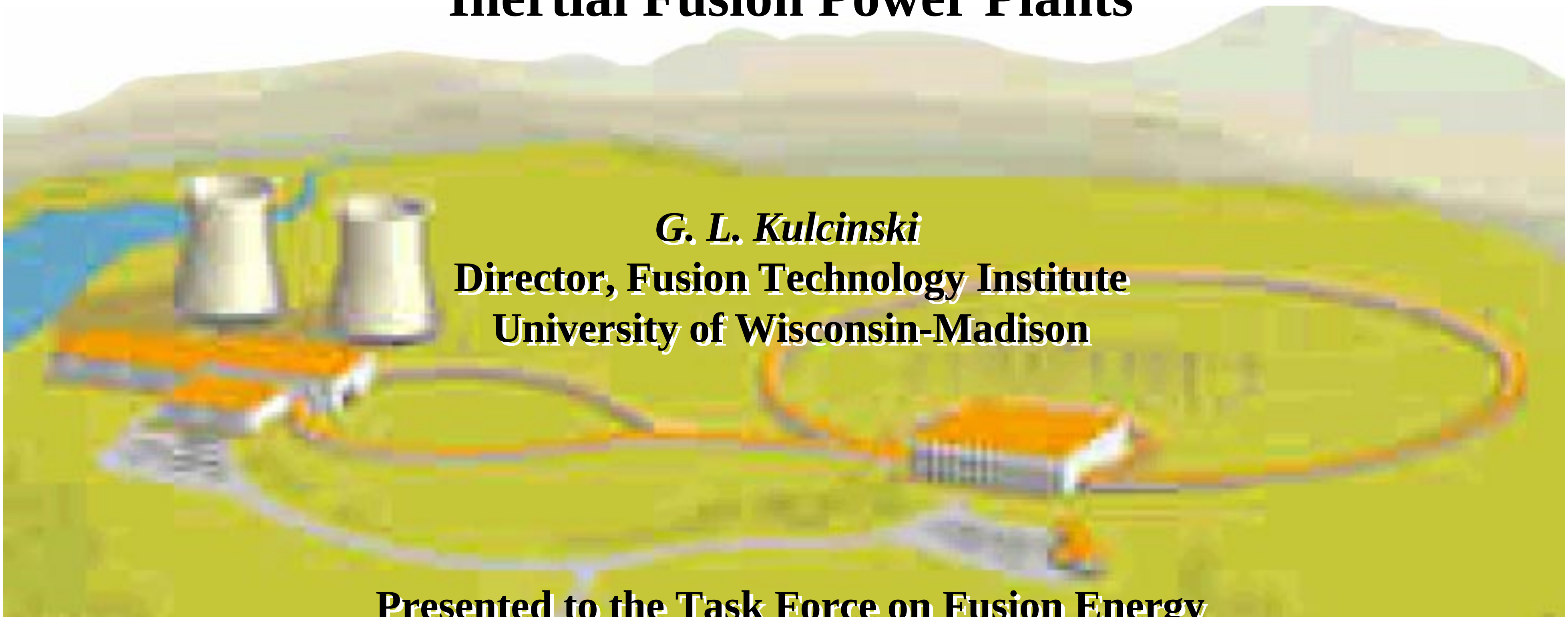
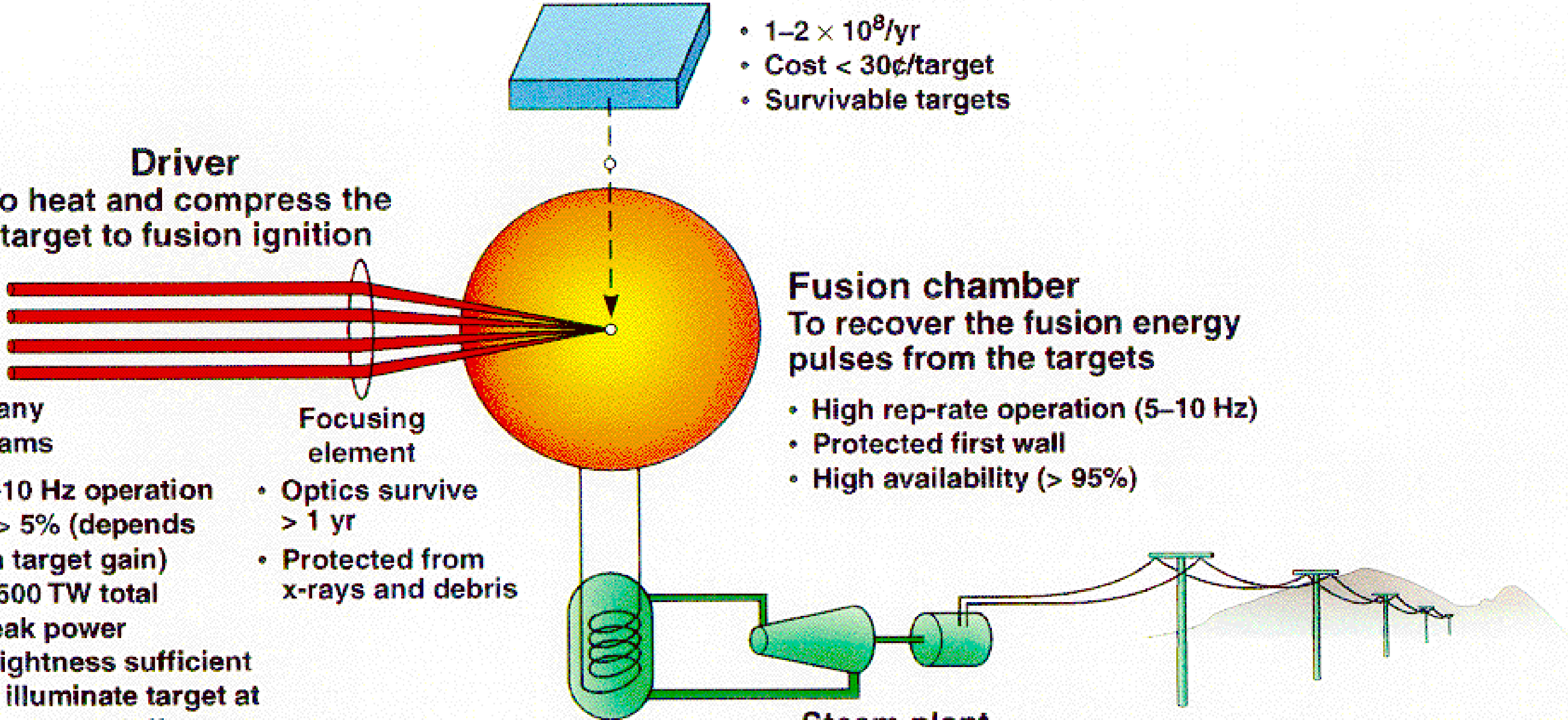
Environmental, Safety, and Economic Studies of Inertial Fusion Power Plants



G. L. Kulcinski
Director, Fusion Technology Institute
University of Wisconsin-Madison

Presented to the Task Force on Fusion Energy
Princeton Plasma Physics Laboratory
April 29, 1999

Inertial fusion energy (IFE) power plants of the future will consist of four parts



Target factory
To produce low-cost targets rapidly

- 1–2 × 10^8/yr
- Cost < 30¢/target
- Survivable targets

Driver
To heat and compress the target to fusion ignition

Many beams

- 5–10 Hz operation
- $\eta > 5\%$ (depends on target gain)
- > 500 TW total peak power
- brightness sufficient to illuminate target at > 5 m standoff

Focusing element

- Optics survive > 1 yr
- Protected from x-rays and debris

Fusion chamber
To recover the fusion energy pulses from the targets

- High rep-rate operation (5–10 Hz)
- Protected first wall
- High availability (> 95%)

Steam plant
To convert fusion heat into electricity

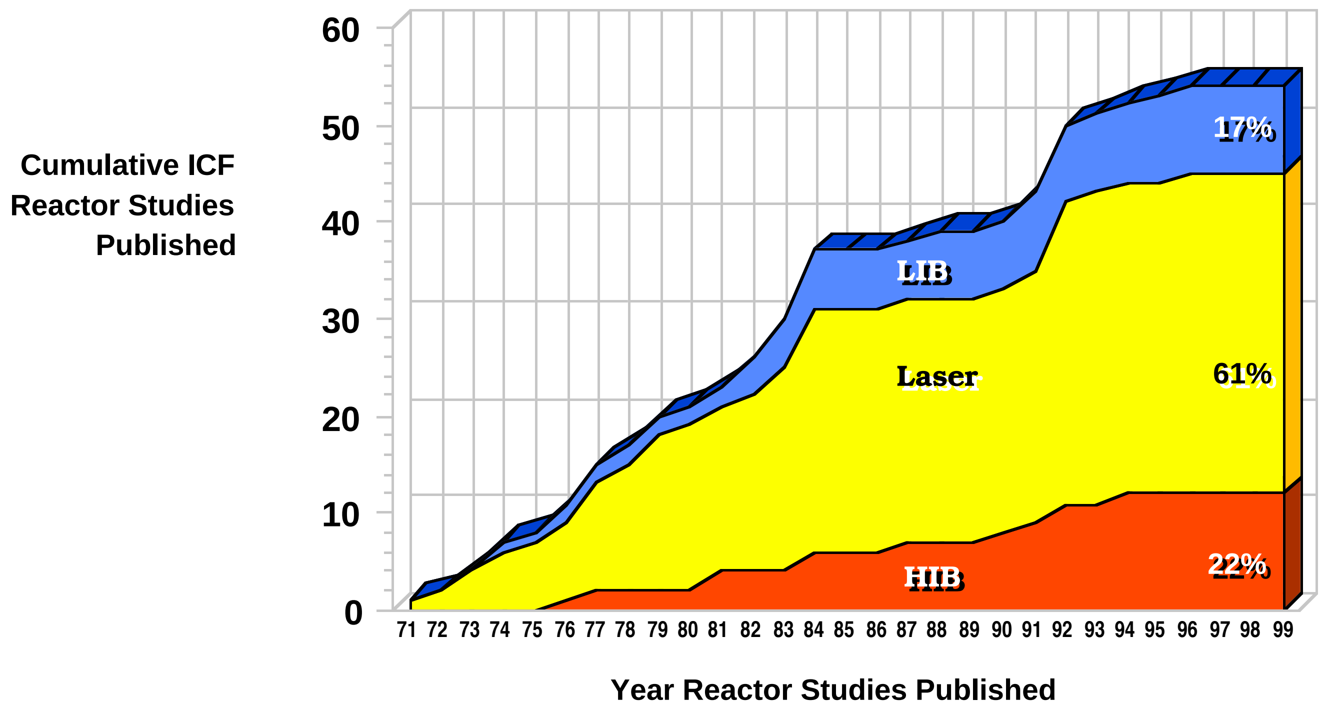
- Conversion efficiency 40–50%

An IFE power-plant would ignite five to ten targets per second to produce as much electricity as today's one gigawatt power plant

Approximately 80% of the IFE Reactor Designs are 15 Years Old and Need to Incorporate Recent Target, Driver, and Chamber Improvements

- The level of research on IFE power plants has historically been much lower (by a factor of ≈ 10) than for MFE power plants

- In spite of the lower level of investment, there have been over 50 individual IFE power plants analyzed since 1972



Inertial Fusion Energy (IFE) Reactor Design Studies Project

Industrial/University Teams Sponsored by USDOE

Objective: *Evaluation of IFE for Electric Power Production*
Start: *October 1990*
Finish: *March 1992*

- W.J. Schafer
- Bechtel
- General Atomics
- Textron
- University of Wisconsin

- McDonnell Douglas
- Ebasco
- KMS
- TRW
- UCLA
- CFFTP / SPAR

SOMBRERO
laser

OSIRIS
heavy ion beam

Prometheus-L
laser

Prometheus-H
heavy ion beam

IFE has potential advantages that could shorten the fusion energy development time and cost, with a more attractive final product

- Modularity of drivers allows one module to validate a full driver and will facilitate future power plant upgrades to higher output in stages
- Small confinement systems (targets) allow new targets to be innovated and tested relatively quickly
- Separation of driver, fusion chamber, and target injection systems allows significant development in parallel and will aid accessibility for future plant maintenance
- Beams can propagate in poor vacuum, which allows liquid chamber wall protection, reducing need for development of damage-resistant materials
- IFE technology has significant spin-off and spin-back benefits
  - Advanced radiography
  - Laser cutting

Purpose of Fusion Power Plant System Studies

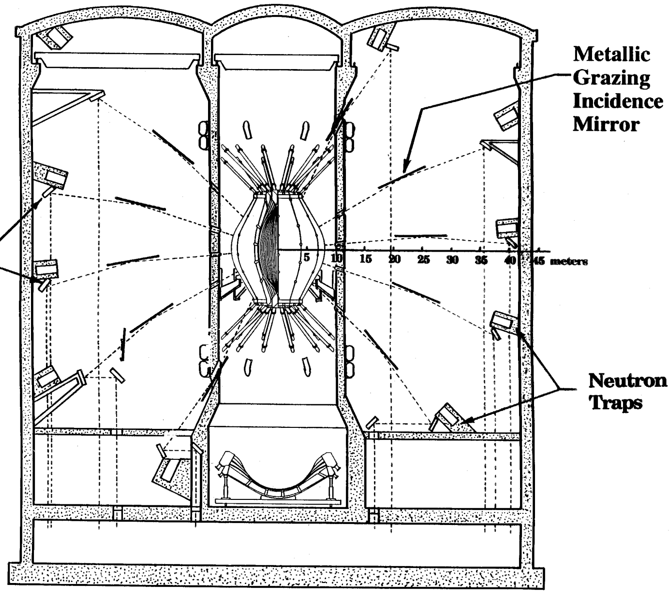
- **To uncover problems that exist at the interface between technologies**
- **To test innovative solutions to those problems and determine the effect of those innovations on the rest of the power plant**
- **To determine whether the innovative solutions improve or degrade the environmental, safety, and economic features of the power plant**

Power Plant System Studies are NOT meant to:

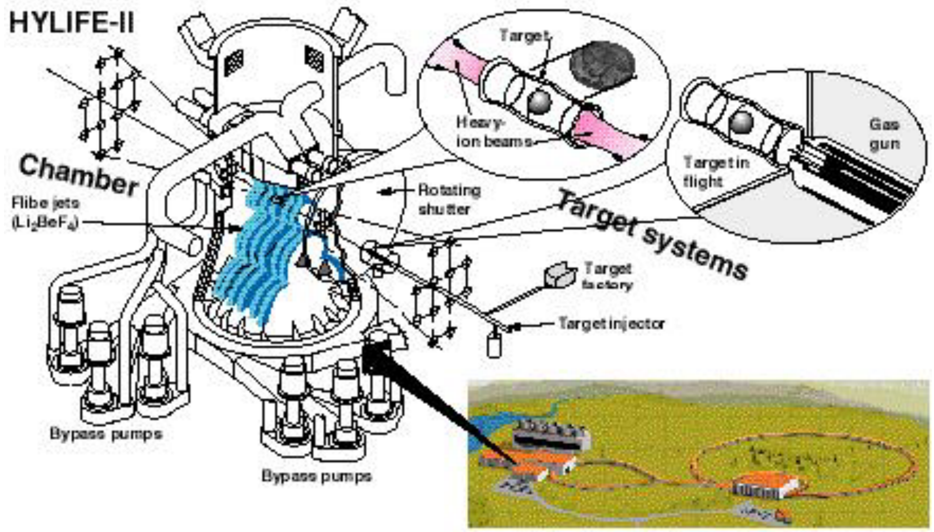
- ***Determine accurate (i.e., $\pm$10%) absolute costs***
- ***Be a "blueprint" for construction***

There are 4 Current ICF Drivers

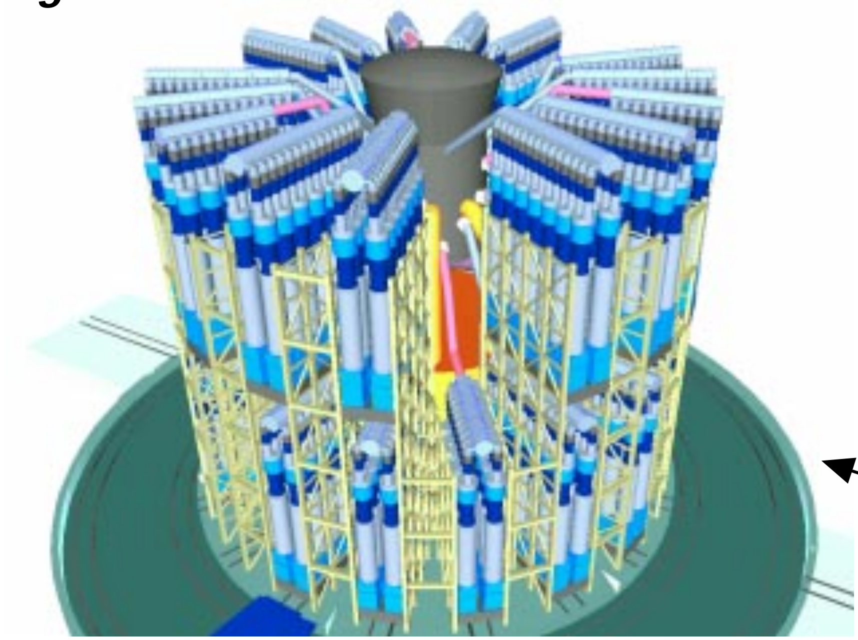
Laser



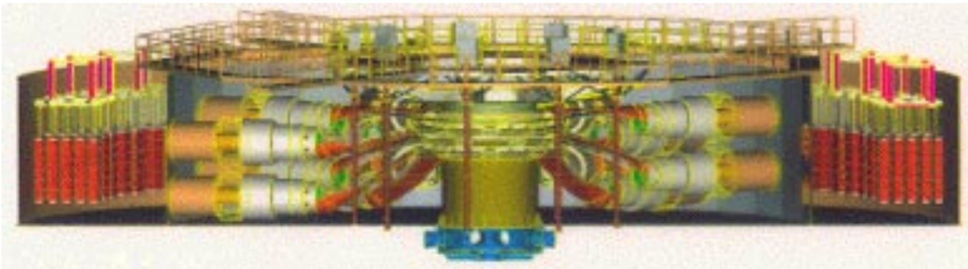
Heavy Ion Beam



Light Ion Beam



Z-Pinch – Energy application depends on finding a credible rep-rate concept



Light ion development currently on hold due to inability to focus adequately

Laser Fusion Reactors Have Evolved Over the Past 20 Years

	SOLASE	HYLIFE	Cascade	SOMBRERO	KOYO
Year Published	1977	1978	1983	1992	1993
Laser	CO_2	SWL	SWL	KrF	DPSSL
Laser Energy, MJ	1	4.5	1.5	4	4
Net Power, MWe	965	1010	800	1000	2840 (4 units)
Driver Eff., %	6.7	5	10	7.5	12
Illumination	quasi-sym.	2-sided	2-sided	symmetric	symmetric
Target Gain	150	400	200	118	150
Rep Rate, Hz	20	1.5	5	6.7	3
n, MW/m^2	5	0.3	0.2	3.5	0.07
Th. Eff., %	43	39	55	47	43
Breeding Matl.	Li_2O	Li	$LiAlO_2$	Li_2O	PbLi
Structural Matl.	C	Steel	SiC	C	SiC

Heavy Ion Beam Fusion Reactor Designs Have Evolved Over the Past 15 Years

	HIBALL-II	HYLIFE-II	Prometheus-H	OSIRIS
Year Published	1984	1991	1992	1992
Accelerator Type	RF Linac	Recirculating Induction Linac	Induction Linac	Induction Linac
Beam Energy, MJ	5	5	7	5
Ion Energy, GeV	10	10	4	5
Net Power, MWe	946 x 4	1083	1000	1000
Driver Eff., %	27	20	20	28
Illumination	cyl. sym.	2-sided	2-sided	2-sided
Target Gain	83	70	103	87
Rep Rate, Hz	5/cavity	8.2	3.5	4.6
n, MW/m^2 (on struc. matl.)	0.3	0.3	7.1	0.1
Gross Th. Eff., %	42	46	43	45
Breeding Matl.	$Pb_{83}Li_{17}$	Flibe	Li_20	Flibe
Structural Matl.	Steel	Steel	SiC	C

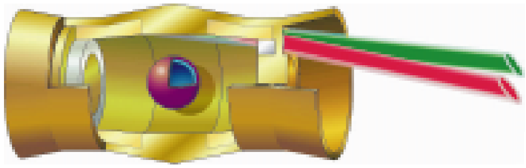
A Variety of Ion Beam Transport Schemes Have Been Investigated Which Could Apply to Light or Heavy Ion IFE Power Plants

Parameter	*LIBRA*	*LIBRA-LiTE*	*LIBRA-SP*
Year Published	1989	1991	1995
Focus Mechanism	Channel Transport	Ballistic	Self-Pinched
Net Electric Power, MWe	331	1000	1000
Li Ion Beam Energy to Target, MJ	4	6	7.2
Target Yield, MJ/Rep Rate, Hz	320/3	600/4	589/3.9
Coolant/Breeder	PbLi	Li	PbLi
First Wall Protection	SiC-INPORT	Steel-INPORT	Fan Spray Rigid Steel Tube
Secondary Heat Transfer Fluid	He	Organic	He

Use 25–35 MeV Li ions from Helia type driver

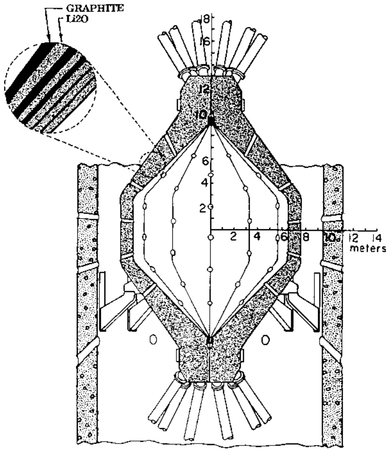
The Environmental, Safety, and Economic Features of IFE Power Plants are Greatly Influenced by 3 Factors

- **Target Designs**

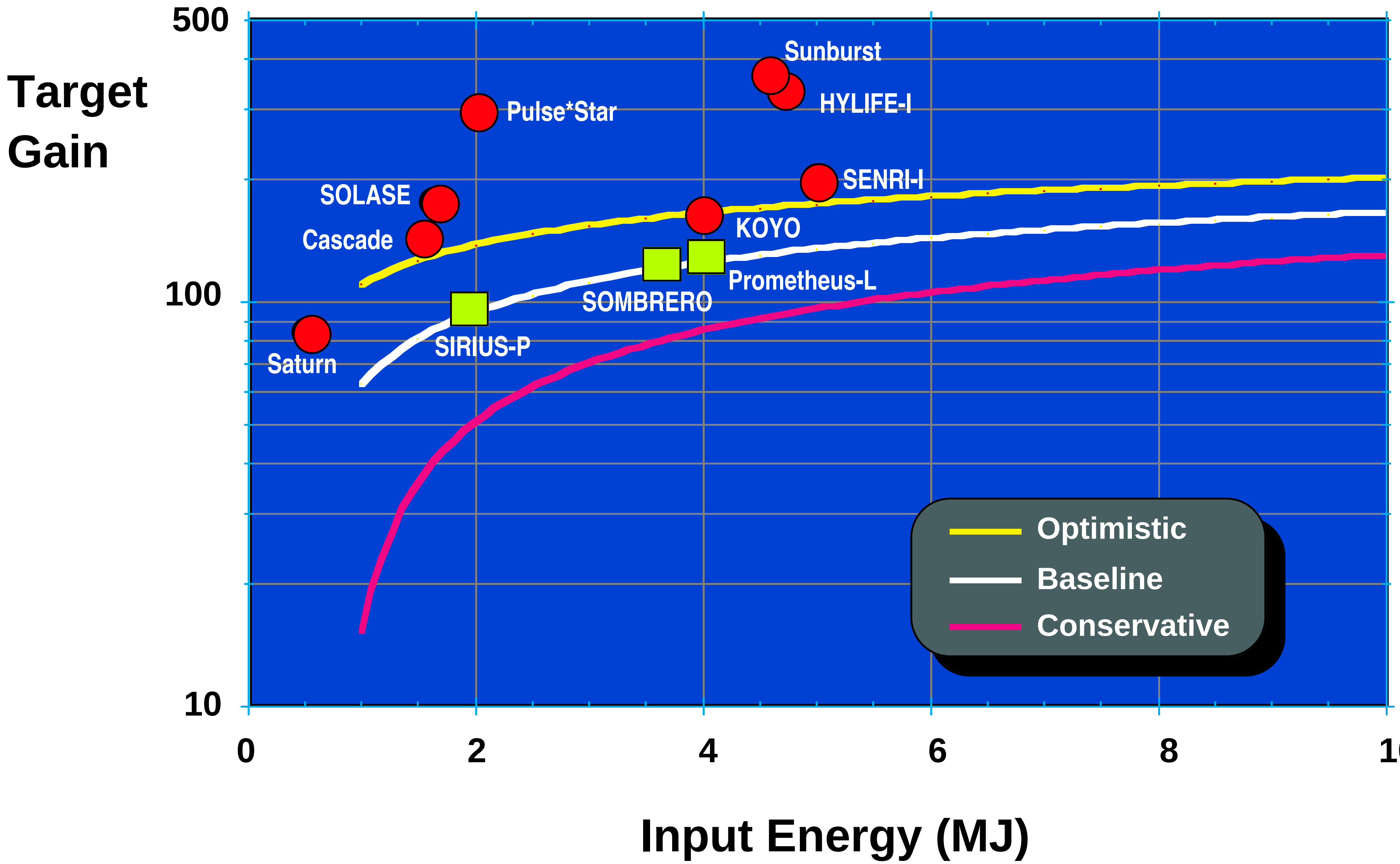


- **Driver Technology**

- **Reactor Chamber Design**

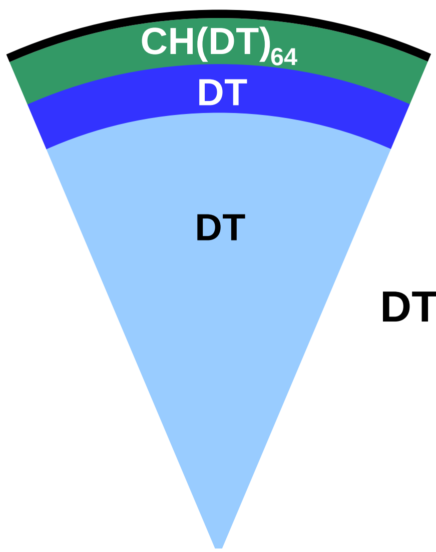


Baseline Target Gain Curves Were Used for the Last Laser Fusion Power Plant Designs



Proposed high gain direct-drive laser fusion target design.

NRL

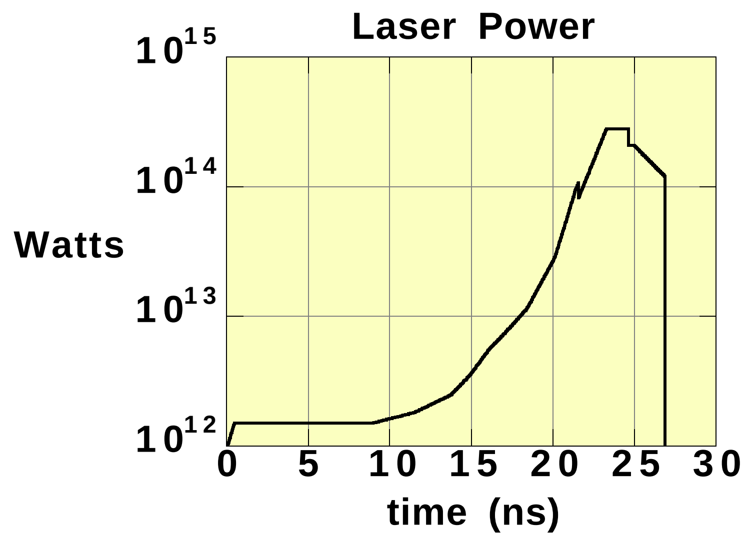


Overcoat: CH + 5% W

Ablator: CH Foam + DT

Fuel: DT

DT vapor



E_{laser} = 1.2 MJ

Yield = 160 MJ

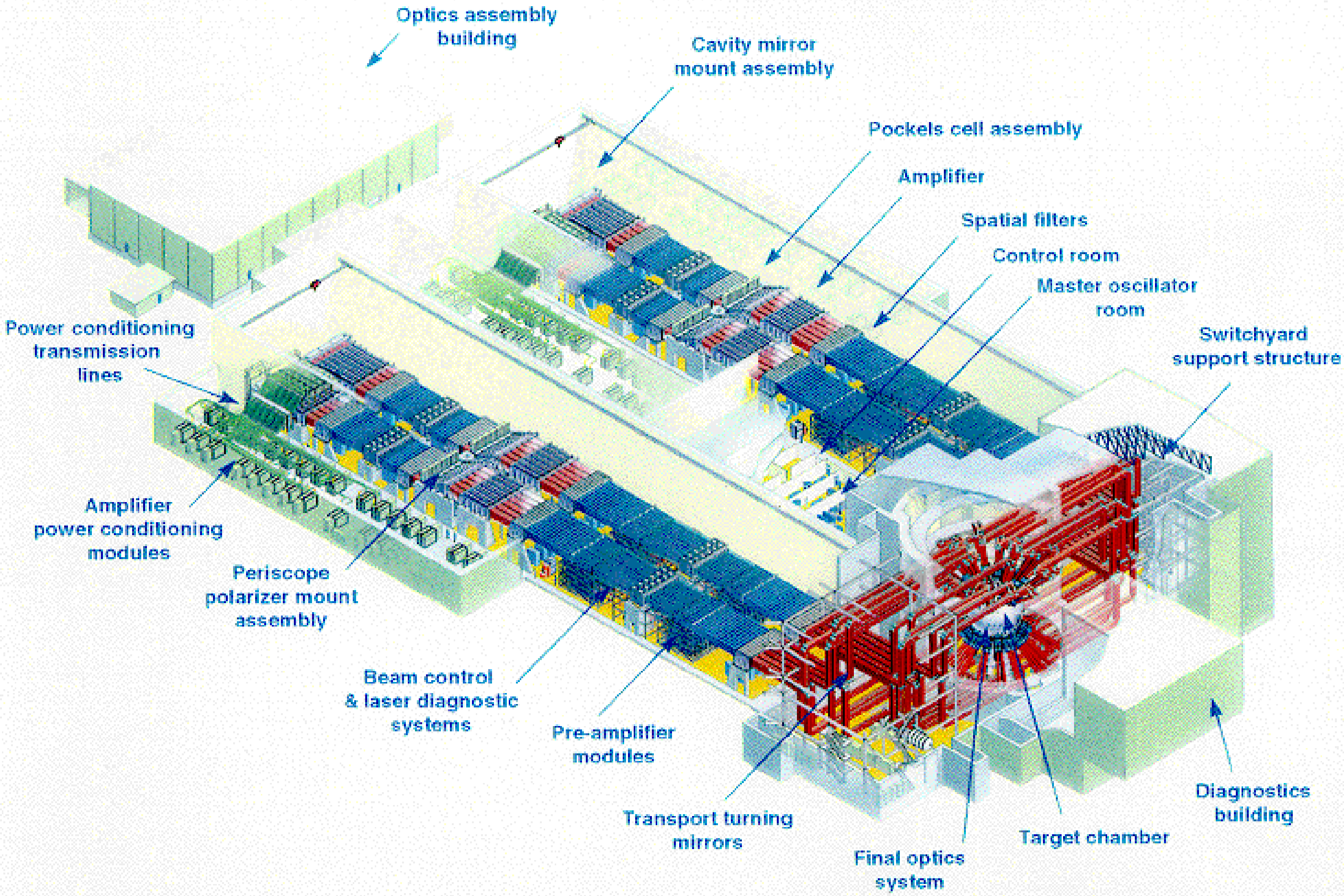
Gain = 135

R_0 = 1900 μm

$R_{hot\ spot}$ ~ 60 μm

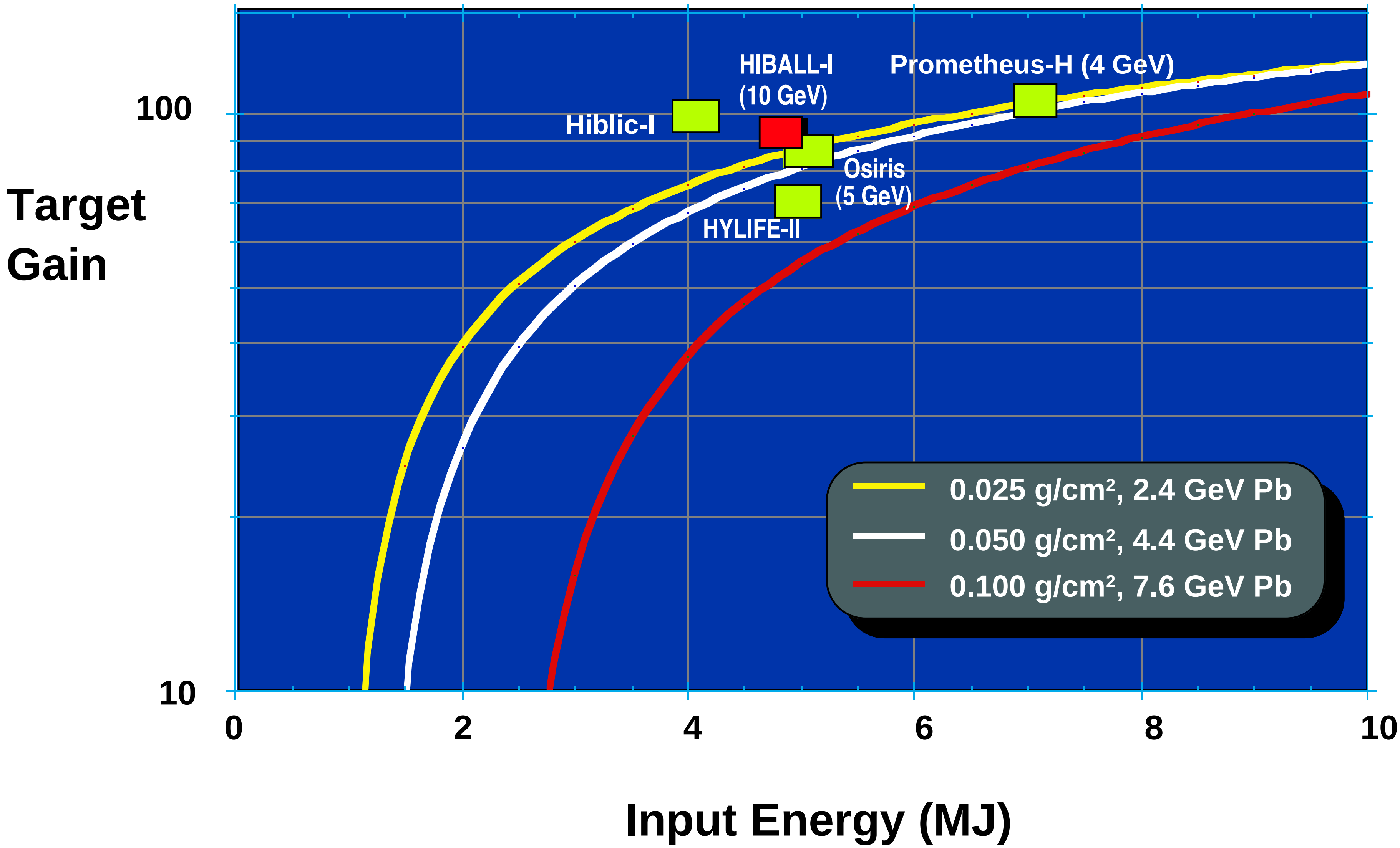
Factor of ~ 30 convergence ratio

The National Ignition Facility and supporting OFES programs gives the U.S. a unique opportunity for world leadership in inertial fusion energy



- Demonstrate ignition and gain for both direct and indirect-drive
- Provide key data on target chamber and target fabrication technologies
- Confirm predictive target modeling capabilities

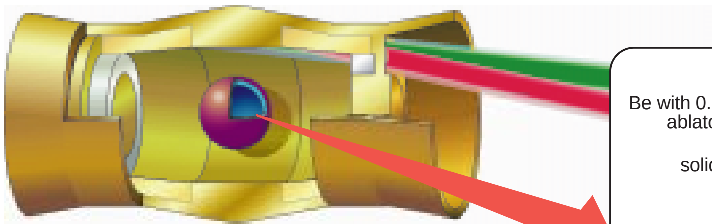
Recent Heavy Ion Beam Fusion Reactor Studies Have Used Conservative Gain Curves



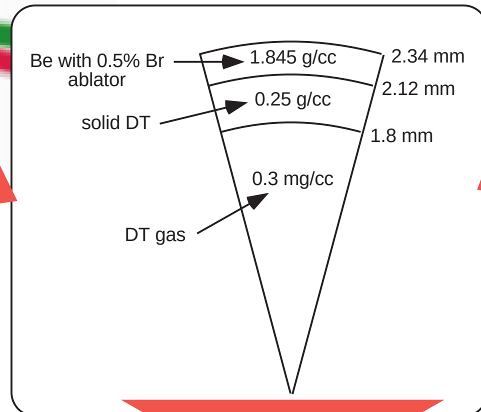
High gain (G > 50) target designs have been developed thru DOE-DP and DOE-OFES sponsorship: indirect drive with heavy ions

LLNL • LBNL

Conventional

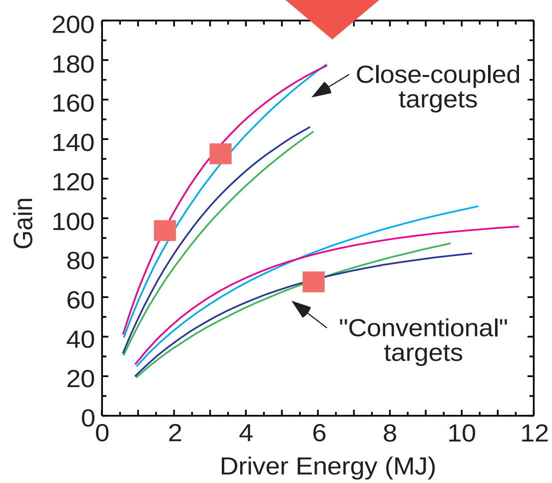


Close Coupled



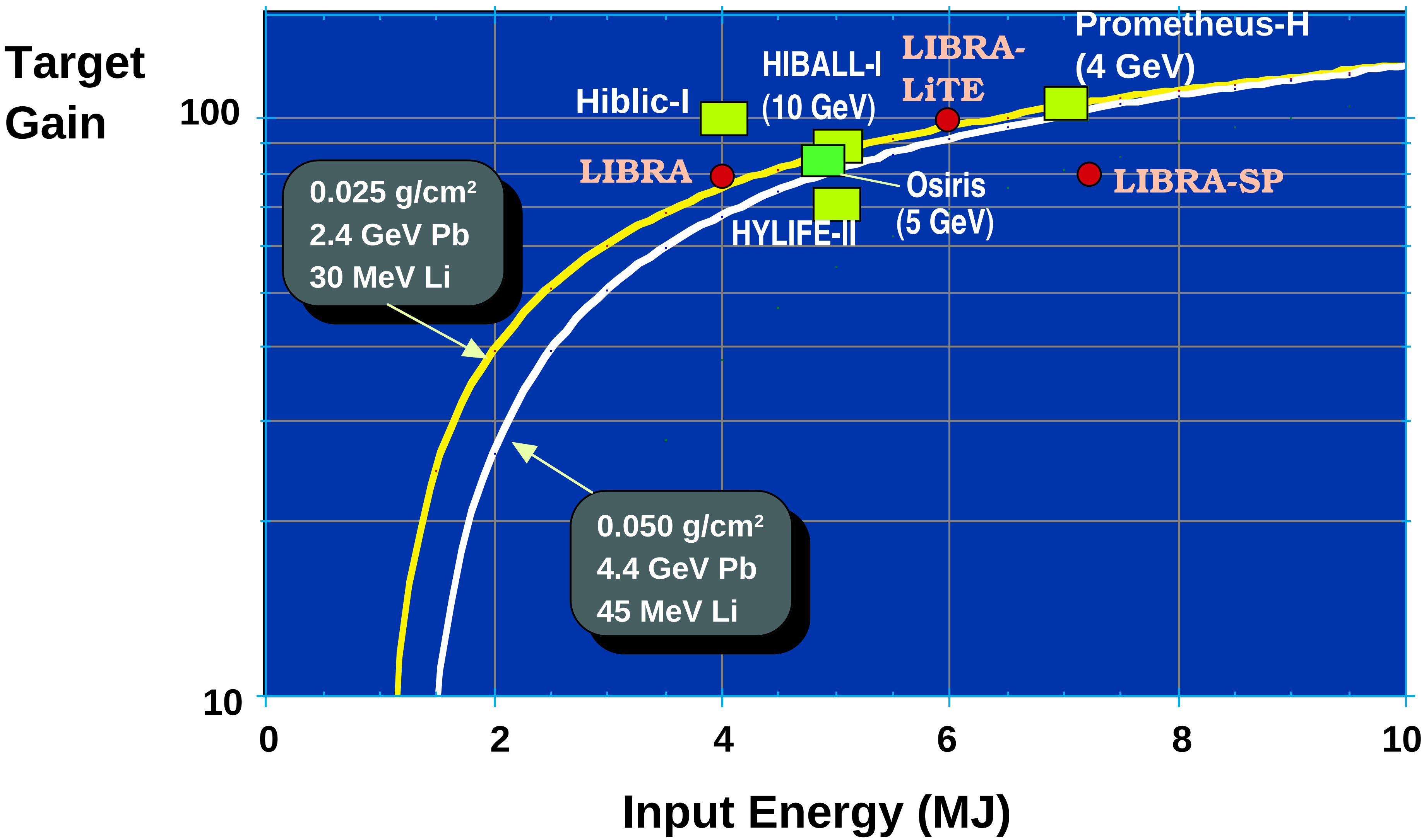
Ion beam characteristics:
- 4 GeV Pb^+ ions
- 5.9 MJ input energy
- 2.7 mm effective radius spot
- T_r = 240 eV

Ion beam characteristics:
- 3.5 GeV Pb^+ ions
- 3.3 MJ input energy
- 1.7 mm effective radius spot
- T_r = 240 eV

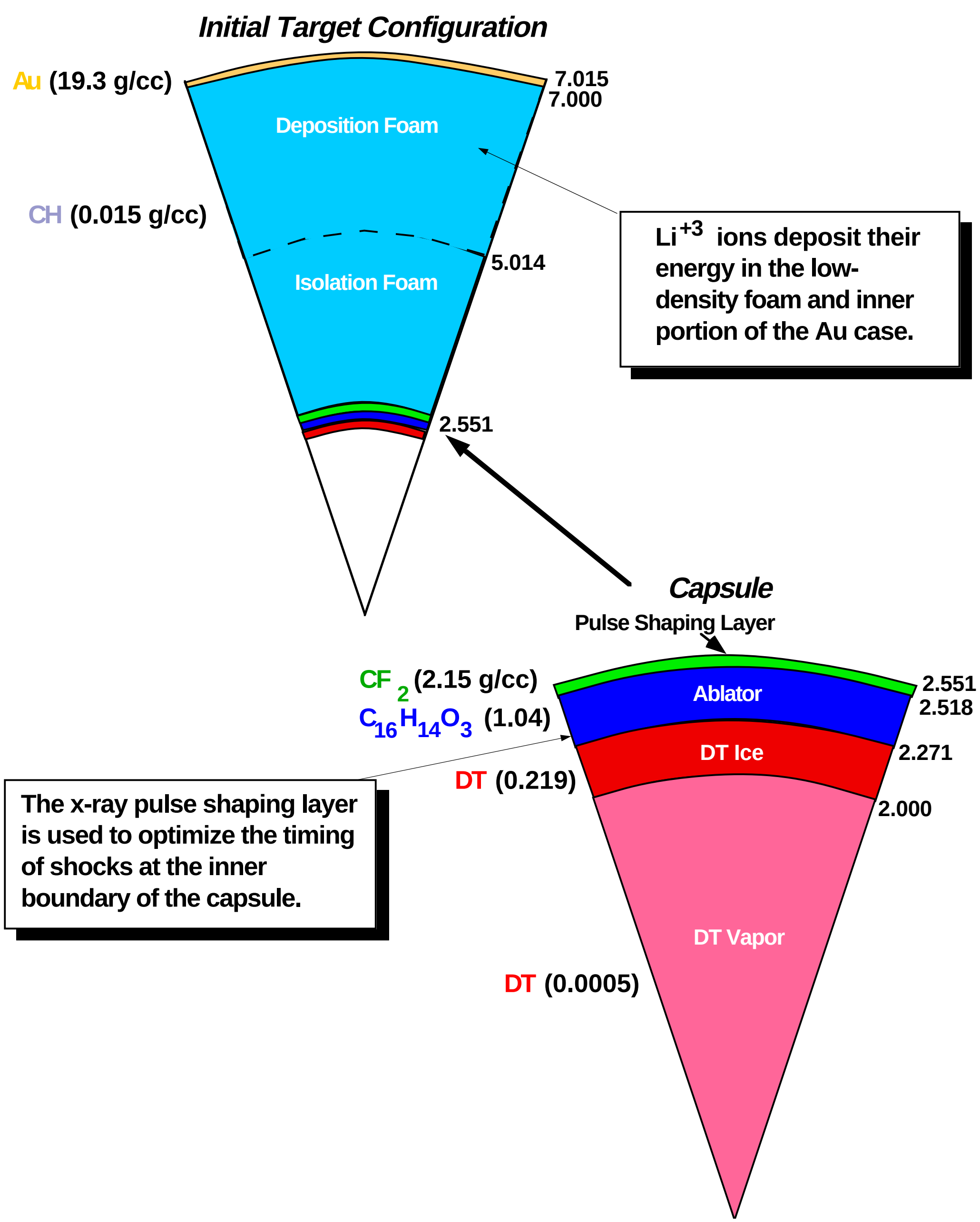


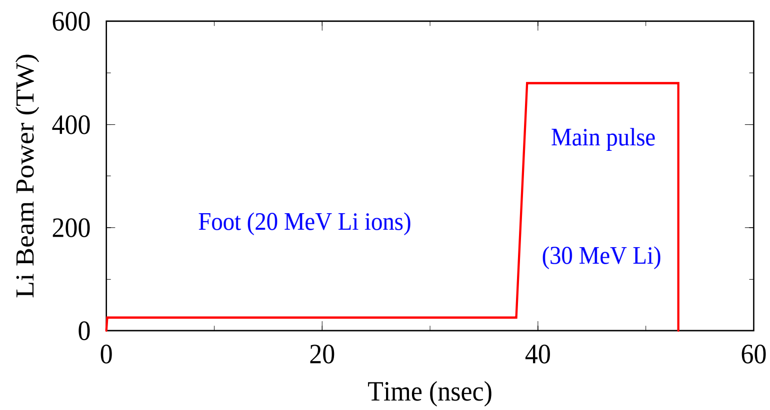
Callahan 3/99

Recent Light Ion Beam Fusion Reactor Studies Have Used Conservative Gain Curves



LIBRA Light Ion Targets are Spherically Symmetric and Use Internal Pulse Shaping





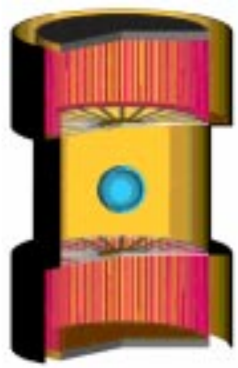
$$E_{\text{ion beam}} = 8 \text{ MJ}$$

$$E_{\text{yield}} = 552 \text{ MJ}$$

$$\text{Gain} = 70$$

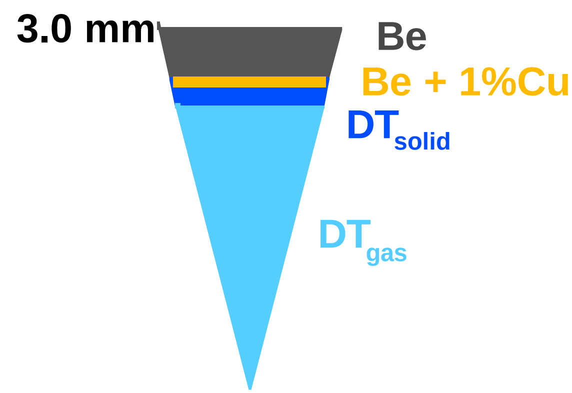
Pulsed-power high yield capsules are designed to the baseline NIF ignition capsule implosion criteria

Z-pinch driven hohlraum
400 - 1200 MJ



Static-walled hohlraum
> 200 MJ

Dynamic hohlraum
600 MJ



High yield capsule

- **Drive Temp. = 300 eV**
- **E_{xray} = 16 MJ**
- **Y = 560 MJ**
- **Gain = 35**

Los Alamos

Key Considerations for IFE Power Plant Designs

	Target
Lasers	• Best data base (30 kJ, 100 TW) • Direct or Indirect Drive
Heavy Ions	• Recent Target Designs Show High Gain • Indirect Drive
Light Ions	• Internal Pulse Shaping Targets Reduce Need for Beam Pulse Shaping • Indirect Drive
Z Pinch	• Recent X-ray Production Experiments Encouraging (2 MJ, 300 TW) • Indirect Drive

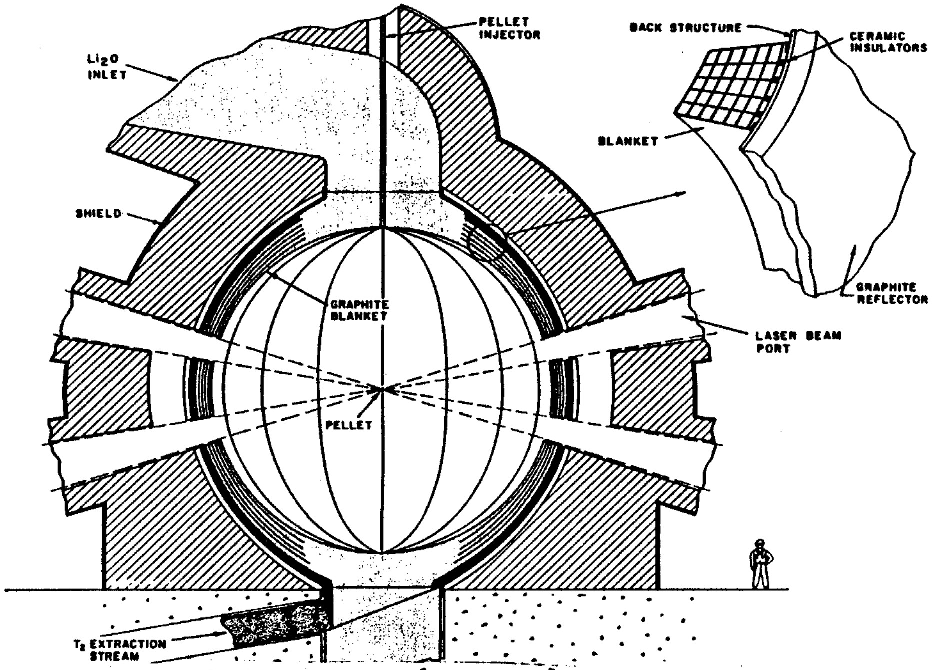
Characteristics of Drivers for Recent IFE Power Plant Designs

	Laser	HIB	LIB	Z-Pinch (estimated)
Energy - MJ/pulse @ ~300-500 TW	1-5	2-5	5-10	5-20
Driver Efficiency-%	>5	25-40	20-25	15-20
Efficiency to Capsule-%	>5	2-3	2-3	1-2
Total # Pulses	$>10^{10}$	$>10^{10}$	$>10^{10}$	$>10^{9}$
Current Status	•Glass ~ 40 kJ, 40 TW x-rays •KrF ~ 5 kJ •DPSSL ~ 0.1 kJ •NIF-1.8 MJ, 500 TW	•SLAC~10^{11} pulses, 180 Hz •I_{inj}~1 A	•Hermes ~ 300 kJ, 13 TW, 10^{-4} Hz •RHEPP-II~3 kJ, 120 Hz	•Z ~ 1.8 MJ, 280 TW x-rays, $2x10^{-5}$ Hz

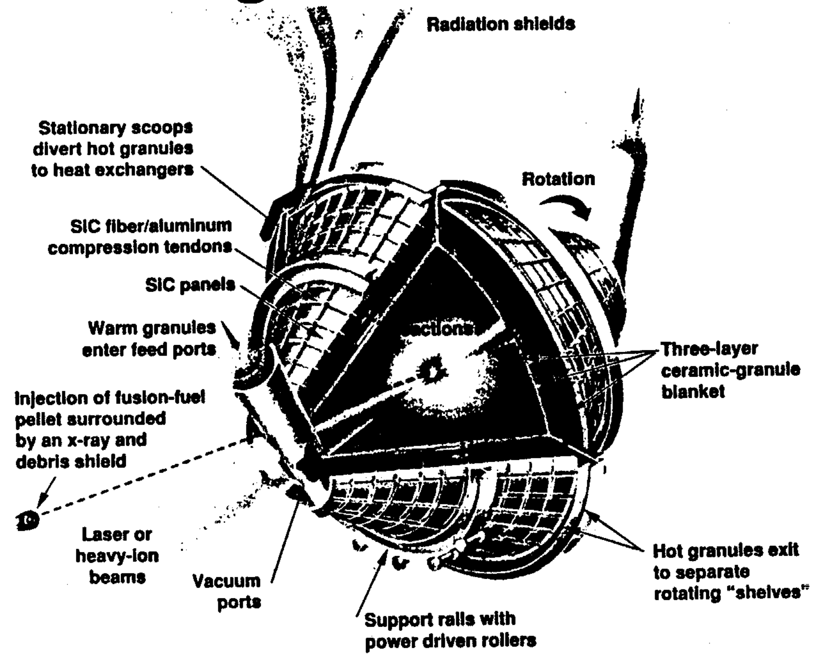
Key Considerations for IFE Power Plant Designs

	Driver
Lasers	• NIF Will Give Reactor Level Energies (1.8 MJ, 500 TW) • SWL KrF/DPSSL Lasers Needed for Rep Rate
Heavy Ions	• RF or Induction Linacs Favored • Must Scale up to Higher Energy (both MJ and GeV)
Light Ions	• "Inexpensive' Hermes Technology Demonstrated at Reactor Level Energies • Have Not Demonstrated Sufficient Beam Focusing and Purity
Z Pinch	• "Inexpensive" Pulsed Power Demonstrated • Rep Rated Coupling to Target Design Not Shown

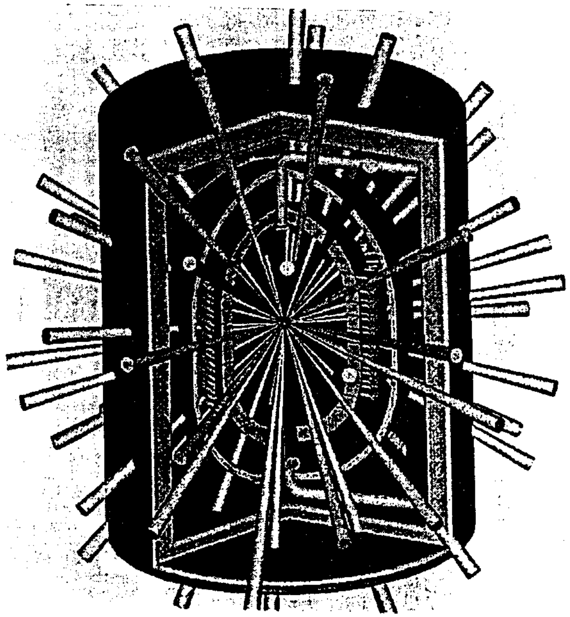
Laser Driven Reactor Designs



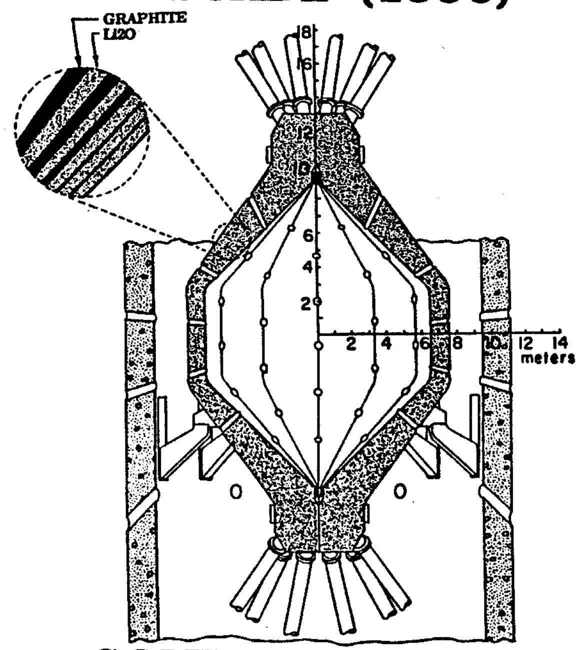
SOLASE (1977)



CASCADE (1990)

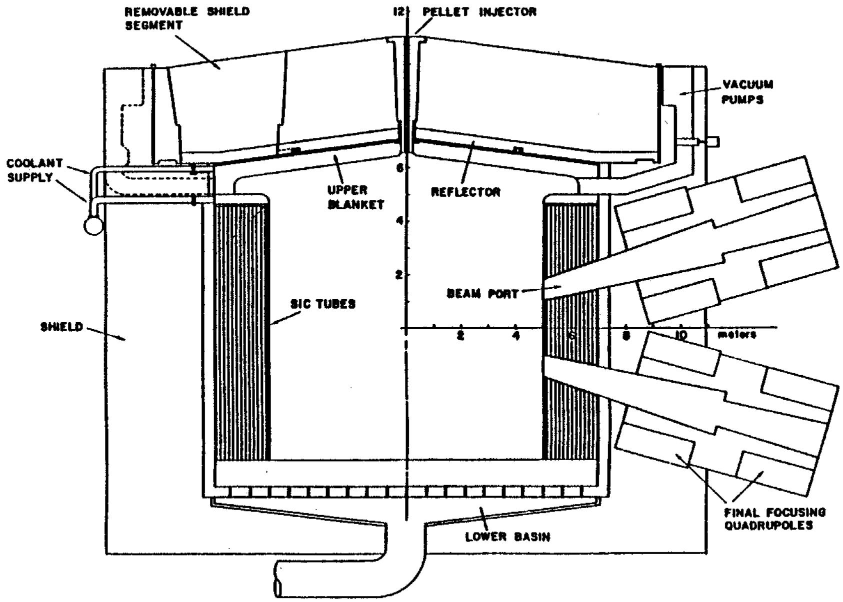


PROMETHEUS-L (1992)

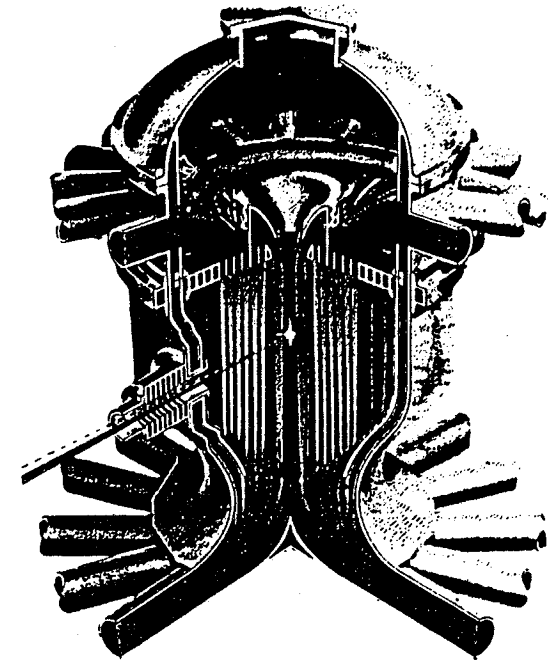


SOMBRERO (1992)

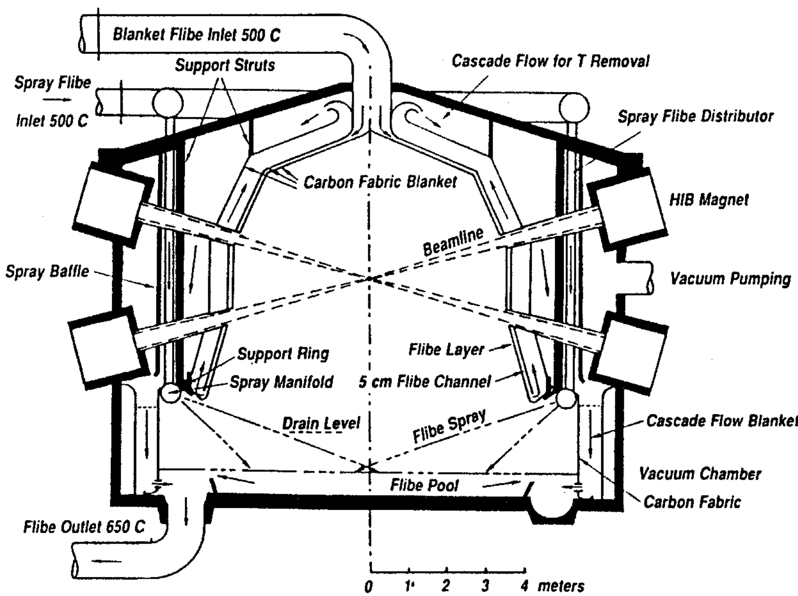
Heavy Ion Beam Driven Reactor Designs



HIBALL (1981)



HYLIFE (1985)



OSIRIS (1992)

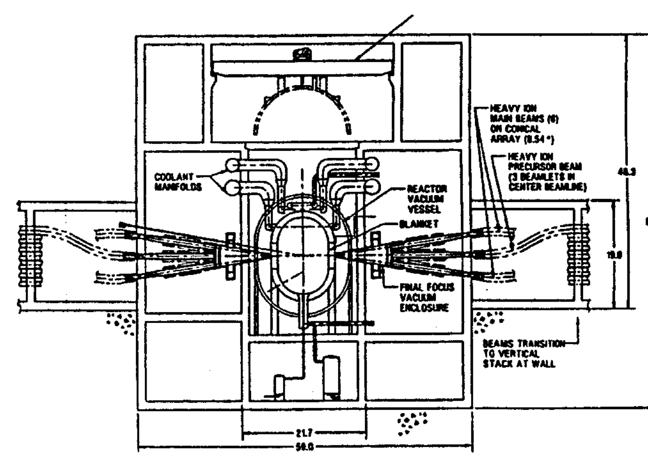
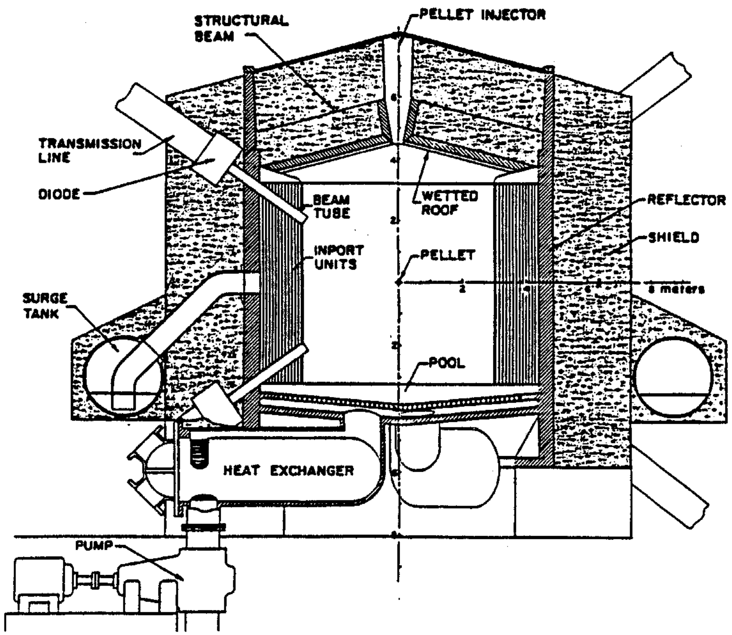


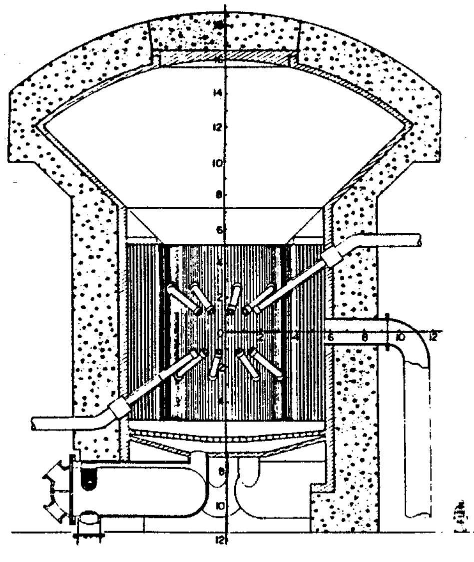
Figure 6.3.2-3 Heavy Ion-Driven Reactor has Two Beam Bundles Located on Opposite Sides of the Reactor Vessel

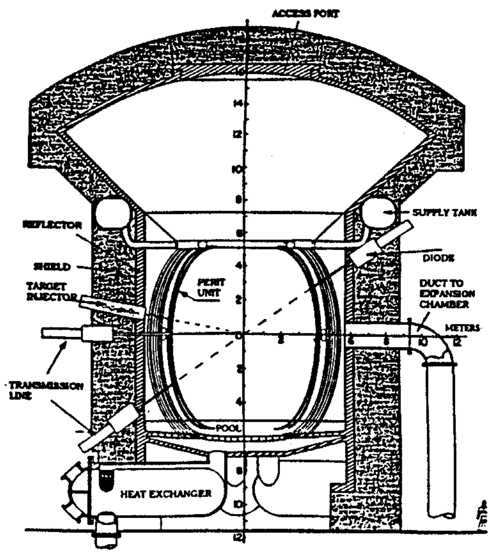
PROMETHEUS-H (1992)

Three Light Ion Beam Propagation Schemes Have Been Utilized

University of
Wisconsin







LIBRA (1989)

Channel beam propagation
Driver technology, HELIA
Li + ions, 25-35 MeV
Energy on target, 4 MJ
Target gain, 80
Rep-rate, 3

LIBRA-Lite (1991)

Ballistic beam propagation
Driver technology, HELIA
Li + ions, 25-35 MeV
Energy on target, 6 MJ
Target gain, 100
Rep-rate, 3.9

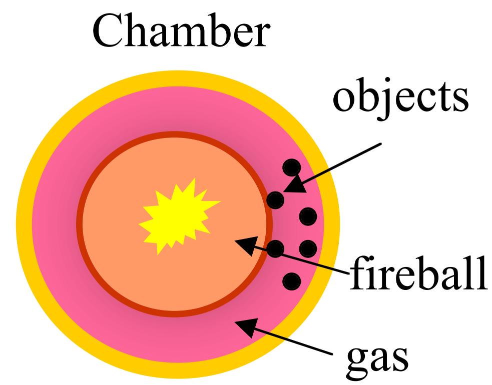
LIBRA-SP (1995)

Self-pinched beam propagation
Driver technology, HELIA
Li + ions, 30 MeV
Energy on target, 7.2 MJ
Target gain, 82
Rep-rate, 3.9

Key Considerations for IFE Power Plant Designs

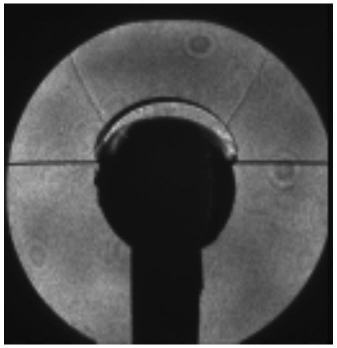
	Chamber
Lasers	• Symmetric Illumination Favors Dry/Wetted Wall Approach With Gas Protection
Heavy Ions	• 2 Sided Indirect Drive Allows for Thick Free or Inhibited Flow Liquid Metallic/Molten Salt Protective Walls
Light Ions	• Could Use Dry/Wetted/Liquid Walls With Gas Protection
Z Pinch	• Chamber Design Uncertain Until Rep Rated System Identified • Shrapnel from Target Will be a Problem

Fireballs and Blasts in Gas Protected IFE Target Chambers



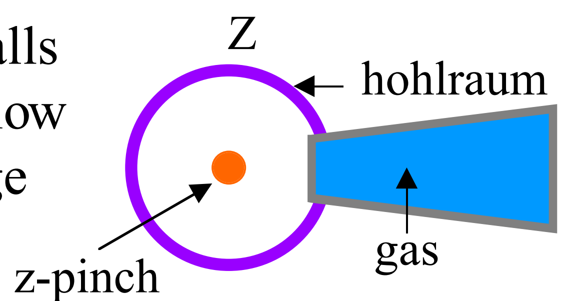
Issue: Target explosions generate fireballs in target chamber fill gases, which transmit a shock and a radiant heat pulse to target chamber structures. The strength of each can be adjusted with gas density and species.

Shock Tube



Status: Radiation-hydro codes (BUCKY, RAGE, Lasnex) can model fireballs. UW Shock Tube simulates blast flow around target chamber structures (100 k$/yr); is a testbed for structural response of target chamber. NRL laser generated blasts in the 80's validated BUCKY ion deposition in gases.

Needs: Shock Tube experiments to optimize flow around structures (100 k$). High energy density fireball experiments on Z would simulate radiation driven fireballs (100 k$). Species and gas density effects on radiation flow and shock strength would be tested. Need a sample large enough to be optically thick.



VLT

Environmental Aspects of IFE Power Plants

- IFE and MFE have many attractive environmental features in common.

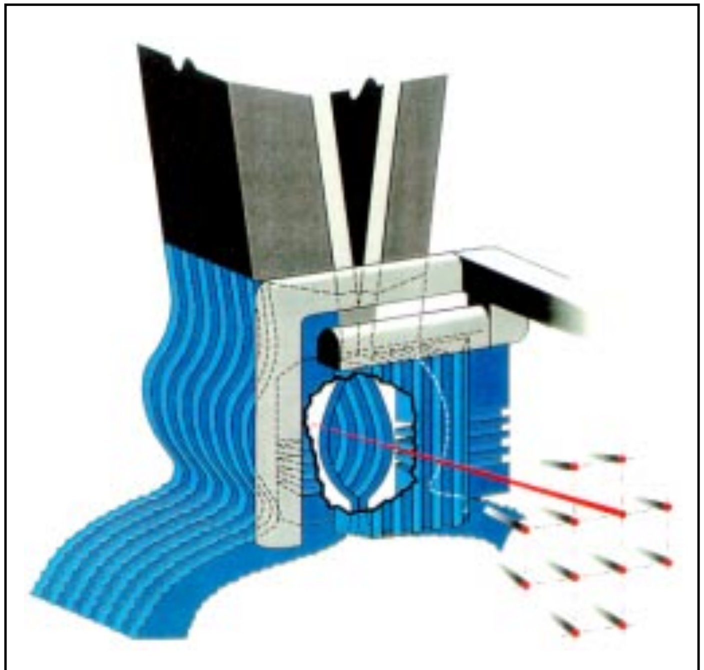
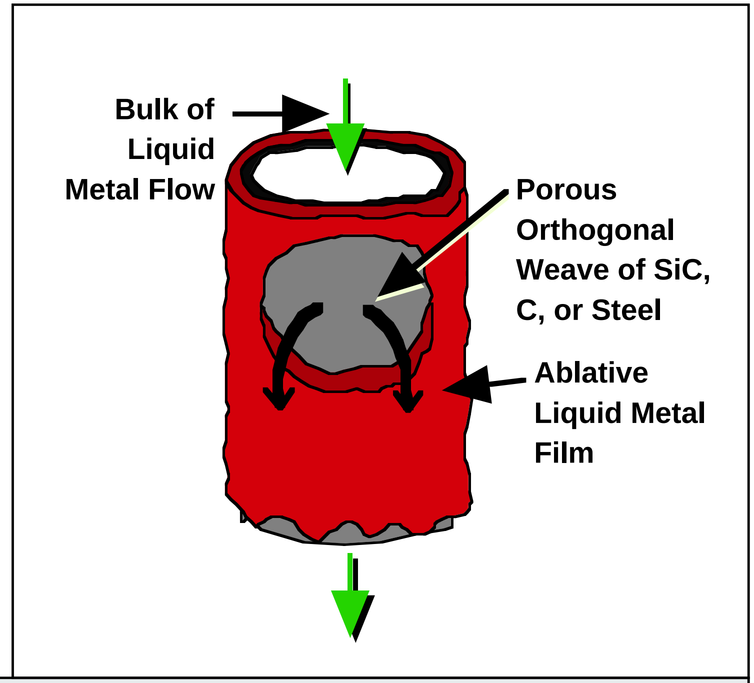
  1) Reduced land disruption to collect fuels and construction materials
  2) Less greenhouse gas emissions than fossil fuels
  3) Lower levels of long-lived radioisotopes than fission reactors

- There are 2 areas where IFE has unique features that could make it even more attractive environmentally.

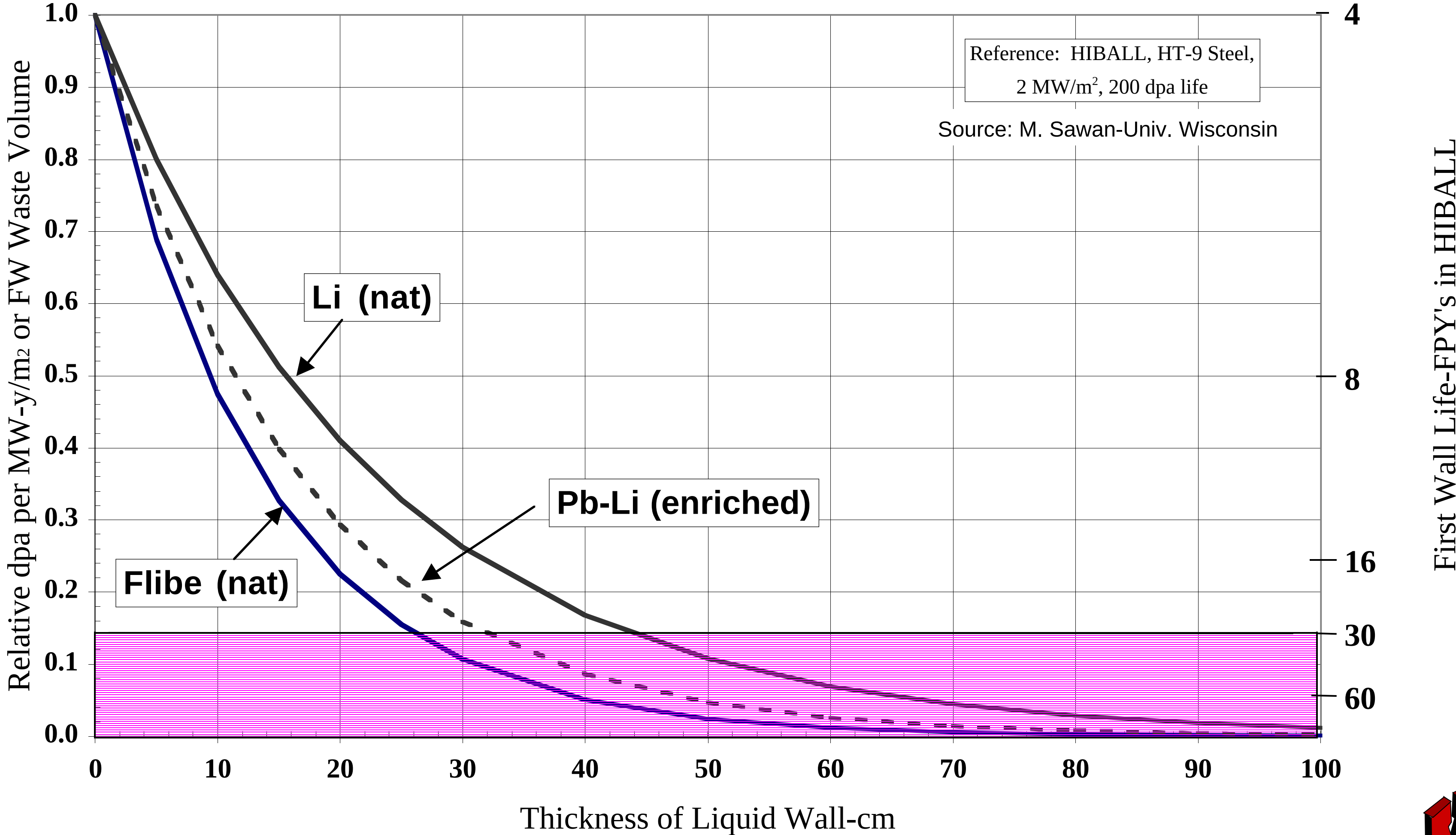
  1) The ability to isolate the driver (e. g., laser, accelerator, pulsed power source, etc.) from the radiation source in the reaction chamber

  2) A more amenable geometry to use thick liquid walls in order to reduce the level of radiation damage, radioactivity, and volume of waste

There Are Two Ways to Use Liquids to Protect IFE Chamber Walls

	Free Flowing Liquids	*Inhibited Flow in Porous Tubes-INPORT*
		
	Reduction in neutron effects by 10 to 100 times	
Advantages	• No exposed structural material • Smaller chamber radius	• Slower flow, larger ΔT(small HX) • Reduced droplets (higher rep rate)
Disadvantages	• Rapid flow, small ΔT • Isochoric heating-disassembly • Low rep rate	• Finite life of porous tubes • Requires larger chamber radius

The Use of Internal Liquid Walls Can Prolong the Life of a Steel First Wall



Recent Studies Have Concluded That the Safety of IFE Power Plants Can Be Superior to Today's Nuclear Facilities

- Favorable Attributes Are Due to the:

  1) Ability to isolate the drivers from the chamber
  2) Low overall power density ➔ low after-heat density
  3) General use of ceramic, non-volatile materials (with the exception of T_2)
  4) General use of low activation structural materials (C, SiC,…)
  5) Use of liquid metals (Li, Pb-Li, Flibe,…) in the chamber to lower the activity in the blanket

- Unique Areas That Require Continued Attention:

  1) T_2 inventory in target factory (could be on the order of 200-300 g)
  2) T_2 inventory in IFE blankets (currently ranges from 10 to 200 g)
  3) Activated target materials (could be as much as 50 tonnes/y)
  4) Pulsed neutron effect on increase in short lived activity

The Driver and Conventional Power Conversion Equipment Dominate the Capital Cost of IFE Power Plants

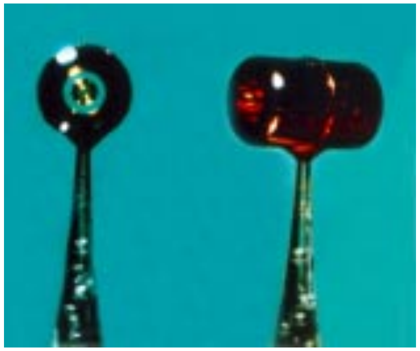
Example

	% of Total Capital Cost in Category				
	Driver	Chamber	Bldgs.	Heat Transfer/ Turbine/Electric	Other
SOMBRERO	31	9	15	34	11
OSIRIS	37	8	9	34	12

Conclusion: Highest leverage is gained through the driver. The cost of the chamber is only of secondary importance with respect to the capital cost.

IFE WILL REQUIRE TARGET DEVELOPMENT

- **CURRENT ICF TARGETS COST ~$500-$2500 EACH DUE TO:**
  - Few-of-a-kind designs — constantly changing
  - Small scale production — batches of ~5-25 targets
  - Extensive characterization — each individual target has a "pedigree"



- **IFE TARGETS MUST COST ≤ 25¢ EACH**

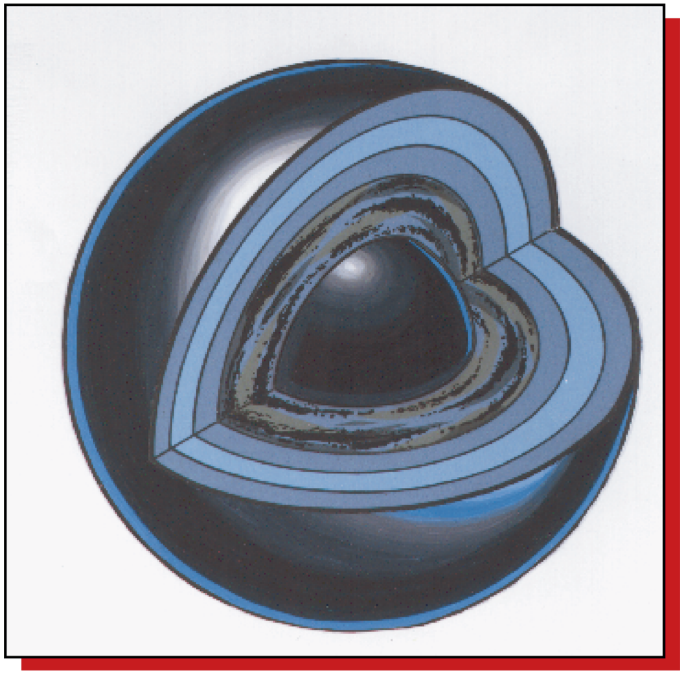
- **WHAT DEVELOPMENT IS NEEDED?**
  - IFE target designs — including fabrication considerations and tolerances
  - IFE-specific target fabrication development — capsules, hohlraums, assembly, fill and layering, characterization

QTYUIOP

10^4 REDUCTION IN HTGR FUEL PRODUCTION COST

- High-temperature gas-cooled reactor (HTGR) fuel has similarity to IFE capsules
  - — Multiple layers of high and low density coatings
  - — Stringent quality requirements
- Over 10^{11} fuel particles have been produced in a small commercial production facility for Fort St. Vrain reactor
- Quality control was carried out by statistical means
  - — Production yield was ~90%
- Cost reduction was ~10^4 due to scale-up
  - — Bench scale 20¢ per particle
  - — FSV was less than 0.2¢ per particle
  - — Projected commercial 0.002¢ per particle

500-1000 μm

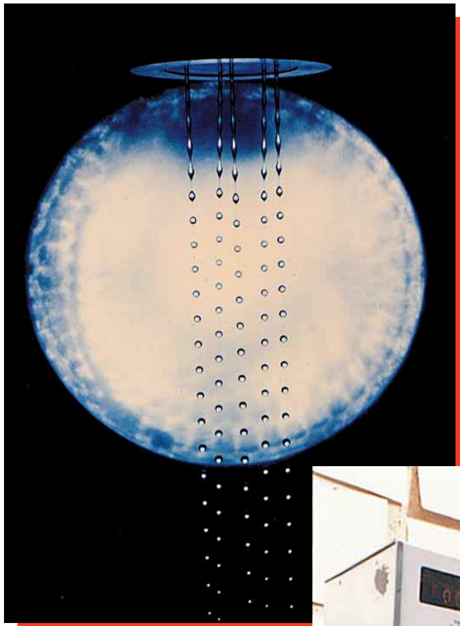


HTGR fuel particle with
4 different coating layers

. . . Indicates that low cost IFE targets are not out of reach, but greater precision will be required

HTGR FUEL FABRICATION USED TECHNOLOGIES THAT CAN BE ADAPTED TO IFE TARGET PRODUCTION

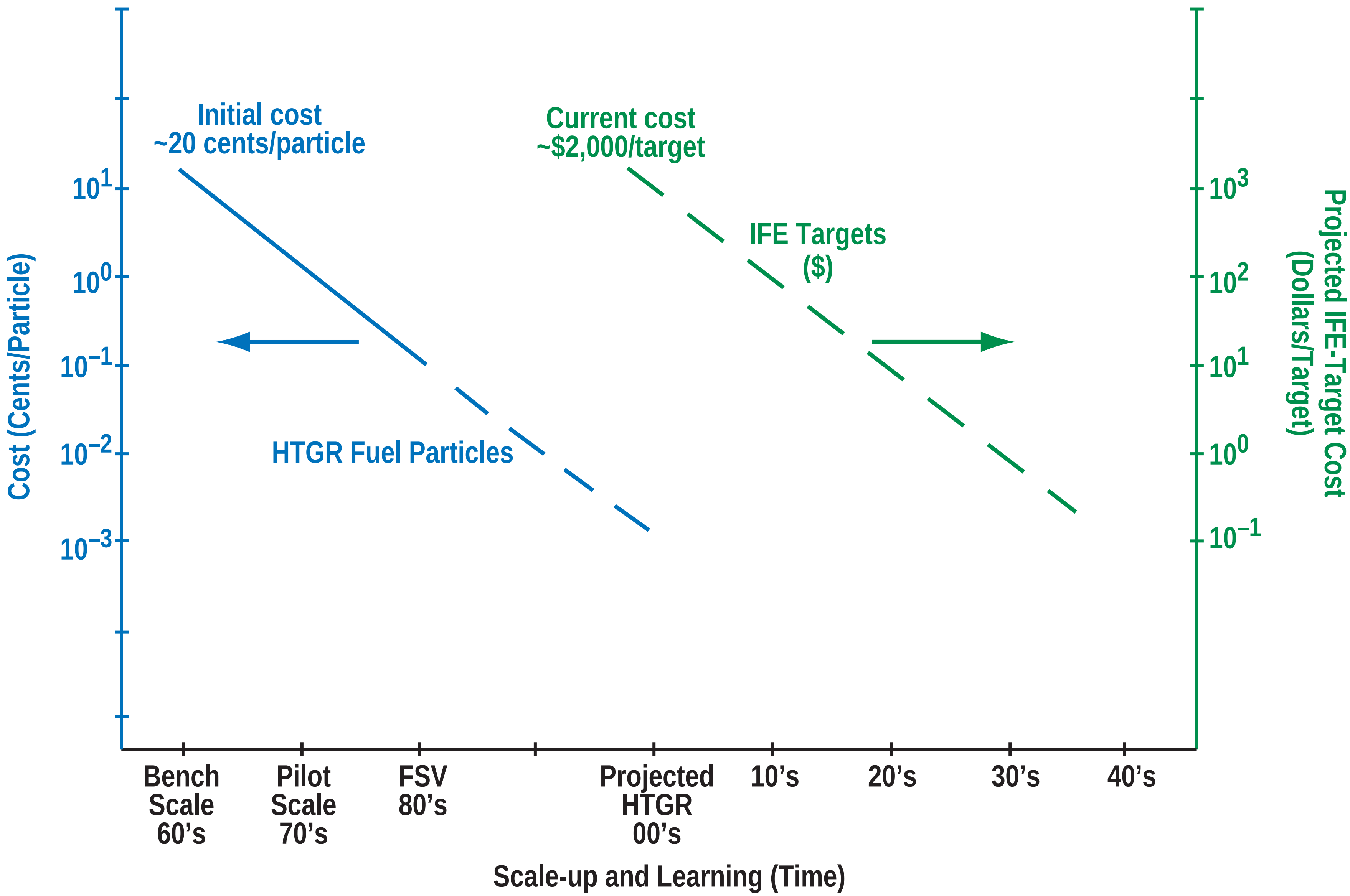
- HTGR and ICF sphere forming technologies have similarities
- HTGR coating technologies may be adaptable to IFE needs
- Filling and DT layering is unique to ICF
- High-volume handling sorting, and quality control technologies may be adapted from industrial practices (semiconductors)



Droplet Generator

Process Control

COST REDUCTION OF HTGR FUEL PARTICLES WAS SIGNIFICANT

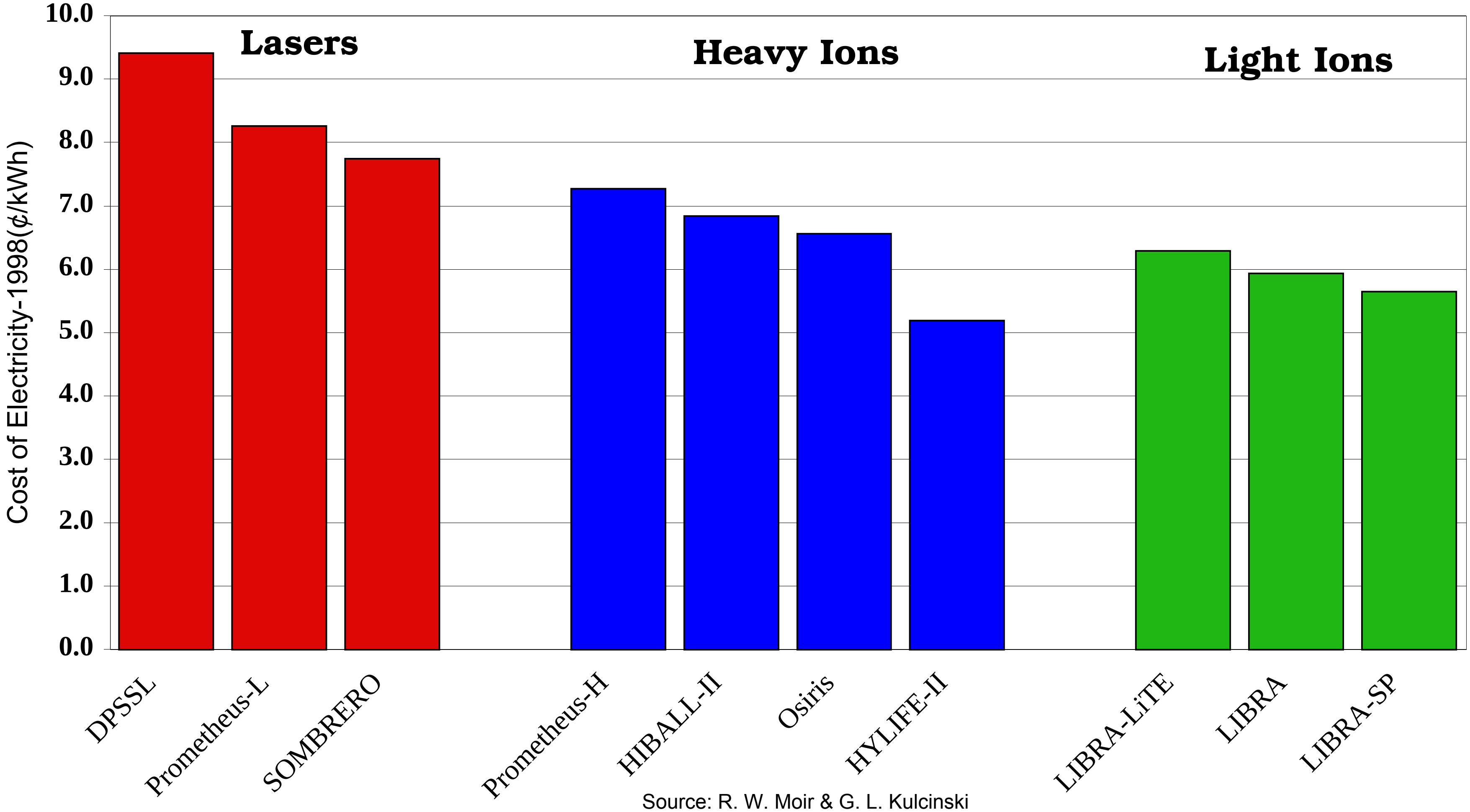


GENERAL ATOMICS

079-99/rs

• **Past IFE Power Plant Studies Have Shown That The Predicted Cost of Electricity Can Be Reduced**

• **New IFE Designs Need to Incorporate the Progress of the Past Decade**



Source: R. W. Moir & G. L. Kulcinski

IFE can be an attractive future energy source if it meets a number of criteria

- Target gain and driver efficiency high enough for <30% of power recirculated to driver (ηG >7) [CoE increases 20% at $\eta G = 5$].

- Low cost driver: <$1 B total capital cost [CoE increases 20% at $2 B].

- Low cost targets: <30 cents/target [CoE increases 20% at $1 .1/target].

- Lifetimes for driver, chamber, final optics allowing >80% plant availability.

- Radioactivity low enough to avoid need for public evacuation plans (<1 REM site boundary dose in worst-case accidents), to avoid active safety systems, and to avoid high-level waste disposal (achieve Class C or better).

- Affordable development-driver test prototype <$150 M hardware and ability to test fusion chambers at reduced scale(<1 m radius).

Phase-I R&D addresses critical issues for chamber and target technologies

Issue	Phase I Goals	Power Plant
High rep-rate chamber	Demonstrate drop clearing with1/4 scale single water jet, use models to determine clearing rate Test of liquid vaporization and condensation (100 kJ of x-ray on Z allows 0.1 scale)	5-10 Hz
First wall protection	Conduct scaled tests of oscillating liquid jets Validate fireball models and establish credibility of gas protection	Ablation of first wall materials prevented
Chamber neutron damage life	Use existing data and modeling to select best candidate materials	Life > few years
Optics survival	Estimate fused silica life using irradiated samples and modeling Determine viability of grazing incidence metal and liquid metal mirrors	Life > 1 year
Target production	Fabricate a few prototype target components Explore/test individual production steps Identify scalable, low cost production methods	I-2 x 10^8 per year < 30 cents/target
Target injection	Test room-temp surrogate targets at few Hz	5-10 Hz with cryo targets
Radioactive waste	Determine acceptable materials Develop recycling scenarios	Meet Class-C classification
Safety	Gather data on release fractions of critical isotopes and conduct safety analyses Designs for cl rem dose at site boundary	No evacuation plan .

IFE Power Plants Can Present Favorable Environmental, Safety, and Economic Features to Future Generations

- Engineers and scientists have used a great deal of innovation (in the limited number of IFE conceptual designs done to date) to solve the technical problems confronting them.

- It is too soon to decide on the final IFE driver/target/chamber configuration for power plants.

- There is a need to conduct small scale tests of the more promising IFE technologies such as liquid metal walls, final focusing mirrors & magnets, and chamber clearing concepts.