

12 Fusion Reactor Design and Technology

12.1 Introduction

An essential aspect of the HiPER project will be to ensure adequate progress in the development of the engineering and material technology required for a subsequent IFE power production programme. This will require close coordination with the international community, as well as with the MFE and advanced fission communities, given the scale of the tasks.

A list of potential experiments in the HiPER facility concerning the assessment of Fusion Technology (relevant for future DEMO IFE reactors) is presented on the basis of a review of previous work on Inertial Fusion Reactors (Fast Ignition / KOYO-F, and central ignition).

A detailed overview of prior work on IFE reactor designs is provided in APPENDIX 1, as are the references and acknowledgements for contributions to this section.

A number of conceptual reactor designs have been developed over the past 20 years. In some cases small experiments have been performed to investigate aspects of the basic physics that support the proposed technologies. In this section we highlight the work performed (mainly in Japan) on a fast ignition variant of a commercial IFE reactor, called KOYO-F. An important aspect of the HiPER project will be to catalyse a renewed, coordinated international effort in the reactor design and technology areas. The facility itself needs to be able to address key issues associated with the emerging design requirements. Analysis of the relevance of these experiments and consequent simulation will be a key task in this Preparatory Phase.

HiPER will provide essential data for IFE in areas of Fusion Technology (in addition to targets or lasers themselves), such as:

- Target chamber phenomena and materials response to target emissions (x-ray, ions, neutrons)
- Prototypical IFE fusion power technologies in the chamber area
- Performance testing of IFE target fabrication and injection methods.

HiPER can thus play a critical role in providing the basis for design of the follow-on “demonstrator reactor” in these areas.

12.2 Examples of Fusion Technology Experiments

Using a well established radiation output from a HiPER fusion target, beneficial knowledge of future technologies could be obtained. For example: nuclear heating, transport and activation, tritium management, IFE materials science, and safety/environmental issues. This would provide early experience in prototypical IFE fusion power technologies. The main impact to consider is their contribution to the total HiPER shot envelope and allowed chamber activation, along with all other user-group shots.

Preliminary proposals include:

- Experimental investigation of the relation between capsule performance and injection acceleration methods
- Time-resolved measurements of radiation-driven shock velocities, multiple shocks (etc) in high gain materials.

- Precision x-ray vaporization experiment
- First-wall material response experiment
- Chamber gas-dynamic and wall-stress experiment
- Many different material source and debris/shrapnel calibration experiments
- Integral activation measurements in IFE neutron spectrum
- Measurement of attenuated neutron streaming up beam ports (with plugs)
- Studies in pulsed-neutron activation analysis
- Irradiation effects on optical fibres
- Benchmarking multi-scale modelling calculations of neutron damage of low-activation materials
- Radiation damage of optical and structural components in HiPER itself or for DEMO IFE facilities
- Debris damage to first wall materials
- Thermo-mechanical damage of optical and structural components
- Tritium removal from molten salt in small testing close samples in some adequate position
- Mini-blanket benchmark experiments
- Feasibility of neutron-multiplying target chamber walls for ICF reactors
- Benchmarking neutron activations of out-of-chamber components and penetration shields for IFE reactors
- Radiation damage limit of new materials for shielding IFE reactors
- Induced radioactivity and biological dose measurements
- Nuclear heating measurements
- Sensitivity of capsule performance to fabrication quality (of course this aspect is general in HiPER but we include here because it is certainly a key aspect for future IFE commercial technology)
- Sensitivity of capsule performance to beam pointing accuracy (of course this aspect is general in HiPER but we include here because it is certainly a key aspect for future IFE commercial technology)
- Target injection (different methods)
- Neutronics experiments under prototypical conditions to IFE are a key issue with two principal objectives: (a) To provide a sufficient experimental database to permit approval and licensing of an IFE device, (b) Verification of the predictive capabilities of various computational codes and associated materials databases in assessing the nuclear performance of various reactor components. This will allow a quantification of the design margins and safety factors to be implemented in future IFE blanket and shield design (system-dependent).

It is noted that a number of the above issues are common to the MFE programme (i.e. associated with the ITER facility). The detailed issues are different – for example, the neutrons generated in the plasma of MFE devices and incident to the first wall / blanket / shield have different angular/energy distributions than those generated in IFE devices and hence different design margins are anticipated. As such, the proposed experiments can be broadly classified as (a) experiments that

validate generic nuclear response and (b) bulk and penetration shielding experiments. Coordination and direct combination with the work associated with MFE is a key objective of this task.

An economics study associated with many of the above issues (as with bulk target manufacture) is also required.

12.3 Chamber Gas Dynamics

For the option of solid first walls with some gas protection (see appendix for details), the goal will be to determine efficacy of chamber gas fill to mitigate debris and soft-x-ray ablation, and its compatibility with laser beam propagation and with cryogenic targets.

IFE benefit: Improves viability of IFE reactors concepts.

Impact on HiPER: Compatibility with cryogenic targets, diagnostics, laser propagation.

The issues to be addressed here can be performed on any suitably configured ignition facility. The discussion below is taken from discussions associated with potential experiments on NIF. There will be specific issues associated with the direct (laser) drive and fast ignition options for HiPER which will need dedicated assessment to suitably inform the design of a future IFE plant. Laser driven fast ignition targets will have different debris production, different x-ray, ion and neutron spectra and fluence, and different sensitivities to their environment.

The measurement of the time at which the chamber conditions recover after a shot to allow injection of the next target and the entrance of the driver beams for the next shot is a key factor in determining an IFE chamber "clearing time. Some of the phenomena important to the clearing time can be studied in the HiPER chamber with an initial gas fill low enough to allow beam propagation without having to provide large pumping (we assume it is not important to pump the gas down to a high vacuum).

The magnitude of (and inhomogeneities in) the gas number density can adversely affect the propagation of the driver beams, especially if the beams enter the chamber prior to the time density inhomogeneities can smooth out. The clearing time of an IFE chamber is important because it establishes the maximum repetition rate of the chamber, which can limit the economical advantages of IFE. It is also important to determine the stress history on the first wall and its higher-order moments. The maximum stress is affected by the number of times that shock waves reverberate between the first wall and the centre of the chamber, and especially by the 3-D aspects of the stress. Both of these effects are dependent on chamber geometry (especially symmetry). The (3-D) higher-order moments of the stress can be critical to the design of the chamber, and are difficult to calculate. The gas-dynamics experiments are thus important in determining the design of the first wall for IFE, especially if smaller chambers will be considered, for their thicknesses are dominated by stress considerations and not by buckling.

Protection of the final optics from soft x rays, plasma debris, and small projectiles is critical for affordable operation of the any laser based IFE facility. However, there has been only limited research both theoretically and experimentally to assess the real impact of these hazardous target emissions. Certainly the experience to be gained from Ignition Facilities such as NIF and LMJ will be critical.

Preliminary proposals for experiments in this area include the investigation of different target chamber gas fills, and the analysis of target-generated fireballs and laser induced breakdown with dense fill gases. For example:

- **Chamber dynamics and clearing time.**

Measure the time history of conditions relating to the gas dynamics and fireball behaviour inside the target chamber for various gas-fill pressures, including the reverberations of accompanying shock waves and the establishment of the late-time thermalized pressure $P(t)$. This objective will determine many aspects important to the clearing, or recovery time in an IFE chamber. This objective will also determine the pressure above which fireballs are evident, and the effective opacities of the gas at relevant fireball conditions.

- **Final optics and wall erosion.**

Assess the erosion hazard to first-wall, final optic materials from target x rays, plasma debris, and particulates as a function of fill gas pressure. This objective requires varying the fill pressure and noting the differences in the erosion rates for various wall and optical materials placed inside the chamber. It requires deployment of diagnostics to measure the prompt momentum transfer (ablation impulse) to the first wall and to the final-optics surfaces. It is also desirable to measure the history of the average wall stress, and to correlate the average stress with the calculated stress history inferred from the measured ablation impulse and the measured $P(t)$ from the above experiment. It is also desirable to measure the nonuniformity of peak wall stress as a function of wall position, and thereby assess the importance of higher-order moments in the peak wall stress history arising from the 3D nature of the chamber wall (e.g., the chamber ports).

- **Driver beam transport.**

Help assess the optimum gas-fill pressure for laser beams, and measure the decay of ionization in ambient gas versus time, important to the study of ion beam transport in various pressure regimes. This objective requires diagnostic deployment to determine the loss of laser irradiation because of SRS, and to analyze the transient temperature, pressure, and density conditions measured above at times many-tens of milliseconds after a shot. For ion beams, this objective does not require the use of such beams; instead, it requires the assessment of the impact of the dynamical conditions inside the chamber on the transport (propagation, neutralization, etc.) of the ions as inferred through additional analyses.

- **Impact on cryogenic targets.**

Measure the impact (especially thermal load and condensation) of a gas fill on a cryogenic target. This objective requires (1) measurement of the buildup of sublimed Ar on the target materials, (2) assessment of the impact of this buildup on the energy-delivering capability of the driver beams, and (3) determination of the added thermal load on the cryogenic cooling systems.

12.4 Liquid Interactions

The goal here is to provide data on disruption of both liquid jets and liquid film layers by neutrons and X-rays for protected-wall IFE concepts such as HYLIFE-II (see Appendix).

IFE-benefit: Extends IFE fusion chamber lifetimes with renewable liquid-protected walls.

Impact on HiPER: Liquid debris ejected into chamber, impact on cleanup system.

Specific Preliminary Proposals include:

- Stability of liquid metal curtains due to shock-wave interaction (splashing)
- Response of first-wall tubes due to target blast
- Condensation effects

- Ablation, gas dynamics, and condensation experiments for IFE
- Isochoric (neutron) heating effects
- Blast effects on film protectant thickness and stability
- Film/substrate interactions due to blast impulse
- Damage rates at dry spots on film protected surfaces

In some of the presently proposed concepts for IFE reactors a protective liquid metal film such as liquid lead is renewed between shots by seeping through a porous structural wall in front of a solid breeding blanket. In others, a liquid lead eutectic or molten-salt coolant is channelled through porous tubes or loose-weave cloth-like channels, with the outer surfaces maintaining a protective liquid film layer. In HYLIFE-II, neutronicly thick jets of molten-salt “FLiBe” are used to protect structural walls from neutrons as well as target x-rays and debris. Some issues common to all of these concepts are the effects of isochoric (constant volume) neutron heating generating transient internal pressures whose subsequent relaxation can cause rapid expansion motion, the effect of surface shocks on the liquids due to soft x-ray ablation and debris, the generation of momentum due to the above effects propelling liquid droplets and jets, the effects of recondensation of vapour back onto the remaining liquid, and the recovery times to re-establish the desired liquid flows after disruptions from each shot (different in each case). Data from these experiments are generally used to benchmark various computer models of these interactions important to future IFE power plant designs. The objective of the Liquid Interactions Experiment is to provide a common experimental test envelope, common diagnostic set, and liquid containment/clean-up for all those experiments with liquid interactions so that the HiPER impacts in the chamber are considered within this one common envelope. The required doses of x-rays and/or neutrons could be varied as required for each test either by adjusting the distance between the target and the sample at fixed yield (e.g., at 20 MJ baseline yield, by varying the distance to target from 0.2 m, to 1 meter, or by varying the target yield.

The major HiPER impact issue with all such experiments is associated with the management of significant quantities of liquids and their condensable vapours which may be released into the chamber. Of particular concern is both the potential condensation of liquids on the final optics and diagnostic windows, compounded by the neutron activation of such materials. The selection of liquids used in experiments to simulate liquid interactions expected in an IFE environment should be first tested for compatibility with the cleanup system. Nonetheless, the less liquids and condensable vapours released, the faster the cleanup will be. Thus, the experimental envelope need to be designed to intend to minimize the release of such condensable and liquids by several methods: 1) Use of a frost-coated window for experiments on the effects of isochoric neutron heating only, providing enough volume within the enclosure to completely and safely contain the liquids vapour pressures generated within the enclosure. 2) Use of fast-closing shutter, which can trap most of the slower moving liquid splash, for experiments that need shots with an initially open aperture for combined x-ray, debris and neutron doses. 3) Use of an internal baffle and cold-trap to rapidly decrease condensable vapour pressures inside the enclosure, mitigating the expulsion of liquids and vapour out the entrance aperture. 4) Combined use of the common liquid experiment enclosure with some proposed cryogenic *mini-chamber* so that exhaust from the common liquid experiment enclosure can be cold trapped within the *mini-chamber*.

12.5 High-repetition rate chamber

The goal of this series of experiments is to provide relevant simulations of protected-wall IFE chamber clearing for single shot and multishot bursts. This would be performed by inserting an overcoated mini-chamber scaled in size to about 100 J/cm^2 wall fluence. The concept of a “Mini-Chamber” is an old idea given in the references of Tobin and Logan where a review of potential experiments for NIF relevant for IFE is done and essentially used here in many aspects due to the close involvement of one of the HiPER partners (UPM) in this study. Another chamber for multishots as programmed in HiPER would perform similar goals including this original minichamber inside.

IFE benefit: Determine gas-dynamic constraints on maximum IFE chamber pulse-rate.

Non-IFE benefit: May allow higher-yield shots with reduced debris-loading on optics.

Impact on HiPER: -about 1 m diameter internal chamber; stagger-firing of laser sections for hi-rep.

The goal of this experiment is to provide a relevant simulation of protected-wall IFE chamber clearing with single shot and multi-shot bursts using $\sim 1 \text{ m}$ diameter, vented minichambers surrounding targets inserted inside the HiPER target chambers. The minichambers would be supported independent of the target positioner on a rigid vertical column, entering the chambers through the bottom 2 m port in the existing NIF design. The size of a reusable minichamber would be scaled down to increase the mini-chamber wall energy deposition due to debris, soft x-rays, and neutrons from the typical level of 1 J/cm^2 at the HiPER target chamber wall at 5 meters radius (as with NIF), to a higher $\sim 100 \text{ J/cm}^2$ wall fluence more representative of protected-wall IFE fusion chambers.

To simulate chamber clearing and vacuum recovery from vaporization of renewable solid and liquid materials protecting walls in IFE concepts, mini-chamber structural walls would be coated with sacrificial coatings or films of materials such as frost or vaporizable solids chosen to simulate transient conditions relevant to IFE. Different mini-chambers can be designed for different targets, including single-shot experiments with high-yield ignition targets, as well as smaller chambers for short 5 Hz bursts of injected foil or disk laser non-ignition targets designed to simulate clearing in a high-pulse rate IFE chamber. The multi-shot experiments would require the capability to stagger-fire different sections of the laser system at 200 ms intervals (or make direct use of the high repetition rate HiPER option, if selected). HiPER would thus be a first step in encountering high-rep-rate challenges of IFE. The mini-chamber experiments complement small-sample wall material experiments by addressing integral chamber dynamic responses at both an IFE-relevant energy fluence and in an IFE-relevant enclosed geometry, which includes important effects of venting and condensation back onto the walls. The single-shot experiments would determine most of the gas-phase dynamics needed to determine basic chamber clearing rates and momentum transfer to structures and liquids, while the multi-shot experiments would include wall ablation changes due to the redeposition of hot condensates from recent previous pulses.

Specific Preliminary Proposals include:

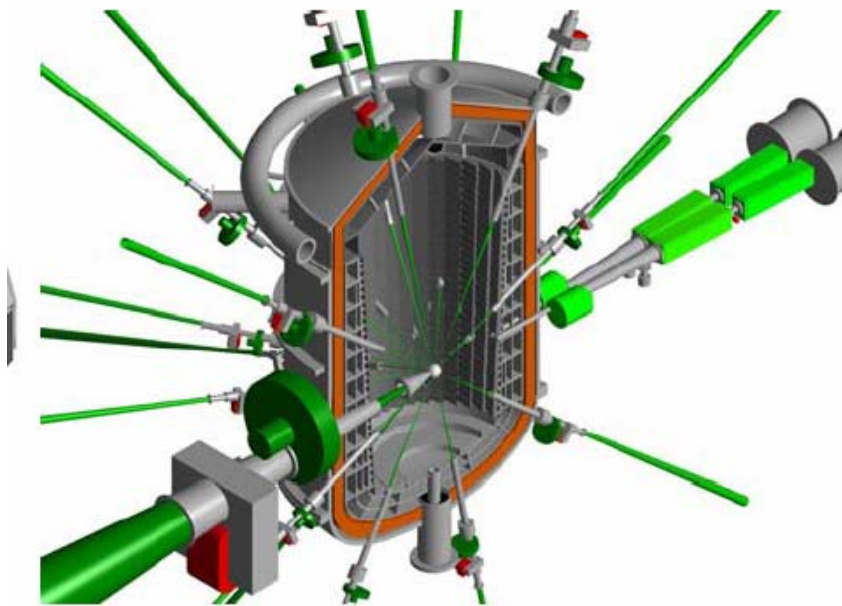
- Study effects of post-ignition chamber conditions on injected targets
- First-wall condensation experiment
- High-rep-rate target chamber dynamics experiment/frosted minichamber for debris-trapping
- Performance evaluation of the cavity during self-clearing
- Evacuation of noncondensibles from cavity
- Chamber conditions after a shot

12.6 Fast Ignition reactor conceptual design

The KOYO-F conceptual reactor proposed by the Institute of Laser Engineering (ILE) of the University of Osaka is based on a laser with 32 beams for compression and one heating beam (Norimatsu et al.). This is presented here to illustrate a potential extension of the Fast Ignition approach to the reactor scale. Many technology issues need to be addressed during the next phase of IFE development. This will require close international coordination.

	Compression laser	Heating laser
Wave length	3ω	1ω
Energy/pulse	1.1 MJ	100 kJ
Pulth width	TBD	30 ps
Pulse shape	Foot pulse + Main pulse	Flat top (2 ps reise time)
Beam number	32	1 bundle
F number	depends on plant design	$F/10 \sim 20$
Uniformity	1 % (foot pulse)	-----
Spot size	Controlled focusing pattern	$\leq 50 \mu\text{m}$
Rep-rate	16 Hz	16 Hz

Typical requirements for a Fast Ignition reactor

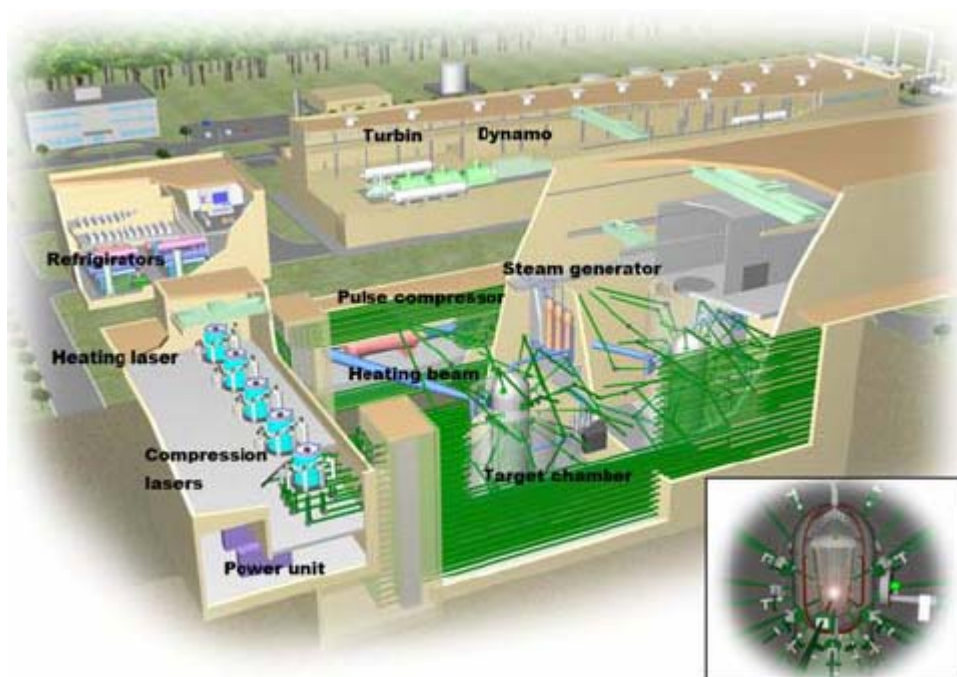


Cross-sectional view of the KOYO-F fast ignition reactor (Norimatsu et al.)

The reactor proposes a Cascade surface flow with mixing channel in order to protect the wall, using SiC panels coated with wetable metal in such a way that tilted first panels make no stagnation point of ablated vapor. In order to have a synchronized system it is proposed to use compact rotary shutters with 3 synchronized disks. The surface flow is mixed with inner cold flow step by step to reduce the surface temperature.

Net output	1200 Mwe (300MWe x 4)
Laser Energy	1.1 MJ
Target gain	165
Fusion output per pulse	200 MJ
Pulse rep-rate in reactor	4 Hz
Blanket energy multiplication	1.2
Thermal output per reactor	916 MWth
Total output at plant	3664 MWth (916 MWth x 4)
Thermal to electricity efficiency	41.5 % (LiPb temperature 500C)
Total electric output of plant	1519 MWe
Laser efficiency	11.4 % (Compression), 4.2%(heating), Total 8%(including cooling power)
Rep-rate of laser	16 Hz
Recirculating power for laser	240 MWe (1.2 MJ x 16 Hz / 0.08) (Yb-YAG laser operating at 150 - 220K)
Total plant efficiency	1200 MWe (1519 MWe- 240 Mwe-79MWe Aux.)

Basic specification for KOYO-F



Bird's eye view of the KOYO-F reactor design (Norimatsu et al)

Some conclusions from the ARIES integrated IFE reactor studies (Najmabadi et al.) that are very significant for assessing the HiPER studies in Fusion Technology were:

- The detailed characterization of the target yield and spectrum has a major impact on the chamber
- It is better to use a thin armor instead of a monolithic first wall for dry-wall concepts;
- In this case of dry-wall concepts with direct-drive targets, the most stringent constraint is imposed by target survival during the injection process
- For relatively low yield targets (250 MJ), an operational window with no buffer gas may exist.
- For dry-wall concepts with indirect-drive targets, a high buffer gas pressure would be necessary that may preclude propagation of the laser driver and require assisted pinch transport for the heavy ion driver;
- Generation and transport of aerosols in the chamber is the key feasibility issue for wetted-wall concepts.