A Review of the Inertial Fusion Energy Program:

Inertial Fusion Energy [IFE] Panel Membership:

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John Lindl, *Lawrence Livermore National Laboratory*
Rulon Linford (Chair), *University of California (Retired)*
Grant Logan, *Lawrence Berkeley National Laboratory*
Keith Matzen, *Sandia National Laboratory*
Gerald Navratil, *Columbia University*
Arthur Nobile, *Los Alamos National Laboratory*
John Sethian, *Naval Research Laboratory*
John Sheffield, *University of Tennessee, Knoxville*
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Presentation of the Final Report to FESAC

29 March 2004

Motivation for Igniting Fusion Fuel in the Laboratory

- Study matter under extreme conditions needed for fusion
- Potential of an attractive energy source

Main Elements of an IFE System

- Driver
- Target
- Chamber

Interrelated Technical Requirements for IFE

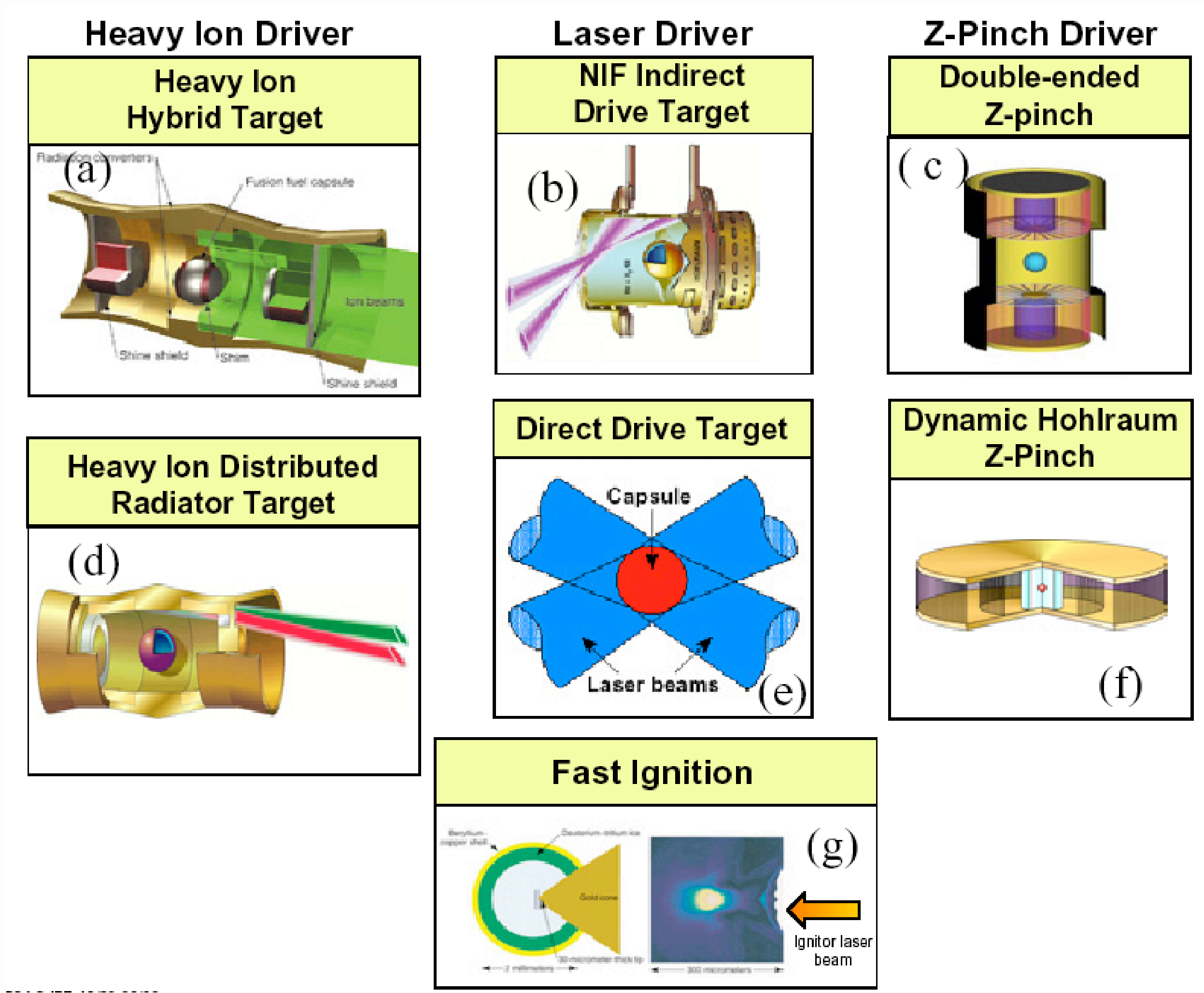
- High energy gain (target) and efficiency (driver)
- Repetition rate (driver/ target/ chamber)
- Energy conversion efficiency & tritium breeding
- Durability consistent with high capacity factor

… must be achieved in a cost-effective and environmentally attractive manner

Main Technical Approaches

APPROACH	DRIVER	TARGET	CHAMBER
Heavy Ion (HI)	HI Accelerator	Indirect Drive	Liquid Wall
High Average Power Lasers (HAPL)	- KrF Laser - Diode-Pumped Solid-State Laser (DPPSL)	Direct Drive Direct Drive	Dry Wall Dry Wall
Z-Pinch	Pulsed-Power Z-Pinch	Indirect Drive	Liquid Wall

Types of IFE Targets



Fast Ignition Concept

- Potentially applicable to all three main approaches
- Separates functions of compression and ignition
- Potential benefits may include:
  - Higher gain
  - Reduced requirement for -
    - targets and compression driver

Charge Letter Excerpts

- “considerable scientific and technical progress”
- “assessment of the present status” of IFE research
- IFE programs in both:
  - Office of Science
  - Defense Programs in National Nuclear Security Agency
- Both “support this review and concur that it be carried out by FESAC”

Charge Letter List

1. The current status of the scientific basis and related technology of each of the approaches to IFE, including an assessment of the quality of work being carried out in the programs.
2. Critical scientific issues identified in each of the approaches to IFE that would contribute to understanding the long-range potential of IFE.
3. The impact that fast ignition as a concept improvement may have on IFE.
4. The potential contribution of the various IFE program elements to the emerging field of High Energy Density Physics.

IFE Panel Membership List

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Panel Member Responsibilities

- *IFE EXPERTS*
  - Make available al relevant information
  - Describe status
  - Identify issues
  - Describe possible research plans
  - Ensure factual accuracy of report
  - Identify potential for HEDP impact
- *EXPERTS OUTSIDE OF IFE*
  - Assess quality of work
  - Identify most critical near-term issues
  - Comment on appropriateness of research plans
  - Evaluate potential impact on HEDP

Panel Schedule

July 17, 2003	– Charge letter to Professor Hazeltine from Dr. Orbach
September 2	– First email to the IFE Panel members
October 28-29	– Meeting in Albuquerque, NM
December 3	– Conference call
December 10	– Conference call
December 16	– Conference call
January 20	– Conference call
January 27	– Conference call
February 12-13	– Meeting in La Jolla, CA
March 19	– Draft Report sent to FESAC
March 29	– Report presentation to FESAC

IFE and Inertial Confinement Fusion [ICF] Program Definitions Used in Report:

- **IFE program --** the DOE-sponsored research in inertial fusion energy, including the OFES research in Heavy-Ion Beams and Fast Ignition, and the NNSA HAPL and Z-Pinch-IFE programs.

- **ICF program --** the NNSA-funded program in inertial confinement fusion, excluding the HAPL and the Z-Pinch-IFE programs.

Sources of Funding for IFE-Relevant Activities

	NNSA Program	OFES Program	Report Section
HEAVY-ION BEAMS			
Driver Science		OFES-IFE	3.2.1
Final Optics (magnets)			3.2.1
Target Physics		OFES-IFE	3.1.1
Target Fabrication			3.1.4
Target Injection	HAPL		3.1.4
Chamber			3.4.1
LASERS			
Driver Science/Technology	HAPL		3.2.2, 3.2.3
Final Optics (mirrors)	HAPL		3.2.3
Target Physics	ICF (+HAPL)		3.1.2
Target Fabrication	HAPL (+ICF)		3.1.4
Target Injection	HAPL		3.1.4
Chamber	HAPL		3.4.1
Z-PINCHES			
Driver Science/Technology	Z-IFE		3.2.4
Recyclable Transmission Line	Z-IFE		3.2.4
Target Physics	ICF		3.1.1
Target Fabrication	ICF (+Z-IFE)		3.1.4
Chamber	Z-IFE		3.4.1
FAST IGNITION			
Petawatt Lasers	ICF		3.3
Target Physics		OFES-IFE	3.1, 3.3
Target Fabrication	ICF	OFES-IFE	3.1.4

Panel Findings Highlighted in Executive Summary

Progress Across the Program -

Experts outside of IFE were "very impressed by the progress across the program, noting that *the three main approaches (HI accelerators, HAPL, and Z-pinch) are at different levels of maturity. The balance between the science and technology emphasis necessarily varies. The recent progress related to these approaches is substantial and the quality of the science and engineering research is excellent. All approaches are currently on track for developing the science and technology to properly evaluate their potential for IFE.* However, the planned termination of technology programs in support of the HI approach is not consistent with their importance to HI-IFE, and the Panel is concerned about the impact of this action."

Panel Findings Highlighted in Executive Summary *(cont)*

<u>Fast Ignition -</u>

"*each of the approaches to IFE may benefit if the technique of Fast Ignition proves effective. However, since FI is at an early stage of development it would be premature for any of the IFE approaches to rely on the success of FI to achieve an attractive fusion energy system. During the next several years, there is an opportunity to assess the potential of the FI concept utilizing facilities in both Japan and the US (OMEGA, Z, and possibly NIF) through modest OFES investments.*"

Panel Findings Highlighted in Executive Summary *(cont)*

Most Critical Near-Term Issues -

From the list of primary issues currently facing IFE, "the Panel identified the single near-term issue that appears to be the most critical for each of the approaches (HI, HAPL, and Z-Pinch) and for the FI concept.

They are:

HI -- *Physics limits to the maximum phase-space density of space-charge-dominated HI beams and the resulting implications for HEDP and fusion ignition.*

HAPL -- *Durability of KrF lasers, and efficiency and beam smoothing in DPSSLs, that will scale to the high-energy requirements for IFE.*

Z-Pinch -- *Physics limitations on power flow in a recyclable transmission line, including the coupling to the pulsed-power driver and the integral target assembly.*

FI -- *Physics of fuel compression to a uniform-density sphere and of energy transport by relativistic electrons to that high-density fuel to achieve ignition."*

Panel Findings Highlighted in Executive Summary *(cont)*

<u>Importance of Other Issues and the ICF Program -</u>

These issues, along with many other important basic and applied science issues that form the basis of IFE research plans, must be addressed to assess the potential of IFE. The critical issues related to fuel ignition and burn affect all of the approaches but were not included in the above list because they are being addressed mainly by the ICF program. The Panel acknowledges this vital role of the ICF program and notes *the tremendous leverage that allows the comparatively modest funding for IFE-specific programs to continue to yield important advances*. This is a synergistic relationship where *IFE research* also *directly benefits the NNSA mission.*

Panel Findings Highlighted in Executive Summary *(cont)*

<u>Potential Contributions to HEDP and other Areas -</u>

"IFE capabilities have the potential for significantly contributing to HEDP and other areas of science. For example, *isochoric heating of substantial volumes to uniform, elevated temperatures should be achievable using HI beams. Investigations of the Fast Ignition concept can lead to exploration of exotic HEDP regimes. Moreover, the rapid turnaround capabilities envisioned for IFE drivers could accelerate progress in HEDP science by enabling a wide community of users to conduct "shot-on-demand" experiments with data rates and volumes far exceeding those obtained on large systems that currently require long times between shots."*

Panel Findings from the Body of the Report

General Findings -

The Panel recognizes and respects the reasons for the differences in near-term focus of OFES and NNSA sponsored programs. Although near-term strategies differ, the ultimate goal of all IFE research is fusion energy production. The long-term potential for fusion power provides an exciting and unifying purpose for all IFE research activities.

IFE research involves a rich set of scientific challenges. Substantial advances in a spectrum of scientific disciplines will be required to effectively assess the long-term potential of IFE. Many outstanding researchers from academia as well as federal laboratories are pursuing a range of exciting IFE science topics.

Panel Findings from the Body of the Report *(cont)*

General Findings (continued) -

Understanding the interrelated scientific and technological issues of the key components of IFE within the framework of an integrated system is an essential input for prioritizing IFE research activities, whether for the science-focused OFES program or for the NNSA program. Careful prioritization is particularly important given the limited resources available to these IFE activities.

The prevailing view in the IFE Panel is that the most efficient way to achieve the ultimate goal of fusion energy is to carry out a coordinated program with some level of research carried out on all of the key components (targets, drivers, and chambers), keeping the requirements of the end product in mind. However, the Panel members had widely varying views on the relative levels of effort among the components and the degree of focus on science or technology that would provide the most efficient development path, given the present state of understanding. Keeping in mind this broad description of a coordinated program, the Panel supports the following finding.

Carrying out a coordinated IFE research program allows a more efficient approach for developing a fundamental understanding of the science that is necessary for IFE.

Panel Findings from the Body of the Report *(cont)*

General Findings (continued) -

The scientific and technical challenges posed by IFE, along with their many connections to HEDP, and the grand ultimate purpose of fusion power highlight both the need and the opportunity to attract outstanding researchers for future success. In order to identify and exploit key opportunities and synergies with HEDP and other exciting topics, improved coordination is needed between various scientific communities. The series of workshops on laboratory astrophysics with lasers is a model that could be emulated.

Panel Findings from the Body of the Report *(cont)*

Targets (Direct and Indirect Drive) -

The combined IFE plus ICF target physics research portfolio is appropriately diverse, and the technical work is of very high quality. Excellent progress involving one or more of the key performance criteria – implosion symmetry, capsule stability, and high gain – continues to be made on central hot-spot targets being designed for the various driver schemes.

Panel Findings from the Body of the Report *(cont)*

Theory and Simulation -

Simulation has a substantial impact on enhancing the performance and understanding of existing and advanced target concepts. The ICF and IFE programs have developed valuable capabilities for driver-matter interactions, including an extensive validation program against experiments performed at NIKE, Z, and OMEGA. Nonetheless, new simulation capabilities are needed, particularly in the areas of material models, laser-plasma interactions, and in the range of scales that can be represented. The IFE program would also benefit from developing an open-source simulation capability in the area of capsule physics, particularly in connection with HEDP.

Panel Findings from the Body of the Report *(cont)*

Targets Fabrication -

Substantial progress in target fabrication has been made, by using a combination of modeling and experiments with surrogate materials, as well as by leveraging the ICF program knowledge base. The work in this area has been of high quality. Current-day targets do not meet all ignition specifications, but concepts for producing practical IFE targets have been developed and there is a plan to demonstrate these concepts. However, many difficult questions have yet to be addressed experimentally. The IFE program will benefit from continuing its emphasis on high-rep-rate target production and target placement in the chamber, including near-term fabrication of materials and targets for testing of physics codes and the development of long-term solutions for mass production. The planned elimination of OFES funding for target fabrication is not consistent with its importance to the HI-IFE program.

Panel Findings from the Body of the Report *(cont)*

Drivers -

The three main approaches (HI accelerators, HAPL, and Z-pinch) are at different levels of maturity. The balance between the science and technology emphasis necessarily varies. The recent progress related to these approaches is substantial and the quality of the science and engineering research is excellent. All approaches are currently on track for developing the science and technology to properly evaluate their potential for IFE.

Panel Findings from the Body of the Report *(cont)*

Fast Ignition -

Each of the approaches to IFE may benefit if the technique of Fast Ignition proves effective. Recent experiments on the GEKKO laser in Japan have offered very encouraging indications that efficient igniter-beam energy transport to and heating of a compressed core are being observed. However, since FI is at an early stage of development it would be premature for any of the IFE approaches to rely on the success of FI to achieve an attractive fusion energy system. During the next several years, there is an opportunity to assess the potential of the FI concept utilizing facilities in both Japan and the US (OMEGA, Z, and possibly NIF) through modest OFES investments.

Panel Findings from the Body of the Report *(cont)*

Chambers -

The dynamic response of chambers following target explosions is a critical scientific issue in determining the repetition rate and durability and hence the ultimate attractiveness of all IFE concepts. Important chamber issues requiring further work for their resolution include thick liquid chamber dynamics and shock mitigation, aerosol generation and transport, armor survival, and chamber clearing. The closeout of chamber R&D being planned by OFES is not consistent with its importance to the HI-IFE program.

Panel Findings from the Body of the Report *(cont)*

<u>Integrated Concept Studies -</u>

Integrated power plant studies play an important role in identifying critical issues and in driving innovation in science, technology, and engineering for IFE. The planned elimination of integrated studies is not consistent with their importance to the OFES HI-IFE program.

Panel Findings from the Body of the Report *(cont)*

Potential Contributions to HEDP and Other Science -

IFE capabilities have the potential for significantly contributing to HEDP and other areas of science. Isochoric heating of substantial volumes to uniform, elevated temperatures should be achievable using HI beams. Investigations of the Fast Ignition concept can lead to exploration of exotic HEDP regimes. Moreover, the rapid turn-around capabilities envisioned for IFE drivers could accelerate progress in HEDP science by enabling a wide community of users to conduct "shot-on-demand" experiments with data rates and volumes far exceeding those obtained on large systems that currently require long times between shots.

Panel Findings from the Body of the Report *(cont)*

<u>IFE Synergies with the ICF Program -</u>

The NNSA-funded ICF program has the vital role of achieving ignition, and its research on target physics offers tremendous leverage that allows the comparatively modest funding for IFE-specific programs to continue to yield important advances. Carrying out a coordinated IFE research program now will guide future experiments on OMEGA, Nike, Z, and soon NIF, to develop the advanced target designs that not only meet the IFE physics requirements of high gain, but also the IFE requirements for fabrication, injection, and recycling.

IFE research directly benefits the NNSA mission. A vigorous IFE research program will continue to foster innovation that may lead to improved NNSA capabilities in targets (design, fabrication, and characterization), driver performance, & chamber/optics components.

Conclusion *(Final Paragraph in Executive Summary)*

"The Panel is of the unanimous opinion that the IFE program is technically excellent and that it contributes in ways that are noteworthy to the ongoing missions of the DOE.

Moreover, the Panel agrees with the IFE community that the most efficient way to achieve the ultimate goal of fusion energy is to carry out a coordinated program with some level of research on all of the key components (targets, drivers, and chambers), always keeping the end product and its explicit requirements in mind. The Panel also notes that *the scientific and technical challenges posed by IFE, along with their many connections to HEDP,* have attracted *many outstanding researchers from academia as well as federal laboratories.* Success will depend on sustaining the commitment and involvement of such people in a broad spectrum of scientific disciplines."

The IFE Panel wishes to thank the many presenters and technical contributors to the report.