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Inertial fusion energy research

Report of consultants meetings held in
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Vienna, Austria, 16–17 June 1997,
Culham, United Kingdom, 23–24 March 1998, and
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FOREWORD

As part of its role in promoting peaceful uses of nuclear technology, the IAEA has, under the guidance of the International Fusion Research Council, carried out a programme of information exchange on the subject of inertial fusion energy (IFE) research. A series of IAEA consultants meetings was held from 1991 to 1994 to organize the writing of a comprehensive introductory book on inertial fusion by 80 experts from around the world. That book, *Energy from Inertial Fusion,* was published by the IAEA in 1995.

Subsequently, a series of four IAEA consultants meetings was held to help the IAEA keep abreast of current IFE developments and to suggest future programme plans. The first meeting was held on 14–15 March 1997, in Osaka, Japan, in conjunction with the IAEA Technical Committee Meeting on Drivers and Ignition Facilities for Inertial Fusion. The second meeting was held on 16–17 June 1997, in Vienna, Austria. The third consultants meeting was held on 23–24 March 1998, at Culham Laboratory, United Kingdom, during the Technical Committee Meeting on Fusion Power Plant Design. The fourth consultants meeting was held 20–22 October 1998 in Yokohama, Japan, during the 17th IAEA Fusion Energy Conference. This TECDOC is based on the final consultants report and contains a summary of the state of the art of IFE research in 17 countries. The sections on individual countries were sent to the governments for their comments, which have been incorporated into the present publication. This publication was reviewed by S. Nakai, and the responsible IAEA officer was T. Dolan of the Division of Physical and Chemical Sciences.

CONTENTS

1. INTRODUCTION

Fusion research is effectively developing a new energy source that is abundant, safe, environmentally acceptable, and potentially economical. There are two major approaches: magnetic fusion energy (MFE) and inertial fusion energy (IFE). These approaches have many common fundamentals including plasma confinement, heating, diagnostics, and energy production. However, they also have different temporal and spatial scales and technologies. The basic physics of IFE (compression and ignition of small fuel pellets containing deuterium and tritium) is becoming increasingly well understood. New megajoule laser facilities under construction in the USA and in France are expected to demonstrate ignition and energy gain in the next decade. Fusion power plant design studies indicate that IFE power plants are feasible and have attractive cost, safety, and environmental features. Recent declassification of many areas of inertial fusion target physics further enhances the prospects of IFE.

2. STATE OF THE ART

Fusion research has reached the point where it is appropriate to consider a strategic approach toward energy production. For example, the National Ignition Facility (NIF), USA, and Laser MegaJoule (LMJ), France, should demonstrate fusion energy gain. The feasibility of fusion power plants should be examined in parallel.

IFE physics, theory, and experiment

High density compression of fuel capsules was demonstrated in the 1980s by laser implosion experiments in the USA and Japan. The method of achieving the fusion product (density times confinement time) required for ignition has been clarified. In the next step, we have to demonstrate that a hot "spark" is formed in high density core plasmas to ignite and burn the fuel by fusion reactions. In order to investigate those research issues, driver and pellet fabrication technologies have been developed. The status of research on implosion physics is listed below:

(1) The following implosion concepts for **compression** have been explored:

   (a) Direct drive (beams or ion beams striking the fuel capsule directly). High density compressions have been demonstrated by the multi-beam laser systems in Japan and the USA. The 24 beam laser system OMEGA at LLE, Rochester achieved 100–200 times solid density (20–40 g/cm^3, deuterium plasma) (1987). The GEKKO-XII laser systems achieved 600 times solid density (600 g/cm^3, CH plasma) compression (1989).

   (b) Indirect drive (beams striking a hohlraum to produce X rays, or dynamic hohlraum based on an imploding liner). The Nova laser system achieved 100 times solid density (20 g/cm^3) compression (1986) starting from D_2 gas with the X ray drive implosion. Volume compression of 10^3 has been achieved at Iskra-5 laser facilities.

   (c) Direct/indirect hybrid drive.

(2) Methods for **ignition** of the compressed fuel capsule are as follows:

   (a) Central spark ignition.

   (b) Off-center ignition (fast ignitor concept).

   (c) Volume ignition by stagnation-free compression.

Imploded core plasmas have been heated to higher than 10 keV in the high velocity implosion and in the intermediate convergence ratio implosions. The GEKKO XII laser and the Nova laser have imploded glass micro-balloons filled with DT gas to yield more than 10^{13} neutrons/shot (1986). Recently, the upgraded OMEGA-laser at Rochester generated 10^{14} neutrons/shot (1996). In those experiments, the plasma density is on the order of solid density.

In terms of high convergence implosion, the indirect implosion by Nova demonstrated the clear core neutron yield, which is consistent with 1D simulation result of radial convergence ratios up to 20. However, in the high density implosion experiments, the neutron yield is degraded in comparison with the 1D-simulation predictions.

As for off-center ignition, experiments on ultra-intense laser–plasma interaction have begun at many laboratories (RAL (UK), LULI (France), ILE (Japan), LLNL (USA), and so on). The laser beams are found to penetrate into higher density plasmas by hole boring.

(3) Theory and **simulation** studies being developed are as follows:

- (a) Compressible sheared flow hydrodynamics.
- (b) Laser absorption and electron heat transport.
- (c) X ray radiation heat transport and optical properties of materials.
- (d) Equation of state for plasmas and solid state matter.
- (e) Liner implosion magnetohydrodynamics.

For high-gain target design, several integrated implosion simulation codes are under development by taking into account many phenomena in one, two, or three dimensions. The codes are being tested with recent hydrodynamics experimental data.

IFE technology

Inertial fusion technology includes the driver, fuel pellet, diagnostics, and reaction chamber. Current status of each technology is summarized here. Activities of the laboratories in countries where IFE relevant research is conducted are summarized in Section 4.

(1) Driver

Implosion experiments have been conducted with multi-beam high power lasers and pulsed power generators. The primary laser driver systems are Nova (40 kJ/10 beams, USA), GEKKO (10 kJ/12 beams, Japan), OMEGA (3 kJ/24 beams, USA), PHEBUS (8 kJ/2 beams, France), VULCAN (2 kJ/6 beams, UK), ISKRA-5 (12 kJ/12 beams, Russia), SG-1 (2 kJ/2 beams, China). The principal pulse power systems are PBFAII/Z (20 MA, 55 TW, USA), and ANGARA5-1 (5.5 MA, 6 TW, Russia). OMEGA has recently been upgraded to 40 kJ/60 beams. Multi-beam megajoule lasers are technically well understood. The National Ignition Facility (USA) and a prototype beam array (LIL) of the Laser MegaJoule (France) are under construction. Irradiation uniformity, temporal pulse shape control, and reliability of operation have been developed for quantitative, well-characterized single-shot experiments. In order to demonstrate near term technical feasibility and to promote long term economic feasibility, based on efficiency and high pulse repetition rates, potential IFE drivers are under development. These drivers include diode pumped solid state lasers (DPSSL), KrF excimer lasers, heavy ion beams (HIB), liner implosions, light ion beams (LIB), and several other advanced concepts.

(2) Fuel pellets

Glass micro balloons and plastic micro balloons of various sizes can be fabricated close to the quality of sphericity and surface smoothness necessary for IFE. Coatings of various materials on the capsule and tracer gases for diagnostics have been used for single shot physics experiments. Pellets with diameters of 1–5 mm filled with liquid fuel are required for an ignition and energy gain experiment. Fuel capsule fabrication techniques, cryogenic fuel technology, liquid fuel layering, fuel pellet handling, and pellet injection are being developed in laboratories throughout the world. For power plants, mass production of low cost fuel pellets, pellet injection and tracking, and guidance systems with good reliability will be required.

(3) Diagnostics

The implosion process is characterized by the emissions of X rays, charged particles, and neutrons. Pictures of the target shells are obtained at various times using temporal streak and framing diagnostics with X rays and with X ray interferometry. Spatial resolution of 10 mm, particle energy resolution of 100 eV, and time resolution of 30 ps (framing camera) or 2 ps (streak camera) have been achieved. Combined measurements using several techniques are essential for the quantitative analysis of imploded core parameters and shell stability.

(4) Reaction chamber

The reaction chambers for single-shot ignition and gain experiments have been designed under conventional engineering rules using current materials (such as aluminum, boron, and stainless steel). Special techniques for wall cleaning have been developed. Radiation shielding, activation by neutrons, and radiation damage must be considered in more detail for the engineering design of IFE facilities.

Fusion power plant design results

The publication "*Energy from Inertial Fusion*" (IAEA, 1995) summarizes the reactor design studies and identifies the technical issues that are important for the development of inertial fusion energy.

The system composition of IFE power plants and the related design issues are:

(1) Driver (efficiency, pulse repetition rate, cost, lifetime, laser or HIB options, etc.).

(2) Pellet fabrication, injection, and tracking (required uniformity, measurement and control system of injection).

(3) Reaction chamber (first wall protection, restoration of chamber conditions for beam propagation and pellet injection, neutron shielding, protection of final optics).

(4) System issues, such as system optimization, economics and safety analysis (direct/indirect drive, lasers/ion beams, modular plant design).

Most of the chamber designs use internal flowing blankets of liquid metal, molten salts, or solid granules to protect the structural wall. Such designs reduce the damage on the structural wall by radiation, shock, and heat flux; facilitate a long chamber lifetime; reduce the volume of radioactive waste material, thus improving its qualification for disposal; and increase the plant's availability.

IFE research is now at a stage where large benefits can be obtained from a co-ordinated approach, with activities to:

- promote fusion energy development;
- promote world wide co-operation;
- encourage plasma/fusion technology transfer;
- emphasize safety and environmental advantages of fusion energy.

3. IFE ISSUES

Physics, theory and experiments

The research on the inertial fusion physics issues concentrates on establishing the energy gain scaling of implosion fusion with the evaluation of the tolerable non-uniformities of laser irradiation and fuel pellets.

(1) Formation of hot spark in direct and hybrid drive:

- Precise control of absorbed laser intensity distribution.
- Characterization of effects of foam buffer layer.
- Effects of X ray prepulse on uniformity.

(2) Formation of hot spark in indirect drive:

- Improvement of X ray radiation uniformity in a cavity.
- Increase of cavity radiation temperature.

(3) Sensitivity of fusion gain to implosion stability and non-uniformities of irradiation and pellet:

- Researches on imprint, feed-through and hydro-instability of ablative acceleration and stagnation.

(4) Improvement of the integrated code for investigating gain scaling and high gain pellet design:

- Numerical modeling of initial phase equation of state of the target and laser absorption characteristics.
- Numerical modeling of turbulent mixing.

(5) New concepts for ignition:

- Ultra-intense laser–plasma interactions.
- Target design for fast ignition.
- Simulation modeling of short pulse laser propagation and absorption.
- Generation and transport of hot electrons, fast ions and hard X rays.

Technical issues

According to our present knowledge, the required specification for the ignition and gain is a pulse energy of about 5 MJ to be delivered within 10 to 30 ns with appropriate pulse shaping. Spatial and temporal control of beams with the imploding target is necessary. Specifically for the reactor plant an overall efficiency of >10%, a repetitive operation of about 10 Hz (one or several reactor cavities), and a life time of about 10^{10} pulses (30 years) are desired. The existing driver concepts fulfil some of these requirements already; the others need extended development programmes. The reliability and redundancy of all subsystems is a general issue for all driver candidates as well as the cost for construction, operation, and maintenance. The inertial fusion technical issues for drivers, target technologies, diagnostics, and reaction chambers are as follows:

(1) Drivers

(1-1) Laser beam drivers

— Energy of several MJ.
— Wavelength shorter than 500 nm.
— Intensity uniformity of irradiation.
— Pulse shaping under saturation amplification.
— Spatial control of beams with an imploding target.
— Overall efficiency approximately 10% and greater.
— About 10 Hz repetitive operation under thermal control.
— Lifetime capability (about 10^{10} pulses).

There are active programmes worldwide on two laser candidates: diode pumped solid-state lasers (DPSSLs) and gas lasers, mainly KrF and iodine.

(1-2) Heavy ion accelerators

— High current acceleration maintaining the required brightness up to final.
— Focusing.
— Sequential merging of beams into one.
— Spatial adaptation of beams to the needs of target design.
— High efficiency of conversion to X ray radiation and radiation confinement (indirect drive).

The high repetition rate and high efficiency (electrical into beam energy of about 20%) are the favorable features of present heavy ion accelerators. Ion sources with adequate current and brightness have been developed. Two types of heavy ion drivers are being investigated in the framework of extensive national research programmes, the rf-linear accelerator with storage rings (Europe) and the induction linac (USA).

(1-3) Light ion beam drivers and liner implosion

— Brightness of diode beams, improvement by two-stage acceleration.
— Repetitive diode operation and life time.
— Pulsed-power generators for high voltage.
— Pulse shaping.
— Suitable beam transport and final focusing scheme through plasma channels.
— Efficient coupling of electric energy to radiation (liner implosion).

The relatively low capital cost of the driver and the modular concept of the pulsed power and diode or liner units are the favorable features of the approach.

(2) Target technology

- Large and thin capsule formation.
- Fine coating of various materials on pellet.
- Cryogenic hydrogen fueling and layering.
- Well defined sputtering on the target surface for quantitative physics experiments.
- Mass production method for repetitive operation.
- Fuel target acceleration and injection into the reaction chamber.
- Tracking of injected target and shooting.
- Characterization of fuel target on material composition, sphericity.
- Uniformity, and surface finish.

The quantitative specifications of the above issues for ignition and gain experiments and for reactors are summarized with the information about the laboratories that are working on fuel target technology.

(3) Diagnostics

- Space-, time-, and energy-resolved X ray emission measurement for temperature and density mapping of implosion.
- Space-, time-, and energy-resolved neutron emission measurement for the fusion reaction and core plasma diagnostics.
- Time-, and energy-resolved charged-particle emission measurements.
- Active measurements applying probing beams of X rays, ion beams, or neutron beams.

The physical processes and parameters diagnosed by the sophisticated methods are:

- Implosion stability at the phase of acceleration, feed through, deceleration and stagnation.
- Plasma parameters and dynamics of the fusion reaction region including ignition and burning.
- Energy relaxation of fusion core, and spectrum and species of energy emission.

(4) Reaction chambers

- Mechanical response of reactor chamber, dynamics of first wall which include X ray and debris absorption, evaporation, shock formation, and fatigue of structural material.
- Radiation damage, neutron activation, and shielding.
- Restoration of chamber environment for driver beam and pellet injection, thermal and dynamic response of the first wall against pulse loading, fluid dynamics inside the large chamber cavity, evaluation of the effect of cavity conditions on driver beam, pellet injection and tracking.
- X ray absorption by Xe gas for dry wall concept and for protection of final optics.
- Damage protection of final element of driver beams, radiation shielding against streaming.
- Tritium breeding blanket and extraction.

— Safety and environmental requirements on operational and accidental conditions.

There are several different reaction chamber concepts to overcome above listed issues. They span from dry wall to thick flowing liquid wall concepts. The assessment of technical issues being based on these design studies is required. This would be best achieved by international collaboration.

4. INTERNATIONAL CO-OPERATION AND BENEFITS

IFE research is conducted in about 17 countries and is based on many fields, including plasma physics, optics, laser engineering, electrical engineering, electronics, mechanical engineering, nuclear engineering, material technology, computer technology, and systems analysis. Therefore, to maximize efficiency, co-ordination is needed between countries and various fields of specialty. International co-operation can have the following benefits:

(1) Avoidance of duplication

Co-operation may help avoid duplication of efforts, which could waste resources.

(2) Acceleration of progress

Manpower sharing.
The expertise of several countries could be combined into a powerful team.
Knowledge sharing.
Theory, computations, experiments, materials, and technology could be shared.
Cost sharing.
Cost-sharing could make expensive projects affordable, in spite of low budgets.

(3) Capability development

Developing countries could improve their R&D capabilities as a result of co-operation with other laboratories.

(4) Government confidence

Governments might be more willing to support international collaboration projects because they would have greater confidence in the value of those projects. IFE research is also producing many spin-offs in basic sciences and industry.

Many laboratories throughout the world that are conducting IFE and closely related research participated in the Technical Committee Meeting on Drivers and Ignition Facilities for Inertial Fusion in Osaka on 10–14 March 1997. The progress of research was presented at that meeting and details can be found in the proceedings of the meeting. We present the research status and plans of countries with IFE related research in the following sections. These reports in many cases do not describe formal programmes but rather IFE relevant research as judged by the consultants and experts. The length of each individual report does not necessarily represent the size and contribution of the IFE programme in that country.

4.1. Australia

Experiments carried out over many years at the Laser Physics Center of the Australian National University (ANU) in Canberra resulted in measurements of the nonlinear (ponderomotive) force, self-focusing, tunnel ionization, reduction of the anomalous absorption, and finally the discovery of the 10 ps stochastic pulsation of laser–plasma interaction. The penumbral X ray diagnostics were developed there and later extended at Livermore to neutron imaging.

Theoretical studies of laser–plasma interaction and of pellet fusion gains are being undertaken at the Department of Theoretical Physics at the University of New South Wales (UNSW) in Sydney. The first generally valid relativistic self-focusing relation was derived and the genuine two fluid model arrived at the discovery of inverted double layers and strong internal electric fields in the highly inhomogeneous laser driven plasma. The 10 ps stochastic pulsation could be explained by self-generation of a (Brillouin-like) density ripple for Laue reflection with its pulsating decay. This would explain why broad-band laser or other smoothing techniques can suppress the rippling, resulting in low reflectivity and smooth transfer of optical energy into plasma at direct drive.

For the methods of ignition of compressed fuel, the alpha reheat and bremsstrahlung re-absorption with the isentropic (self-similarity) compression led to the discovery of the high gain volume ignition.

The Central Queensland University in Rock Hampton, ANU, and UNSW are co-operating on 100 fs experiments of tunnel ionization. Mechanisms for the fast ignitor are studied in contact with centers outside Australia.

4.2. Canada

Canada currently has no dedicated IFE target facilities but is nonetheless performing fundamental work in IFE through its universities, government-supported institutes, and foreign collaborations. The main centers of IFE focused work in Canada are at the Institut National de la Recherche Scientifique (INRS) in Quebec, the University of Alberta (UA), and the University of British Columbia (UBC), while work related to IFE is ongoing at other universities such as Waterloo, Toronto, and Laval and at the National Research Council (NRC) and at the Hydro Quebec Research Institute (IREQ). UBC researchers are studying equation of state of materials both in Canada and collaboratively in the USA, UA workers are active in fast ignitor research with collaborations in the USA, United Kingdom, and France. Fundamental laser–plasma interaction studies, diagnostic developments, and IFE relevant theory and simulations are active at INRS and NRC. Canadian IFE researchers have utilized CO_2, Nd:glass and KrF lasers and have recently concentrated on short pulse laser systems (both KrF lasers and solid state lasers using chirped pulse amplification). Canada has benefited from its IFE related studies through interdisciplinary research with other fields and industrial spin-offs.

4.3. China

The Chinese IFE programme is working towards a fusion energy source for the 21st century.

In the past ten years, the fundamental research for both laser–plasma interaction and implosion dynamics of target physics, which is the main tasks of both Institute of Applied Physics and Computational Mathematics (IAPCM) theoretically in Beijing and Southwest Institute of Nuclear Physics and Chemistry (SWINPC) experimentally in Sichuan, was conducted on the solid state laser Shenguang-I (SG-I 2kJ/2 beams) at National Laboratory of High Power Laser and Physics (NLHPLP) in Shanghai, which retired in 1994. The neutron yield from thermonuclear reactions was observed in the imploding process in 1990, and was repeated in 1991. In addition, there has been another solid state laser called Xingguang-II (XG-II) at SWINPC, which is of hundred-Joule output, available for IFE physics research. In order to further develop IFE in China, an overall plan was completed in 1992, and the National Hi-Tech ICF Committee was officially authorized and established in 1993 to organize and support the scientists from institutes and universities in China to do IFE research work.

The new solid state lasers, Shenguang series, are planned and developed. The SG-II at NLHPLP, which has output laser energy of 6 kJ at wavelength λ = 1.05 mm and 3 kJ at λ = 0.35 mm, will be operational in 1997. A project to build a new generation facility, SG-III, which will be serving IFE physics research before ignition, is expected to be completed in 2005. To meet those requirements, the SG-III design will have output laser energy of 60 kJ with 60 beams at λ = 0.35 μm. The architecture for SG-III will adopt many advanced technologies. Two steps for the SG-III have been decided; the first step is to construct a two-beam prototype as a synthesized test bed in 2000–2001, and the conceptual design was finished in 1997; the second step is to complete SG-III. The ignition facility, SG-IV, will commence in 2010.

The KrF excimer laser named Heaven-1 (H-1) at the China Institute of Atomic Energy in Beijing is one of the candidates for drivers in IFE in China, and is operating and under development. Furthermore, short pulse technology and drivers for fast ignition are also in progress.

The target physics research for IFE stresses theoretical and experimental research, diagnostics, target fabrication that are being developed in a co-ordinated effort. The reactor design is mainly at Tsinghua University and IAPCM in Beijing.

4.4. Czech Republic

The Academy of Sciences of the Czech Republic keynote research area No. 8 is “Physics of plasmas and the interaction of radiation with matter”. The Institute of Physics, Academy of Sciences of the Czech Republic is proceeding with the research.

The iodine photodissociation laser system, Perun, at the Institute of Physics, produces pulses of infrared light (1.315 μm), which are 500 ps long with an energy of 40 J and can be focused in a diameter of 100 μm. The attainable power density on the target is thus roughly 10^{15} W/cm^2, enough to form a high temperature (1 keV) laser plasma. Conversion to the second (2λ and third (3λ) harmonics with about 50% efficiency is possible using a pair of deuterated-KDP crystals. The system is routinely used for target experiments.

Fusion related research is concentrating on model experiments relevant both for direct and indirect drive. The first case is represented by attempts to smooth out the ablation pressure profile on the target, where the inhomogeneity is imprinted by the laser beam. Using a plasma formed by a weaker prepulse of the red (2λ) light, the main blue (3λ) may have its profile smoothed out by passing through. For indirect drive, the passage of the laser light through a tiny hole in a foil target was studied. This situation is simulating the illumination of the inner surface of a hohlraum where the light is entering through a small entrance hole.

Other lines of research are concerned with the illumination of high-Z targets and examination of the ion charge and energy spectra in the expanding plasma far from the focus.

Ni-like ions ($Ta^{45}+$, $Pb^{54}+$, $Bi^{55}+$, etc.) and beyond are identifiable in the fast ion groups observed in the spectra. The ion composition is of interest for the development of an ion source for large colliders as well as for ion implantation.

If the focus is extended, a plasma column is formed, which in turn may serve as a laser medium for an X ray lasing. Though the power density on the target is severely reduced when extending the focal spot, a viable scheme of lasing using the Ne-like $Fe^{16}+$ ions has been proposed. The pumping scheme also relies on a weak prepulse, and the wavelength scaling favors the iodine laser over the Nd:glass. In a preliminary study, the prepulse plasma was examined by optical interferometry.

4.5. France

In France, the research programme on fusion energy is developed at the CEA (Commissariat à l'Energie Atomique), and is based on MFE.

However, activities relevant to IFE are conducted at different institutes:

(1) Laboratoire de Physique des Gaz et des Plasmas (LPGP), Université Paris Sud-Orsay; research on HIF.
(2) Laboratoire pour l'Utilisation des Lasers Intenses (LULI), Unité Mixte CNRS, Ecole Polytechnique, Palaiseau; research on laser–matter interaction physics.
(3) Commissariat à l'Energie Atomique/Direction des Sciences de la Matière (CEA/DSM), Centre d'Etudes de Saclay, research on laser IFE.

The Centre d'Etudes de Limeil-Valenton (Commissariat à l'Energie Atomique, Direction des Applications Militaires) has been carrying out a laser programme devoted to nuclear weapons physics for nearly 35 years. This centre was closed in 1999, as France decided to build a megajoule class laser facility at CESTA (Centre d'Etudes Scientifiques et Techniques d'Aquitaine) near Bordeaux.

The LMJ (acronym for Laser Megajoule) is intended to reach thermonuclear ignition and study the burn of DT capsules by means of X ray driven implosion.

The main specifications are:

— energy: 1.8 MJ,
— power: 500 TW,
— wavelength: 351 nm.

According to the schedule, reaching the final level of 1.8 MJ is expected before the year 2010.

4.6. Germany

1. Heavy ion beams

Activities are focused on the *investigation of basic problems of IFE* with heavy ions and of *key issues of driver and target physics*. They are carried out predominantly at the Gesellschaft für Schwerionenforschung (GSI) accelerator facilities in collaboration with a number of universities and research centers. The facilities are:

(1) A linac for all ion species up to 10 MeV/nucleon;

(2) A heavy ion synchrotron (1 GeV/nucleon);
(3) A heavy ion storage and cooler ring;
(4) A Nd-glass laser (150 J, 15 ns) used in combination with the ion beam.

Intensity upgrade of the injector by a factor of 100 for the very heavy ions (e.g. lead) is now under construction and will be finished by 1999, opening new opportunities for the plasma physics and beam dynamics research programmes.

Topics of experimental and theoretical research are as follows:

— The interaction of intense heavy ion beams with matter (especially with dense plasmas).
— Atomic physics and materials issues of IFE.
— Diagnostic techniques for dense plasmas.
— Fine focusing of ion beams, in particular by plasma lenses.
— Ion sources, low-energy acceleration of intense ion beams.
— Dynamics of space charge dominated beams.
— Numerical simulations for target physics and target performance.

By the initiative of GSI Darmstadt, ENEA Frascati, DENIM Madrid, and the Research Center Karlsruhe, the European Study Group was established in 1995 with the aim of elaborating on an accelerator concept for the next logical step towards a heavy ion reactor driver facility. Participants in this study are:

— GSI, CERN (Geneva), Frankfurt University, Rutherford Appleton Laboratory and FZ Juelich for accelerator issues.
— ENEA Frascati, VNIIEF Arzamas, Frankfurt University and MPQ Garching for target issues.
— LPGP Orsay, Erlangen University, ITEP Moscow and IPC Chernogolovka for ion beam–target interaction.
— DENIM Madrid and FZ Karlsruhe for reaction chamber issues.

GSI is in the process of developing a long term perspective for a future heavy ion high-intensity accelerator facility for the nuclear physics and plasma physics user community. Future research in *IFE plasma and accelerator physics* is playing an important role in the present discussions of the scientific programme at such a facility. It has been decided to establish a Nd-glass laser facility operated in two modes (1 kJ at 1–10 ns and 400 J at 500 fs) to be used for experiments with combined laser and heavy ion beams.

2. Light ion beams

The light ion programme is carried out at FZ Karlsruhe at a pulsed-power facility, KALIF, a voltage generator of 1 MV producing a power of 1 TW and a specific power density in a target of 200 TW/g. An upgraded facility for 6 MV, KALIF-HELIA, is under construction. Research is concentrated predominantly on the investigation of materials properties at high temperature and pressure.

System studies for a light ion driven power station (LIBRA, LIBRA-Lite, and LIBRA-SP) have been accomplished in collaboration with Wisconsin University. In addition, the development of light ion diodes is a substantial part of the Karlsruhe research programme.

3. Laser beams

Activities on IFE target physics are carried out at the laser facilities of the MPQ in Garching. The working horse of the past decade, the high-power Iodine laser facility Asterix (1 kJ, 2 ns) has been replaced by a new femtosecond-laser, the Ti-sapphire laser facility ATLAS.

The programme includes opacity and shock wave experiments for determining the equation of state of material in the pressure regime of multi-ten Mbar (Cu, Au). Opacity measurements address the radiation-dominated energy transport in indirectly driven fusion targets. Shock wave investigations provide useful information on the materials enclosing the hohlraum and for a refined estimation of its temperature. X ray laser experiments aim at developing illumination sources, minimizing the pump power demand, and being suited for probing the high density plasmas by interferometric techniques. First experimental efforts related to the *fast-ignitor* concept were started. These investigations strongly benefit from the results of a recently developed 3-D particle in cell code, which simulates the interaction of an ultra-short laser pulse with an underdense or overdense plasma in the regime of relativistic intensities (1017 to 1020 W/cm^2).

4.7. India

IFE related research was started in India at Bhabha Atomic Research Centre, Bombay, in 1975, using a 10 GW/5 ns single beam glass laser chain and a range of plasma diagnostics. Initial experiments provided several interesting measurements, such as energy balance, energy transport (lateral/axial) coronal jetting, optical/X ray driven ablation and stabilization of fluid instabilities.

In 1985, a project to build a four beam 2 TW/3 ns phosphate glass laser was started. Development work on high-quality laser glass, high-damage-threshold optics, flash lamps, etc. was also started in parallel.

In 1993, the entire IFE programme was shifted to a new laboratory now known as the Centre for Advanced Technology (CAT) at Indore in Central India. At present, the IFE programme has constructed a kilojoule/3 ns four-beam phosphate glass laser in operation and use. In addition, several smaller glass lasers in the ps and ns regime are also being used for diagnostic development purposes. The irradiance level in the present experiments is in the range of 10^{12}–10^{15} W/cm^2 at 1.054 μm wavelength.

The main emphasis of the present programme is to understand the physics of dense plasmas, equation of state at extreme conditions, radiation physics, fluid instabilities in IFE, and their control.

The programme maintains regular collaboration with some major research and educational institutes. Major collaborative institutes are:

(a) Theoretical physics divisions (Bhabha Atomic Research Centre, Bombay)

Areas of interest: include hydrodynamic codes, fluid instabilities.

(b) Physics department (Indian Institute of Technology, New Delhi)

Areas of interest: parametric instabilities, coronal physics, turbulence, ultra-short laser–plasma interaction.

(c) Jadavpur University Calcutta

Areas of interest: Radiation transport, self-magnetic field generation, plasma jetting.

4.8. Israel

The main IFE research in Israel is carried out at Soreq NRC with the purpose of understanding the physics and building a miniature magnetic bottle induced by circularly polarized laser light.

The concept of the miniature magnetic bottle relies on the hybrid use of inertial and magnetic confinements and megagauss field generation by circularly polarized light (CPL). The schematic structure of this configuration is as follows: A DT plasma is created inside a cylindrical or a spherical heavy conductor (or superconductor) shell with a hole. The plasma is irradiated by an intense circularly polarized laser beam. The CPL creates a toroidal current in the plasma, which in turn induces axial magnetic fields inside and outside the plasma in addition to the toroidal magnetic field formed by the (grad n) × (grad T) mechanism. The plasma is heated resonantly by the CPL to about 5 keV during a time of a few ns. After the laser is turned off, a process of expansion and diffusion of the magnetic field lines begins into both the walls and inside the plasma.

The main difference between ICF (with high compression) and the present proposal (without compression) is that the necessary compression for a spark ignition scheme in ICF is not required.

IFE plasma physics activities in Israel:

(a) Hebrew University

- Interaction of femtosecond lasers with matter.
- Atomic physics of highly ionized atoms in plasma.

(b) Weizmann Institute:

- Spectroscopy of plasma physics of ion beam diodes.
- Plasma, switches and Z-pinches.

(c) Negev NRC

- Transport phenomena (charged particles, electrons, X ray in IFE plasmas).
- Atomic physics of highly ionized atoms in plasma.
- Hydrodynamic instabilities under ablatively driven acceleration typical of IFE plasmas.
- One- and two-dimensional self-similar solutions to the burn propagation problem and its relation to the ignition criteria of IFE targets.

(d) Soreq NRC

- Laser induced shock waves.
- Magnetic and electric fields in laser–plasma interaction.

4.9. Italy

Most of the fusion activities in Italy are co-ordinated by ENEA in the framework of the Association EURATOM–ENEA on Fusion. The same applies to IFE.

The mission of the Italian IFE activities in the Association is to “maintain a critical evaluation capability on IFE physics and technology”.

In the Association IFE activity is conducted at ENEA Fusion Division in the Center for Energy Research in Frascati (Laboratory of ICF Physics and Technology). The research installation is the ABC facility, which is powered by a 2-beam Nd^{3} + glass laser (100 + 100 J at 1.054 µm, max. diameter = 75 mm, conversion to 2 ϖ). This is the principal experimental facility on IFE in Italy.

Research topics: ablation induced hydrodynamics, hydrosimilar experiments, smoothing techniques for on-target laser energy deposition, code development (1D, 2D), advanced IFE schemes.

Outside the Association there are groups in universities and research institutes working on IFE theory and on theoretical and experimental subject related to light matter interaction. These activities are supported with national funding and with UE programmes such as “Training and Mobility of Researchers” and “Access to Large Scale Facilities”.

The main groups are:

1. INFM (National Institute for Physics and Matter), Milan

   “Fisica dei plasmi densi prodotti da laser”.

   Activities are conducted in collaboration with European institutes, such as LULI and Rutherford Appleton Laboratory.

   Main interest: equations of state of condensed matter, shock dynamics, X ray sources.

2. CNR-IFAM (Institute of Atomic and Molecular Physics), Pisa.

The group uses two laser systems, one capable of producing about 10 J in 7–10 ns, the other up to 10 GW in 30–40 ps together with refined diagnostic equipment. Activities are conducted, in co-operation with several European laboratories, on: generation and application of short X rays pulses, interaction of very high intensity laser pulses with solid materials.

4.10. Japan

The Institute of Laser Engineering (ILE), Osaka University is the center of Japanese Inertial Fusion Energy research. It is expected to co-ordinate the Japanese activity, which proceeds mainly in Universities, and which are financially supported by the Ministry of Education. The Electro-Technical Laboratory (ETL) of the Ministry of International Trade and Industry (MITI) is proceeding with the development of a KrF laser for inertial fusion.

The co-ordination of the inertial fusion activities is summarized as follows.

(1) Implosion experiment: ILE.

(2) Driver technologies:

- Lasers: ILE, ETL, Tokai University, Osaka, Institute of Technology.
- Particle beams: Tokyo Institute of Technology, Technical University of Nagaoka, University of Tokyo, Kumamoto University.

(3) Pellet fabrication: ILE, Gifu University, Kinki University, University of Tokyo, Kyushu University, and Toyama University.

(4) Diagnostics: Hokkaido University, Gifu University, Hiroshima University, ILE.

(5) Simulation code development: ILE, Tokyo Institute of Tech., Okayama University, and Kyushu University.

(6) Reactor technology and design: Kyoto University, University of Tokyo, ILE ETL, Kyushu University National Institute of Fusion Science (NIFS).

The major facility for the implosion experiments is the GEKKO XII glass laser at ILE, which has 12 beams and 10 kJ in a ns pulse of 3λ. The 13th beam of short pulse (0.5 ps) and high intensity (100 TW) output has been recently implemented for the fundamental experiments on the fast ignitor concept. The ILE is reorganized to demonstrate the scientific feasibility of high gain implosion with new ignition schemes. The KrF laser system Super-ASHURA (12 beam, 3 kJ) at ETL has been commissioned recently for the laser–target interaction experiment at UV wavelength.

Taking into account the recent progress on implosion experiments and the construction of giant lasers for ignition experiment, the R&D of IFE reactor technology has been initiated. The key technical issue for that is the development of a driver that has the capability of MJ-pulse output energy with high efficiency up to 10%, and repetitive operation of a few Hz. The system design of a laser fusion power plant for example KOYO is proceeding to evaluate the technical and economical feasibility of IFE.

4.11. Korea, Republic of

The Republic of Korea has several acting groups related with IFE research work.

The Korea Advanced Institute of Science and Technology (KAIST) completed a high power Nd:glass laser system (Sinmyung Laser, 2 TW with 40 ps) in 1994 under a National Project for the basic research and educational works on IFE. KAIST has also developed a ultra-short-high-power laser system (2 TW, 30 fs Ti:sapphire) and several high power laser systems (iodine and CO2 lasers) for laser–plasma interaction studies. They work on nonlinear optics such as stimulated Brillouin scattering phase conjugation and Raman conversion, high-harmonic generation, high density gas jet experiments, and spectroscopy of atomic and highly ionized states.

Postech has developed a 30 GW Nd:glass laser system (10 joules, 3 ns) for X ray generation. Chongju University is working on LD (laser diode) pumped solid-state laser systems for the next generation high power laser system.

The Korea Atomic Energy Research Institute (KAERI), the biggest working group in lasers and their applications in the Republic of Korea, has various activities related with IFE. One of the main activities is the development of high-power lasers and their related technologies. Many types of lamp-pumped multi-stage Nd:YAG lasers have been developed. Various optical pumping methods by using laser diodes are being investigated, and high-current stable power supplies for laser diodes are also under development. The activities in KAERI also include a study on non-linear optics for efficient conversion of fundamental frequency into higher harmonics. Laser induced Breakdown Spectroscopy (LIBS) has been studied for several years in KAERI for the purpose of plasma diagnostics as well as analytical purposes.

The Atomic, Molecular, and Optical Database System (AMODS) of KAERI contains numerous data related to fusion science, including charge transfer data between atoms and ions, backscattering coefficients of light ions from solids, sputtering yields, and so on. The AMODS of KAERI is now a member of the Data Center Network for Fusion Research supervised by the IAEA.

4.12. Poland

1. Investigations relating to IFE are being accomplished in Poland within the programmes on the study of physics and applications of plasma with thermonuclear parameters. These programmes are included in the activity of the institutes subordinated to the National Atomic Energy Agency, namely the Institute of Plasma Physics and Laser Microfusion (IPPLM) in Warsaw and the Soltan Institute for Nuclear Studies (SINS) in Swierk near Warsaw. These programmes are financed mainly by the State Committee for Scientific Research.

2. Investigations relating to IFE are being performed at the IPPLM in two departments, the Laser-Produced Plasma Department and the Magnetized Plasma Physics Department, and at the SINS in the P-5 department, the Plasma Physics and Technology Department.

3. Investigations on IFE use the following equipment:

    (i) At the IPPLM:

    - a two-beam Nd laser (2 × 20 J, 1 ns) with a plasma chamber equipped with a diagnostic apparatus,
    - a one-channel Nd laser (20 J, 1 ns) with a plasma chamber equipped with a magnetic coil generating magnetic field of up to 50 T and with a diagnostic apparatus,
    - a high-power laser (1 J, 1 ps, 1 TW) with a plasma chamber equipped with a diagnostic apparatus,
    - a high-current generator, PF-1000 (1.2 MJ, 40 kV, 12 MA), connected to a plasma chamber for discharges of the “plasma-focus”, “pinch” and “imploding liner” type.

    (ii) At the SINS:

    - a “plasma focus” device, PF-360 (360 kJ, 50 kV, 3 MA).

4. The main research topics related to IFE in progress in Poland are:

(i) Investigations of the properties of a laser-produced high-Z plasma by means of ion and X ray diagnostics with reference to indirect-driven laser fusion (properties of the plasma generated on the inner hohlraum wall).

(ii) Investigations on the possibility of controlling the dynamics of a laser-produced plasma near the hole in the hohlraum target by means of an external magnetic field.

(iii) Investigations of fast liner implosion by means of a high-current pulse for compression and heating of a thermonuclear plasma.

(iv) Investigation of the possibility of application of the PF-1000 (plasma focus) system as an intense pulsed source of fast neutrons and X rays for investigations of their influence on various materials.

(v) Investigation of the inertial and magnetic confinement of plasma generated in a "plasma-focus" type of discharge.

Research topics (i)–(iv) are being investigated at the IPPLM, and topic (v) at the SINS. All the above mentioned work is performed in broad international collaboration, mainly with research centres in Russia, the Czech Republic, Italy, Germany, and the USA.

4.13. Portugal

1. Activities relating to IFE in Portugal are restricted to one laboratory belonging to the Instituto Superior Tecnico, the leading engineering school in the country. This laboratory is called Grupo de Lasers e Plasmas (GOLP). The research team is composed of 16 researchers, 4 of whom are PhD researchers.

2. The main financing agency is Junta National de Investigacao Cientifica e Technologica (JNJCT). We receive money through several different projects concerning topics closely (but not explicitly) related to IFE research. Since 1997, we have also received financial support from EURATOM, for keeping in touch with activities on inertial confinement.

3. The main facility is a 20 terawatt laser system, delivering a pulse with a duration of 500 fs and a repetition rate of one shot per minute. It is based on a Nd YLF oscillator, a regenerative Ti:sapphire amplifier, and Nd:glass amplification stages.

4. The experimental activities for 1997 are: (a) Installation of a class 100,000 clean room to be used as a high-power laser laboratory and target area; (b) Installation of the first version of the laser system (2 terawatt power level) and associated diagnostics; (c) Installation of a 1 m × 0.8 m steel vacuum chamber, associated pumping system and basic plasma diagnostics; d) execution of experiments related to photon acceleration and relativistic self-focusing at LOA.

5. The experimental activities foreseen for 1998 are: (a) Construction of an electron spectrometer with a detection range from 1 to 100 MeV; (b) Planning and execution of experiments on laser–plasma interaction at IST, namely plasma production by optical field ionization and characterization, Raman instability studies and X ray emission studies; (c) Upgrade of the laser system to the 20 terawatt level by addition of a larger Nd:glass amplifier; (d) execution of experiments related to electron acceleration at LOA.

6. In parallel with the above experimental activity we develop independent theoretical and numerical studies on laser–plasma interaction.

7. Our main collaborations in the experimental and theoretical areas are with RAL (UK), LOA and LULI (France), U. Bochum (Germany) and UCLA (USA).

4.14. Russian Federation

Russian research on IFE programmes are carried out with the maintenance of, and are financed by, the Ministry of Atomic Energy and Russian Academy of Science. At present the following Russian institutions are participating in IFE work:

- Russian Federal Nuclear Center-VNIIEF (Sarov, previously Arzamas-16).
- Russian Federal Nuclear Center-VNIITF (Snezhinsk, previously Chelyabinsk-70).
- FIAN (Moscow).
- TRINITI (Troitsk).
- NIIEFA (St. Petersburg).
- GOI (St. Petersburg).
- Experimental research is carried out mainly at the facilities ISKRA-5, ISKRA-4, ANGARA, MISHEN (TARGET).

Russian IFE research plans

(1) Direct and indirect drive target experiments at ISKRA-4 and ISKRA-5 laser facilities.

(2) Development and construction of the ISKRA-6 laser facilities with laser energy 300 kJ at third harmonic generation.

(3) Theoretical designing and development of the target for IFE.

(4) Investigation of the radiation damage and shielding of IFE reactor chamber and final element of drive channels.

Heavy ion fusion activities in Russia

(1) Development and design of the HIF powerful 10 MJ and 3.2 MJ accelerator driver based on the simultaneous acceleration of the negative and positive ions. (Institute of Theoretical and Experimental Physics, ITEP).

(2) Numerical simulation of the HIF targets and ignition processes, consistent with the driver design (VNIIEF, ITEP).

(3) Experimental modelling of HIF targets operation by using the powerful laser facility ISKRA-5 at VNIIEF (VNIIEF).

(4) Upgrading of the ITEP-TWAC accelerator facility for intense heavy ion beams production with the output power level 1 TW (~100 kJ/100 ns).

(5) Experimental and theoretical study of the high energy in matter, produced by heavy ion beams (ITEP-VNIIEF).

4.15. Spain

(1) The Nuclear Fusion Research Programme is going to be included in the National Energy Programme to be started in 1998. Presently the Research in Magnetic Confinement Fusion is centered and developed in the Centro de Investigaciones Energéticas y Medioambientales (CIEMAT) (formerly the Junta de Energía Nuclear, Nuclear Research Center of Spain).

(2) The activities on IFE research are centered and namely developed in the Instituto de Fusión Nuclear (DENIM) of the Polytechnical University of Madrid, which is integrated by 17 professors and 30 Masters and Bachelors, running for about 20 years. Also a small group of 4 researchers at the ETSI Aeronauticos (ETSIA) in the same University than DENIM works in target physics in collaboration with MPQ of Garching.

(3) No facilities for IFE R&D are running in Spain. However, in the framework of the European Programme "Access to Large Facilities", experiments have been/are being performed at PHEBUS laser (CEA-Limeil Valenton, France).

TARGET physics

An implosion-burnup code, NORCKLA, was developed 15 years ago to perform 1-D spherical high gain target simulations driven by laser and ions. A 2-D hydrodynamics code (ARWEN) and a radiation-hydrodynamics code (SARA 1D–2D) have been developed and tested against experiments. These 2-D codes are becoming integrated implosion codes with multi group radiation [diffusion with non-LTE opacities (ARWEN), and implicit non-LTE transport (SN) (SARA-2D)]. Plans include: direct/indirect targets and central/off-center (fast ignitor) schemes; IFE aneutronic fusion; targets different from those of mainstream research. New experiments will be proposed to be performed in the PHEBUS laser (CEA, Limeil, France) in the framework of the European Programme “Access to Large Facilities” in hydrodynamics, targets, and radiation physics. Recent experiments performed at PHEBUS include indirect–direct drive targets, hydrodynamics instabilities, and ignition jets from conical liners. The ERSIA group has been working on the linear regime of the RTI in a *self-consistent* way and they have developed the codes MULTI-1D/2D in close collaboration with MPQ of Garching.

ATOMIC physics

DENIM has developed LTE and non-LTE atomic physics codes for opacities and emissivities calculations for use in radiation-hydrodynamics codes, and compared with experiments. The LTE JIMENA code will be improved to include new developments of statistical transition array (STA) to describe a higher number of transitions. Two non-LTE codes have been developed: CARMEN and M3R, which solve time-dependent kinetic rate equations. Future plans include: development of analytical potentials including plasma effects; determination of static and dynamic properties of hot dense plasmas; time-dependent collisional radiative model solving radiative transfer equation in a SN approximation; and flexible access of opacity data to implosion radiation-hydrodynamics codes.

REACTOR/MATERIALS physics

3-D neutron–gamma simulations were performed for an IFE reactor (recently HYLIFE-II, KOYO). An inventory code (ACAB) was developed including IFE pulsed effects and magnitudes for recycling and disposal. Damage for metals and ceramic materials (with development of a molecular dynamics code for SiC simulations, MOLDYCASK) has been studied, including transmutants. Plans include: re-evaluations of designs and emission spectra; basic damage data as input for an engineering database; effects of sub cascades formation on the microstructure (in SiC); coupling molecular dynamics and diffusion models for correlation of micro and macro responses on materials; developments on ACAB code: uncertainty analysis, long term activation of all natural elements in IFE components, activation from debris, pulsed irradiation of X ray and debris with wall protections.

4.16. United Kingdom of Great Britain and Northern Ireland

The Central Laser Facility (CLF) at the Rutherford Appleton Laboratory is the focus of an experimental and theoretical research effort in the physics of direct and indirect drive IFE and contributes to Europe's watching brief on IFC. This is carried out by in-house scientists, members of the UK university community, European researchers with EU funding, and a community of international collaborators.

The CLF's Nd:glass laser, Vulcan, has already enabled experiments in the 1019 W/cm^2 regime and will be on-line to users at 100 TW, 1020 W/cm^2 in the near future. Short pulse experiments relevant to the fast ignitor concept include the study of channelling, relativistic self-focusing, fast electron production and propagation. X ray lasers have been used to measure beam imprinting and instability growth in directly driven targets.

The theory and computation group at the CLF is closely associated with the experimental programme, providing simulation and modelling support to experiments. It also plays a co-ordinating and supporting role within the university research community collaborating in short-pulse interaction studies, X ray laser modelling, and studies of the radiation physics of high density, high-temperature plasmas.

With its broadly based science programme, highly competitive large scale laser facilities and expertise in laser development and plasma diagnostics, the CLF and its user community is well placed to make a significant contribution to the development of IFE.

4.17. United States of America

Providing the knowledge base for a sustainable and environmentally attractive fusion energy option (either MFE or IFE) is an important part of the US Department of Energy's strategic plan. The USA is a major contributor to IFE through the Department of Energy (DOE), Office of Science's Office of Fusion Energy Sciences (OFES) and through contributions to inertial fusion science by the DOE's Defense Program's Office of Inertial Fusion and NIF Project (OIFNP). OFES currently supports heavy ion accelerator development and IFE chamber research while OIFNP, as part of its Stockpile Stewardship Programme, currently supports fusion target physics research, and target technology development for high gain. Both fusion programmes complement each other in contributing to the science and technology of IFE.

The USA through OIFNP currently supports indirect-drive inertial fusion research at Lawrence Livermore National Laboratory with its Nova laser (40 kJ/0.35 µm) and direct-drive research at the University of Rochester, Laboratory of Laser Energetics, with its recently upgraded Omega laser (40 kJ/0.35 µm), both lasers based on Nd:glass. OIFNP also supports indirect drive experimental and theoretical efforts at Los Alamos National Laboratory and pulsed power (light ion and Z-pinch) driver and target experiments at Sandia National Laboratory. General Atomics provides target fabrication support. In addition, OIFNP supports direct drive research at the Naval Research Laboratory with its ultra-smooth-beam Nike laser (5 kJ/0.25 μm) based on KrF. Advanced driver development of diode-pumped solid state lasers is being pursued by Lawrence Livermore National Laboratory.

The USA National Ignition Facility (NIF), currently under construction in Livermore, California, will provide the first demonstration of inertial fusion ignition and gain early in the next century. NIF is based on a 192-beam Nd:glass laser driver designed to produce 1.8 MJ at 0.35 μm with primarily indirect drive and secondarily direct-drive irradiation capability. Demonstration of ignition is of central importance to both Stockpile Stewardship and IFE. The three main applications of NIF research are defence, energy, and basic science. NIF will be a national user facility and will be available to scientists around the world for IFE experiments such as chamber dynamics, wall protection, and material response to fusion target emissions.

The DOE through OFES supports heavy ion beam driver development for application specifically to IFE because of the efficiency and rep-rate offered by heavy ion drivers. The two major heavy ion fusion (HIF) activities are at Lawrence Berkeley National Laboratory and Lawrence Livermore National Laboratory. These programmes are developing accelerators to produce suitably bright, high current beams and HIF target designs. Smaller activities at the University of Maryland, the Naval Research Laboratory, and the Princeton Plasma Physics Laboratory are investigating fundamental physics of heavy ion beam transport. OFES also supports studies including IFE technology issues at the University of California at Los Angeles, the University of California at Berkeley, and the University of Wisconsin.

CONTRIBUTORS TO DRAFTING AND REVIEW

Consultants:

Bock, R.	Gesellschaft für Schwerionenforschung, Germany
Decroisette, M.	Commissariat à l'Energie Atomique, France
He, X.	Institute of Applied Physics and Computational Mathematics, China
Hutchinson, H.	Rutherford Appleton Laboratory, United Kingdom
Kirillov, G.	Russian Federal Nuclear Center–VNIIEF, Russian Federation
Nakai, S.	Institute of Laser Engineering, Osaka University, Japan
Powell, H.	Lawrence Livermore National Laboratory, United States of America
Velarde, G.	Instituto de Fusión Nuclear (DENIM), Polytechnical University of Madrid, Spain

Experts and Observers:

Andre, M.	Commissariat à l'Energie Atomique, France
Dolan, T.	International Atomic Energy Agency
Edward, C.	Rutherford Appleton Laboratory, United Kingdom
Garanin, S.G.	Russian Federal Nuclear Center–VNIIEF, Russian Federation
Hofmann, I.	Gesellschaft für Schwerionenforschung, Germany
Hora, H.	University of New South Wales, Australia
Joshi, A.	Centre for Advanced Technology, India
Kong, H.	Korea Advanced Institute of Science and Technology, Republic of Korea
Kozaki, Y.	Institute of Laser Engineering, Osaka University, Japan
Lin, Z.	National Laboratory of High Power Laser and Physics, China
Logan, B.G.	Lawrence Livermore National Laboratory, United States of America
Mima, K	Institute of Laser Engineering, Osaka University, Japan
Miyanaga, N.	Institute of Laser Engineering, Osaka University, Japan
Norimatsu, T.	Institute of Laser Engineering, Osaka University, Japan
Pant, H.C.	Centre for Advanced Technology, India
Perlado, M	Instituto de Fusión Nuclear (DENIM), Polytechnical University of Madrid, Spain
Schneider, U.	International Atomic Energy Agency
Sluyter, M.	Department of Energy (retired), United States of America
Smirnov, V.	Kurchatov Institute, Russian Federation
Yamanaka, M.	Institute of Laser Engineering, Osaka University, Japan