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Editorial

Topical issue on “Inertial Confinement Science and Applications”

Fusion of light nuclei is a potentially inexhaustible, environmentally attractive and economical power source for base load electrical power generation. Fusion is the process that powers the sun and stars and is a clean form of nuclear power which can contribute to the worlds energy needs. To overcome the strong electrostatic repulsion of the positively-charged reacting nuclei, the fuel must be heated to very high temperatures (in excess of roughly 100 million °C) and confined for as long as possible. At such temperatures, the fuel is a plasma in which the electrons are not bound to the positively-charged nuclei. Gravity is the confinement working in the sun and stars and two strategies have been pursued on earth to control fusion: magnetic and inertial confinement.

Although the common goal of magnetic and inertial fusion is to produce more energy from the fusion reactions than that invested in order to reach the required reaction conditions, the two approaches differ dramatically. In magnetic fusion the plasma is confined within an optimized magnetic arrangement which should prevent the plasma from touching the walls. The plasma pressure is limited by both confining magnetic fields and magneto hydrodynamic instabilities. This leads to an optimum temperature of about 10 keV and limited pressure and density inside the plasma (of the order of 10^5 Pa and 10^{20} particles/m^3, respectively). These low densities and pressures are compensated by a very large volume (of about 10^3 m^3) and long duration of the discharges (of the order of 500 seconds). In a totally different manner, Inertial Confinement Fusion (ICF) aims at creating a high temperature and high density plasma, at the expense of low volume and short duration, by isotropically compressing a spherical pellet containing the thermonuclear fuel; compression results from the high surface pressure associated with ablation caused by intense radiation of lasers, X-rays or ion beams. In both cases, the fusion burn of the plasma is sustained if confinement times and particle densities are adequately large. This is quantitatively set by the Lawson criterion, requiring that their product exceeds roughly 10^{14} seconds/cm^3.

The deuterium-tritium reaction ($\mathrm{D}+\mathrm{T} \rightarrow {}^4\mathrm{He}+n$) has the highest reaction rate at the plasma temperatures which are currently achievable; it also has a very high energy release. The neutron escapes from the plasma with a kinetic energy of 14.1 MeV and can be trapped in a surrounding “blanket” structure, where the $n+{}^6\mathrm{Li} \rightarrow {}^4\mathrm{He}+\mathrm{T}$ reaction can be used to produce tritium fuel. Because of its positive charge, the alpha particle (helium-4 nucleus) interacts strongly with surrounding material and stops rapidly, depositing 3.5 MeV of heat in the plasma. With 33 g/m^3 in natural water, the quantity of deuterium is almost unlimited on earth and one litre of water is energetically equivalent to sixty litres of petrol. In the future, other reactions involving deuterium only, helium-3, or boron are under consideration. The inexhaustible fuel supply and the potential for almost negligible environmental impact makes fusion a very promising contribution to the world wide energy problem. Nevertheless, significant technical barriers must be overcome before fusion can compete economically with other energy sources.

Controlled fusion research is pursued in most industrial countries and has made significant progress since its inception in the early 1950s. It is the purpose of this topical issue to review the state of the art of research in inertial fusion sciences and applications. This issue follows some of the major presentations at the fourth International Conference on Inertial Fusion Sciences and Applications held in Biarritz in September 2005.

The principle of inertial fusion is the following: laser or particle beams are focused onto the surface of a capsule a few millimetres in diameter, containing a small quantity of fuel. The evaporation and ionization of the outer layer of the material leads to the formation of a plasma corona. This expands and, as in a rocket, generates an inward-moving compression front which heats up the inner layers of material. The core of the fuel is thus compressed to as much as one thousand times its liquid density, and ignition occurs when the core temperature reaches about one hundred million degrees. Thermonuclear combustion spreads rapidly through the compressed fuel, producing energy equivalent to several times the amount deposited on the capsule by the beams. The period of time during which these thermonuclear reactions occur is limited by the inertia of the fuel itself; hence the term 'fusion by inertial confinement'. There are two ways of depositing the beams energy on the capsule surface. In direct illumination drive a number of laser or charged-particle beams, arranged with maximum symmetry, are aimed at the capsule. In indirect illumination drive the capsule is placed inside a metal container, called a hohlraum; the beam energy is deposited on the inner surface of this container, producing black-body radiation which is absorbed by the capsule to be imploded.

Laser inertial confinement requires highly compressed cores with densities more than 1000 times liquid density, along with ionic temperatures of a few keV to ignite the DT fuel. These requirements can be met in direct drive ICF at the expense of an optimized pulse shaping to ensure the high density through successive shocks, and an appropriate design of a hollow-shell target to ensure the formation of a hot spot. The main challenge in direct drive ICF is how to prevent or at least reduce seeding and growth of Rayleigh Taylor (RT) hydrodynamic instabilities. This puts stringent requirements on laser non-uniformities, fluctuations of power among the beams, target outer-surface roughness as well as inner interfaces that inevitably suffer distortion during the implosion. Indirect drive is less sensitive to RT instability which relaxes constraints on the aspect ratio and minimum roughness of the capsule as well as on laser beam uniformity requirements. However, parametric instabilities can be driven at the entrance window and in the gas filling the hohlraum, reducing the efficiency of the coupling of the beams with the plasma, producing beam bending and high energy electrons that may cause capsule preheating and reduce the compression.

Two very large laser facilities for inertial fusion are presently under construction: the National Ignition Facility (NIF) at Livermore, USA, and the Laser MegaJoule (LMJ) near Bordeaux (France). The LMJ and its program are presented in the paper by D. Besnard and the NIF project is presented in the paper by E. Moses et al. Both NIF and LMJ have been designed to achieve ignition, with more energy produced in nuclear fusion reactions than is brought to the target, thus satisfying the so-called break-even condition. These two systems will work within the same range of energy, one to two MJ. This is the optimal range determined by numerical simulations, and validated by experiments with previous big laser systems as well as physics done with smaller systems and the Centurion Halite program. The LMJ and NIF designs have many similarities and joint French-US efforts have led to fruitful advances in technology and lower cost of laser glass and KDP crystal production. There are however significant differences, the first being that NIF has 192 beams compared to 240 in the LMJ. Another important difference between NIF and LMJ is the focusing system of the laser beams. LMJ will use diffractive optics, allowing one to select the 3ω harmonic and to prevent the residual 1ω and 2ω light from entering the cavity, whereas NIF will use focusing lenses. Construction of NIF, as well as LMJ, was approved only after scientists and engineers demonstrated that their laser design worked by building a single laser beam line, the Beamlet for NIF and the LIL (Ligne d'Intégration Laser) for LMJ.

LIL is a full scale bundle of four LMJ beams with a maximum energy per beam of 9.4 kJ after frequency tripling (with projected upgrading to 8-beam/60 kJ). LIL is a unique facility in Europe for physics experiments within the perspective of inertial confinement fusion and high energy density physics. Twenty percent of the laser time is allocated to basic physics experiments which are selected out of submitted proposals by an international scientific community purely on the grounds of excellence and originality. The Institute of Lasers and Plasmas (ILP), under the auspices of CEA, CNRS, University of Bordeaux, and École Polytechnique, is the exclusive access point of the academic community today on LIL and later on LMJ. LIL will be essentially available for academic basic research once LMJ is fully operational. It is complementary to other facilities such as LULI in France and OMEGA in USA. A growing scientific, technological and programmatic cooperation between the various existing facilities is essential to optimize the benefits and build up a strong community able to attract and train a new generation of scientists to embrace the ambitious challenges that will come up.

Thanks to a long experience acquired over the last 30 years with such high energy laser facilities, such as the former PHEBUS in Paris and NOVA in Livermore, or the ongoing OMEGA at Rochester and LULI near Paris, safe margins on the LMJ-NIF parameters could be set. Indeed, the strong confidence that ignition will be reached within the 1.8 MJ total energy objective, is substantiated by continuous progress in many technological aspects. These are in the design of targets and the ablation processes, in the optimization of the X-conversion rate on the hohlraum walls, in controlling the parametric instabilities, in optics technology, and above all in a perfect control of all the beam power balance and pointing on target in order to ensure the required symmetry of explosion. The necessity that the target solid DT fuel remains at a cryogenic temperature below 18 K until the precise moment of the laser shot is a spectacular example of the highly stringent technological requirements.

Five papers are dedicated to these issues. The first two are dedicated to the indirect drive scheme, papers by P.A. Holstein et al. in the context of LMJ and paper by S.W. Haan et al. in the context of NIF. Laser-plasma interaction physics, symmetry irradiation, target design, wavelength of the driver, numerical simulations and diagnostic development are among the main topics. The path to ignition is being explored with hydrodynamically scaled, direct-drive implosion experiments on the 60-beam, 30 kJ OMEGA Laser System and is presented in the paper of R.L. Mc Crory et al. The advantage of the direct-drive approach is that it is potentially more efficient and could lead to a higher thermonuclear gain than indirect drive. The risk of direct drive is hydrodynamic instabilities which could prevent attainment of sufficient density in the compressed core. The NIF and the LMJ will be initially configured for the indirect X-ray drive, with no equatorial beams to symmetrically irradiate the targets. Although the implementation of a direct-drive beam configuration is planned for both systems in the future, prospects for direct-drive ignition with the X-ray drive configuration will start earlier using ingenious solutions such as polar direct drive or focal spot zooming.

Experiments have started with the two prototypes of LMJ and NIF, the LIL and NEL (NIF Early Light) respectively. The first NEL results on shock propagation, laser-plasma interaction, hohlraum energetics and hydrodynamics are reported in the paper by O. Landen et al. Illustrative aspects of the evolution of the USA Inertial Confinement Fusion (ICF) Program at Lawrence Livermore National Laboratory (LLNL), with examples of the development of diagnostics and target fabrication are described in the paper by J.D. Kilkenny. An inertial fusion program is pursued in China including laser development, target fabrication, Z-Pinch device and diagnostics. A project using a megaJoule class laser, the National Ignition Driver (NID) has been authorized. The latest advances on inertial fusion physics and drivers in China are presented in the paper by X.T. He et al. One challenge is to minimize the instabilities associated with laser-plasma interactions that lead to the loss of energy and possible preheating. Numerous physical phenomena need to be accounted for, such as non linear filament formation and self-focusing of the laser beam, stimulated Raman and Brillouin scattering on plasma density fluctuations, these instabilities possibly interacting one with the other. Some recent results on stimulated Brillouin scattering are presented in the paper by C. Labaune et al.

The fast ignition scheme appears as a promising complementary approach to hot spot ignition in direct or indirect drive approaches. The concept underlying fast ignition is to separate compression and ignition of the nuclear fusion fuel by using an external trigger to ignite the fuel. Separation of pre-compression on a low adiabat from the hot spot formation at the centre would relax the severe requirements on both laser irradiation uniformity and target design. Thus there would be no more need to ensure symmetry of implosion and minimize the hydro instabilities. The advent of picosecond petawatt laser pulses, thanks to the Chirped Pulse Amplification (CPA) technique proposed by G. Mourou provides an appropriate external trigger. Practically, fast ignition consists in creating a hot spot in the pre-compressed plasma with a high energy petawatt (HEPW) laser whereas compression has been achieved by long nanosecond laser pulses in either direct or indirect modes or ion beams. The hot spot is created by very fast particles (electrons or protons). Relativistic electrons, with currents as high as 100 MA, have already been observed. However there are major physical problems to solve, such as controlling the transport of energy from the laser interaction zone at the critical density to the highly compressed zone with densities which are several orders of magnitude higher than the critical density. One can take advantage of the self ability of the ultra intense laser beam to bore a hole into the plasma. Experiments have also shown that it is possible to guide the beam by a gold cone. Fast ignition requires laser pulses of ultra high intensity of the order of 10^{21} W/cm^2. At these intensities, relativistic plasma is formed and the underlying physics still needs to be clarified in order to have control of the ongoing phenomena and eventually the formation of a hot spot. The rapid progress in fast ignition physics yields high confidence in future facilities combining high energy nanosecond lasers and high power picosecond lasers. The path to Fusion Energy including fast ignition is discussed in the paper by M. Tabak.

A few installations are under construction to couple long and short pulses to test the concept of fast ignition. In France, the PETAL project will couple a multi-petawatt laser (3.5 kJ in 0.5 to 5 ps pulses) with the eight beams, 60 kJ, of LIL at CESTA. PETAL is the first phase of a coordinated European program, HiPER, a large scale laser system designed to demonstrate significant energy production from inertial fusion, whilst supporting a broad base of high power laser interaction science. In the USA, a HEPW capability is being constructed at Rochester adjacent to the existing OMEGA compression facility. The OMEGA EP (Extended Performance) will add two short-pulse (∼10 ps duration), 2.6 kJ beam to the 60-beam, 30 kJ, OMEGA laser system. Fast ignition research is actively conducted in Japan. A review of the Japanese program is given in the paper by O. Motojima. By coupling a petawatt (400 J/0.5 ps) laser to the Gekko XII beams, the neutron yield increased from 10^4 to 10^7. This indicates that the thermonuclear fusion is enhanced by raising the temperature of the core plasma with PW laser heating. These results and the FIREX I (10 kJ PW + 10 kJ 2ω) are presented in the paper by K. Mima et al.

Heavy ion beams is another option to compress and heat a fuel pellet, to produce fusion reactions. Heavy ions offer high energies, powers, and pulse frequencies, high efficiencies and good energy deposition. In addition, operation of accelerators has been shown to be very reliable over long periods. Other attractive features are the ballistic transport of heavy-ion beams through the reactor chamber and the excellent beam-target coupling which is well understood from basic physics of single ion stopping, in the MeV range, in dense and strongly ionized plasmas. Interaction of intense ion beams with matter is also interesting to study fundamental high-energy-density physics. A review of different aspects and applications involving the present and future ion beams and the coupling with a petawatt short pulse laser at GSI is given in the paper by D.H.H. Hoffmann et al. Finally, fusion reactions can be driven by very powerful laboratory X-ray sources as produced in pulsed power generators. Fast high-current Z-pinch experiments are being carried out studying promising schemes, but they are not described in this issue.

Inertial Confinement Fusion is at a new stage of development with the NIF and LMJ facilities now under construction in the USA and France respectively. We confidently expect that thermonuclear ignition with substantial energy gain will be achieved during the next decade. Worldwide joint efforts on three different modes of ICF, namely direct drive, indirect drive, and fast ignition, will shed light on whether an inertial fusion reactor is a reasonable albeit remote possibility. Technological barriers must be overcome before an attractive fusion reactor can be designed. In the inertial program, "drivers" such as particle beams and advanced lasers must be developed to provide repetitive compressions of the targets; plasma-facing materials and configurations must be improved to handle the exhaust power; and low activation materials would reduce the radioactive waste. These big laser installations will also open yet unexplored domains of physics of paramount importance for our fundamental understanding of matter and radiation under extreme conditions of temperature and pressure.

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