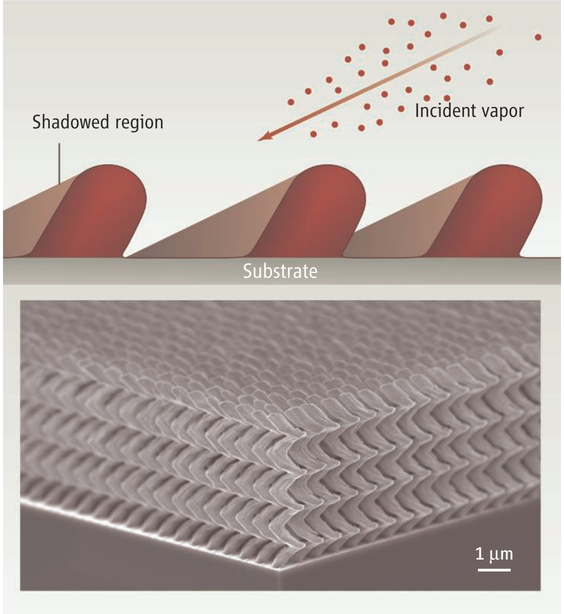

Oblique strategies. (**Top**) A conceptual view of column growth. Incident vapor atoms are blocked from the shadowed regions by the developing columns. As a result, deposition is restricted to the tops of the nuclei, which grow toward the vapor source. (**Bottom**) Scanning electron microscope image of a microstructured surface. By rotating the substrate, silicon columns have been sculpted into a square spiral configuration. Such an arrangement is useful for photonic crystal devices.

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microstructures with GLAD also leads to novel devices. For instance, there is an obvious visual similarity between a film of helical columns and a bed of springs. The microstructured helices also exhibit the mechanical spring behavior of their macroscopic counterparts (*9*). Electrically controlled squeezing of microhelices has been elegantly demonstrated. By passing a current through cobalt-coated silicon helices, Singh *et al.* induced an attractive force between adjacent coils and compressed the structure (*10*). Dice *et al.* sandwiched helices between aluminum layers in a parallel-plate capacitor arrangement (*11*). Charging the plates creates an electrostatic force and squeezes the microsprings. The ability to actuate such small structures could find use as stand-alone resonant devices or when integrated into microelectromechanical systems (MEMS).

The GLAD process allows the fabrication of submicrometer columnar structures over a macroscopic area in a single processing step. Because the nucleation process is stochastic, the columns grow randomly over the surface. For the majority of applications, it is not detrimental to have randomly arranged columns. Certain devices, however, have stringent requirements on column location and uniformity. In the three-dimensional photonic crystal architecture proposed by Toader and John (*12*), identical square spiral columns must be arranged in a tetragonal lattice. To defeat the randomness inherent in the nucleation process, the substrate is patterned (via lithographic techniques) with a seed nuclei template before deposition. Properly spaced, these seeds initiate the shadowing process and columns grow at the seed site only (*13*, *14*). Control over the planar arrangement of columns is therefore achieved, as is greater uniformity among the columnar structures (see the figure, bottom panel). Following this procedure, Jensen and one of us (M.J.B.) demonstrated the existence of a three-dimensional photonic band gap in the important telecommunications window near the infrared 1.6-µm wavelength (*15*). With GLAD, we can precisely fabricate complex structures over large areas, making it competitive with other photonic crystal fabrication techniques.

A major advantage of the GLAD process is its compatibility with many materials. Dielectrics, metals, semiconductors, and organic materials capable of fabrication by physical vapor deposition are suited to the GLAD process for engineering microstructure. However, applications requiring high surface area and porosity can make use of the many materials generated by simpler chemical means. GLAD will find its niche in devices requiring both a porous material and a precisely engineered microscale architecture.

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PHYSICS

Complexity in Fusion Plasmas

Peter A. Norreys

Images of imploding fusion plasmas reveal complex electric and magnetic field structures.

The November 2007 report by the United Nations Intergovernmental Panel on Climate Change concluded that the changes in climate worldwide were most likely due to rising greenhouse gas emissions. Strategies are urgently needed to reduce these emissions, and there is a clear need for nonpolluting, environmentally safe alternatives to the burning of fossil fuels for electricity generation. One possibility is fusion energy, where the by-products of the thermonuclear reaction are helium and neutrons. Among the proposals for fusion energy, reactions in laser-compressed plasmas have garnered substantial attention and resources. The plasma produced this way, however, can be complex and unstable. On page 1223, Rygg *et al.* have found a way to make detailed images of the density and electric field structures in these extreme environments (*1*), information that is necessary for better control of the reactions.

Research over the past 50 years has shown that achieving energy gain from fusion reactions (that is, more energy out than in) is a lot more difficult than was originally envisaged. The principal reason is that the fusion fuel has to be heated to

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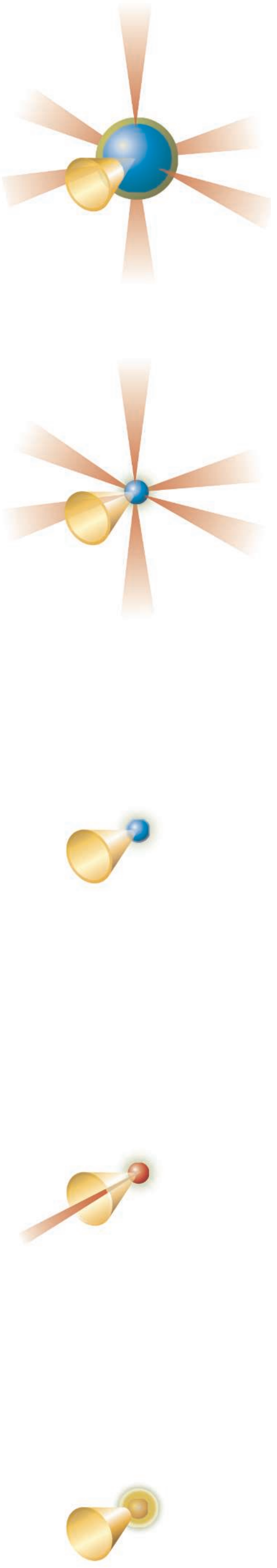
temperatures of a hundred million degrees centigrade so that the ions have sufficient kinetic energy to overcome the repulsive electrostatic barrier and their nuclei can fuse. The combined mass of the fusion products is lower than that of original fuel, and the difference is given out as kinetic energy of the fusion products.

Clearly, no vessel can withstand these temperatures, so the fuel has to be confined in some manner to prevent contact with the reactor walls. One method is to confine the fusion fuel at relatively low densities by means of strong magnetic fields for a long time—the magnetic confinement fusion approach (*2*). An alternative, inertial confinement fusion, relies on the compression of a hollow, millimeter-sized shell containing the fusion fuel to ultrahigh densities, either directly with a symmetrical array of nanosecond-duration laser pulses (*3*) or indirectly by placing the shell inside a radiation cavity, converting the laser energy to soft x-rays, and using that radiation to drive the implosion (*4*). One can think of these two alternative approaches to fusion energy as being analogous to the conventional furnace and the internal combustion engine.

At the start of the laser pulse in direct drive, the electric field strength at the surface of the pellet is enormous—many millions of volts per centimeter. The material is ionized within one or two oscillations of the laser electric field. The ionized electrons and ions—or plasma—are heated to millions of degrees centigrade, and pressures of millions of atmospheres are generated. The plasma then rapidly expands into the vacuum, and momentum conservation demands that the shell starts to implode—the rocket effect. Eventually, the internal pressure prevents further compression of the fuel (at the stagnation point) and a fusion burn ignites and propagates through the compressed fuel.



Fast ignition. In the fast ignition approach to inertial confinement fusion (from top to bottom), symmetrically arranged lasers first compress the spherical fuel target to high density. Then another laser focused on the tip of a gold cone generates energetic electrons that heat the hot spot in the compressed fuel to ignition temperatures.

The direct- and indirect-drive approaches rely on ignition by a central spark generated by the collapse of a number of accurately timed shock waves at the center of the fuel at stagnation. Matter is heated to higher temperatures behind the shock front, and thus a considerable amount of energy is needed to compress the material to the ultrahigh densities needed for fusion energy gain.

"Fast ignition" is a less mature approach but has received considerable worldwide interest since it was first proposed by Tabak *et al*. (*5*). The scheme allows the separation of fuel compression and the heating of the spark region to ignition temperatures (see the figure). It relies on the generation of a large number of MeV electrons when a petawatt laser pulse is focused into the tip of a cone placed very close to the stagnation point (*6*, *7*). The fast electrons do not have far to propagate, and they heat the matter to the ignition temperature so quickly that the plasma does not have time to respond.

The real beauty of the idea is that the symmetry requirements are relaxed and higher gain can be obtained for less drive energy. However, the exact degree of uniformity needed for the compression of the fuel for direct-drive fast ignition remains an issue. In their remarkable new observations, Rygg *et al.* have compressed cone-attached hollow shell targets. They used 36 beams of the OMEGA laser facility at the University of Rochester to drive the implosions. Radiographs were made using monoenergetic proton fusion products generated in a second implosion target, placed 1 cm away. They unequivocally show that magnetic field structures of 60 T are generated between the ablation front (where the material is evaporated) and the critical density surface (where the laser energy is either absorbed or reflected), with a modulation period of ~150 μm. They also show for the first time that there is an electric field generated as a result of a pressure gradient near the ablation front.

The authors attribute the magnetic field structures to a hydrodynamic instability that is seeded during the early stages of the implosion (caused by plasma density variations) or to the development of instabilities caused by heat flow. It is not clear at this stage which is the answer; more experiments are needed to clarify the generation mechanism. If the magnetic field is due to the early stage hydrodynamic instability, then the new method of "adiabat pulse-shaping" may be able to mitigate the effects (*8*). This new method has recently been shown to work for fully symmetrically irradiated targets. The idea is to irradiate the pellet with a short, intense laser pulse that creates a shock that propagates through the outer shell but whose strength decreases as it progresses. It has the effect of lowering the ablation front density while increasing the ablation velocity and shell thickness, thereby reducing the growth of the hydrodynamic instability. If the heat-flow instabilities are the cause, then other solutions must be considered. Whatever the outcome, Rygg *et al.* have developed a powerful new tool to study the growth and structure of these fields and strategies to reduce them.

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