser Fusion through its experience. Some groups, in collaboration with Universities (e.g. UPM) are already involved in basic and applied research in some very specific fundamental physics areas in materials, computation, remote handling for fusion and some in particular for inertial (laser) fusion.

Universities

Since 1980, the main contributor to research in inertial fusion (both laser and ion driven) has been the Universidad Politécnica De Madrid (UPM) through its specific Research Institute Instituto Fusion Nuclear (DENIM). DENIM is the unique centre with a programmatic goal for energy from Laser Inertial Fusion in Spain and it is conducting dedicated research in this area. Contributions from DENIM, both in theory/computation and experiments, are in high energy density physics (both radiation hydrodynamics and atomic physics), in materials for functional and structural requirements, and full study capability for power plant research under a coupled scheme of simulations and specific developments and analysis for the many different research goals in each one of the components of the systems: first wall, cooling, breeding, tritium handling, activation, safety and environment.

The Universidad Nacional de Educación A Distancia (UNED) is also engaged with inertial fusion in collaboration with DENIM, particularly in the areas of activation, safety and power plant.

There are other universities in Spain with groups working in magnetic fusion that might contribute to Laser Energy. These include Universidad Autónoma de Madrid / Centro de Aceleradores, Universidad Carlos Iii de Madrid, Universidad Complutense de Madrid, Universidad del Pais Vasco and Universidad Politecnica de Cataluña.

In addition, the Centro Láser de Pulsos Ultracortos, Instalación Científico Tecnológica Singular [Laser Centre for Ultra short Pulses/National Users Facility] within the Universidad de Salamanca will operate the largest laser in Spain (in the femtosecond and Petawatt regime). This could make an important contribution to Spain's national role in Laser Energy.

11 Strategy Options for a European Laser Energy Programme

High level options for the European response to the Laser Energy opportunity are identified as follows:

11.1 Option 1: Do nothing

The "***Do nothing***" option will consign Europe indefinitely to customer status in the Laser Energy arena. "***Do nothing***" would risk Europe being strategically and commercially exposed in a future energy landscape dominated by laser driven fusion when this is taken forward by others.

11.2 Option 2: Postpone investment until NIF Ignites

First ignition of a Deuterium/Tritium target at NIF is widely accepted as a critical milestone in demonstrating the commercial viability of the Laser Energy scheme. Current progress at NIF indicates that this achievement is expected within the next 18 months.

Postponement of investment in HiPER until NIF ignites would minimise expenditure in the short term but the delay imposed would be supplemented by the timescale required to produce a coherent business case for Phase 2 and 3. This would result in loss of the collaborative culture built between participants in the HiPER project to date. Opportunities to capture commercial advantage by harnessing key intellectual property which would have arisen early during Phase 3 would also be delayed, placing these in jeopardy as rival communities continue their development.

The current European Laser Energy community is small and must be grown in key technical areas. This requires base level funding in the period leading up to ignition at NIF, to maintain the community, prepare a business case and establish a platform from which a HiPER Laser Energy programme can be launched.

11.3 Option 3: Postpone investment until LMJ Ignites

This option concerns the approval in principle of a HiPER programme following review of the Business Case, but postpones allocation of any funding until after ignition has been demonstrated at LMJ. It minimises short and medium term expenditure but incurs significant delay. The current community would not be maintained, far less enabled to grow appropriately to represent a competitive capability on the necessary timescale. At best this would result in a "cold start" to the programme in the "post ignition" era and all of the advantage gained through the Preparatory Phase of the HiPER Project would be lost. Against the background of continuing development in the US, this loss of project momentum would seriously undermine credibility of any European effort and put at risk much of the potential economic benefit of a future programme.

11.4 Option 4: Staged and progressive investment

A balanced programme of technology development, industrial engagement, environmental and safety studies and commercial modelling is undertaken within Europe and, potentially, with other international partners. Development would be undertaken within the framework of a European "HiPER" Programme on Laser Energy.

The programme would be profiled to balance spend in early Phase 3, "Pre-ignition at LMJ", technology development being funded during this time at levels commensurate with the protection of European interests in intellectual property and to establish a knowledge base. The work undertaken would then be used in the formulation of a business case carefully timed to coincide with ignition on LMJ which would permit rapid ramp-up of Technology Development activities, "post- ignition" at LMJ.

The early Phase 1 programme would include continuation of the technical work required to capture early arising intellectual property. This will enable Class A (+/- 10%) estimates of Phase 2 and 3 to be developed and identification of associated risks. Work would continue with key stakeholders including industry, academia and national governments.

Following ignition at LMJ, the Phase 2 programme of technology development and risk reduction would ramp up upon release of Main Gate funding commensurate with the retention of the Phase 3 option for independent construction of the prototype in the 2030's.

11.5 Recommendation

The recommendation of the HiPER Project community is to follow Option 4; to establish a European "HiPER" Laser Energy Programme, to continue funding business case development, preparatory technical and industrial engagement activity (Phase 1), with the first significant investment in technology development and risk reduction following demonstration of ignition at NIF being funded at moderate levels and full funding for technology development being approved following the achievement of ignition at LMJ. T his option represents the best balance of technical and commercial risk. It positions Europe to take full advantage of commercial opportunities arising from technology development in the short and medium terms and clean energy supply benefits in the long term.

The investment profile is designed to be affordable in the short term whilst positioning Europe as a major player following NIF ignition and in the "post LMJ ignition" era. In the short to medium term, technology development will enhance opportunities for revenue generation and job creation through exploitation of the intellectual property generated. In the longer term it positions Europe in a key role as a supplier of advanced "second generation" Laser Energy plants.

12 Phase 1 & 2 HiPER Programme

Summary

The HiPER Laser Energy Programme will build on existing capabilities and exploit strategic international partnerships, avoiding duplication while maintaining the strategic option to proceed with future construction on a European basis. It will exploit previous investment in the technical work of the HiPER Project and give best advantage for Europe in the short, medium and long term.

It develops Europe's position in the future supply chain for Laser Energy and widens further the portfolio of knowledge and industrial and academic contacts established during the HiPER preparatory phase. Finally, it maintains the opportunity to reinforce existing, long-term relationships with international partners.

Over the next 10 to 15 years, work will be concentrated in two main areas as shown in Figure 1. The physics of shock ignition will be developed leading to a demonstration of ignition at LMJ in the early 2020s (Phase 1). In Phase 2, laser technology will be developed, along with fuel capsule mass production and development of the fusion chamber concept. Investment in these areas will be phased with increased funding following ignition at LMJ. Phases 1 & 2 will culminate in the production of a Business Case for the construction of HiPER with a decision anticipated at the end of the 2020s.

As the technology development proceeds, significant commercial exploitation potential is expected which has the potential to reduce the entry level cost of the HiPER construction phase.

12.1 Phase 1 Work programme, cost estimate and delivery schedule

Shock ignition roadmap

The shock ignition and systems engineering roadmap will be developed, cost estimates and schedules preopared. Early stage S.I. experiments will be conducted on existing facilities as funds allow. The plan for integrated systems modelling will be developed and the systems engineering requirements identified. Finally, full scale D-T fusion experiments will be conducted using the shock ignition platform developed at Laser Méga Joule.

Phase 1 Cost Estimate

The cost estimate (±10%) to undertake this work over a two and a half year period is 7.5MEuro**.** This includes a 20% margin for risk.

12.2 Phase 2 Work programme, cost estimate and schedule

Shock ignition systems engineering

The programme of shock ignition systems engineering will be conducted including identification of engineering solutions for reactor operation based on the shock ignition scheme including cryogenic D-T fuel capsule delivery and survival, fusion chamber scheme design and reactor systems modelling.

Laser driver development

Building on the progress with the LUCIA and DiPOLE DPSSL laser development programmes in Phase 1, the systems will be extended to the 1kJ / 10Hz regime and a programme of life testing will be conducted to determine the thermal, optical, electrical and mechanical operating envelopes for the system. Exploitation plans will be developed and implemented in accordance with the CALTA and LUCIA business plans.

Design work will be carried out during Phase 2 with the preparation of a subsidiary Business Case for the 10kJ prototype laser beamline construction for submission towards the end of the Phase. If approved, this will enable early construction and commissioning to underpin the case for investment funding of Phase 3.

Fusion chamber

In the first part of Phase 2, work will proceed on schematic design, materials development, blanket design, target injector mechanisms and tracking technology development. Following LMJ ignition and approval of HiPER Business Case 2, prototyping of blanket segments and full scale chamber concept design will commence.

Fuel pellet mass production

Mass production of shock ignition fuel pellets at low unit cost is a key requirement for the Laser Energy scheme. Building on the work conducted during Phase 1, activities will include the development of wet foam chemistry, new filling techniques, mass production of shells, automated assembly, storage and handling.

Governance arrangements

An appropriate legal entity for the programme and the necessary international agreements will be established. This includes Environment, Safety, Health and Regulatory aspects of the international roll-out of Laser Energy stations, project management arrangements, etc.

Economic modelling

This activity extends the economic modelling to support investment in pilot plant construction (Phase3) and informs technical decisions in Phase 2 based on economic drivers. Currently based on several key assumptions, the models will be refined as new information becomes available during Phases 1, 2 and 3.

Preliminary design and estimating for Phase 3

Concept design of the Phase 3 construction to a level of detail sufficient to enable preparation of improved cost estimates and schedules. This work will be informed by the results obtained in Phase 2 and 3 and by international partners as information becomes available.

Construction Business Case development and International Strategy

Following LMJ ignition and approval to proceed with the development of the Business Case for Construction, a paper will be prepared by the Project Sponsor for consideration by the Governments of the day and potential investors. The paper will include:

- A review of progress in Technology Development to date
- A review of achieved benefits
- A review of current and possible future strategies (international partnership opportunities, etc.)
- A recommendation on the way forward

Given a favourable response to proceed, the project team will begin to develop the Phase 3 (Construction) Business Case in collaboration with international partners with the objective of achieving Class A (+/- 10%) estimates of construction cost and schedule for Construction Main Gate submission towards the end of Phase 3.

12.3 Combined HiPER Phase 1 & 2 and spend profile

The high level schedule and spend profile for the next phases of HiPER is shown in Figure 8 below.

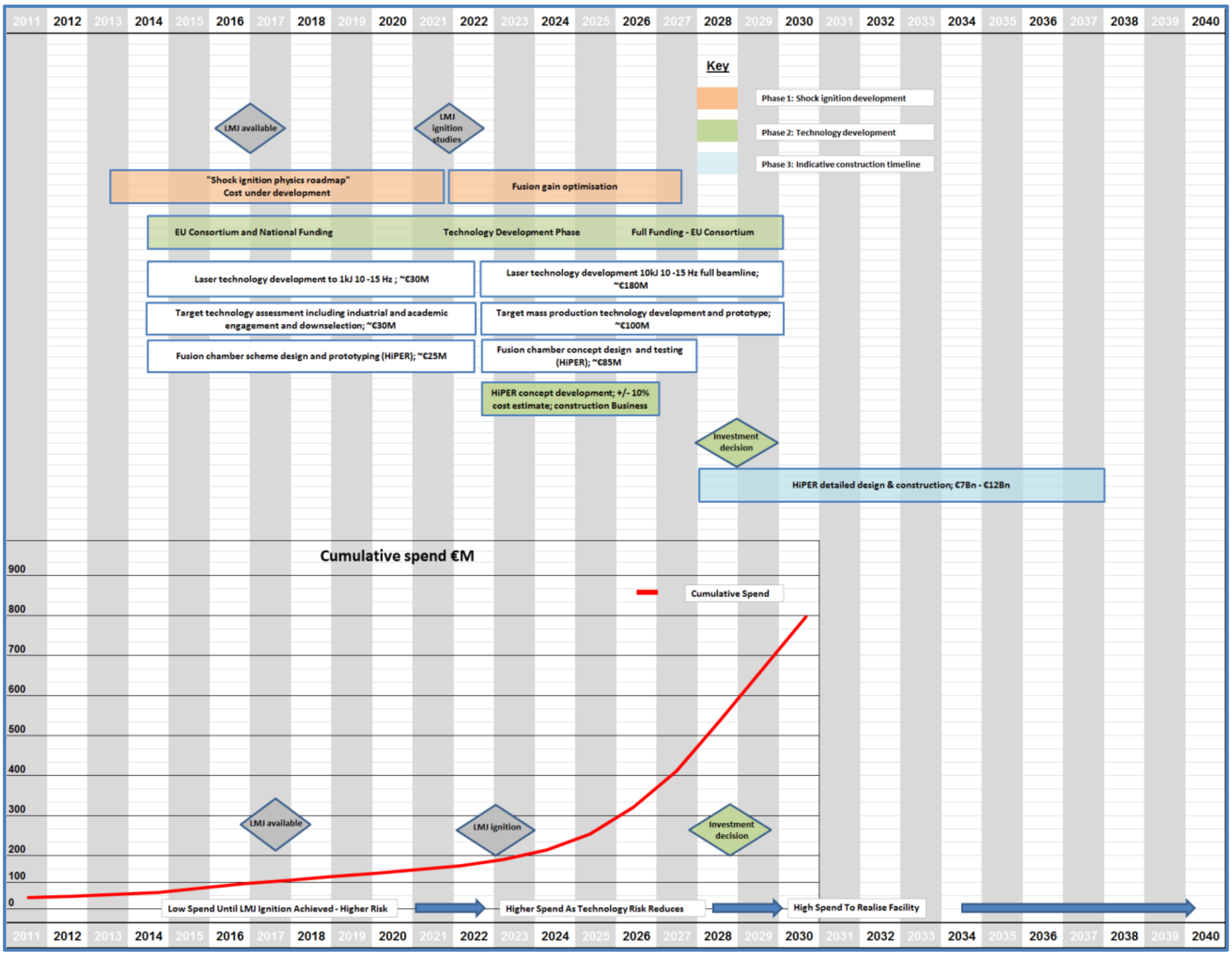


Figure 8: Programme of Work for HiPER Phases 1 & 2

12.4 Cost Estimate: Phase 1 & 2

Both estimate and plan for this period shown in Figure 8 above are to an accuracy of +100%, -50% and require further development during Phase 1 & 2. Costs of the shock ignition roadmap experimental programme on intermediate scale facilities have not been included and are being developed.

12.5 "First of Type" Facility: Overall Estimate

Risk reduction of the key elements of Laser Energy technology will have occurred during Technology Development (Phase 2) to the level at which it is hoped to attract private sector investment for construction of the "first of type" demonstrator plant. This strategy is consistent with the use of public sector funding, or retention of a "golden share" to retain European interest in the technology, should this be the preferred option.

The purpose of the First of Type Laser Energy plant is to provide a platform at minimal cost for full closed-loop integration of all major technology elements. The plant will operate with the minimum number of lasers and minimum infrastructure required to achieve fusion at a level capable of a small ~20MW(e) energy surplus. Subsequent commercial plants are expected to scale their generating capacity to between 500 MW(e) and 2 GW(e) to meet energy demands (co-located industrial processing or hydrogen production) or electrical distribution infrastructure needs. These capacity levels accord with commercial operations determined by preliminary economic studies carried out during the HiPER preparatory phase.

The ROM cost estimate of the first plant, including technology development, is €7B-€12B. This estimate, and associated delivery schedules, will be developed as a Phase 2 activity along with the Business Case for construction as shown in Figure 1.

13 Project Support Activities

13.1 Environment, Safety and Health (ESH)

To enhance the European position as a supplier of Laser Energy technology and to facilitate installation of power plants worldwide, it will be necessary to build and maintain a specialised knowledge of environment, safety and health (ESH) aspects. Differences in regulatory regimes must also be assessed. This will require a small multi-disciplined coordinating team to accumulate knowledge, to brief regulators and to engage with economists to maximise market penetration of the technology.

13.2 Economic Modelling

As Phases 1 and 2 3 progress, more detailed and accurate data will become available to underpin modelling of the commercial viability of Laser Energy. Models will be updated and developed to inform investment decisions on construction of the prototype Laser Energy plant. Economic modelling will also be extended to the economic prospects and impact of technological spin-offs and their industrial applications.

A number of economic analysts who have been introduced to the Laser Energy concept during the HiPER Preparatory Phase will be able to undertake this work in collaboration with Phase 1 and 2 engineering and technology teams.

13.3 Stakeholder Management

- Stakeholder management activities were undertaken during the HiPER Project Preparatory Phase and this work is now being refocused in the context of the next phase of the programme. Key activities include:
- Promotion of Laser Energy to the European Commission and the need for a European Programme
- Promotion of Laser Energy across the academic community to ensure an appropriate skills base to underpin the programme, exploitation of arising intellectual property and roll-out of Laser Energy plants. Existing university courses will be extended and augmented to support the new technology required for the Laser Energy programme

- Informing European industry of the benefits of engaging with the Laser Energy programme; giving advice on future planning and helping to promote relevant capabilities.
- Increasing public awareness and building support for Laser Energy as a technology capable of meeting future energy needs.

13.4 Governance

Appropriate governance arrangements will be essential to ensure that realistic plans, processes and procedures are in place. These include the formation of a legal business entity for the project, estimating future funding needs and cash flow requirements, developing commercial agreements, provision of control mechanisms for intellectual property and patent applications, ensuring effective project management and providing appropriate reporting and communications capability.

14 Technology exploitation

The development identified for Laser Energy risk reduction within the Phase 2 Technology Development Programme is in high technology which offers substantial and diverse spin-off exploitation potential. Examples are identified below. These will be analysed in more detail and an exploitation plan will be developed to ensure that Europe maximises the value of the Laser Energy investment in the short and medium term.

14.1 Laser development

To achieve the Laser Energy mission, three prototype platforms are proposed, 10J, 100J and 1 kJ, in order to reach the goal of 10 kJ at 10-15 Hz. From the 1 kJ level, 10 kJ will be achieved by straightforward parallel operation of 1kJ base units albeit that, post LMJ ignition, a full 10kJ beam line will be required to reduce risk of purchasing 100 or more of these beam lines for HiPER.

Good progress is already being made on development DPSSL high rep-rate high average power laser technology. At the LULI laboratory in Paris, the LUCIA DPSSL laser is operating at 10J / 10Hz and is shortly to be upgraded to the 10’s of Joules level.

In the UK, the STFC Diode Pumped Optical Laser for Experiments (DiPOLE) project is developing the foundation for high average power repetition rate lasers with high “wall plug” efficiencies (>10%). DiPOLE has already demonstrated 10 J / 100 W operation and is funded to the 100 J / 1 kW level.

These and other “next generation” DPSSL systems will advance high power high repetition rate laser technology to the applications stage, opening an extensive potential for advanced industrial applications. These include:

- Material surface treatments
- Advanced structured finishes and machining techniques Advanced medical therapies and imaging
- Lidars
- Semiconductor, flat panel display and photovoltaic imprinting
- Advanced imaging (X-ray, THz and Gamma)
- Table top accelerators
- Homeland security applications

14.2 Fuel Pellet Performance Modelling and Gain Optimisation

Laboratories in CEA (France), AWE (UK) and academic institutes throughout Europe have “world class” capability in the modelling and design of targets for Laser Energy applications. Virtual models are run on supercomputing platforms to optimise the energy gain of targets.

Considerable economic benefits from Laser Energy target design and modelling will be realised over the longer term. The modelling activity is of high value as it already provides independent and impartial review of proposed US designs, giving independent verification of high cost experiments currently being undertaken in the USA on NIF. For the European HiPER programme, modelling provides physicist with insight into the likely behaviour of advanced ignition targets. This information will provide the cornerstone for the development of advanced ignition and its experimental verification as the programme progresses. The longer term benefits of undertaking this work are assessed as follows:

- Intellectual property in respect of target design (estimated to realise €0.01 – €0.1 per target) could provide a revenue stream per 1GW(e) laser energy station of €40M - €400M per year. With a potential world market of ~5,000 1GW(e) stations predicted, (excluding life cycle based replacements), even a small share of this IP would deliver a very significant revenue stream
- Retention and enhancement of capability in target design and modelling provides Europe with the opportunity to undertake advanced ignition scheme target and reactor development.

14.3 Mass-Production of Fuel Capsules

Laboratories in the UK and France are already pursuing the development of new manufacturing techniques including Atomic Layer Deposition (ALD), microfluidics and dielectrophoretics, micro laser machining (MLM), micro electrical-mechanical systems (MEMS), automated micro assembly, nanotechnology, etc. When fully developed and suitably combined, these techniques will achieve the high volume production required for economically viable supply of Laser Energy fuel pellets.

Automated micro-assembly is a critical technology in the two emerging markets of microsystems technology (MST) and nanotechnology (NT). The global MEMS market in 2009 was €5.3Bn pa and is expected to grow to €9Bn pa by 2014, doubling every five years thereafter. Atomic layer deposition, a relatively new technique, established a marketplace of €140M pa by 2009. This market is already worth €693M pa and continues to grow.

Applications of the technologies that will be developed on the journey to HiPER are diverse. Applications in the automotive industry alone include:

- Air bag system manufacture
- Sensors and actuators (all types)
- High strength lightweight materials
- Nanostructured material finishes Industrial:
- High density high complexity assembly (Watches, Laptops, Pads, Smartphones, etc)
- Smart material coatings with adjustable thermal conductance (for buildings)
- Sensors and actuators (all types) Medical:
- Microsurgery (beyond human capability)
- “In vivo” medical diagnostic and drug delivery systems

14.4 Fusion Chamber Development

Details of the current knowledge and programmes required to develop fusion chamber concepts are available in Appendix VII: Fusion Chamber, summarized below.

Wall materials

Spain is already developing wall materials for HiPER and have sought and obtained low levels of National funding to support these efforts. High heat absorption, high conductivity materials that are stable in a pulsed fusion environment and which possess a short radiation half-life will have wide and diverse applications in industry. Some examples include:

- High operating temperature reactors e.g. permitting direct hydrogen conversion or other high temperature chemical processes
- Generation 3 fission life extension
- Submarine reactors
- Generation IV fission
- Magnetic Fusion (first wall and divertor)
- High temperature combustion (rocket systems)
- Space vehicles
- Space thruster systems (e.g. ion drives)

Target injection

Accurate injection of targets at a high repetition rate into a fusion chamber within a vacuum environment is a prerequisite for HiPER.

The technology for this exists, in part, within the military examples being hyper-velocity launchers. Novel work has been performed within the Czech Republic, France and the UK marrying together known technologies with some very unique concepts. These provide potential for commercial return from both military and industrial applications. Examples include:

- High efficiency hyper-velocity launchers
- Surface treatments (peening)
- Paint removal and scouring
- Radioactive decommissioning (e.g. accurate contaminated surface layer removal using high velocity dry-ice)

There is a high potential for economic return through exploitation of all the above developments making lasers, target modelling, target mass manufacture, fusion chamber materials and target injection all very attractive areas for investment in both the short and medium terms. Long term, these investments will position Europe as a key player within the Laser Energy market with the associated economic benefits of leading-edge technology.

15 HiPER Preparatory Phase Project membership

15.1 HiPER Executive Board

The membership of the HiPER Preparatory Phase Executive Board and their affiliations was as follows:

Prof. Carlos Alejaldre	ITER
Prof. John Collier	Director, Central Laser Facility, STFC, U.K.
Prof. Steven Cowley	Chief Executive, United Kingdom Atomic Energy Authority, U.K.
Dr. Didier Besnard	C.E.A., France
Prof. Dimitri Nanopoulos	Texas A & M University, Texas, U.S.
Dr. Francis Kovacs	C.E.A., France
Prof. François Amiranoff	Director, LULI Facility, Ecole Polytechnique, Paris, France
Prof. Karel Jungwirth	Institute of Physics, Czech Academie of Science, Prague, Czech Rep.
Prof. Mario Calvetti	Director, Laboratori Nazionali di Frascati, Italy
Prof. Michel Spiro	C.N.R.S., France
Prof. Steven Rose	Vice-Principal Physical Sciences, Imperial College, London, U.K.
Prof. Wolfgang Sandner	Director, Max Born Institute, Berlin, Germany
Prof. Tito Mendonça	Head of Physics, Instituto Superior Técnico, Lisbon, Portugal
Prof. John Womersley	Chief Executive, STFC, U.K.

The Board was chaired by the Preparatory Phase Project Director

15.2 HiPER Project Management Committee

The membership of the HiPER Preparatory Phase Project Management Committee was as follows:

Prof. Manolo Perlado	(WP8)	UPM, Madrid, Spain
Prof. Stefano Atzeni	(WP9)	University of Rome, Italy
Prof. Dimitri Batani	(WP10)	CELIA, Bordeaux University, France
Mr. Martin Tolley	(WP11)	Central Laser Facility, STFC, U.K.
Prof. Michaelis Tatarakis	(WP12)	University of Crete, Greece
Dr. Jean-Christophe Chanteloup	(WP13)	LUCIA laser facility, Ecole Polytechnique, Paris, France
Dr. Bruno LeGarrec	(WP14)	C.E.A., France
Dr. Bedrich Rus	(WP15)	Institute of Physics, Prague, Czech Rep.
Prof. François Amiranoff	Deputy HiPER Co-ordinator, Ecole Polytechnique, Paris, France	
Prof. Guy Schurtz	CELIA, Bordeaux University, France	
Prof. Leonida Gizzi	INO, CNR, Italy	
Prof. Thierry Massard	Chief Scientist, D.A.M., C.E.A. France	
Mr. Mike Tyldesley	HiPER Engineering Manager, Central Laser Facility, STFC, U.K.	

The Project management Committee was chaired by the HiPER Project Director

15.3 HiPER Partners

Funding agency partners

Science & Technology Facilities Council	UK
Commissariat Energie Atomique	France
CNR - Consiglio Nazionale delle Ricerche	Italy
Centre National de la Recherche Scientifique	France
Conseil Regional d'Aquitaine	France
Ente per le Nuove tecnologie, l'Energie e l'Ambiente	Italy
General Secretariat for Research and Technology	Greece
Ministry of Education, Youth and Sports	Czech Republic

Institutional partners

Universidad Politecnica de Madrid	Spain
Consorzio Nazionale Interuniversitario per le Science Fisiche della Materia	Italy
Forschungsverbund Berlin e V	Germany
Gesellschaft fur Schwerionenforschung mbH	Germany
Institute of Applied Physics of the Russian Academy of Science	Russia
Institute of Plasma Physics and Laser Micro-fusion	Poland
Instituto Superior Tecnico, Universidade Technica de Lisbon	Portugal
P.N Lebedev Physical Institute of Russian Academy of Sciences	Russia
Academy of Sciences of the Czech Republic	Czech Republic
Technological Education Institute of Crete	Greece
Technische Universitat Darmstadt	Germany
Technical University of Crete	Greece
Oxford University	UK
Strathclyde University	UK
Queen's University Belfast	UK
University of York	UK
Imperial College of Science, Technology & Medicine	UK

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17 Appendix I:Laser development programme

17.1 Overview

The Laser Energy business case recognises the need to develop high efficiency high average power repetition rate lasers drivers as a key part of the energy mission. Current high-power laser systems (NIF, LMJ, LULI 2000, Vulcan, Orion) use pulsed flashlamps to pump the gain medium and generate laser light. These systems are of very low efficiency, ~0.02%, and, for the highest energy beams (~kJ) , are limited to repetition rates in the order of one pulse per hour. These limitations arise from the need to naturally cool flash lamps and gain media between shots. As the repetition rate increases, cooling limitations progressively impose reductions in beam energy and laser efficiency. Flashlamp-based laser technology is tried and tested, but an inherently unsuitable technology basis for Laser Energy.

To be commercially viable, a Laser Energy plant must repeatedly achieve fusion of injected fuel pellets at rates between 10Hz and 15Hz. Work undertaken during the HiPER preparatory phase shows that the minimum number of laser spots required to engage with a target and achieve fusion is approximately 48, each at a laser energy of ~10kJ. This equates to 480kJ of total laser power per injected target. Greater energy will be required if second or third harmonic frequency conversions are needed to match the laser driver frequency to that required to initiate fusion of a particular target design. Assuming the availability of a suitable driver, ignition modelling shows that the maximum feasible energy gain from a single target is likely to be in the region of 100. From best practice in industry, heat to electrical conversion efficiencies can be derived. All this information is compiled schematically in Figure 1.

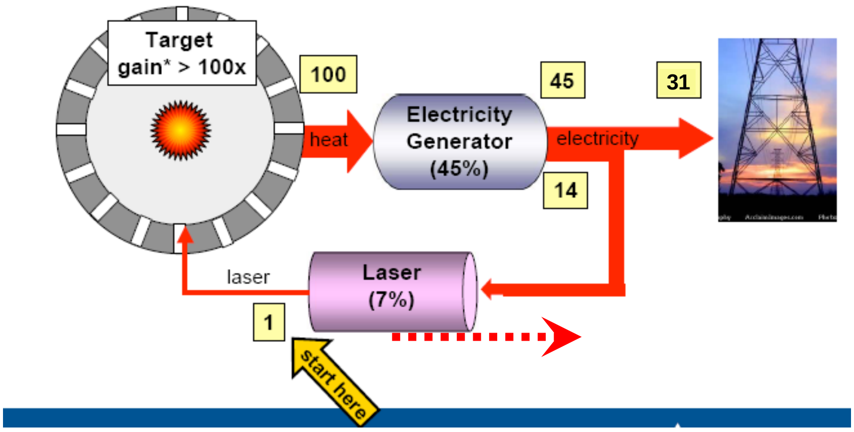


Figure 9: Operating schematic of a Laser Energy station

A laser output of 1 and a target gain of 100 would provide 100 units of thermal energy at the target chamber output. High efficiency thermal/electric energy generation using, as an example, Ultra Super Critical Steam (USCS), generates electricity with an efficiency of approximately 45%. This provides 45 units of electricity to supply both the national grid and the laser driver plus ancillaries. If all the electricity were fed back into the laser, the required laser efficiency would be ~2.5%. This would result in a continuous process with no net output and, therefore, no commercial benefit. Even a 2.5% efficiency is incompatible with current flashlamp-based laser designs. The HiPER Project has determined, using economic modeling, that the minimum laser efficiency required for commercial viability is ~7% providing a balance between the electricity required to drive the lasers and that fed to the grid.

A step change in laser technology is required to meet the driver specification. This is now possible through the development of high-efficiency laser diodes. Designed primarily for use in the telecommunications industry, semiconductor laser diodes provide a highly efficient means of producing very specific, “tailored” wavelengths of light which can be used to pump high-power laser gain medium efficiently. This class of device is termed a “Diode Pumped Solid State Laser” (DPSSL). DPSSL offer high average power high repetition rate operation at high efficiency, and is therefore much more suitable as a Laser Energy driver.

Laser diodes, currently retailing at ~2Euro per watt output, are not mass-produced in any meaningful sense. Prices are falling as applications become more numerous, and industry surveys predict diode prices as low as 0.03 Euro per watt within the next ten years as high-volume mass production develops.

During the HiPER Preparatory phase, the layout of a suitable DPSSL driver was investigated. Conceptual designs suiting both indirect drive and direct drive ignition schemes were proposed. These consisted of 48 units each of 10kJ energy per pulse with a repetition rate of 10Hz. Designs also provided the capability to shape pulses, engage with targets and provide different frequencies of light within each spot, utilising frequency conversion crystals.

Industrial capability to produce the required optical elements was separately assessed. Optical manufacturing limitations and the high cost of large optics led to a beam design in which each of the forty-eight 10kJ beams consisted of a matrix of 9 to 16 ~1kJ beamlets, arranged in three-by-three, three-by-four or four-by-four arrays with overlapped output beams. This met the “single spot” energy requirements on target, including allowance for losses through frequency conversion. The configuration meets the requirements for HiPER and also limits technical risk. See Figure 2 below.

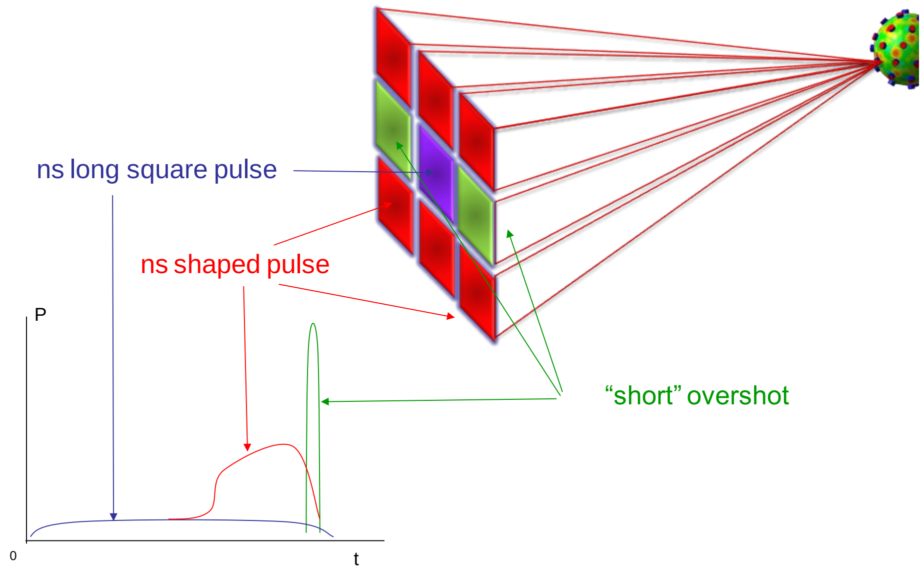


Figure 10: HiPER Laser solution – 3 by 3 (or 4 by 4) array ~10kJ spot energy on target

The minimum requirement of a beamlet laser component of a 10kJ bundle for a Laser Energy plant is thus set at 1kJ, operating at between 10 and 15Hz pulse repetition rate with an overall total efficiency better than 7%.

While providing an essential building block for Laser Energy, a beamlet laser of this power and capability would also have a major impact on industry. Many applications would emerge, including advanced medical treatments, industrial material treatments, table top accelerators, homeland security (imaging) and chemical processing. This would produce spin-off benefits to the development programme.

Awareness of the breadth of scientific applications and industrial market potential for this new breed of laser prompted STFC to seed-fund the Centre for Advanced Laser Technology and Applications (CALTA) at £1Mpa. CALTA’s mission is to develop DPSSL lasers to the 1kJ 10Hz level as a platform for both scientific research and industrial applications. The LUCIA DPSSL programme at the LULI laboratory at the Ecole

Polytechnique in Palaiseau, France is currently operating in the 14J / 2Hz regime and has embarked on a development programme to deliver 10's of J output at 10Hz.

The development path for HiPER is based on continual risk reduction. A series of prototypes are proposed at energy levels 100J at 10Hz and 1kJ at 10Hz, with each prototype de-risking the next. Prototype energies were selected appropriate to the performance testing required for confidence in gain media thermal properties and heat extraction technology, diode pumping arrangements and amplified spontaneous emissions (ASE). Each prototype is considered as an individual project within the programme.

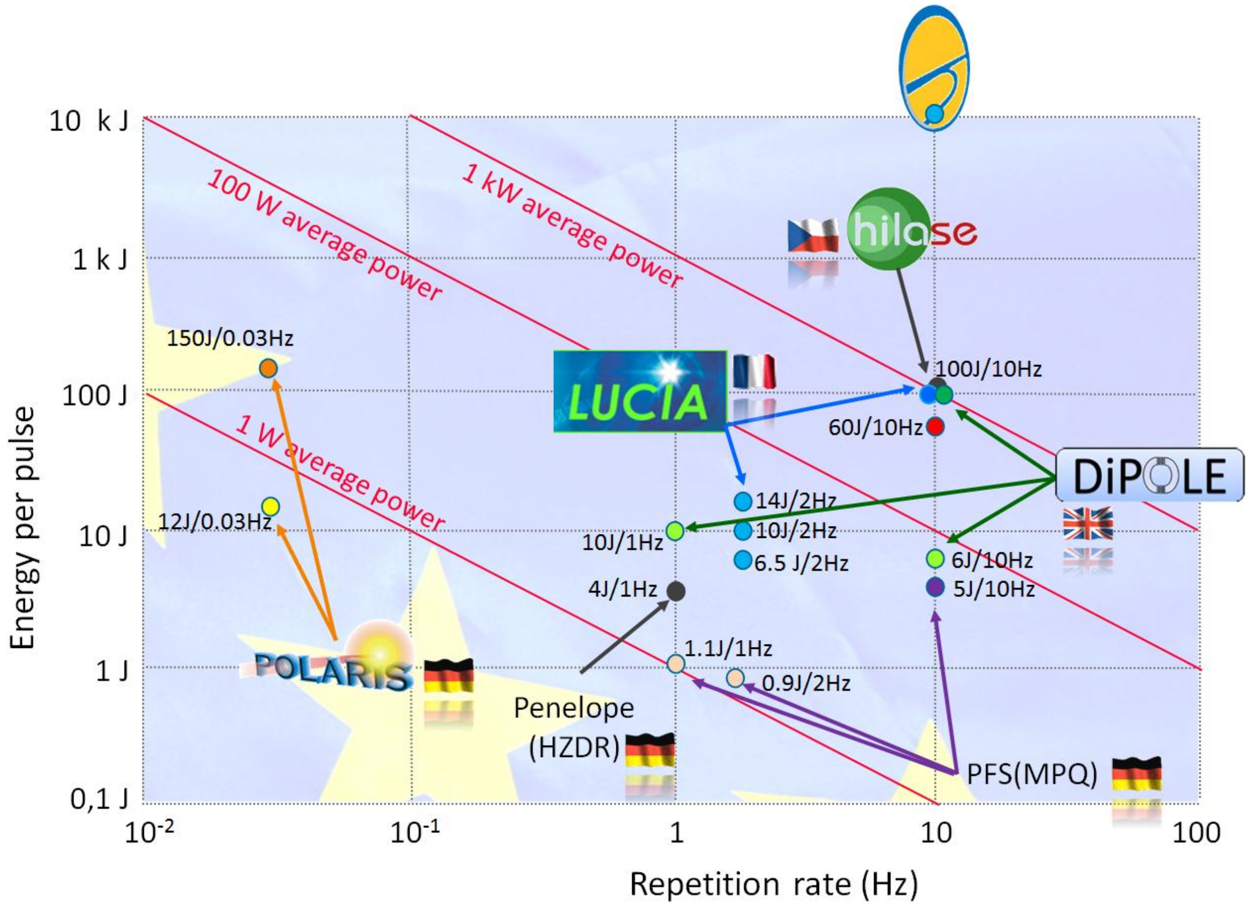


Figure 11: Energy v Repetition rate for existing technology

Energy versus repetition rate graph illustrating End of 2012 DPSSL European landscape with 10Hz/10kJ HiPER requirement on top right. Three laser prototypes are aiming at an intermediate 100J/10Hz goal, namely Lucia, France (with 14J/2Hz achieved), DiPOLE, UK (with 6J/10Hz and 10J/1Hz demonstrated) and HiLASE, Czech Republic (not yet operational). Three German programs are also relying on similar technology and will contribute to HiPER laser physics bottlenecks explorations: Polaris in Jena with 12J achieved for a goal of 150J, PFS in Munich with 0.9J/2HZ for a 5J/10Hz goal and the new Penelope program in Dresden aiming at 4J/1Hz. The red 60J/10Hz is for the (now decommissioned) Mercury program developed by LLNL, USA in the early 2000 years.

17.2 Requirements for the 1kJ Laser Energy Beamlet

The requirements for a 1kJ beamlet were derived during the HiPER preparatory phase and are based on a systems breakdown of the HiPER Facility. Key Laser Energy requirements are tabulated below with those of DiPOLE / LUCIA in comparison:

Laser Energy Requirements				DiPOLE / LUCIA Requirements			
No	Description	Importance	Risk	No	Description or comment on Laser Energy requirement	Importance	Risk
1	1kJ energy per pulse	H	H	1	1kJ energy per pulse	H	H
2	10 to 15Hz rep rate	H	H	2	10Hz rep rate	H	H
3	7% minimum efficiency	H	M	3	9% minimum efficiency	M	M
4	MTBF > 10^9 shots	H	H	4	Conservative high reliability design suitable for industrial use	M	M
5	Cost of diodes <10p/watt	H	L	5	Implied equivalent requirement to stimulate sales to industry	M	L
6	Compatible with DD IFE (high bandwidth)	H	M	-----	Bandwidth assessed as sufficient at 175K operating temperature for gain media		
7	Compatible with IDD IFE	H	L	-----	If requirement 6 for LE is satisfied requirement 7 is satisfied		
8	Potential for development spin-offs or industrial applications	M	L	6	Potential for development spin-offs or industrial applications	H	L
9	Compatible with US LIFE Project designs	H	M	------	Requires adoption of similar systems to breakdown and lowest replaceable item list of the LIFE Project		
10	Designed in-line replaceable units	H	L	------	Easily accommodated and will benefit serviceability		
11	Incorporate automatic alignment systems	H	M	7	Implied requirement - must be saleable to industry		
12	Self diagnostics (auto shutdown on major fault)	H	M	8	Implied requirement – safety in operation		
13	Steerable beam to engage with target (>10 kHz frequency response)	H	H	------	Difficult to achieve with high pointing accuracy		
14	High efficiency rep rate frequency conversion	H	H	------	May be required for some industrial applications		
15	Final optic suitable for high neutron flux operation	H	H	------	Not required. No capability to test		
16	All laser equipment (except final optic) must be serviceable without shutting down the facility i.e. protected from neutron/radiation environment and beams enclosed	H	L	------	Not generally required although enclosed beamlines may be required for safety (see requirement 8)		
17	Safe to operate	H	L	9	Safe to operate	H	L
18	Compatible with 10kJ overlapped beamlet driver concept	H	L	------	(This is relatively easy to achieve)		
19	Cost comparable and preferably cheaper than US solution	H	M	------	Scalable design probably cheaper to produce than Nd:Glass equivalent which will require more diodes		

Table 1 Laser Energy and DiPOLE / LUCIA requirements comparison

17.3 TRL assessment

Assessment and categorisation of the individual laser technologies required for a Laser Energy plant demands adoption of a standard, giving an assessment of each element in terms of the specification required and current progress towards that goal.

The Technology Readiness Level assessment system (originally devised by NASA) is currently used within MOD UK. Standard TRL definitions are detailed in Annex D.

Technology development (10J 10Hz), already undertaken by DiPOLE and LUCIA, has a direct influence upon technology readiness levels for DPSSL. Of note, the availability of ceramic doped Yb YAG gain media (now available in 12cm square section), use of diamond crystal pinholes and multi-pass reversors has served to improve TRL's, which nevertheless remain in the 4 to 5 region, since scaling issues have yet to be addressed. Risk has been significantly reduced however.

Laser technologies already in use on large facilities such as (LMJ, NIF, Omega etc.) may require adaptation or re-engineering to meet Laser Energy requirements.

Components evaluated at a TRL equal to 7 or above are usually considered as prototype components, whose technology is sufficiently mature for use in Laser Energy. Components assessed below TRL 7 require further development. This information feeds a "Technology Development Plan" (TDP) which, in turn, provides a "roadmap" to the required Laser Energy beamlet drivers.

Analysis of the TRL's for a laser beamline requires assessment of the following laser sub-systems :

Master Oscillator Assembly

Front end

Main Amplifier Section

Beam Transport

Compressor

Final Optics Assembly

Technology capability within the sub-systems differs between commercial, academic and defence sectors. Technologies in each capability area are analysed separately against Laser Energy requirements.

Component	Current technology status and derived TRL		
	Commercial technology	Defence laser facilities	Academic laser facilities & other development projects

MOA (Master Oscillator Assembly) & pulse shaping

Pulse generator		3	4
Beam splitting system (for 10kJ matrix)			4
Probe beam pulse generator			4

Component	Current technology status and derived TRL		
	Commercial technology	Defence laser facilities	Academic laser facilities & other development projects

Front End

Spatial pulse shaping addressable system		5	
Beam amplification		5	
Small optics for beam pointing and centering	7		
Input beam diagnostic station		5	

MAS (Main Amplifier Section)

Injection lens	7		
Injection mirror	7		
Spatial filter lenses		7	6 (Lucia)
Diamond crystal pinholes on DiPOLE		5	5 (DiPOLE) 3(Lucia)
Yb-Yag Amplifiers	5 (12cm by 12cm Yb-Yag ceramic available)		Was 4 now 5 (DiPOLE); 2 (Lucia) (16cm by 16cm required for 1kJ)
Polarizers	7		
Pockels cells	5	6	0
Faraday Rotator	4	5	0
Reversor optics (8 passes single head option)			5 (DiPOLE)

Beam Transport

HR Transport Mirror	7		
1% loss Transport Mirror	7		
Diagnostic Collimator		5	
1w output diagnostic station		5	

Compressor

Gratings		4	4
Phased Mirrors		4	4
Compressor Hardware		3	3

FOA (Final Optic Assembly)

2ω Frequency conversion crystal	4		4
3ω Frequency conversion crystal	4		4
Colour separators	5		

Component	Current technology status and derived TRL		
	Commercial technology	Defence laser facilities	Academic laser facilities & other development projects
Absorber plate	7	7	
Phase plate		6	
First focusing lens	7		
Large 2ω and 3w 0.5% loss mirrors	7		
Conical pinhole		2	
Second focusing lens (final optic)		2	
2-3ω Diagnostic & alignment station		5	
Debris shields		5	

TRL's have been estimated by experts in the field. As the 1kJ laser baseline design becomes more defined at sub-system level, this assessment will be refined.

17.4 Development Plan

The development plan arises from the requirements to be met and the associated TRL assessment. As demonstrated by the laser requirements listing in section 1, there is strong synergy between the DiPOLE and LUCIA projects and Laser Energy requirements.

Current technology for the master oscillator is at ~TRL 4 whilst the front end is at ~TRL5. The TRL for synchronization is low as some 600 individual beamlets must be linked. At the front end, the ability to modify the laser output pulse shape is needed. Synchronisation itself is a well-understood issue, but must be demonstrated prior to construction of the large numbers of lasers (~600) required for a Laser Energy development facility. This can be done during Phase 2 of the programme and may thus be segregated from laser development. In respect of the front end, the DiPOLE 100J demonstrator, when built, will provide basic pulse shaping capability.

Success of the current DiPOLE and LUCIA 10J 10Hz prototype raises the TRL for the main amplifier to ~5. Risk reduction for both the cooling and amplified spontaneous emissions studies requires a 100J 10Hz demonstrator as the next viable step to de-risk the 1kJ system.

Beam transport development is required in terms of diagnostic systems to align and analyse the laser and to determine further actions to be taken in the event of failure, which would necessarily lead to automatic shutdown of the laser due to the repetition frequency of operation. The design of such a system will be implemented on the 100J prototype.

17.5 Annexe B – Detailed Requirements for the Laser Energy Driver

The requirements set for the laser are a subset of the requirements for the Laser Energy development facility. The generic facility requirements include safety and environmental needs. These apply both to the facility as a whole and to the laser driver.

B.1. System Engineering Team Requirements

M = Mandatory, full compliance is required

M-SEN = Mandatory but must be negotiated with the Systems Engineering Team due to the existence of an interface with other system engineering solutions.

Unique ID	Description	Status
LAIN001	The constraints related to the integration of equipment in the laser bay and target areas shall be defined by the laser area sub-system engineering team; these include :- **Regulatory constraints** - Personnel and nuclear safety **Operational constraints** – Integrated Logists Support(ILS) and Reliability Availability and Maintainability (RAM)	M-SEN
LAIN002	A complete Engineering model of the Laser Beam Performance shall be developed, taking into account the various parameters to be delivered (spatial, temporal and spectral shaping, energy, power …) at the target.	M
LAIN003	The Laser beam model shall be capable of defining the input/output performance of each laser section (Master oscillator – Front End – Amplification – Transport – Conversion and focusing) to target engagement. This model will optimize performance of these elements during concept design.	M
LAIN004	The Laser Engineering Team shall assume the integration role for all major laser equipment within the facility. This shall include: lasers, supporting space frames, laser beam tubes, final optic assemblies etc. The team shall maintain engineering interfaces with target area and facility engineering teams in respect of laser diagnostics and alignment aids, target engagement devices, laser interfaces etc.	M-SEN
LAIN005	The Laser engineering team shall assume the task of integrating all support equipments including electrical and optical cable space reservations	M-SEN
LAIN006	The laser engineering team shall assume the role of engineering integrators for all equipments required to support accurate positioning of optical elements.	M-SEN
LAIN007	The laser engineering team shall be responsible for integration of all requirements related to ventilation (e.g. cleanliness, humidity, temperature, vibration, etc.) required to maintain the performance of optical components.	M-SEN
LAIN008	The laser engineering team shall assure the coherence of all laser command and control systems and their interfaces with the facility Integrated Computer Control system	M-SEN

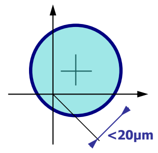
B.2. Laser Driver Requirements

The requirements described below form a reference point for the laser design. The stepped delivery strategy for the laser includes a scalable (10-100J) demonstrator, a beamlet demonstrator (~1kJ at 10Hz) and a full laser demonstrator (~10kJ at 10Hz). These demonstrators support both technical and commercial de-risking strategies.

Requirements are designated “M” for Mandatory or “P” for Preferable. Preferable requirements may be the subject of negotiation or modification during the Technology Development Phase. After negotiation, the preferential requirements will attain Mandatory status.

The SEN label (**S**ystem **E**ngineering **N**egotiation) identifies requirements shared with other sub-systems, or which depend upon the physics of ignition. These must be approved prior to completion of the laser design.

Unique No	Description	Status
L001	The laser driver system shall be capable of focusing laser pulses on a fusion target with wavelength, pulse duration, temporal profile, spot size and coherence supporting the needs of the target physics.	M-SEN
L002	The laser driver shall provide a shot rate of a minimum of 10 shots per second. This should not preclude the capability to increase the shot rate to 16 Hz.	M
L003	A minimum wall plug efficiency of 9% must be achieved for the laser.	M-SEN
L004	The laser shall deliver temporally shaped pulses at a repetition rate of at least 10Hz (whilst maintaining all other parameters) for extended periods of time (days). Four types of temporally shaped laser pulses shall be available, to include Compression, Shock and Probe (diagnostic) beamlines. The expected performance of each beamline type shall be determined when target physics is proven.	M-SEN
L005	**Compression Pulse** The lasers will provide a pulse suitable for ignition by indirect drive at appropriate angles to the target (Polar arrangement). The pulse shall also be suitable for reconfiguration to compress a projected future shock ignition target.	P - SEN
L006	**Ignition Pulse** The laser design will not preclude the provision of an ignition pulse synchronized with the compression pulse. This is consistent with the energy required to achieve target ignition for a future shock ignition scheme.	P - SEN
L007	**Diagnostics** Active Diagnostic Beams and associated Optics for Ignition Experiments. The active diagnostics shall provide X-ray, proton, and ion pulses for probing the plasma generated by the main laser. The laser beams driving the backlighters will be delivered both to small auxiliary targets and to the fusion target. The focus size and precision of the laser pulses will be commensurate with requirements for generating backlighters. Active diagnostics will operate in the same regime as the main laser, i.e. at a repetition rate of 10Hz or higher. The system will incorporate up to 5 Chirped Pulse Amplification (CPA) diagnostic beams (<ps pulses) for X-ray or proton backlighting. These will be synchronized with the main laser in picosecond steps, independently timed, with a precision of one picosecond or better. A 5kJ/1ω beam (~ps) will be required, equipped with 2ω and 3ω frequency conversion (to be specified)	P - SEN

Unique No	Description	Status
	Auxiliary diagnostic beams (<10 ps pulses) may be required, at a level of 100J, independently timed to the main laser. An array of long-pulse (>microsecond) auxiliary tracking lasers will be required for target tracking.	
L008	**Beam Positioning Accuracy** The 1 KJ laser will deliver beam target engagement precision (displacement of centre of the target vs. common beam convergence point): For future shock ignition target designs, <20microns (TBC)  This constraint may be relaxed when target dynamics have been fully understood.	P - SEN
L009	**Beamlet Positioning Accuracy** The RMS "statistical" displacement of the centroids of all foci with respect to specified aiming position shall not exceed 20microns.	P - SEN
L010	**Beam synchronizing accuracy** The RMS "statistical jitter" of the beam engaging the target shall not exceed ~50ps.	P - SEN
L011	**Power Balance** The RMS deviation in the power delivered by the laser beams from the specified power shall be less than 8% of the specified power averaged over any 2 nanosecond (ns) time interval.	P - SEN
L012	**Pre-pulse Power** The laser intensity in both compression and ignition beams, delivered to the target during the 20-ns interval prior to arrival of the main laser pulse, shall not exceed 10^{8}Wcm^{-2}.	M - SEN
L013	**Pre-pulse Power** The intensity delivered by the ignition pulse to the target <20 ps prior arrival of the laser pulse shall not exceed 10^{9}W.cm^{-2}	M - SEN
L014	**Laser Pulse Spot Size** Each compression beam shall deliver its design energy and power within a nominal 500 micron diameter spot at the target plane or its equivalent, with precision of +/-10%. The ignition beams will produce foci with a nominal diameter to be determined.	P - SEN
L015	The lasers shall interface with a master oscillator system	M - SEN
L016	A single laser shall be made up of a number of beamlets whose aperture shall lie within the range 12cm to 18cm each (estimate currently 9 to 16 in a 3x3, 3x4 or 4x4 array)	P - SEN
L017	Each beamlet shall be capable of providing approximately 1kJ of energy in the infra-red (1ω)	P
L018	The beam arrangement at the entrance to the chamber must be compatible with ion, alpha particle, debris and neutron protection requirements.	M - SEN
L019	Optical components of the laser shall be capable of a minimum of 10^{9} shots prior to scheduled maintenance. Lifetime for the final optic is to be confirmed.	P - SEN
L020	Each laser shall incorporate a control system and diagnostics to enable automatic alignment of laser components	M

Unique No	Description	Status
L021	Each laser control system shall interface with the facility central shot control system. This interface shall permit :- Variation to the timing of the laser output pulse - (to facilitate target engagement) - is likely to be delivered via a triggering pulse. Variation to the focal point - (to facilitate target engagement) - likely to be delivered by moving mirrors in the laser front end.	M - SEN
L021	Each laser shall interface with a final optic assembly which shall incorporate the following functions :- Frequency conversion to 2ω, via 2ω -> 3ω.	M - SEN
L023	The laser final optics and controllable pulse timing variance capabilities shall be suitable for the engagement of a target which passes within a 3mm radius of the target chamber centre datum point. This should be consistent with the pointing capability of plasma diagnostics.	M - SEN
L024	The final optic shall be remote from the chamber at a minimum distance to permit inclusion of magnetic and electrostatic debris guarding equipment.	P - SEN
L025	The lasers shall interface with building systems. Specific requirements related to laser components shall be established, covering heat removal, mechanical stability, vibration, seismic protection, thermal drift, cleanliness, etc.,	M - SEN
L026	A complete subset of specific Personnel Safety requirements (Laser hazard, High voltage protection etc., and Nuclear Safety requirements shall be defined for laser components located within the target area.	M - SEN
L027	A complete set of Reliability Availability Maintainability calculations as well as Integrated Logistic Support analyses shall be conducted to define the Laser equipment and its sub component contribution to the overall RAM and ILS performance of the facility.	M - SEN

B.3. Derived Laser Driver Requirements

Requirements are designated "M" for Mandatory or "P" for Preferable. Preferable requirements may be the subject of negotiation or modification during the Technology Development Phase. After negotiation, the preferential requirements will attain Mandatory status.

The SEN label (**S**ystem **E**ngineering **N**egotiation) identifies requirements shared with other sub-systems, or which depend upon the physics of ignition. These must be approved prior to completion of the laser design.

Unique ID	Description	Status
LOF001	The Master Oscillator (see L015) and Front End shall deliver to the amplifier section laser pulses with appropriate performances. Spatially shaped (TBD) Temporally shaped (TBD) Spectrally shaped (TBD) Output Energy (TBD) Output Power (TBD)	P
LAM001	The **L**aser **AM**plifier section shall deliver 1ω output laser pulses with appropriate performances (TBD): Spatially shaped (TBD) Temporally shaped (TBD)	P

Unique ID	Description	Status
	Spectrally shaped (TBD) Output Energy (TBD) Output Power (TBD)	
LAM002	The nominal energy (1ω) of each integrated laser beam shall be 10 kJ or greater.	P
LAM 003	The number / output energy of beamlets forming the laser beam shall be in the range 9 to 16, each delivering a nominal output of 1kJ at 1ω	P
LAM004	The amplifier section will integrate the design of the following :- Amplifier heads Diode drivers (continuous and pulsed modes) Beam extraction and spatial filtering design depending on beamlet size (TBD)	P
LAM005	The amplifier section shall provide heat rejection requirements to the building design. Cleanliness levels, humidity and temperature stabilization criteria will be confirmed.	P
LTR001	The beam transport to the Final Optic Assembly shall be designed to minimise optical pathways to the target, avoiding non linear effects.	P
LFO001	The final optics assembly concept shall integrate the following functions :- Convert, focus and (if necessary) compress the beams on the target with appropriate spatial and spectral performances. Diagnose the frequency converted beams "on target" Perform functions necessary to align and synchronize laser beams for target engagement. Note: target engagement functions may be undertaken further up the laser chain where there is benefit in terms of frequency response etc.	M
LAL001	The laser alignment system shall automatically align all the laser beamline sections before an operating sequence and shall maintain alignment against deleterious effects during operations.	M
LAL002	The Laser Alignment system shall contribute to the positioning and synchronization of beams on targets to accuracies suitable for target engagement.	M
LAL003	The Laser Alignment system shall be interfaced with the Integrated Computer Control System which supervises all laser and target area controls.	M
LAL004	The Laser Alignment equipment located near or inside the target areas shall withstand all the constraints induced by the environment. (eg EMP, Radiation, Neutron damage etc.)	M
LAL005	The Laser Alignment equipment shall define constraint requirements to the Building sub-system (stability, vibrations, thermal drift etc.).	M-SEN
LDG001	The Laser Diagnostic system shall provide appropriate measurement capability to control the laser beamline performance at a repetition rate of 10Hz (not precluding operations at 16Hz). Measured parameters shall include laser power, energy, spatial, temporal and spectral profiles and synchronization on target.	M
LDG002	Diagnostic stations shall sample representative parts of the beams at each section output, and shall be integrated into the final optical assembly for frequency-converted beams.	M
LDG003	The Laser Diagnostic system shall be interfaced with both the Integrated Computer Control system and the Target Engagement	M

Unique ID	Description	Status
	system.	
LDG004	The Laser Diagnostic equipment located near or inside the target areas shall withstand all induced effects. (e.g. EMP, Radiation, Neutron damage, etc.)	M
LOP001	The Laser optics components shall be designed to be compatible with the achievement of defined and agreed laser performance.	M
LOP002	The mechanical/optical parameters (including the process to define transmission , reflection and damage thresholds) shall be defined for each component	M
LOP003	The constraints induced by optical components to maintain their performance over time will drive requirements for the building sub-system (e.g Hygrometry, air cleanliness, temperature stability etc.). These will be managed by the Laser Engineering Team.	P-SEN

17.6 Annex C – Laser Driver Detailed Technology Development Plan

To execute the development programme the following services have been assumed to be available:

- An optical assembly area at sufficient level of cleanliness for elements of the beamlet prototype.
- Laboratory capability for characterisation and test of optical components manufactured for the facility.
- An amplifier and test bench and a performance evaluation facility.
- A frequency conversion test and evaluation bench
- Capability to model beam amplification, stress, cooling and beam transport factors
- Facilities for development of timing diagnostics
- Access to an existing facility for Neutron testing of optics (e.g. – Rochester, NY)

Both the Central Laser Facility of STFC and the LUCIA laboratory at LULI have access to these facilities.

Delivery of a suitable Laser is a programme of component and sub-system development, scalable at 10J, 100J and 1kJ, 10Hz level.

The technology development plans described in brief below are based on the TRL analysis performed elsewhere in this document. Where components (such as optics) are not shown on the development listing, these have been evaluated as having attained TRL 7 or above, (i.e.- they are currently sufficiently developed to be introduced into the laser chain).

Element	TRL Step	Technology Development Plan	Risk
Oscillator (Creating the primary laser pulse)	5 to 6	Define all the interfaces between this device and other facility components including the control-command sub-system. Produce REX model. Design and test industrial full scale oscillator model. Validate laser beam quality.	Low
Oscillator (Creating the primary laser pulse)	6 to 7	Incorporate design in prototype beamlet (1kJ 10Hz) and confirm operation	Low
Beam Splitting and Amplification	5 to 6	Define all the interfaces between this device and the other facility components including the control and command sub-system. Produce REX model Design and test industrial real scale oscillator model. Validate laser beam quality	Low
Beam Splitting and Amplification	6 to 7	Incorporate design in prototype beamlet (1kJ 10Hz) and test	Low
Temporal Pulse Shaping	6 to 7	Define the temporal modulator at the right wavelength and design and build a prototype. Test to validate	Low
Spectral Pulse Shaping	4 to 5	Define the real needs for the 1kJ prototype. Design and build a breadboard model and test to solve FM/AM issues.	Low
Spectral Pulse Shaping	5 to 6	Design and test industrial scale spectral pulse shaper. Validate laser beam quality	Low
Spectral Pulse	6 to 7	Design and build a prototype. Test to validate on 1kJ 10Hz	Low

Element	TRL Step	Technology Development Plan	Risk
Shaping		beamlet prototype	
Control System Hardware	6 to 7	Perform engineering design of control system architecture. Build and test system.	Low
Control System Software	2 to 3	Explore control system software architecture and establish timing of essential functions. (To be performed in parallel with development of diagnostic stations)	Medium
Control System Software	3 to 4	Real time software development must be undertaken from the architecture document. In many cases code generated will not be time critical but in some cases this may require certain functions to be programmed in machine code or incorporated into segregated sub systems. Initial coding suitable for bench test will achieve TRL 4.	Medium
Control System Software	4 to 5	Bench testing of code on simulated laser and achievement of desired test parameters will satisfy TRL 5.	Medium
Control System Software	5 to 6	Integration of the control system with the laser and completion of sub-system testing will achieve TRL 6.	Medium
Control System Software	6 to 7	Full system testing of the software on the 1kJ 10Hz laser beamlet prototype will achieve TRL 7.	Medium
Spatial Beam Shaping Addressable System	6 to 7	Technology exists and is proven. Define the complete specification – Reduce the 10 Hz risk level. Design and build a prototype. Conduct tests to validate	Low
Pulse Energy Amplification	5 to 6	Technology exists and is proven. Define the complete specifications – Reduce the 10 Hz risk level. Design and build a prototype. Conduct tests to validate on bench..	Low
Pulse Energy Amplification	6 to 7	Design and build a full scale prototype. Conduct tests to validate on 1kJ 10Hz beamlet prototype.	Low
Input Beam diagnostic station	5 to 6	Technology exists and is proven. Define the complete specifications – Reduce the 10 Hz risk level. Design and build a prototype. Conduct tests to validate on bench.	Low
Input Beam diagnostic station	6 to 7	Design and build a full scale prototype. Conduct tests to validate on 1kJ 10Hz beamlet prototype	Low
Conical SF Pinholes (for amplifier)	4 to 5	High rep rate design is required. Ablation is a known issue. A materials study is required.	Low
Conical SF Pinholes (for amplifier)	5 to 6	Design prototype and field on test bed at high rep rate (1000Hz)	Low
Conical SF Pinholes for amplifier)	6 to 7	Design prototype for operation on high intensity test bed 1kJ 10 Hz repetition rate	Low
Yb-YAG gain media	5 to 6	Integration of scale gain media into an amplifier housing and demonstration of the ability consistently to amplify to 1kJ 10Hz achieves TRL 6.	High
Yb-YAG	6 to 7	Integration and test as a part of the 1kJ 10Hz beamlet laser chain achieves TRL7.	High
Cooling cryo/other for amplifiers	5 to 6	Test loop at 1kJ 10Hz scale with full scale, 6 slabs, using REX and possibly the ELI-beam line arrangement.	Low
Cooling cryo/other for amplifiers	6 to 7	Test bed within the 1kJ 10 Hz beamlet prototype will achieve TRL 7.	Low
Diode Array	4 to 5	Development is essentially “industry seeding” for mass production of diodes, establishment of cooling technique	Low

Element	TRL Step	Technology Development Plan	Risk
		and incorporation of micro-lens arrangements suitable for coupling of the diodes to gain media.	
Diode Array	5 to 6	Integrated design capable of mass production at rates suitable for Laser Energy needs.	Low
Diode Array	6 to 7	Implementation on 1kJ 10Hz beamlet prototype	Low
Modelling and Prototyping Amplifiers	5 to 6	A 100J prototype amplifier must be built and evaluated to satisfy TRL 6.	Low
Modelling and Prototyping Amplifiers	6 to 7	A 1kJ 10Hz prototype amplifier must be built and evaluated to satisfy TRL 7.	Low
Plasma Electrode Pockel Cell (PEPC)	3 to 4	Design and selection of the non-linear material forming the PEPCI. At small scale, design and test PEPCI modules using these materials to evaluate and select non-linear material and concept design of electrodes.	Medium
Plasma Electrode Pockel Cell (PEPC)	4 to 5	Design and build half scale PEPCI and undertake testing of extinction ratio and optical transmission quality using pencil beam test bench. Evaluate electrode life on continuous test at high rep rate.	Medium
Plasma Electrode Pockel Cell (PEPC)	5 to 6	Design and build full scale PEPCI and confirm operation on test bench.	Medium
Plasma Electrode Pockel Cell (PEPC)	6 to 7	Integrate and test PEPCI as a part of the 1kJ 10Hz beamlet prototype.	Medium
Faraday Rotator	4 to 5	Define prototype needs for 1kJ laser and investigate suitability of various materials. Design, build and test brassboard model. (Unit may require cryo-cooling for superconducting magnetic coils). **Note** – Alternative technology to PEPC. Future down-select to be made between these technologies.	Medium
Faraday Rotator	5 to 6	Design, build and evaluate full-sized FR device.	Medium
Faraday Rotator	6 to 7	Integrate and test on 1 kJ 10Hz beamlet prototype	Medium
1ω Diagnostic Collimator	5 to 6	After definition of 1kJ 10Hz laser measurement requirements and confirmation of amplifier down select, the diagnostic collimator may be designed and built using existing technology. Confirmation on a bench test of measurement accuracies for the laser being achieved will satisfy TRL 6.	Medium
1ω Diagnostic Collimator	6 to 7	Integration of the collimator onto the 1kJ 10Hz beamlet prototype and the suitable and sufficient running of the prototype will satisfy TRL 7.	Medium
1ω Output Diagnostic Station	5 to 6	Define measurements required, to include classical and safety and safety elements for 1kJ rep rate laser. A diagnostic station suitable for high fluence beams must then be designed for measurements at the required accuracy at 10Hz. Demonstration of the diagnostic station at bench test will satisfy TRL 6.	Medium
1ω Output Diagnostic Station	6 to 7	Integration of the diagnostic station with the 1kJ 10Hz beamlet prototype and satisfactory operation in this environment will satisfy TRL 7.	Medium
Transmission	5 to 6	Technology for transmission gratings exists but has yet to	Low

Element	TRL Step	Technology Development Plan	Risk
Gratings		be demonstrated at high repetition rates. TRL 5 to 6 is achieved through testing under repetition rate operating conditions.	
Transmission Gratings	6 to 7	Fielding and testing of gratings of suitable size for operation in a 1kJ 10 Hz environment will satisfy TRL7.	Low
2ω and 3ω Frequency Conversion Crystals	3 to 4	LBO crystal testing at ALIZE in CEA CESTA at fluence $1GW/cm^2$ has been conducted on 7cm diameter crystals. This has demonstrated the ability to grow crystals of suitable size. Similar testing must be undertaken for YCOB crystal variants.	Medium
2ω and 3ω Frequency Conversion Crystals	4 to 5	The crystal medium required must be down-selected from YCOB or LBO. Successful demonstration and testing of growth, polishing and grinding of crystals of an appropriate aperture for the 1kJ 10Hz beamlet prototype will satisfy TRL 5.	Medium
2ω and 3ω Frequency Conversion Crystals	5 to 6	Full scale growth, polishing grinding and coating of crystals, as well as definition of storage conditions and bench testing will satisfy TRL6.	Medium
2ω and 3ω Frequency Conversion Crystals	6 to 7	Manufacture and quality control of appropriate crystals and their fielding on a 1kJ 10Hz beamlet prototype will satisfy TRL 6.	Medium
Short Pulse Frequency Conversion Crystals	2 to 3	Proof of concept has been achieved for short pulse crystals, but issues affecting fluence and diffraction limit on 2ω installations must be addressed. A similar programme is required to that for long pulse crystals. This will demand more time due to the higher fluences and damage threshold limitations involved. Material growth and availability criteria will satisfy TRL 3.	High
Short Pulse Frequency Conversion Crystals	3 to 4	Testing of different crystal types under representative scaled conditions will inform down-selection. Completion of the programme will identify the material(s) preferred for development.	High
Short Pulse Frequency Conversion Crystals	4 to 5	The crystals required for 1kJ must be selected from the above. Successful demonstration of growth, polishing and grinding of suitable crystals and their subsequent testing will satisfy TRL 5.	High
Short Pulse Frequency Conversion Crystals	5 to 6	Full scale growth, polishing grinding and coating of crystals, as well as definition of storage conditions will satisfy TRL6.	High
Short Pulse Frequency Conversion Crystals	6 to 7	Manufacture and quality control of appropriate crystals for a 1kJ 10Hz beamlet prototype and fielding on the prototype will satisfy TRL 6.	High
Colour Separator	5 to 6	Colour separator technology exists but has not been proven at the fluence and repetition rate appropriate to Laser Energy. Testing and confirmation that the technology is suitable for continuous repetition rate operation in a scaled environment will satisfy TRL 6.	Medium

Element	TRL Step	Technology Development Plan	Risk
Colour Separator	6 to 7	Final demonstration of the technology will require a full-sized optic and the 10kJ 10Hz prototype.	Medium
Phase Plate	5 to 6	Phase plates currently exist and the technology required for 1kJ will not differ substantially from current practice. Manufacture of a suitably sized phase plate arrangement will satisfy TRL 6	Low
Phase Plate	6 to 7	Fielding of the phase plate arrangement on the beamlet demonstrator will satisfy TRL 7.	Low
3ω Conical Pinhole	2 to 3	The 3ω conical pinhole for 1kJ will reduce the neutron fluence on the turning mirror. It is subject to high intensity 3ω damage and high energy neutron flux. Requirements for these environments must be defined and candidate materials for this application must be identified and tested. This will satisfy TRL 3.	High
3ω Conical Pinhole	3 to 4	Pinholes of selected materials will be tested in representative conditions. Down-selection of material and pinhole dimensions will satisfy TRL 4.	High
3ω Conical Pinhole	4 to 5	Confirmation of the ability to build pinhole arrangements to the required specifications will satisfy TRL5.	High
3ω Conical Pinhole	5 to 6	Testing of the pinhole arrangement for an appropriate period of time on the 1kJ 10Hz beamlet prototype will satisfy TRL 5.5. TRL 6 can only be achieved when neutron fluxes are available from repetitive fusion events.	High
3ω Conical Pinhole	6 to 7	TRL 7 may only be achieved after a period of operation in a fusion environment.	High
Debris Shield	5 to 6	Initial calculations have shown that adequate debris shielding can be provided by intense electric and magnetic fields. Gas protection within a reactor would provide additional protection. Experiments will confirm modelling. Appropriate testing will satisfy TRL 6.	Medium
Debris Shield	6 to 7	The solution cannot be finally proven until demonstration is possible in an operational reactor environment.	Medium
2 and 3ω Diagnostic and Alignment Station	5 to 6	Refined measurements are needed in the 1kJ 10Hz beamlet prototype. A diagnostic station must be designed to achieve this to the required accuracy at 10Hz. Successful demonstration of operation will satisfy TRL 6.	Medium
2 and 3ω Diagnostic and Alignment Station	6 to 7	Integration of the diagnostic station will be tested on the 1kJ 10Hz beamlet prototype. Satisfactory operation of the station in this environment will satisfy TRL 7.	Medium

17.7 Annex D - Generic Definitions of Technology Readiness Levels

Technology Readiness Level (TRL)		Working Level	Basic objective of TRL	Components Involved	Degree of Integration	Tests and Environment
1	Basic principles observed and reported.	Desk Studies.	Research to prove feasibility.	None.	None.	Desktop environment.
2	Technology concept and/or application formulated.	Desk Studies.	Research to prove feasibility.	None.	Paper studies indicate that components should work together.	Academic environment. Emphasis remains on understanding the science but beginning to consider possible applications of the scientific principles.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Pieces of components.	Research to prove feasibility.	No system components, just basic laboratory research equipment to verify physical principles.	No attempt at integration. Still exploring functionality of individual technology components. Laboratory experiments with available components will demonstrate this.	Uses of the observed properties are postulated and experimentation begins with potential elements of sub-system. Laboratory work to validate pieces of technology without attempting integration. Emphasis is on validating predictions made during earlier analytical studies to ensure firm scientific underpinning of the technology.
4	Component and/or breadboard [1] validation in lab environment.	Low fidelity breadboard.	Demonstrate technical feasibility and functionality.	Ad hoc and available laboratory components are surrogates for system components which may require special handling, calibration, or alignment to achieve functionality. Not fully functional but representative of technically feasible approach.	Available components assembled into sub-system breadboard. Interfaces between components are realistic.	Tests in controlled laboratory environment. Laboratory work at less than full sub-system integration, although starting to verify that components will work together.

[1] Breadboard – prototype configured for testing within a laboratory to determine the feasibility of the intended product, and to generate associated technical and operational data

Technology Readiness Level (TRL)		Working Level	Basic objective of TRL	Components Involved	Degree of Integration	Tests and Environment
5	Component and/or brassboard [2] validation in relevant environment.	Mid- fidelity brassboard (e.g., non-scale or form components).	Demonstrate technical feasibility and functionality.	Fidelity of components and interfaces are improved from TRL 4. Some special purpose components combined with available laboratory components. Functionally equivalent but not of same material or size. May include integration of several components with reasonably realistic support elements to demonstrate functionality.	Fidelity of sub-system mock-up improves (e.g., from breadboard to brassboard). Integration issues become defined.	Laboratory environment modified to approximate operational environment. Increases in accuracy of the controlled environment in which tests are conducted.
6	System / Sub-system model or prototype demonstration in relevant environment.	Sub-system closely configured for intended project application. Demonstrated in relevant environment. (Shows it will work in desired configuration).	Demonstrate applicability to intended project and sub-system integration. (Specific to intended application in project.)	Sub-system is a high fidelity functional prototype, very similar in material and size. Probably includes the integration of many new components and realistic supporting elements/sub-systems if needed to demonstrate full functionality. Partially integrated with existing systems.	Components are functionally compatible (and very close to operational system in material and size. Component integration into system is demonstrated.	Relevant environment inside or outside the laboratory, but not the eventual operating environment. The testing environment does not reach the level of an operational environment, although moves beyond controlled laboratory environment into a close approximation to reality for the intended application.
7	Sub-system prototype demonstration in an operational environment.	Sub-system configured for intended project application. Demonstrated in operational environment.	Demonstrate applicability to intended project and sub-system integration. (Specific to intended application in project.)	Prototype improves to preproduction quality. Components are representative of project components (material, size, and function) and integrated with other key supporting elements/sub-systems to demonstrate full functionality. Accurate enough representation to expect only minor design changes.	Prototype not integrated into intended system but onto surrogate system.	Operational environment, but not the eventual environment. Operational testing of system in representational environment. Prototype will be exposed to the true operational environment on a surrogate platform, demonstrator, or test bed.

[2] Brassboard – prototype configured for out-of-the-laboratory testing, to determine the feasibility of the intended product, and to develop its technicaland operational data

Technology Readiness Level (TRL)		Working Level	Basic objective of TRL	Components Involved	Degree of Integration	Tests and Environment
8	Total system completed, tested, and fully demonstrated.	Full integration of sub-systems to show total system will meet requirements.	Applied/integrated into intended project application.	Components are right material, size, and function, compatible with operational system.	Sub-system performance meets intended application and is fully integrated into total system.	Demonstration, test, and evaluation completed. Demonstrates system meets procurement specifications. Demonstrated in eventual environment.
9	Total system used successfully in project operations.	System meeting intended operational requirements.	Applied/Integrated into intended project application.	Components are successfully performing in the actual environment—proper size, material, and function.	Sub-system has been installed and successfully deployed in project systems.	Operational testing and evaluation completed. Demonstrates that system is capable of meeting all mission requirements.

Acknowledgement:
The above table has been adapted from one presented in US Government Accountability Office report GAO-07-336, March 2007, “Major Construction Projects Need a Consistent Approach for Assessing Technology Readiness to Help Avoid Cost Increases and Delays”

18 Appendix II: Roadmap to shock ignition at LMJ

18.1 Summary

Following consideration by the HiPER Executive Board in December 2010, it was decided that HiPER would be based on the shock ignition, "direct drive" scheme. This approach offers important advantages over the alternative, indirect drive scheme adopted for the National Ignition Campaign (NIC) at Lawrence Livermore National Laboratory (LLNL) in the US. Advantages include a potentially simpler target design, high gain, and the possibility of demonstrating ignition with lower laser drive energy.

The main disadvantage of the shock ignition scheme is that it is comparatively less well developed than the indirect drive approach. Systems engineering issues, (fuel capsule survival after injection into the fusion chamber, etc) must be addressed in order to demonstrate repetitive operation, as required for commercial energy production.

The Shock Ignition Roadmap, currently under development, will identify the programme of experiments, numerical simulations and systems engineering studies required to develop shock ignition to the point at which it can be demonstrated in single-shot ignition events at Laser Mega Joule (LMJ) and developed into a credible ignition platform for commercial energy production.

18.2 Introduction

Two distinct approaches exist to driving a fuel capsule to ignition and burn using laser drivers. These are "direct drive" (DD) and "indirect drive" (IDD). Both schemes involve the compression by laser pulse of a thin shelled capsule containing deuterium (D) and tritium (T) to extremely high density and then heating a small region of the D-T fuel to 5 keV (50 million K), at which point the fuel ignites and a burn wave propagates through the compressed fuel. The schemes differ in the manner of delivering laser energy to the fuel capsule.

In the case of indirect drive, the laser is focussed onto the inner surface of a high – Z metal can, or Hohlraum, which surrounds the fuel capsule. As the metal surface heats, it emits soft X-rays which bathe the fuel capsule in a uniform field of radiation. While the Hohlraum material is chosen to optimise the emission of X-radiation, the overall laser-to-X-ray conversion efficiency of 30% - 35% represents a significant loss of energy. The advantage of the indirect drive scheme is the high level of drive uniformity acting upon the fuel capsule experiences. This helps to suppress the onset and growth of hydrodynamic instabilities which tend to occur as implosion of the capsule shell accelerates.

With direct drive, the laser is focused directly on the surface of the fusion capsule. Avoiding the X-ray production stage of indirect drive in this way brings potential benefits in terms of overall energy efficiency of the ignition process, but requires extremely uniform irradiation of the capsule to control the growth of Rayleigh Taylor and other hydrodynamic instabilities. A further complication is that, as the fuel capsule compresses, it presents a reducing area to the incoming laser drive beams which must be compensated for focussing in order to maintain their intensity upon the diminishing target.

18.3 Shock ignition

Shock ignition is a direct drive scheme in which the fuel capsule is first compressed to moderately high density using long pulse laser irradiation directly on the surface of the fuel capsule. As the stagnation point is reached at the end of the compression phase, a convergent spherical shock wave is launched into the compressed fuel, using a high intensity laser "spike". The shock wave converges on the high density core and collides with the rebound shock. Both shock convergence and shock collision give pressure amplification and, with appropriate target design, simulations predict that the temperature of the fuel can be raised to ignition point.

The shock ignition scheme has important advantages. The lower in-flight aspect ratio and lower implosion velocity lead to reduced hydrodynamic instability. The energy required for the modest initial compression is reduced leading to high net energy gain. The shock ignition pulse requires less energy to achieve ignition since only the hot spot is raised to ignition pressure. In common with “fast ignition”, the direct drive scheme avoids the inefficiency of the Hohlraum’s X-ray conversion process and overall energy gain of the target is increased.

18.4 LMJ availability for full scale ignition demonstrations

Relevant areas of physics must be explored numerically and experimentally to validate the shock ignition scheme. As identified within the Shock Ignition Roadmap, the experimental programme can be addressed using existing large scale laser facilities. In particular, calculations suggest that a full-scale ignition demonstration is well within the capability of the NIF and LMJ facilities. Furthermore, the current strategy of CEA, (the LMJ operator), is that up to 30% of beam time will be made available to the academic community when the machine comes on line in 2015. Current estimates are that shock ignition of a D – T fuel capsule could be demonstrated at LMJ by 2022. This represents an extremely important opportunity for the HiPER project.

The scientific and engineering programme including underpinning experiments on medium scale facilities, and the fielding of a full scale “scale 1” ignition campaign on LMJ represents a substantial scientific and engineering challenge for the European community. The funding, scheduling and resourcing requirements of such a campaign are currently being developed and will form a major element of the Phase 1 HiPER Business Case.

Some of the most important aspects of the Shock Ignition Scheme which require development are identified below.

Drive uniformity with existing facilities

In all ignition schemes, it is necessary to deliver uniform drive on the fuel capsule in order to reduce the growth of low mode Rayleigh Taylor hydrodynamic instabilities. In both shock ignition and fast ignition, drive uniformity must be achieved through the disposition of beams around the capsule. Ideally this would be achieved by arranging distribution of many drive beams over the entire capsule surface. This arrangement is not available for the foreseeable future at the NIF or LMJ facilities, which are configured for indirect drive with beams distributed around two (LMJ) or three (NIF) axial cones. A promising solution to this issue is a hybrid “polar direct drive” (PDD) arrangement whereby some of the beams from the higher angle cones are re-pointed towards the equator of the fuel capsule.

The advantage of the PDD arrangement is that it can be fielded on NIF and LMJ facilities in their “Day 1” configuration; i.e. no modifications to the facility are required beyond re-pointing the beams. Further enhancements are available at modest cost by making changes to the phase plates which modify the energy distribution of each beam on the target surface.

Calculations suggest that the PDD arrangement produces sufficient drive uniformity to achieve the required level of compression without driving hydrodynamic instabilities. Experimental verification is required before a compelling case can be made for full scale compression experiments at LMJ or NIF. A series of experiments is being planned using existing intermediate scale facilities such as Orion (AWE, UK) and Omega (University of Rochester, US).

Laser plasma interaction physics

There is a high level of confidence in the hydrodynamic performance of relatively large targets (>1.5mg) with correspondingly large laser drive energy (~ 1MJ). The performance of smaller targets, with laser drive energies within the reach of existing facilities configured for polar direct drive is less well understood. Preliminary experiments performed to date also have yet to achieve ablation pressures in the 300Mbar regime, as is required for shock launch. There also remains uncertainty as to the role of hot electrons generated in the interaction of the laser spike and the compressed fuel. In the traditional central hot spot ignition scheme, hot electrons lead to target pre-heat and lower compression for given laser drive; in shock ignition hot electrons are potentially beneficial, as they may contribute to enhanced energy transport and improved shock uniformity.

A comprehensive series of experiments is therefore required to explore the regimes of importance and to increase the fidelity of numerical models needed to design full-scale ignition experiments. These experiments are being specified as part of the shock ignition roadmap definition activity.

Systems engineering and reactor modelling

Provided that the experimental and simulation programmes identified within the Shock Ignition roadmap are favourable, ignition and burn of a fuel capsule at high energy gain by shock ignition using the "Day 1" configuration of LMJ or NIF is a real possibility. This will be a vital demonstration, altough important systems engineering issues must be addressed in order to progress to commercial power production.

Currently the most important systems consideration is the technical strategy for delivery of the shock ignition fuel capsule to the ignition point within the reactor vessel. The first shock ignition demonstration experiments at LMJ, or NIF, will be conducted in a cold, evacuated target chamber with the cryogenically cooled target mounted in a fixed position. This is far removed from the conditions which will be encountered in a power plant environment.

A power plant chamber will probably be operating at elevated temperature, possibly 600 deg C and above, and will be filled with a low pressure gas, - possibly xenon, to protect the first wall from X-ray ablation and ion bombardment. Targets accelerated to 100's msec^{-1} before injection into the chamber must survive all of these environmental factors up to the point of engagement with the laser beams and subsequent ignition. For example, to maintain the target at the D-T triple point requires a short exposure time to the hot chamber environment, which in turn requires high injection velocity and thus high acceleration. Survival of the target under such acceleration and its travel through the chamber gas at high velocity will impose constraints on the target's mechanical design, some of which are likely to affect ignition performance.

To satisfy all of the above requirements, and others which will emerge as understanding of the problems improves, requires a comprehensive systems engineering approach. The extent of the systems engineering effort required for the next phase of the project is not yet fully known and will be the subject of investigation in the first part of the next phase.

18.5 Timeline for scale 1 shock ignition demonstration

An indicative timeline for first demonstration of shock ignition at LMJ is shown in Figure 12.

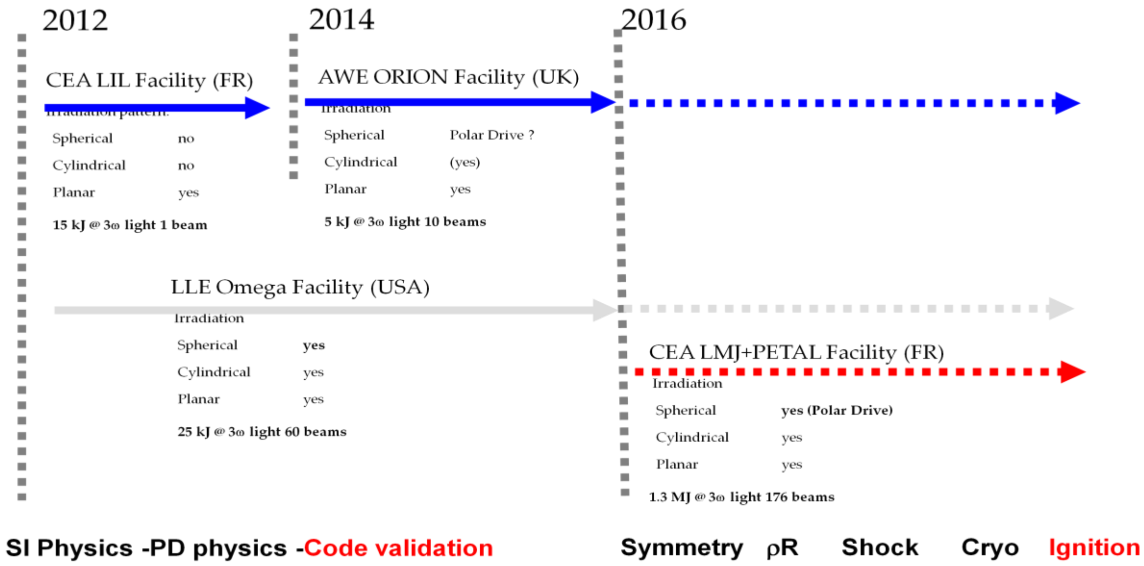


Figure 12: Indicative timeline for shock ignition demonstration on LMJ

In the period to 2016, existing facilities including LIL (France), Omega (US) and Orion (UK) are used in a series of experiments to improve the fidelity of numerical simulations and to study outstanding aspects of the physics of shock ignition.

In 2016, a programme of experiments will be conducted using the LMJ facility to prepare the shock ignition platform. This includes validation of the hydrodynamics using the polar direct drive arrangement, compression experiments to demonstrate that high density conditions can be created and studies of shock generation and propagation. These experiments will be conducted initially using warm (non-cryo) targets. The cryogenic D-T campaign will commence by 2020 and, given sufficient beamtime at the facility to perform the necessary tuning and optimisation, ignition is expected around 2022.

The cost of the experimental programme at LMJ will depend on many factors, including the negotiation of beam time costs and charges for experimental support, target manufacture and diagnostics provision. These costs will be identified following negotiations with the facility operators, to be conducted early in the next phase of the project.

19 Appendix III: LMJ shock ignition campaigns

Foreword

Demonstrating shock ignition on LMJ is central to HiPER, realistic, and requires a joint effort of our community. It is for the time being not sufficiently detailed to define an experimental roadmap. The intention is to determine a suitably detailed roadmap during the remainder of the HiPER Preparatory Phase Project.

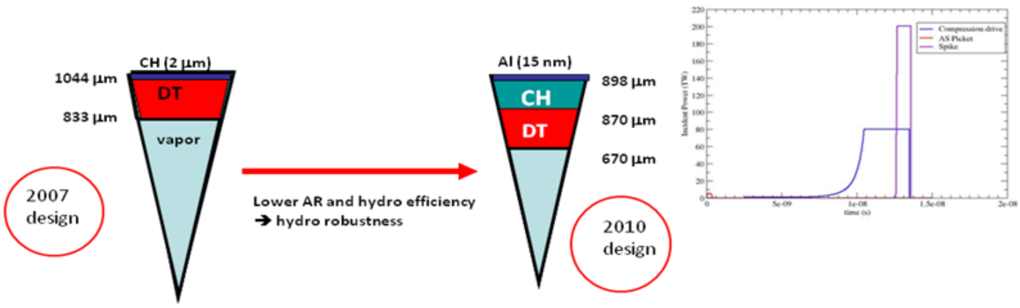
19.1 Introduction

The HiPER project was launched on the emerging belief (2002-2008) that laser driven Fast Ignition of DT could be achieved with an energy of 130 kJ for target compression and a short 70 kJ additional pulse for ignition. The construction cost of a single shot fast ignition facility was estimated at ~ 800 ME. This vision is presently obsolete for the following reasons:

- The steering committee of the project determined that there was no merit in campaigning for construction of a single shot facility which would not be operational until the 2020'a.
- Scientific issues in Fast Ignition appear to be more difficult to circumvent than expected.
- A severe gap between demand and availability of energy will need to be bridged circa 2040, making the scientific and economical case for a commercial reactor a very strong priority.

These reasons form the rationale for a single step to the demonstration of energy production. From the target physics point of view, a reactor design must build on a robust, simple, and demonstrated ignition scheme. Shock Ignition, where the fuel is compressed on a low isentrope, and low velocity by classical means, and further ignited by a converging shock has the potential to meet these requirements. The target is a simple plastic shell containing a cryogenic DT layer and is a priori amenable to low cost mass production. First studies indicate that compression and hot spot ignition of SI targets are more robust than conventional direct or indirect drive central ignition. The laser requirements fall within the operating domain of NIF and LMJ, which indicates that SI could be demonstrated on these facilities between 2016 and 2020. Achieving this goal on LMJ will give Europe a definite leadership in the field of Inertial Fusion Energy and strongly encourage a collaboration between EU, US, and Asia aiming at the design of an IFE demonstrator.

19.2 Targets and gain curves



	IFAR 75%r_0	Mass	Compression	Vimplo	η %	Spike	Gain
ALL DT	4.5 (t=0) 30 (75%r_0)	.59 mg .29 fuel	180 kJ 50 TW 600 g/cc 1.5 g/cm²	280 km/s	9%	160 TW 80 kJ	Y = 20 MJ G ~ 76
CH	3.4 (t=0) 18 (75% r_0)	.67 mg .38 mg fuel	260 kJ 80 TW 720 g/cc 1.83 g/cm2	240 km/s	5%	200 TW 150 KJ	Y = 32 MJ G ~ 80

Figure 13: Evolution of the baseline HiPER target

Figure 13 displays the evolution of the targets envisioned for HiPER. The ALL-DT target was first proposed in 2007 by Stefano Atzeni and widely used by the computational groups in HiPER for first assessment of performance and robustness. It also allowed detailed code comparisons and gave us mutual confidence in code predictions. The CH/DT target is more amenable to fabrication and is also significantly less efficient, but should be more robust thanks to a lowered in flight aspect ratio and reduced implosion velocity. This target requires 260 kJ, 80TW for compression and an additional 100 kJ, 200TW for ignition. It may be upscaled in order to increase its robustness with respect to mix. A Euler scaling of factor h increases the compression power by h^2, but decreases the power required for ignition and therefore strongly reduces the intensity in the ignition spike.

A sensible domain to consider for shock ignition involves targets scales in the range $1<h<1.5$. For $h=1.5$, the compression is achieved with 880 kJ, 180 TW, and ignition requires an additional 150 TW, 80 kJ. The corresponding 1D clean gain is 130.

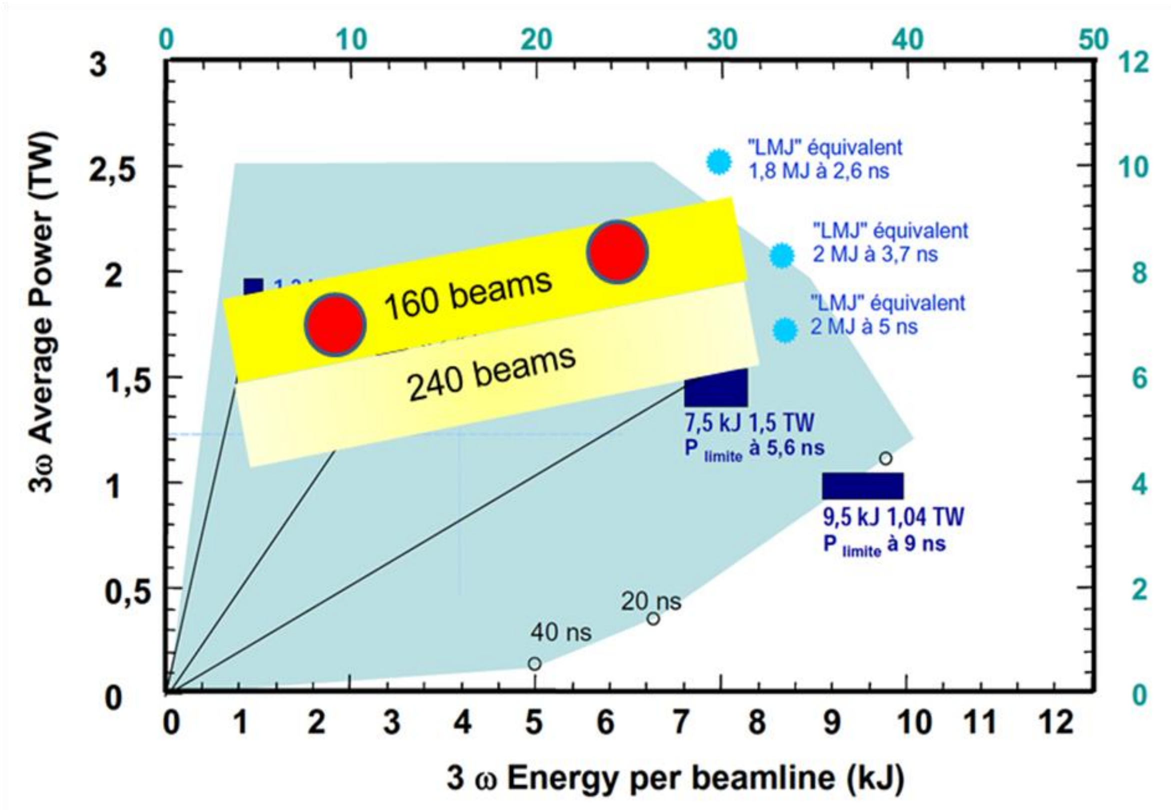


Figure 14: Operating domain of LMJ (blue area).

The yellow band contains possible SI designs with gains ranging between 80 and 150 for a 160 beams configuration. The maximum power per beam can be reduced by 10% using the full 176 beams LMJ design and by ~33% using the original 240 beams pattern (yellow shaded area). Red dots are two extreme SI designs with different trade-offs between ignition safety and damage to final optics.

These designs are plotted in red on Figure 14, where the operating domain of LMJ is represented in the EnergyXpower (per beam line) plane. Nominal LMJ will feature 40 quads for target compression and 4 additional quads for diagnostics. Using these 16 additional beams will reduce the power requirement for ignition to 1.6 TW, 2KJ per beam for the scale 1 design and to 1.95TW, 6KJ per beam for the scale 1.5 design. All of the proposed designs fall within the capacity of LMJ. Designs with $1<h<1.25$ can be experimented at low risk for the facility.

19.3 Target Illumination

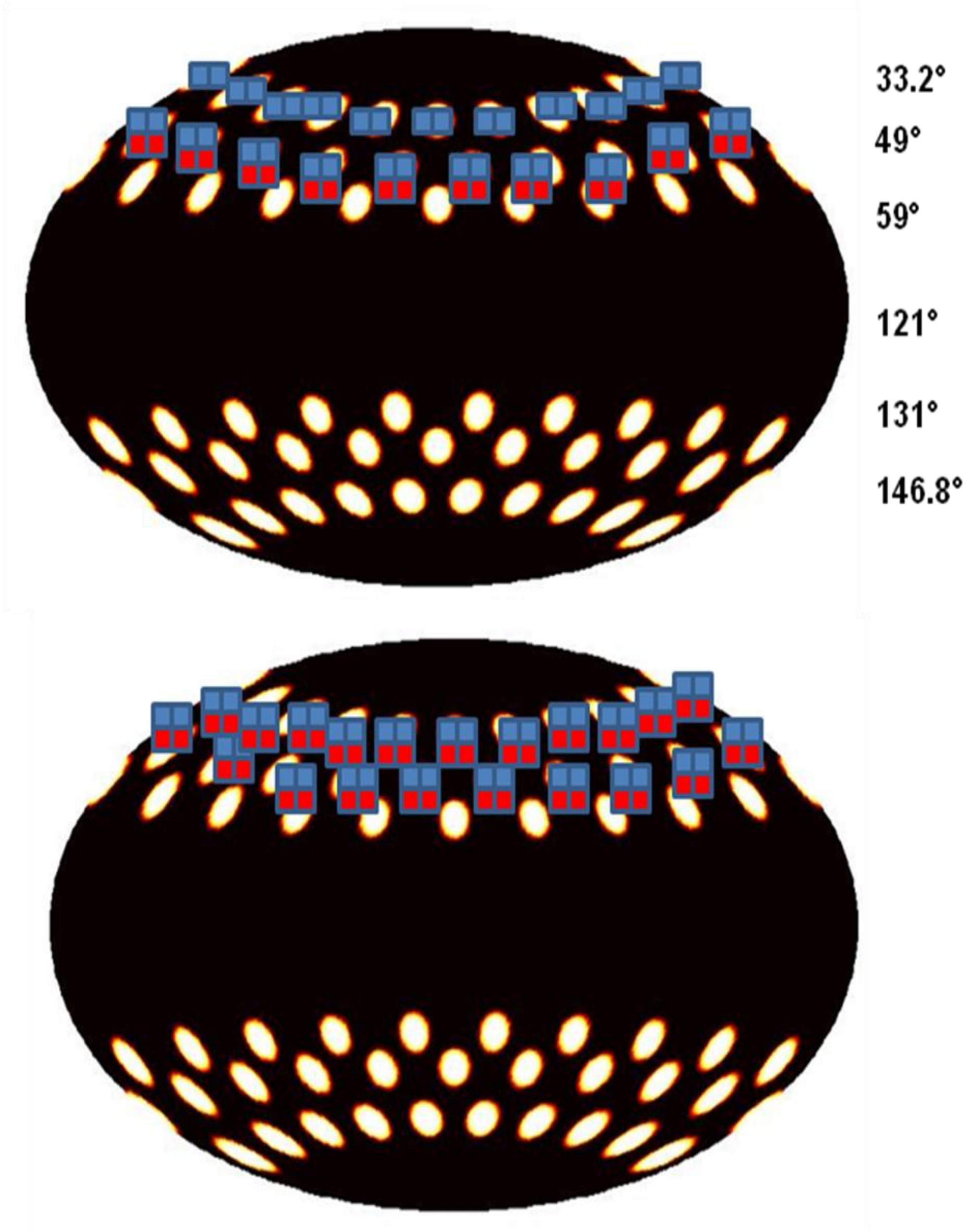


Figure 15: Polar drive irradiation on 160 beams LMJ. Compression will use half of the 33° beams (lower beams – 33a) and all 49° beams, splitted into 2 rings (49°a &b). All beams are repointed and defocused. The shock will be driven by all beams.

19.4 LMJ nominal irradiation pattern.

Although the energy-power performance diagram of LMJ is perfectly suitable for SI experimentation, the irradiation pattern of the facility is poorly adapted to direct drive implosions as it is. LMJ will feature 160 main beams organized in quads and focused on 40 elliptical focal spots. The laser ports on the LMJ target chamber are placed in 4 rings with polar angles 33°2, 49°, 131°, 146.8°. Beam angles and focal spot sizes are designed in order to ensure the proper illumination of the inner wall of a cylindrical casing (“Indirect Drive” geometry). A ring of laser ports has been drilled at 59° and 121° in prevision of a 240 beam illumination. Some of these ports will be used by 4 additional quads for diagnostic purposes.

The proposed strategy for access to LMJ is to use the facility as it is, with minimum modifications. The irradiation pattern of LMJ can be tuned to provide a quasi uniform illumination of a sphere using three knobs : beam repointing, beam defocusing, pulse shaping.

19.5 Quad splitting and Pulse shaping

Each preamplifier module (PAM) of LMJ addresses 2 beams, and each pulse shaping device addresses two PAMs. This means that the same pulse shape can be delivered to the two lower (resp. upper) beams of a given quad and the two lower (resp. upper) beams of the corresponding quad in the opposite hemisphere as shown in Figure 16.

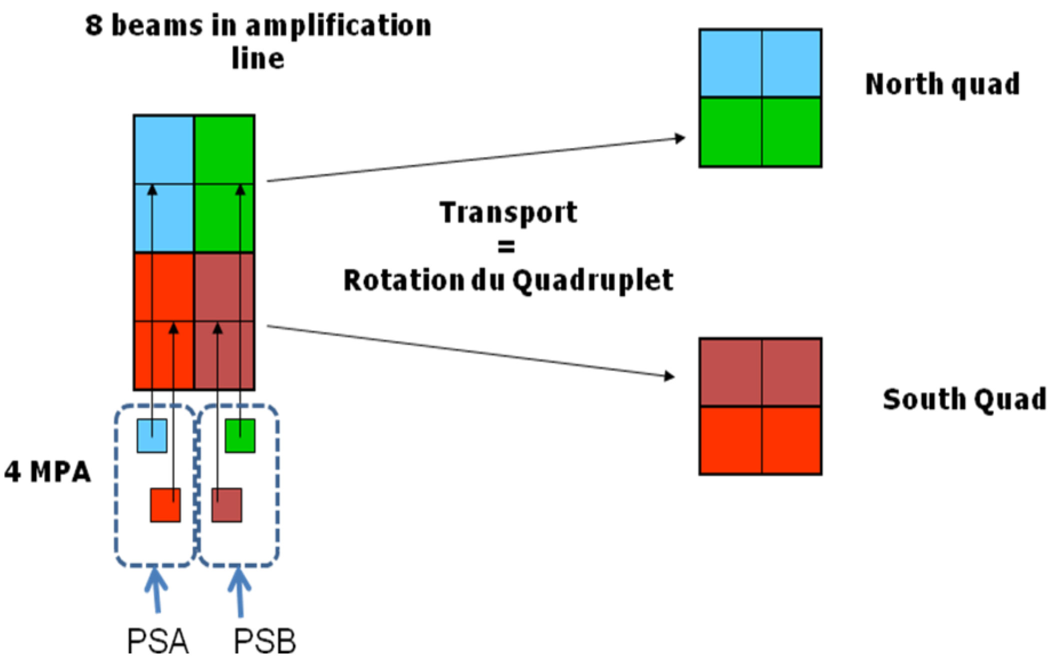


Figure 16: Distribution of pulse shapes on LMJ quads

This feature allows to split a given ring of LMJ in two distinct rings with different pulse shapes. In what follows the 49° (131°) ring will be splitted into two rings 49a and 49b, used for compression and spike. The 33.2° (146.8°) ring is splitted into a 33a ring for compression and spike and a 33b ring for spike only. Hence, ring to ring power balance can be tuned to minimize the irradiation non uniformity.

19.6 Defocusing

The focusing optics of LMJ produce elliptical focal spots with different super Gaussian exponents and HWHM on their main axes. Figure 17 displays the caustic of a full quad of LMJ where the 4 focal spots overlap at z=0 (best focus). Since the focal spot width at best focus is too narrow for the proper illumination of a sphere, we will need to defocus the quads. Note that the 4 beams of each quad must have the same defocusing distance, but may be pointed at different locations.

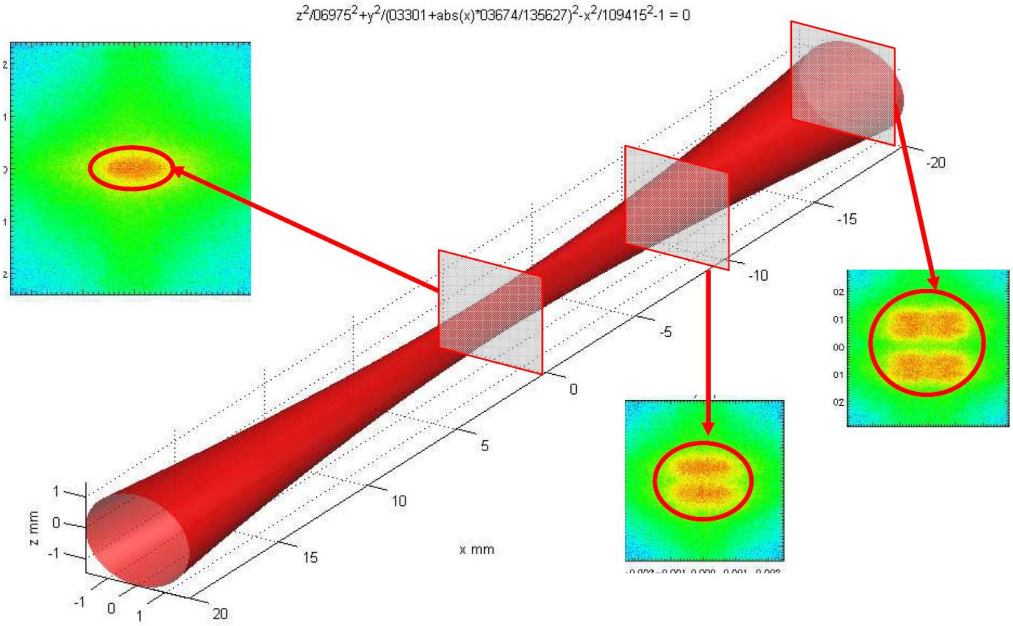


Figure 17: Distribution of intensity at different distances from best focus for a LMJ quad

1.1 Repointing

Repointing beams towards the equator of the target is necessary in order to provide a uniform illumination. The amount of repointing depends on the target diameter. A scale 1.1 (2mm diameter) target is considered in the example given in fig.6; the two lower beams of the 33°2 cone are repointed at 27.9° (-3° angular shift), 2 beams of the 49° ring are repointed at 61.5° (~15° shift), and the remaining two beams of 49b are repointed at 80.2° (29° shift). This 3 rings polar drive illumination, defocused by 1.8 cm behind the target yields a departure to uniformity close to 2.1% rms. Tuning the relative power among rings improves this figure to 1.27%rms. (in this case the optimal balance is close to 34% on 33a , 31% on 49a and 35% on 49b). The geometrical absorption coefficient is 97%.

During the implosion, the apparent radius of the target decreases down to 50-60% of its initial value, causing the symmetry indicator and absorption coefficient to degrade. This effect is enhanced by refraction effects but mitigated by thermal smoothing. Two dimensional simulations are therefore mandatory to finely tune the irradiation pattern.

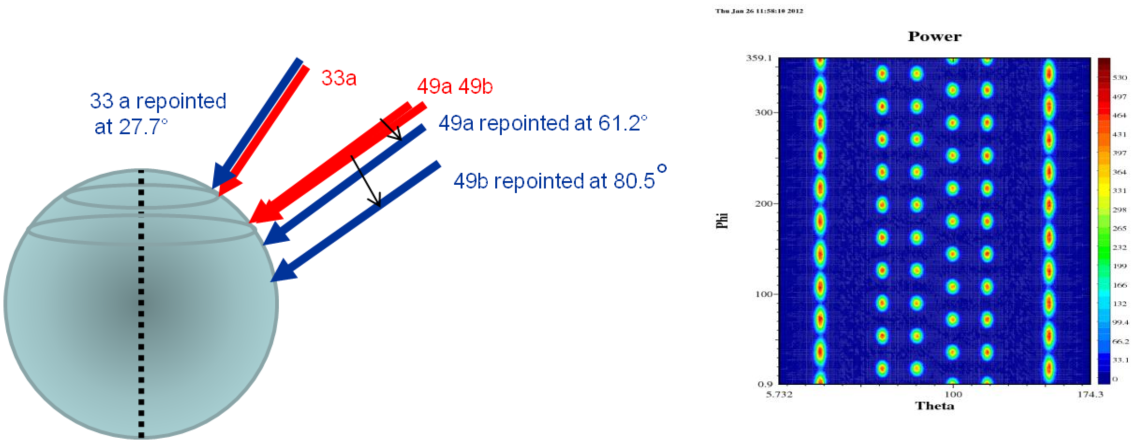
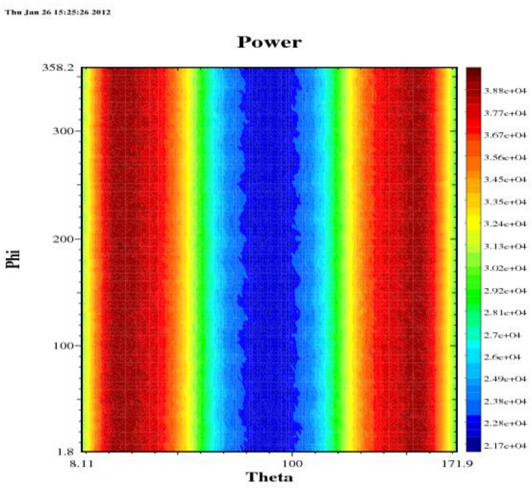


Figure 18: 3 PDD ring illumination using 120 beams of LMJ optimized to 1.27% rms. 6b displays the locations of the 120 focal spots on a r=1mm sphere

19.7 Bipolar pattern of the ignition Spike.

In the previously mentioned PDD configuration using 3 rings, 120 beams are switched on for compression and all 160 beams are used for the spike, all at full power (equal balance). Irradiation non uniformity in this case is evaluated at 20%, with 98% of geometrical absorption. However, the actual critical radius at spike time (ie end of the compression pulse) is close to 500 microns, in which case the irradiation non uniformity is 11% with 58% geometrical absorption. In both cases, the irradiation peaks on the poles of the target and the illumination is clearly two-sided as displayed in Figure 19.



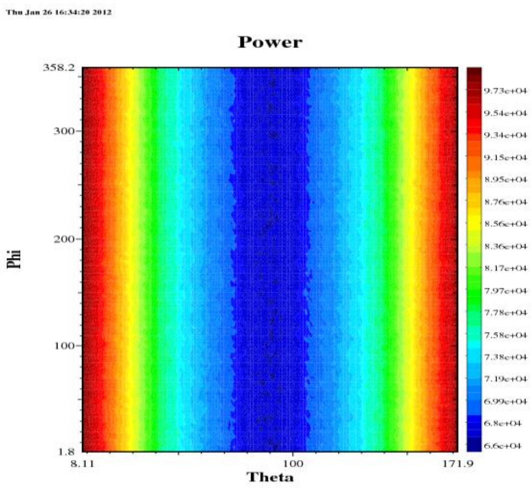


Figure 19: Intensity on target at spike time using all 120+40 beams. 7-a on a sphere of 1mm radius. 7-b at critical surface

Numerical simulations of a spherically imploded target ignited by a 2 sided ignition spike indicate quasi nominal ignition. This is due to two effects : large absorption occur in the bulk of the plasma and strong lateral thermal smoothing produce a weakly non uniform ablation pressure. This effect would probably be enhanced by the presence of a high energy tail in the electron distribution, but may be inhibited by self generated magnetic fields. Detailed hydro simulations including electron kinetics should address these issues. The 16 additional diagnostic beams have not been used here.

19.8 Dynamic repointing

Reckoning that the illumination symmetry as well as the absorption efficiency are time dependant, one would wish to vary the repointing in time. The focusing optics of LMJ do not use lenses but gratings; this makes the focusing angle to depend on the wavelength. First estimations (C.Rouyer, X. RIbeyre) indicate that a time dependant tuning of the wavelength could be achievable on LMJ, allowing to move the fs location by a few hundred microns between the early time of irradiation and the final spike. This very elegant solution could provide an optimal symmetry and absorption efficiency during the implosion. LIL laser experiments could be used to validate the concept.

19.9 Roadmap

When deciding what the roadmap to ignition on LMJ will be, we must consider how we envision progress to full scale ignition attempts on LMJ, and how we get ready to it. A major constraint will be the relative timescales of HiPER and LMJ. HiPER needs ignition to be demonstrated before 2020. First beams of LMJ will be commissioned at the end of 2014 and full LMJ will be commissioned a few years later.

Preparations required:

- identify most physical issues and demonstrated our understanding and ability to model them.
- Design codes are shown to be predictive in the relevant domain.
- Point ignition design is defined and ignition robustness is assessed using intensive simulation campaigns.
- Targets are specified , manufacturing process validated, delivery planned.
- Laser specifications are complete.
- Diagnostics are defined according to an ignition metric and qualified.

Proceeding to ignition involves

- Checking (not investigating) control of physical issues and code predictivity at scale 1
- Defining successive milestones to qualify progress and engagement of successive phases
- Define the performances to be demonstrated in “low risk” experiments before going to “high risk” experiments
- Plan the delivery of targets and availability of diagnostics accordingly.

19.10 General Physical issues

Most physical issues in SI are scale dependant and can only be observed on full LMJ experiments. However, the number of LMJ shots will be limited for reasons of cost and availability of the facility. This requires relevant physics to be integrated in numerical codes and code predictions to be validated by parts using existing facilities. Since a convergent geometry is most often required, Omega is best appropriate for this work. The possibility to use Orion must also be examined.

Plasma Physics

One generally assumes that shock ignition relies on classical laser driven hydrodynamics, for which we have more than 30 years of experience and validated codes. This appears to be true when one considers large reactor size targets with fuel mass larger than 1.5mg and drive energy of 1.5MJ or more. Looking into details of smaller size targets, one is forced to admit that the interaction regime of SI, with intensities of a few 10^{15} W/cm2 (3 to 8, according to the design) is not that well known, and that nobody has up to now evidenced ablation pressures of 300 Mb (typical for shock launch). Recent calculations of the laser plasma interaction in characteristic regimes of SI indicate 70% laser absorption efficiency, mainly through collective effects as cavitation and double raman scattering. A moderate hot electron spectrum is associated to these effects with energies in the 40-70 keV range.

Small targets are expected to be much more sensitive to these effects because they require larger spike intensities and because of their lower areal mass at spike time. Conversely, hot electrons in the 50 keV range may be beneficial, as being more efficient than thermal conduction in producing high ablation pressures and also providing a better shock uniformity. A larger target requires a larger laser power and energy, but a lower intensity in the spike, so represents a different trade-off between LPI uncertainties and laser risk. Hence, understanding and modelling LPI and transport have a strong impact on target design and choice of operating point for SI.

Progress to ignition requires therefore the inclusion in hydro codes of semi empirical models for LPI and hot electron sources as well as a kinetic treatment of hot electron transport, including self consistent DC fields. These models must be validated by part using large scale PIC or FP simulations, dedicated experiments and tested in first LMJ campaigns.

Shock Dynamics

Multiple shock experiments must be performed in order to validate the modelling of major ingredients of shock ignition : Guderley amplification and stability under convergence, shock amplification by collision, Rayleigh Taylor mitigation by a strong shock.

Mix is a strong issue for central ignition. It is a consequence of the growth of target imperfections, mainly due to inner roughness of the ice shell, under the strong deceleration at shell convergence. Since mix reduces the effective volume of the hot spot, its potential occurrence leads to larger targets and larger energy provisions to secure ignition. SI is believed to be less sensitive to mix than conventional central ignition, because of lower implosion velocities and apparent mitigation of Rayleigh Taylor growth by a converging shock. Omega SI experiments indicate that SI implosions encounter less mix at high convergence that conventional ones. SI calculations involving a perturbed implosion and a spherical shock evidence a lower Raleigh Taylor growth at stagnation than an unshocked implosion. These observations did not receive at present time a complete analysis and their interpretation remains controversial. The direct observation of the interaction of a RT-unstable interface with a shock will help addressing this issue and support the credibility of SI modelling and design.

19.11 Specific LMJ issues.

One major challenge of the proposed work is to succeed in obtaining quasi spherical implosions and high areal mass fuel assembly using “day-1” LMJ hardware.

1. *Polar Direct Drive implosions. The tasks to perform are :*
    a. *Establish PDD LMJ scenarii with optimization of repointing, defocusing, beam balancing.*
    b. *Perform intensive campaigns of 2D simulations including realistic LMJ focal spots and beams. Assess robustness of implosion at different target scales*
    c. *Study specific PDD physics as Cross Beam Energy Transfer, absorption efficiency, thermal smoothing, and magnetized transport in PDD configuration.*
    d. *Validate hydro code predictions using Omega and Orion experiments and progressive inclusion of PDD physics.*
    e. *Final assessment of the credibility of PDD fuel assembly and requirements to the facility.*
    f. *Study of alternative scenarii : design of specific RPP’s, modifications of beam transport, construction of additional beam lines,….*
2. *Use LIL laser or plasma experiments in order to study*
    a. *Structure of focal spots at 1-2 cm from best focus.*
    b. *Partial spot overlap of defocused beams and consequences on LPI.*
    c. *Control of focal spot motion under wavelength time dependant tuning (if this process is to be retained).*
3. *Two Sided (“bipolar”) Shock Ignition*
    a. *Numerical and experimental study of shock uniformity under a two sided illumination*
    b. *Study the possibility to use the 8 diagnostic beams as additional beams for the spike.*
    c. *Progressive implementation of SI physics (including 2D non thermal transport) in codes and assessment of gain robustness.*
    d. *Specifications for ice roughness and initial temperature. Assessment of the LMJ cryogenic target positioning device to meet the requirement.*
4. *Detailed design and schedule of LMJ experiments, including targets and diagnostics.*

19.12 LMJ campaigns

We do not expect LMJ to provide nominal performances during the first years of operation, so our strategy will be to propose experiments with progressive complexity and laser requirements, in order to benefit from LMJ in its intermediate states of growth. For instance, early time symmetry and absorption efficiency may be studied using exploding pusher experiments with less than 100 kJ of laser energy.

This can be coordinated with CEA in the common goal of diagnostic activation; e.g. neutron and charged particles diagnostics.

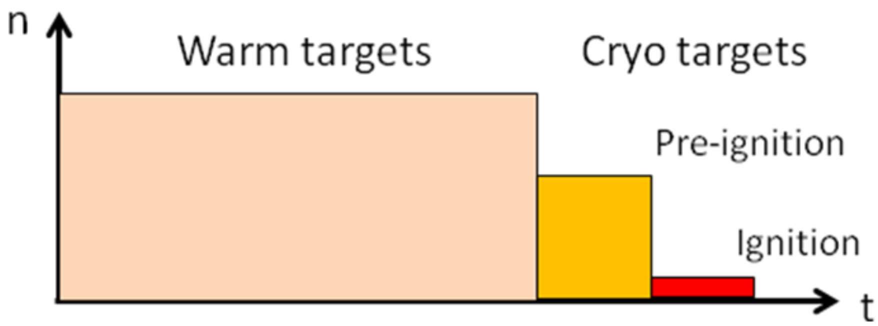


Figure 20: Number of LMJ –SI shots as a function of time. Actual scales presently unknown

This overall strategy is sketched in Figure 20 where the number of shots is plotted as a function of time. Most of the physical data that we must gather in order to assess the performances of fuel assembly using PPD can be obtained from warm targets, starting from simple exploding pusher shells, and ending with hydro equivalent low adiabat CH/D2 implosions. First experiments on shock recompression of imploded shells will also use warm targets. The success of these campaigns is the condition for the fielding of cryogenic targets.

Figure 21 shows the thermonuclear yield as a function of the shock tuning parameters : spike time and spike power. The white dotted line in fig.9 corresponds to the maximum neutron yield, which is obtained when the converging shock collides with the stagnation return shock at the optimal location. This line comes from numerical simulations but may also be obtained analytically from shock kinematics and classical ablation modelling. It spans both the ignition and non-ignition domains, relying on similar shock physics. Hence, shock tuning experiments can be performed far under the ignition threshold, requiring moderate laser powers and non-fusion cryo targets. The final tuning of ignition should therefore require a limited number of high power DT shots.

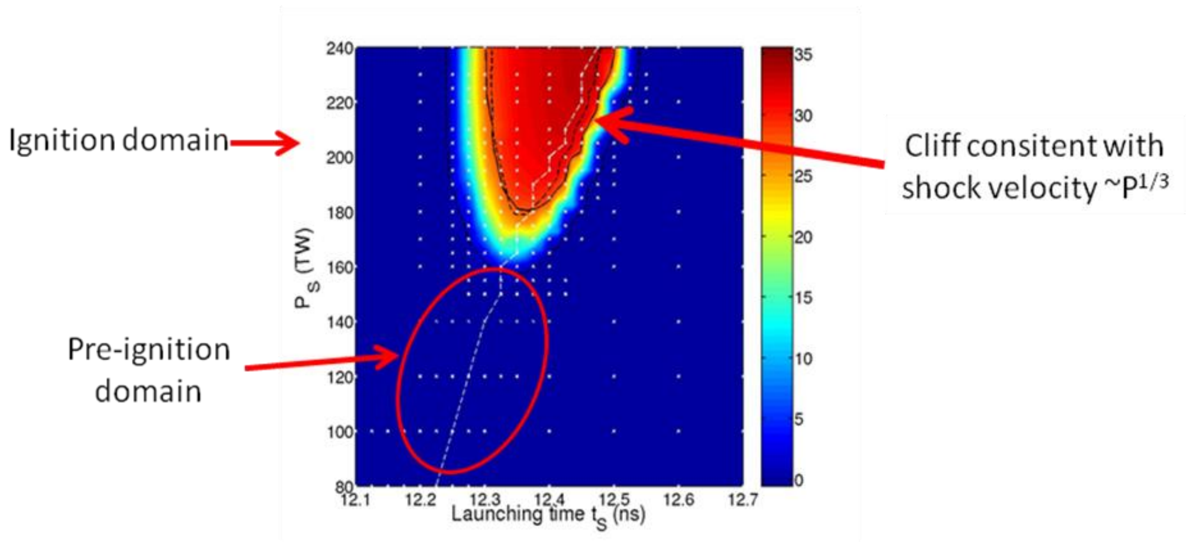


Figure 21: Thermonuclear yield of a CH/DT scale 1.1 target in the coordinates

Major milestones:

1 Symmetry tuning in low convergence, low energy, PDD exploding pusher implosions.
2 Symmetry tuning using warm targets in pulse shaped ablative implosions.
3 Low adiabat implosions and core imaging of warm hydro equivalent targets.
4 Areal density larger than 1 g/cm2 using surrogate warm targets.
5 Shock efficiency and timing
6 Demonstrate obtention of ignition conditions on cryo D2 targets. (Full power LMJ ~300 TW).
7 Full DT ignition if successful.

19.13 Conclusions

- *Shock Ignition requires half of LMJ energy and 2/3 of LMJ maximum power, which means the facility is used at low damage.*
- *May be demonstrated in 2020-2022.(the actual timing depends on the schedule of LMJ, unknown from the authors at this stage).*
- *Condition is that no major modification of the facility is required. This means than the PDD scheme must be used*
- *Success of PDD is not granted. Addressing PDD issues and validate PDD designs are urgent tasks to be performed. Alternative solutions must also be envisioned and costed*
- *SI physics and PDD physics must be studied on non ignition facilities, with a strong emphasis on Omega. A collaboration with LLE is of strategic importance with this respect. It will require financial support*
- *Laser issues must be studied on LIL before closure of the facility*
  A direct drive (cylindrical ?) implosion platform on Orion should be considered

20 Appendix IV: Target fabrication for IFE

20.1 Overview

This appendix describes the activities for Target Design and Mass Production to be undertaken in Phase 1 (Interim), and Phase 2 (Technology Development). It provides a Class A estimate (+/- 10%) of the cost of the work in Phase 1 and an outline schedule and a Class C estimate and schedule of work to be undertaken on this element of the Project in Phase 2 (+100%/-50%).

Phase 1 runs for two years from Project Approval. During Phase 1, the primary work streams for Target Design are :-

- To capture and build upon capability for shock ignition modelling in the academic community harnessing computational modelling available at AWE and in the recently announced new STFC Daresbury computer facility
- To plan, cost and assess risks for Phase 2 work
- To formulate the Target Design Business Case for gateway submission including cost, schedule, risk and assumptions analysis for Phase 2, Technology Development

During Phase 1 the primary work streams for Target Mass Production are :-

- To develop a team of eight key capability leaders, each interfacing with industry and academia in their capability areas
- To select two or three likely shock ignition target designs for production process analysis in consultation with Target Design
- To assess potential production mechanisms including likely contributing techniques
- To produce a systems engineering breakdown of requirements and process diagrams illustrating interconnectivity of process steps and the most likely employed techniques
- To involve industry and academia and, where possible, form working groups to ensure commonality of understanding and purpose
- To assess techniques and report cost, timescales and risk during development
- To formulate the Target Production business case for gateway submission; to include cost, schedule, risk and assumptions for Phase 2, Technology Development

20.2 Physics Target Design and Modelling

Physics modelling of target performance and design and development of high gain targets is required for direct drive shock ignition. This will establish parameter sets which can be used as an approximation for the most likely target that will require mass production. A balance must be achieved between target physics modelling needs and the ability to mass produce targets on time, to cost and to quality. Target design and target production solutions are thus highly interdependent.

Direct drive design and modelling will be pursued in the UK in the academic community in collaboration with AWE through the Centre for Inertial Fusion Studies (CIFS), in France within CELIA (University of Bordeaux) and the academic community in Italy (University of Rome). This work will concentrate on the shock ignition scheme, designing and modelling the performance of shock ignition targets and devising experiments to be fielded initially on the Omega facility, followed by ignition scale experiments at NIF and/or Laser Mégajoule (LMJ) in France.

20.3 Target Mass Production

The strategy for mass production of high gain, low cost targets will include preparation of documentation for the “Gateway Submission” following first ignition at NIF, intellectual property and patent management, stakeholder management, industrial and academic community engagement and engagement with regulators.

Production of Laser Energy fuel, D-T capsules and heat shields to the tolerances required for reliable ignition, in sufficiently high volumes (circa 1 million per day per GW) and at low unit cost (<€0.30) is crucial to the realisation of commercial power generation from Laser Energy. The Laser Target will be the fundamental consumable of the Laser Energy process and this strongly influences the cost of electricity production. Valuable intellectual property will arise from this aspect of Laser Energy.

In Phase 1, the strategy to mass produce Laser Energy targets will be developed on the basis of principles identified during the Preparatory Phase of the HiPER project. Two or three selected target types will be used with wide specification ranges. These will be agreed between physics designers and the target production team.

20.4 An Introduction to Laser Energy Targets

A Laser Energy target contains deuterium and tritium components of fusion fuel. Targets are injected into a chamber and engaged by multiple laser pulses, which implode and heat them to reach the density and temperature required for fusion. The targets are small but extremely precise. They must meet or exceed specification at the point of engagement by the lasers.

Target specifications are developed through optimisation of many parameters which are modelled by the HiPER scientific community to confirm that target physics and operational criteria are met. Initial shots may be undertaken on sub-ignition laser systems but final proof will be required on ignition scale systems (NIF or LMJ).

The requirements for a target (volume, fuel mixture, sphericity, etc.) are complicated by physical constraints associated with injection and the fusion chamber environment. These include chamber temperature, vacuum, acceleration during injection and cryogenic temperature, etc. The mechanical design must meet all requirements and constraints, and must also be capable of fabrication, storage and metrology prior to injection.

Target fuel pellets are currently fabricated in small numbers for existing single-shot high power lasers. An operational Laser Energy plant will require over one million per day. This step change in mass production technology cannot be achieved using current manufacturing capability. Automated mechanised mass production will be essential to achieve the volumes required for commercially viable Laser Energy. Mass production capability must be built into every fabrication step, and these steps then integrated into a precise and efficient mass production line. This will demand development of new manufacturing technologies, a challenge which will impact upon wider areas of UK industry. The techniques required for Laser Energy fuel target production are common to a wide range of other applications. Potential benefits are outlined in Appendix 6 of this Business Case and will be amplified as a result of Phase 1 work.

To deliver the requirement for targets, six key challenges must be met. These are :-

1. To develop target designs which are feasible for mass production whose performance in use will meet specifications
2. To demonstrate an appropriate process for mass production of individual components of fuel targets
3. To demonstrate appropriate means of handling target components as may be required en-route to assembly (i.e. in a Tritium environment)
4. To demonstrate appropriate means of component assembly
5. To demonstrate by metrology and experiment that the completed fuel target assembly meets all criteria

6. To demonstrate that, at mass production scale, the cost per target will meet or exceed economic criteria for commercial operation of Laser Energy plants (£0.30p per target.)

20.5 Target Types

Several preferred targets types have been identified for Laser Energy. As the physics roadmap matures these are likely to evolve through down selection and target development. Ultimately a single target type is likely to become the standard. For all ignition schemes, the objective is to utilise the laser energy to compress and heat a millimetre-scale capsule containing Deuterium/ Tritium fuel for sufficient time that the nuclei will fuse, liberating more energy than is required to drive the reaction.

A section of a typical direct drive target is depicted in Figure 22 below.

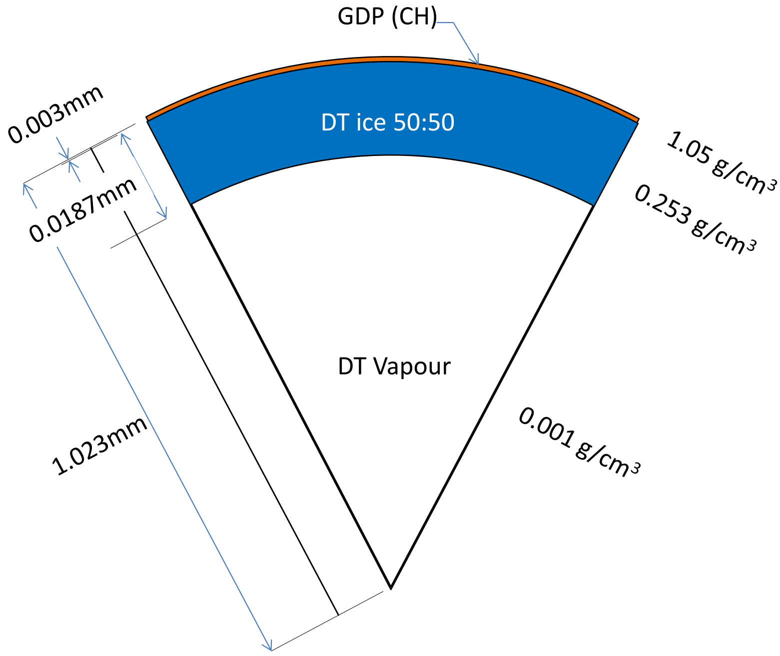


Figure 22: A generic direct drive target

20.6 UK Target Design & Modelling

The UK has two established centres of excellence providing through-life capability in target fabrication. These two facilities, located at AWE Aldermaston and STFC Rutherford Appleton Laboratory, provide services for their respective host facilities Orion, VULCAN and Astra Gemini, and for their partners and collaborators at NIF, Omega, LULI and elsewhere.

AWE

AWE Aldermaston is the premier facility in the UK for physics modelling and design of both IDD and DD targets. Small pockets of capability exist within the academic community working on DD modelling but these are still embryonic.

Through its expertise in high performance computing, modelling and simulation of laser / plasma interactions, AWE will be at the forefront of work to optimise target performance. AWE has a long-standing close working relationship with the Lawrence Livermore National Laboratory in the USA, which will grow further as collaboration on Laser Energy develops.

See Annex A for greater detail in AWE modelling and verification capability.

STFC Daresbury/Academia

Funding for the Daresbury computational element of this work is already in place through an EPSRC grant (Evans & Bell) and through an STFC funded programme of radiation hydro-dynamics (rad-hydro) code development centred at the new Hartree computer centre at Daresbury.

STFC Computational Science and Engineering Centre (CSEC) at Daresbury provide world-class expertise and support for the UK theoretical and computational science communities, in both academia and industry. CSEC currently supports Laser Energy modelling, and a recent agreement between STFC and the University of Chicago for access (including source code) to the sophisticated Adaptive Mesh Refinement (AMR) code "FLASH", when adapted and ported to these systems will provide a substantial enhancement of the UK's academic capability in rad-hydro simulation.

This new facility, coupled with the Centre for Inertial Fusion Studies (CIFS) at Imperial College London, will unite the community currently developing shock ignition physics and modelling within the UK.

20.7 Target production capability

In UK the field of Target Fabrication has complimentary centres of excellence at STFC RAL and AWE Aldermaston. These centres make extensive use of National Laboratories, Industry and Academia, where specialist expertise is needed.

Target fabrication facilities produce complex targets of high quality using both robotic assembly techniques and traditional manual assembly, requiring operatives with very high levels of hand-eye co-ordination plus the skills required for operation of target manufacturing aids. Manual assembly is unsuitable for the high volume of targets required for a Laser Energy plant. Full automation is the required solution.

AWE

At an early stage in development target assemblies were not treated as highly demanding and were carried out by junior scientists. With target requirements and designs being very simple, they were allocated few resources but, inevitably, as targets were also very small, appropriate skill-sets were developed to handle components at this challenging scale. As target designs increased in complexity and demands for accuracy and precision became more stringent, the need was recognised for precision engineering methods and Target Fabrication evolved as an independent discipline.

Over the past 30 years Target Fabrication Group has provided in excess of 10,000 targets for its own lasers and for collaborative experiments in the USA. Today the Group has 18 full time employees; scientific and technical specialists in physics, chemistry and engineering disciplines.

AWE is already producing micro-scale targets for scientific programmes on ORION, NIF and the Rochester lasers, and will play a key role in the UK's contribution to mass-production of fusion fuel pellets, underpinning the commercial credibility of Laser Energy.

The synergy between AWE's physics design and modelling capabilities enriches the partnership with STFC, UK academia and industry. AWE makes a unique and leading contribution to advancement in this field.

STFC RAL

Target Fabrication at RAL was established in 1977 and, by the-mid 2000's, over 3000 targets in more than 160 design types were shot annually on the Vulcan laser. With the high power Gemini laser coming on-line in the late 2000's its higher repetition rate demanded a step change in target production numbers with several thousand targets used in one six-week experiment. This imperative, with implied further increases in future demand led to the introduction of a range of novel micro-target production techniques.

It also became apparent that high speed, high precision micro-target positioning was an integral part of the wider targetry challenge and a range of novel insertion and injection techniques have also been developed.

Both production and insertion/injection techniques at high rates have required significant innovation with consequent generation of IP. The trend towards higher repetition rates is set to continue for high power/energy laser systems and on the road to IFE, there are potentially significant staged opportunities for early commercialisation, especially in view of the consumable nature of fuel micro-targets.

Having already proven a market for micro-targets within the high-power laser community, STFC set-up a spin-out company, (Scitech Precision Ltd), in 2009 with the remit of commercial micro-target production. This company continues to operate successfully and grow in size.

20.8 UK Capability Supporting Target Design and Mass Production

AWE, STFC and other UK National Laboratories possess essential skills for target design and mass production, supported by a range of expertise in academia. Some key elements of relevant UK capability are listed below.

National Physics Laboratory (NPL)

NPL is the UK's national measurement institute and is a world-leading centre of excellence in developing and applying the most accurate measurement standards, science and technology. The techniques developed at NPL are of particular interest for characterisation of fabricated pellets in which extraordinary precision is essential. NPL expertise can play a vital role in meeting the challenge of characterising these micro-targets in high volume.

Culham Centre for Fusion Energy (CCFE)

CCFE is supported by the EPSRC and the European Union’s Euratom programme. It is the UK’s centre for magnetic confinement fusion research. Its primary UK facility is the Mega-Amp Spherical Tokomak (MAST) system but it also hosts the EU’s Joint Europe Torus (JET) Tokomak. Using MAST and JET, it undertakes a wide range of fusion research supporting the European ITER project. Elements of this research, particularly in materials, component testing, Tritium handling and recovery are relevant to Laser Energy.

Imperial College - Centre for Inertial Fusion Studies (CIFS)

Imperial College has a long heritage in plasma physics research relevant to ICF and advanced engineering with numerous programmes underway. CIFS was established in 2009 to provide an important interface between the academic and AWE communities. It has become a valuable asset for growing the academic and engineering groups which will be essential to deliver future steps to Laser Energy.

University of York - Plasma Institute

A collaboration between the University of York and EPSRC to establish a world-leading interdisciplinary plasma institute for the UK. Covering both magnetic and inertial fusion, it has theoretical, computational and experimental activities which can be utilised in a National Programme for Laser Energy. These include, for example, the recent advances in Shock and Fast Ignition approaches to ICF.

University of Warwick - Centre for Fusion, Space and Astrophysics

Although fusion activities are predominately focused on the magnetic confinement approach, there is also significant activity in the Inertial Confinement approach. A recent ESPRC grant, combined with STFC support from the STFC-CSEC, will lead to development of an open access “Adaptive Lagrangian-Eularian” (ALE) radiation hydrodynamic code for UK academics working on Laser Energy. Activity will concentrate on the direct drive approach to ICF (as advocated by HiPER) and, in particular, on Shock Ignition

University of Oxford
Conducts a wide range of research relevant to a Laser Energy programme, including experimental plasma physics, computational modelling and materials research in challenging environments, including neutronics. An Oxford group was the first in Europe to gain access to the NIF facility through its first open access call. An Oxford academic also chairs the NIF User Group.

University of Strathclyde
Working on a range of laser-plasma interaction studies. Of particular relevance to a Laser Energy programme, Strathclyde is very active in advanced ignition research.

University of Southampton – Nanofabrication Centre
A £100M development has recently been completed. The Centre offers the finest suite of precision micro- and nano- manufacturing capability available in the UK and probably within Europe. This is highly relevant to a future Laser Energy programme, enabling progress in wafer-based micro target mass production.

University of Nottingham – Faculty of Engineering
A leading centre in advanced manufacturing. The Faculty's advanced capabilities in production micro-assembly integrated with a range of high throughput micro-fabrication technologies will enable key R&D activities which will inform the design for a production line in a Laser Energy plant.

St. Andrews University - School of Chemistry
Has expertise in foam production with research programmes in shell production which are key to an ICF programme.

University of Cranfield – School of Applied Sciences
Offers a wide and integrated range of precision manufacturing capabilities which are highly relevant for the industrial scale-up of precise fabrication processes.

Huddersfield University – Centre for Precision Technology
A leading UK centre for advanced characterisation, bringing the capability in high speed high precision metrology which will be needed for an ICF micro-target production line.

Cardiff University – School of Engineering
Offers cutting-edge capability in microfluidics. Mass production of high precision shells is crucial to the success of an ICF programme and microfluidics has been demonstrated as a potential solution. The UK could make a significant advance by leveraging on previous work.

University of Sheffield – Department of Electronic Engineering
Specialist expertise in holographic lithography of high aspect ratio patterned wafer substrates. A key step in enabling mass production of micro targets using wafer-based techniques.

Loughborough University – School of Mechanical and Manufacturing Engineering
Has advanced capability in optical metrology. A patented analysis algorithm (in collaboration with NPL) opens a new strategy enabling accurate metrology of the interior of fuel pellets. This offers a very significant international advantage to a UK ICF Programme.

20.9 Target Mass Production

Target production is a highly specialised discipline which relies upon integrating a wide range of micro-technologies. It is usually found that existing production processes must be modified to be effective on the micro-scale.

Micro-targets have traditionally been produced a few at a time, with emphasis on precision rather than time or cost. Micro-components were generally made by precision micro-machining, chemical techniques or thin film coating. Micro-assembly was either performed manually, using specially designed jigs, or utilising micro-assembly stations.

IFE demands mass-production of micro-targets. This implies two key challenges; making micro-targets with sufficient precision and at the required production rate.

The precision challenge has, to some extent, already been met with production of micro-targets for NIF.

The mass production challenge is largely new for micro-target fabrication although many manufacturing sectors produce precision components and assemblies at appropriate rates. All micro-fabrication techniques share the challenges of precise system control, managing relevant parameters to reduce variability in the end product, to give high productivity and reduce costs.

Environmental changes are a particular problem in micro-fabrication. Minor variations in ambient temperature can cause unacceptable variations in the finished product. Even low levels of vibration, such as road traffic, can be a problem. Cleanliness is also crucial. The presence of a speck of dust on any surface can put the product out of specification.

Gravity can also be a complex factor in micro-fabrication. For very small components, the dominant force experienced may not be gravity, but forces such as electrostatics or surface tension.

New challenges also arise from the requirement to move micro-targets within a production facility. Equipment already exists for this, running at the rates required, but it will be challenging to demonstrate compatibility for repetitive output of such precise components in a (partially) cryogenic environment <u>and</u> in the presence of Tritium. It may be possible to exploit synergies with the medical/pharmaceutical sectors to meet the need for specialist environmental controls.

Micro-fabrication has recently been used to develop micro-electro-mechanical systems (MEMS) and their extension into nano-scale NEMS, for which micro-fabrication techniques were re-used and adapted. Fabrication of flat-panel displays and production of solar cells are examples of this.

Laser target micro-fabrication differs in one significant aspect from other micro-fabrication techniques. With the exception of laser target production, all micro-fabrication techniques are based upon 2-dimensional construction, relying upon layering techniques to produce components. Laser targets are three-dimensional objects however, and are designed to meet exacting standards in three dimensions.

The techniques which will be used for IFE target production are likely to be either extensions of existing methods or, where necessary, based upon entirely new techniques. Concepts and principles of micro-fabrication have already undergone much development, including microlithography, thin film processing, etching, laser machining, bonding and polishing.

Micro-target fabrication facilities have begun actively pursuing high repetition rate production. RAL has successfully demonstrated a suite of techniques for batch production to support the repetition rate of the Gemini laser (one shot every 20 seconds), while General Atomics in the US are undertaking a range of mass production development programmes to support IFE.

Phase 2 of the HiPER Project will encompass a number of generic approaches, scaling up known mass-production processes to high rates.

20.10 Key Techniques for Production of Laser Energy Targets

Mass production of Laser Energy fuel targets requires development of eight key technology areas prior to down selection and engineering of a mass production plant. These key areas are shown schematically in Figure 23 below.

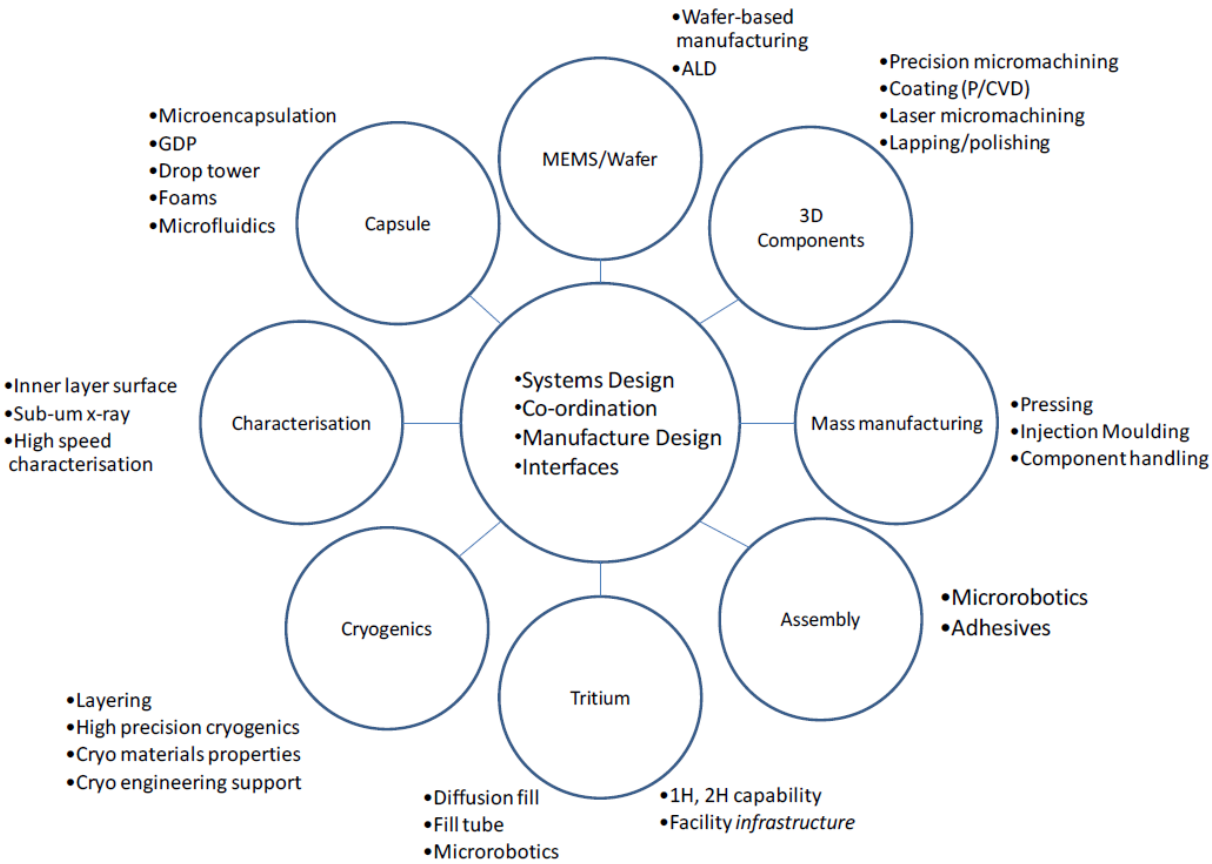


Figure 23: 8 Key Capability Areas for Laser Energy Target Mass Production

The eight key technology areas are interdependent and each has sub-capabilities, as illustrated above. A suitable mass production solution will be reached through iterative analysis of available routes and subsequent down-selection on merit. Development in some sub-capabilities will be required to progress down selection. The most cost effective and efficient route to achieving high repetition rate production will be identified through this process. Multiple aspects of '*Mass production*' engineering solutions must be pursued concurrently with '*development engineering*' to ensure an integrated approach which satisfies all stakeholders, including regulatory bodies.

Key techniques are described in more detail below.

Capsule

All Laser Energy target types share a common component, a hollow spherical shell (capsule) coated internally with a layer of DT fuel at cryogenic temperatures. The capsule and its internal fuel coating are possibly the most challenging target parts for production in large numbers and must be fabricated with extremely high precision and repeatability. An essential element on the critical path of any Laser Energy programme, capsule production is a likely source of valuable Intellectual Property (IP).

Three techniques may be used for highly uniform capsule production :-

- Wet chemistry (combined with thin film CVD coating)
- Atomic layer deposition
- Micro-fluidics/di-electrophoretics (DEP)

Baseline target designs are likely to require differing post-production processing and modification, depending upon the selected methodology of filling with DT fuel. Two filling methods are considered to have significant potential merit :-

- **Injection** Fuel mixture is injected into the capsule (via an attached ultra-small bore fill tube) through a micro-hole bored in the wall
- **Permeation filling** Fuel is forced to diffuse through the capsule wall using elevated external pressures and suitable temperatures

A suitable filling technique for mass production must also minimise the Tritium inventory within a plant which, in turn, may necessitate the adoption of new capsule filling techniques. Production processes, target types and fill techniques are closely inter-related, and should not be considered in isolation from one another. (See below for further details)

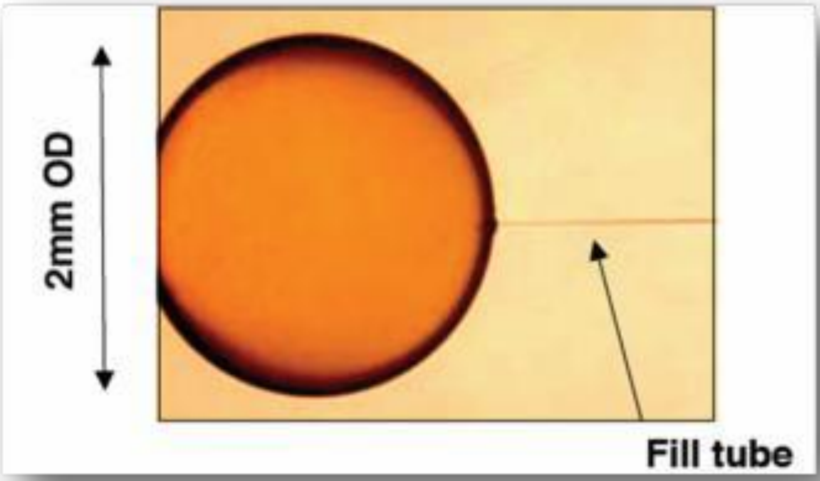


Figure 24: Capsule with fill tube

The fill tube approach to filling capsules with DT may not be practicable for a mass production arrangement and novel filling methods may therefore be required. Use of a foam inner layer, radially graded materials, composites and ultra-hard materials for capsules may prove to be viable alternatives. External metallic coatings to protect DD capsules have also been considered, primarily to provide infra-red reflection during target transit from injector to fusion chamber centre.

Novel capsule filling techniques which have recently reached sufficient levels of maturity, may offer opportunities for cost- effective scaling to mass production.

All Laser Energy target capsule specifications demand stringent capsule sphericity and internal and external surface roughness, which vary between target types. Conventional ‘single shot’ experiments such as those in the National Ignition Facility at Livermore specify targets for experimental physics needs with exceptionally stringent dimensional and physical characteristics. These are fabricated at a high cost in order to maximize the probability of the desired experimental result. Cost per target in mass production may permit some relaxation of these requirements once ignition has been achieved, gain optimized and target design is better understood. While this applies for target components, the fuel capsules themselves will almost certainly offer the greatest scope for cost reduction per unit in design and mass production.

Wet Chemistry / Thin Film Coating

Capsules have been successfully produced for NIF and LMJ, meeting tolerances for sphericity and roughness. A hollow polyalphamethylstyrene (PAMS) mandrel is produced using micro-encapsulation then overcoated with glow discharge polymer (GDP) before heating to vaporize the substructure, which diffuses out through the more thermally stable GDP layer leaving an intact GDP capsule.

Figure 25: PAMS Mandrel 1.1mm diameter

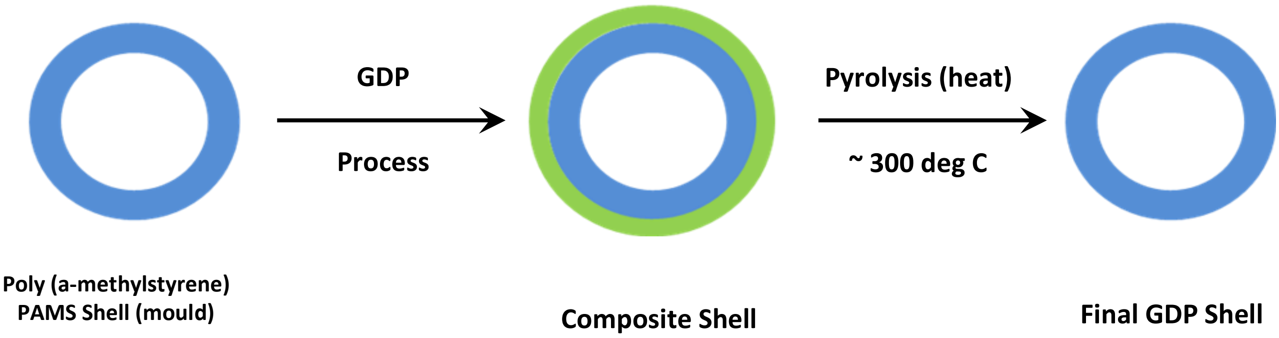


Figure 26: The overall process

There is a need to establish a robust UK-based capsule production capability. In the early stages of phase 2, this should be able to deliver capsules at the anticipated specifications for the target design programme. It may be possible to use wet chemistry/coating techniques in plants operating in parallel to provide the target numbers required for scaling trials in the latter half of Phase 2.

Atomic Layer Deposition (ALD)

ALD is a mature technology widely used in industry. In this technique surfaces are deposited one layer at a time. Precursor gases are sequentially introduced into a deposition chamber to deposit a thin film on a surface. Each mono layer is self-limiting, which enables production of a highly controlled film.

Techniques are already established for production of sufficiently high quality PAMS substrates. ALD may be used to coat substrates, giving fine control of capsule designs. ALD is a slow process, particularly for capsule thicknesses needed for Laser Energy, but the coating technique can treat large numbers of capsules simultaneously. Thus it can be considered for mass production.

ALD equipment is commercially available and the focus would be on materials development to improve mandrel removal. ALD coating expertise is available at several UK centres of excellence, giving the potential to enhance a UK Laser Energy target development programme. It may be suitable for integration into the target design process early in Phase 2 while, later in the phase, the process could be automated and integrated into the wider production line.

This possibility of integration means that ALD techniques may have significant impact on mass production of all target designs.

Microfluidics and dielectrophoretics (DEP)

This highly promising wafer-based technology for capsule production could permit filling and layering in a single process.

Microfluidics have been demonstrated in an industrial context and concentric spheres have been shown as a potential basis for target shell production. Shell quality is also significantly improved by application of a high frequency external electric field. A high degree of control can be achieved over wall thickness, diameter and concentricity. Introduction of DT before polymerisation with possible capsule over-coating and close beta layering to control the inner surface finish renders the technique intrinsically scalable to mass production, particularly when running multiple processes in parallel. This may be a solution for capsule production in all target design types for Laser Energy.

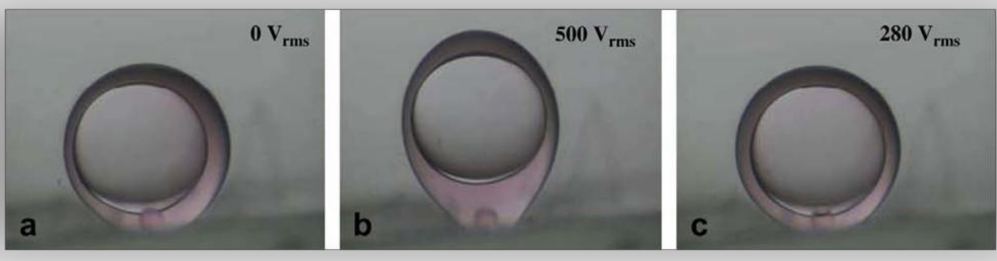


Figure 27: Dielectrophoretic (DEP) Capsule Production

Combined DEP and microfluidic technologies could provide significant advantages for target mass production. For shock ignition targets, assembly processes can be envisaged in which microfluidic-produced layered capsules are inserted into a heat shield assembly prior to injection. This technique has been demonstrated for capsule production, however extra development will be needed to refine the process and to introduce, form, characterise and refine the DT layer. The first step will be to select suitable dielectrophoretic materials for manipulation by electric fields, which are also suitable for use in Laser Energy.

Future Capsule Production Capabilities

Future capsule designs may incorporate an internal foam layer as a possible alternative carrier for the DT fuel. Several early development programmes have begun on such targets. By injecting and polymerising the foam pre-cursor within a spinning capsule it may be possible to fabricate foam capsules. Some DD Laser Energy designs require a polar driven laser configuration with a requirement for a non-uniform capsule wall thickness. This technique has the advantage of utilising differing polar and equatorial accelerations, which will result in a variation in the foam capsule wall thickness and may therefore be suitable for this application.

Capsule designs, especially for direct drive, often include a thin (tens of nanometres) external, reflective outer coating (typically metal).

Production of uniform coatings of precisely controlled thickness in a wide variety of materials is a requirement common to many industries. Uniformity across the surface of capsules - especially with a finish accurate to within a few nanometres - may prove challenging.

Use of ALD could permit growth of complex non-axially symmetric material structures such as radial struts or for capsules configured for polar laser engagement.

Advanced materials or possibly meta-materials may be used in capsule fabrication. Development has yet to be undertaken. If this is considered appropriate it would need to be clearly defined as a requirement for Phase 2.

20.11 3D Components

3D components can be fabricated using a variety of techniques not all of which are suitable for mass production. Key techniques are summarised below:

Micro-machining

Current demonstrable capability in precision micro-machining of 3D components, (usually from oxygen-free high-conductivity copper, (OFHC copper), is limited to batches of 50, using ultra-precision micromachining and coating techniques. To scale up to mass-production of heat shields for shock ignition or cones for fast ignition, it will probably be necessary to use hot pressing (in which many tens of thousands of micro-components are pressed simultaneously) or micro-injection moulding. In both cases the techniques required for ultra-precision press and mould manufacture can be derived from 3D micro-component batch production techniques.

Physical Vapour Deposition (PVD)

Capsule designs may call for an ablation layer applied to the outside surface of the capsule. These layers are typically of the order 30-70 μm (0.03-0.07 mm) in thickness and are usually made from materials with a low atomic number such as high-density carbon (HDC). Production of these layers requires deposition of the material onto the surface from a vapour. Physical Vapour Deposition (PVD) techniques work within a vacuum chamber by atomising the material from its source, transporting it through the vacuum to the substrate - in this case, the capsule.

Laser micro-machining

As well as driving the fusion process for Laser Energy, industrial-scale lasers play a role in target production. Some Laser Energy target designs call for the introduction of entry holes into the capsule for fuel filling. Laser micro-machining offers both high machining speed and positional accuracy. Figure 28 shows examples of targets fabricated using laser micro-machining techniques.

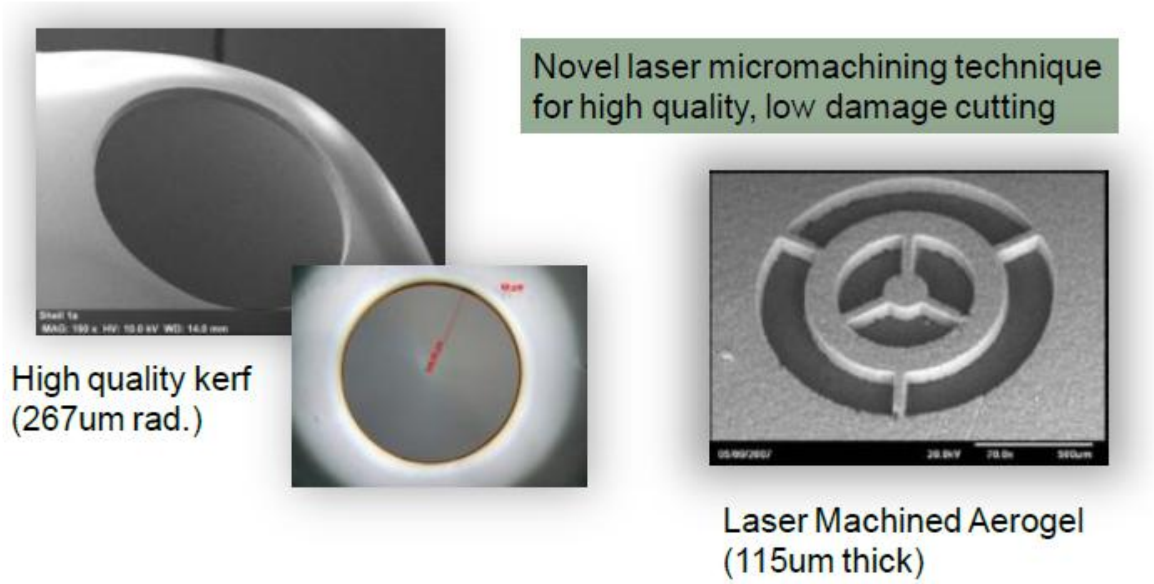


Figure 28: Examples of laser micromachining techniques on capsule surfaces

20.12 Material post-processing

For fusion to be initiated when a capsule is compressed following engagement with laser pulses, in most target designs it is essential to achieve minimal deviation from spherical symmetry. Target components such as capsule surfaces require a very fine surface finish. Due to surface nucleation, materials tend to deposit preferentially at nucleation sites. This can degrade surface finishes. Most layered materials, whether deposited on capsules or CVD produced, need further processing to meet the laser target specification. The best available method to achieve such fine surface finishes on a scale adaptable for mass production is high precision lapping/ polishing. Substrates are then removed by chemical dissolution and final parts can be laser machined and characterised before assembly.

20.13 Micro-electromechanical (MEMS) / wafer based micro-fabrication

These are mainly 2D thin film objects. Processes for their production depend upon the material required. Low atomic numbers and high strength are usually the essential characteristics, frequently limiting the choice to carbon-hydrogen based materials such as plastics and synthetic diamond. Wafer-based production for plastic components has already been demonstrated. Diamond thin film micro components are challenging to produce, largely because of difficulties in controlling internal stresses. This is particularly true for shaped “micro-tents”. The process of fabricating target parts similar to those required for Laser Energy target designs such as synthetic diamond capsules, LEH windows and synthetic diamond “tents” has already been demonstrated. These techniques are of particular interest as they are compatible with wafer-based techniques, but further development will be required to scale the process for mass production.

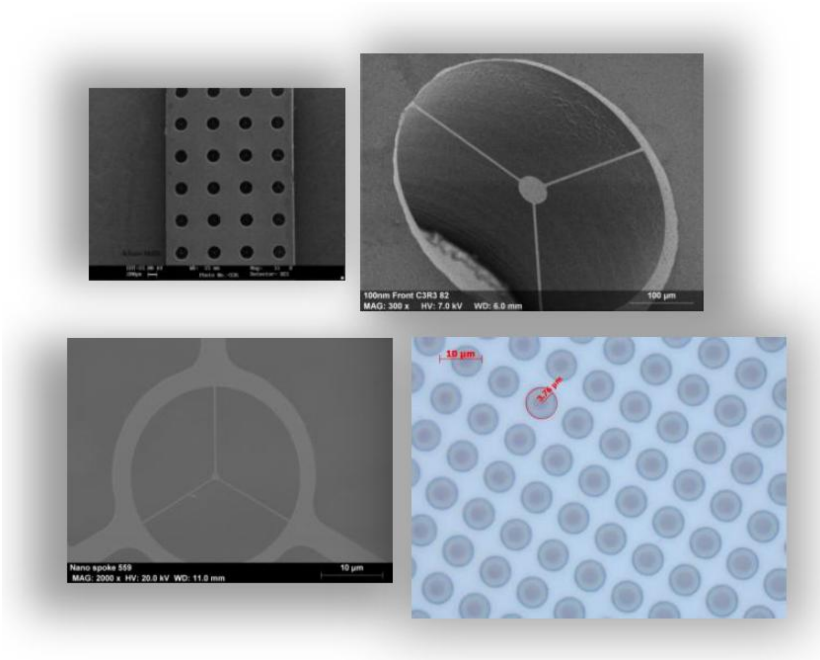


Figure 29: 2D wafer based micro-fabrication

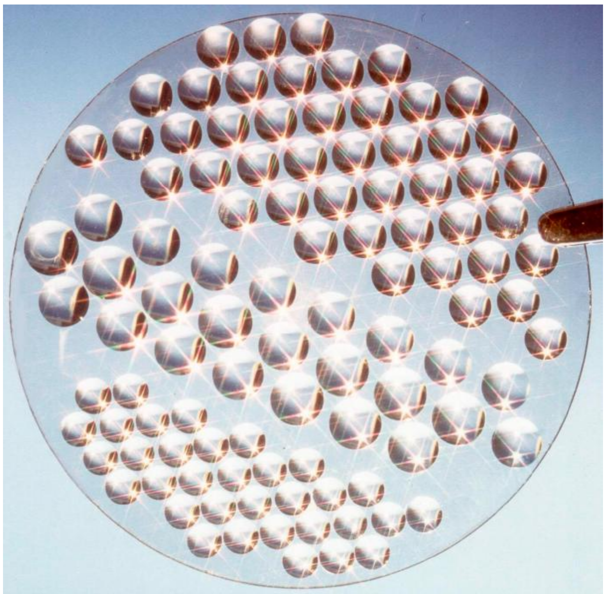


Figure 30: CVD produced diamond parts

Courtesy of the Fraunhofer-Institute for Applied Solid State Physics, IAF, Freiburg, Germany

Capability in MEMS wafer-based approaches may also be extended for mass production of Laser Energy fuel capsules, particularly for multi-component micro targets or assemblies. If coupled with ALD, such techniques could produce micro-targets with a successfully reduced requirement for micro assembly. (See Figure 31 and Figure 32 below, showing MEMS 2.5D and 3D capability to date).

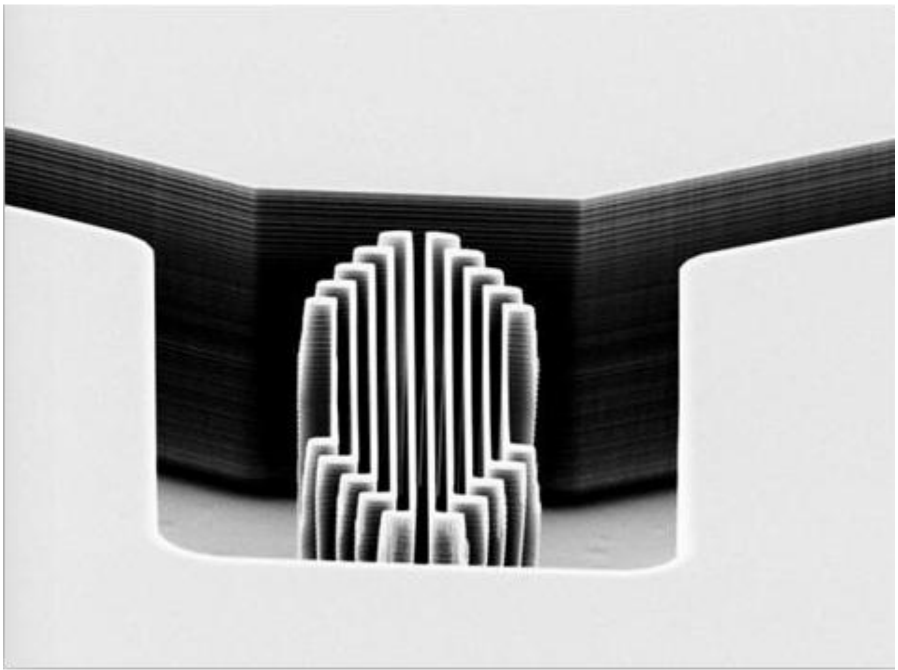


Figure 31: 2 ½ D MEMS micro fabrication

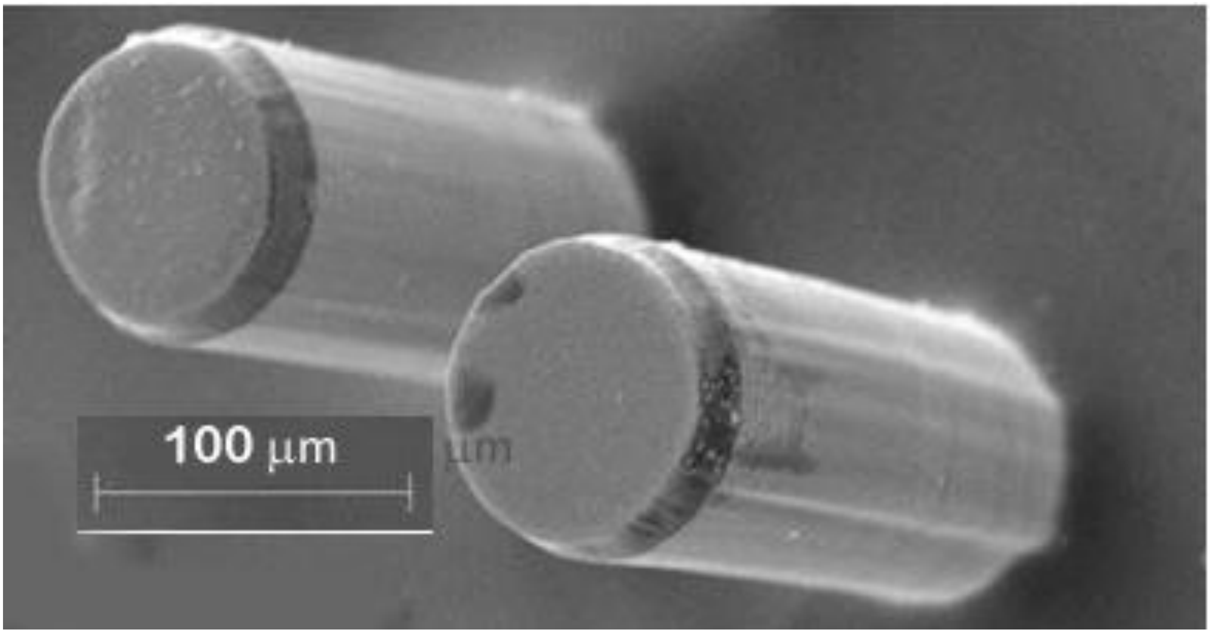


Figure 32 High aspect ratio 3D mass production on single wafer single-step lithography

20.14 Assembly

Micro-assembly (the task of assembling micro components) often requires application and curing of adhesives. Precision alignment of micro components is necessary during assembly, as well as allowing for subsequent misalignment from complications such as the curing of adhesives. Extensive characterisation is often required to verify assembly processes. Micro assembly is particularly relevant to indirect drive target designs but, even for shock ignition targets, it could be required if fill tubes were used.

At NIF, LMJ, OMEGA and ORION micro-assembly is used extensively for target fabrication. Sophisticated specialist micro-assembly stations have already been designed and are in use in the US and UK. To deploy current techniques for Laser Energy, further automation would be required with systems optimised to increase throughput. New technology should also include robotic vision systems. To date, some work has been done in this field. The most challenging area has been information feedback into the assembly process from vision systems. Although introduction of optimised automation will increase speed, micro assembly stations are still quite slow, largely due to the very high precision required. Feeding fuel pellets to a laser energy station is therefore likely to require multiple systems operating in parallel.

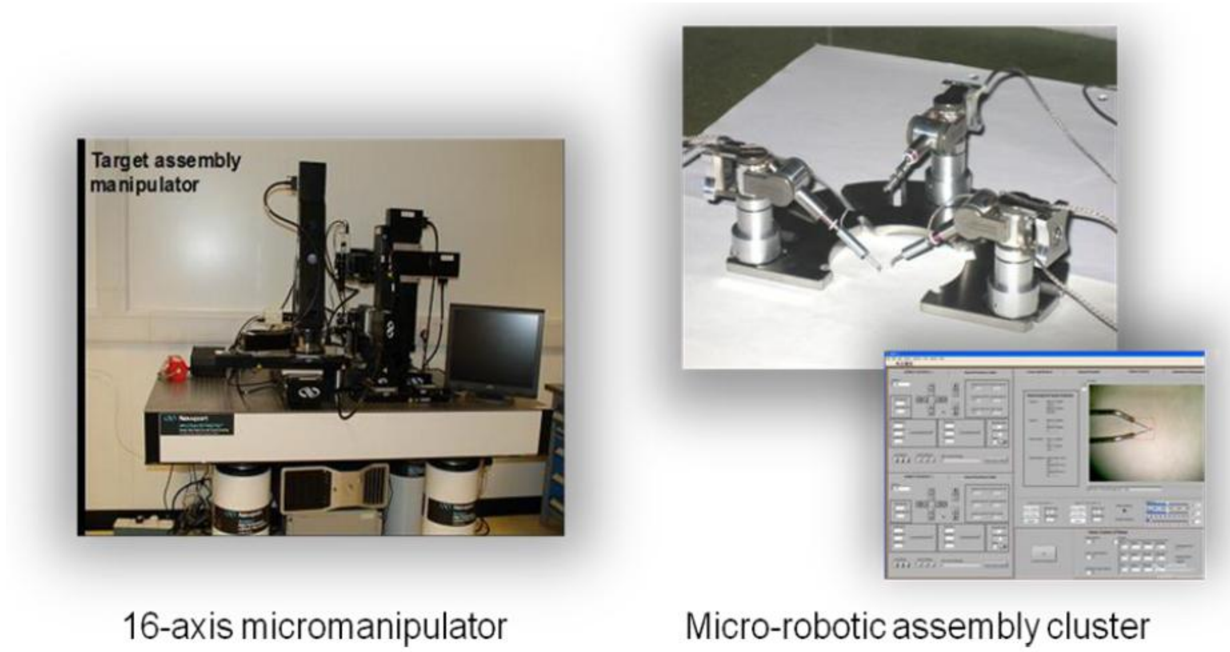


Figure 33: Advanced micro-assembly tooling

20.15 Characterisation

Micro target characterisation challenges include materials combinations (e.g. measuring DT ice layering inside a capsule with an opaque IR reflection coating) and achieving very fine measurements (nm-scale roughness measurements on a capsule surface).

Experience in mass production has shown that on-line product quality assurance in a process stream can often be reduced to a simplified parameter set. The parameters used in an IFE production environment are almost certainly process-specific rather than fundamental. As understanding of micro target production processes improves it will be possible to identify crucial parameters. As an example, information on system gain will be continuously fed back to target modelling for progressive refinement between designs and production processes, optimising the parameter set most useful for product assessment in mass production.

It should be noted that generic micro- and nano-metrology challenges are seen as major enablers for the UK and the European economies. These will deliver significant development through EURAMET and Co-Nanomet, during the technology development phase.

Characterisation during production, transport and storage

Aspects of characterisation during target production, transport and storage within the facility include:-

- Capsule characterisation (including layering)
- Micro component characterisation.

- Assembled micro target characterisation
- Assessment of deterioration
- Unacceptable drift in environmental conditions.

Capsule characterisation is currently a slow process, particularly for outer surface roughness. As this is a highly sensitive parameter for IDD and DD fusion, it must be measured with extreme accuracy (a few nanometres) – preferably over the entire surface. This is typically performed using sphere mapping with an atomic force microscope (AFM) and can take between tens of minutes and hours to complete. Interior DT surfaces are typically metrologised using reflectometry when the capsule is optically transparent and micro-source x-ray radiography when optically opaque. It may be possible to speed up these techniques; a novel optical technique has recently been demonstrated, showing that large sets of capsule exterior and interior metrology data can be acquired and analysed at approximately 1Hz. It will be necessary to perform characterisation of fuelled capsules under cryogenic conditions – a key factor for consideration throughout development of the characterisation process.

Micro components and assembled targets generally have less precise specifications than the outer surface of capsules. Automated micro metrology is quite mature and is currently used in mass-production environments. For Laser Energy targets however there is the additional challenge of cryogenic temperatures within a tritiated environment. Persistent radioactivity may effect the sensitive measuring equipment. These issues must also be assessed.

Mass Characterisation

It is crucial to establish acceptable defect levels in target production. Drawing upon experience of mass production systems such as those used in the pharmaceutical industry, characterisation of every target is not practical but it may not be possible to control fabricated tolerances by maintaining Statistical Process Control (SPC) with sample characterisation. The acceptable level of failure must be assessed in a “defect budget” driven by cost analysis. This will probably be no more stringent than six sigma, (equating to 3.4 defective Laser Energy targets per million produced). However, practical experience in high-throughput mass-production environments shows that the actual requirement will probably be less challenging. Current characterisation procedures are slow but faster techniques will almost certainly be possible. Developing a proven set of key parameters will ultimately enable appropriate characterisation.

Target and plant deterioration/damage will be characterised at points in the production line, determined by acceptable defect-level/cost analysis. Minor faults in process stream conditions, such as dust, will be detected in the on-line characterisation data. This will be used forensically to compliment extensive monitoring of environmental and supply conditions for the target production line. Characterisation data from the target production line is essential to understanding key parameters and generating feedback to fine-tune the production line and associated plant.

20.16 Mass Production

Two candidate techniques have potential for large scale production of components for shock ignition target heatshields. These are precision pressing and Metal Injection Moulding (MIM). Techniques developed using ultra-precision micromachining are applicable to mould, die and mandrel production, as required for hot pressing or MIM.

UK industry has a tradition in both the technology and skills required for precision pressing. Companies such as Brandauer in the West Midlands have many years of experience designing such systems. Applying precision machining and design techniques to die design, may make it possible to press finished components from sheet materials. This technique is currently used to fabricate parts of geometries, dimensions and tolerances similar to those required for production rates appropriate to the demands of a Laser Energy plant.

Mass production includes systems for moving targets and their component parts through a target production facility and ultimately into the magazine of a target injector. The underpinning design principle of “Just-in-time” (JIT) production should be considered to minimize the Tritium inventory within the facility and consequently the need for costly “Tritium-capable” floor space. In practice, if for example there were short term delay issues of a few seconds within the injector or laser driver, the possibility of shunting viable targets into a storage loop would be useful. If the target production stream were to encounter short term interruptions, a “populated on-line loop” could be used to maintain continuous target delivery.

Two main options exist for the ‘*transport system’* design; mechanical and levitation.

In the latter case targets could be carried either by direct levitation or levitated on micro pallets, each carrying a single layered target or component. Levitation techniques would integrate well with micro-fluidics-based continuous stream target production and levitated pallet techniques with wafer-based micro target mass production. The selected design is very likely to use advanced target transport systems which must operate reliably for prolonged periods under cryogenic conditions and within a tritium / radiation environment. Target characterisation may be used to facilitate rapid feedback into, and modification of the production process. Provision for remote fault intervention must be included at levels appropriate to ensure reliability of the target transport system.

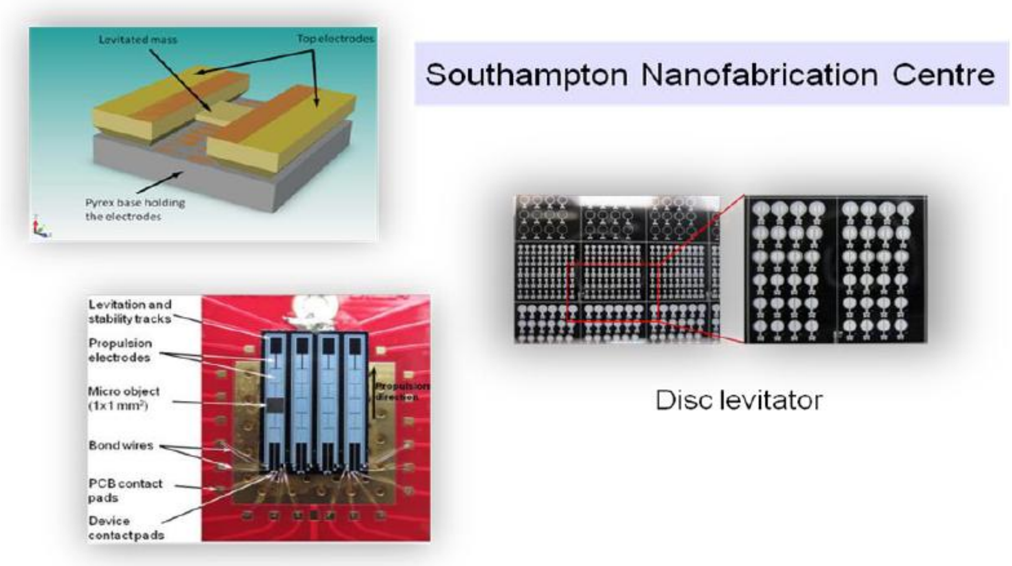


Figure 34: Micro-component levitators

20.17 Tritium

Tritium and deuterium form the two fuel components which are fused to release energy. Tritium is a radioactive ß emitter with a half-life of 12.3 years and a specific activity of 357 TBq/g. At room temperature tritium is also a gas. It must be carefully controlled, with quantities minimised in any area of a plant. A single fuel target will contain less than 1mg of tritium. With its extremely small molecular size, tritium is very difficult to contain. Like most small molecular gases, it can “migrate” through most “solid” materials using interstitial spaces between larger molecules as pathways. Tritium loss mitigation therefore necessitates specialised design consideration. Work with tritium must be undertaken in a bespoke facility capable of handling and containing the gas.

Effect of Tritium on design of Mass Production Equipment and Facilities

Because of the high mobility of Tritium, materials directly exposed to it must be stored for approximately 40 years before they may be disposed of as "free-release" or very low activity waste. Reliability of equipment prone to direct exposure must be carefully considered to reduce maintenance burdens and thus minimize stored waste.

To eliminate exposure of plant workers, all operations involving Tritium must be undertaken remotely, either using robotics, purpose built machines or remote maintenance techniques. Mechanisms, tools and materials used within Tritium areas will also have to be assessed for durability in the radiation environment. It is likely that Tritium operations will be contained within glove box structures - even for robotic operations. This would provide an effective multi-layer containment barrier. The atmosphere within these glove boxes will be recycled using a Nuclear Heating Ventilation and Air Conditioning system. Maintaining box pressure below that of atmosphere will form a dynamic containment barrier. Layers of containment will also be provided using the building's air lock arrangements. The atmosphere evacuated from the building will be passed through a Tritium scrubber before release to atmosphere to minimize any risk of discharge.

The fire system within a Tritium building would likely be based on CO_2 or dry suppressant technology as water based systems could spread contamination.

Capsule fill and layering

Two capsule filling techniques have been developed at NIF and LMJ. These are by permeation and by fill tube. In the permeation filling technique, one or more capsules are overpressured at suitable temperatures in a DT environment, forcing DT through the capsule wall. The fill tube technique uses a narrow bore tube, (typically 10 μm (0.01 mm) internal diameter and 20 μm (0.02 mm) overall diameter) attached to the capsule. A narrow diameter hole is drilled by laser through the capsule surface and the DT fuel is introduced through the tube. Both filling techniques have positive and negative aspects.

Permeation filling can take many hours. The exact rate is limited by a complex relationship between capsule (primarily) wall thickness and permeability. For wall thicknesses of a few μm the permeation rate is relatively high, although the wall has a greater tendency to rupture due to its low mechanical strength. Permeation can be used to fill hundreds of thousands of targets simultaneously, apparently increasing its suitability as a technique for mass production. The requirement for a larger Tritium inventory with which to fill the capsules makes this undesirable however.

The fill tube technique requires a capsule to be laser drilled and a fill tube attached. Tubes less than 20 μm (0.02 mm) in diameter are introduced to within an acceptable positional accuracy, but additional assembly tasks add complexity - drilling, tube installation, gluing to seal the tube, removing the tube after filling and capping the remaining hole are all demanding operations which make this approach less desirable for mass production. The fill tube technique is typically used for IDD targets.

Extending either technique to mass production will be challenging, particularly in view of the imperative to minimise the tritium inventory. Once the capsule is filled a cryogenic layering process can be used to form the DT ice layer with the required ultra-low roughness and sphericity on its inner surface.

In the case of cone and shell targets a third possibility for filling exists in which a fill tube is formed within the wall of the cone during manufacture.

20.18 Cryogenics

Microtargetry for HiPER will require extensive application of sophisticated, tritium-compatible cryogenics which, for purposes of specifying cryogenic requirements, can be broken into the following general areas to indicate generic cryogenic requirements.

1. Liquid DT filling of capsules. The actual filling, whether using permeation or fill tube, might be performed at temperatures of ~35K.
2. Layering of the DT – i.e. forming a smooth ice layer. Layering typically is performed at ~19K and requires mK/min temperature control
3. Within the Target Production Facility layered targets will need an assured isothermal stability to within 1mK between any two points of the DT ice (to avoid delamination). The main processes experienced by layered targets will be transport on the production line (including the buffering loop) and possible (short term) storage.
4. Loading of layered targets into the injector.

Shell Layering

In a filled shell the liquid DT will settle in an equilibrium shape determined by the effect of gravity pulling the liquid to the base of the shell, opposed by surface tension pulling the liquid up the walls. The effect of gravity is greater and the liquid tends to sag to the lower part of the shell with some creep up the inside wall.

In the presence of tritium in sufficient concentrations, a natural layering process –β-layering - occurs. The spontaneous radioactive decay of tritium emits a beta-particle, causing highly localised heating which, under suitable conditions, leads to highly localised melting. Larger localised volumes containing tritium undergo increased heating and melting which in turn causes redistribution - tending towards equal thickness of the fuel.

Not all targets produced will contain tritium or have sufficient levels for β-layering to occur (for example in non-fusion experimental shots or fusion chamber validation shots.) In the low/no tritium case, layering is achieved using an enclosed layering unit in which alternate warming and cooling cycles are applied to a fuelled shell to achieve the required layering. Warming is typically achieved using an IR laser and cooling by cryogenic helium gas. Note that the cooling cycles do not always produce freezing.

Both layering processes have been demonstrated and can produce very smooth, typically mono-crystal, ice layers.

For mass production layering a fluidised bed approach could be considered in which an assembly of fuelled shells have cryogenic helium gas forced through from below. The process would both cause freezing and randomly agitate the shells to cause redistribution. Clearly the process might be expected to form nanocrystalline ice and the effects of such structure would need to be assessed during the R&D phase of HiPER. General Atomics have built and performed tests with a cryogenic fluidised bed layering chamber. Surface damage also has to be characterised especially since the exterior roughness is known to be a crucial parameter for shell ignition. As noted in section 5.7.2 the need for reducing tritium inventory as far as possible would the maximum size of fluidised bed layering module.

The Lebedev Physical Institute (LPI) has proposed Free Standing Target (FST) technology for filling and layering targets for HiPER. In the FST technique fuelled shells descend in a spiral tube, designed to ensure randomized motion, through a cryogenic enclosure which freezes the fuel. Layering units for undersize shells have been built and demonstrated to produce layered shells with a layering time of order 10 seconds. At such production rates multiple layering units (~100) running in parallel could potentially produce sufficient layered targets for continuous IFE operation. LPI has also proposed designs for a full scale target delivery system for the HiPER facility running in burst mode (100 shots) with sabots carrying the target through an electromagnetic injector to the target chamber.

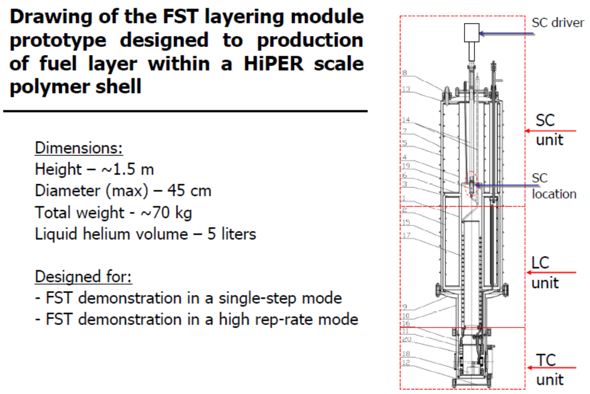


Figure 35: FST Layering prototype for HiPER facility (designed by LPI)

With the FST approach it is known, from mechanical measurements, that nanocrystalline ice is produced. As already noted the effects of such structure will need to be assessed.

Shell designs have been proposed in which there is an interior low density (foam) layer into which the DT wicks, possibly removing the need for layering. Such designs must also be assessed during the R&D phase, particularly for survival of the conditions experienced during injection. Obviously the effects of low density material within the DT layer need to be assessed. Initial experiments and modelling suggest that such material could be acceptable.

If layering is required, it will probably be performed in one of three scenarios:-

1) Small batch processing of 1 - 1000 targets at a time using an LMJ-scaled layering chamber which is of particular relevance for HiPER operating in burst mode.

2) Large batch processing of 10 000 – 1 000 000 targets at a time using, for example, a fluidised bed technique for application for HiPER operating in extended operations mode.

3) Continuous production, running at 10 Hz possibly with parallel production units, based on, for example, FST technology.

Parameters of materials in a cryogenic environment and the volume of cryogenic areas must be considered early in the design. Materials must be selected to ensure robustness at the extreme temperatures involved. Material properties can change substantially when cryogenic temperatures are reached and some uncertainty exists in the published data. Parameters of interest to HiPER will need to be measured during the R&D phase. The volume of cryogenic processing equipment should be kept to the minimum practicable as less power will be required to achieve and control these very low temperatures. Early in Phase 2 access will be needed to a facility offering cryogenic conditions in order to select materials for these environments.

20.19 Phase 1 Activities

A Target Strategy Group will be established to identify the requirements for targets and mass production techniques necessary to meet the risk reduction objectives of the Technology Development Phase. The activities of this group will build on the progress made during the Preparatory Phase. Key tasks will include the following:

Technique Identification and Assessment

In their key areas, the group will identify possible tools and techniques for delivering targets. This will require development in some areas and will include placement of contracts with institutions and industry to provide information. As the knowledge base increases, group members will work with target designers to assess the techniques and determine those preferred for mass production. Companies and Institutions associated with those selected will then be contracted to produce detailed plans and costings, including risk analysis for development of these techniques within Phase 2. No formal down-selection of mass production technique will be made during Phase 1. A suitable number of potential candidate techniques will be assessed, since choice of approach is appropriate as a risk mitigation measure.

Establish Common Written Understanding of the Challenge

In parallel with activities to identify potential production techniques, systems engineering will be employed on the selected target parameters. A systems breakdown of the requirements will be undertaken, including those for mass production. This will give sets of requirements and relationship diagrams for each target type. From these an estimate will be made of the Technology Readiness Levels (TRL's). Techniques will be related through process diagrams, providing a perspective of what the manufacturing process could entail. This gives a common understanding of target production issues, facilitating stakeholder management and communications activities of the central project management team, which will ensure that industry, academia and all participants are kept fully aware of developments in the target production challenge. This in turn may lead to the emergence of new techniques for consideration.

Costs, Plans and Risk Assessments

The ultimate conclusion of Phase 1 work will require technical specialists to produce estimates, detailed plans and risk analyses for work they may undertake in Phase 2. Assessments will also be made of the potential economic impact on UK of the work in short (0-2 years), medium (2-5 years) and long (5-10 year) terms. The results will be assessed by the working group. For risk reduction, Phase 1 work will include establishing mutually acceptable terms on which to place development contracts to be undertaken when funding becomes available during Phase 2.

Phase 2 Business Case Production

From Phase 1 work a business case will be developed providing technical background, investment preferences, anticipated short, medium and long term benefits to the UK from this work and an estimate of the degree of risk involved. A +/-10% costing and an overall plan will also be provided for work to be delivered.

20.20 Phase 1 Estimate

Cost

A provisional estimate of the cost of the Phase 1 programme is €1.47M over two years.

Assumptions

1) It is assumed that participants identified for Phase 1 working group activities will be in a position to devote at least 50% of their time to the task for the two year period. Until funding for Phase 1 is obtained, it is not possible to approach industry and academia to obtain consent for this. Phase 1 may thus be subject to a significant start-up time to permit the release of key personnel.

2) It is assumed that NIF will ignition before the end of Phase 1. It is also assumed that Phase 1 activities will be undertaken irrespective of NIF progress. This will permit formulation of an appropriate Business Case for Phase 2 funding. Should timescales be shortened due to NIF ignition and an earlier Business Case be needed, the accuracy of estimates and plans produced may be of a lower order.

20.21 Phase 2 activity

Phase 2 activity, schedules and detailed costs will be developed during Phase 1. As technologies mature, preferred production techniques will be selected and incorporated into production process diagrams and the conceptual designs for a target production plant.

As the format of plant is not yet known, (for example, whether to use high-volume parallel processing or a small number of sequential lines) - it is inappropriate to extrapolate the type of layout of a production facility until later in Phase 2. The aim of Phase 2 is to demonstrate capability for full scale production at the rates required for a Laser Energy plant and to reduce risk by proving that an operational facility can be built during Phase 3.

Process and Manufacturing Engineering

Process and Manufacturing Engineering will be essential integrating components for all technical areas explored during Phase 2. Process flow, mechanical flow and material mass balances will be required for all aspects of the design. These are compared to requirements sets, confirming that the requirements are met. Process and Instrumentation discipline can then detail the production process before other engineering disciplines produce floor and room layouts, building structural and heating, ventilation and air conditioning designs, etc.

Early engagement with regulatory bodies is essential in the design of new nuclear manufacturing processes. Early availability of process flow, mechanical flow and material mass balances permits timely regulatory discussion so that demands of the regulators are fed into the overall requirement set and appropriately considered. Tritium is not a fissile material and its use is not subject to the Nuclear Installation Act. Regulation of its use is currently undertaken by local authorities and the Environment Agency.

Target Production Roadmaps

Target production roadmaps must be developed for each proposed target design. To provide insight into what this entails, a simplified example using the LIFE IDD point design is shown below.

Requirements
Indicative high level requirements for target fabrication to support Laser Energy include:

- Production rate of 15Hz
- DT layer must have *rms* of less than 0.001 mm on the inner surface
- DT vapour pressure must not exceed capsule rupture pressure
- Minimum gain of 40
- Target gain / € equal to or higher than 40
- All manufactured systems must be automated
- Capsule concentricity < 0.001 mm (in x, y and z planes)
- Contains Tritium
- DT layer density must be 0.253 g/cm3
- DT layer thickness must be variable 0.0187 +/- 20%
- Production facility must meet all regulatory requirements
- Production Yield of 3 sigma (3000 failures in a million)
- Must maintain spec at acceleration of 1000G
- Must survive 973K during injection period
- Target cost less than €1
- Target must be maintained at 13K
- Production systems must be fail safe
- Production system must be capable of recovering released Tritium within the facility
- Target production system must be operational 24/7/365
- Target production systems must be able to operate long-term in a radioactive environment
- Target must be vacuum compatible (0.002 Pa)
- Targets to be sample characterised at 0.016 Hz
- Tritium used in production must be recycled
- Capsule possibly to contain low density < 150 mg/cc aerogel
- Diagnostic gain feedback loop into target production requirements
- Production system must be licenced for storage of 1kg of Tritium
- Production system must be linked to injector system
- Production systems must be accessible (glove box)
- Must be able to produce DT ice layer
- Targets costs must be reduced by 1% per year of plant lifecycle
- All raw materials used must have redundancy of supply
- Production system must maintain WIP of 5.10^5 targets
- Production systems must be modular

20.22 Physics Design and Modelling

To meet target survival modelling needs will require development of a modelling capability which includes performance of the injector and target chamber (described below)

Facility Model – Injection and Reactor

From production to fusion burn, a fuel pellet target must maintain the required specification if fusion is to occur. It must be designed with appropriate protection to survive the environmental changes to which it will be exposed before the laser pulses strike it.

The life of a target consists of eight key stages :-

- Production
- Storage
- Transport to injector loader
- Injector loading
- Injection
- Separation from sabot (if used)
- Steering
- Exposure to the chamber environment during travel to chamber centre.

Modelling of perturbations during each of these stages is critical to understanding whether each target design will survive and remain viable for fusion upon reaching chamber centre.

It will be essential to consider the requirements of starting the facility target chamber from ambient temperature and running up to its full operating temperature. Targets must be capable of fusing in target chamber temperature ranges between 20°C and 700°C. As targets are introduced and fused, the chamber will heat up, but this also impinges upon the vacuum within the chamber. Injectors may include a gas gun, whose operation would also influence the chamber environment.

As a result, a target could be exposed to a wide range of conditions. This necessitates construction of a model allowing assessment of target survivability under a broad range of conditions.

Areas considered for modelling are outlined in Annex B to this document.

20.23 Modelling Platform

The chamber model may be run as a single entity on a supercomputing platform. It could also be integrated with physics models to provide an overarching design tool. Using a common central data set approach, the model could also be run as discrete elements, output from each being entered into the data set. In practice this method is very time consuming. It is therefore preferable for the model to be run as a single entity, permitting higher throughput.

As with all simulations, only a limited degree of assurance can be provided by a model. True certainty may only be demonstrated through experimental validation. This cannot be achieved until a first of type development facility for Laser Energy is built. This requirement underpins the strategy of a first of type facility with two chambers, initially for development and integration of equipment and, subsequently, to demonstrate power production.

20.24 Target Design Validation – Experimental Programme

A target design is validated by three key qualities:-

- Ability of a designed target to fuse with appropriate gain
- Ability to survive injection into the fusion chamber
- Ability to endure the fusion chamber environment through trajectory to point of fusion

These validation issues are dealt with below;

Fusion and Gain Demonstration

An essential factor in target design is access suitable facilities in which to validate target performance against predictive modelling. While some parameters can be validated using sub fusion-capable laser facilities such as Orion, Vulcan and Omega, access will be required to fusion-capable drivers such as NIF or LMJ, both to confirm fusion capability in a target and to validate predicted gain.

Injection Demonstration

Target injection parameters may be met using a shortened injector demonstrator capable of achieving appropriate accelerations. These may differ according to target type.

The four main issues affecting target survivability in the injector are :-

- DT layer deformation/fracture caused by sabot/target acceleration
- Mechanical oscillation of the target due to acceleration
- Environmental disturbances influencing target or sabot, such as thermal gradients or debris
- Changes of phase of the DT fuel

Ultra high speed imaging is likely to be the primary characterisation technique for assessing DT layer fracture and phase changes, while oscillations may be measured using laser-Doppler techniques. In view of the possibility of performing capsule metrology at 1Hz a target may be scanned at access points in the lower speed part of the Injector and the limited data compared with more extensive data taken immediately prior to loading. This comparison will provide information about DT layer integrity and condition.

Reactor Survival Demonstration

After injection targets will be subject to adverse conditions in the fusion chamber, most notably, vacuum/low pressure gas conditions, IR background and a debris field.

These conditions may be simulated by adding a vacuum oven onto the demonstration injector. Although targets will not be travelling at full injection velocity, the timescale for degradation may be assessed, with results fed back into design modifications.

20.25 Phase 2 Cost Estimate

Based on the work done in the HiPER preparatory phase, a cost estimate of c.£80M has been developed, together with a schedule of the work to be done in the Target Design and Mass Production technology development element of Phase 2. A high degree of uncertainty currently exists in the estimate (+100%, -50%), as outreach to industry and academia was not completed. This would give increased confidence of cost and schedule. The work will be completed during Phase 1.

20.26 Annex A Target Chamber Model

The following comprises a list of areas which would require consideration to form a model of the target chamber for target survivability modelling.

Number	Modelled Element
1	Dynamic vacuum model of injector While such a model does not currently exist for the injector, codes do exist for vacuum modelling of complex structures which can be configured to perform this task.
2	Dynamic fusion event product model Fusion event modelling is currently undertaken using existing codes developed for research. These exist.
3	Target injection model including acceleration, sabot separation and steering Work done to date requires integrating. Assessed at TRL of 3
4	Dynamic chamber gas fill behaviour and gas polishing model
5	Dynamic chamber first wall exfoliation and spallation model
6	Dynamic chamber blanket and cooling model
7	Target chamber environment interaction model
8	Target engagement (control systems) model The principles of control system modelling are well understood however this is a complex undertaking, hence TRL 2.
9	Target thermal management model Thermal management models for the target exist although these will need to be at a higher level of efficacy to demonstrate the integrity of the layering, hence TRL 3
10	Breeder Tritium and Helium evolution model The reactions of Lithium are well known and game theory modelling can be harnessed to predict these. Based on the current theory, TRL is evaluated at 4.
11	Integration of individual models into a coherent overall model capable of evaluating changes to any element and their effects
12	Target model – a dynamic model of the target which demonstrates similar properties to the target under the influence of all environments predicted by the reactor and injector models. This model is target design dependent and multiple models may therefore be produced.

21 Appendix V: Exploitation opportunities for Industry

The most immediate opportunities for commercial exploitation of the technology required for inertial fusion energy is associated with the “next generation” laser technology that combines high peak power with high average power at high efficiency and potentially low cost.

Within Europe, this technology is being developed in France, Germany and United Kingdom. In U.K., a centre for the development and exploitation of this new technology has been established by STFC at the Rutherford Appleton Laboratory. The Centre for Advanced Laser Technology and Applications (CALTA) has already won several multi £M contracts for the supply of this technology.

Some promising future applications of this technology are summarised below.

Chemical Processing

Laser light can be used to enhance chemical reactions either through the wavelength of the laser being at an appropriate frequency to transfer energy to a reactant at the atomic level or through simply adding photonic energy to the reaction in what can essentially be described as photonic stirring. This application area is one which is emerging for high power lasers.

Remote Re-fuelling

High power lasers may be used to renew energy reserves in powered devices. This technique can be used over great distances.

Laser Driver for Launch of Vehicles

High power lasers (both pulsed and continuous wave) have been proposed for use as a launch mechanism for small satellite packages. This is a new application for lasers but one which warrants further examination, the cost benefits for a repetitive launch system being highly significant over that of currently utilized technologies.

Undersea Communications and Acoustic Imaging

One technique that can be used to expand and improve both naval and commercial underwater acoustic applications, including undersea communications, navigation, and acoustic imaging is to use a laser to ionize a small amount of water. The water then absorbs laser energy and superheats. The result is a small explosion of steam which can generate a corresponding 220 decibel pulse of sound.

The optical properties of water can be manipulated with very intense laser light to act like a lens, allowing the laser beams to focus themselves. Because the slightly different colors of the laser travel at different speeds in water, they can be arranged so that the pulse also compresses in time as it travels through water, concentrating the light even more.

Because these two effects are much stronger in water than air, a properly tailored laser can travel many hundreds of meters through air, remaining relatively unchanged, then quickly compress upon entry into the water, allowing aircraft to communicate with submarines.

The technique could also be used for underwater acoustic imaging by using a moveable mirror to create an array of pops whose echoes would give a detailed picture of underwater terrain.

High Power Pulsed X ray Sources

A high power repetition rate laser may be used as a high power x-ray source enabling security scanning for hidden objects/material in a variety of applications. The limiting factor in current x-ray security scanning systems is the possibility that humans may have hidden in cargo etc, even the possibility of their presence limiting the energy of the x-ray system.

In conjunction with appropriate time gating the high power X-ray source can potentially provide real-time dynamic images of processes taking place on the sub-microsecond time-scales. This lends itself extremely well to fast moving vehicle inspection thereby obviating the need for queues at various checkpoints. Other applications could include, as an example, optimising aircraft or car engine functionality during the testing phase of a prototype. This would be a significant breakthrough for all engine manufacturers as it would assist in optimising efficiency and in identifying potential failure modes at an early stage before engines go into full manufacture.

In science research such a tool would be invaluable for investigating processes on such short timescales and may well open up a completely new discipline for both macro as well as microscience.

Table Top Accelerators
Using the “Laser Wakefield” effect, table top accelerators are possible. These are described more fully below.

Food Industry
Currently, the preferred method for area sterilization in the food industry is by means of mercury vapour lamps working at around 245nm. This process is not only labour intensive but potentially hazardous due to concerns regarding UV skin burns and eye inflammation. Furthermore, the use of mercury , although deemed non-hazardous from a single lamp, could potentially become a concern when using a number of lamps simultaneously. This is particularly acute in the water industry where banks of lamps might be used to sterilise water passing through water columns with additional complications arising from safe disposal of such systems.

In order to address this particular area the high power laser will need to generate the fourth harmonic which, although reducing its power output considerably would make it adaptable for this application. The types of additional applications that such a system would address include medical theatre and tissue culture facility sterilisation.

Laser Manufacturing Industry
Existing single shot high power laser installations could be upgraded to provide increased capability and efficiency through the use of diode pumped amplification chains and alignment feedback systems. Whilst of significant cost, these upgrades could extend the life of such facilities and permit scientific exploration in new fields. A further subtle but significant effect is that the cost of ownership will be considerably reduced for such installations. Laser diodes have improved in reliability and lifetimes significantly over the past 5-10 years – a requirement driven primarily by the telecoms industry. Consequently the upgrade could potentially pay for itself over a short period of time and provide cost savings over the longer term.

Materials
The applications of high power lasers within the materials industry are diverse and range from the production of novel materials using high powers and small areas or materials in larger quantities (lower power or larger area). Lasers are also used in the jointing, doping and measurement and analysis of materials. The world is undergoing what can be considered a materials revolution at this time. As a result, a significant number of applications for the laser in this area are expected.

Mechanical Engineering
Production technology accounted for 6% of the overall worldwide photonics market of €228bn in 2005 and included materials processing, applications in the semiconductor industry as well as in the flat panel display sector. This is projected to double by 2015 . The UK contributed approximately €150m to this sector and is likely to benefit significantly from its developments.

Laser Cutting

Laser cutting is performed by a large number of industrial companies. Advantages of using lasers include high throughput, precise and repeatable results and high quality products.

The 1kJ 10Hz laser produces a high average power beam, the pulsed nature of the output will result in short plasma creation bursts around a beam focus. In the case of material cutting this will provide an advantage by producing high pressure scouring of debris from the kerf and limiting the timescale for heat conduction. The effect will reduce the heat affected zone around the cut and offer a distinct advantage when cutting brittle and crack-sensitive materials such as glass.

This phenomenon has been recognized for many years but has not been exploited on an industrial scale because of the prohibitively high entry level cost of suitable lasers. The Laser Technology Centre, and the other large scale facilities planned for construction using DPSSL technology, will drive price reductions to the point at which such systems are affordable by industry. It is conceivable that this technology could spawn a capability and market for curved profile cutting of, as an example, toughened glass windows.

Laser Peening

Material hardening, in particular the use of laser shock peening, is a highly promising industrial market for the 1kJ 10Hz laser. The cost of the special lasers needed for peening, together with their slow processing rates, has limited applications to very high value critical components, predominantly in the aerospace and nuclear industries.

Examination of peening system production rates that are needed to yield commercially viable components, as used in the automotive, railroad or bearings industries for example, show that no suitable laser is currently available. The lasers that are currently used have arisen from fusion research programmes. These are capable of producing the required laser pulse energies but at low repetition rate and low average power. The needs of this emerging industry for high peak power, high average power and low cost is precisely the specification of the laser.

The laser requirements for shock peening can be understood from an examination of the physical processes involved. The technique relies upon the creation of an intense shock wave on the surface of the metal. The shock is initiated by a very short, intense laser pulse focused through a transparent layer, such as water, onto the metal. The intense electric field causes a high pressure plasma to form at the interface. The energy in the plasma is tamped by the mass of the water. This is a form of inertial confinement that couples the explosive force of the expanding plasma into the metal as a shock wave. When the pressure imposed by the shock exceeds the yield strength of the metal, the plastic deformation leaves the material with a residual compressive stress.

One consequence of the resulting compressive stress layer is its ability to slow the rate of production and growth of fatigue driven cracks in the metal component. The greater the depth of the residual compressive stress, the greater the fatigue strength of the component. Other benefits arising from residual compressive stress layers include the ability to influence the hardness of some surfaces as well as their friction and weld properties. It is also possible to use the predictable stress induced distortion of plane surfaces to produce complex shapes in sheet material.

The over-riding advantage of laser peening is its capacity for creating residual compressive stress at depths that are over four times greater than conventional shock peening techniques. It can produce this performance enhancement in materials ranging from exotic titanium and aluminium alloys to cast iron and stainless steels.

For aircraft components such as engine compressors or turbine blades, the large cyclic stresses place great demands on these specific components. These cyclic stresses are usually highest at the material surface. Over time, these stresses can cause the initiation of cracks which propagate from the surface of the material. Surface hardening is therefore essential to improve the lifetime and reliability of such components.

In the automobile industry, producers are seeking for new ways to harden valve seats in engine cylinder blocks, crank-shafts and many other components.

This type of market is dominated by a small number of large companies, including Laser Shock Peening Technology (LSPT) and the Metal Improvement Company (MIC). In Europe, due to the high cost barrier to entry, the established companies dominate the market and without a major change in the market, this situation is unlikely to change. The Laser Technology Centre will bring about such a change.

The Laser Technology Centre will be an open research and development facility, welcoming all industrial and scientific users alike. The availability of such powerful lasers in an open research environment, based on the emerging DPSSL technology which promises price reductions in the medium term, will help to reduce the market entry cost and open up the technology to new companies. The centre will encourage automobile, aeronautics and other producers to conduct laser peening experiments, improving efficiency and increasing competition

21.1 Paint Removal and Surface Treatment

Cleaning and coating techniques using lasers are known in industry but the use of diode pumped solid state lasers (DPSSLs) has been limited due to the high entry level costs compared with more conventional lasers. The cost reductions which are expected in the medium term (10 years) will make DPSSL systems more affordable, resulting in high demand for beam time for experiments to assess the benefits of this technology.

A large potential application area is cultural heritage preservation and in particular the cleaning of historical buildings, fragile statutes or art works that have deteriorated over a number of years. Existing laser techniques have demonstrated a high capability to ablate the surface layer but associated strong heating can cause sub-surface damage. The short duration, high intensity pulses available will be effective at ablation, whilst reducing the undesirable heating.

Recent experiments using femtosecond lasers to clean artworks have been successful and there may be demand for beam time to conduct experiments over large area samples for which more conventional lasers are unsuitable.

21.2 Medical

The use of laser in medical application is a developing market. High power pulsed lasers, when appropriately configured, are able to generate gamma rays, x rays, neutrons and protons. These are currently being used in advanced cancer therapies. High power lasers may also be used for sterilization of both areas and instruments.

Mining

Within the mining industry and particularly in oil and gas exploration, the use of lasers for drilling to access difficult to reach reserves has been proposed. Currently, the technology is in its infancy having lacked an appropriately sized laser source and the means of transmitting the source energy to point of use. Repetition rate lasers are preferred as a source due to their ability to repeatedly shock and ablate the target.

Nuclear

The projected budget for nuclear decommissioning in the UK alone is £2.8bn per year and with 17 nuclear sites being decommissioned and more to enter decommissioning in the coming years, the potential for impact in this sector is significant. (NDA Business Plan – 2010-2013)

The nuclear industry has a need to remove surface contamination when undertaking decommissioning work. The use of lasers to remove surface layers on materials would reduce the volume of materials sentenced as higher level or intermediate level wastes. The practice of removing the surface layer is currently undertaken using,shot blasting methods, scabbling or grinding techniques which are both time consuming, manpower intensive and expensive. Given the ability of a laser to also cut up residuals, a single tool performing multiple functions is possible, reducing the time involved in decommissioning and hence does incurred etc.

Another area of current interest is nuclear waste containers and the concerns around weld cracking. Laser peening could replace some of the current methods such as shot peening or Low Plasticity Burnishing, to improve damage tolerance and metal fatigue life.

Light Detection and Ranging (LIDAR)

Any object needs to produce a dielectric discontinuity to reflect a transmitted wave. At radar (microwave or radio) frequencies, a metallic object produces a significant reflection however non-metallic objects, such as rain and rocks produce weaker reflections and some materials produce no detectable reflection at all, meaning some objects or features are effectively invisible at radar frequencies. This is especially true for very small objects (such as single molecules and aerosols).

Lidars provide one solution to these problems. The beam densities and coherency are excellent. Moreover the wavelengths are much smaller than can be achieved with radio systems, and range from about 10 micrometers to the UV (ca. 250 nm). At such wavelengths, the waves are "reflected" very well from small objects. This type of reflection is called backscattering. Different types of scattering are used for different lidar applications, most common are Rayleigh scattering, Mie scattering and Raman scattering as well as fluorescence. Based on different kinds of backscattering, the LIDAR can be accordingly called Rayleigh LiDAR, Mie LiDAR, Raman LiDAR and Na/Fe/K Fluorescence LIDAR and so on. The wavelengths are ideal for making measurements of smoke and other airborne particles (aerosols), clouds, and air molecules.

A laser typically has a very narrow beam which allows the mapping of physical features with very high resolution compared with radar. In addition, many chemical compounds interact more strongly at visible wavelengths than at microwaves, resulting in a stronger image of these materials. Suitable combinations of lasers can allow for remote mapping of atmospheric contents by looking for wavelength-dependent changes in the intensity of the returned signal.

LIDAR has been used extensively for atmospheric research and meteorology. With the deployment of the GPS in the 1980s precision positioning of aircraft became possible. GPS based surveying technology has made airborne surveying and mapping applications possible and practical. Many have been developed, using downward-looking LIDAR instruments mounted in aircraft or satellites. A recent example is the NASA Experimental Advanced Research Lidar.

This is an emerging market area and applications will be found for High power lasers in these devices.

21.3 Flat Panel Displays

The industrial use of transparent conductive thin films is essential in the manufacture of both Flat

Panel Displays (FPDs) and Solar Cells – two very significant markets both of which are in growth. These thin films allow the creation of circuitry that is largely transparent in the visible spectrum including complex monolithic electronic structures on substrates like glass. It is possible to create thin films of metallics, semiconductors and even organic materials. The most widely employed thin films in FPDs belong to the family described as Transparent Conducting Oxides (TCOs). These are generally deposited on glass and are required to be sufficiently conductive to act as active electrode structures when patterned, whilst remaining transparent in the visible spectrum. The most common industrially employed TCO is Indium Tin Oxide (ITO), which is more correctly described as Tin-doped Indium Oxide. An n-type semiconductor, it offers an optimum performance in terms of conductivity and transparency that is industrially proven.

In order to utilise properties of thin films such as ITO it is necessary to deposit them and then pattern them to create functional structures. The conventional industrial method for doing this is to use wet-etch lithographic techniques analogous to those used in the semi-conductor industry. Such techniques require multiple process stages, large expensive machinery, employ toxic chemicals and are extremely costly.

One alternative to this could be laser ablative deposition and thence 'laser direct write' or Laser Patterning (LP), in which a high intensity laser pulse is used to remove sections of the ITO layer directly from the substrate without damage. By interacting the laser appropriately with the ITO and then the ITO film on its substrate, it becomes possible to both deposit and then pattern large areas of active thin-films.

Scanned patterning using Q-switched diode pumped solid state lasers (DPSSL) is employed in

high volume production industry. These lasers are compact, low maintenance and robust. They offer nanosecond pulse durations, wavelengths in the near-IR and the option for output in the visible and UV through non-linear frequency conversion. These devices are of relatively high average power (in the order of 800W) and operate at repetition rates of approximately 1kHz. The predominant means of use is scanning across the surface of the substrate to achieve the required pattern.

Work done on these lasers has shown that optimal quality of production is found at deep ultraviolet (DUV), 262nm, where absorption in the ITO layer and also at the glass-ITO interface results in uniform heating and consistent evaporation of the thin film. However, at 1047nm it is found that the ITO absorbs more strongly than the glass substrate and although ablation quality is not quite as uniform as in the DUV, infra-red is sufficient to achieve the consistent electrical isolation required for the formation of semiconductor junctions. The higher pulse energies available at the fundamental wavelength of these lasers mean that higher-speed scan patterning of large areas is possible at an acceptable quality for manufacture.

Glass panels requiring processing are increasing in size and these will soon be in the order of 2160 x 2460mm. There is the potential that these may be processed in significantly shorter timescales using higher power (in the order of 2 to 10kW) rep-rate DPSSL lasers.

The techniques described could be applied to all types of FPD and further, to production in the silicon wafer and solar cell industries where similar techniques are applied. The next natural evolution for FPD's could see large flat screen production on foldable media such as plastics, the display technology of the future.

Commercial Market Potential

The flat panel display market in 2010 was in the order of \$120Bn(US). Experts estimate that this will grow at approximately 2% per annum until 2015. This is a very large market, significantly dominated by a few key players (Samsung, Sony etc) with high potential for the adoption of technologies which reduce production costs and hence enhance the potential for an increased market share.

21.4 Space Debris Removal

Functional satellites represent only a small fraction of the estimated 200,000 or more objects larger than 1 centimetre in diameter which are currently in low-Earth orbit (LEO). Most are fragments of larger man-made objects which have broken up in explosions and other events. Since these objects travel at velocities of approximately 8 kilometres per second, any collision is likely to cause significant damage to a satellite or other space vehicle. As the quantity of debris in orbit continues to rise, so does the likelihood of collision.

On February 11, 2009, a US communications satellite collided with a non-functioning Russian satellite, destroying both and creating a debris field which continues to endanger other orbiters.

A distinctive ring marks the geostationary orbit, where satellites orbit at a rate matching the Earth's rotation. This orbit is invaluable for weather and communications satellites. When geostationary satellites are taken out of operation, they are moved to a different orbit to keep the geostationary zone clear. Between the geostationary orbit and the low-Earth orbit is the "Molniya" orbit, used by GPS satellites or those in a highly elliptical orbit, to monitor the far north and south latitudes.

Of the known objects, only ~10% of the total are tracked. Collisions between large objects are rare because each orbit is well known and flight controllers can manoeuvre satellites out of danger. NASA needed to make three such satellite moves in 2010. For small items of debris, satellite shielding is currently the most cost-effective solution. As the number of debris items increases the problem will worsen. Scientists anticipate that, within 50 years, this will preclude the launch of new satellites on grounds of life expectancy.

Economic Risk

The use of space is vital for future economic and political power and the threat of orbital debris to satellites raises important economic questions. It must be decided at what threshold the risks are too high and action becomes necessary. That threshold must balance the likely impact to the mission, resources available to accomplish the mission, and the technical and cost feasibility of reducing that risk. In summary, if there is a practical way to reduce risk, then it is probably prudent to do so.

Space debris is found in all sizes, at all inclinations and at various altitudes, ranging in size from the microscopic to several metres. Most objects are small but a satellite colliding with any significant object would end its useful service life at costs significantly exceeding one billion dollars.

Current orbital debris protection effectively shields satellites against hypervelocity objects less than 1 cm in size, but this shielding is extremely expensive. The cost of increasing from 1 cm to 2 cm, the critical module protection for the International Space Station, would be approximately 100 million dollars in launch cost alone.

For objects greater than 10-30 cm in size, satellite operators rely on the tracking networks to provide early warning and will manoeuvre to avoid collisions. Provision of manoeuvring systems adds substantially to launch and build costs. Tracking networks do not provide total protection, especially during solar flare events, when they may lose objects for days at a time.

No system exists to protect against the approximately 180,000 objects ranging from 1-10 centimetres in size. Hypervelocity collision of one of these with a satellite would almost certainly reduce that satellite to a large quantity of orbital debris. Further cascade effects will produce many smaller objects, and thus the overall risk to objects in orbit increases.

While the probability of a collision with an individual satellite is quite low, the probability of a collision occurring within the entire population of space assets is by no means remote. Analysis suggests that, at the current level of orbital debris and satellite sizes, one collision per year is likely, with associated revenue losses of billions of dollars, as well as the replacement and launch costs of the satellite itself.

A possible solution and estimated cost

An elegant, cost effective and feasible solution could be to use high power repetition rate laser technology.

A high power pulsed mode ground- based laser facility with adaptive optics has the ability to focus laser energy from the ground and ablate space debris objects, causing thrust which will result in debris re-entering the atmosphere and burning up.

Operating near the equator, such a facility could probably remove most orbital debris up to an altitude of 800 km in a two to three year period. The estimated cost of such a facility would be in the region of $350M.

Satellites typically cost several hundred million dollars and, given the hundred million dollar cost of launchers, this investment is relatively small but has high potential to reduce risk.

Development of this technology could stimulate other markets such as laser power beaming and attitude correction, removing the costly requirement for satellites to be launched with propulsion capability.

21.5 Table-top accelerators

Conventional particle accelerators require hundreds of metres of length to accelerate electrons to energies in the GeV range. By accelerating electrons to near light-speed, large synchrotrons generate brilliant beams of light from infra-red to X-rays, for use in academic and industrial research.

High power repetition rate lasers can produce plasmas which support electric fields thousands of times greater than those produced in conventional accelerators. These can be used to accelerate electrons to very high energies over very short distances. Thus lasers are a suitable basis for next-generation "table-top" particle accelerators.

Technological Background

The "laser wakefield" accelerator exploits the radiation pressure of an intense laser pulse to displace the electrons in a laser-induced plasma, leaving a large electric field in its wake. In 2002 it was shown that electrons could be accelerated to energies of 200 MeV over distances as short as a millimetre by "surfing" such a wake-field. Electron beams produced were of poor quality however, because the electrons emitted had a wide range of energies. This problem has now been overcome using variations on the wakefield approach as explained below:-

- Pre-formed plasma channels were used to guide the laser beams over distances which are long compared to the natural diffraction distance of the laser beam. (This diffraction would normally limit the distance over which particles are able surf the wake).

- A "forced" laser wake field approach was also tried, in which the plasma wave actually "breaks" as the laser beam propagates through the plasma. This can lead to some of the electrons in the wave being "self-injected" into the wave. When breaking first occurs, this bunch of electrons has ther narrow energy spread required.

- A laser was also used to create a "bubble" in the plasma, trapping and accelerating the electrons. "The main applications were anticipated to be in radiobiology, medicine and chemistry, but it was also surmised that such an electron source would be ideal for use in compact synchrotrons and free-electron lasers."

This work, by three groups, having achieved balanced coherent beam energies in the MeV region, has now led to the aspiration to reach GeV energies by accelerating the particles over longer distances.

Achievement of the GeV regime represents the energies to which electrons are accelerated within new and existing high power synchrotron light sources. In the new Diamond Light Source synchrotron at the Rutherford Appleton Laboratory, electrons are first accelerated to the 100MeV regime using a conventional linear accelerator. They are then further accelerated using a synchrotron to ~3GeV energy and are fed to a storage ring where synchrotron light is produced with more energy being added to balance losses during each circuit of the ring.

Laser accelerators are already capable of achieving 200MeV regimes and could now replace many linear accelerator applications. Given continued development of the technology, the GeV region of operation will be a reality within the next couple of years.

Market

With more than 40 operating high energy synchrotron light sources in the world, the provision of "table top" accelerators based on Lasers will have a massive impact on the future market.

At the industrial and medical level, market opportunities in industry include oncology, x-ray sources, proton sources, non destructive testing and homeland security. Laser based accelerators can replace older and far more expensive technologies in these applications.

Potential areas of industrial input are summarised below:

Industrial area	LMJ Ignition (~2021)	HiPER Technology Development (~2021 to 2028)	HiPER Facility (~2027 to 2040)	Rollout of Laser Energy (~2044 onwards) Potential market ~4800 * 1GWe plants worldwide
Optics	Scientific development DiPOLE, LULI and JENA	Increasing level of involvement ramping up in the later years – DPSSL industrial applications	Will require at least 600 off 1kJ 10Hz DPSSL Lasers. Highly significant market change	Scaled involvement to suit rollout programme
Optical Supports etc	Scientific development DiPOLE, LULI and JENA	Increasing level of involvement ramping up in the later years – DPSSL industrial applications	Will require at least 600 off 1kJ 10Hz DPSSL Lasers. Highly significant market change	Scaled involvement to suit rollout programme
Pump diode	Scientific development DiPOLE, LULI and JENA	Increasing level of involvement ramping up in the later years – DPSSL industrial applications	Will require at least 600 off 1kJ 10Hz DPSSL Lasers. Highly significant market change	Provision of equipment to satisfy rollout programme of plants
Laser construction, installation and maintenance	Scientific development DiPOLE, LULI and JENA	Increasing level of involvement ramping up in the later years – DPSSL industrial applications	Will require at least 600 off 1kJ 10Hz DPSSL Lasers. Highly significant market change	Provision of equipment to satisfy rollout programme of plants
Cryogenics	Small scale involvement mainly in laser development	Larger scale involvement - laser development and target mass manufacture development ramping up toward end of phase	High level of involvement – systems for each laser (600 off minimum) and for target mass manufacture at rate of 1 million targets per day	Provision of equipment to satisfy rollout programme of plants
Micro Electro-Mechanical Systems (MEMS)	Small scale involvement in developing technologies for target mass manufacture	Small scale involvement but ramping up toward the end of the phase for target mass manufacture demonstration	Input relating to the provision of equipment for the mass production of targets at rate of 1 million per day	Provision of equipment to facilitate target mass manufacture in power production plants
Micro-assembly	Small scale involvement in	Small scale involvement but	Input relating to the provision of	Provision of equipment to

Industrial area	**LMJ Ignition (~2021)**	**HiPER Technology Development (~2021 to 2028)**	**HiPER Facility (~2027 to 2040)**	**Rollout of Laser Energy (~2044 onwards) Potential market ~4800 * 1GWe plants worldwide**
	developing technologies for target mass manufacture	ramping up toward the end of the phase for target mass manufacture demonstration	equipment for the mass production of targets at rate of 1 million per day	facilitate target mass manufacture in power production plants
Nanotechnology	Small scale involvement in developing technologies for target mass manufacture	Small scale involvement but ramping up toward the end of the phase for target mass manufacture demonstration	Input relating to the provision of equipment for the mass production of targets at rate of 1 million per day	Provision of equipment to facilitate target mass manufacture in power production plants
Microfluidics	Small scale involvement in developing technologies for target mass manufacture	Small scale involvement but ramping up toward the end of the phase for target mass manufacture demonstration	Input relating to the provision of equipment for the mass production of targets at rate of 1 million per day	Provision of equipment to facilitate target mass manufacture in power production plants
Chemistry	Small scale involvement in developing technologies for target mass manufacture and tritium handling techniques	Small scale involvement but ramping up toward the end of the phase for target mass manufacture demonstration including tritium handling techniques	Input relating to the provision of equipment for the mass production of targets at rate of 1 million per day and associated tritium recovery and handling	Provision of equipment to facilitate target mass manufacture and tritium recovery in power production plants
Target Mass Manufacture		Development and down selection of appropriate techniques for target mass manufacture including demonstration at scale	Provision of target manufacturing plant capable of 1 million targets per day	Provision of target manufacturing plants for power production
Materials development (fusion chamber and targets)	Small scale involvement mainly including materials	Small scale involvement ramping up toward end of	Production of fusion chamber including all ancillaries for	Production of fusion chambers for power production plants

Industrial area	LMJ Ignition (~2021)	HiPER Technology Development (~2021 to 2028)	HiPER Facility (~2027 to 2040)	Rollout of Laser Energy (~2044 onwards) Potential market ~4800 * 1GWe plants worldwide
	development for fusion chamber first wall and energy extraction systems	phase including materials development for fusion chamber first wall and energy extraction systems	power production later in phase	
Energy extraction and breeder blanket	Small scale involvement at scheme level	Conceptual and detailed designs including scaled demonstrator. Ramping up in this stage.	Production of breeder blanket and energy extraction systems toward middle of phase	Production of breeder blankets etc for power production plants
Physics modelling and target design	Supporting LMJ campaign	Supporting LMJ campaign and down-selecting target for HiPER	Supporting HiPER and increased gain	Supporting power plants in operation and continuous improvement
Defence (injection and Tracking)	Small involvement – mainly science	Conceptual and detailed design suitable for power production including prototype	Production of injector and tracking systems suitable for power production	Supply to power plants including maintenance and continuous improvement
Vacuum systems	Small input mainly supporting laser development	Support laser development. Concept and detailed designs for power production including prototype	Production of systems to support 600+ lasers and fusion chamber	Supply to power plants, maintenance and continuous improvement
Remote handling and maintenance	Small input mainly supporting fusion chamber and target mass manufacture studies	Significant input to reactor and target mass manufacture conceptual and detailed design including prototyping	Supply of remote handling equipment for HiPER	Supply of remote handling equipment for power plants, maintenance and continuous improvement
Architecture	No involvement	Concept and detailed design of HiPER	Concept and detailed designs for power plants	Oversee construction of power plants and continuous improvement in design

Industrial area	**LMJ Ignition (~2021)**	**HiPER Technology Development (~2021 to 2028)**	**HiPER Facility (~2027 to 2040)**	**Rollout of Laser Energy (~2044 onwards) Potential market ~4800 * 1GWe plants worldwide**
Health, Safety and Regulatory Compliance	Small involvement assessing schemes	Significant involvement in conceptual and detailed designs including provision of safety cases for HiPER	Significant involvement in conceptual and detailed designs of power plants including provision of country specific safety cases	Periodic reviews of safety cases and operations in plants
Telecommunications	Minimal involvement	Concept and detailed design of systems for HiPER	Implementation of HiPER designs and concept and detailed designs for power plants	Implementation of power plant designs, care and maintenance
Computing, Control Systems, Networking and Data Management	Minimal involvement	Concept and detailed designs for HiPER	Implementation of concept and detailed designs for HiPER. Concept and detailed designs for power plants	Implementation of power plant designs, care and maintenance
Turnkey Projects	Minimal involvement	Concept and detailed designs for HiPER and larger scaled prototypes. Supply chain management	Implementation of HiPER design. Concept and detailed designs for power plants. Supply chain management	Implementation of power plant designs. Supply chain management.
Construction	Minimal involvement	Involvement in small and large scale prototype construction	HiPER Construction	Power plant construction

22 Appendix VI: Virtual Reactor model

22.1 Definition & Context

That the definition of a Virtual Reactor can be formulated as follows:

"The Virtual-Reactor is a means to simulate the reactor assembly (physical design) and the reactor operations (functional design) of the "to-be" reactor before its actual integration in order to deliver at TRLX a "competitive", "okay for operations & services", "okay for certification" and "okay for production" definition file."

The objective is therefore to simulate the complete system its interfaces to a Technology Readiness Level (TRL) as close as possible to level 6

The generic aspects of a Virtual Reactor are described into details in ref (1).

If we look at the Inertial Fusion Energy (IFE) reactor global structure, two loops are obvious as shown in Figure 36. The first loop is related to the targets from their manufacturing process to the fusion reaction and the re-treatment, the second one being related to the energy created by the fusion and its transformation. However the reality is much more complicated with numerous coupling structures between up to 7 major subsystems (cf. ref. (2)) –the driver, the target factory, the target injection, the fusion chamber, the steam-turbine generator, the waste treatment system and the buildings.

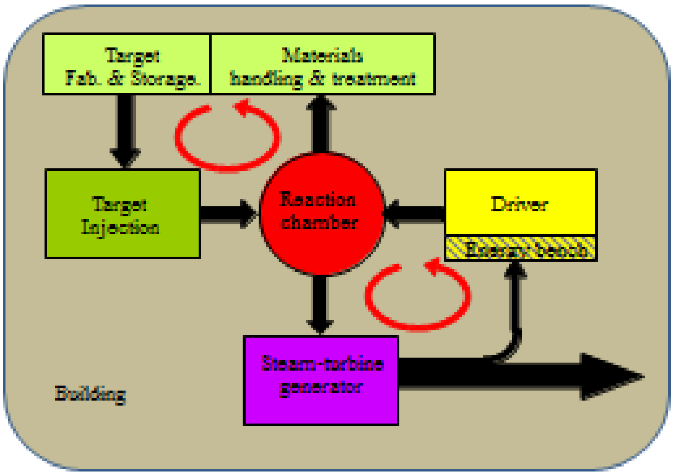


Figure 36: Laser Energy Reactor Global Structure

22.2 Rationale for a Virtual Reactor Model (VRM) for Laser **Energy**

If theoretical research, experimentation and simulation are the three major approaches to explore the world and to develop new complex systems, with increasing development of computer technologies such as High Performance Computing (HPC), numerical simulation is playing a major central role in those activities. HPC, automatic modelling, scientific visualization , virtual reality (assembly and simulation) , multiphysics coupling concepts, are key disciplines for developing a VRM or a digital reactor.

A VRM or digital reactor can be developed by taking advantage of information technology, integrating modelling, computing and data analysis in nuclear inertial fusion energy processes and by building an integrated simulation platform.

The two main goals of a VRM are the following:

- To validate VIRTUALLY the concept and to develop the design

22.3 VRM development: Main tasks

The main identified tasks for developing a VRM for IFE are the following:

Establish the Functional architecture

Identify “end to end” numerical process (workflow analysis with input/output data)

Establish the Testing Generic Process

Establish virtual labs (platforms) for each subsystems and a global virtual platform coupling the virtual labs*

age the CAD-CAE links

Establish a backbone unified middleware for managing simulation data, hierarchical models (from analytics to multiphysics and multiscale models) and results (Simulation Life Cycle Management – SLM - tools).

22.4 Inputs and Focus Points of a VRM Workpackage

We consider that the main inputs of a VRM workpackage should be

- The functional architecture
- The identification of the main “end to end” numerical process (workflow analysis with input/output data).
- These two tasks could be accomplished during specialized workshop organized with the project main contributors.
- The main outputs of a VRM workpackage should be
- Developments of Virtual Labs (platforms for each subsystems or main functions) and of a VRM global virtual platform coupling the virtual labs.
- Establishment of a SLM backbone for managing simulation data, hierarchical models and results.

We can consider that the VRM consists in this VRM global virtual platform driven by an efficient SLM backbone (SLM engine).

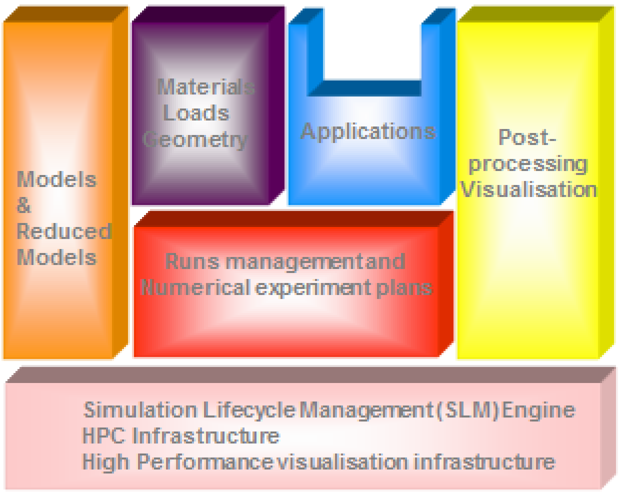


Figure 37: SLM-driven VRM Global Virtual Platform

Although the purpose of the VRM is specific in its application to the Inertial Fusion Energy, the VRM concept can show some simlilarities with other approaches as the concept of the Virtual Tokamak library whose functionality, malor components and method of used developed by Russian Universities are described in the extract here-below.

"The library is designed to predict, support, and interpret experiments as well as handle measurements on tokamak instruments implementing the idea of energy production on the basis of controlled thermonuclear fusion. The library software consists of an interactive graphic shell and a number of interrelated computer codes simulating various processes in the tokamak plasma, its structural elements, diagnostics and control system. This is a specific implementation of advanced information technologies including Internet technologies and approaches of distributed computations in the field of the mathematical modeling of plasma. The Virtual Tokamak is unique in terms of combined application and system software."

22.5 VRM Global Virtual Platform: main features

The VRM Global Virtual Platform will be organized in different platform levels and will present a high degree of interoperability between these different levels.

First Platform Level – Main Functions Detailed Simulation

On the 1st platform level, the simulation codes workflows will be organized by fusion reactor main functions articulation as shown in Figure 38 & Figure 39 and described in Reference 3). Figure 39 shows the suggested priority level identifications for the main functions.

Each workflow presents different levels of coupling (weak, strong, staggered, ..) and all these workflows must be coupled at the right level for global system simulations.

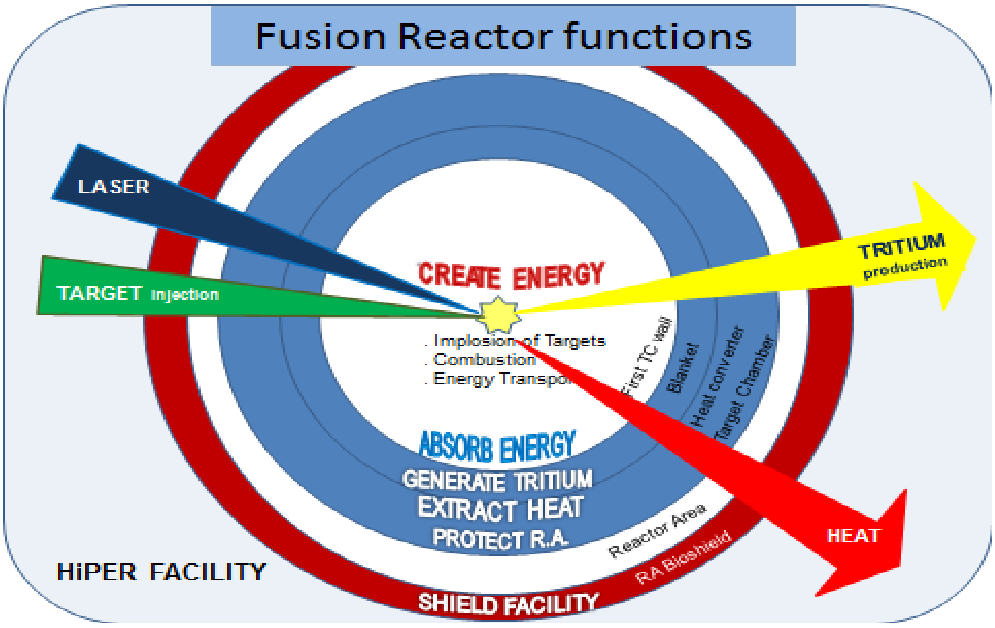


Figure 38: Fusion reactor functions

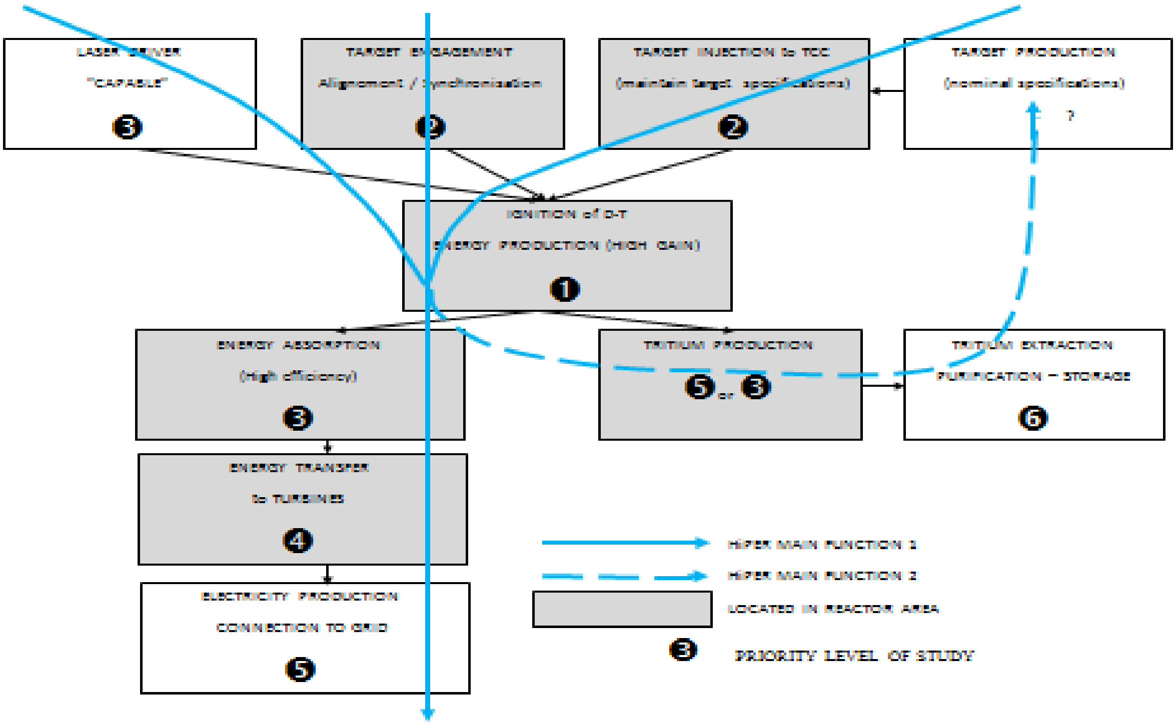


Figure 39: HiPER main Function

The 1st level platform also includes the following features:

- Capabilities to generate meta-models or surrogate models starting from workflows main functions detailed models;
- Links with materials, stresses data bases

- Links with experiments results data base (eventually through the SLM engine, cf. section 6).
- Links with Verification & Validation toolbox (through the SLM engine, cf. section 6).

An example of simulation platform architecture based on this “levels concept” is shown in Figure 40.

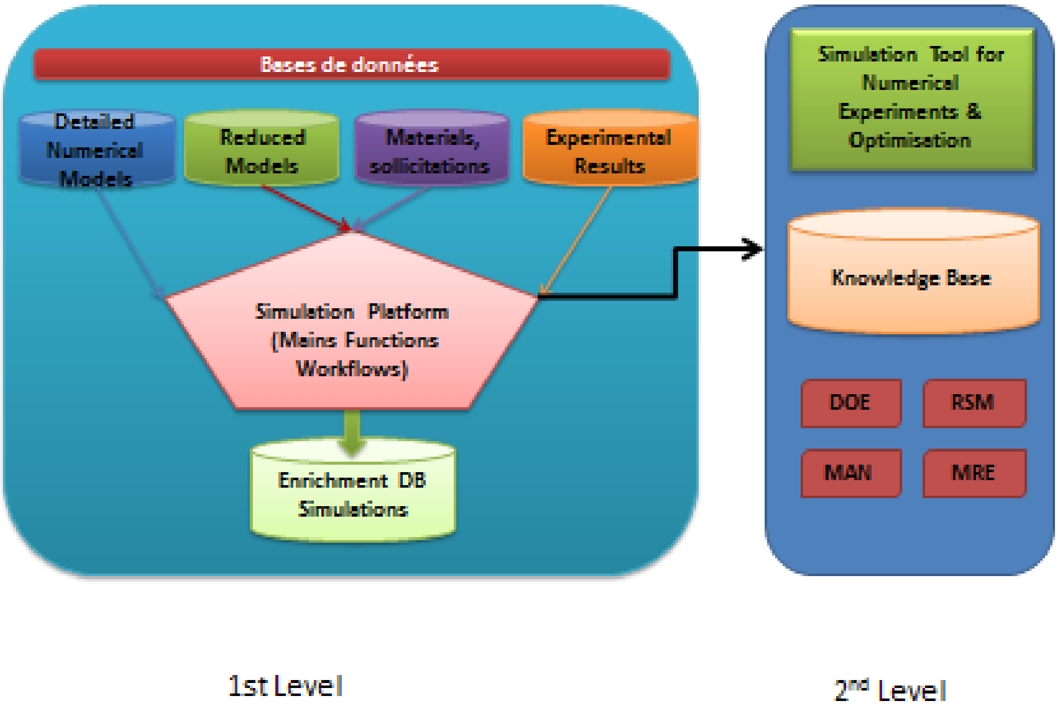


Figure 40: Simulation platform architecture

22.6 Multi-Physics Coupling Treatment

Due to the multiple coupling conditions, we recommend to equip the 1st level platform with a specific coupling module (an Application Programming Interface) enabling the platform user to couple 3rd party applications with other workflow codes. Figure 6 shows the example of a virtual aircraft aeroelastic platform including such a coupling module. The platform user can design the appropriate partitioned analysis procedure to achieve the desired numerical stability and solution accuracy.

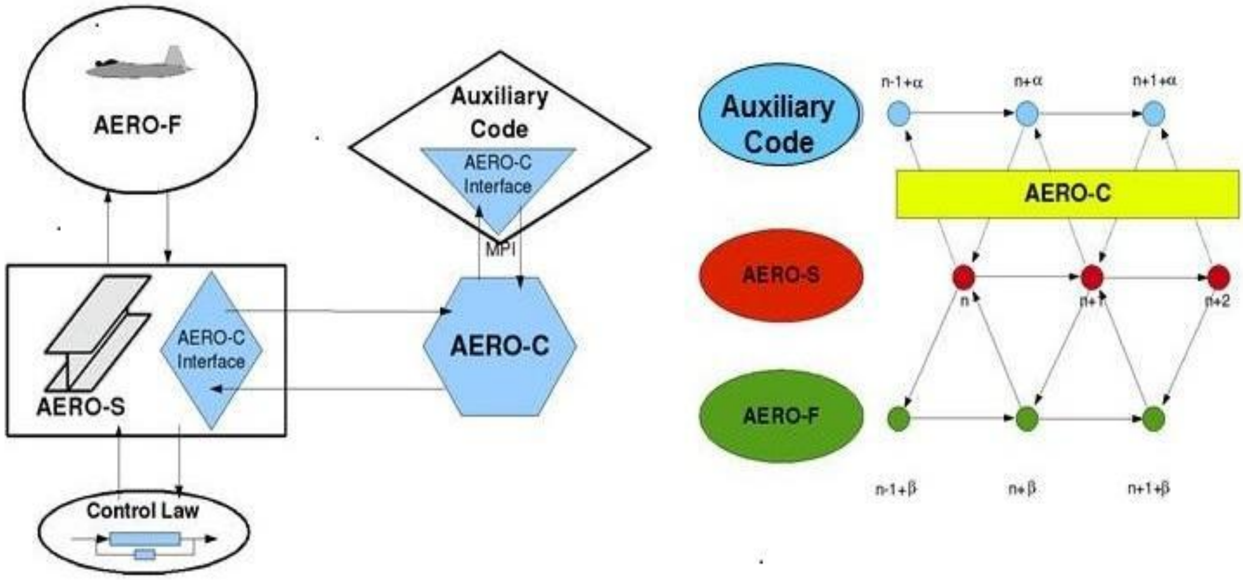


Figure 41: Virtual Aircraft Aeroelastic Simulation Platform

Second Platform Level – Design of Expts. (DOE) and Multidisciplinary Optimization (MDO)
The 2nd level platform is based on a knowledge data base recording the detailed simulations and meta-models-based simulations issued from the 1st level platform.

This platform enables DOE and MDO analysis using different technologies like surrogate models, reduced order models and neural networks.

This 2nd level platform is the key element to generate large scale numerical experiments in order to produce simulation-based responses to experts fundamental scientific questions and in a second step to design the functional core of the fusion reactor.

22.7 SLM Engine Main Features

During the project successive phases, all the simulation results included in the global virtual platform will progressively contribute to refine and to fix design decisions. These decisions will have to be justified regarding different references and authorities (experiment, safety, economics, technology). These decisions will be articulated to the system global design, then to the PLM (Product Life Cycle Management) representation that will drive the industrial development phase until the exploitation and the dismantling.

This process will need an environment enabling historical, secured and robust management of simulations (models and results) and enabling to track at any time and with high precision the decision fluxes induced by these simulation results. An efficient SLM engine can be such a good environment.

Numerical design is constrained by industrial project requirements
Data and tools used in numerical design process for the modelling and simulation of the system behavior generate results for justifying design concepts and for demonstrating that these concepts and choices respect the constraints given by the project. The nature of these activities is depending on:

The different phases of the design project that rely upon different scales of modelisation: simplified models for feasibility studies, refined project models for margins performance analysis (reference models for modelisations at the state of the art), “industrial models” for analysis during the life of the system.

The different tasks assigned to numerical design activities: nominal run design, design with respect to safety rules (incidents and accidents simulations), …

On the other hand, at the end of the design phase, industries will take in charge the process engineering that will be managed through a PLM system in order to assure the control of the entire process (costs, delays and quality). It is necessary to have a link between the reality expressed by the PLM system and the design decisions that have validated this reality in order to assure the conformity of the implementation.

Furthermore, when the system in on service, different numerical actions are still necessary during the system life: impacts of differences between "built" and "specified", incidents analysis, dysfunctions analysis, respect of safety rules evolutions, …These actions require an analysis phase where engineers should be able to re-use models and simulations that have driven design phases.

Needs induced by design environment

In order to to fully meet the project needs and constrains, the numerical design environment must enable an exploitation of simulation resources that offers 3 guarantees :

The assurance to transform generic V&V process issued from the quality control of simulation tools to a "project V&V" in order to generate validated models including uncertainties propagation analysis, and a mastering of projects margins. This requires also a strong link and a good coherence between design process, experimental process and safety referential.

The assurance to guarantee the tracking of design decisions for safety demonstrations, or to efficiently analyse the impacts of updates and modifications to efficiently revisit the design workflow.

The assurance to allow to re-use the design numerical models during the entire system life-cycle for maintenance purpose (incidents and fatigue analysis) or for safety rules evolution purpose.

All these constraints demonstrate that the numerical design environment has to be driven by a powerful SLM engine with the following features enabling:

- to track, to document and to justify simulation data and process in relationship with the design decisions
- to guarantee the coherence between multi and inter-disciplinary analysis during all the design phase
- to efficiently re-use simulation models during the entire life of the product
- to guarantee the coherence between simulation models and experimental programs
- to facilitate collaborative engineering around the product during the entire cycle life.

The SLM engine that will drive the Global Simulation Platform will have the main following features:

- Continuous tracking of models and results with coherence guarantee
- Simulation integration for real global design
- Coherence of the numerical mock-up with the project phasing
- Evolution impacts analysis and tracking

- Efficient collaborative engineering process

The features of the require VRM platform SLM engine are articulated around 2 levels in order to keep dynamically the project life:

- The entire inventory of all the components of the digital mock-up and their history in the design environment. This includes data, results, scripts, tools, … but also the tracking of the constraints, the analysis, the project approbations, etc …

- The “genealogy” of these components, imported or generated into the environment. The first case concerns for example the introduction of new codes versions or scripts for which we want to control the right usage; the second case concerns for example the data generation by the application of a software to a set of data. This allows to master all the logical links between components (results vs constraints; calculation models used vs results status, etc …).

An analytical decomposition of the services and features required for a SLM engine is shown in Figure 42.

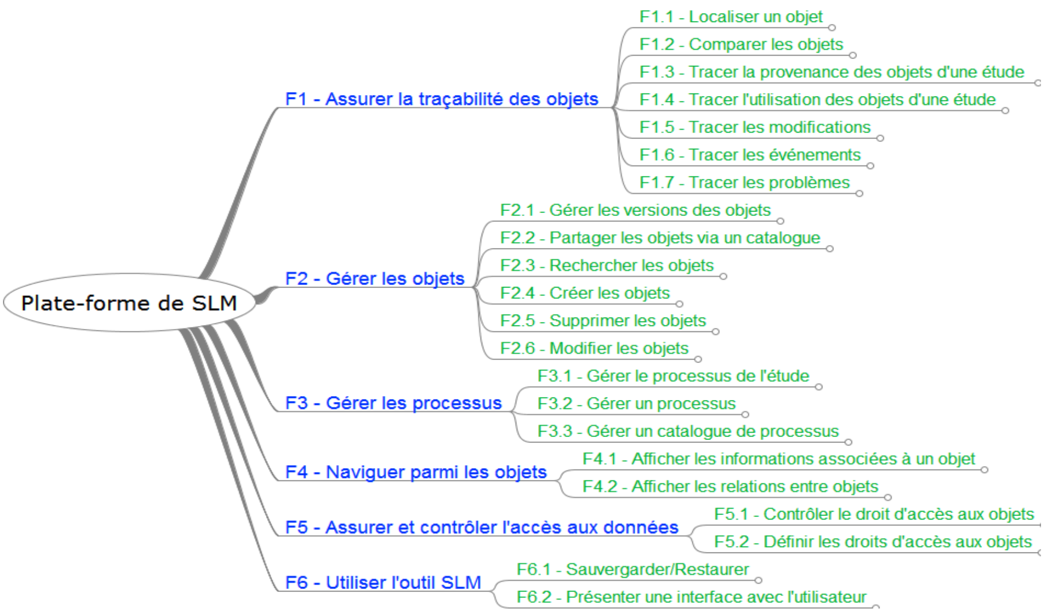


Figure 42 Analytical Decomposition of Required Services for a SLM Engine

22.8 Synthesis

The proposed architecture development of the VRM will start by defining the main functions that constitute the reactor assembly and simulating them. The model will include the simulation of the interfaces and the workflow of the functions. The Virtual Reactor Model will allow to optimize each of these functions, the interfaces and the workflow.

For a specific function, the model development will consist in developing a specific platform or Virtual Lab.

Each of these platform will integrate 2 levels:

- the first level includes complex detailed models that will be analyzed through multiple simulation runs. Reduced models or meta-models will be created in association with the results of these runs.
- The second level will capitalize on the reduced models to speed up the run times and will feed a knowledge data base that be the key element to generate large scale numerical experiments.

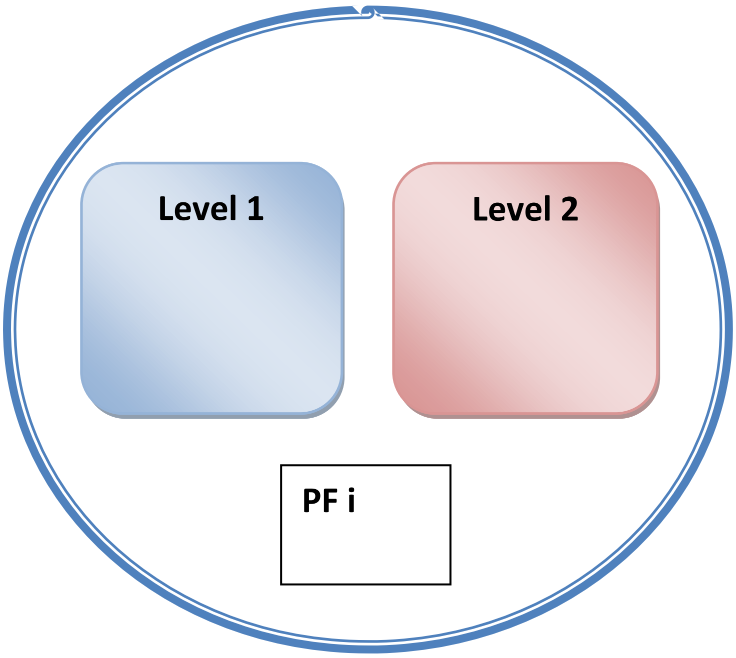


Figure 43: Function Simulation Global Platform Concept

At the platform level, an optimization process is performed through multiple runs. The VRM consists in the assembly of all functions, and therefore all platforms.

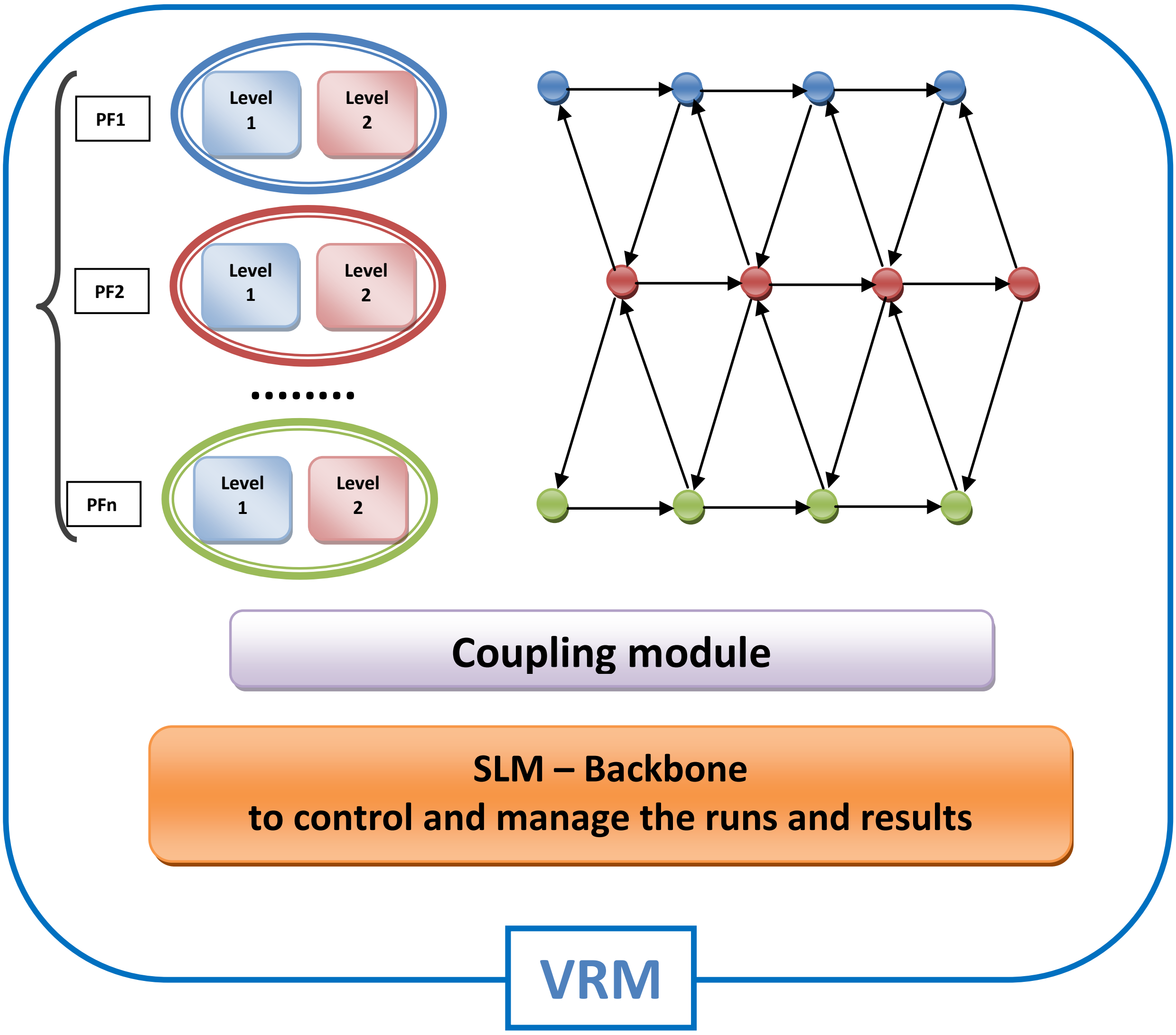


Figure 44: Global Staggered Platforms-Based and SLM-Based VRM Architecture Concept

List of Abbreviations

Abbreviation	Definition
CAD	Computerized Aided Design
CAE	Computerized Aided Engineering
DOE	Design Of Experiments
HPC	High Performance Computing
IFE	Inertial Fusion Energy
MDO	Multi-Disciplinary Optimization
PLM	Product Life cycle Management
SLM	Simulation Life cycle Management
TRL	Technology readiness Level
VRM	Virtual Reactor Model

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23 Appendix VII: Fusion Chamber

23.1 Introduction

Different proposals of Laser Fusion Energy have been envisioned in the last years. Those concepts cover Engineering Facility at large scale in *Energy*, to *Power* Prototyping and final DEMO Reactors. HiPER (Europe/ESFRI Project), LIFE in USA, LIF_T in Japan, and other initiatives, are entering a new phase where is critical the integration of systems (lasers, target manufacturing and injection, chamber and blanket, tritium handling and power cycles). The decision to start studies for a Engineering Burst (in HiPER) facility with a very low repetitive laser operation, with simply hundreds to thousands of shots at 5-10 Hz rate in one run and no operation between those bunches, and small gain under continuous (24/7) repetition (Prototype) or final high gain Demo Reactor will be of critical importance. The comparative results performed in such HiPER project are a representation of what is the difference between Ignition+first proofs of repetition, and Power facilities.

It is important to consider the difference between Prototype and Demo, because the different target energy gains could have consequences in the first wall and optics. The Engineering Test Bed results will be able to demonstrate with the lowest risk**,** repetitive laser-injection systems in an already defined model of Chamber without blanket and tritium breeding. Assuming those conditions, it could be possible to accommodate Experiments in Technology relevant for Prototype and Reactor.

This paper shows the differences in designing an engineering chamber for repetitive shot operation in a non-power use (engineering), or power plant repetitive systems, centered into Chamber area, activation and damage in optics, wall and structural materials and also dose assessment. A summary of the differences in new designs from Engineering, Prototyping and Demonstration approaches will be the key goal. The IFE community by lasers is clearly conscious that in addition to demonstrate ignition using the different schemes, a long list of tasks are in addition needed and mentioned here above. However, the research already under way in those lines gives a clear possibility to run the programs such as it is proposed in HiPER (see **Error! Reference source not found.**) [1, 2, 3] or in approaches such as LIFE [4, 5].

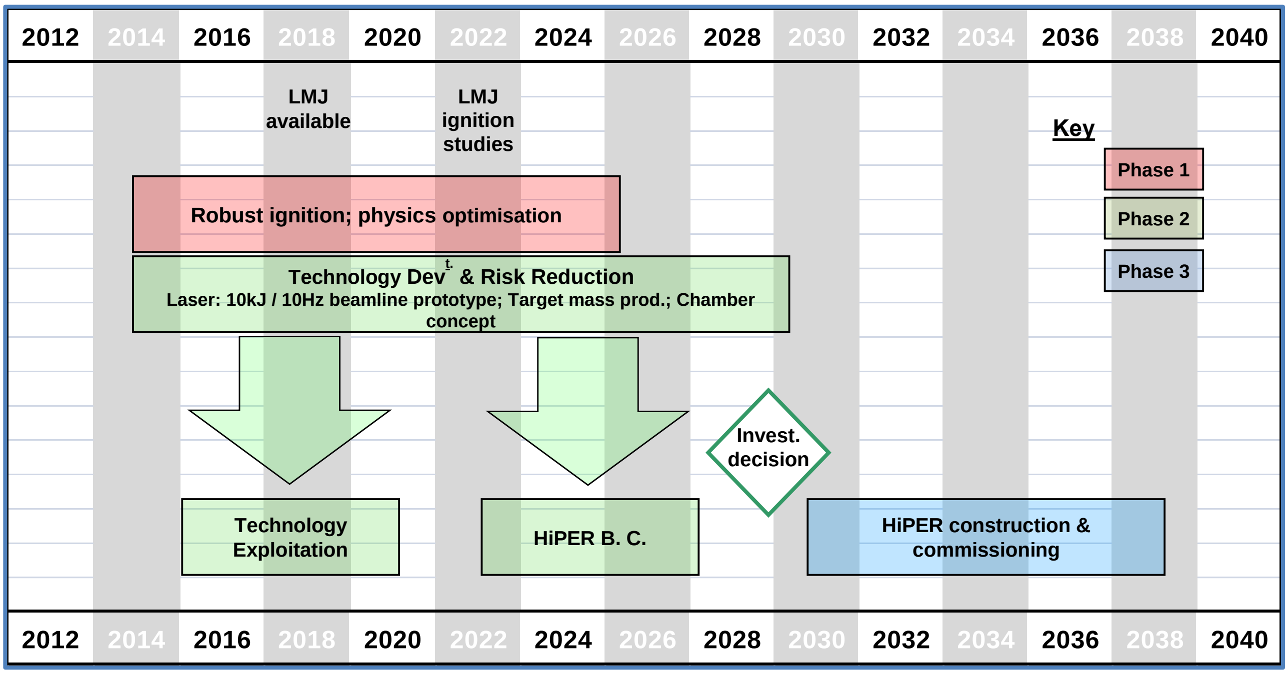

Figure 46: High level HiPER delivery strategy

The final tasks envisioned to be developed when making the transition from Ignition/experimental to Reactor/Power Plant systems includes:

- Target fusion performance demonstration under Shock Ignition (even that under no official HiPER policy, indirect drive effects can be pursued independently by some groups or countries to follow immediate demonstration of NIF targets)
- Diode based lasers (repetition)
- Mass production of targets at the required rate (repetition)
- Target injection and tracking (development of adequate systems depending on chamber atmosphere) (repetition)
- Fusion environment (repetition)
    - Laser beam propagation (study of under different protection schemes)
    - Protecting first wall (development of new advanced materials)
    - Materials to withstand ion flux and He implantation
    - Magnetic diversion of ions
    - Modular chamber (power plant with blanket assuming short or long standing in the power plant)
    - Final focusing optics (development of materials or strategies for protection)
    - Balance of plant

A list of systematic approach of tasks are needed, here described more in detail for HiPER: a) assessment of Target emissions from burn with more detail in the structures emerging from them; that also includes target survival and engagement depending on protection choice; b) knowledge of physics for damage in first wall materials and protection of the chamber walls and optics from debris ions, x-rays, alpha particles and shrapnel, that condition the advanced materials to select; c) provision of a lifetime suitable for commercial applications.

This implies work to be performed in both areas of Materials: resistant to irradiation and being of low/reduced activation minimizing the radioactive waste in the facility; d) effect of repetitive operation and the potential for re-setting the first wall protection after a shot to a level suitable to permit another shot to be undertaken; e) minimising the effect of first wall ablation or aerosol sputtering effects from posting increased challenges to the injection and engagement of a target; f) breeds tritium at a minimum breeder ratio of 1.1 to permit continued operation with minimum tritium; inventory. That also includes tritium transport (depending on coolant) and extraction with consideration of potential non desired diffusion or trapping in a full cycle of tritium facility; g) determination of energy deposition in the blanket (when blanket) and transport through coolant in the thermodynamic cycle; h) ensuring a good assembly of all systems in the Reactor including the Power Plant Cycle systems evaluation; i) radioprotection design of the different areas of the reactor HiPER in its different options (Shielding, penetrations and operation conditions depending of areas, including necessity of remote handling or potential personnel intervention in time intervals).

From that list, our Chamber design inside HiPER has started to identify key aspect correlated with experiments proposed for a near future. Neutron sources are necessary and proposals from presently designing ESS- Bilbao source is inside our scope.

23.2 Radiation Emissions from Target

The primary aspect to consider is which are the options in developing the Engineering and Proto or DEMO systems. There are different solutions in this moment that are partially represented in the following Figure 47 [6] for European and US strategy.

	Experimental facility	Prototype plant	Demo plant	LIFE.1	LIFE.2
Operation	Bunches of 100 shots, max. 5 DT explosion	Continuous (24/7)	Continuous (24/7)	Continuous (24/7)	Continuous (24/7)
Yield (MJ)	<20	<50	>100	27	132
Rep. rate (Hz)	1-10	1-10	10-20	16	16
Power (GWt)	-	< 0.5	1-3	0.4	2.2
T cycle	No	Yes	Yes	Yes	Yes
Blanket	No	Yes	Yes	Yes	Yes

Figure 47: HiPER development strategy and LIFE scenarios

The objective is to give a first idea of differences between the first (Experimental) and the second and third cases for HiPER. That is a clear example on how full repetitive operation for reactor is diverse compared with we can expect in experiments in burst with low repetition rate.

One key aspect that conditions the decision of type of Chamber technology is that HiPER is assuming a Shock Ignition Direct Drive that conducts to Dry Wall scheme instead of other options. However, LIFE is working with indirect drive target that allow some gas protection and LIF_T with fast ignition is demonstrating a low-pressure gas or maybe a magnetic protection. For this case of HiPER Shock Ignition, we present the energy spectrum of neutrons, X-Rays and charged particles emerging from target after explosion, which is our input for study.

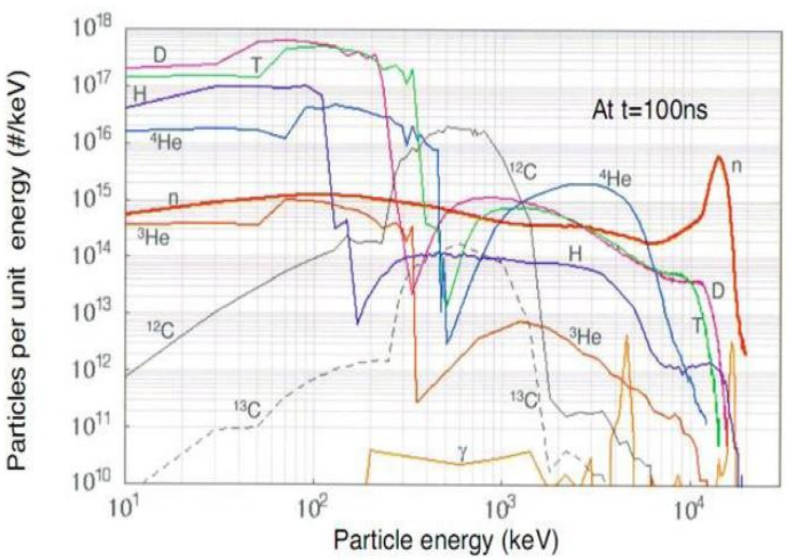

Figure 48: Neutron, Radiation and Ion emission from shock ignition target

23.3 Effects of Low Repetition in Burst Mode or Full Reactor Operation

There will be really different questions to define: how those emissions will propagate through the chamber atmosphere, which depends on the concept and the contents inside the chamber; and how those particles arrive on time to the wall. We escape from the consideration of neutrons that will do their work on the blanket in the reactor and they will need simply to be stopped adequately in the engineering low number of shots (activation and radioprotection).

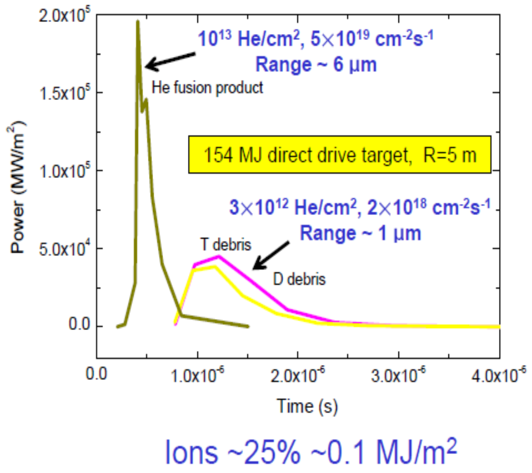

Figure 49: Power from Ion species in the wall at 5 m radius

The major threat to first wall materials subject to direct drive target explosions is due to energetic ions that carry nearly 30% of the total energy released by the explosion. Figure 50shows the deposited power by the most significant ions as a function of their time of flight to a wall located 5 m away from the target.

IFE ions produced by direct drive target explosions are very penetrating. In order to study effects on materials it is more meaningful to use the power density that accounts for radiation-matter interactions and allows one to compare both cases. When considering the burst mode, Fig. 4, the conditions for W as first wall could indicate that from Thermo-mechanical aspects such solution will be good including the release and retention of tritium in it [8, 9, 10]. From a **thermo-mechanical** point of view the adequate plasma facing materials must have good refractory properties and good resistance to fracture under irradiation (to avoid cracking).

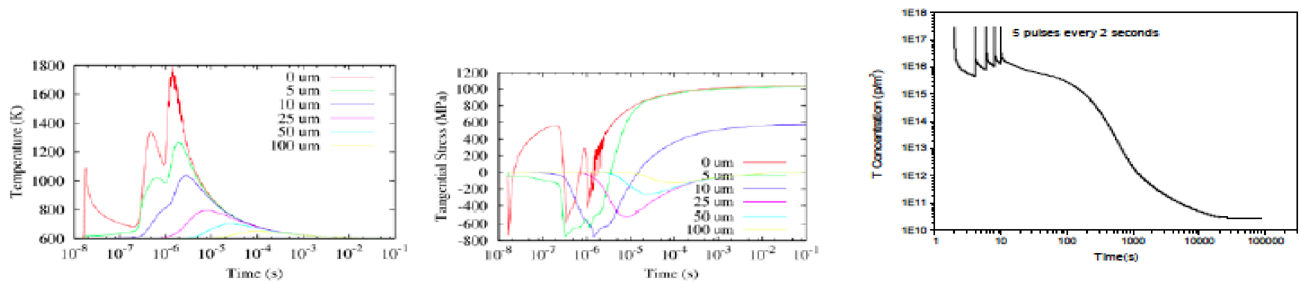

Figure 50: Temperature, Stress and Tritium retention in a Burst Mode operation

Severe cracking or mass loss are unacceptable, otherwise the protection role of the first wall would be lost. Studies on engineered 3D surfaces are being carried out. The idea is to increase the surface area and thus, minimize the deposited energy density in the material. Structures such as dendrites, needles and foams are promising provided their thermal conductivity remains high. W- and C-based materials could fulfill these thermo-mechanical requirements and are being considered for the first wall. The study and understanding of defect generation and evolution as well as its interaction with light species (D, T, He) is very relevant (clustering and bubbling which produce macroscopic effects such as swelling).

However, understanding these **atomistic effects** is not straightforward. W-based materials present a serious problem regarding He nucleation in vacancy clusters (origin of blistering with fatal exfoliation). This problem is common to both Magnetic and Inertial approaches. There are some evidences indicating that in Inertial Fusion with direct drive targets, fluences two orders of magnitude lower lead to similar effects. In both cases modelling of blistering is not trivial due to synergistic effects that take place (co-implantation, simultaneous trapping of different gas species). The atomistic effects must be considered to develop new materials. In fact, the atomistic effects will be the final bottleneck once the thermo-mechanical response of the materials is adequate. Strategies to minimize the nucleation of gases in vacancy clusters include: enhancement of porosity to facilitate the release of He and other light species and development of self-healing materials, e.g., nano-crystals in which vacancy migration to grain boundaries competes with vacancy clustering, leading to effective vacancy annihilation. The development of materials with these properties will be useful for both approaches, and a large program is developed at the Institute, including proposals for irradiation systems and characterization and development of materials [10, 11, 12].

When considering lens effects we know that the experimental facility will operate in bunch mode at room temperature, therefore, the lens temperature prior to the pulse arrival can be considered uniform. Important information is the deposited energy by neutrons and gammas in LIFE 2 and in HiPER prototype lenses that are quite similar, Table 2 [6]. On the other hand, the prototype and demo reactors will operate in continuous mode. Assuming for the prototype reactor a steady state situation the lens surface temperature will be 866 K and higher in the centre at the beginning of the pulse.

Disregarding ions, the major contribution to the temperature enhancement at depths ≤ 10 m is due to X-rays. The radiation-induced temperature enhancement as a function of time after one explosion at several depths underneath the lens inner surface is depicted in figures 5(a) and 5(b) [6] for the HiPER experimental and prototype reactor, respectively. The surface temperature increases 7 K for the experimental and 15 K for the prototype reactor. The temperature drops fast as a function of time after the explosion and as a function of the distance from the lens surface. The temperature gradient at depths ≤ 10 m disappear after 100 s and the temperature at a depth of 10 m increases only 2 K due to the heat transferred by conduction from the inner surface. In the case of the prototype reactor, the neutron and -ray contribution leads to a temperature rise of about 0.1 K per shot along the whole lens thickness.

This contribution is negligible for the experimental reactor. The temperature rise generates cyclic stress at the irradiated inner surface depths ≤ 10 m, see figures 5(c) and 5(d). The X-ray thermal shock increases the volume of the inner surface material generating compression stress, In the case of the prototype facility, figure 4(d), the initial traction radial stress due to the initial temperature decreases until compression values are reached at layers ≤ 0.5 m. When working in continuous mode, the average lens temperature increases if the energy deposited in one pulse is higher than that radiated by the lens surfaces. When both contributions balance each other, steady state is achieved. Assuming that the lens temperature equals the surrounding temperature (T_o = 600 K) before startup reactor, the steady state maximum temperature into the lens reaches 938 K for the prototype reactor and 1304 K for demo reactor, below and above the maximum silica service temperature (1223 K), respectively.

The steady state situation occurs after 32000 pulses for the prototype reactor and after 25000 pulses for the demo reactor. Note that in continuous mode the neutron and gamma contributions are very relevant since (ignoring ions) they carry most of the energy. The energy deposited by laser absorption is negligible (and therefore not considered here) because the high temperature reached in continuous mode keeps the optical absorption low. Therefore, even when disregarding ions, we conclude that silica lenses cannot operate under HiPER demo reactor conditions in the present configuration. A possible solution could be to use external coolers for the lenses or modify the configuration moving the final lenses further away from the chamber centre. Both possibilities imply a detailed study beyond the scope of this work [6, 13].

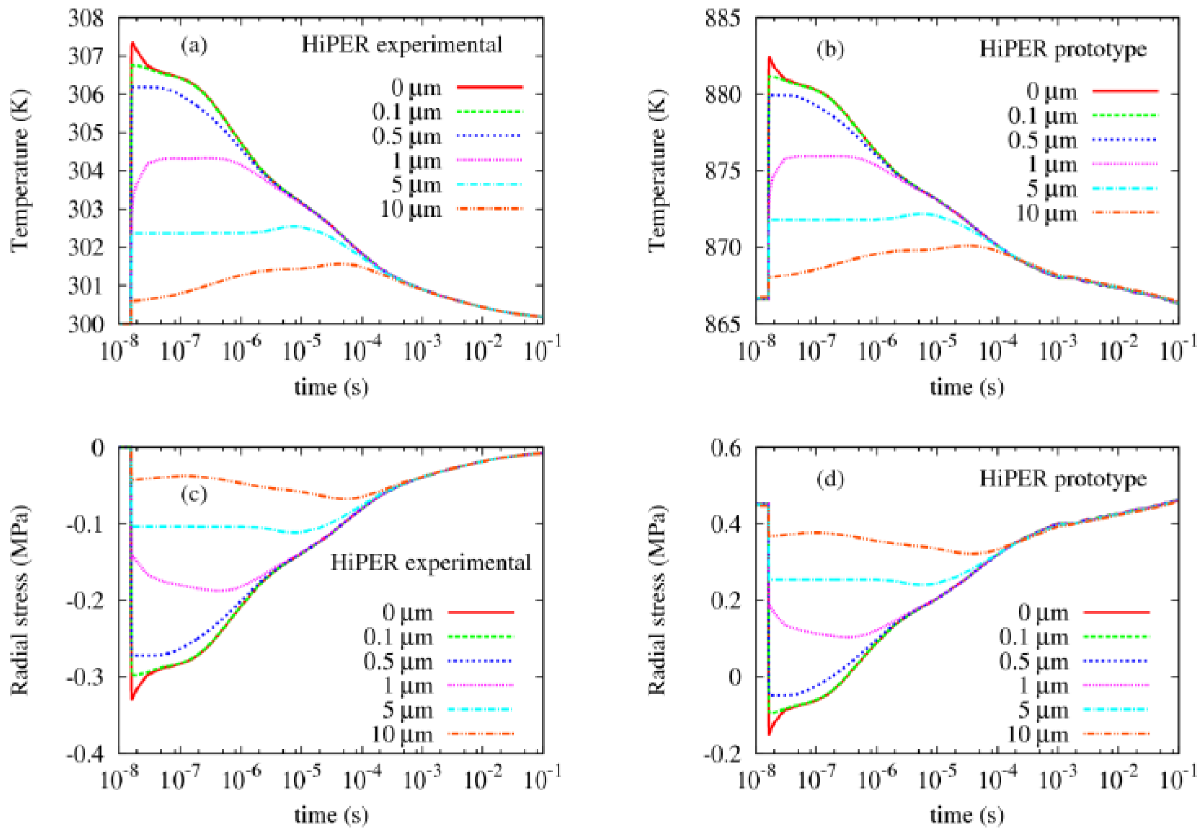

Figure 51: Final lens temperature as function of time after each explosion for different depths in the HiPER experimental facility (a) and in the prototype facility (b). Radial stress evolution at different depths for experimental facility (c) and for the prototype facility (d).

The final aspect that makes a large difference is that of assuming an experimental facility as that proposed under burst mode rather than full operation as a reactor from the area of blanket and design of components and systems [14, 15, 16, 17].

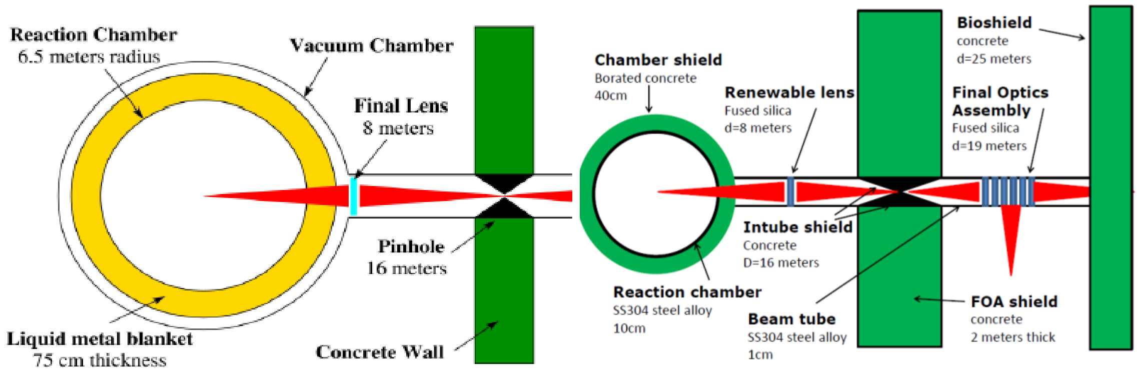

Figure 52: Structure of Reactor (left) and burst mode operation system

In the case of an experimental facility our goal has been to design a full system with most operative possibilities for experiments and diagnosis and proof of systems in a non-continuous operation. The result is that our work, following that input given by the laser allocation and remote handling teams, is related essentially to know the neutron and gamma effects from the aspects of activation and radioprotection. Damage is low enough and operation simple to react to consequences with present materials and no heat recovery and tritium breeding is needed what indicate no blanket design, see Figure 52. In the case of Power Plant / reactor we need essentially consider the full design of blanket, including tritium recovery and power plant cycles.

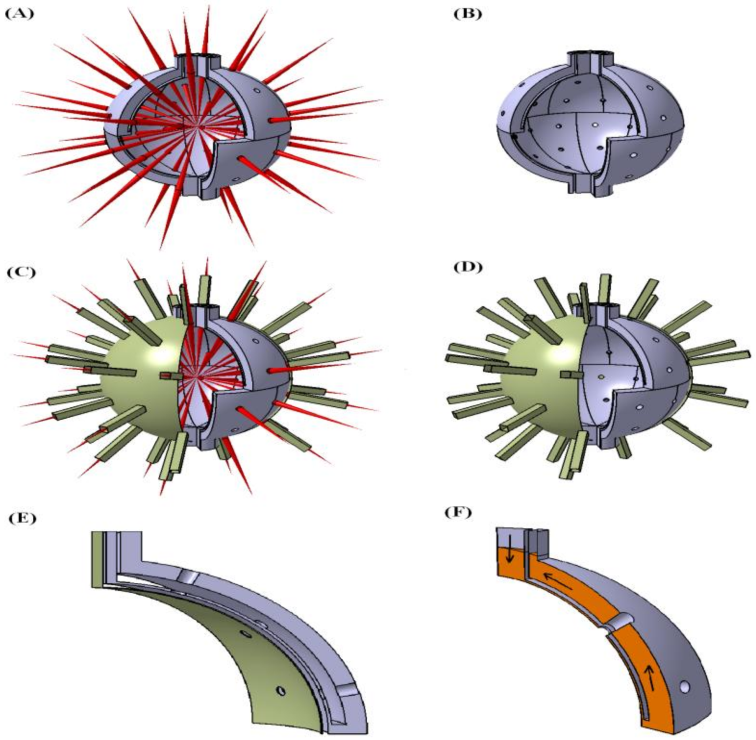

Figure 53: Proposed blanket for HiPER

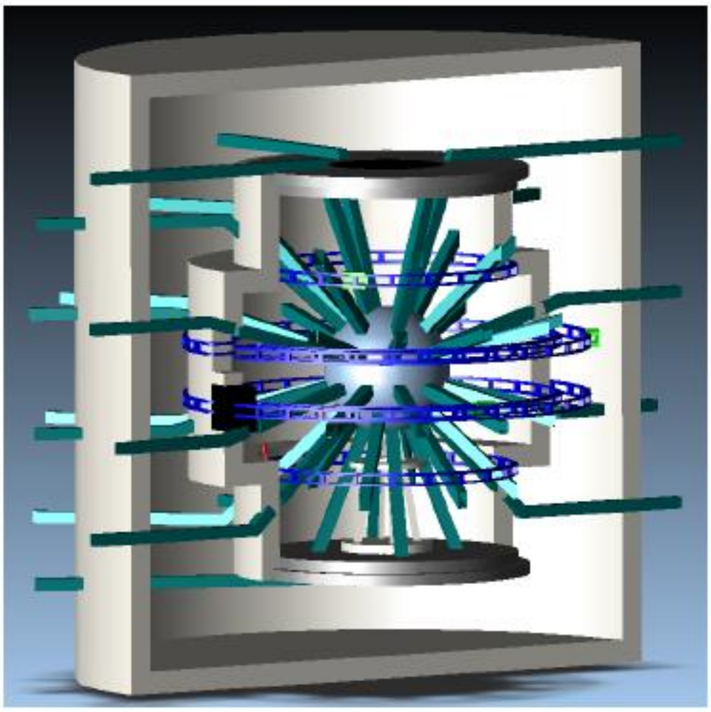

Figure 54: Conceptual design of HiPER chamber (burst mode)

	Thin blanket	Thick blanket
Tritium breeding ratio	1.1	1.1
Inner ch. thickness	8 cm	8 cm
Outer ch. thickness	42 cm	67 cm
LiPb volume	310 m^3	475 m^3
6Li enrich.	75%	25%
$\eta_{blanket}$	1.04	1.09
TBR range	0.66-1.21	0.89-1.36
T p. pressure	3 mPa	3 mPa
T inventory	54 mg	83 mg
^{210}Po DRC	4140	18110
^{203}Hg DRC	11.6	12.3
VV dpa @ 40y	50	17
VV thickness	52 cm	39 cm

Table 2: HiPER reactor blanket parameters

A full design is done for HiPER Engineering with a clear vision of operation and neutron gammas transport identifying the areas allowed for operation critical in that machine.

In the case of a full reactor we tackle the neutronics and activation studies and power cycle of a preliminary reaction chamber based in the following technologies: unprotected dry wall for the First Wall, Self-cooled Lead Lithium blanket, and independent low activation steel vacuum vessel. The most critical unfixed parameter in this stage is the blanket thickness, as a function of the ^{6}Li enrichment. After a parametric study, we select for study both a “thin” and “thick” blanket, with “high” and “low” ^{6}Li enrichment respectively, to reach a TBR=1.1.

Prompt Dose Rate

	Zone 1 *Sv/yr*	Zone 2 *Sv/yr*	Zone 3 *Sv/yr*
Neutrons	$3.46 \cdot 10^5$	32.9	$1.69 \cdot 10^{-7}$
Gammas	$8.70 \cdot 10^5$	0.63	$1.88 \cdot 10^{-6}$
Total	**$3.55 \cdot 10^5$**	**32.6**	**$2.05 \cdot 10^{-6}$**

Limit for workers (ICRP): 20mSv/yr or 10μSv/h

Exclusion area during operation

Standing allowed area during operation

Figure 55: Response for Radioprotection of HiPER in Burst Mode

To help to make a choice, for both blanket options, we compute, in addition to the TBR, the energy amplification factor, the tritium partial pressure, the ^{203}Hg and ^{210}Po total activity in the LiPb loop, and the vacuum vessel thickness required to guarantee the re-weldability throughout its lifetime. The thin blanket shows a superior performance in the safety related issues and structural viability, but it operates at higher ^{6}Li enrichment. However, the vacuum vessel shows to be unviable in both cases, with the thickness varying between 46 and 59 cm. Further chamber modifications, such as the introduction of a neutron reflector, are required to exploit the benefits of the thin blanket with a reasonable vacuum vessel.

23.4 Appendix VII References

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