Snowmass Fusion Summer Study (July 11-23, 1999)
Inertial Fusion Concepts Working Group
Final Report

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Overview (Craig Olson)

The Inertial Fusion Concepts Working Group was organized around the Snowmass theme of examining issues and opportunities for the next decade. Organization of this working group began almost a year before the Snowmass meeting, when it was decided to structure this working group into four Subgroups as follows:

(1) Targets
(2) Drivers and Standoff
(3) Inertial Fusion Power Plants
(4) IFE Metrics and Development Paths

To guide the discussions, a series of key questions, or "hot topics" was developed. The purpose of these questions was to establish the status and issues of the various areas of IFE, and examine how existing (and possibly new) facilities could be used to address these issues during the next decade. A complete listing of the Convenors, Subgroup Leaders, and Session Leaders is given in Table 1. A complete listing of the "hot topics" questions is given in Table 2.

The format of this Working Group's Sessions was to have open discussions. During the first week, the first three Subgroups had parallel Sessions. Each Session had one Session Leader and spent a morning (three and a half hours) discussing the answer to one "hot topics" question. Speakers were invited to give short presentations to initiate the discussions. Each speaker was asked to give a concise summary of the present status of the particular issue in question, and then propose a "strawman" answer to the question to initiate discussion. The discussion period after each talk was typically as long as, or longer than, the talk. In addition, if anyone wanted to give a relevant, brief talk, they were invited to contact the Session Leader, who arranged it in the schedule of their Session. There were no predetermined conclusions. It was hoped that consensus would be reached in most cases. However, if there were clearly diverging opinions, then it was agreed that both sides should be presented in this final report. The Session Leader was responsible for coordinating the written answer to their Session's question, with input from speakers, contributors, and all participants. At the end of the first week, and during the second week, the entire Inertial Fusion Concepts Working Group met in plenary

Table 1. Inertial Fusion Concepts Working Group

Organizer: Craig Olson

Convenors: John Barnard, John Lindl, Craig Olson, Steve Payne,
John Sethian, Ken Schultz, Rick Spielman

Subgroup Leaders:
(1) Targets: Max Tabak, Jill Dahlburg,
Rick Olson
(2) Drivers & Standoff: Steve Payne, John Barnard,
John Sethian, Rick Spielman
(3) Power Plant Concepts: Ken Schultz, Robert Peterson,
Per Peterson
(4) Metrics & Pathways: Wayne Meier, John Perkins

Session Leaders:
Question 1A : Max Tabak
Question 1B: Jill Dahlburg
Question 1C: Rick Olson
Question 2A: John Sethian
Question 2B: John Barnard
Question 2C: Rick Spielman
Question 3A: Robert Peterson
Question 3B: Per Peterson
Question 3C: Ken Schultz
Question 4A: John Perkins
Question 4B: Wayne Meier

Table 2. "Hot Topics" Questions.

Targets

- **(1A)** **What are the key scientific issues for validating each target concept, and how can they be resolved?**
- **(1B)** **How can existing (and new?) facilities be used to test each concept?**
- **(1C)** **What IFE target physics issues will not be resolved on NIF? What is required to get to high yield? What is the significance to IFE of experimentally demonstrating high yield/high gain?**

Drivers and Standoff

- **(2A)** **How can the source brightness, beam uniformity, pulse shaping accuracy, efficiency, reliability, repetition rate, and cost of each driver concept be improved?**
- **(2B)** **What are the key standoff issues for each driver scenario and how can they be addressed? (e.g., final optics for lasers, final transport and focus for laser beams, final focus magnetic lenses for heavy ion beams, power feed for rep-rated z-pinches,…)**
- **(2C)** **What would convincingly demonstrate that each driver concept is a viable driver candidate for IFE? Specifically, what is a convincing Integrated Research Experiment (IRE) for each driver candidate?**

Inertial Fusion Power Plant Concepts

- **(3A)** **What are the key IFE power plant concepts, advantages, and issues?**
- **(3B)** **What are the key scientific issues for the fusion chamber (e.g., first wall protection, …), and what are the proposed solutions? What experiments could be done to test the relative merits of these solutions?**
- **(3C)** **What are the issues in target fabrication, target characterization, target injection, target robustness (e.g., tolerances), and what is the path for addressing them?**

IFE Metrics and Development Paths

- **(4A)** **What are the metrics for an entire IFE system for each step of development (e.g., concept exploration, proof of principle, performance extension, fusion energy development, DEMO, attractive commercial fusion power plant)? How are these incorporated into the IFE Road Map? How do we insure that there is a mechanism in place for new concepts to Initiate a development path?**
- **(4B)** **What is the status and development path of each present IFE scenario?**

session to discuss the Subgroup 4 Topics, and then to continue discussions from the first week on some of the more difficult issues.

The summaries of the four Subgroups and of the eleven "hot topics" Sessions form the core of this report. Before presenting these detailed results (which are given in the following sections), we would first like to give an overview as to how all of the inertial fusion elements should fit together during the next decade, and then give brief summaries of each Subgroup. Lastly, brief summaries are given of the discussions on "special issues."

IFE Overview

An IFE power plant is an integrated choice of:

1. Target (direct drive, indirect drive, etc.)
2. Driver (heavy ion, KrF laser, DPSSL laser, z-pinch, light ion, etc.)
3. Chamber (dry wall, wetted wall, liquid wall, etc.)
4. Power conversion (Rankine, Brayton, etc.)

The separation of the power plant into four separate areas offers unique advantages for the inertial fusion approach to energy. Within certain constraints, it allows one to optimize the choice from each category to make the best integrated choice for any particular driver. Presently, there are two mainline approaches to inertial fusion energy - heavy ions and lasers. The present preferred heavy ion scenario uses an induction linac heavy ion driver, an indirect-drive target, and a liquid-wall or wetted-wall chamber. The laser scenario uses either a Krypton Fluoride (KrF) laser driver or a Diode-Pumped Solid State Laser (DPSSL) driver, a direct-drive target, and a dry-wall chamber. Other driver concepts also exist as exploratory concepts: a z-pinch scenario would use a pulsed power z-pinch driver, an indirect drive target, and a liquid wall or possibly solid Li with voids and a density gradient; a light ion scenario would use an ion diode driver, an indirect-drive target, and a wetted-wall chamber. Other exploratory concepts include the Fast Ignitor target concept, and Magnetized Target Fusion (MTF), which is between IFE and MFE.

An overview of the present IFE program is given in Table 3, organized according to drivers. The mainline approaches include heavy ions and lasers: these are at the Proof of Principle (PoP) stage, and are progressing toward the Performance Extension (PE) stage. Also, at the Concept Exploration (CE) level are z-pinches, light ions, and MTF. In addition to entries for drivers, targets and power plants, note the entries for stand-off issues. Standoff refers to the interface between the driver and the target, and involves specific chamber issues associated with, e.g., final optics or final transport in the chamber. While science was the main charter of this Snowmass meeting, the FY99 funding levels for IFE are also given in Table 3, to show the present scale of these programs. In the last column, aspirations for the next decade are given. The three mainline approaches are currently at the PoP level: each desires a funding level of about \$16M for 4-5 years, following which a decision would be made to as to whether to proceed on to the PE level. The Integrated Research Experiment (IRE) is at the PE level and would cost of the order of \$50M -\$150M. It is suggested that a decision should be made in 4-5 years (given adequate funding during that time) to proceed with 0, 1, or more IRE's. In addition, CE level support is needed for the next several years for z-pinches,

Table 3. IFE Overview.

Approach	Driver	Target	Standoff Issue	Power Plant Concept	FY99 Funding for IFE	Aspirations for Next Decade
Main-line approaches (from PoP to PE)	Ion -heavy ion induction linac	Indirect-drive	Ion beam Transport	Liquid wall	$8M	Each program: 4-5 years research* at ~$16M/year , leading to an IRE for ~$50M-$150M (0,1, or more IRE's)
	Laser -DPPSL	Direct-drive	Final optic	Dry wall	$4M	
	-KrF	Direct-drive	Final optic	Dry wall	$8M	
Concept Exploration (CE)	Z-pinch	Indirect-drive	Recyclable transmission line	Solid Li	$0.2M	Investigate concept and rep-rate
	Ion-light ion diode	Indirect-Drive	Ion beam transport	Wetted Wall	0	Science-level ion source development
	Magnetized target fusion	Magnetized plasma	Recyclable transmission line	Solid Li	$1M	PoP experiment (~$21M/3 years)

*includes chamber, target development, environmental attractiveness,…

light ion sources, and MTF (as well as for the fast ignitor target concept, and new IFE concepts). Note that the current desired funding includes support for chamber development and target development.

As discussed in the summaries to follow, issues for target physics will be addressed mainly with existing facilities during the next decade. Specifically, target development (indirect-drive and direct-drive), ignition, and the start of propagating burn will be studied on Omega, Nike, Z, and NIF (all of which are funded through DOE DP). It is important to note that it was envisioned at Snowmass that no new "target shooter" facilities will be required during the next decade, because NIF will be coming online. The question of if and when a high-yield/high-gain single-shot facility is needed was debated (see discussion below). For IFE, the main facilities envisioned for the next decade are one or more IRE's.

Brief summaries of the main points of discussion of the four Subgroups are as follows:

Targets:

There are several key physics issues for targets that need to be resolved during the next decade. (Note: target fabrication and injection are covered under Subgroup 3 - Inertial Fusion Power Plants.) For indirect drive, key issues are laser-plasma interaction, target gain, and capsule stability. For HIF indirect drive, the deposition profile and the hydrodynamic motion of the converter are of concern. For z-pinch indirect drive, the coupling efficiency, wire array stability, and the symmetry and temporal history of the radiation are key issues. For direct drive, the most critical issue is hydrodynamic stability, and ultimately, 3D integrated hydrodynamic calculations will be required. For the fast ignitor, coupling efficiency is the most critical issue. For MTF, the key issue is whether the Q will be large enough for fusion energy.

Several facilities will be used to address these issues. NIF will be used to study gain energetics, pulse shaping and compression, symmetry for indirect drive, hydrodynamic instability for direct drive, and ignition and burn. OMEGA will be used to study spherical warm and cryogenic pellets, direct drive cylinders, scale '1' hohlraums, planar targets, tetrahedral hohlraums, and shock-tube hohlraums. Nike will examine hydrodynamic instability effects, EOS measurements, and preheat effects. Z will be used to study hohlraum features (energetics, wall opacity, wall motion, hole closure), capsule ablator EOS, DT EOS, shock propagation in ablator materials and ablator burnthrough. GSI can provide a capability to obtain stopping power data relevant the HIF. Atlas and ShivaStar can be used to study MTF.

Looking ahead to NIF and beyond, there was a discussion concerning what physics issues will not be resolved on NIF. For indirect drive, these included issues that can't be studied on NIF (e.g., ion deposition) or that are not in the current NIF plan (e.g., fast ignitor). For direct drive, issues that can't be studied included, e.g., high yield. Several possible approaches to high yield were discussed. For the Z approach, the path to ZX/X-1 would lead to high yield (LLNL has calculated yields of 400 -1000 MJ using the X-1 power pulse input) . For indirect drive with glass lasers, assuming that an "advanced- coupling target" is feasible, it may be possible to do modest gain on NIF; recent 2D calculations give a 70 MJ yield, and it is believed that this could be significantly higher. In general, it is believed that "bigger is easier" for targets. There was debate over whether or not a high-yield/high-gain, single-shot facility is needed for IFE development. Arguments against included, e.g., ignition and burn physics are scale-size invariant, and that high yield may be possible on NIF. Arguments for included, e.g., that DOE DP has a high yield mission need and might provide a ~$1B single-shot, high-yield facility, and that this would greatly reduce the risk for IFE development. The debate continued throughout Snowmass (see "special issues" below).

Drivers and Standoff

Presently, there are five driver candidates in IFE: heavy ions, KrF lasers, DPSSL's, z-pinches, and light ions. Over the past two decades, heavy ions have been the primary approach to inertial fusion energy, because of their perceived high efficiency and excellent durability. In the last few years, KrF lasers and DPSSL's have also developed viable fusion energy programs. Very recently, a z-pinch approach to fusion energy has been proposed. The light ion approach, after a decade of research, is on hold - the key problem is the ion source, and it is suggested that a science-level program (e.g., at universities) to develop a light ion source might eventually leverage the past investment in this approach.

Standoff refers to the method used to separate the driver from the target. For ions, the standoff distance is typically of order 5 meters (distance from the target to the final focus magnet system); for lasers, the standoff distance (distance from the target to the final optic) is typically 25 meters. Ion beam standoff involves final transport and stability issues of beams in the fusion chamber. Heavy ion beams use vacuum transport or partially-neutralized transport, or any of several channel-like transport schemes. Light ion transport uses fully-neutralized transport, or any of several channel-like transport schemes. The use of high-current (~100 kA) proton beams to model stripped heavy ion beams was advocated (since there are no high current heavy ion beams presently). For KrF or DPSSL's, the final optic may be a grazing incidence metal mirror; in addition, a hot fused silica wedge or grating may be used for DPSSL's. For z-pinches, a recyclable transmission line (RTL) is being considered. All standoff scenarios need further development.

IRE scenarios were discussed for each of the five driver scenarios. The heavy ion, KrF, and DPPSL IRE's are the most developed. Approaches to IRE's for z-pinches and light ions were also discussed. The key IRE issues (which are therefore critical opportunities for development) are in neutralized and channel-like transport for heavy ions; in durability for KrF (survivability of the pumping foil); in cost of diodes for DPSSL's; in durability for z-pinches (ability to recycle the transmission line); and in durability for ion sources and final transport for light ions.

Inertial Fusion Power Plant Concepts

IFE power plant concepts were discussed, including studies for heavy ions, light ions, lasers (relevant to both KrF and DPSSL's), z-pinches, and MTF. The mainline approaches use liquid walls or wetted walls for ions, consistent with indirect drive having a limited input solid angle; and dry walls or wetted walls for KrF or DPSSL's, consistent with direct drive having a large input solid angle. Z-pinches or MTF would use thick liquid walls or possibly solid Li with voids and a density gradient for shock dissipation.

Requirements for the IFE chamber were enumerated, and the relative advantages of dry wall, wetted wall, and thick liquid walls for various drivers were discussed. The major technical issues were identified. Several areas (e.g., liquid hydraulics) can be studied in scaled experiments at universities. Also, the existing Z facility may be used to study, e.g., radiation effects on wall materials or fireball reradiation effects for wall shielding.

Target fabrication, characterization, and injection were discussed at length. Target manufacturing requires extreme precision of manufacture, extreme reliability of delivery, and a manufacturing cost orders of magnitude lower than current ICF target performance. For indirect-drive IFE, target fabrication is the main issue; for direct-drive IFE, target survival during target injection is the main issue.

IFE Metrics and Development Paths

Metrics for the various stages of development were discussed. These include Concept Exploration (CE), Proof of Principle (PoP), Performance Extension (PE), Fusion Energy Development (FED), and DEMO. The IFE Road Map, as shown in Fig.1, was discussed and debated. Note that the mainline IFE approaches - heavy ions, KrF, and DPSSL's - are all presently at the PoP level. Z-pinches, light ions, and the fast ignitor are all at the CE level. The main thrust for the next decade is to develop an attractive IRE approach to IFE.

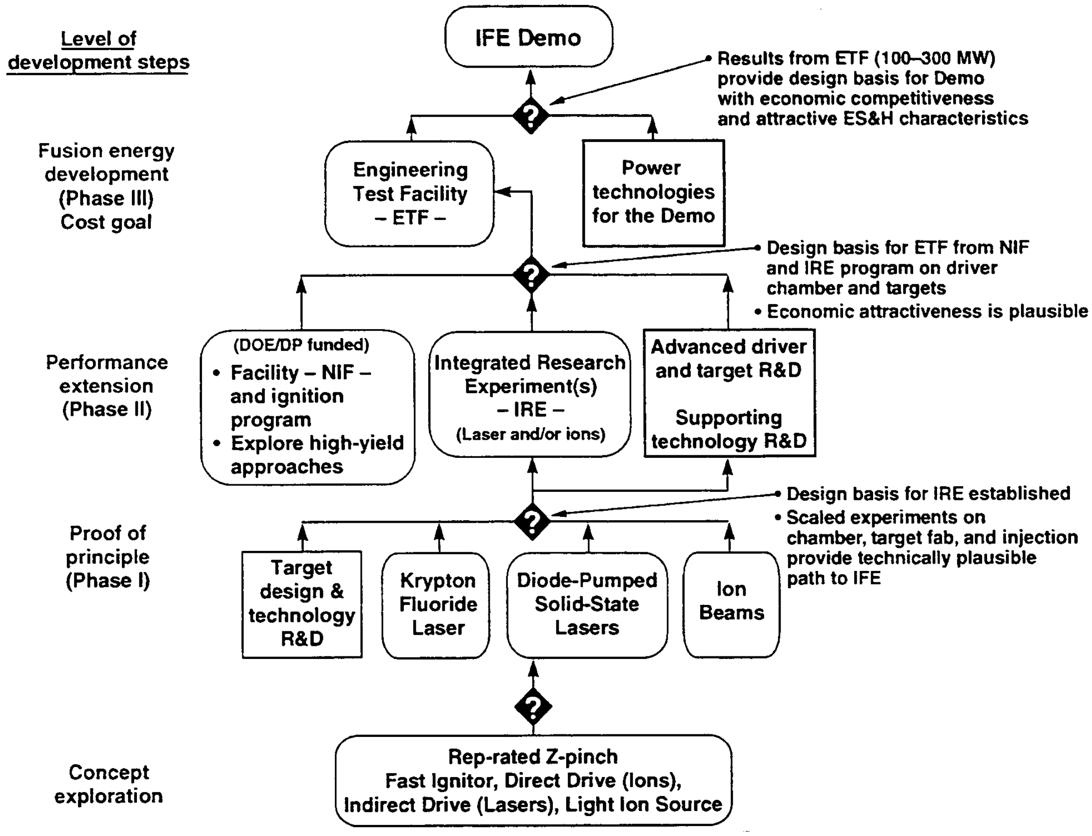

Fig. 1. The IFE Road Map

Special Issues

During the second week in IFE plenary sessions, the following list of special issues was discussed and debated. Very brief summaries of the results of these discussions are as follows:

(1) Why carry two laser options (KrF and DPSSL)? The question as to whether to down select now to one or zero laser options was debated. The consensus was that more demonstrated results are needed to make a rational down selection. At present, the different strengths of the two laser approaches should justify continued research on both at this time.

(2) Should the IRE decision be delayed until there are results on NIF? Presently, an IRE decision would be made in about 5 years, the same time at which NIF will just be starting to get results. Wouldn't it be prudent to wait a couple of more years to see the initial NIF results? Presently, the IRE goal is to validate an integrated driver concept. An IRE will not implode capsules, and will typically be at only ≤ 1/10 scale of a full driver. The purpose of the IRE is to investigate full system, rep-rate issues, in a scaled

experiment; i.e., the IRE and NIF would be complementary. The IRE will help sort out target/driver/chamber choices. At Snowmass, it was argued that there is sufficient confidence that NIF will work, and that the combined results of NIF + IRE would give the basis for moving on to the next stage (ETF). It was also argued that parallel development of target gain and driver/chamber technology (similar to parallel development of confinement schemes and fusion technology in MFE) is the most efficient.

(3) Is a demonstration of high yield/high gain needed for IFE (on a single-shot basis? This question was an extension of discussions that began in the Target group session. First, what is high yield? Present IFE power plant studies all have yields within the range of 300 - 800 MJ, at a rep-rate of 3-7 Hz. Therefore, the median choice for high yield is 500 MJ. The opposing view was to lower this requirement to, e.g., 200 MJ or less. This would, of course, increase the required rep-rate, and increase cavity-clearing difficulties. This issue was not resolved. To determine if a demonstration of high yield/high gain is needed, a good definition of the goals and cost of an ETF is needed. The ETF is after an IRE, and just before a DEMO. At the DEMO stage, there is, of course, agreement that high yield/high gain is required. Since all physics issues must be resolved before the DEMO stage, this means that the ETF, or before, should demonstrate high yield/high gain. During the first week of Snowmass, an ETF was defined to be a facility that is rep-rated at ~ 25 MJ yield, will demonstrate high yield in a separate chamber, with a driver energy of 1-2 MJ, and at a cost of < $2B. When it was argued that the cost would more likely be $5B for the listed requirements, the requirement for demonstration of high yield in the ETF was withdrawn (although this was not unanimous). The enduring theme is that the ETF should be rep-rated at ~25 MJ yield with a small-radius chamber to produce power-plant-level wall fluences. The issue of whether an ETF would demonstrate high yield in a separate chamber, and at what cost, was not resolved. During the IFE plenary discussions, the debate continued and there was a call for a vote. The question was "Do we need a single-shot, high-yield facility as a separate box on the road map?" The majority vote was a clear "no". However, the only place high yield is mentioned on the road map is under "explore high-yield approaches" inside the NIF box. It remains as an unanswered question as to where a high-yield demonstration will actually occur on the road map, which by definition, must be before a DEMO.

(4) Is the IFE program balanced between drivers, targets, chamber technology, etc.? This question was in response to a request by Marshall Rosenbluth in his invited plenary talk on the first day of Snowmass to dedicate some portion of funds (~$10M) to study beam propagation and chamber issues, and try to settle some of these questions once and for all. After initial discussions, a vote was called on the question "Should the relative amount of funding for chamber technology and transport & focus be increased from current levels?" The vote was a unanimous "yes". This means that even within the existing funding levels, the relative amount of funding within a particular program for studying beam propagation/chamber issues should be increased.

(5) Is further work on Metrics needed? It was clear that there is a strong need to establish quantitative metrics for the IRE, the ETF, etc., and that these need to be applied to all driver candidates in a uniform manner. It was suggested that a "Tiger Team" be created to develop a set of IFE metrics.

(6) What if NIF does not reach ignition? The discussions on this issue began with the statement that there is "sufficient confidence" that NIF will reach ignition. If it doesn't, then it depends on exactly why. For example, laser/plasma interaction is a possible issue. There will be an extended campaign to demonstrate ignition, and many targets and laser beam configurations can be tried. The time window will be about 10 years for indirect drive, and about 5 years for direct drive. In addition, a contingency plan could be formulated.

(7) Is there sufficient interaction between targets, drivers, chambers, etc.? One of the advantages of IFE is that the targets, drivers, and chambers can all be studied and developed separately. However, optimizing any one system without consideration for the requirements of the other parts may result in conflicts. Optimization must be done for the overall power plant system. Interactions are improving in this area and the discussions at Snowmass made important contributions to these mutual interactions.

Following are Summaries from the four Subgroups.