Inertial Confinement Fusion

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Inertial confinement fusion (ICF) is an alternative way to achieving controlled thermonuclear fusion. The basic idea is to ignite and burn a few milligrams of deuterium-tritium fuel by means of high-power laser or ion beam pulses. Two large laser facilities are presently under construction which should demonstrate within the next 5 to 10 years the feasibility of single micro-explosions. These are the National Ignition Facility (NIF) in Livermore, US and the Laser MegaJoule (LMJ) in Bordeaux, France. The latter will be described later in this issue (*see André and Decroisette, chapter 5.3*)

It should be noted that ICF has emerged from the neighbourhood of nuclear weapons research, and significant parts of ICF research had been classified until recently. This changed in 1994 when declassification took place in the US which opened the door for international collaboration in this field for the first time. Still, both the NIF and the LMJ project are part of so-called 'stockpile stewardship programmes' in the US and France, serving to maintain the stockpile of thermonuclear weapons in these countries under the conditions of the comprehensive test ban treaty. Detailed information on NIF concerning energy applications as well as stockpile stewardship can be found on the internet at *lasers.llnl.gov/lasers/nif.*

Basics of inertial confinement

In ICF fusion burn occurs in highly compressed deuterium-tritium (DT) fuel, heated to an ignition temperature of 10^8 K. In the standard scheme compression and heating is achieved by spherical implosion of small capsules containing the fuel (*figure* 1a). A short pulse of radiation (laser, ion beam, or X-ray radiation) is used to ablate the outer layer of the capsule and to implode the inner part, driven by the ablation pressure like a spherical rocket. The energy yield of the ignited capsule (up to some 100 MJ) can be contained in a reactor vessel. For civilian energy production the scheme implies pulsed operation with a few micro-explosions per second.

In contrast to magnetic confinement fusion (MCF), inertial confinement involves no magnetic fields to contain the fuel, but relies exclusively on mass inertia. The imploded fuel of density ρ and radius R keeps together inertially for a small time interval $t_{con} \approx R/c_s$, where $c_s \approx 10^8$cm/s is the sound velocity of the igniting fuel. For a typical R = 100 µm this time is 100 ps. In order to burn a significant portion of the fuel in such a short time one has to compress it to high densities so that the fusion reactions occur more rapidly. The time for a fusion reaction is given by $t_{fus} = \mu / <\sigma v>\rho$, where $<\sigma v>$ is the reaction rate and μ the average molecular weight. It turns out that the fraction of fuel that is burnt depends only on the confinement product ρR and is given approximately by $\Phi \approx \rho R / (H_b + \rho R)$, where $H_b \approx 7$ g/cm². From this we learn that it requires $\rho R \cong$ 3 g/cm² to burn 30% of the fuel. For R = 100 µm this gives ρ = 300 g/cm³ which is 1500 times the solid density of DT.

Such high compression is possible when one starts with a frozen fuel layer as shown in *figure* 1b and keeps fuel entropy low during implosion by using temporally shaped driver pulses. The capsules for NIF and LMJ rely on such cryogenic design, and a corresponding implosion simulation is given in *figure* 1c. The main pulse generating an ablation pressure of some 100 Mbar accelerates the shell to about 400 km/s, and most of the compression occurs only at the end, when the imploding fuel stagnates in the centre. At this time the pressure reaches about 200 Gbar and is higher than in the centre of the sun.

Driving all the fuel to ignition temperature (volume ignition) requires much drive energy and therefore degrades the energy gain, which is the ratio of fusion energy yield to the energy invested for ignition. For power reactors one needs target gains in the range of 50 - 100. One way to obtain such high gains is to ignite only a central hot spot in the fuel from where a burn wave then propagates into surrounding colder DT that has been compressed at much lower energy costs (hot spot ignition). The hot spot forms all by itself during implosion from the DT vapour filling the hollow interior initially.

Gains calculated for the NIF capsule and a potential reactor capsule are plotted versus beam energy in *figure* 2. Notice the sharp onset of the gain curves, jumping from negligible gain to high values at some ignition energy. This is because most of the gain stems from burning the cold fuel, but depends on successful ignition. The exact location of the ignition cliff is difficult to predict because it critically depends on symmetry and stability—issues which are discussed below. For example, the shaded regions in *figure* 2 mark the uncertainty due to surface roughness of the capsule. One has to operate these capsules at energies sufficiently above the cliff (black dots), where ignition becomes less dependent on these details.

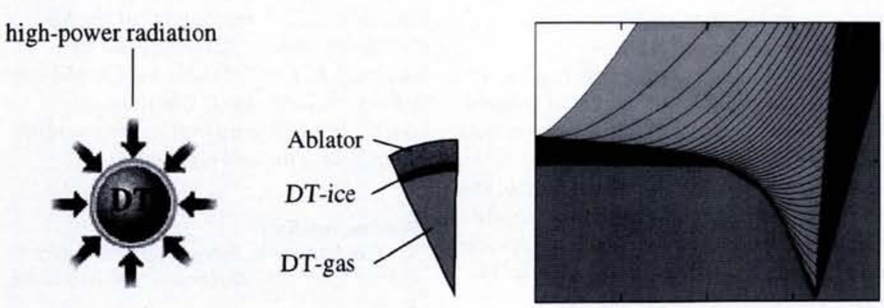

Fig 1a Principle of spherical implosion driven by external radiation. **1b** Sector of a cryogenic capsule. **1c** Flow diagram of an x-ray driven implosion (one-dimensional simulation using NIF parameters)

Symmetry and stability

Compression of the fusion fuel and creation of a central hot spot with a radius as small as 1/50-1/30 of the initial target radius requires a high degree of spherical symmetry during implosion. The chal-

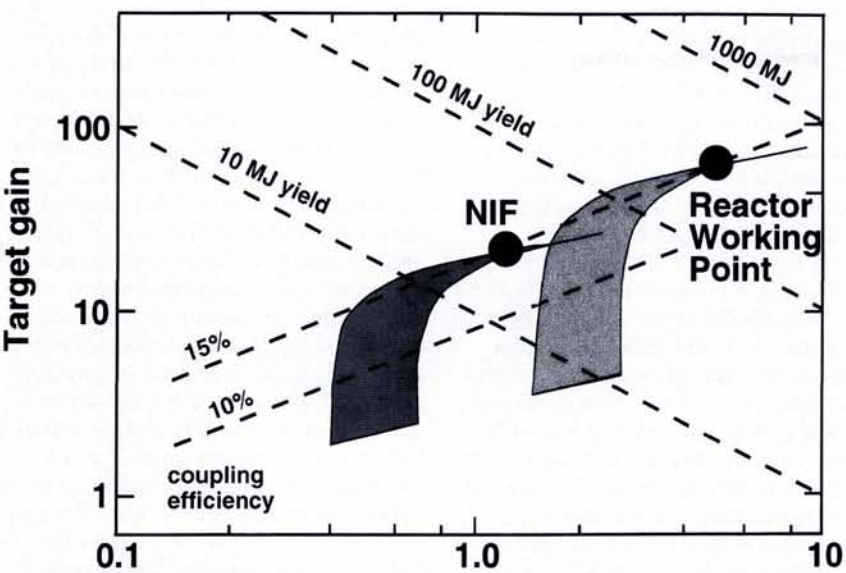

Fig 2 Target gain versus laser energy for two cases of x-ray drive. **Left** shaded area refers to the NIF design with 300 eV hohlraum radiation leading to 400 km/s implosion velocity. **Right** shaded area right is for a larger, reactor-sized capsule with 225 eV and 300 km/s. The shaded regions mark the ignition uncertainty due to non-uniformities: the left-hand edges correspond to perfectly uniform implosions while the right-hand edges correspond to capsules with surface roughness of 50-100 nm. These capsules will operate at sufficiently high energies (black points) to become independent of the non-uniformities. Lines of 10% and 15% coupling efficiency from laser to x-ray energy absorbed by the capsule are shown and also lines of constant fusion output (*from J. Lindl, Phys. Plasmas 2, 3933 1995*)

lenge is to keep the relative non-uniformity of the driving pressure below 1%. Another crucial difficulty is due to Rayleigh-Taylor instability (RTI), which has been the single most studied topic in ICF. As illustrated in *figure* 3a, it first occurs at the outer surface of the shell (the ablation layer) where the tenuous, beam-heated plasma accelerates the shell inwards, and later at the inner surface, when decelerated by the less dense, hot central material. The former process may lead to rupture of the shell, while the latter mixes hot and cold fuel, thus hindering formation of the hot spot. In fact, ignition with a MJ driver requires the implosion of a very thin shell having an in-flight-aspect-ratio of $R/\Delta R \approx 40$ (ratio of shell radius to shell thickness during implosion). Increasing ΔR makes the shell more robust, but implies also higher driving pressure (and therefore higher beam power) to drive the shell to the required velocity.

According to the classical RTI theory, a small perturbation with wavelength λ at an unstable surface grows exponentially with the rate $\gamma = (ka)^{1/2}$, where $k = 2\pi/\lambda$ and a is the acceleration. As the amplitude becomes comparable to λ, the pace of growth slows, but then different wavelengths couple nonlinearly, giving rise to a turbulent mixing layer of depth h, which grows in time as $h \approx 0.07\ at^2$. These basic results, when applied to the unstable ablation front, would render ICF practically impossible. Fortunately, experiments performed over the last two decades have shown convincingly that RTI always grows less than classically. The actual growth rate can be described by $\gamma = [\ ak\ /\ (1 + kL)\ ]^{1/2} - \beta k v_a$, where L is a measure of the thickness of the unstable layer, v_a is the ablation velocity, and $\beta \approx 1.5 - 3$ depends on material, heating mechanism and details of the flow. Apparently, strong ablation (occurring for implosions driven by lasers or thermal X-rays, but not by ion beams) stabilizes RTI for small wavelengths. The growth rate of the most dangerous modes with wavelengths comparable to the thickness of the shell is typically reduced by a factor of 2-3. This feature is now well established by both measurements and numerical simulations. Also, much progress has recently been made in analytical understanding.

Denoting the perturbations by mode numbers $l \approx 2\pi R/\lambda$, corresponding to spherical harmonics, the relevant RTI modes at the outer surface seeded by target defects and early irradiation imprint lie in the range of $l \approx 10$-500. They couple to the inner surface of the shell, smoothed by a factor $\exp(-l\Delta R/R)$, where they sum up to the deformations caused by irradiation asymmetries and seed the inner RTI with relevant modes between $l \approx 8$-30. Significant insight has been obtained by comparing implosion experiments with computer simulations. An example of a 2D simulation of a stagnating shell with a dominant $l = 8$ perturbation is given in *figure* 3b, showing ignition despite the strong deformation of the hot spot. More recent 3D computations at higher resolution confirm these results. Presently, the most advanced 3D codes correctly predict the experimentally observed neutron yields. This is a crucial test because neutron yield is highly sensitive to RTI growth and mixing. Based on these results, it is now believed that the RTI problem can be solved by keeping irradia-

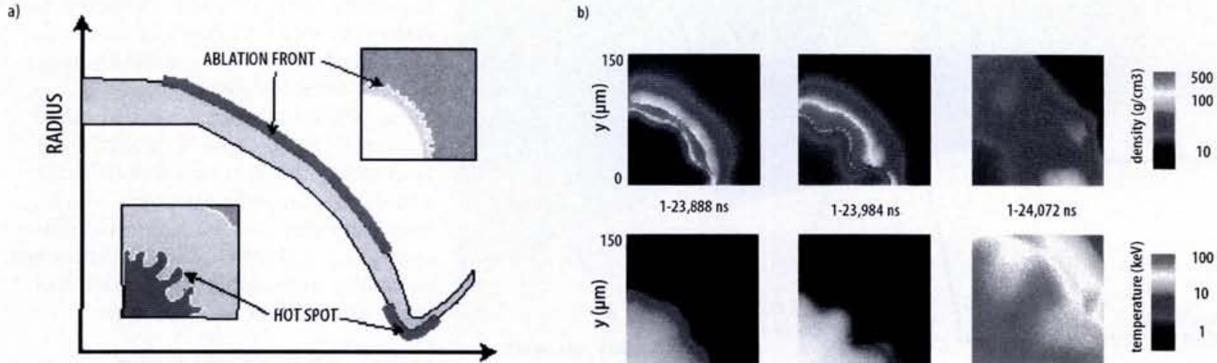

Fig 3 Rayleigh-Taylor instabilities in the implosion of an ICF shell. **3a** Radius versus time flow chart of an imploding shell, where unstable layers are indicated by the thick grey lines. The inserts show the deformations of the shell caused by instabilities. **3b** Central ignition of a reactor-sized fusion target (*from S. Atzeni, Laser & Particle Beams 9 1991*). Density and ion temperature maps obtained from 2D simulation clearly show that despite the growing shell deformation (upper row) the central hot spot first self-heats and then propagates to the whole fuel. The target has an initial radius of 2 mm and is directly irradiated by a laser pulse of 1.6 MJ, imposing a perturbation with peak-to-valley amplitude of 0.7%. The computed fusion yield exceeds 100 MJ

tion asymmetries below 1 - 2% and by developing capsules with a surface roughness of less than 100 nm.

Direct and indirect drive

Presently, there are two paths to achieving uniform irradiation. Firstly, the direct drive approach, where a large number of overlapping beams is shone directly on the fusion capsule, and secondly, the indirect drive approach, where one converts the beam energy into X-rays which then drive the capsule implosion. At present, direct drive is thought to be possible only with lasers. Significant progress has been made to reduce the spatial and temporal coherence of the laser light which causes interference speckles on the target that seed the Rayleigh-Taylor instability. Different smoothing techniques have been developed where one splits the laser beam into many beamlets and then randomizes the phases. Direct drive laser ICF will depend crucially on these methods.

Quite different is the indirect drive approach, using so-called hohlraum targets. In simple terms, the idea is to enclose the fusion capsule in a casing (the hohlraum) which is heated with ion or laser beams like an oven. As a result the capsule is bathed in highly isotropic hohlraum radiation so that it ablates and implodes very symmetrically. An example of a hohlraum target is shown in *figure* 4, it was designed during a recent study on heavy ion beam fusion. The ion beams are stopped in the converter elements which heat the interior of the gold casing to a temperature of $T = 300$ eV. This gives a radiation flux of $\sigma T^4 \approx 10^{15}$ W/cm², just enough to drive the capsule to ignition. Apparently, such hohlraum targets are quite flexible concerning irradiation geometry. For heavy ion beams, they may be the only target option.

Also for NIF and LMJ, hohlraum targets will be used in the first operation phase. They look similar to the design in *figure* 4, but with laser beams entering through windows near the axis and X-ray conversion taking place on the inner surface of the gold casing. The coupling efficiency between incident beam and X-ray energy absorbed by the capsule is in the range of 10 - 15% according to simulations and scaled experiments. The parameters of both *figures* 1 and 2 refer to NIF; the 1.2 MJ laser pulse of the NIF design results in 167 kJ absorbed by the capsule and leads to a yield of 16 MJ. This implies a target gain of 15. Coupling efficiencies for heavy ion beam targets critically depend on final beam focussing and the converter mass which is determined by the focal radius and the ion stopping range. This is still an area of active research, and coupling efficiencies of 10 - 15% are expected for reactor-sized targets, driven by 10 MJ pulses.

Lasers

High-power lasers represent the leading driver option to demonstrate ignition and high target gain in single shot experiments. The Laser Megajoule ignition laser, which will be built in the near future, is described in *chapter* 5.3. The advantage of lasers is that one can easily generate pulses much shorter and focus them to spots much smaller than that finally needed for ICF. This makes it possible to reach an intensity of 10^{15} W/cm² which is already relevant for ICF studies with small lasers, much below the MJ level. Over the last 30 years most ICF-related experiments on laser-plasma interaction, on hohlraum heating, on ablative acceleration of matter and Rayleigh-Taylor instability have been performed with such lasers, as have capsule implosions, which have demonstrated 600 times compression and 10^{14} fusion neutrons from single implosions. Recently, the leading machines have been NOVA in Livermore, GEKKO-XII in Osaka and OMEGA in Rochester. In Europe laser fusion research has been carried out with PHEBUS in Limeil near Paris, VULCAN in Oxford, UK, ASTERIX in Garching, ABC in Frascati and some other machines, in particular in Russia.

Heavy ion accelerators

For power stations generating inertial fusion energy (IFE), drivers having high repetition rate (10 Hz) and high driver efficiency are needed. Heavy ion accelerators are leading candidates in this respect. Driver efficiencies of 20 - 30 % are expected, relaxing the need for high target gain. Also, accelerators can deliver the pulses at rates of up to 100 Hz, which could possibly serve several reactor cavities. Two types of heavy ion systems have been considered: induction linacs at LBL Berkeley and RF linacs combined with storage rings and buncher units at GSI Darmstadt in Germany. All this work is still at an early development stage, but will certainly gain momentum as soon as ignition is demonstrated with lasers.

The main disadvantage, which has impeded heavy ion driven ICF in the past, is the relatively high cost of accelerators, particularly for medium-sized test facilities. However, the cost scaling is favourable for large units such as power stations. When compared to competing laser drivers for IFE, such as KrF-lasers and diode-pumped glass lasers, which may also reach acceptable levels of efficiency and repetition rate, it is the proven durability and reliability of accelerators that distinguish heavy ion drivers.

Light ion beams and X-rays

Pulsed power technology provides another option for low-cost drivers. It may be used to produce either intense light ion beam pulses or X-ray pulses by Z-pinch implosions. Pulsed power machines have proven

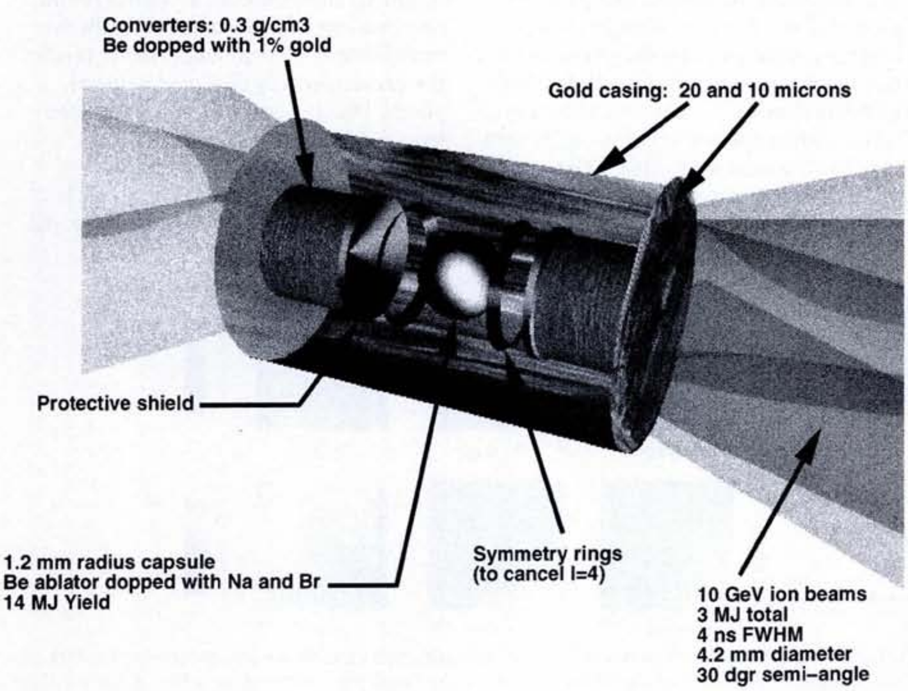

Fig 4 Perspective view of a hohlraum target driven by heavy ion beams *(from R. Ramis et al., Proc. 12th Int. Symp. on Heavy Ion Inertial Fusion, eds. I. Hofmann et al., Heidelberg, Sept. 24-27, 1997)*

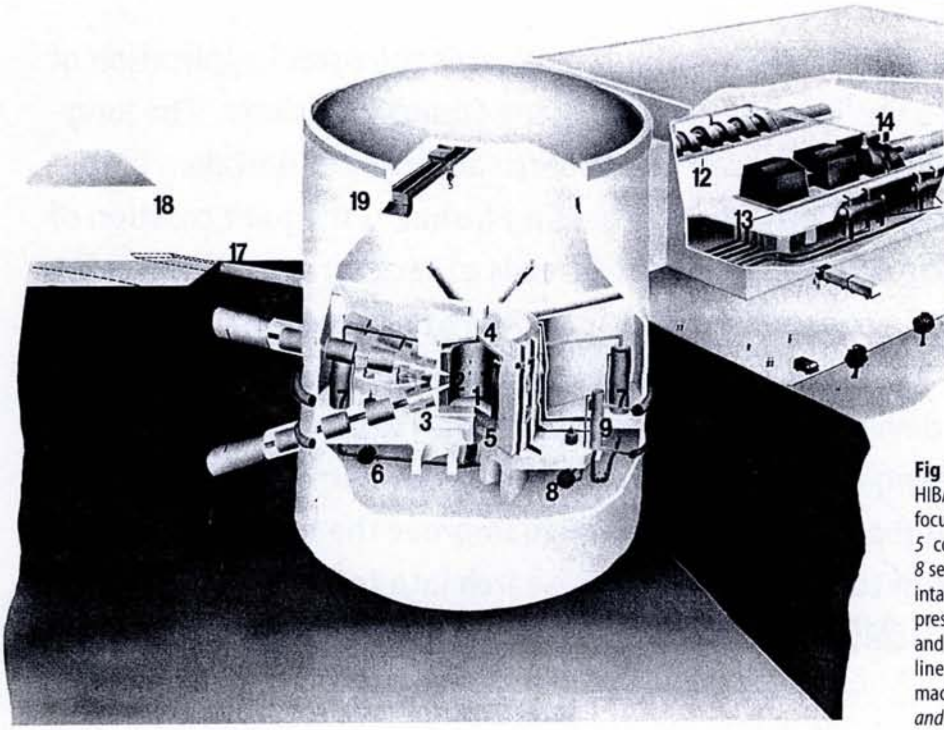

Fig 5 The design of the heavy ion driven ICF reactor HIBALL *1* reactor chamber, *2* INPORT blanket, *3* final focusing quadrupole magnets, *4* rotatable top shield, *5* coolant exit, *6* primary pump, *7* heat exchanger, *8* secondary coolant pump, *9* steam generator, *10* water intank, *11* steam exit, *12* high-pressure turbine, *13* low pressure turbine, *14* electricity generators, *15* condenser and water preheater, *16* beam lines, *17* target transport line, *18* target factory, *19* reactor containment, *20* machine building. (*Badger et al. report KfK-3202, vol. 1 and 2, Kernforschungszentrum Karlsruhe, 1981*)

very useful for ICF physics experiments and may even succeed in single-shot capsule ignition, but it is difficult to see how to make them IFE drivers, satisfying the requirements of high repetition rate and long-life operation. Solutions for this have been proposed but need to be studied.

Light ion beam pulses are generated in diodes, used to discharge up to a few MJ of energy from capacitor banks with cathode electrons insulated by a magnetic field and ions extracted from an anode plasma. By properly shaping these diodes, focussed proton beams depositing 10 - 1000 TW/g into target material have been demonstrated. Future light ion beam drivers for ICF will accelerate Li or C beams in two-stage diodes up to some tens of MeV. Targets would be foam-filled spherical hohlraums.

A new version of X-ray production by means of pulsed power is Z-pinch implosion of cylindrical wire arrays, which turn out to be much more stable than solid liner implosion and lead to significant conversion into X-rays. Recent work at the Sandia laboratories has demonstrated 200 TW / 1.8 MJ of X-ray pulses from 20 MA discharges performed on the Z machine (K. Matzen *Phys. Plasmas* 4 1519, 1997). There are plans for a larger facility capable of ICF capsule ignition.

Reactor design

An important feature of IFE reactors is that driver and reactor chamber are separated from each other and can therefore be developed independently. Another specific point is that fusion chambers can be designed with protected first walls, which may turn out to be a critical advantage. Also, for the single-shot facilities, presently of interest, complex reactor issues like repetitive operation, pellet injection, remote handling, and many others, do not have to be solved. Nevertheless, a number of design studies have been performed to obtain a comprehensive view of IFE reactors and to understand the interdependence of parameters. One of the most complete studies was the HIBALL study, a design of a heavy ion driven IFE reactor. *Figure* 5 shows the HIBALL reactor block. In the HIBALL chamber, the first metallic wall is protected from the target X-rays, ions and neutrons by an array of porous SiC tubes through which liquid PbLi is flowing and wetting the outer surface.

IFE and MFE reactors have many problems in common. This is evident for questions concerning, for example, breeding blankets and other components exposed to high heat and neutron fluxes. A less evident example of synergy is the production and repetitive injection of cryogenic fuel pellets into the reaction chamber. Though the DT-ice pellets used for refuelling in MFE are less structured than IFE targets, the pneumatic techniques developed in MFE of accelerating them to high velocity without heating will certainly become of interest for IFE reactor development.

Target manufacturing is a critical issue for IFE. Methods of producing capsules with the required smoothness of surfaces and layer interfaces, including the cryogenic DT layer, have been developed. While this is sufficient for the single-shot proof-of-principle phase of ICF, the IFE reactor phase will require mass production of such targets at low cost (a few euro cents per target). Certainly, one has to learn from single target ignition about the options available.

Problems still to be solved

The scientific and technological basis has been developed to ignite and burn microfusion targets by means of MJ laser pulses. In scaled experiments, implosions with high convergence ratio and neutron yields have been achieved, showing close agreement between experiment and multidimensional simulations. The crucial problem of symmetry and stability is approached along two lines, direct drive using laser smoothing techniques and indirect drive using gas-filled hohlraums. For further reading, we refer to the review by J. Lindl *Phys. Plasmas* 2 3933 (1995).

Still missing is the actual demonstration of target ignition and high gain, but this is expected to happen within the next 10 years using the laser facilities NIF and Megajoule. In case of success, ICF research will move on to develop reactors for inertial fusion energy. The search for the most suitable reactor driver having first of all high efficiency and repetition rate will then become the main focus. Presently, heavy ion beams appear to be the most promising candidates, but also KrF lasers and diode-pumped glass lasers may meet the efficiency and repetition requirements. Some of the reactor issues also apply for magnetic fusion and may be solved jointly.