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Inertial confinement fusion: steady progress towards ignition and high gain (summary talk)

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Abstract
Based on the results presented at the 20th IAEA Fusion Energy Conference 2004, this paper highlights the most important recent advances in inertial confinement fusion (ICF). With the construction of the National Ignition Facility (NIF) and the Laser Mégajoule facility and many improvements in the target design, the conventional indirect-drive approach is advancing steadily towards the demonstration of ignition and high gain. The development of the polar direct-drive concept also made the prospects for direct-drive ignition on the NIF very favourable. Substantial progress was reported on the exploration of the fast-ignition approach to ICF. Parallel to that, multi-wire Z-pinches have become a competitive driver option for achieving ignition at the lowest possible cost. In heavy-ion fusion, experiments have been devoted so far to studying the generation, transport, and final focusing of high-current ion beams. A new concept for a power plant with a heavy-ion driver, based on a cylindrical direct-drive target compressed and ignited (in the fast-ignition mode) by two separate beams of very energetic ($E_i \gtrsim 0.5\,\mathrm{GeV\,u^{-1}}$) heavy ions, has been proposed.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

This paper is based on a summary talk given at the 20th IAEA Fusion Energy Conference (Vilamoura, Portugal, 1–6 November 2004) to review the contributions on inertial confinement fusion (ICF). Despite a number of reports on inertial fusion (28 out of a total of 437 papers), the present overview is by no means exhaustive. The author's main goal was to highlight the most important recent achievements and interesting new ideas rather than to give a comprehensive account of all the reported results. The author acknowledges a certain degree of subjectivism and personal bias in his choice of material, and offers his apologies to the authors of contributions not covered in this summary. The full list of ICF-related papers presented at the conference is given at the end of the conclusion section; papers mentioned in the present summary are marked with an asterisk (e.g. OV/3-1*), and referred to by the contributing author and the conference notation in the text.

Energy production by means of ICF should rely on a repetitive sequence of thermonuclear microexplosions, and each of these microexplosions should generate a high enough energy gain in the range of $G = 50$–200, depending on the driver efficiency. Clearly, the first experimental demonstration of a single microexplosion will be the most important milestone on the way to inertial fusion energy (IFE) by means of ICF. With the beginning of the construction of the National Ignition Facility (NIF) in the USA, and of the Laser Mégajoule (LMJ) facility in France, the stage has been set for reaching this goal in 6–7 years from now (Lindl, OV/3-1).

First ignition experiments are planned in the indirect-drive mode with the conventional ignition scheme based on a central hot spot. Ignition of the directly-driven laser targets should also be demonstrated on the NIF, perhaps several years after the indirect-drive ignition. The recent spectacular progress in many areas of the target physics has significantly improved the safety margin and confidence level for this basic approach to ICF.

At the same time, alternative routes to ignition experiments are also being explored. Major efforts have been undertaken towards realization of the fast ignition concept with a petawatt (PW) laser. The fast ignition realization experiment (FIREX) project initiated at the Institute of Laser Engineering (ILE) in Osaka has the ambitious goal of demonstrating a fusion gain in excess of unity with two 50 kJ lasers; one in the ns mode for compression, and the other in the ps (PW) mode for fast heating of the compressed fuel. A new concept for fast ignition with heavy-ion beams has been proposed by scientists from the Institute for Theoretical and Experimental Physics (ITEP) in Moscow.

The remarkable success in generating 1–2 MJ, $\gtrsim$200 TW pulses of thermal x-rays with a wire-array Z-pinch has recently put forward this type of pulse-power machine as yet another promising candidate for achieving ignition in ICF. The first implosion experiments at the Z facility at Sandia (USA) have been very encouraging and have stimulated an IFE-aimed research programme for finding a solution to the repetition-rated standoff (separation of driver and target) problem. As such, a concept of recyclable transmission line (RTL) has been worked out and is currently under investigation at Sandia.

2. The nominal scheme: indirect laser drive with central ignition

Research on the practical realization of ICF began more than 30 years ago. In the early nineties, as a sufficient amount of data had been collected, the first realistic scheme for achieving ignition was formulated and adopted as a basis for the future NIF and LMJ projects [1]. It is based on an indirect-drive target with a cylindrical hohlraum (see figure 1) driven by a carefully tailored pulse of laser light with the total energy of $E_{dr} = 1.8$ MJ at the third harmonic (3ω, $\lambda = 0.35\,\mu$m) of the basic frequency of the Nd : glass laser. Laser light is absorbed on the inner surface of the hohlraum wall, made of a high-Z material, and re-emitted in the form of soft x-rays with a time-varying temperature $T_x \approx$ 100–300 eV. The x-rays heat up and ablate the outer surface of a spherical fusion capsule placed at the centre of the hohlraum cavity; the resulting ablation pressure drives a highly symmetric implosion of the initially frozen deuterium–tritium (DT) shell. Ignition is initiated by a central hot spot (thermonuclear spark), which is naturally formed at the time of stagnation as a result of sufficiently fast implosion of the dense DT shell toward the centre of the inner capsule cavity filled with a low-density DT vapour. Careful pulse shaping is required to preserve the entropy of the bulk of the DT fuel around the hot spot at the lowest possible level.

2.1. Construction of the NIF and LMJ ignition facilities

Some very encouraging news for ICF is that the construction of both the ignition facilities—the NIF in the USA and the LMJ in France—is fully underway. At NIF, the main building and the beam path infrastructure for all the 192 laser beams have been completed, and the first four beams have been installed in the target chamber and activated for experiments (Lindl, OV/3-1). The first experiments have demonstrated all the primary NIF per-beam requirements: 21 kJ in 1ω light (equivalent to 4.0 MJ in 192 beams of the full NIF), 10.4 kJ in 3ω (equivalent to 2.0 MJ in 192 beams) and 25-ns shaped pulse according to NIF specifications. Beam-energy balance and synchronization have also been tested. Further experiments should focus on laser-plasma interaction and laser propagation in large ignition-scale hohlraum plasmas.

The French LMJ project is also making headway with some delays when compared with the NIF: construction of the main building has been started recently, the installation of the main target chamber is planned in 2006 and physics experiments with the four prototype laser beams (LIL) should begin in 2005 (Holstein, IF/1-3).

2.2. Advances in fusion capsule design and better control of hydrodynamic instabilities

In recent years significant progress has been achieved in the area of indirect-drive ignition-scale target design. First of all, it was demonstrated that fusion capsules with a beryllium ablator (see figure 2) perform significantly better than the original NIF baseline capsule with the CH ablator. Figure 3 shows the results of a comparative study of three choices of a uniformly distributed ablator material [2]. It is seen that the Be capsules can tolerate a factor of 3–4 times larger initial roughness for both the outer ablator surface and the inner DT-ice surface than the original CH capsule. Polyimide shows intermediate results between CH and Be but has some technological advantages over the latter. If the peak hohlraum temperature is lowered from 300 to 250 eV, a Be capsule can absorb more energy (190 kJ instead of 150 kJ) and generate a higher yield (28 MJ instead of 15 MJ) when compared with the NIF baseline design [3].

However, at lower x-ray-drive temperatures, fusion capsules become generally more susceptible to hydrodynamic instabilities and pose severe constraints on the initial roughness of all surfaces and material interfaces. Nevertheless important progress concerning this issue has been made recently: it was found that capsules, made of beryllium with copper *doped in a radially varying concentration*, can tolerate more than an order-of-magnitude rougher surfaces than previous designs. For the outer ablator surface, the acceptable roughness level increases from rms ~50 nm for uniform doping (as shown in figure 3(*b*)) to rms ~500 nm for graded doping by Cu; tolerance to the DT-ice roughness also becomes better, namely 5 μm instead of 1 μm (Lindl, OV/3-1). These latter findings lead to a considerable widening of the ignition island in the laser power-versus-energy parametric plane.

2.3. Improvements in the hohlraum efficiency and the overall target energetics

Significant advances have also been made in improving the energy coupling efficiency in the hohlraum. A new mixture of high-Z elements for the hohlraum wall composition has been identified: the $(U\,Nb_{0.14})_{0.6}\,Au_{0.2}\,Dy_{0.2}$ cocktail has been found to exhibit a noticeably higher albedo for the x-rays than pure Au; as a result, the energy absorbed by a Be capsule (all other factors being equal) can be increased from ≈200 to ≈240 kJ (Lindl, OV/3-1). Further potential for improving the hohlraum efficiency is associated with placing radiation shields against the laser entrance holes; also, capitalizing on the progress in the predictive power of the numerical codes, one can use tighter hohlraums. All in all, a hohlraum efficiency of $\eta_h \approx 0.2$ may be quite realistic for advanced NIF targets, as compared to $\eta_h \approx 0.1$ for the NIF baseline target (Lindl, OV/3-1).

On the other side, lowering hohlraum temperatures and a better understanding of the laser-plasma interaction processes open the possibility of using a 2ω light instead of the 3ω one, which means about 10% more laser energy will become

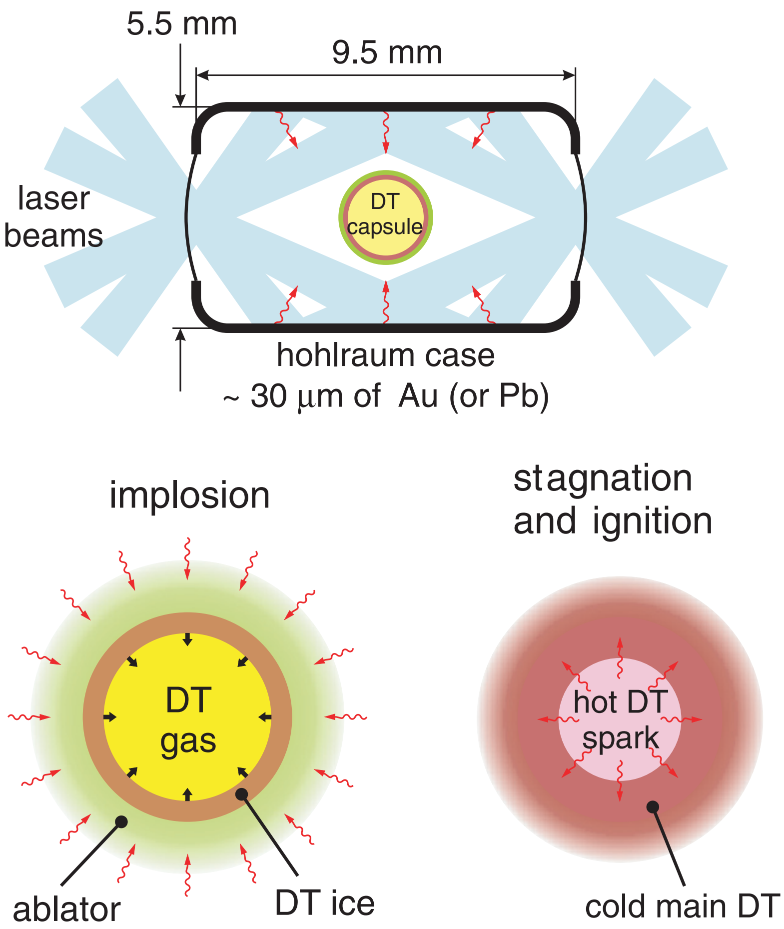

Figure 1. Indirect drive laser target with central hot-spot ignition as originally designed for the NIF project.

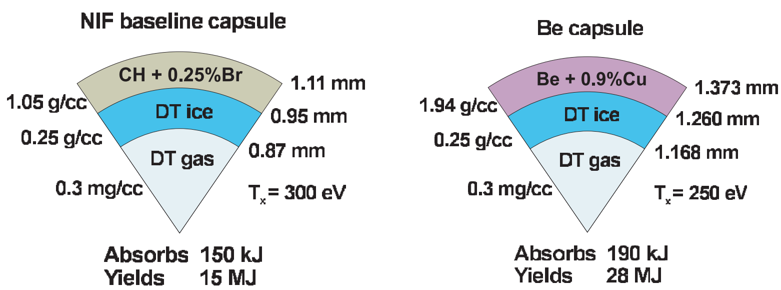

Figure 2. Fusion capsule with a Be ablator from [3] versus the original NIF baseline capsule.

available for target irradiation (Suter, IF/P7-32). In addition, longer pulse durations owing to larger Be capsules will allow the use of two additional laser slabs in the NIF output amplifiers for extracting about 20% additional laser energy (up to 2.5 MJ in 3ω) than originally planned [2].

Steady progress is also being made in indirect-drive target design at CEA-DAM (France) for ignition experiments at the LMJ facility (Holstein, IF/1-3). Several point designs have been worked out using two-dimensional integrated simulations with the FCI2 code [4]. These point designs were subjected to a robustness study with respect to the uncertainties associated with laser beam imbalance, pointing and fabrication errors. A high ($\gtrsim$90%) probability of ignition with the baseline LMJ specifications (5% rms laser beam imbalance, 50 μm rms pointing errors and 15 μm rms uncertainty in target dimensions) have been confirmed [4] (Holstein, IF/1-3).

Taken together, all these advances increase significantly the safety margin for demonstration of ICF ignition on the NIF and LMJ facilities. Instead of a near-threshold ignition of a 150 kJ capsule, one might be able to ignite indirectly-driven DT capsules which absorb up to 400–600 kJ of the x-ray energy and demonstrate energy gains in the range of $G = 30$–60 [2].

3. Progress in laser direct drive

Without the x-ray conversion step, direct-drive laser targets have intrinsically higher energy efficiency than the indirect-drive targets. This advantage, however, is partially offset

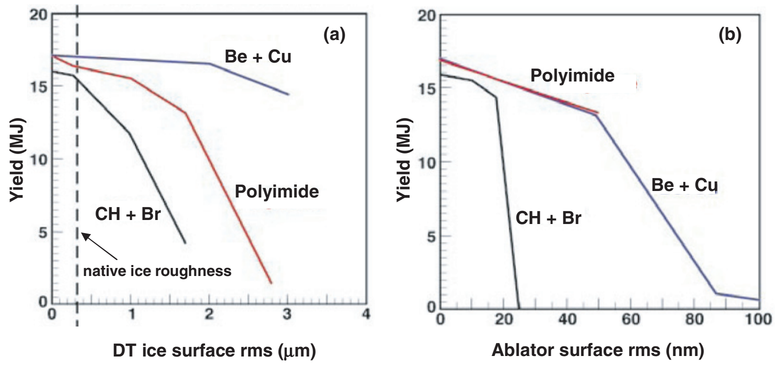

Figure 3. Tolerance of fusion capsules with different ablator materials to the initial surface roughness as calculated with the three-dimensional code HYDRA [2]. In each case the ablator has a uniform structure. The peak hohlraum temperature was fixed at $T_x = 300$ eV. (*a*) Yield versus ice roughness for 10 nm rms ablator surfaces. (*b*) Yield versus ablator roughness for best ice surfaces.

by additional measures required to mitigate drive asymmetry and hydrodynamic instability of ablation under direct laser irradiation: direct-drive targets (i) are more sensitive to intensity variations among individual laser beams and (ii) suffer from the Rayleigh–Taylor (RT) instability seeded via imprinting of the short-scale non-uniformities of the laser light within individual focal spots. The latest calculations indicate that, for the NIF conditions, direct-drive targets should have about the same ignition threshold but a higher energy gain by about a factor of 2 than the best indirect-drive designs [2]. Direct-drive ignition experiments are foreseen at both the NIF and LMJ facilities, and corresponding target designs have been investigated recently [5, 6].

A major experimental programme for testing and validating the physics of the direct-drive laser fusion is being conducted at the 30 kJ OMEGA laser operational at the University of Rochester's Laboratory for Laser Energetics (LLE). High uniformity of laser irradiation needed for direct drive requires special techniques for beam smoothening and power balancing. These techniques have been demonstrated on OMEGA and successfully applied to cryogenic D_2 target implosions [7]. Cryogenic implosions with DT targets are planned for the year 2005 (Regan, OV/3-3).

The latest important developments for the direct-drive ICF have been (i) the introduction of a 'picket' pulse shape and (ii) an ignition-target design in polar direct-drive configuration. Figure 4 shows schematically three versions of laser direct-drive targets. The NIF baseline target (figure 4(*a*)) is driven by a 1.5 MJ 3ω laser pulse with a 'conventional' temporal power profile. Mitigation of the RT instability is achieved by adiabat shaping of the ablator shell. Recently, it was found that a significantly more efficient adiabat shaping can be obtained by launching an unsupported shock wave into the target shell with a short ($\sim$100 ps), intense, Gaussian laser pulse ('picket') at the beginning of the implosion [8]. Direct x-ray radiography experiments with planar surrogate foam targets (see figure 5) have confirmed the efficiency of picket pulses in suppressing the RT instability at shorter wavelengths (Regan, OV/3-3).

Originally, direct-drive ignition on the NIF was planned to be achieved with a spherically-symmetric beam arrangement, significantly differing from the beam geometry in the indirect-drive mode. The corresponding experiments would have been delayed by several years (until 2014). Advances in the target design due to the picket pulse shape and enhanced laser absorption in a wetted-foam ablator (see figure 4(*b*)) can be employed for direct-drive ignition experiments while the NIF is still in the x-ray-drive configuration [9]. This involves re-pointing some of the beams towards the equator of the target to improve uniformity of the target drive—an approach called polar direct drive (PDD). Recent simulations have demonstrated an energy gain of $G \simeq 10$ for the PDD mode (Regan, OV/3-3). As a result, direct-drive ignition may be demonstrated several years earlier than originally planned.

The advantages of picket pulses can also be used to improve the performance of IFE-scale targets. Figure 4(*c*) schematically shows a recent direct-drive target design, irradiated by a 2.5 MJ laser picket pulse, which demonstrates a two-dimensional energy gain of $G \gtrsim 150$ [10].

4. Fast ignition

4.1. Fast ignition with intense laser beams

Fast ignition is an alternative method of igniting the compressed DT fuel by a very fast (within 10–50 ps) injection of energy (10–100 kJ) into a small ($\langle \rho r \rangle \simeq 0.5$–$0.6\,\mathrm{g\,cm^{-2}}$) portion of the fuel mass to heat it up to a temperature of $T \simeq 10$ keV. This old idea has caught new attention [11] after the invention of the chirped laser-pulse amplification, allowing the raising of the laser power by orders of magnitude to a multi-PW level. The principal advantage of fast ignition over the conventional hot-spot ignition is mainly in relaxed demands on the symmetry of implosion and the peak power required for fuel compression, which can, in its turn, be translated into a lower ignition threshold and/or a higher energy gain.

Impressive progress in exploring the concept of fast ignition with a PW laser has been achieved at the ILE (Osaka), which has virtually become a dedicated laboratory for this approach to ICF (Izawa, OV/3-2). The principal scheme is based on a cone-guided implosion, shown schematically in figure 6. Here, a conical sector is cut out of the usual spherical DT capsule and replaced by a concentric hollow cone of gold (figure 6(*a*)). The implosion of the partially spherical capsule is driven in the usual way, with the DT shell sliding along the gold cone towards the centre. Perturbations from the interaction with the cone wall are expected to be moderate, so that a good-quality compressed DT state is reached by the end of the implosion near the tip of the gold cone (figure 6(*c*)).

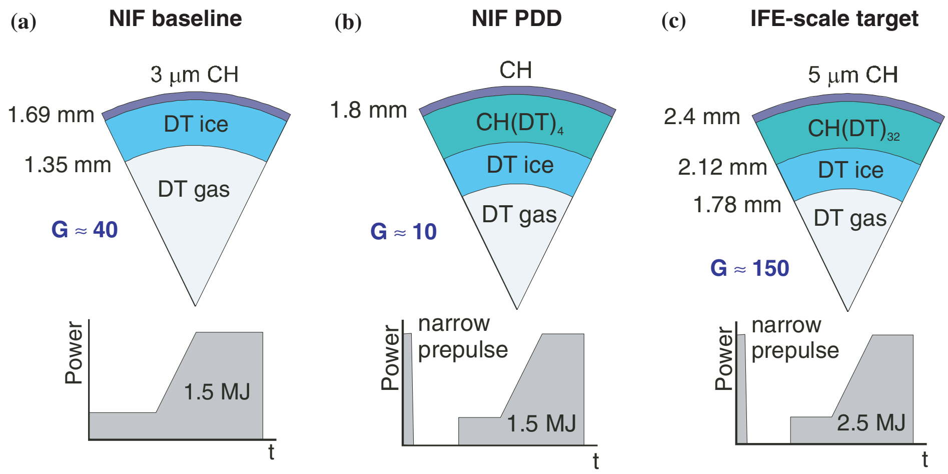

Figure 4. Schematic view of three versions of direct-drive laser targets: (*a*) the NIF baseline design; (*b*) target with a picket pulse proposed for the polar direct-drive ignition on the NIF; (*c*) reactor-scale target proposed in [10] with a two-dimensional energy gain of $G \gtrsim 150$.

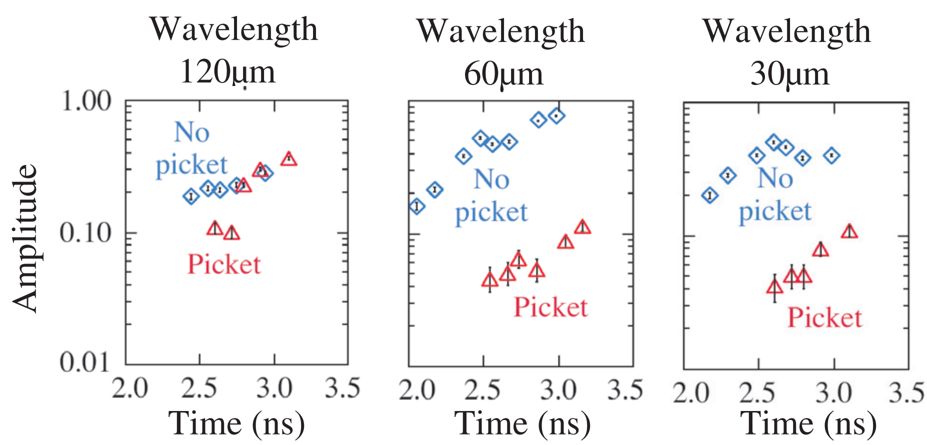

Figure 5. Results of planar RT-growth experiments at LLE with picket pulses: optical-depth modulations are significantly reduced at shorter wavelengths using the picket pulse (Regan, OV/3-3).

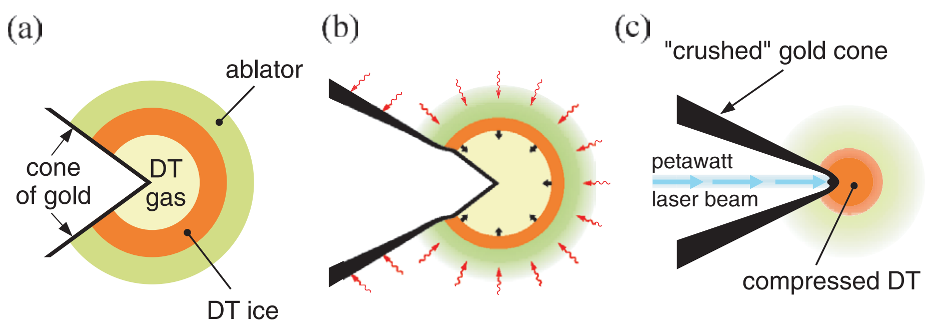

Figure 6. Cone-guided implosion of a not fully spherical fusion capsule: (*a*) initial state, (*b*) intermediate stage of implosion, (*c*) assembled fuel at stagnation.

Because the cone wall is more sluggish than the ablator-fuel shell, the partially 'crushed' gold cone still remains open by the time of fuel stagnation and allows the igniting laser pulse to be delivered in the immediate vicinity of the fuel core. Experiments at ILE with the GEKKO XII laser to drive the cone-guided implosion, and a 400 J/0.6 ps PW laser to heat up the compressed core, have demonstrated an increase in the neutron yield from 10^4 to 10^7 due to the fast heating of the core [12]. A coupling efficiency of 20–25% between the heating laser and the core plasma was obtained.

Based on this success, a new project FIREX has been started at ILE, with the final goal of achieving ignition of a direct-drive DT target in the fast-ignition mode (Izawa, OV/3-2). The project is split into two phases. The first phase, FIREX-I, began in 2003 with the construction of a new 10 kJ PW heating laser, Laser for Fast Ignition Experiment (LFEX), that should be applied to cryogenic cone-shell targets imploded by the GEKKO-XII laser. At this stage, a DT plasma with parameters $\langle \rho r \rangle \approx 0.15\,\mathrm{g\,cm^{-2}}$, $T \approx 8\,\mathrm{keV}$ should be created, and a gain of $G \approx 0.1$ should be demonstrated. If the FIREX-I stage proves to be successful, it is planned to go over to the next stage, FIREX-II, where both the implosion and the heating lasers will be upgraded to 50 kJ and fusion gains in excess of unity will be achieved.

Fast ignition is also an active area of research at LLE (Rochester). A high-energy PW capability, OMEGA EP (extended performance), is being constructed at LLE next to the existing OMEGA compression facility (Regan, OV/3-3). This new laser will add two short-pulse (with pulse durations between 1 and 100 ps), 2- to 3-PW, 2.6 kJ beams to the existing OMEGA laser system to study the physics of fast ignition with focused intensities up to $6 \times 10^{20}\,\mathrm{W\,cm^{-2}}$. Experiments designed to validate the physics of fast ignition will be performed with scaled cryogenic capsules. The first experiments are planned for the year 2008.

Besides ILE and LLE, many important experiments on fundamental issues of fast-ignition physics are conducted on the 100 TW laser at LULI (Ecole Polytechnique, France) and on the VULCAN laser at the Rutherford Appleton Laboratory (RAL, UK), which was recently upgraded to a 1 PW total power and a $10^{21}\,\mathrm{W\,cm^{-2}}$ peak irradiance on target [13]. VULCAN at RAL is the only laser other than GEKKO at ILE's laser facility where integrated fast-ignition experiments with cone-guided implosions have been performed [14]: in particular, a 20% conversion efficiency of the laser energy into the electron flux was confirmed (Key, IF/1-4Rb). New results on the penetration of intense laser beams into overdense plasmas (Tanaka, IF/1-4Ra), on the generation and transport of intense electron beams (Key, IF/1-4Rb), and on the generation of ultra-high (up to $\simeq$300 MG) magnetic fields (Haines, IF/P7-27) under intense laser irradiation have been reported.

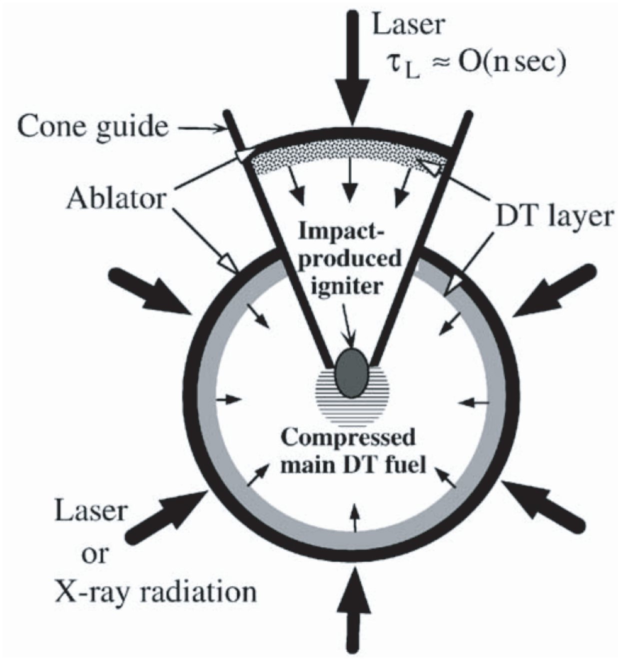

Figure 7. Schematic illustration of the impact ignition concept according to Murakami *et al* (IF/P7-31).

4.2. Impact ignition

An interesting alternative concept of fast ignition, schematically illustrated in figure 7, was proposed recently by Murakami *et al* (Murakami, IF/P7-31; Azechi, IF/1-1Ra). Compression of the main DT fuel in this scheme is accomplished in the same way as in the cone-guided implosion shown in figure 6. However, the igniting hot spot is created not by an ultra-short pulse of a PW laser, but by the impact of a high-velocity fragment of a DT shell accelerated separately inside the gold cone to a velocity of $\sim 10^8\,\mathrm{cm\,s^{-1}}$, sufficient for generating shock temperatures in excess of 5 keV. For ablative acceleration to such a hyper-velocity, a separate laser pulse with a duration of several nanoseconds will be needed. The feasibility of this scheme is still to be demonstrated by clarifying many important details of the cone-guided implosions, and by verifying the ability to withstand hydrodynamic instabilities when accelerating to super-high implosion velocities.

5. Heavy-ion driven fusion

The general attractiveness of the heavy-ion driven fusion for IFE has always been associated with (i) a high efficiency ($\gtrsim$25–30%) of heavy-ion accelerators, and (ii) a readily available high repetition rate ($\gtrsim$10 Hz), which virtually comes for free once the accelerator is built. On the other hand, compared with the laser pulses, ion beams are much more difficult to compress in space and time in order to create the required irradiation intensity on target. By now, many aspects of heavy-ion fusion have been analysed theoretically, and several scenarios of a thermonuclear power plant have been considered. Nevertheless, there still exists no dedicated experimental programme aimed at implosion experiments and ignition under the action of heavy ions.

5.1. Possibility of fast ignition with heavy ions

A novel heavy-ion IFE concept has been presented by (Sharkov, OV/3-4). This concept is based on fast ignition of a cylindrical target with a very powerful heavy-ion pulse. As it was suggested in [15], under the conditions that (i) the ion energy is increased from the conventional 5–10 GeV to $\simeq$100 GeV per ion, (ii) the method of non-Liouvillian compression of beams of simultaneously accelerated ions with four different masses and opposite electric charges is employed and (iii) neutralization of the electric charge density is achieved by combining the beams of opposite charges at the last stage of beam compression, a 400 kJ pulse of heavy ions could be focused on a spot of 50 μm in radius within 200 ps. Such a pulse would produce an irradiation intensity of $2.5 \times 10^{19}\,\mathrm{W\,cm^{-2}}$ and might be suitable for fast ignition.

In this scenario one is compelled to use cylindrical rather than spherical target geometry because of the relatively long-stopping ranges (5–10 $\mathrm{g\,cm^{-2}}$) of 100 GeV heavy ions. Cylindrical compression is accomplished by a separate low-power 10–15 MJ beam of the same $\simeq$100 GeV heavy ions within the direct-drive scheme, as shown in figure 8. A high degree of azimuthal uniformity of the ion energy deposition, needed for cylindrical direct-drive, is supposed to be ensured

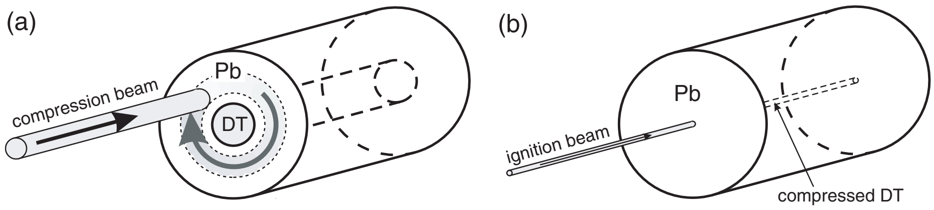

Figure 8. Schematic view of a cylindrical fast-ignition target for heavy ion fusion: (*a*) target implosion is driven directly by a low-intensity compression beam, rapidly rotating around the target axis; (*b*) at maximum compression of the DT fuel, its fast ignition is initiated by a second ultra-intense beam of heavy ions.

by the fast rotation of the compression beam around the target axis (see figure 8(*a*)). A two-dimensional study [16] has shown that 8–10 beam revolutions over the main portion of the compression pulse should be sufficient to reach the needed radial convergence of the implosion.

A combination of one-dimensional and two-dimensional simulations [17] has shown that the DT fuel in such a target can be compressed to a state with $\rho_{\mathrm{DT}} = 100\,\mathrm{g\,cm^{-3}}$, $R_{\mathrm{DT}} = 50\,\mu\mathrm{m}$ ($\langle\rho r\rangle_{\mathrm{DT}} = 0.5\,\mathrm{g\,cm^{-2}}$), and a self-sustained burn wave can be launched along the compressed DT fibre by an ignition pulse with the above mentioned parameters. For a target length of $\simeq$1 cm one can expect a thermonuclear yield of $\simeq$1 GJ per shot, which would imply an energy gain of $G \approx 100$.

A concept of a heavy-ion driven thermonuclear power plant with 4 reactor chambers, based on the above scenario of fast ignition with heavy ions, has been worked out (Sharkov, OV/3-4). Each reactor chamber consists of two compartments and has a liquid first wall. The liquid film is formed on the SiC porous wall by the $Li_{17}Pb_{83}$ coolant. Target explosions (two per second in each chamber) occur in the smaller upper compartment. The larger lower compartment is sprayed with coolant jets, which accelerate vapour condensation after each explosion. The heat conversion system with three coolant loops has a net efficiency of $\sim$35%.

5.2. *Ongoing experiments with heavy-ion beams*

Experimental programmes related to heavy-ion fusion have been dedicated so far to studying the generation, transport and final focusing of high-current heavy-ion beams. One of the major challenges for heavy-ion fusion is final beam focusing onto a sufficiently small spot. A possible solution would be to use beam transport with charge and current neutralization in a plasma channel. Encouraging results for neutralized transport have been obtained recently at LBNL (Logan, IF/1-2), where for a high-brightness 300 keV K^+ beam it was demonstrated that plasma neutralization reduces the focal-spot radius from $\sim$1.1 cm (vacuum focus) to $\lesssim$0.14 cm (neutralized focus). In the near future, experiments are planned to investigate neutralized beam transport not only in the target chamber but also in the drift compression region between the accelerator and the target chamber, aimed at efficient longitudinal compression of the ion pulse. Recent numerical simulations indicate that, by using neutralized drift compression, it may be possible to achieve more than 100-times axial compression accompanied by 20-times radial focusing to produce a 40 000-times increase in the beam intensity on target (Logan, IF/1-2).

Experiments aimed at creating high-energy-density ($1–10\,\mathrm{kJ\,g^{-1}}$) states of matter with intense ion beams are conducted and planned at the existing synchrotrons at GSI (Darmstadt) and ITEP (Moscow). A major upgrade of the existing accelerator complex toward acceleration and accumulation of high-current heavy-ion beams is making headway at ITEP (Sharkov, OV/3-4). The ITEP-TWAC (TeraWatt Accumulator) facility uses a new laser-ion source, which produces some 5×10^{10} ions per shot. The main acceleration to several hundred megaelectronvolts per nucleon is accomplished by the existing U-10 synchrotron. A non-Liouvillian single-turn injection using a foil stripper is employed to minimize the phase space. The bunch is compressed from 1 μs to $\sim$170 ns and focused onto a $\sim$1 mm spot. In 2003 the entire beam manipulation complex was commissioned by demonstrating the stacking of some 10^{10} ions of C^{6+} and their fast extraction to the experimental area.

6. Inertial fusion with wire-array Z-pinch

In recent years Z-pinch technology with multi-wire arrays has demonstrated spectacular progress in generating 1–2 MJ pulses of soft x-rays with radiation temperatures in excess of 200 eV [18]. A relatively high efficiency ($\gtrsim$15%) of energy conversion into thermal x-rays makes Z-pinches another attractive driver option for IFE. Also important among all the driver candidates, is the lowest cost per joule (about 30$; Olson, OV/3-5Ra) of the produced x-rays.

Two types of indirect-drive targets have been proposed for ignition experiments and energy production with Z-pinches, namely, a double-pinch hohlraum [19], shown in figure 9(*a*), and a dynamic hohlraum [20], shown in figure 9(*b*). Implosion experiments have been performed for both target types on the 20-MA Z-facility at SNL (Albuquerque). Generally, the double-pinch target offers an easier way to control the x-ray drive asymmetry, but is inferior to the dynamic hohlraum in term of efficiency of energy transfer into the DT capsule.

Using a double-pinch hohlraum target on the 20-MA Z-facility (Sandia), x-ray temperatures $\simeq$70 eV were obtained, and capsule implosions with radial convergence ratios between 14 and 21 were realized (Olson, OV/3-5Ra). In a dynamic hohlraum target, a 2.1 mm-diameter deuterium-filled CH capsule absorbed up to 35 kJ of x-ray energy from the 220 eV hohlraum. Capsule convergence ratios of 5–10 and thermonuclear DD-neutron yields of up to 8×10^{10} have been measured. These results make a good case for building the next-generation 60-MA facility for demonstrating ICF ignition with a wire-array Z-pinch.

In the context of IFE, the next goal for the Z-pinch program is to extend the recent single-shot results on Z to a repetitive-shot Z-pinch power plant concept for economical production

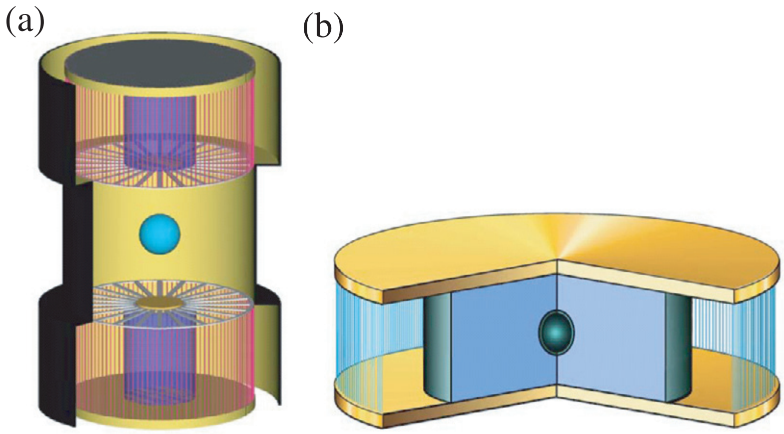

Figure 9. Schematic view of (*a*) a double-pinch target, and (*b*) a dynamic hohlraum target for ICF with wire-array Z-pinches.

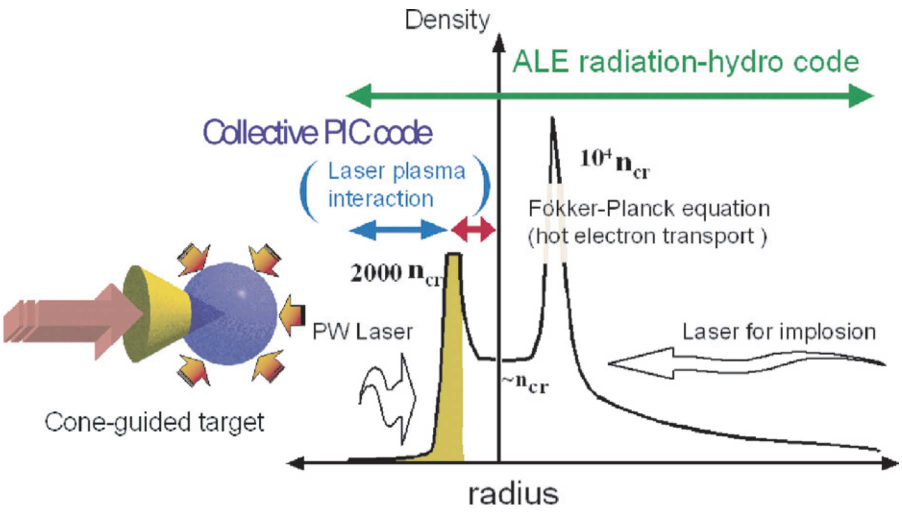

Figure 10. Illustrative scheme for different applicability domains of the principal constituents of the FI^3 code (Nagatomo, IF/P7-29).

of electricity. As one of the simplest and most robust solutions, a concept of RTL has been proposed, and an experimental programme has been initiated to test this concept (Olson, OV/3-5Ra).

7. Code development

Much of the recent progress towards realization of ICF has been due to the advances in the development of numerical codes. Extensive three-dimensional hydrodynamic simulations of the indirect-drive DT capsules at the Lawrence Livermore National Laboratory (LLNL) with the HYDRA code have been very important for achieving a new confidence level in the control of drive asymmetries and hydrodynamic instabilities (Lindl, OV/3-1). Such simulations use up to 12.8 million mesh cells and 120 processors. Adequate three-dimensional modelling of radiation transport and coupling efficiency in ICF hohlraums should become possible in the near future [2]. Three-dimensional simulations of LMJ targets are to begin in 2005 at CEA-DAM in France (Holstein, communication at this conference).

One of the critical issues for the success of the NIF and LMJ projects is the ability to predict and control the propagation and absorption of the laser light in the hohlraum plasmas. The related physical phenomena are so complicated that no numerical code with a satisfactory predictive capability has been made available so far. Presently, advances in theory and particle-in-cell (PIC) code modelling are being used at LLNL to develop reduced-description models for saturation of laser-plasma instabilities to be implemented in a parallel three-dimensional LPI/hydro code (pF3D), capable of modelling the propagation of a full-sized beam through several millimetres of plasma (Lindl, OV/3-1).

Integrated simulations of fast-ignition targets pose another major challenge to numerical modelling in ICF. A combined approach to this problem was adopted at ILE (Osaka), where a Fast Ignition Integrated Interconnecting code (FI^3) has been developed (Izawa, OV/3-2; Nagatomo, IF/P7-29). The principal constituent parts of the new code include a collective PIC code (FISCOF1), a relativistic Fokker–Planck (RFP) code, and a two-dimensional radiation-hydrodynamics code (PINOCO). Figure 10 schematically illustrates the domains of applicability for each of the constituent codes over a characteristic plasma-density profile. Target simulation starts with the PINOCO, which calculates the hydrodynamics of the cone-guided implosion. Then, the relevant profiles are passed to the PIC and RFP-hydro codes, which calculate, respectively, the energy distribution of fast electrons resulting from the PW-laser pulse, and the energy deposition by these electrons in the compressed DT core.

8. Technology issues

Technological progress in the fabrication of high-quality spherical DT capsules is crucial to the success of future ignition experiments. For indirect drive, the focus of recent efforts was on the Be-ablator capsules. Significant progress has been achieved with spherical mandrels that are coated with the ablator material. Smooth capsules have been fabricated at LLNL by overcoating mandrels with uniform beryllium and polyimide ablator layers, meeting the ignition requirements (Lindl, OV/3-1). At the same time, the first graded-dopant Be capsules still do not meet specifications for surface smoothness and further improvements are needed. A major advance was the development of microencapsulation techniques to produce a large number of high-quality mandrels in batch mode, and the development of decomposable mandrels (Kilkenny, FT/2-1Ra). Substantial progress has been made in metallurgical techniques for the refinement of the grain size of the bulk Be metal. Methods to diagnose DT layers in beryllium capsules with the phase-contrast x-ray radiography are under development.

Since beryllium is not permeable for DT, filling of the Be-ablator capsules with DT poses another challenge. Currently developed schemes for filling Be shells involve a ‘drill and plug’ scenario, using a laser for drilling and weld-sealing of the hole after filling, and insertion of a fill tube of a few micrometres in diameter (Lindl, OV/3-1; Kilkenny, FT/2-1Ra). Impressive progress has also been achieved in producing smooth cryogenic fuel layers: D_2 ice layers with a roughness below $1\,\mu$m rms were demonstrated recently (Regan, OV/3-3).

9. Conclusion

The laser fusion programme, based on the conventional hot-spot ignition mode, advances steadily towards demonstration of ignition and high gain at the NIF and LMJ facilities that are currently being constructed in USA and France. Remarkable progress in the confidence level and performance margin for both indirect-drive and direct-drive targets has been achieved in recent years.

Parallel to this main route, the concept of fast ignition is being explored and perfected both theoretically and experimentally. The FIREX project at ILE (Osaka) has the goal of demonstrating fast ignition and significant gain with a combination of two 50 kJ lasers, one for compression in the ns mode and the other for ignition in the ps mode. Wire-array Z-pinches have also become another competitive option for conducting single-shot ignition experiments and as a driver option for IFE.

Experimental investigations in heavy-ion-driven fusion have been focused so far on the generation, transport and final focusing of high-current ion beams. The latest innovative ideas concerning ion-beam compression and final focusing could make fast ignition with heavy ions a viable and competitive option for IFE.

List of papers on ICF presented at the 20th IAEA Fusion Energy Conference 2004

OV/3-1* Lindl J.D., Recent advances in indirect drive ICF target physics.

OV/3-2* Izawa Y Laser Fusion research with GEKKO XII and PW laser system at Osaka.

OV/3-3* (McCrory R.L.) Regan S.P., Direct-drive inertial confinement fusion research at the Laboratory for Laser Energetics: charting the path to thermonuclear ignition.

OV/3-4* Sharkov B.Yu., Acceleration technology and power plant design for fast ignition heavy ion inertial fusion energy.

OV/3-5Ra* Olson C.L., Progress on Z-pinch inertial fusion energy.

OV/3-5Rb Haines M.G., Wire array Z-pinch precursors, implosions and stagnation.

OV/3-5Rc Grabovski E.V., The research of radiating Z-pinches for the purposes of ICF.

IF/1-1Ra* Azechi H., New mitigation schemes of the ablative Rayleigh–Taylor instability.

IF/1-1Rb Li D., Effects of magnetic field, shear flow and ablative flow on the Rayleigh–Taylor instability.

IF/1-2* Logan B.G., Overview of US heavy-ion fusion progress.

IF/1-3* Holstein P.A., Update on LMJ target physics.

IF/1-4Ra* Tanaka K., Direct heating and basic experiments for fast ignition.

IF/1-4Rb* Key M.H., Comparative study of electron and proton heating for fast ignition.

IF/1-5 Nakao Y., Two-dimensional Fokker–Planck analysis of core plasma heating by relativistic electrons.

IF/P7-5 Kozaki Y., A new concept of laser fusion experimental reactor with fast ignition target.

IF/P7-14 Nagai K., Fabrication of cryogenic targets for fast ignition realization experiment.

IF/P7-26 Kalinin Yu, Study on the pulsed power fusion at the Kurchatov Institute.

IF/P7-27* Haines M.G., Fast ignition studies and magnetic field generation.

IF/P7-28 Sen Gupta S., Generation of relativistic electron beam and its anomalous stopping in the fast ignition scheme.

IF/P7-29* Nagatomo H., Development of fast ignition integrated interconnecting code (FI3) for fast ignition scheme.

IF/P7-30 Osman F., Theory of ps-laser nonlinear force driven ion beams for fusion.

IF/P7-31* Murakami M., Innovative ignition scheme for IFE—impact ignition.

IF/P7-32* Suter L.J., Recent findings in NIF ignition target physics and potential implications for IFE

IF/P7-34 Velarde G., Progress in Inertial Fusion Energy Modelling at DENIM.

IF/P7-36 Shukla M., Laser ablation induced shock pressure amplification in multi layered thin foil targets.

IF/P7-52 Starodub A.N., Laser driver for IFE: novel approach.

FT/2-1Ra* Kilkenny J.D., From one-of-a-kind to 500 000 high quality ignition targets per day.

FT/2-1Rb Norimatsu T., Development of key technologies in DPSSL system fpr fast-ignition, laser fusion reactor-FIREX, HALNA, and protection of final optics.

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