

**Summary Report of the
2nd Research Coordination Meeting on
The Element of Inertial Fusion Energy Power Plants
Vienna, Austria, IAEA Headquarters, 4-7 November 2003**

**Prepared by
The Participants of the CRP
and
R. Miklaszewski
IAEA, Physics Section**

Abstract

This report contains a summary of the 2nd Research Coordination Meeting for the Coordinated Research Project entitled, “The Elements of Inertial Fusion Energy (IFE) Power Plants,” held at the IAEA Headquarters, Vienna, Austria, from 4 to 7 November 2003. The goal of the project is to promote and support international collaboration on various aspects of IFE power plants with a focus on addressing interface issues for drivers, targets and chambers. This report includes abstracts of the activities that the participants described in oral presentations at the meeting. Copies of the presentations have been posted on the web site:

<http://aries.ucsd.edu/LIB/MEETINGS/0310-IAEA-IFE-CRP/index.shtml>

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1. Introduction and Summary

Fusion research is proceeding effectively to develop a new energy source that is abundant, safe, environmentally acceptable, and economical. There are two major approaches, Magnetic Fusion Energy (MFE) and Inertial Fusion Energy (IFE). The basic physics of IFE (compression and ignition of small fuel pellets containing deuterium and tritium) is becoming increasingly well understood. New megajoule-class laser facilities under construction in the USA and in France are expected to demonstrate ignition and energy gain in this decade. Fusion reactor design studies indicate that IFE power plant are feasible and have attractive cost, safety and environmental features.

In December of 2000, the IAEA approved the start of a Coordinated Research Project on the Elements of IFE Power Plants. The overall objective of this CRP is to stimulate and promote the Inertial Fusion Energy development by improving international cooperation. The first Research Coordination Meeting (RCM) for the CRP on the Elements of IFE Power Plants was held 21-24 May 2001 at the IAEA Headquarters in Vienna, Austria. Documentation from that meeting is found at:

<http://aries.ucsd.edu/PUBLIC/IAEAIFECRP/meetings.shtml>

The second RCM was held 4-7 November also at IAEA Headquarters in Vienna. The meeting agenda is given in Appendix 1. This summary report is a compilation of the abstracts submitted by the participants. In general, full papers were not submitted for this meeting. Copies of the presentations given by the participants have been posted on the web site indicated above.

Participants reported that some collaboration had begun but felt that more could be accomplished. Discussions between participants at the meeting started to lay the groundwork for new or enhanced collaborations. The responsibility for follow-up on these ideas was left to the individuals involved and was not documented at the meeting. The group agreed to think about and propose ideas for the next phase of the CRP, as this one will end in 2004. It was suggested that participants circulate ideas for follow-on by mid-2004 so that discussions could occur before the next RCM, which is scheduled for 14-15 October 2004 in Daejeon, Republic of Korea. This RCM will be held in conjunction with the Third Technical Meeting on the Physics and Technology of Inertial Fusion Energy Targets and Chambers (11-13 October).

2. Abstracts of Activities of Participants

Abstracts follow in order of the presentations. Only the first author is listed here.

Wayne Meier (USA), “Update of IFE Research at LLNL”

Boris Sharkov (RUSSIA), “IFE Research at ITEP-Moscow”

Manuel Perlado (SPAIN), “Progress in Materials Analysis for IFE Reactors at the Instituto de Fusion Nuclear”

Dieter Hofmann (GERMANY), “Basic Physics for Inertial Fusion Energy in High Energy Density Physics with Intense Heavy Ion and Laser Beams. Present and Future Prospects of High Energy Density in Matter Research at GSI”

Elena Korosheva (RUSSIA), “Development of a Full-Scaled Scenario for Repeatable IFE Target Fabrication and Injection based on the FST Technologies”

Dan Goodin (USA), “Target Fabrication and Injection for Inertial Fusion Energy”

Stanislav Medin (RUSSIA), “Design Concept of Fast-Ignition Heavy Ion Fusion Power Plant”

Farrokh Najambadi (USA), “Assessment of IFE Chambers and Research Activities on IFE Chambers and Optics at UC San Diego”

P. Calderoni (USA), “Feasibility Exploration of Vapor Clearing Rates for IFE Liquid Chambers: Transient Condensation of Lithium Fluoride Excited Vapors for IFE Systems”

Koichi Kasuya (JAPAN), “Peripheral Elements and Technology Associated with Pulsed Power Inertial Fusion: Part 2 and Appendix”

Hong Jin Kong (KOREA), “Feasibility Study of the Application of Phase Locking of a Beam Combination with SBS-PCM for Unlimited Highly Repetitive High Power Laser Systems over 10 Hz”

Rudraiah Nanjundappa (INDIA), “Effects of Magnetic Field, Laser Radiation and Nano Structure Porous Lining at the Ablative Surface of IFE Target”

Milan Kalal (CZECH REPUBLIC), “Thermal Smoothing by Laser Produced Plasma of Porous Matter”

Minami Yoda (USA), “Hydrodynamics of Liquid Protection Schemes for Inertial Fusion Energy Reactor Chamber First Walls”

Jerzy Wolowski (POLAND), “Investigation of the High-Z Laser-Produced Plasma with the use of Ion Diagnostics for Optimization of the Laser Interaction with Hohlraum-type Targets”

István Földes (HUNGARY), “Laser Plasma Research in Hungary Related to the Physics of Fast Igniters”

Rajababby Khaydarov (UZBEKISTAN), “Investigation of Secondary Processes by Interaction of Plasma Streams with Various Materials”

Craig Olson (USA), “Z-Pinch Inertial Fusion Energy”

Update on IFE Research at LLNL

Wayne Meier, Ryan Abbott, John Barnard, Andy Bayramian,
Camille Bibeau, Debbie Callahan, Alex Friedman, Mike Key,
Jeff Latkowski, Steve Payne, John Perkins, Max Tabak
Lawrence Livermore National Laboratory
P.O. Box 808, Livermore, CA 94551 USA

Synopsis

Lawrence Livermore National Laboratory (LLNL) is engaged in a broad range of activities that support the development of Inertial Fusion Energy (IFE). The National Ignition Facility (NIF) is being constructed at LLNL, and experiments are already being conducting with the first group of beamlines. The demonstration of ignition on NIF will be an important milestone for IFE. The current schedule calls for completion of all 192 beams by 2009. The ignition campaign will take several years with ignition planned for 2011 or 2012. Our target design work includes target concept development and detailed computer simulations to determine the performance of various types of targets (heavy-ion, laser, fast-ignition). In the past year, work on heavy ion targets has shifted from the distributed radiator design to the hybrid target that will accommodate large beam spot sizes. For direct-drive laser targets, LLNL has completed implosion calculations using a picket-spike pulse shape, which improves stability of high gain targets. LLNL is conducting experimental and theoretical work on fast ignition and is exploring the possibility of adding PW capability to NIF. LLNL scientists are working with others around the world to understand the physics of the generation and propagation of electrons and ions produced by PW lasers for fast ignition. LLNL has significant activities in both heavy-ion and laser driver development. LLNL is a key member of the Heavy Ion Fusion (HIF) Virtual National Laboratory (VNL) that is responsible for developing the science and technology base for using a heavy ion accelerator as a driver for IFE. Several small-scale experiments are being conducted as part of this collaboration including the source/injector test stand (STS), high current experiment (HCX), and neutralized transport experiment (NTX). The next major facility proposed is the Integrated Beam Experiment (IBX). Our Diode Pumped Solid State Laser (DPSSL) program is developing an efficient, high-repetition-rate laser as a candidate driver. The Mercury laser has already operated with one amplified head and generated 34 J in single shot and 114 W in average power 5 Hz operations. When the second amplifier head is installed, Mercury is expected to reach its goals of 100 J and 10 Hz at 10% efficiency. Work also continues on chamber and power plant design studies for both heavy-ion and laser-driven IFE. For the heavy ion driver, the focus continues to be on the thick liquid wall chamber using molten salt. An updated heavy ion fusion power plant design, referred to as the Robust Point Design was completed last year. For laser IFE, the XAPPER pulse x-ray exposure experiment is being used to study damage to candidate materials for first walls and final optics. Currently we have national and international collaborations in all of these areas. This talk gives an update on progress since the last Research Coordination meeting.

*Work performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

IFE Research at ITEP-Moscow

Boris Sharkov, Nikolai Alexeev, Dimitry Koshkarev, Pavel Zenkevich, Michael Basko,
Michael Churazov, Alexander Golubev, Alexander Fertman, Sergei Kondrashev

Institute for Theoretical and Experimental Physics (ITEP-Moscow) is engaged in a broad range of Heavy Ion Inertial Fusion Energy (IFE) activities supported by Minatom of the Russian Federation. The heavy ion terawatt accumulator facility (ITEP-TWAC) is being constructed at ITEP, and the non-Liouvillian scenario of the beam accumulation-acceleration has been proven and commissioned. Experiments are already being conducted with the first beams of carbon ions. The current schedule calls for completion of the intensity upgrade in year the 2006 aiming at 1 TW power of a Cu 27^+ ion beam concentrated on a 1 mm spot diameter.

Our target design work includes target concept development and detailed computer simulations to determine the performance of various types of heavy-ion targets with fast-ignition. In the past years, work on heavy ion targets has shifted from the indirect-drive target concept to a directly driven cylindrical target option that will accommodate hollow beam irradiation of hollow cylinder by 100 GeV Pt^+/Pt^- ion beams.

ITEP is conducting theoretical and experimental work aimed at fast ignition by heavy ion beams and is exploring the possibility of adding a 300 MHz RF beam wobbling system to the experimental beamline of the TWAC facility.

ITEP is a key member of the Research Council of Russian Academy of Science (RAS) that is responsible for analysis and development of the science and technology base for IFE. This Council brings together the groups from numerous institutes of Minatom RF and RAS pursuing the development of the Heavy Ion IFE power plant concept.

The considerations of heavy ion fusion power plant concept based on the fast ignition principle for fusion targets are under development. The cylindrical target is irradiated subsequently by a hollow beam in compression phase and by an ignition beam at the burning phase. The ignition is provided by the high energy 100 GeV Pt ions of different masses accelerated in RF-linac. The efficiency of the driver is taken $\sim 25\%$. The main beam delivers ~ 5 MJ energy and the ignition beam ~ 0.4 MJ to the target. Cylindrical DT filled target provides ~ 600 MJ fusion yield, of which 180 MJ appears in X-rays and ionized debris and 420 MJ in neutrons. The repetition rate is taken as 2 Hz per reactor chamber.

The first wall of the blanket employs “liquid wall” approach, particularly the wetted porous design. The lithium-lead eutectic is used as a coolant, with initial surface temperature of 550°C . Computation of neutronics results in blanket energy deposition with maximum density of the order of 10^8J/m^3 . The heat conversion system consisting of three coolant loops provides the net efficiency of the power plant of $\sim 35\%$.

Substantial contributions to the field have been achieved recently in numerous national and international collaborations. In this phase, the progressing activities are oriented towards theoretical and experimental investigations of the state of matter under extreme conditions,

experimental and theoretical study on heavy ion beam-plasma interaction, powerful driver issues and to development of computer codes for comprehensive numerical simulations of heavy ion driven IFE in source-to-target scenario. International collaboration plays significant role in ITEP activities. ITEP scientists are working with other laboratories around the world to explore the physics of beam-plasma interaction and High Energy Density physics. The experiments are conducted by joint groups at GSI-Darmstadt, Orsay (France) and in RIKEN (Tokyo). As soon as the beam intensity of the ITEP-TWAC facility provides specific energy deposition level above 1 kJ/g, the joint international experiments will start.

This talk gives an update on the progress in ITEP experimental and theoretical activities since the last Research Coordination meeting.

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Progress in Materials Analysis for IFE Reactors at the Insituto de Fusión Nuclear

J.M. Perlado, O. Cabellos, M.J. Caturla⁺, E. Domínguez, R. Falquina, D. Lodi^{*}, J. Marian[@], F. Mota, A. Rodríguez, M. Salvador, J. Sanz, M. Velarde

Instituto de Fusión Nuclear (DENIM) / E.T.S.I.I./ Universidad Politécnica de Madrid
also ^{*}SCK CEN (Belgium), [@]CALTECH (USA), ⁺Universidad Alicante (Spain)
J. Gutiérrez Abascal, 2 / 28006 Madrid (Spain) mperlado@din.upm.es

Time-dependent neutron fluxes at the Structural Material behind protections of Flibe and LiPb have been obtained including energy spectra, for different target implosion and compositions. A long-term program on Reduced Activation Ferritic Alloys (RAFMs) is being pursued macroscopically in Fusion Programs, and a very efficient lifetime is actually envisioned that will be compared with that estimated in IFE reactor. However, from our simulations, comprehension of basic mechanisms of radiation damage is not fully understood to obtain predictive consequences. The level of multiscale simulation in comparison with microscopic experiments is presently out of range, and the results on the simplest material representing such steels (Fe) give some preliminary comparison that will be presented. The value of techniques such as Transmission Electron Microscope (TEM), Positron Annihilation and Atom Probe is remarked and located in their corresponding hole, and their comparisons with simulations will be remarked.

Silica is one of the candidate materials for final focusing mirrors in inertial fusion reactors that could be exposed to neutron irradiation during operation. Radiation damage results in point defects that can lead to obscuration, that is, degradation of the optical properties of these materials. Threshold energies of the components have been calculated using Molecular Dynamics with code MDCASK. This stability study of defects has been made simulating recoil energies in steps of 5 eV starting in 30 eV. We also will present a study of the behavior of Amorphous Silica for primary recoil atoms with energies larger than 5 keV, as well as to test the effects for different temperatures. The oxygen deficient centers (defects already known) generated during irradiation will be studied because they will be able to convert into the critical E' centers responsible of undesired effect. Moreover, unknown defects will be searched to be responsible of potential degradation under neutron irradiation.

The SiC composite research and, in particular that of radiation effects, is being developed to a large extent from the macroscopic. However, the results from theory and simulation to explain that physics are being slowly represented. The systematic identification of type of stable defects is the first task to do, and that will be presented after verification of new tight binding techniques reported in the past. The different level of knowledge between simulation and experiments will be remarked.

Uncertainties of Nuclear Data and their consequences in Materials Activation have been assessed using new models in IFE Reactors. Tritium Atmospheric Diffusion from Fusion Reactors has been studied considering the different paths and chemical compositions (HT, HTO, and OBT) and the importance of each one in the final environmental response has been analyzed.

Development of a full-scaled scenario for repeatable IFE target fabrication and injection based on the FST technologies.

E.R. Koresheva

Lebedev Physical Institute of RAS, Moscow, Russia; koresheva@sci.lebedev.ru

A wide research and development program to supply targets for inertial fusion energy (IFE) is underway in Russia under the leadership of the Lebedev Physical Institute (LPI) [1-7]. Technologies based on using free-standing targets (or FST technologies) in each production step are being developed at LPI since 1989. The activity of LPI under the IAEA Project #11536/RBF is aimed to answer the question: Whether it is possible to apply the FST technologies as a basis of IFE target factory?

This report covers the research area of the FST technologies application for pre-shot target handling including the following issues:

- IFE targets production and their repeatable assembly with protective sabots;
- Protective sabot pre-acceleration with the aim of sabot-and-target delivery to the injector;
- Minimization of target overloads and overheating during the injection process;
- Rapid characterization using threshold algorithms and fast computer processing of target backlit images.

Particular emphasis is paid to: (a) adding a minor dope to the fuel to form fuel layer in a glassy state (MD-technique), (b) using large shells with a metallic layer on the outer surface to shorten the layering time for reactor targets, (c) using the rotating and bouncing cell (R&B cell) for FST technology, and (d) designing a prototypical facility for repeatable target fabrication and assembly.

The following experimental and theoretical results are presented:

- FST-layering inside a polystyrene shell with outer layer from Pd of 150 Å thickness.
- Cryogenic layering using “Enhanced FST”, which is the combination of the MD-technique and the FST.
- Protective cryogenic layer formation on the outer surface of a target using the R&B cell.

The 5-year R&D program on the development of a prototypical facility for cryogenic targets fabrication and their repeatable assembly with protective sabots is discussed. The current results obtained within the program are presented (Table 1, Fig. 1). It is emphasized that the facility creation will allow us to demonstrate repeatable IFE target fabrication and injection based on the FST technologies.

References

1. E.R. Koresheva et al., *Progress in the extension of free-standing target technologies on IFE requirements*. Presented at the 2nd IAEA-TM on Physics and Technology of IFE Targets and Chambers (June 17-19, 2002, San Diego, USA) and at the XXVII European Conference on Laser Interaction with Matter (October 7-11, 2002, Moscow, Russia); *Fusion Sci.&Tech.* **43**, May 2003.

2. I.V. Aleksandrova et al., *Extension of free-standing target technologies on IFE Requirements*. in: *Inertial Fusion Science and Application 2001* (eds. K.A.Tanaka et al.), ELSEVIER (Paris), p.762, 2002.
3. I.E. Osipov et al., *A device for cryotarget rep-rate delivery in IFE target chamber*. Ibid. p.810, 2002.
4. E.R. Koresheva et al., *A new method of fabrication of the transparent solid hydrogen layer inside a microshell: the application to inertial confinement fusion*. *J.Phys.D: Appl.Phys.* **35** pp.825-830, 2002.
5. I.V. Aleksandrova et al., *An efficient method of fuel ice formation in moving free-standing ICF/IFE target*. *J.Phys.D: Appl.Phys.* (in Press).
6. E.R. Koresheva et al., *A mechanism of formation of a smooth solid layer of hydrogen inside a microshell*. Presented at the XXVII European Conference on Laser Interaction with Matter (October 7-11, 2002, Moscow, Russia), SPIE (in Press).

TABLE 1. Current Performance Data of Target Handling using the FST Technologies

PARAMETERS		PERFORMANCE DATA
Polymer shell		Demonstrated: up to 1.8 mm
Fuel material		D2 + different doping agents (0.3 – 16%) Demonstrated: D2+Ne; H2+HD; H2+D2
Fuel layer thickness		10 – 100 μm Demonstrated: for millimeter size targets
Outer protective layers	Metal reflective layer	Pd, Pt/Pd or Au (100 – 200 A°) Demonstrated: Pd (150 A°), Pt/Pd (200 A°)
	Cryogenic solid layer	Demonstrated: cryogenic solid layer of O_2
Target production rate		Demonstrated: 0.1 Hz
Fill pressure at 300 K		Demonstrated: 100 – 1000 atm
Sabot geometry		Demonstrated: OD 2.8 mm; Length 10, 15 and 20 mm
Sabot material		Ferromagnetic iron
Sabot acceleration up to 8 m/s (for one coil)		Demonstrated: 300 K, 77 K, 4.2 K

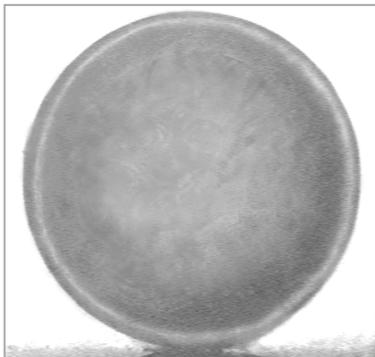


Fig.1. The results obtained with a modified FST layering module.

CH shell of $2R = 1.5 \text{ mm}$
 Outer coating of 200 \AA Pt/Pd
 Layer composition: $\text{D}_2+3\%\text{Ne}$
 $50\text{-}\mu\text{m}$ solid layer

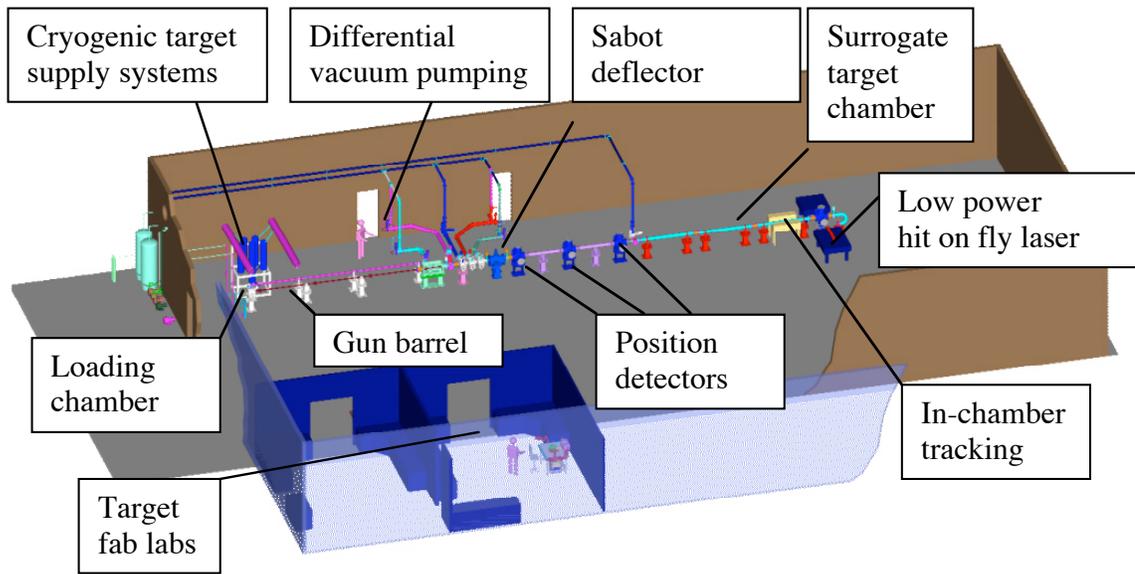
Target Fabrication and Injection for IFE

Dan Goodin
General Atomics
San Diego, CA USA

A central feature of an Inertial Fusion Energy (IFE) power plant is a target that has been compressed and heated to fusion conditions by the energy input of the driver. The ability to economically manufacture and inject cryogenic targets is a significant feasibility issue for future inertial fusion energy power plants. This presentation summarizes the development programs and recent advances in the USA that are important to demonstrating IFE target supply feasibility.

The target is injected into the target chamber at a rate of 5–10 Hz. The DT layer must survive the exposure to the high temperature chamber and remain highly symmetric, have a smooth inner ice surface finish, and reach the chamber center at a temperature of about 18 K. Models of the thermo-mechanical effects on the advanced materials during injection have been developed. Recent calculations show even direct drive targets can withstand the injection into a high temperature chamber if they are overcoated with a very thin insulating layer of hydrocarbon foam. Fundamental measurements of the properties and response of DT under these unique conditions are being carried out. Recent experiments show improved DT ice inner smoothness can be achieved by using an underlying layer of low-density foam. The target must be positioned at the center of the chamber with a placement accuracy of ± 5 mm and an alignment of the beams and the target of ± 20 μm or ± 200 μm for direct drive and indirect drive, respectively. An experimental injection and tracking system is being constructed to develop technologies and to demonstrate meeting these challenging requirements. This presentation reports the status of this experimental system, and recent results on placement accuracy and tracking capability.

Design studies of cost-effective power production from laser and heavy-ion driven IFE have found a cost requirement of about \$0.25-0.30 each. Major "paradigm-shifts" in target fabrication methodologies will be needed to economically supply targets for IFE power plant fueling. We have completed initial engineering analyses that show that "nth-of-a-kind" Target Fabrication Facility costs are within the range of commercial feasibility for laser-driven and for heavy ion driven IFE.



Concept for “Phase II” target fabrication and injection facility. This facility will be a key element of the plan to develop laser IFE with direct drive targets and solid wall chambers. It is the final step before construction of an Engineering Test Facility. Elements of the facility include mass production (in batch mode) of cryogenic targets that meet the specifications of high gain, target injection into the chamber and target tracking in the chamber.

Design Concept of Fast-Ignition Heavy Ion Fusion Power Plant

S.A. Medin¹, M.M. Basko², M.D. Churasov², D.G. Koshkarev², B.Yu. Sharkov²,
Yu.N. Orlov³ and V.M. Suslin³

¹*Institute for High Energy Densities, Moscow, Russia*

²*Institute for Theoretical and Experimental Physics, Moscow, Russia*

³*Keldysh Institute for Applied Mathematics, Moscow, Russia*

The goal of this study is a conceptual analysis of parameters of power plant elements for fast-ignition heavy ion fusion (FIHIF). The power plant characteristics are evaluated as well.

The concept of fast ignition for inertial confinement suggests a detonation burning of precompressed deuterium – tritium fuel as a basic physical scenario for target ignition. This scenario is realized in a target of cylindrical geometry. The target is driven by the two high power heavy ions beams of 100 GeV ions. The first beam of hollow tube geometry deposits its energy into the shell and the second sharply focused beam, after the fuel is compressed by imploding shell material, impacts on the front end of the high density cord of fuel, thus initiating a detonation wave propagating along the cord.

The compression beam of Pt_{192}^{+} ions is arranged by rotation of a single beam of 0.12 cm diameter with a frequency of 10^9 Hz. The total energy of the beam is 7.1 MJ profiled in 75-ns pulse. The ignition beam of very high power and current, total energy of 0.4 MJ and duration of 0.2 ns, composed of Pt ions of four different masses and plus/minus one charge states. The efficiency of the driver is evaluated as 0.25.

The design of the target is coupled with the beam configuration. The target parameters were determined in computational experiments on compression and ignition of the target. The target length is 0.71 cm and the diameter is 0.80 cm. The mass of DT fuel is 6.3 mg, the total target mass is 3.7 g. The target compression results in the following fuel parameters: density $\rho = 100 \text{ g/cm}^3$ and $\rho_R = 0.5 \text{ g/cm}^2$. The ignition of 50-mm fuel cord generates a burn wave in which an energy of 750 MJ can be released. This energy is partitioned in 546 MJ for neutrons, 187 MJ for debris and 17 MJ for X-rays. The neutrons have mean energy of 12 MeV. The X-ray pulse is characterized by very long duration of about 0.7 ms and by mean temperature of 30 eV.

A wetted wall design is chosen for the reactor chamber. The chamber consists of the two adjacent sections: the upper section is the explosion section itself and the lower section is an expansion volume for the condensation of vapor on sprayed jets. The diameter of upper section is 8 m. The coolant is eutectic $\text{Li}_{17}\text{Pb}_{83}$ with temperature of 823 K before the shot. The first wall of chamber is manufactured from porous SiC; the tubing is made of vanadium alloy.

The response of the reactor chamber to the microexplosion results in preliminary evaporation of 5.4 kg of coolant under X-ray irradiation and in additional reevaporation of 45 kg of coolant under ion debris impact. The condensation time computed by means of kinetic model of condensation equals to 0.12 s. This time is much less than the time of

gravitational sedimentation of droplets in the chamber. Therefore, the repetition rate of microexplosions was taken as 2 Hz.

The neutron heating of the blanket is computed for a design, which is represented by a multilayer cylinder. The energy deposition at the first wall is determined as 25 MJ/m^3 for liquid film and 19 MJ/m^3 for SiC porous structure. This should result in pressure pulse generation, the amplitude of which is evaluated for isochoric heating as 400 bar for SiC material. Tritium breeding ratio for the blanket of 0.5m - thickness is 1.05 and blanket multiplication factor is 1.1.

The energy conversion system consists of three loops. The coolant of the intermediate loop is sodium. The third loop is a steam turbine cycle. The maximum temperature of $\text{Li}_{17}\text{Pb}_{83}$ in the first loop is taken as 823 K. The inlet temperature in the reactor chamber is 623K. The initial steam pressure is taken as 180 bar. The efficiency of the steam cycle equals 0.417. The resulting net efficiency of the power plant is 0.37, providing the net power for one reactor chamber of 670 MW.

Future research is oriented towards the contraction of the driver length, coupled simulation of target compression and burn and more detailed description of the chamber response.

Results from ARIES-IFE Study and Research Activities on IFE Chamber and Optics at UC San Diego

Farrokh Najmabadi
University of California, San Diego, CA USA

1. Results from the ARIES-IFE Study

The ARIES-IFE study, a national US effort involving universities, national laboratories and industry was an integrated study of IFE chambers and chamber interfaces with the driver and target systems. Rather than focusing on a single design point, the study aimed at identifying design windows, trade-offs, and key physics and technology uncertainties for various IFE chamber concepts. We have selected heavy-ion indirect target designs of LLNL/LBL and direct-drive target designs of NRL as our reference targets. Detailed spectra from these two targets have been calculated -- their photon and ions/debris spectra are vastly different. Three main classes of chamber concepts are analyzed including dry walls, solid structures with protective zones (*e.g.*, wetted walls), and thick liquid concepts.

Dry-wall Chambers

We have found that details of target emission spectra have a significant impact on the thermal response of the wall. In particular, time of flight of ions reduces heat flux on the wall significantly. For direct-drive targets, the design window for successful target injection in a gas-filled chamber (*e.g.*, Xe) is quite small (gas pressure $< \sim 50$ mTorr, wall temperature $< \sim 700^\circ\text{C}$). Contrary to past studies, detailed thermal analysis indicates that no buffer gas is necessary to protect the wall. This is due to the lower energy in the X-ray channel and accounting of ion time of flight. We find that it is prudent to use a thin armor instead of a monolithic first wall. Armor can then be optimized to handle rapid particle and heat flux while the first wall is optimized for structural function and efficient heat removal at quasi-steady-state. In fact, by using an armor, most of first-wall and blanket concepts developed for MFE will be applicable to IFE applications.

We have developed design windows for several systems such as target injection and tracking, thermal response of the first wall, and laser or heavy-ion propagation and focusing. For direct-drive targets, it appears that a dry-wall chamber with equilibrium wall temperature of $500\text{-}700^\circ\text{C}$ filled with $< 10\text{-}50$ mTorr of Xe satisfies requirements for all systems. For indirect-drive targets, we have found no major constraints for successful injection of indirect drive targets in a gas-filled chamber (*e.g.*, Xe) because indirect-drive targets are well insulated by hohlraum materials. Because of large energy in the X-ray channel, thermal analysis indicates that buffer gas (> 200 mTorr Xe) is necessary for the protection of the first wall/armor. The amount of the gas in the chamber depends on details of beam transport schemes.

Thin-liquid Protected Chambers

A thin liquid film wall configuration for IFE provides the possibility of high efficiency and renewable armor. Key issues include film re-establishment and coverage, and aerosol formation and behavior relative to the pre-shot chamber conditions.

Analysis of wetted wall re-establishment and coverage indicates that (i) liquid film stability may impose a limit on the minimum repetition rate in order to avoid liquid “dripping” into the chamber between shots; and (ii) a minimum injection velocity will be required to prevent the film thickness from decreasing below a minimum value dictated by wall protection requirements. Analysis of thin liquid film forced flow indicates that the normalized detachment distance strongly depends on the Froude number and surface characteristics (*i.e.* wettability). Efforts in the film dynamics area include generation of generalized charts to help system designers establish parametric design windows.

Liquid wall ablation is important for an indirect-drive target case because of the large amount of photon energy which is deposited over a short time (\sim ns). The heating rates are comparable to laser material ablation cases from whose studies and experiments IFE ablation processes can be inferred. Under such high heating rates, surface evaporation and heterogeneous nucleation play a minor role in the boiling process. Instead, homogeneous nucleation is the dominant process. The liquid is rapidly superheated to a metastable liquid state with an excess free energy. At temperatures approaching 90% of the critical temperature, avalanche-like explosive growth in homogeneous nucleation rate (by 20-30 orders of magnitude) occur leading to the explosive decomposition of the superheated liquid into liquid and vapor phases (also referred to as spinoidal decomposition). This is an area where much remains to be learned. For instance, it is not clear what the form of the ejecta is (vapor, liquid droplet size and distribution). Future studies of IFE candidate liquid wall materials (such as flibe and Pb) under such conditions are needed. For example, simulation of the photon energy deposition in X-ray and/or laser facilities under IFE-like heating rates and deposition profiles and with the right diagnostics capabilities would greatly help in further understanding this process.

An additional ablation term could result from the shock wave imparted on the liquid film by the explosive boiling ejecta. Depending on the liquid and reflecting wall acoustic impedances, this shock wave could be followed by a rarefaction wave, resulting in spalling if the net tensile stress in the liquid is higher than its spall strength. This is another area requiring future experimental and modeling effort.

Bounding estimates of liquid wall ablation based on explosive boiling were made for use as source terms in subsequent aerosol analysis. Such analysis of aerosol behavior indicates that significant amount of aerosol would be formed and, depending on the wall boundary conditions, could be present prior to each shot. The combination of aerosol and vapor in the chamber at that time must be compatible with driver firing and target injection requirements, as discussed in ref. [1]. The aerosol modeling performed for this study relies on simplifying assumptions, such as the assumption of a fully reflective liquid wall surface and the absence of particle slips. Further modeling and experimental efforts are needed to better understand and assess aerosol formation and behavior in an IFE chamber.

2. Final Optics Research & Development

The grazing incidence metal mirror (GIMM) is a primary candidate for the final optic of a laser-driven IFE power plant. Although multi-layer dielectric mirrors offer much higher laser damage threshold as compared with metal mirrors, neutron irradiation effects in dielectrics such as color center formation and swelling are thought to rule out dielectric mirrors, especially for UV wavelengths.

The construction of the mirror segments likely will include a stiff, radiation-resistant substrate such as silicon carbide with a thin metallic coating, and environmental overcoats as needed. The use of aluminum as the reflective material can provide absorptivity below 1% for s-polarized UV light down to 248 nm when used at an angle of 85° to the normal³. Figure 1 shows the ideal reflectivity of Al vs. angle for s- and p-polarized light at 248 nm.

One of the critical issues for final optics is their survivability and optical quality over a period of months to years in the presence of several damage threats, including target emissions, chamber contamination and the high-fluence laser itself. In this work we have concentrated on studies of the laser-induced damage characteristics. Our goal is to provide an optic that passes a laser fluence of 5 J/cm² normal to the beam for shot counts up to 10⁸, which corresponds to 2 years of continuous operation in a power plant.

Al mirrors were fabricated using several different techniques which resulted in different surface characteristics and morphologies. These mirrors were then tested using 25-ns pulses of 248 nm light at fluences up to 5 J/cm² normal to the beam.

Results highlight the potential deficiencies of polycrystalline Al. Cyclic damage normally occurs as a result of grain boundary and slip plane distortions at the surface. Diamond-turned surfaces respond much better to cyclic loading than polished surfaces. Smaller grains or fully amorphous microstructures are preferable in order to avoid grain separation and slip line transport.

Thin films can be formed with highly amorphous microstructures, but traditional thin film deposition techniques produce relatively thin coatings which are too delicate and too thin to avoid large interfacial stresses, which limit mirror performance. Damage usually occurs as a result of defects in the coating or detachment from the substrate.

The ideal Al mirror would have a coating thickness greater than the thermal diffusion skin depth, but thin enough to take advantage of the desirable neutronic and mechanical properties of a SiC substrate. Electroplating appears to offer the best combination of thickness and microstructure. These mirrors survived 100,000 shots with no visible evidence of damage. Future research will concentrate on filling in the damage database, including testing at higher fluence and higher shot counts, and on scaling the mirrors to larger sizes.

3. Chamber Dynamics & Clearing Simulation

Many physical phenomena with different time scale occur in the chamber following the target explosion. After the target-generated x-rays and ion debris traverse the chamber, the chamber environment is in a non-equilibrium phase (e.g., non-uniform pressure) and material is introduced in the chamber (e.g., ejecta from the wall as well desorbed target constituents implanted in the wall). Afterward, the chamber environment evolves mainly in the hydrodynamics time scale. Understanding the evolution and dynamics of chamber environment at this "long" timescale is essential in developing a rap-rated laser-fusion facility.

We have developed SPARTAN code to investigate chamber evolution. Strong shocks born out of the target blast are captured by a second order Godunov algorithm for compressible Navier-Stokes equations. Arbitrary chamber geometry is incorporated into a Cartesian grid and resolved by embedded boundary method. Simulation demonstrates the robustness of the numerical algorithm in treatment of highly nonlinear chamber dynamics with fast moving discontinuities. For this purpose, the effects of selected parameters (viscosity and heat conduction) on the chamber state prior to the insertion of the next target are estimated.

SPARTAN simulation of target explosion in a laser-IFE chamber shows:

1. Two-dimensional affects are critical in assessing chamber dynamics.
2. Both gas conductivity and viscosity impact the chamber environment.
3. Gas conductivity is not sufficient to cool down the chamber to equilibrium with the chamber wall in between shots (~ 100 ms) as previously envisioned.
4. A hot central region is formed after the convergence of reflected shock in the chamber center. As a result, there exists background plasma in the chamber. Radiation from and electron heat conduction of this plasma can cool down the chamber in a much more rapid manner. It is essential to include this background plasma in the simulations, a feature that will be shortly implemented in SPARTAN.
5. Viscous effects generate eddies in the chamber. However, viscosity of neutral gas is insufficient to damp out these eddies in the time between shots. These eddies may impact the target trajectory during the injection into the chamber. Since the laser beam channel geometry has a major impact on the initiation of these eddies, the larger number of beam channel in a laser-IFE facility will lead to more numerous but smaller eddies that may be damped out more readily. In addition, cool down of the chamber background due to the presence of background gas can help in reducing the size of these eddies.

Experimental and Numerical Study of Transient Condensation of Lithium and Beryllium Fluoride Excited Vapors for IFE Systems

P. Calderoni, A. Ying, T. Sketchley, M.A. Abdou
University of California, Los Angeles

UCLA has constructed and operated an experimental facility to study the transient cooling and condensation of excited vapors generated from the ablation of IFE prototypical materials. The work is part of the effort to provide an experimental feasibility assessment of the application of liquid blankets to inertial fusion energy systems. Although the experiments have been scaled considering the thick liquid wall HYLIFE-II design as a reference and the molten salt flibe as prototypical material, the results are also relevant to thin liquid wall concepts, and the experiment could be extended to other materials, such as lithium-lead eutectics.

The presentation summarizes the results obtained during the year 2003. At first the excited vapor were generated by ablation of a solid sleeve of pure lithium fluoride crystals in a high-current electrical discharge, and injected in an expansion chamber under hard-vacuum conditions. The diagnostic system employed to study condensation includes uniform chamber pressure monitoring, excited gas emission spectroscopy, optical time-of-flight technique and mass spectroscopy of the residual gases. The preliminary results (Fig. 1) showed that the condensation of LiF vapor is compatible with the stringent requirements of IFE systems repetition rates. But the vapor source design was characterized by the generation of a high amount of non-condensable gases due to the fragility of the LiF solid material. Although the presence of non-condensable gases did not seem to influence the condensation rate, it did inhibit the complete condensation of LiF at the end of the transient process. Because of this, a different configuration of the vapor source was used with flibe. The main difference is that the ablated material is now the surface of a liquid pool of flibe that is held by a cup of nickel that functions both as a crucible for melting the flibe and as an anode for the electrical discharge. The results show that the pressure drop associated with the condensation of flibe vapors is well fitted by an exponential decay (Fig. 2). The condensation rate can be related to the decay constant, which for the two experiments obtained at 1.44 kJ and 2.56 kJ discharge energy was respectively 4.22 ms and 4.27 ms. The experimental measurement of T_1 will be completed by investigating the effect of the variation of the chamber wall temperature on the condensation rate. SEM analysis of collecting plates (Fig. 3 and 4) showed evidence of micron and sub-micron aerosol formation and impingement on the plate perpendicular to the velocity of the vapors, while the plate parallel to the vapor velocity was characterized by film condensation.

A numerical module has been coupled with the numerical code Tsunami, developed at UCB to simulate gas dynamics in the chamber of IFE systems, to account for condensation at the boundaries of the numerical domain. Results of the application of the code to the geometry and conditions of the experiments showed that the simulation overestimates the condensation rate by one order of magnitude even after the presence of a non-condensable component in the gas mixture was considered (Fig. 5).

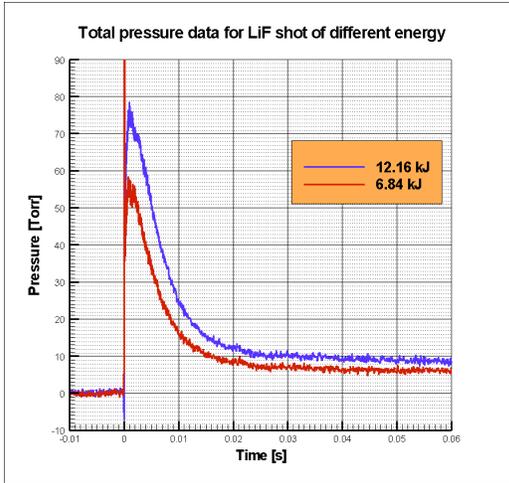


Fig.1 Pressure decay due to LiF vapors condensation

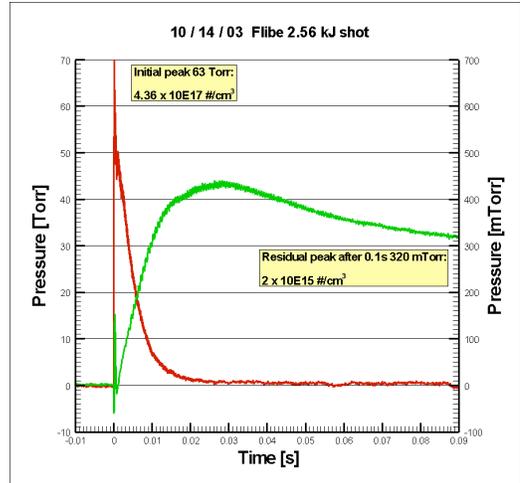


Fig.2 Pressure decay due to flibe vapors condensation

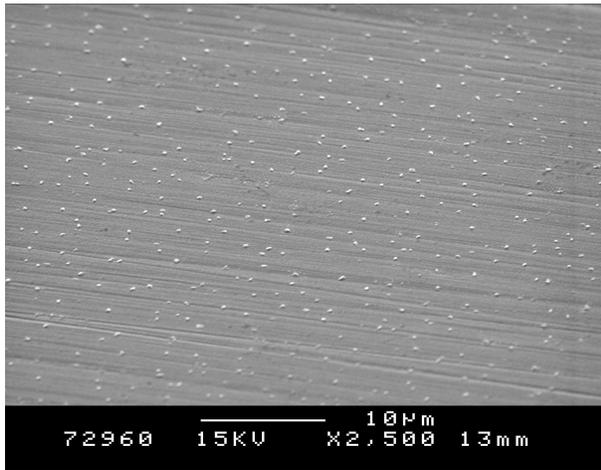


Fig.3 SEM picture of flibe droplet deposition on SS plate

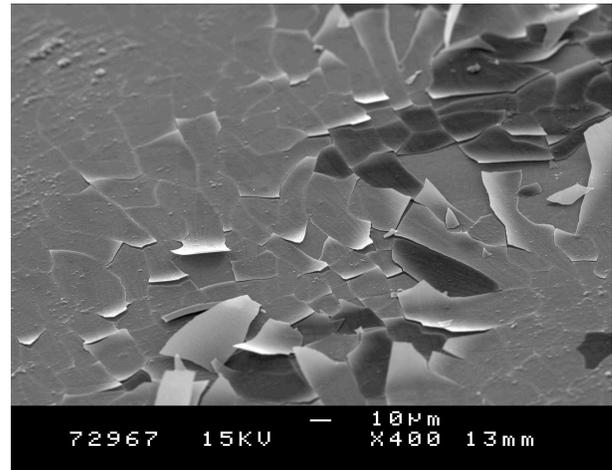


Fig.4 SEM picture of flibe film condensation on SS plate

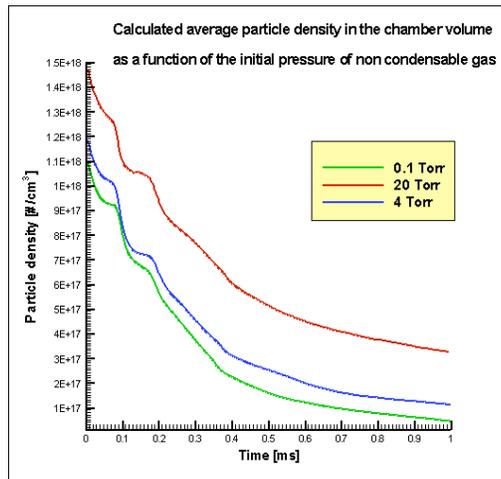


Fig.5 Simulated particle density decay due to flibe vapors condensation as a function of non-condensable gas initial pressure

Peripheral Elements and Technology Associated with Pulsed Power Inertial Fusion: Part 2¹

Koichi KASUYA²

Department of Energy Sciences, Interdisciplinary Graduate School of
Science and Engineering, Tokyo Institute of Technology,
4259 Nagatsuta, Midori-ku, Yokohama, Kanagawa, Japan 226-8502

Various candidate materials were collected from many sources. They were irradiated with intense proton beams at Tokyo Institute of Technology (TITech), with intense nitrogen beams at Sandia National Laboratories (SNL), Albuquerque, and with short pulse UV laser at IOE-MUT, Warsaw. A series of preparatory numerical calculations of x-ray ablations was performed at TITech, which results were compared with the experimental ones. Our aims were to supply necessary data for the future design of inertial fusion reactor chambers. One of the key issues in this field was the ablation thickness of the various chamber wall materials with intense beams under typical inertial fusion reactions. We measured the ablation thickness of various samples, and we also observed the surface conditions of the samples before and after the irradiations with a microscope, an x-ray luminescence composition analyzer and 3D-surface profiler.

Under the proton beam irradiation with the dose of about 10 J/cm² per shot, the ablated rates were up to 20 micron for carbon, and 26 micron for LiPb and SiC. The change of the rate was investigated with the change of the dose. Under the nitrogen beam irradiation with the dose of 4 J/cm², the ablated thickness of up to 6 micron was observed for SiC, while no remarkable ablation was observed for Al₂O₃. Surface conditions before and after the nitrogen beam irradiation was investigated with a microscope and x-ray fluorescence analysis. SiC surface turned into Si surface, while no discernible change was seen for Al₂O₃. Under the x-ray irradiation of LiF, SiC/Si and SiC, the ablation thickness of 3, 0.5 and 0 micron was observed under the dose of 40, 7 and 7 J/cm². Under the UV laser irradiation of W and C, the surface-change could be observed with a 3D surface profiler. More experiments and calculations with more advanced methods are scheduled in the near future.

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² Collaborations with A.Kasamatsu, Y.Kinoshita, T.Kamiya (Dept. of Energy Sciences, TITech), T.Norimatsu, Y.Kozaki, T.Yamanaka, S.Nakai (ILE, Osaka Univ.), T.Renk, C.Olson (SNL), W.Mroz, A.Prokopiuk (IOE, MUT).

Keywords: Inertial fusion, Reactor Chamber Database, Wall Materials, Surface Ablation with Ions, X-rays and UV Laser Light.

Peripheral Elements and Technology Associated with Pulsed Power Inertial Fusion: Part 2 Appendix

Koichi KASUYA

Department of Energy Sciences, Interdisciplinary Graduate School of
Science and Engineering, Tokyo Institute of Technology,
4259 Nagatsuta, Midori-ku, Yokohama, Kanagawa, Japan 226-8502

Followings were the subjects discussed by the same Japanese delegate, as the Appendix to the main presentation on the second day of this RCM with the same title:

1. Nuclear fusion in Japan (recent decision),
2. Typical ions and radiations derived from target implosions,
3. Fundamental research results concerning heavy ion inertial fusion,
4. Subjects to be discussed for the future of this CRP.

After the ITER promotion authorized by the Japanese Cabinet in May 2002, the top Japanese committee decided to promote the Fusion Program in Japan along the four major lines including (1) the Tokamak (Upgrade of JT-60, Naka-JAERI), (2) the Large Helical Device at NIFS (National Institute of Fusion Science, Toki), (3) the Laser Fusion (ILE, Osaka University) and (4) the IFMIF (Neutron Source & Material Science, nation-wide and international). As for the Institute of Laser Engineering, Osaka University, there are two large research topics after 2002. They are (1) the Laser Fusion (Fast Ignition etc.) as the long-term campaign and (2) the Development of EUV Light Source for Lithography (as the short-term campaign).

As the sample results from the Japanese inertial fusion groups, the group of Yasuji Kozaki (chamber technology group, ILE, Osaka University) calculated the various kinds of produced ions and radiations associated with the laser target implosion both for the 400 MJ direct drive case and the 200MJ fast ignition case. The heat loads on the reactor chamber surfaces at different distances from the chamber centers were also shown. The group of Masao Ogawa (TITech at Tokyo) showed parts of the heavy ion research works at TITech. They were (1) the grid control of extracted ions in the case of laser produced ion source and (2) the energy loss of heavy ion beam in dense He plasma.

Although Prof. Sadao Nakai (ILE, Osaka University and Kochi Tech. College) was absent, he asked the attendee of the present RCM to discuss and know (1) the long-term schedule of this CRP, (2) the third RCM as the short-term schedule (including the deadline to submit the final reports to IAEA and the schedule to prepare the final reports), (3) the nuclear fusion activity of IAEA in next year and the year after next, for examples, the major IAEA Conf.; France (Lyon) and Portugal (MFE and IFE), the other RCP, and the IAEA Technical Meetings, (4) the deadline for new proposal or application to IAEA from our CRP group, and (5) future direction of this CRP; for example, a power plant design. To the IAEA secretariat he asked to deliver all information including the RCM agenda and reports to the CRP members even if they are absent from the RCM.

Keywords: Inertial fusion, Recent decision in over-all Japanese fusion field, Wall loads with ions and radiations under ignitions, Ion beam fusion, Future direction of current CRP.

Feasibility Study of the Self-Phase-Locking of a Beam Combination with SBS-PCM for Unlimited Highly Repetitive High Power Laser System over 10Hz

IAEA CRP project #11636/R1

Hong Jin Kong, Seong Ku Lee, and Dong Won Lee
Dept. Physics, KAIST, Kusong-dong 373-1, Yusung-gu, Daejeon, Korea 305-701,
hjkong@kaist.ac.kr

Summary

We have demonstrated the feasibility of the self-phase-locking of the beam combination for the realization of the laser driver for inertial fusion energy (IFE), which can produce an enough high power laser system with high repetition rate over 10 Hz. The existing laser technology, however, limits it at most 1 shot per every hour because it takes very long time to cool down the laser gain medium for its large volume [1]. To achieve the high repetition rate, we have considered the beam combination as one of the most applicable techniques [2-6]. The laser system using the beam combination technique in which a laser beam is divided into several beams and recombined after the separate amplifications needs no large gain medium. Therefore, it can operate at the high repetition rate more than 10 Hz, regardless of the output energy and also is easily applicable to the existing laser amplifier technology. In addition, a stimulated Brillouin scattering-phase conjugate mirror (SBS-PCM) gives many advantages to the high power laser system because it reflects a phase conjugate wave, so that it compensates the thermally induced optical distortions generated inside the gain media [7]. Besides, using the symmetric cross type SBS-PCMs in the beam combination laser proposed by the authors [5,6], the alignment is insensitive to misalignment of the optical components and it becomes so easy and perfectly accurate that the recombined beam can be considered as a single beam.

For the beam combination laser, the phase locking between the neighboring beams must be accomplished to get a good beam quality when they are recombined together after the separate amplifications. That is, the phase difference between the laser beams must be smaller than $\lambda/4$ to keep the constructive interference at the boundaries between the neighboring beams. If not, the laser beam can produce a randomly distributed spatial spiking profile, which can damage the optical components. For SBS-PCM, the absolute phase of the reflected beam is very random because SBS originates from the random acoustic noise. We have considered that the self-phase-locking for the SBS-PCM could be accomplished, if the acoustic noise is initiated at a fixed point [8]. We have induced a weak periodic density modulation at the focal spot area inside the SBS-PCM by forming a standing wave as shown in fig. 1. The pump beam is reflected by the uncoated concave mirror ($\sim 4\%$ reflectivity) with $R = 300$ mm and then injected into SBS-PCM to build up a standing wave. It is seen that the relative phase fluctuation are less than 0.25λ over 90 % of the laser pulses. It implies the phases of the two beams are almost locked.

If we get the probability it with 100% for the continuing project, this self-phase-locking technique is feasible to apply practically to the laser fusion driver with the ultra high power and the high repetition rate over 10 Hz.

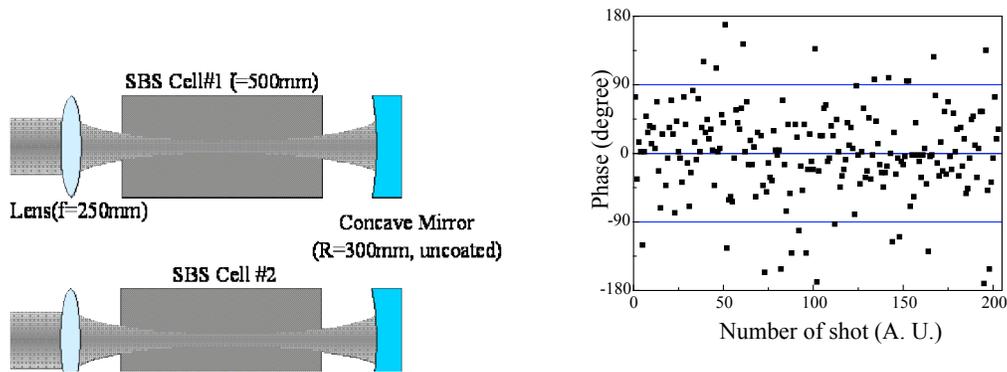


Fig. 1. Scheme of the phase locking and the relative phase difference between two laser beams: Each point represents one of 160 laser pulses and the standard deviation is $\sim 0.33\lambda$.

References

- [1] W. J. Hogan, et al., *Energy from Inertial Fusion* (International Atomic Energy Agency, Vienna, 1995), Chap. 3.
- [2] D. A. Rockwell and C. R. Giuliano, *Opt. Lett.* **11**, 147 (1986).
- [3] T. R. Loree, D. E. Watkins, T. M. Johnson, N. A. Kurnit, and R. A. Fisher, *Opt. Lett.* **12**, 178 (1987).
- [4] M. W. Bowers and R. W. Boyd, *IEEE J. Quantum Electron.* QE-34, 634 (1998).
- [5] H. J. Kong, J. Y. Lee, Y. S. Shin, J. O. Byun, H. S. Park and H. Kim, *Optical Review* **4**, 277 (1997).
- [6] H.J.Kong, US patent # 5832020A
- [7] D. A. Rockwell, *IEEE J. Quantum Electron.* QE-24, 1124 (1988).
- [8] This will be submitted soon.

Laser Driven Ablative Surface Instability in IFE

IAEA Project No. 302.F1-IND-11534

Prof. N. Rudraiah^{1,2}, Prof. M. Venkatachalappa^{1,2}, Prof. I. S. Shivakumara^{1,2}, Prof. B. S. Krishnamurthy^{1,2}, Prof. Tara Desai^{1,2}, Ms. A. S. Jalaja², Mr. Siddalinga Prasad²

- 1) National Research Institute of Applied Mathematics, Bangalore, India
- 2) UGC-CAS in Fluid Mechanics, Bangalore University, Bangalore, India

Abstract

For efficient extraction of IFE it is essential to reduce the growth rate of surface instabilities in laser accelerated ablative surface of IFE target. The following three different types of surface instabilities namely: Rayleigh–Taylor Instability (RTI), Kelvin–Helmholtz Instability (KHI) and Richtmyer–Meshkov Instability (RMI) are observed. At present the mechanisms like i) the gradual variation of density assuming plasma as incompressible heterogeneous fluid, ii) compressible fluid and iii) IFE target shell, filled with foam layer or porous lining are used to reduce the RTI growth rate. In contrast to these we have used porous lining or magnetic field to reduce the RTI growth rate in the absence of laser radiation. In the third year of our project, we have investigated the **Effects of Laser Radiation, Magnetic Field and Nano porous Lining on RTI in an Ablatively Laser Accelerated Plasma**. This work was presented on November 6, 2003 at the second CRP meeting on Elements of Power Plant Design for IFE held at Vienna during November 4 – 7, 2003. The reduction of RTI growth rate n is expressed analytically in the closed form

$$n = n_b - \beta \ell v_a$$

where n_b the classical growth rate is a function of δ - the stress gradient, v_a is the normal velocity to the ablative surface. In this expression both v_a and β are functions of Hartmann number M , slip parameter α and porous parameter σ . Here ℓ is the wave number of the perturbation at the interface. Further, n_b and v_a are also functions of Bond number B and δ . From this dispersion relation, we can obtain easily the results of Rudraiah (2003) in the limit $M \rightarrow 0$ (absence of magnetic field) and Rudraiah et al (2004) in the limit of $k \rightarrow \infty$ (absence of porous lining). The effect of laser radiation appears through δ in n_b and v_a . By solving the energy equation separately for the shell and porous layer including the radiation effect and using the radiation boundary condition, we have obtained the temperature distributions for Boussinesq compressible fluid. From these expressions, we have computed temperature distribution. For different values of M and σ the interface temperature θ_s is computed and the results are depicted graphically. It is shown that the effects of M and σ are to reduce θ_s for small values of M and σ and reaches saturation for large values of M and σ . The growth rate n given in the above dispersion is computed for different values of α , σ , M and B . We found, that the growth rate decreases with decrease in Bond number implying surface tension stabilizes the interface. The maximum growth rate corresponding to maximum wave number is computed for different values of α , σ and M and we found that it decreases considerably even up to 92% compared to the classical growth rate.

Thermal Smoothing by Laser Produced Plasma of Porous Matter

Milan Kalal¹, Sergey Gus'kov⁵, Andrzej Kasperczuk⁴, Vladimir Kondrashov⁶,
Eduard Krousky², Jiri Limpouch¹, Karel Masek², Tadeusz Pisarczyk³, Karel Rohlena²,
Jiri Skala², Petr Straka², and Jiri Ullschmied³

kalal@troja.fjfi.cvut.cz

- (1) Czech Technical University in Prague, Brehova 7, 115 19 Prague 1, Czech Republic
- (2) Institute of Physics, AS CR, Na Slovance 2, 182 21 Prague 8, Czech Republic
- (3) Institute of Plasma Physics, AS CR, Za Slovankou 3, 182 21 Prague 8, Czech Republic
- (4) Inst. of Plasma Physics and Laser Microfusion, Hery 23 St., 00-908 Warsaw 49, Poland
- (5) P. N. Lebedev Physical Institute of RAS, Leninski Avenue 53, 119991 Moscow, Russia
- (6) Troitsk Inst. for Innovation and Fusion Research, 142190 Troitsk, Moscow Region, Russia

During the *second* project year the first series of experiments was conducted on the PALS iodine laser facility to study the *physics of laser-light absorption in porous matter*, the *absorbed laser energy transfer inside the porous matter*, the *formation of ablation pressure* in the laser-produced plasma of the porous matter and the *ability of that pressure to accelerate a thin solid foil* (modelling the shell of an ICF target).

In these experiments, the laser provided a 400 ps (FWHM) pulse with the energy up to 600 J at the basic harmonic ($\lambda_1 = 1,32 \mu\text{m}$) and up to 300 J at the third harmonic ($\lambda_3 = 0.44 \mu\text{m}$) of the laser light. Target irradiances at both wavelengths were varied from $I \approx 10^{14} \text{ W/cm}^2$ up to $I \approx 10^{16} \text{ W/cm}^2$ for different sets of measurements. Such intensity variations were obtained not only by laser energy variations but also by defocusing the laser beam with respect to the target surface. The radius of irradiation area on the target was changed for different sets of measurements from $R_L \approx 40 \mu\text{m}$ up to $R_L \approx 150 \mu\text{m}$. Two types of planar targets were employed in these experiments: (i) single layer foam targets, (ii) double layer targets (a thin *Al*-foil was attached to a foam layer from its rear side). The foam layers with thickness from 300 μm to 1000 μm were made of polystyrene with two different average densities $\rho_1 = 10^{-2} \text{ g/cm}^3$ and $\rho_2 = 2 \times 10^{-2} \text{ g/cm}^3$. Thickness of the *Al*-foil was either $\Delta_{Al} = 5 \mu\text{m}$ or $\Delta_{Al} = 2 \mu\text{m}$. The dimensions of the targets were 2000 μm x 2000 μm .

The most relevant result from the point of *laser imprint treatment* was the demonstration of a *very fast energy smoothing process* in laser-produced plasma of porous matter, with the velocity $(2-5) \times 10^7 \text{ cm/s}$. The laser intensity distribution in the irradiated area was not quite uniform and had several concentric diffraction rings. These structures were *smoothed away*.

Analysis of the time evolution of the *Al*-foil surface positions for different thickness (at practically the same conditions of target irradiation and the same foam layers of double layer targets) shows the following values of *Al*-foils *velocities*: velocity of 5 μm - *Al*-foil was $(1-2) \times 10^6 \text{ cm/s}$ and velocity of 2 μm - *Al*-foil was $(5-6) \times 10^6 \text{ cm/s}$. On the basis of these velocity values and taking into account the foil acceleration time, the average

ablation pressure of laser-produced plasma of the porous matter could be estimated to be in the region from 4 to 6 Mbar [1-3]. Effective acceleration of thin solid foils by the pressure of foam absorbers of laser radiation was clearly demonstrated.

Theoretical predictions based on the theory developed by us for ablation pressure of the laser-produced plasma of porous matter and for the velocity of thin solid foil accelerated by such a pressure [1-3] are in a good agreement with the PALS experimental results supposing that most of the laser energy is absorbed in the supercritical foam layer.

Computer simulations were also performed and their results published [4]. Foil velocities measured in experiments, calculated from the developed analytical model and obtained in simulations are compared in Table 1.

Table 1:

Laser	Target	V_{exp} (cm/s)	V_{simul} (cm/s)	V_{max} (cm/s)
92 J	(CH) _n	6.0×10^6	4.9×10^6	4.8×10^6
173 J	(CH) _n	8.0×10^6	8.2×10^6	6.7×10^6
238 J	(CH) _n		1.1×10^7	8.2×10^6
238 J	PVA	1.4×10^7	3.5×10^7	1.32×10^7

Here (CH)_n is polystyrene foam with 2 μm Al-foil and PVA is 100 μm thick PVA foam of density 5 mg/cm³ with 0.8 μm Al-foil. Experimental and simulation velocities are represented by their average values in the interval 4–7 ns after the laser pulse maximum.

References

1. M. Kalal, J. Limpouch, E. Krousky, K. Masek, K. Rohlena, P. Straka, J. Ullschmied, A. Kasperczuk, T. Pisarczyk, S. Yu. Gus'kov, A. I. Gromov, V. B. Rozanov, V. N. Kondrashov; ***Thermal smoothing by laser-produced plasma of porous matter***, Fusion Science and Technology 43 (3), May 2003, 275-281, ISSN 1536-1055.
2. M. Kalal, A. I. Gromov, S. Yu. Gus'kov, A. Kasperczuk, V. N. Kondrashov, E. Krousky, J. Limpouch, K. Masek, T. Pisarczyk, K. Rohlena, V. B. Rozanov, P. Straka, J. Ullschmied; ***Laser Imprint Problem and its Treatment***, Second IAEA Technical Meeting on *Physics and Technology of Inertial Fusion Energy Targets and Chambers*, San Diego, California, 17-19 June 2002.
3. J. Limpouch, S. Guskov, A. I. Gromov, M. Kalal, A. Kasperczuk, V. N. Kondrashov, E. Krousky, B. Kralikova, K. Masek, T. Pisarczyk, M. Pfeifer, K. Rohlena, V. Rozanov, J. Skala, J. Ullschmied; ***Thin foil acceleration by the pressure of laser-produced plasma of porous matter***, ECLIM 2002 - 27th European Conference on Laser Interaction with Matter, SPIE Vol. 5228 (2003), Eds: O. N. Krokhin, S. Yu. Gus'kov, Yu. A. Merkul'ev, 111-120, ISBN 0-8194-5101-0.
4. J. Limpouch, N. N. Demchenko, S. Yu. Gus'kov, V. B. Rozanov, A. Kasperczuk, T. Pisarczyk, M. Kalal, V. N. Kondrashov, E. Krousky, K. Masek, P. Pisarczyk; ***Iodine Laser Interactions with Porous Matter***, Book of Proceedings (TuPo2.27), IFSA 2003, September 7–12, Monterey, USA.

Hydrodynamics of Liquid Protection Schemes for Inertial Fusion Energy Reactor Chamber First Walls

M. Yoda and S. I. Abdel-Khalik
Georgia Institute of Technology
Atlanta, GA 30332-0405 USA

Abstract

Several liquid protection schemes have been proposed to protect solid structures in fusion power plants by attenuating damaging radiation. In the thick liquid protection concepts proposed for the High-Yield Lithium-Injection Fusion Energy (HYLIFE-II) inertial fusion energy (IFE) power plant, arrays of liquid sheets form a sacrificial barrier between the fusion event and the chamber first wall while permitting target injection and ignition. In the thin liquid film wall protection concepts proposed for the Prometheus IFE power plant, a sacrificial attached thin liquid film protects the reactor chamber first walls from damaging radiation and thermal stresses.

Over the last five years, the Georgia Tech group has carried out extensive studies of the hydrodynamic aspects of thin and thick liquid protection schemes. Experimental studies have been carried out for both stationary and oscillating turbulent liquid sheets, the “building block” for thick liquid protection. Planar laser-induced fluorescence (PLIF) has been used to directly measure free-surface fluctuations in these flows. Mass collection has been used to estimate the “hydrodynamic source term”, i.e. the amount of droplets ejected by turbulent breakup in these flows. The effects of initial conditions, including nozzle and flow straightener design, upstream blockage and boundary layer cutting on surface ripple and the hydrodynamic source term have been characterized.

For thin liquid protection, numerical and experimental studies of the “wetted wall” concept, involving low-speed injection of a liquid coolant through a porous wall normal to the surface, have been performed. An experimentally validated level contour reconstruction method has been used to investigate the three-dimensional evolution of the liquid film surface on porous downward-facing walls. The impact of various design and operational parameters on the frequency of liquid drop formation and detachment, detached droplet size, and minimum film thickness between explosions, has been analyzed. The “forced film” concept, involving high-speed injection of a liquid coolant through slots tangential to the surface, has been experimentally studied. The mean detachment length was measured for high-speed water films injected onto downward-facing flat and curved surfaces of varying contact angle (*i.e.*, surface wettability) at different orientations.

The data obtained in this research will allow designers of inertial fusion energy systems to identify the parameter ranges necessary for successful implementation of both thick and thin liquid wall protection systems.

Investigation Of The High-Z Laser-Produced Plasma with the use of Ion Diagnostics for Optimization of the Laser Interaction with Hohlraum-Type Targets

Chief Scientific Investigator: Jerzy Wo_owski, Institute of Plasma Physics and Laser Microfusion, Hery St. 23, 00-908 Warsaw, Poland (e-mail: wolowski@ifpilm.waw.pl)

Abstract

The main objective of this project is application of ion diagnostic methods to investigate the physical properties of high-Z plasma generated by the laser beams, similar to the plasma produced inside the Hohlraum target.

The studies of laser-generated ions and comparison of ion and x-ray emissions from the high-Z plasmas were continued at the PALS Research Centre in Prague with the use of the iodine PALS laser system with output energy up to 750 J at the fundamental wavelength (1.315 μm) or up to 250 J at 3rd harmonic wavelength (0.438 μm) in the 0.4-ns pulse. The investigations performed at the PALS RC in Prague were carried out within multilateral collaboration with several institutes. At the IPPLM in Warsaw studies of fast ion generation in the plasma produced by 1-ps high intensity (up to 10^{17} W/cm²) have been also continued.

Investigations of ion emission were carried out by means of ion energy analyzer, ion collectors and solid state track detectors. The soft and hard X-ray emissions from the high-Z laser-produced plasmas were measured with the use of improved X-ray photodiodes.

Using the high-intensity long-wavelength as well as short-wavelength PALS laser beams the production of highly charged, high-energy ions have been demonstrated (for Ta ions: $z_{\text{max}} = 57 +$ and $E_i > 20$ MeV). The characteristic of both fast ions and hard X-rays change clearly depending on the laser intensity and these changes are well correlated with each other. At sharp focusing these changes were manifested by an abrupt rise of hard X-ray emission, lowering the amount of ions and narrowing the ion angular distribution.

An efficient production of highly charged high-energy ions by an intense short-wavelength laser pulse suggests that the mechanisms of the fast ion generation in this case are different from the classical process of fast ion acceleration by hot electrons which decreases with the decreasing of the wavelength. It is believed that in this case phenomena only weakly dependent on the laser wavelength (e.g. ponderomotive forces and self-focusing) of laser radiation may contribute to the acceleration of ions in the high-Z Hohlraum-like plasmas.

The characteristics of forward-emitted proton beams and hard X-rays produced from both single-layer and double-layer foil targets have been determined for various targets irradiated by the 1-ps laser pulse at intensities up to 10^{17} W/cm². It is found that using a double-layer target, containing high-Z front layer and low-Z hydrogen-rich back layer, one can obtain significantly higher energies and a current of protons as well as shorter proton pulse duration than in the case of a commonly used single-layer target. These results are related to the concept of the fast ignition of the compressed thermonuclear fuel with the use of fast protons or deuterons.

Laser Plasma Research in Hungary Related to the Physics of Fast Ignitors

István B. Földes

KFKI-Research Institute for Particle and Nuclear Physics

Association EURATOM

H-1525 Budapest, P.O.B. 49.

(IAEA Contract No. 11633)

Abstract

The experimental work in Hungary is carried out – as previously – within the frames of a joint project between the Plasma Physics Department of the KFKI-Research Institute for Particle and Nuclear Physics Budapest and the Department of Physics of the University of Szeged in the HILL Laboratory. Laser plasma experiments are carried out with a KrF laser system on the 248 nm wavelength. The pulse duration is 600 fs with an energy of 15 mJ. Recent efforts are summarized, in which the beam is focused with an off-axis parabolic mirror to a focal spot of 2 μm diameter. Approximately 55% of the laser intensity was inside this focal spot, which corresponds to $5 \cdot 10^{17}$ W/cm² intensity with an ASE prepulse as low as 10^7 W/cm².

Investigation of high harmonics generation was continued on solid targets with observing harmonics down to 62 nm wavelength. High harmonics generation besides being a nonlinear mechanism, gives information about the absorption mechanisms near the critical layer. The recently observed 4ω radiation is crucial when deciding the mechanism of generation. Our single shot spectra in the VUV range also shows signs of a heat wave driven by electrons deeply penetrating into the solid, heating it isochorically even for this – still nonrelativistic – intensity.

In a collaboration with the Max-Planck-Institut für Quantenoptik the generation and transport of fast electrons was investigated using the ATLAS laser system (1J, 150fs). In experiments with preformed plasmas the scattered 2ω light shows filamentary structure, referring to self-focusing. The x-ray pinhole photographs show the post-ionization of the preformed plasma by the ultrashort laser beam but it does not show filaments, probably because of the low density of the plasma. Rear side x-ray pinhole photography shows no significant divergence of the electron beam inside the solid target, the angle of divergence was found to be less than 12° , similarly to other groups, which refers to nearly parallel propagation of fast electrons, thus opening the possibility both for direct fast ignitor applications.

Finally some new results and trends in fast ignitor physics are summarized.

Investigation of Secondary Processes by Interaction of Plasma Streams with Various Materials

R.T. Khaydarov, M.R. Bedilov, G.R. Berdiyurov, U. Kunishev,
M. Khalmuratov, E. Tojikhonov

Scientific-Research Institute of Applied Physics at the National
University of Uzbekistan, Tashkent, Uzbekistan
Cable Address: 700174 Uzbekistan, Tashkent,
Vuzgorodok, Institute of Applied Physics
Telephone: 00+ 998-712-46-48-01
Facsimile: 998-71-144-32-53
E-mail: ragab@iaph.tkt.uz

Abstract

It is known that the Inertial Fusion Energy (IFE) research and development are based on a large number of advanced concepts and technologies such as drivers, target fabrication and reaction chamber systems. Simultaneous investigations of drivers, target fabrication and reactor chamber systems provide a reasonable approach of possible designing of powerful power stations on the basis of the inertial nuclear fusion. From above-stated problems our tasks within the project were the following: (i) investigation of the secondary processes at the interaction of laser-produced plasma beams with different materials for the reactor chamber, (ii) investigation of possibilities to improve the characteristics of laser-source of ions by using lasers in frequency mode and adding light elements into heavy element targets in different concentration.

Z-Pinch Inertial Fusion Energy

Craig Olson

Sandia National Laboratories
Sandia, Albuquerque, NM USA

Z-Pinch Inertial Fusion Energy (IFE) extends the single-shot Z-pinch results from Z in the Inertial Confinement Fusion (ICF) program to a repetitive concept for an IFE power plant for the production of energy. Z-pinches have already demonstrated 1.8 MJ of x-rays on Z, relatively low capital cost (\$30/J for ZR), and very high efficiency (15% for wall plug to x-rays on Z). ZR (Z Refurbishment) will be operational in 2006, and will be within a factor of 2-3 in current (4-9 in energy) of a high-yield driver designed to produce 0.5 GJ yields. A first study of a 1000 MW_e Z-Pinch IFE Demo power plant uses 3 GJ yields at low repetition rate (0.1 Hz) per chamber, with multiple chambers. A Z-Pinch IFE Road Map has been created that shows the complementary development of single-shot fusion targets with NIF, and with Z-ZR-High Yield. Simultaneously, it is envisioned that Z-Pinch IFE will be developed through the Integrated Research Experiment (IRE) phase, and then the single-shot High Yield facility will be upgraded to a repetitive-shot Engineering Test Facility for IFE.

Z-Pinch IFE has a matrix of possibilities that are beginning to be investigated. A Z-Pinch power plant consists of a Z-Pinch Driver, a Recyclable Transmission Line (RTL), a Z-Pinch Driven Target, and a Power Plant Chamber. The Z-Pinch Driver may use (1) Marx generator / water line technology, (2) magnetic switching technology as demonstrated in RHEPP at up to 120 Hz, or (3) Linear Transformer Driver (LTD) technology. The RTL may be made from a frozen coolant (Flibe plus a thin electrically conductive coating), or a material immiscible in the coolant (such as low-activation ferritic steel). The Z-Pinch Driven Target may be a double-pinch driven hohlraum, a dynamic hohlraum, or a fast ignition target. (Capsule compression ratios of 14-20 have been demonstrated with a double-pinch target on Z, and $\sim 3 \times 10^{10}$ DD fusion neutrons have been demonstrated with a dynamic hohlraum target on Z.) The Power Plant Chamber could be a dry-wall, wetted-wall, thick-liquid wall, or solid/voids (e.g., Flibe foam) chamber. Presently, the preferred choice for Z-Pinch IFE is to use LTD pulsed power technology, an RTL made from low activation ferritic steel, a dynamic hohlraum target, and a thick-liquid wall chamber.

The present "Concept Exploration" development of Z-Pinch IFE has been supported for the last few years through LDRD (Laboratory Directed Research and Development) internal funds at Sandia National Laboratories. The next phase of development, the "Proof-of-Principle" phase, is envisioned to begin now. This phase will consist of four sets of experiments, *plus* IFE target development, *plus* IFE power plant studies. The four experiments are (1) RTL experiments culminating in an RTL experiment on Z, (2) repetitive driver (LTD presumably) development at 1 MA, 1 MV, 0.1 Hz, (3) shock mitigation scaled experiments with explosives/water hydraulics to study containment of high yields with minimal shocks to the structural wall, and (4) a full RTL cycle scaled integrated repetitive experiment (1 MA, 1 MV, 0.1 Hz, with RTLs and small z-pinch loads). The anticipated cost for the Proof-of Principle experiments is \$14M/year for 3-5

years. Presently, \$4M is eminent for FY04 to begin this phase of development of Z-Pinch IFE.

When funded, Z-Pinch IFE will involve collaborations between universities, industry, national laboratories, and US-Russia (Sandia-Kurchatov). Further international cooperation will be encouraged through, e.g., the IAEA CRP on IFE Power Plants.

Appendix A

Agenda for Research Coordination Meeting

Research Co-ordination Meeting on
Elements of Power Plant Design for Inertial Fusion Energy

4-7 November 2003

Room A07, IAEA Headquarters, Vienna

TENTATIVE AGENDA

Tuesday, 4 November, 10:00

Welcome Address: Director, Division of Physical and Chemical Sciences

Introductory Comments: Gunter Mank, Head, Physics Section, NACP

Modification of Agenda

Selection of Chair/s and Rapporteur

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|---------------|--|
| 10:30 - 11:30 | Wayne Meier, "Update of IFE Research at LLNL" |
| 11:30 - 12:30 | Boris Sharkov, "Beam Plasma Interaction - Issue for Heavy Ion Reactor" |
| 12:30 - 14:00 | Lunch break |
| 14:00 - 15:00 | Manuel Perlado, "Progress in Materials Analysis for IFE Reactors at the Instituto Fusion Nuclear." |
| 15:00 - 16:00 | Dieter Hoffmann, "Basic Physics for Inertial Fusion Energy in High Energy Density Physics with Intense Heavy Ion and Laser Beams. Present and Future Prospects of High Energy Density in Matter Research at GSI" |
| 16:00 - 16:10 | Coffee break |
| 16:10 - 17:10 | Elena Korosheva, "Development of a Full-Scaled Scenario for Repeatable IFE Target Fabrication and Injection" |

Wednesday, 5 November

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|---------------|---|
| 9:00 - 10:00 | Dan Goodin (given by W. Meier), "Target Fabrication and Injection for Inertial Fusion Energy" |
| 10:00 - 11:00 | Stanislav Medin, "Design Concept of Fast-Ignition Heavy Ion Fusion Power Plant" |
| 11:00 - 11:10 | Coffee break |
| 11:10 - 12:20 | Farrokh Najambadi, "Assessment of IFE Chambers and Research Activities on IFE Chambers and Optics at UC San Diego" |
| 12:20-14:00 | Lunch break |
| 14:00 - 15:00 | Patrick Calderoni, "Feasibility Exploration of Vapor Clearing Rates for IFE Liquid Chambers: Transient Condensation of Lithium Fluoride Excited Vapors for IFE Systems" |
| 15:00 - 16:00 | Koichi Kasuya, "Peripheral Elements and Technology Associated with Pulsed Power Inertial Fusion; Part 2" |
| 16:00 - 17:15 | Discussion |
| 17:30 - 19:00 | Reception |

Thursday, 6 November

- 9:00 - 10:00 Hong Jin Kong, "The Feasibility Study of the Application of Phase Locking of the Beam Combination to the Laser Fusion Driver with the Indefinite Output Power and Energy"
- 10:00 - 11:00 Rudraiah Nanjundappa, "Effects of Magnetic Field, Laser Radiation and Nano Structure Porous Lining at the Ablative Surface of IFE target"
- 11:00 - 11:15 Coffee break
- 11:15 - 12:15 Milan Kalal, "Thermal Smoothing by Laser Produced Plasma of Porous Matter"
- 12:15 - 14:00 Lunch break
- 14:00 - 14:30 M. Yoda (given by W. Meier), "Hydrodynamics of Liquid Protection Schemes for Inertial Fusion Energy Reactor Chambers First Wall Chamber Design"
- 14:30 - 15:30 Jerzy Wolowski, "Investigation of the High-Z Laser-Produced Plasma with the use of Ion Diagnostics"
- 15:30 - 17:00 Discussion, documents' preparation

Friday, 7 November

- 9:00 - 10:00 István Földes, "Laser Plasma Researches in Hungary Related to the Physics of Fast Igniters"
- 10:00 - 11:00 Rajabbay Khaydarov, "Investigation of Secondary Processes by Interaction of Plasma Streams with Various Materials"
- 11:00 - 11:15 Coffee break
- 11:15 - 13:00 Final discussion

Appendix B

List of Attendees

CZECH REPUBLIC

Dr. Milan Kalal
Faculty of Nuclear Sciences and Physical Engineering
Czech Technical University in Prague
Brehova 7
115 19 Prague 1
FAX: 420 284 684 818
E-mail: kalal@troja.fjfi.cvut.cz

GERMANY

Dr. Dieter Hoffmann
Gesellschaft fuer Schwerionenforschung
GSI, Plasmaphysik
Planckstr. 1
D-64291 Darmstadt
FAX: 49 6159 2888
E-mail: hoffmann@physik.tu-darmstadt.de

HUNGARY

Dr. István Földes
KFKI Research Institute for Particle and Nuclear Physics
H-1121 Budapest
Konkoly-Thege u. 29-33
H-1525 Budapest, P.O.B. 49
FAX: 36 1 392 2598
E-mail: foldes@rmki.kfki.hu

INDIA

Dr. Nanjundappa Rudraiah
Honorary Director
National Research Institute for Applied Mathematics (NRIAM)
and Honorary Professor UGC-CAS in Fluid Mechanics
Department of Mathematics, Bangalore University
Bangalore – 560001
FAX: 91 080 2259843, 6764356
E-mail: nrudraiah@hotmail.com

JAPAN

Dr. Koichi Kasuya
Tokyo Institute of Technology
Department of Energy Sciences, Interdisciplinary Graduate School
4259 Nagatsuta, Midori-ku
Yokohama, Kanagawa 226-8502
FAX: 81 45 924 5575

REPUBLIC OF KOREA

Dr. Hong Jin Kong
Korea Advanced Institute of Science & Technology (KAIST)
373-1 Kusong-dong
Yusong-gu Taejeon
FAX: 82 42 863 957
hjkong@mail.kaist.ac.kr

POLAND

Dr. Jerzy Wolowski
Head of Laser-Produced Plasma Department
Institute of Plasma Physics and Laser Microfusion
23 Hery St.
00-908 Warsaw 49
FAX: 48 22 6668372
E-mail: wolowski@ifpilm.waw.pl

RUSSIA:

Elena Koresheva
Head of the Cryotarget Group
P.N. Lebedev Physical Institute (LPI) of Russian Academy of Sciences
Neutron Physics Department
Leninsky Prospect 53
Moscow 119991
FAX: 007 095 132-5044
E-mail: koresh@sci.lebedev.ru

Dr. Boris Sharkov
Institute for Theoretical and Experimental Physics
B. Cheremushkinskaya 25
Moscow 117259
FAX: +7095 123 3028
E-mail: boris.sharkov@itep.ru

Dr. Stanislav Medin
Institute for High Energy Densities
Izhorskaya Ul., 13/19
125412 Moscow
FAX: 007 095 4857990
E-mail: medin@ihed.ras.ru

SPAIN

Dr. J. Manuel Perlado
Institute of Nuclear Fusion
Universidad Politecnica de Madrid
Jose Gutierrez Abascal, 2
Madrid 28006
FAX: 34 336-3002
E-mail: mperlado@din.upm.es

USA:

Dr. Farrokh Najmabadi
Department of Electrical and Computer Engineering
Center for Energy Research
University of California, San Diego
460 EBU II
La Jolla, CA 92093-0438
FAX: 858 822 2120

E-mail: najmabadi@fusion.ucsd.edu

Dr. Patrick Calderoni
UCLA - MAE Department
Fusion Science and Technology Group
Engineering IV, Room 44-114
Los Angeles, CA 90095-1597
FAX: 310 825 2599
E-mail: patcal@fusion.ucla.edu

Dr. Wayne Meier
Deputy Program Leader for IFE, Fusion Energy Program
Lawrence Livermore National Laboratory
P.O. Box 808, L-641
Livermore, CA 94551
FAX: 925-424-6401
E-mail: meier5@llnl.gov

UZBEKISTAN

Dr. Rajabbay Khaydarov
Scientific Research Institute of Applied Physics
National University of Uzbekistan
Vuzgorodok, Tashkent 700174
FAX: 998-71-144-3253
E-mail: ragab@iaph.tkt.uz