Inertial Fusion Concepts: Summary

Snowmass Fusion Summer Study
Friday, July 23, 1999

Organizer: Craig Olson

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

Subgroup Leaders:

- **Targets:** Max Tabak, Jill Dahlburg, Rick Olson
- **Drivers & Standoff:** Steve Payne, John Barnard, John Sethian, Rick Spielman
- **Power Plant Concepts:** Ken Schultz, Robert Peterson, Per Peterson
- **Metrics & Pathways:** Wayne Meier, John Perkins

Contributors: All Snowmass IFE Participants

IFE Offers an Attractive Path to Fusion Energy

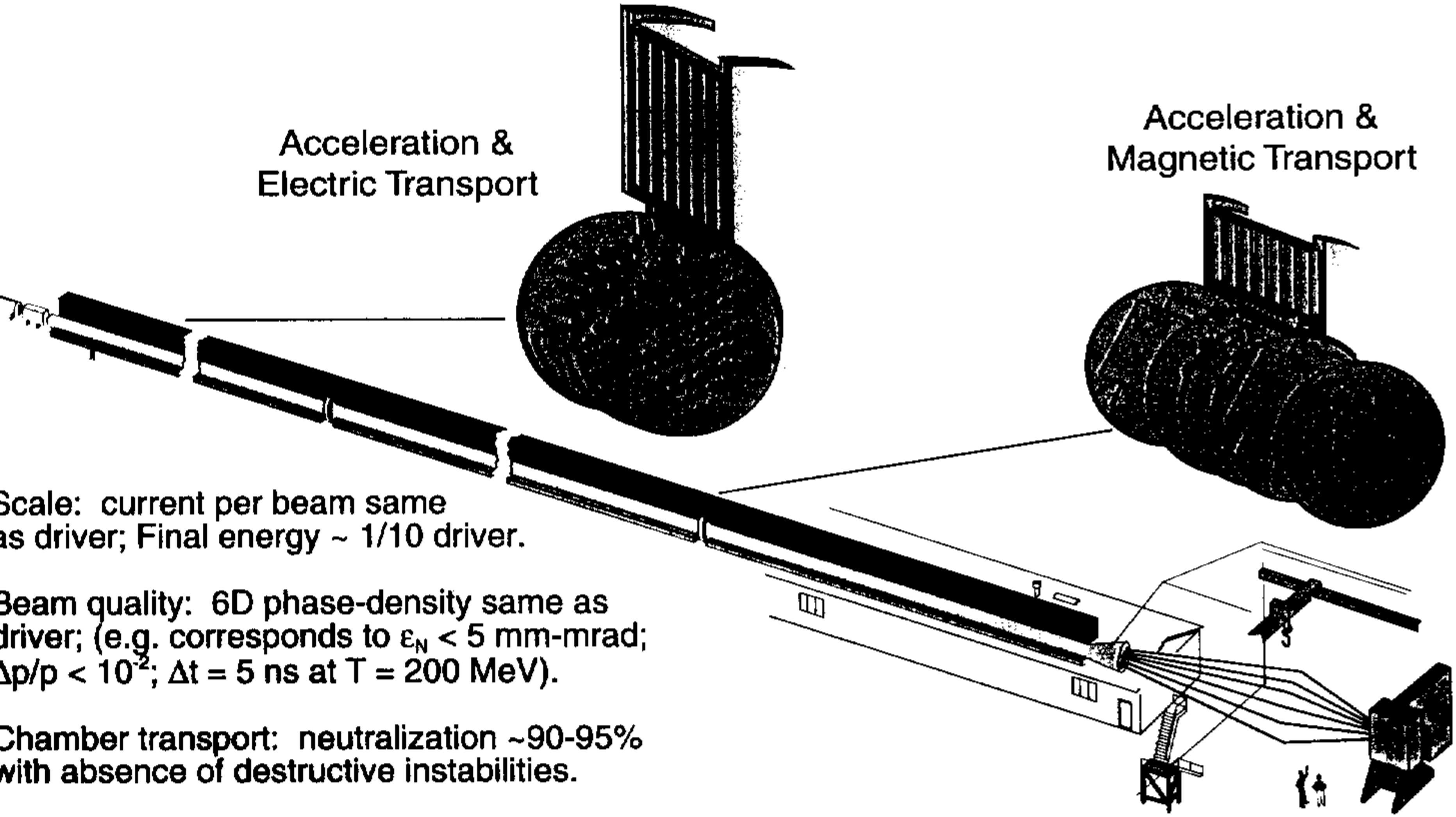
- An IFE Power Plant concept is an integrated choice of:
  - **Target** (Direct or indirect drive)
  - **Driver** (HIB, Laser, LIB, Z-pinch, etc.)
  - **Chamber** (Thick liquid, wetted wall, dry wall; various materials)
  - **Power conversion** (Rankine, Brayton, others)
- Each driver has a choice of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

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

*includes chamber, target development, environmental attractiveness,...

An example of an Integrated Research Experiment facility



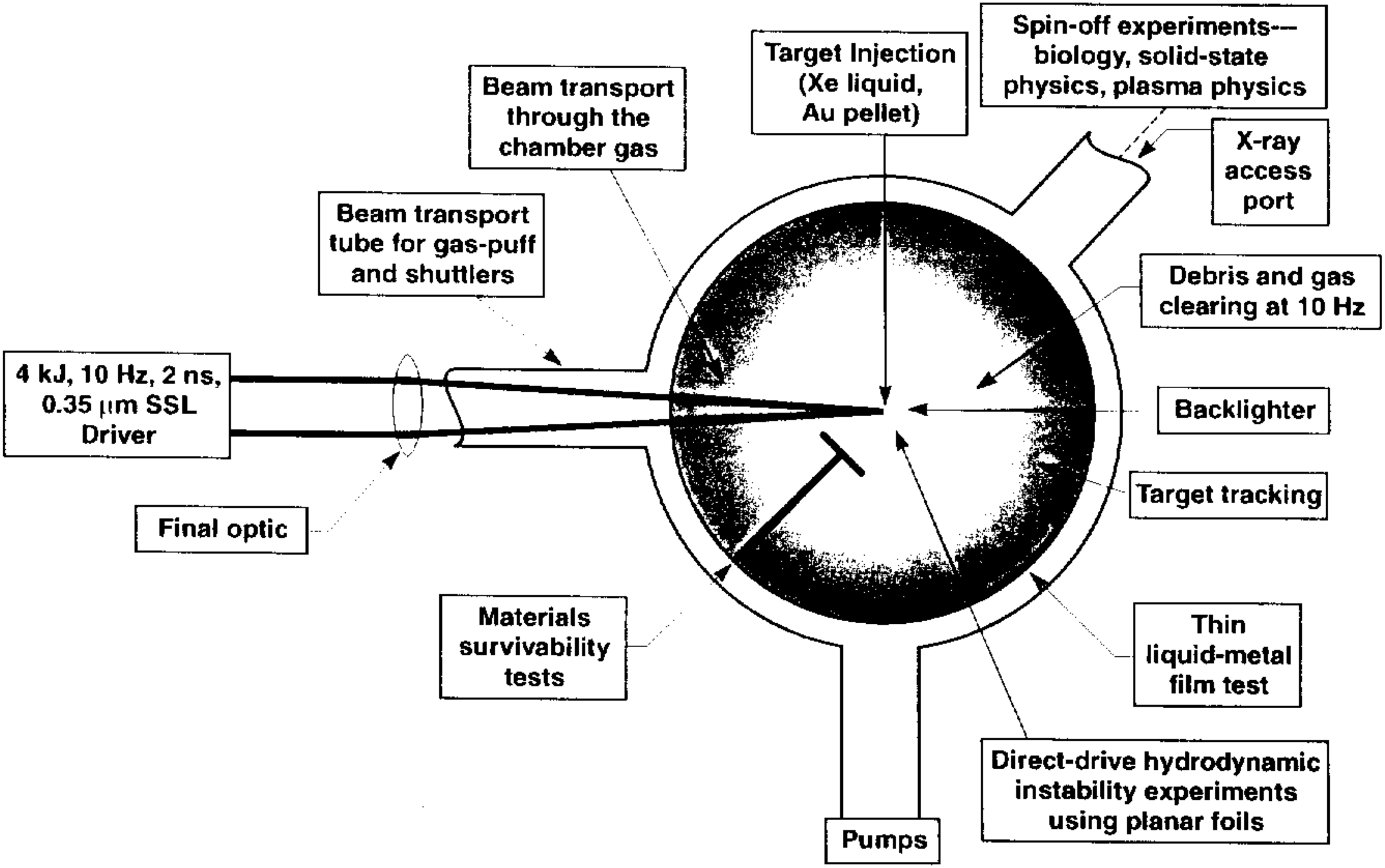
Scale: current per beam same as driver; Final energy ~ 1/10 driver.

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

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

Achievement of goals leads to ~ 10^{15} W/cm^2 at driver beam energy.

Integrated Research Experiment (IRE) can address many IFE chamber issues



Inertial Fusion Concepts Working Group

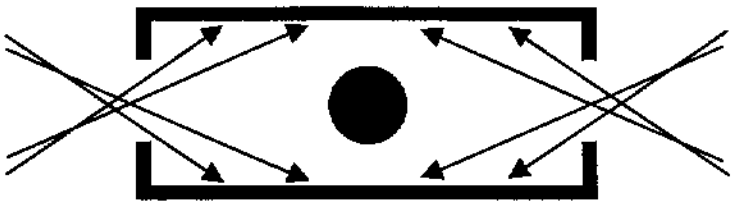
Subgroups: Targets
Drivers & Standoff
Power Plants
Metrics & Pathways

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

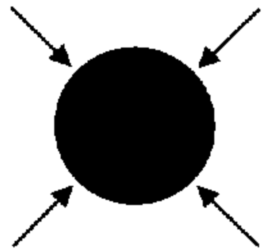
Process: One 3-hour session per question
Short talks + extensive discussions
Further discussions in IFE plenary session

Targets(1) What are the key scientific issues for validating each target concept, and how can they be resolved ?

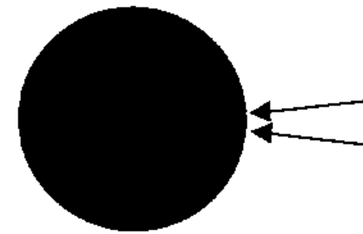
Targets(2) How can existing (and new?) facilities be used to test each concept?



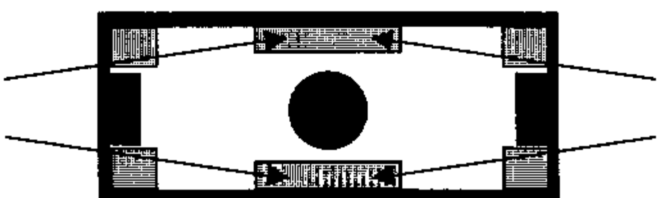
Laser indirect drive



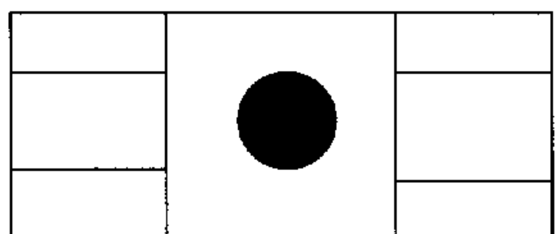
Direct drive



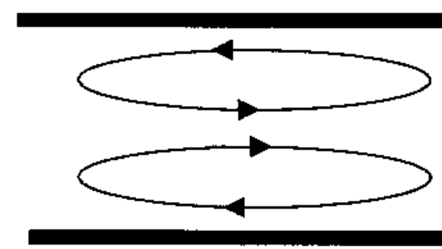
Fast Ignitor



Ion beam indirect drive



Z-pinch



Magnetized target fusion

Key scientific issues for IFE targets will be addressed on several facilities

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

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"

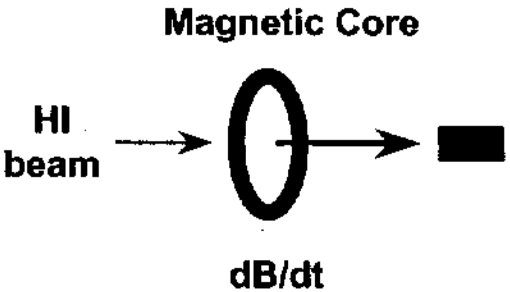
Significance of high yield/high gain for IFE

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

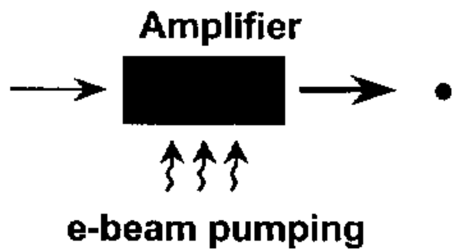
Proof of Principle

Heavy Ions



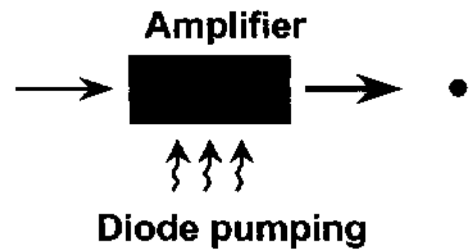
- •inductive acceleration
- •ballistic, neutralized or channel transport
- •indirect drive

KrF



- •MeV electron pump
- •lens @ 25 m
- •direct drive

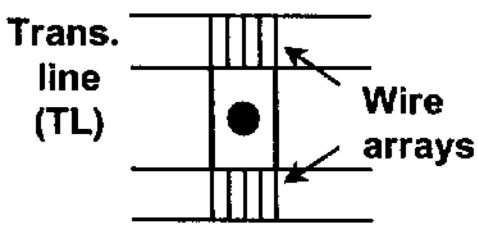
DPSSL



- •optical pumping
- •lens @ 25 m
- •direct drive

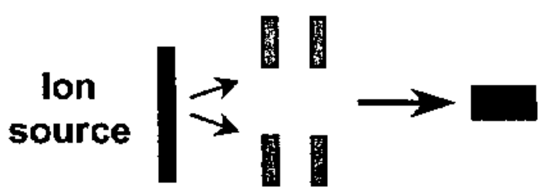
Concept Exploration

Z-Pinch



- •60 MA & 8 MV drive
- •replaceable TL
- •indirect drive

Light Ions

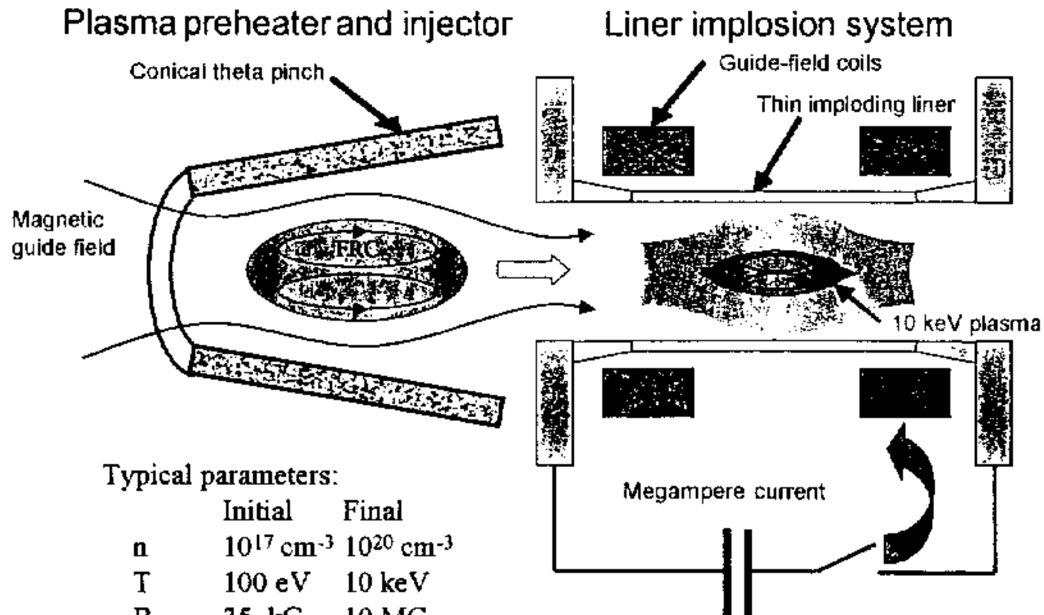


- •HV acceleration
- •neutralized or channel transport
- •indirect drive

Other Possibilities

- • MTF
- • Medium weight ion accelerators

MTF (an OFES PoP) is an option between IFE and MFE parameters



Typical parameters:

	Initial	Final
n	10^{17} cm^{-3}	10^{20} cm^{-3}
T	100 eV	10 keV
B	35 kG	10 MG

- 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

Drivers	Brightness	Uniformity	Shaping	Efficiency	Durability	Rep Rate	Cost
Heavy Ions	Phase space density 1000x requirement	X-radiation smoothing	Velocity tilts and beam-stacking	45% for Kr, based on e-linacs and core losses	10^8 shots, based on Astron and improved source	10Hz	$150/J for Kr (vendor estimated)
KrF	$3x10^{17}$ W/cm^2 str 10x requirement	0.2% meas. for one beam; meets spec	Pulse-stacking	7% by component validation	10^2 shots currently; 10^5 shots with R&D	>5Hz in literature	$225/J (extrapolated costs)
DPSSL	$3x10^{18}$ W/cm^2 str; 100x requirement	0.04% calc'd; 0.1% needed on target	10^4:1 demo'd; meets spec	10% by component validation	10^8 shots for diodes	10Hz in small testbed; meets spec	$400/J; presumes 5c/W diodes, large extrapolation
Z-Pinch	x-rays from wire array drive hohlraum	%-level demo'd	%-level demo'd	15% to x-rays demo'd	10^2 shot burst mode with replaceable trans. line	single-shot now, 0.1 Hz with replaceable trans. line	$30/J of x-rays demo'd
Light Ions	10% of IFE; 2nd diode stage needed	X-radiation smoothing	TBD	64% demo'd	10^4 shots; many issues to resolve	Single shot now; ultra pure carbon anode needed	Lowest estimated cost and least complexity

Question 2: What are the key standoff issues for each driver and how can they be addressed?

Drivers	Final Optic or Power Feed Lifetime	Power Transport Efficiency and Focusability
Heavy Ions	Design of superconducting final optic based on data and neutronics	Assess neutralization and channeling
KrF	Metal mirror and heated silica studied at low-to-moderate dose	100% transport at <0.5 Torr of Kr to reduce x-rays
DPSSL	More data needed	Assess gas-breakdown and target heating issues
Z-Pinch	Develop replaceable transmission line	67% transport through present TL (okay as is) X-rays from wire array drive hohlraum
Light Ions	Assess/manage irradiation of lens	Assess neutralization and channeling

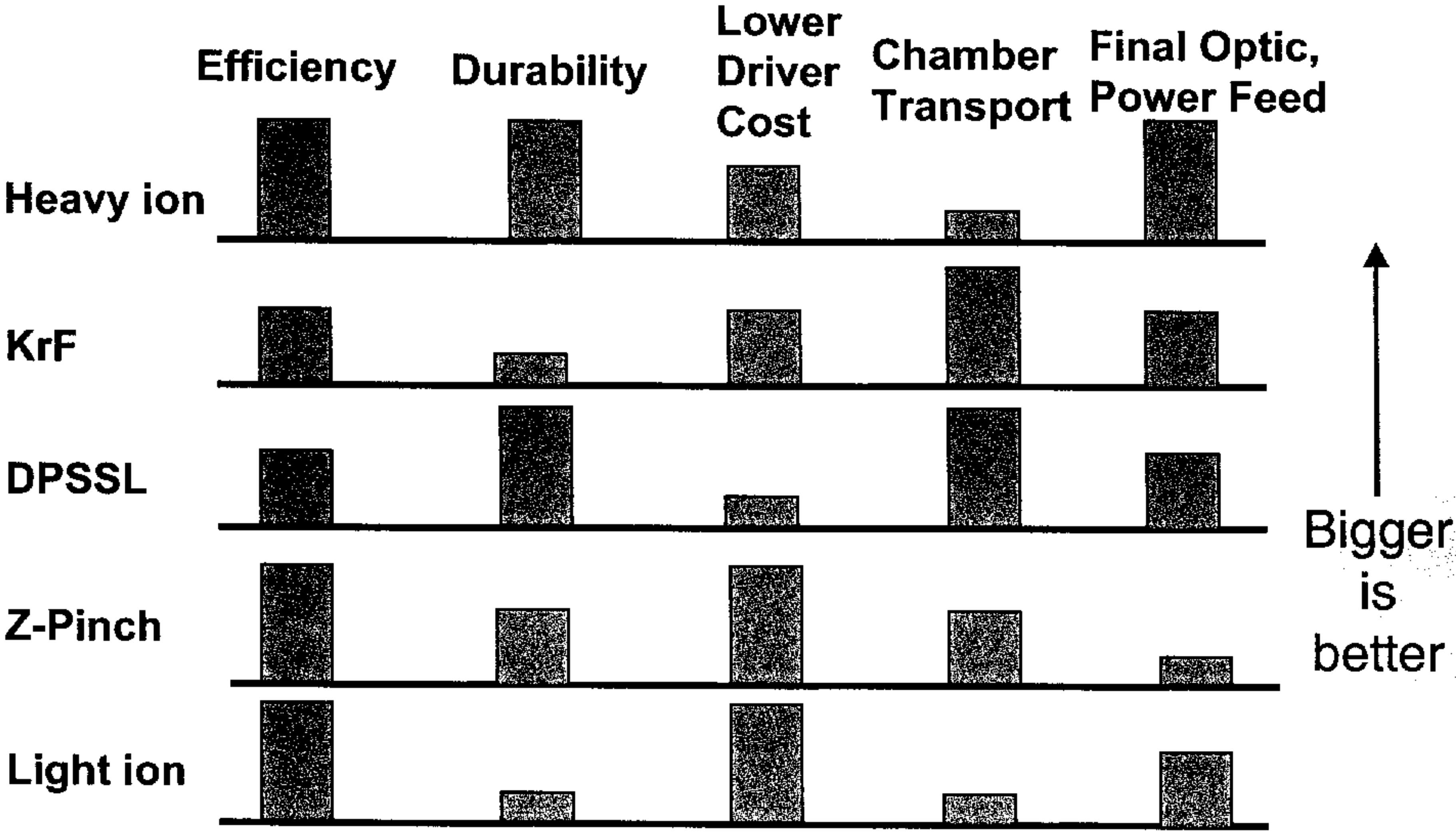
Question 3: What *Integrated Research Experiment* (IRE) would convincingly demonstrate that each driver concept is a viable candidate for IFE

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

Drivers	Brightness and Uniformity	Focusability & Chamber Transport	Durability	Driver Cost
Heavy Ions	V	V,E	I	I
KrF	I	I	E	I
DPSSL	I	I	I	E
Z-Pinch	V	I	E	I
Light Ions	V	V,E	E	I

- **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**

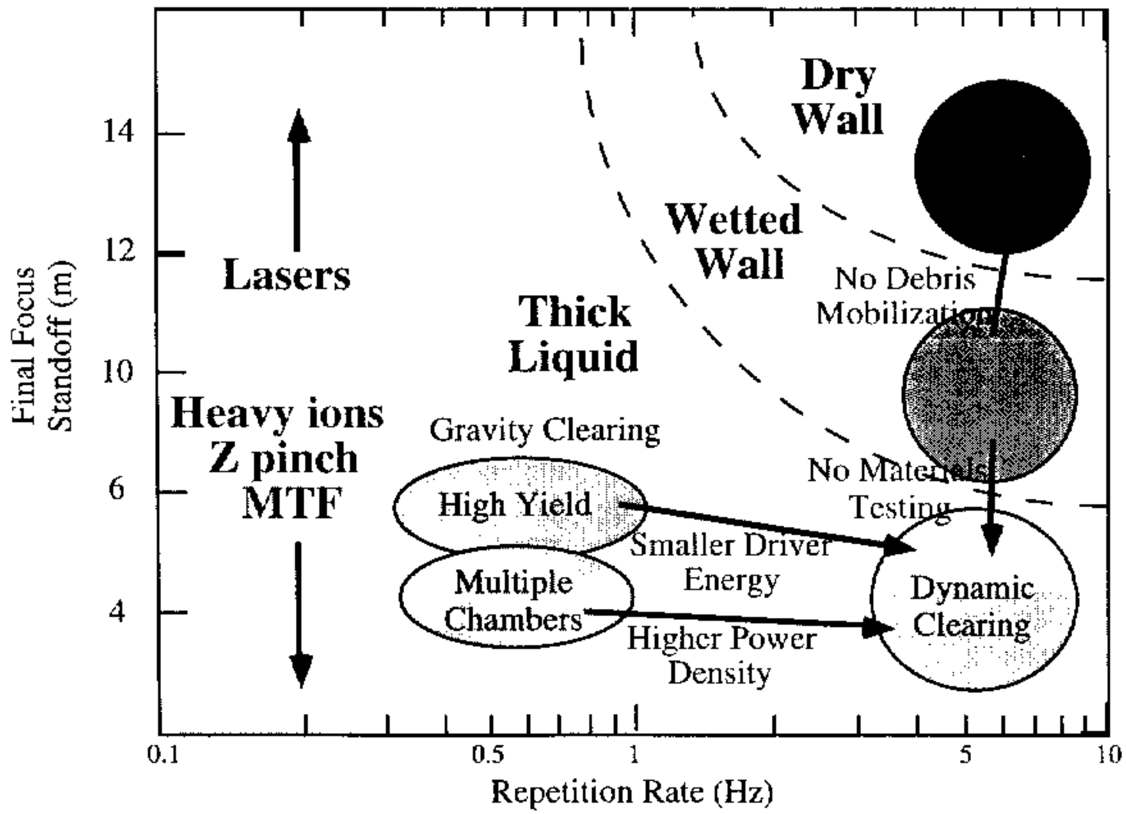
IFE has a variety of driver options that offer different strengths and weaknesses



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



Question 2: What are the Key Scientific Issues for the Fusion Chamber?

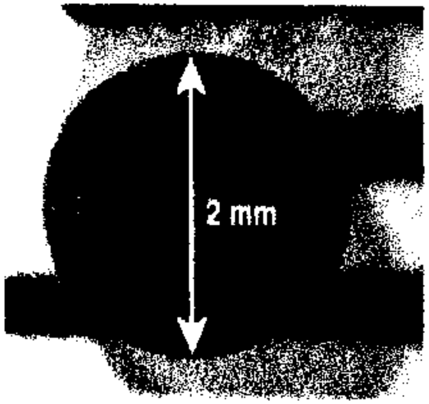
- Phase I experiments and analysis have been defined to resolve key feasibility issues and support decisions to proceed with Phase-II IRE experiments

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

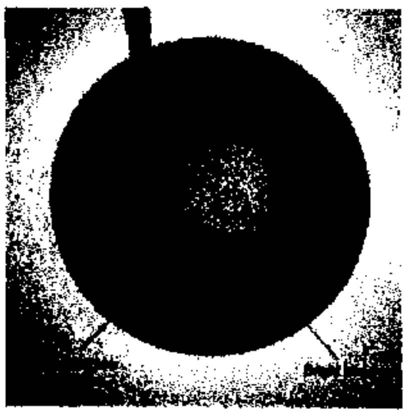
Question 3: What are the Key Issues for Target Fabrication and Injection?

- 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

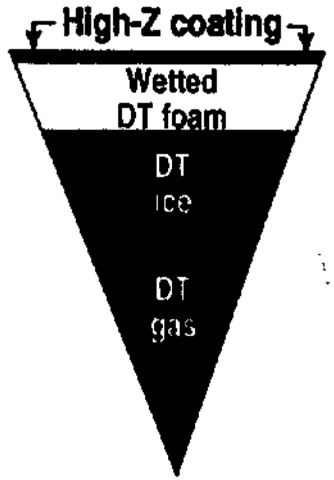
IFE CAN BUILD UPON ICF TARGET FABRICATION TECHNIQUES



Foam Shells

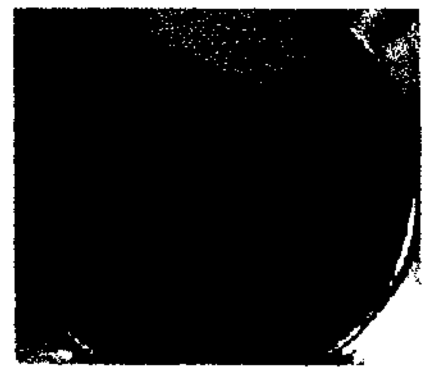


DT Ice Layer



Radiative Preheat Direct Drive IFE Target Design

Overcoated Foam

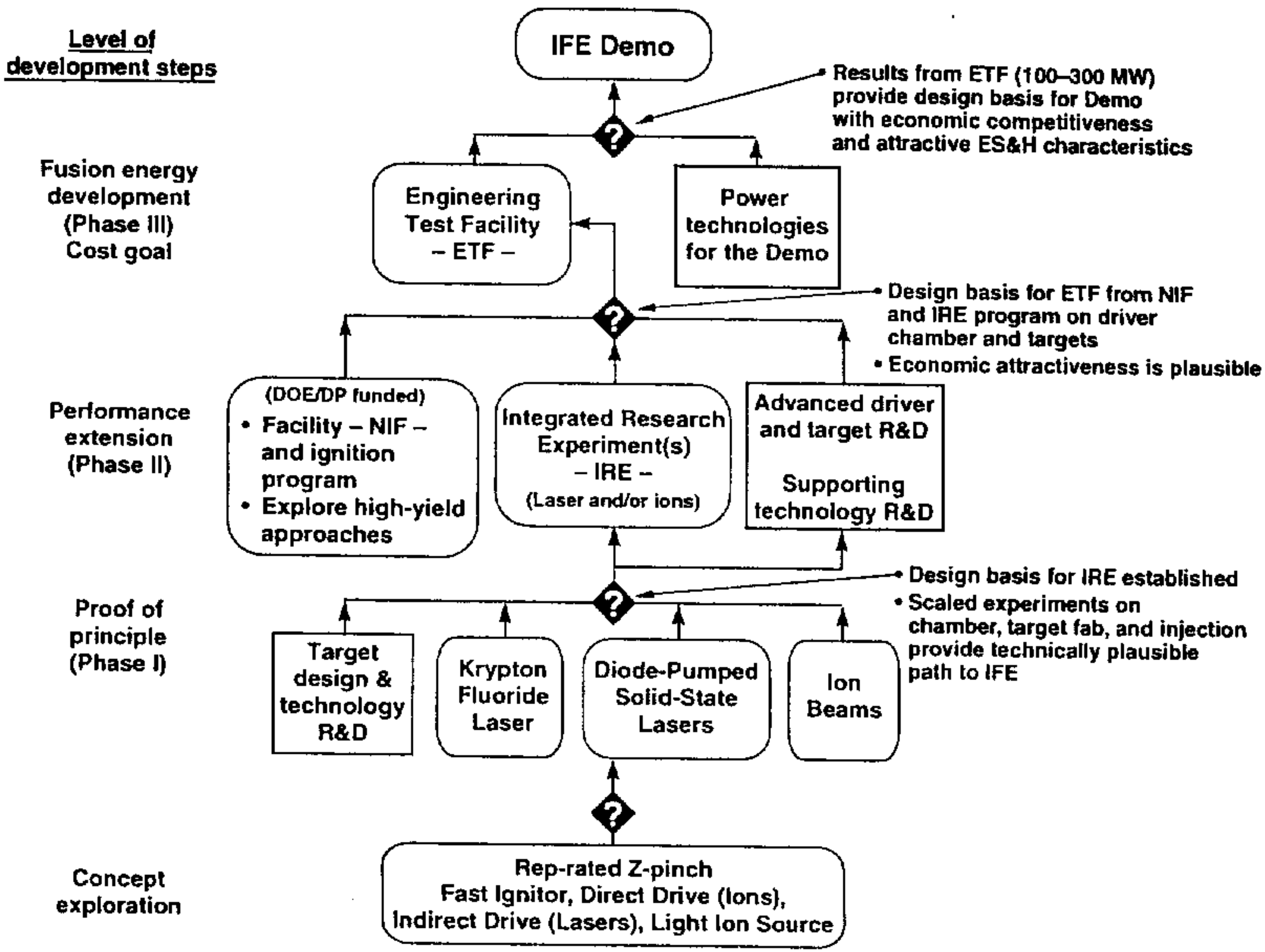


Metal on Foam

GENERAL ATOMICS

Metrics and Pathways

(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?



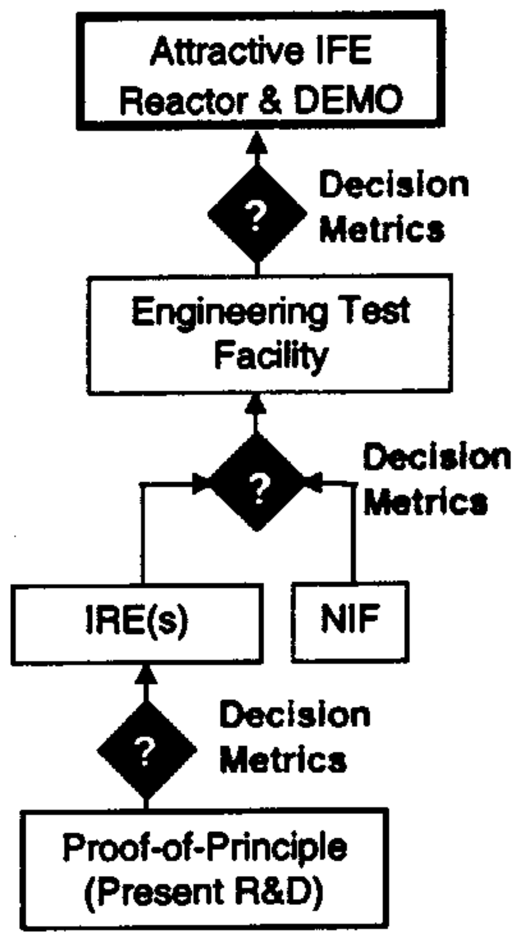
IFE Roadmap and Metrics

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 Acccommodating 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 (≤ 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 ~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?

(continued)

(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

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