Inertial Fusion Concepts: Summary
Snowmass Fusion Summer Study
Friday, July 23, 1999

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Metrics & Pathways: Wayne Meier, John Perkins

Contributors: All Snowmass IFE Participants
IFE Offers an Attractive Path to Fusion Energy

- An IFE Power Plant concept is an integrated choice of:
  - **Target** (Direct or indirect drive)
  - **Driver** (HIB, Laser, LIB, Z-pinch, etc.)
  - **Chamber** (Thick liquid, wetted wall, dry wall; various materials)
  - **Power conversion** (Rankine, Brayton, others)

- Each driver has a choice of chamber options. Prime candidates:
  - **HIB**: Indirect drive with thick liquid wall or wetted wall
  - **Laser**: KrF or DPSSL, Direct drive with dry wall or wetted wall

- Exploratory concepts also exist: LIB, Z-pinch, MTF, Fast Igniter, ...

- Target, driver and chamber development programs are part of the IFE Roadmap leading to Integrated Research Experiments (PoP level) and an Engineering Test Facility (CE level)
# IFE Overview

<table>
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<th>Approach</th>
<th>Driver</th>
<th>Target</th>
<th>Stand-Off Issue</th>
<th>Power Plant Concept</th>
<th>FY99 Funding for IFE</th>
<th>Aspirations for Next Decade</th>
</tr>
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<tbody>
<tr>
<td><strong>Main-line approaches</strong></td>
<td>Ion-HIB induction linac</td>
<td>Indirect drive</td>
<td>Ion beam transport</td>
<td>Liquid wall</td>
<td>$8M</td>
<td>Each program: 4-5 years research* at ~ $16M/yr leading to an IRE for ~$100M (0 or more)</td>
</tr>
<tr>
<td></td>
<td>-DPSSL Laser</td>
<td>Direct drive</td>
<td>Final optic</td>
<td>Dry wall</td>
<td>$4M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-KrF</td>
<td>Direct drive</td>
<td>Final optic</td>
<td>Dry wall</td>
<td>$8M</td>
<td></td>
</tr>
<tr>
<td><strong>Exploratory Concepts</strong></td>
<td>Z-Pinch</td>
<td>Indirect drive</td>
<td>Recyclable transmission line</td>
<td>Liquid wall</td>
<td>0</td>
<td>Investigate concept and rep. rate</td>
</tr>
<tr>
<td><strong>(EC)</strong></td>
<td>Ion-Light Ion Diode</td>
<td>Indirect drive</td>
<td>Ion beam transport</td>
<td>Liquid wall</td>
<td>0</td>
<td>Science level ion source development</td>
</tr>
<tr>
<td></td>
<td>Magnetized Target Fusion</td>
<td>Magnetized Plasma</td>
<td>Recyclable transmission line</td>
<td>Liquid wall</td>
<td>$1M</td>
<td>PoP experiment (~$21M/3 yrs.)</td>
</tr>
</tbody>
</table>

*includes chamber, target development, environmental attractiveness,...
An example of an Integrated Research Experiment facility

Scale: current per beam same as driver; Final energy ~ 1/10 driver.

Beam quality: 6D phase-density same as driver; (e.g. corresponds to $\varepsilon_n < 5 \text{ mm-mrad}$; $\Delta p/p < 10^{-2}$; $\Delta t = 5 \text{ ns at } T = 200 \text{ MeV}$).

Chamber transport: neutralization ~90-95% with absence of destructive instabilities.

Achievement of goals leads to $\sim 10^{16} \text{ W/cm}^2$ at driver beam energy.
Integrated Research Experiment (IRE) can address many IFE chamber issues

- Beam transport through the chamber gas
- Target Injection (Xe liquid, Au pellet)
- Spin-off experiments—biology, solid-state physics, plasma physics
- X-ray access port
- Debris and gas clearing at 10 Hz
- backlighter
- Target tracking
- Thin liquid-metal film test
- Direct-drive hydrodynamic instability experiments using planar foils

4 kJ, 10 Hz, 2 ns, 0.35 μm SSL Driver

Final optic

Materials survivability tests

Pumps
Inertial Fusion Concepts Working Group

Subgroups: Targets
Drivers & Standoff
Power Plants
Metrics & Pathways

Key Questions: Eleven “hot topics” that focus on issues and opportunities for the next decade

Process: One 3-hour session per question
Short talks + extensive discussions
Further discussions in IFE plenary session
Targets(1) What are the key scientific issues for validating each target concept, and how can they be resolved?

Targets(2) How can existing (and new?) facilities be used to test each concept?

- Laser indirect drive
- Direct drive
- Fast Ignitor
- Ion beam indirect drive
- Z-pinch
- Magnetized target fusion
Key scientific issues for IFE targets will be addressed on several facilities

<table>
<thead>
<tr>
<th>Target concept</th>
<th>Issues</th>
<th>Facilities</th>
<th>Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct drive w/ Lasers</td>
<td>Stability, illumination geometry</td>
<td>NIF, Omega, Nike</td>
<td>2D/3D instability calculations</td>
</tr>
<tr>
<td>Indirect drive w/ ion beams</td>
<td>Beam dep., symmetry control</td>
<td>GSI (beam dep), IRE, NIF, Z</td>
<td>Instability, 2D/3D integrated burn calculations</td>
</tr>
<tr>
<td>Z-pinch</td>
<td>Transport efficiency, symmetry, pinch stability</td>
<td>Z, NIF</td>
<td>MHD implosion, integrated burn calculations</td>
</tr>
<tr>
<td>Magnetized target fusion</td>
<td>Gain, MHD stability of liner</td>
<td>Z, Atlas, Shiva Star</td>
<td>2D/3D MHD calculations</td>
</tr>
<tr>
<td>Fast Ignitor</td>
<td>Light transport through underdense plasma, hole boring, electron transport, corona minimization</td>
<td>Compression driver and high intensity laser, NIF, Vulcan, GEKKO, SPIRE</td>
<td>Implosion calculation, laser transport through underdense plasma, electron transport</td>
</tr>
</tbody>
</table>

No new major facilities requested for testing target physics
Targets (3): What IFE target physics issues will not be resolved on NIF? What is required to get to high yield? What is significance to IFE of experimentally demonstrating high yield/high gain?

Issues not resolved on NIF:
- 2-sided laser illumination with small solid angle
- physics of energy deposition for other drivers
- indirect drive implosion coupled to fast ignition

What is required to get to high yield?
- Z (1.8 MJ x-rays, >200 TW, >150 eV) now
- X-1 (16 MJ x-rays, >1000 TW, >300 eV) ~$1B

would produce yield ~1,000 MJ

NIF: advanced coupling target + new chamber (~$100M)
- 2D calculations give ~70 MJ yield
- HY on NIF is “by no means assured”

HY scaling from capsule calculations:
- “bigger is easier”

Significance of high yield/high gain for IFE
- Single-shot facility not needed:
  - ignition & propagation physics are scale-size invariant
- HY/HG may be possible on NIF

Single-shot facility needed:
- Step from “NIF to ETF is enormous”
- DOE/DP may provide a $1B single-shot HY facility
Drivers and Standoff: Five driver options are being considered at this time

Proof of Principle

**Heavy Ions**
- Magnetic Core
  - HI beam
  - dB/dt
- Inductive acceleration
- Ballistic, neutralized or channel transport
- Indirect drive

**KrF**
- Amplifier
- E-beam pumping
- MeV electron pump
- Lens @ 25 m
- Direct drive

**DPSSL**
- Amplifier
- Diode pumping
- Optical pumping
- Lens @ 25 m
- Direct drive

Concept Exploration

**Z-Pinch**
- Trans. line (TL)
- Wire arrays
- 60 MA & 8 MV drive
- Replaceable TL
- Indirect drive

**Light Ions**
- Ion source
- HV acceleration
- Neutralized or channel transport
- Indirect drive

**Other Possibilities**
- MTF
- Medium weight ion accelerators
MTF (an OFES PoP) is an option between IFE and MFE parameters

- Potentially low development cost: $3/J liner (pusher) kinetic energy.
- Liner driver for PoP already demo'd on ShivaStar (30% wall-plug to liner kinetic energy).
- 25 MJ liner kinetic energy demo'd in non-fusion context.
- Standoff concepts include recyclable electrodes (synergistic with Z-pinch).
- Design calculations at reactor scale needed (in progress).
- Issues include: plasma formation, transport, mix, ηG.
### Question 1: Status and potential of IFE drivers

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Brightness</th>
<th>Uniformity</th>
<th>Shaping</th>
<th>Efficiency</th>
<th>Durability</th>
<th>Rep Rate</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy Ions</td>
<td>Phase space density 1000x requirement</td>
<td>X-radiation smoothing</td>
<td>Velocity tilts and beam-stacking</td>
<td>45% for Kr, based on e-linacs and core losses</td>
<td>$10^8$ shots, based on Astron and improved source</td>
<td>10Hz</td>
<td>$150/J for Kr (vendor estimated)</td>
</tr>
<tr>
<td>KrF</td>
<td>$3 \times 10^{17}$ W/cm$^2$ str 10x requirement</td>
<td>0.2% meas. for one beam meets spec</td>
<td>Pulse-stacking</td>
<td>7% by component validation</td>
<td>$10^7$ shots currently; $10^5$ shots with R&amp;D</td>
<td>&gt;5Hz in literature</td>
<td>$225/J (extrapolated costs)</td>
</tr>
<tr>
<td>DPSSL</td>
<td>$3 \times 10^{18}$ W/cm$^2$ str; 100x requirement</td>
<td>0.04% calc'd; 0.1% needed on target</td>
<td>10:1 demo'd; meets spec</td>
<td>10% by component validation</td>
<td>$10^9$ shots for diodes</td>
<td>10Hz in small testbed; meets spec</td>
<td>$400/J; presumes 50W diodes, large extrapolation</td>
</tr>
<tr>
<td>Z-Pinch</td>
<td>x-rays from wire array drive hohlraum</td>
<td>%level demo'd</td>
<td>%level demo'd</td>
<td>15% to x-rays demo'd</td>
<td>$10^3$ shot burst mode with replaceable trans. line</td>
<td>Single-shot now; 0.1 Hz with replaceable trans. line</td>
<td>$30/J of x-rays demo'd</td>
</tr>
<tr>
<td>Light Ions</td>
<td>10% of IFE; 2nd diode stage needed</td>
<td>X-radiation smoothing</td>
<td>TBD</td>
<td>64% demo'd</td>
<td>$10^4$ shots; many issues to resolve</td>
<td>Single shot now; ultra pure carbon anode needed</td>
<td>Lowest estimated cost and least complexity</td>
</tr>
</tbody>
</table>
Question 2: What are the key standoff issues for each driver and how can they be addressed?

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Final Optic or Power Feed Lifetime</th>
<th>Power Transport Efficiency and Focusability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy Ions</td>
<td>Design of superconducting final optic based on data and neutronics</td>
<td>Assess neutralization and channeling</td>
</tr>
<tr>
<td>KrF</td>
<td>Metal mirror and heated silica studied at low-to-moderate dose</td>
<td>100% transport at $&lt; 0.5$ Torr of Kr to reduce x-rays</td>
</tr>
<tr>
<td>DPSSL</td>
<td>More data needed</td>
<td>Assess gas-breakdown and target heating issues</td>
</tr>
<tr>
<td>Z-Pinch</td>
<td>Develop replaceable transmission line</td>
<td>67% transport through present TL (okay as is)</td>
</tr>
<tr>
<td>Light Ions</td>
<td>Assess/manage irradiation of lens</td>
<td>X-rays from wire array drive hohlraum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Assess neutralization and channeling</td>
</tr>
</tbody>
</table>
Question 3: What Integrated Research Experiment (IRE) would convincingly demonstrate that each driver concept is a viable candidate for IFE

Key:  
- I = Integrate & Optimize Components  
- V = Validate Physics / Engineering Issues  
- E = Explore Physics / Engineering Issues

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Brightness and Uniformity</th>
<th>Focusability &amp; Chamber Transport</th>
<th>Durability</th>
<th>Driver Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy Ions</td>
<td>V</td>
<td>V,E</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>KrF</td>
<td>I</td>
<td>I</td>
<td>E</td>
<td>I</td>
</tr>
<tr>
<td>DPSSL</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>E</td>
</tr>
<tr>
<td>Z-Pinch</td>
<td>V</td>
<td>I</td>
<td>E</td>
<td>I</td>
</tr>
<tr>
<td>Light Ions</td>
<td>V</td>
<td>V,E</td>
<td>E</td>
<td>I</td>
</tr>
</tbody>
</table>

- Efficiency, rep-rate and pulse shaping will be demonstrated for all drivers  
- IRE performance parameters differ among the drivers  
- IRE does not address neutronics of the final optic
IFE has a variety of driver options that offer different strengths and weaknesses.

<table>
<thead>
<tr>
<th>Driver Type</th>
<th>Efficiency</th>
<th>Durability</th>
<th>Lower Driver Cost</th>
<th>Chamber Transport</th>
<th>Final Optic, Power Feed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy ion</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>KrF</td>
<td></td>
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<tr>
<td>DPSSL</td>
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<tr>
<td>Z-Pinch</td>
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<tr>
<td>Light ion</td>
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Our development plan and IRE will sort out the potential of each driver to meet IFE requirements.
Question 1: What are the Key IFE Power Plant Concepts, Advantages and Issues?

- IFE chambers provide the interface between driver, target, blanket, and balance of plant, have major leverage on power plant attractiveness.

- Chamber is optimized to meet driver stand off requirements:
  - HIB: Indirect drive with thick liquid walls or wetted walls
  - Laser: Direct drive with dry wall or wetted wall

![Diagram showing the relationship between final focus standoff (m) and repetition rate (Hz) for various drive concepts. The diagram includes categories such as Lasers, Heavy ions, Z pinch, MTF, Thick Liquid, and Dry Wall, with specific advantages and issues highlighted.]
Question 2: What are the Key Scientific Issues for the Fusion Chamber?

- Phase I experiments and analysis have been defined to resolve key feasibility issues and support decisions to proceed with Phase-II IRE experiments.

<table>
<thead>
<tr>
<th>Research Area</th>
<th>Thick Liquid</th>
<th>Wetted Wall</th>
<th>Dry Wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber Dynamics</td>
<td>Target induced impulse loads to liquid</td>
<td>Condensation of target and ablation debris by droplet sprays</td>
<td>Direct drive target emission</td>
</tr>
<tr>
<td></td>
<td>(Z-pinch, university experiments)</td>
<td></td>
<td>Fireball reradiation or magnetic diversion of target ions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Z-pinch experiments)</td>
</tr>
<tr>
<td>Chamber Materials</td>
<td>Corrosion, hohlraum material recovery from coolant</td>
<td></td>
<td>Fusion neutron effects on structures</td>
</tr>
<tr>
<td></td>
<td>No requirement for fusion neutron source</td>
<td>Fusion neutron effects on flow structures</td>
<td>(structures development parallels MFE efforts)</td>
</tr>
<tr>
<td>Liquid Hydraulics</td>
<td>Formation of free jets</td>
<td>Liquid film formation and stability</td>
<td></td>
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<tr>
<td></td>
<td>Pocket disruption and droplet clearing</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(water experiments with scaled impulse loads)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutronics/Safety/Environment</td>
<td>3-D modeling of final focus neutron and gamma irradiation</td>
<td></td>
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<tr>
<td></td>
<td>Hohlraum, coolant and structure materials activation</td>
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<td></td>
<td>Accident mobilization and off site dose minimization</td>
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<td></td>
<td>Waste minimization</td>
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<td></td>
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<tr>
<td></td>
<td>(mobilization experiments with liquid coolants)</td>
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IFE
Inertial Fusion Energy
Question 3: What are the Key Issues for Target Fabrication and Injection?

- **Indirect Drive** — target fabrication is main issue
  
  - Distributed radiator hohlraum with Be capsule current mainline design. Gain ~50-130. High Z foam hohlraums have no ICF analog — design iteration and development is needed.
  
  - Hohlraums provide thermal protection for target injection; preliminary experiments at LBNL met accuracy and repeatability specs.

- **Direct Drive** — target injection is main issue
  
  - Radiatively preheated CH foam capsule target current prime candidate, builds on ICF experience. Gain ~130.
  
  - High reflectivity surface should protect from thermal radiation, but chamber protective gas heats capsule and affects target trajectory. Chamber/target design integration needed.

- **IFE** can build upon ICF target fabrication, layering and handling experience and OFES IFE VLT effort
  
  - Omega and NIF will demonstrate cryogenic target fill, layering and handling
  
  - Phase I: A modest program will show a credible pathway exists for IFE target fabrication and injection before investing in the IFE IRE.
  
  - Phase II: Fabrication and injection of surrogate targets into the IRE.
IFE CAN BUILD UPON ICF TARGET FABRICATION TECHNIQUES

Foam Shells

2 mm

DT Ice Layer

High-Z coating

Wetted DT foam

DT ice

DT gas

Radiative Preheat Direct Drive IFE Target Design

Overcoated Foam

Metal on Foam

GENERAL ATOMICS
(1): What are the metrics for an IFE system?
   How are these incorporated into an IFE road map?
   How do we insure a place for new concepts?
(2): What is the development path for each present IFE scenario?
IFE Roadmap and Metrics

What Was Discussed?

- The IFE "roll-back" roadmap
- Metrics
- How to nurture new ideas in the development path

Critical Issues

- What is the proposed development path that rolls back from the attractive IFE power-plant?
- What are the objectives at each stage of the roadmap?:- attractive reactor, DEMO, ETF, IRE (or IRP?)
- What are the decision/performance metrics that permit concept(s) to be promoted from stage to stage?
- How do we formally accommodate new initiatives/innovations into the development path at the exploratory concept level for both advanced physics and technology?

Resolution of Critical Issues

- Direct an IFE "tiger team" to condense present goals into a unified, concise "bible" containing objectives and decision metrics for each stage of the development path for all concepts.
  (use an HTML-based tabular method for comparison metrics?)
Possible Formalism for Accommodating New Ideas at the Concept Exploration Level

- New funding starts every year with a recognized date for calls and submissions; reviewed every year

- Compete for seed money in one of two tiers: say, ~$50k - $250k and $250k - ~$2M

- Strict peer review (including an additive “reactor implications” metric)

- 3-year lifetime with rolling horizon. After 3 years, project competes for programmatic funding

- Program solicits innovative proposals on advanced physics and advanced technology and reactor paradigms

- Consider the DOE Labs’ LDRD IR&D program as a possible model
Special issues were discussed vigorously

(1) **Why carry two laser options?** (KrF/DPSSL)
    down selection debated
    need more demonstrated results to choose
    different strengths justify continued research at this time

(2) **Timing of IRE relative to NIF**
    IRE goal is to validate an integrated concept
    IRE will not implode capsules ($\leq 1/10$ scale full driver)
    IRE will help sort out target/driver/chamber choices
    sufficient confidence that NIF will work
    NIF + IRE gives basis for moving to ETF
    parallel development (as in MFE) is most efficient

(3) **Need for high yield/high gain**
    what is high yield? 500 MJ (median IFE reactor value) or ?
    what is ETF? rep-rated at $\sim 30$ MJ yield
    + high yield in separate chamber (withdrawn)
    + driver 1-2 MJ
    for $<$2B
    (need better definition of ETF and its cost)
    "Do we need a single-shot, high-yield facility as
    a separate box on the road map?"
    Vote: no
    unanswered question: Where does high yield demonstration
    occur on road map?
(4) Is IFE program balanced between drivers, targets, chamber technology, etc.?

"Should relative amount of funding for chamber technology and transport & focus be increased from current levels?"

Vote: yes (unanimous)

(5) Metrics

need to establish quantitative metrics for IRE, ETF,... need "Tiger Team" for IFE metrics

(6) What if NIF does not reach ignition?
sufficient confidence that it will if it doesn’t, depends on why demonstration time window will be many years could formulate a contingency plan

(7) Is there sufficient interaction between targets, drivers, chambers, etc.?
interactions improving need to constantly check
IFE Offers an Attractive Path to Fusion Energy

- An IFE Power Plant concept is an integrated choice of:
  - **Target** (Direct or indirect drive)
  - **Driver** (HIB, Laser, LIB, Z-pinch, etc.)
  - **Chamber** (Thick liquid, wetted wall, dry wall; various materials)
  - **Power conversion** (Rankine, Brayton, others)

- Each driver has a choice of chamber options. Prime candidates:
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  - **Laser**: KrF or DPSSL, Direct drive with dry wall or wetted wall

- Exploratory concepts also exist: LIB, Z-pinch, MTF, Fast Igniter, ...

- **Target**, driver and chamber development programs are part of the IFE Roadmap leading to Integrated Research Experiments (PoP level) and an Engineering Test Facility (CE level)

Current Research is Leading to IRE(s) in the Next Decade