Drivers for IFE

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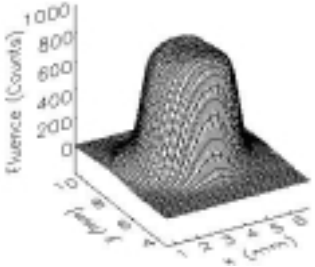
The driver working group includes four subgroups

Subgroup	Driver	Primary Target Type	Other Target Types
D1	Lasers: KrF & DPSSL	Direct Drive (DD)	ID, FI
D2	Heavy Ion Accelerator	Indirect Drive (ID)	DD, FI
D3	Z-Pinch	Indirect Drive (ID)	FI
D4	Drivers for Fast Ignition	Fast Ignition (FI)	

KrF Lasers

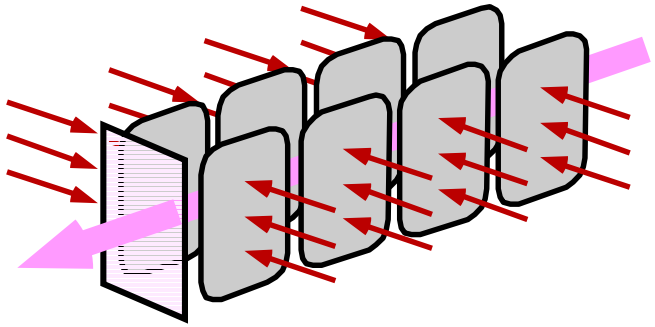
Why we like KrF lasers

1. Demonstrated outstanding spatial uniformity minimizes hydrodynamic instabilities



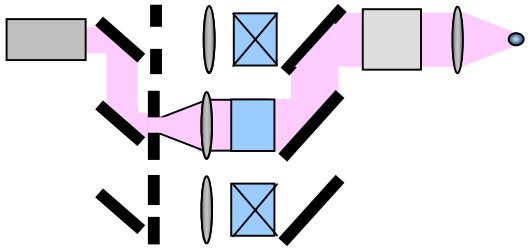
2. Shortest wavelength (1/4 μm) maximizes absorption and rocket efficiencies, minimizes risk from laser plasma instabilities

3. Electron beam pumped architecture scalable to large systems



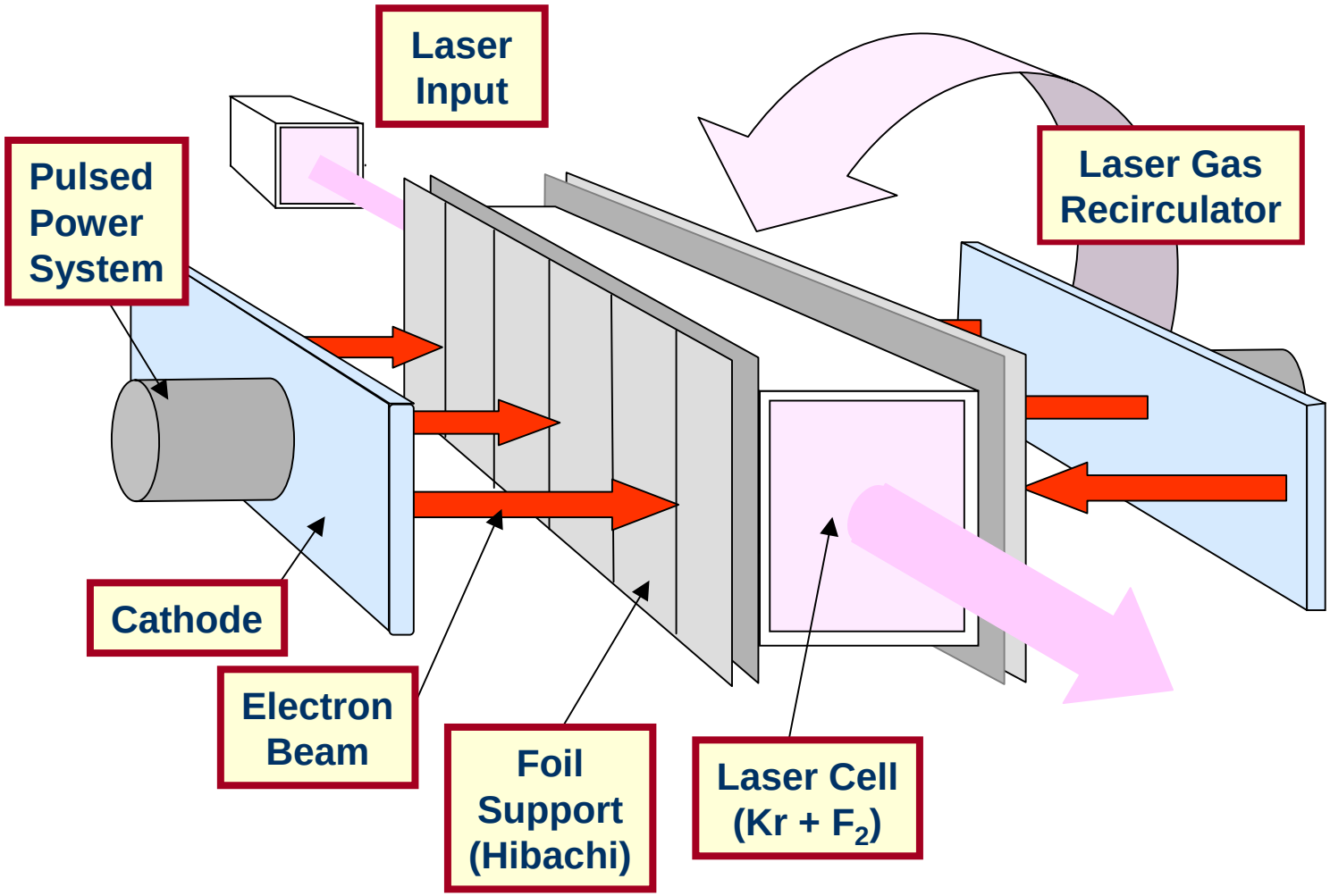
4. Low cost (pulsed power is cheap!)

5. Pulse shaping & zooming achieved at low energy in front end "seed" amplifier



6. Modular nature lowers development costs

The key components of a Krypton Fluoride (KrF) Laser



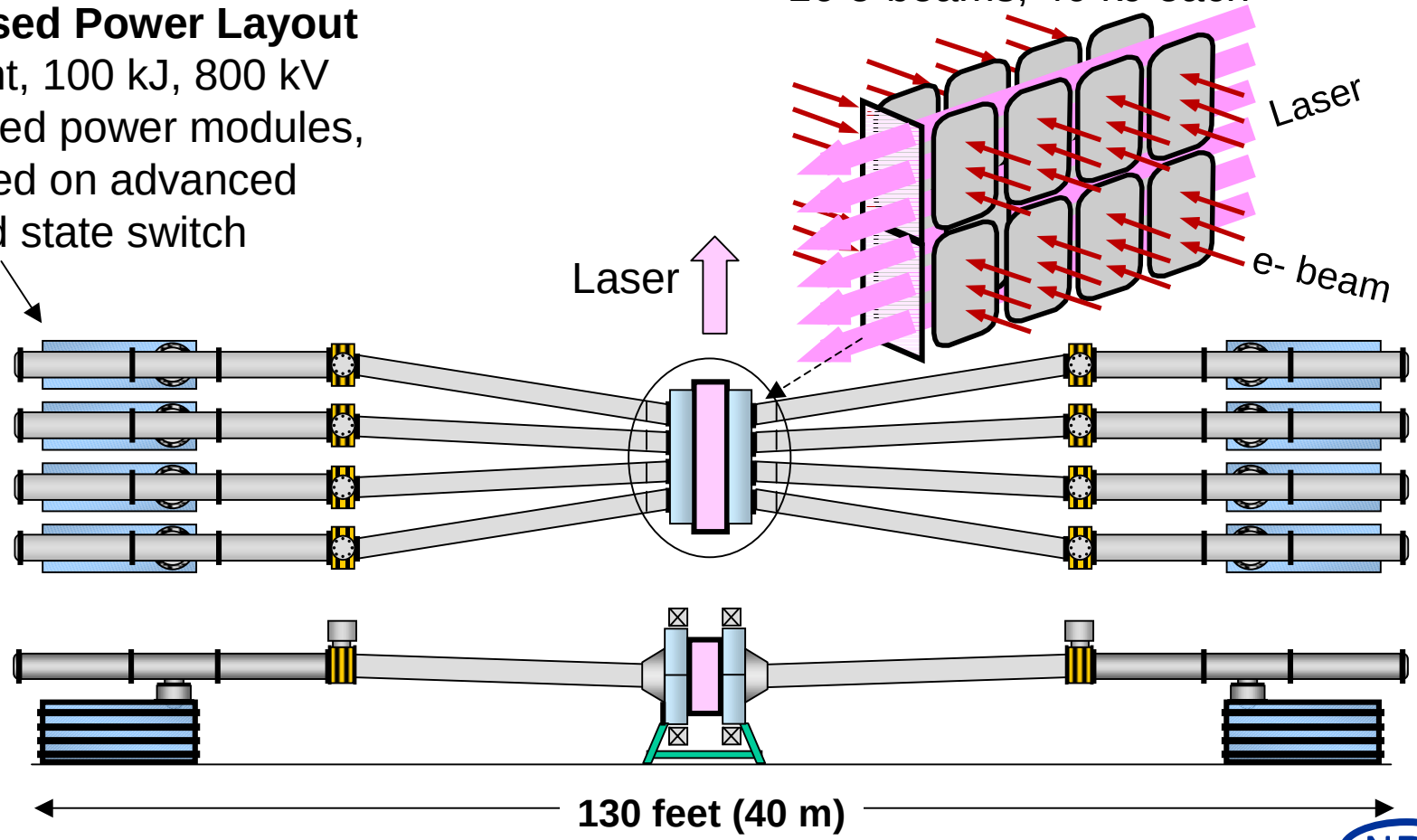
$$\text{ENERGY} + (Kr + F_2) \Rightarrow (KrF)^* + F \Rightarrow (Kr + F_2) + h\nu\ (248\ \text{nm})$$

A KrF Laser IFE Driver would consist of an array of identical beam lines
Example: 40 beam lines, each with 60 kJ output
(Total Laser Energy = 2.4 MJ)

60 kJ KrF Laser Amplifier

Pulsed Power Layout
Eight, 100 kJ, 800 kV pulsed power modules, based on advanced solid state switch

Laser Cell / e-beam diode layout
16 e-beams, 40 kJ each

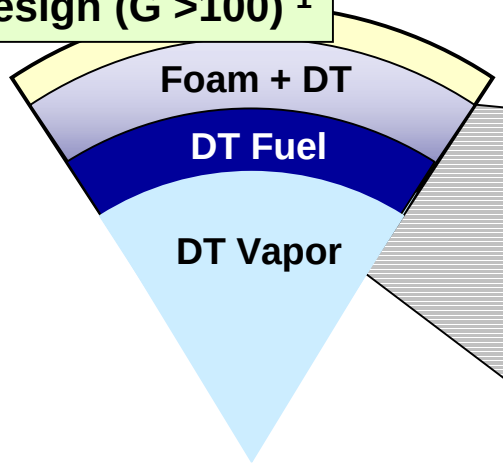


Optimal Laser Architecture to be determined by systems studies

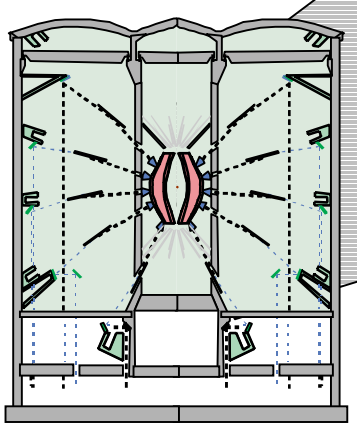
800 kJ x 80% (e-beam flat top energy/stored energy) x 80% (hibachi transmission) x 12% (KrF efficiency) = 62 kJ

Target gain and power plant studies define the laser requirements and key issues and challenges

High Gain Target Design (G >100) [1]



Power Plant Study [2]



Laser IFE Requirements

	IFE	NIKE
Beam quality (high mode)	0.2%	0.2%
Beam quality (low mode)	2%	N/A(4)
Optical bandwidth	1-2 THz	3 THz
Beam Power Balance	2%	N/A(4)
Rep-Rate	5 Hz	.0005
Laser Energy (amplifier)	30-150 kJ	5 kJ
Cost of pulsed power(1)	$5-10/J(e-beam)	N/A3
Cost of entire laser(1)	$225/J(laser)	$3600/J
System efficiency	6-7%	1.4%
Durability (shots) (2)	3×10^8	20
Lifetime (shots)	10^{10}	10^4

Easy

Hard

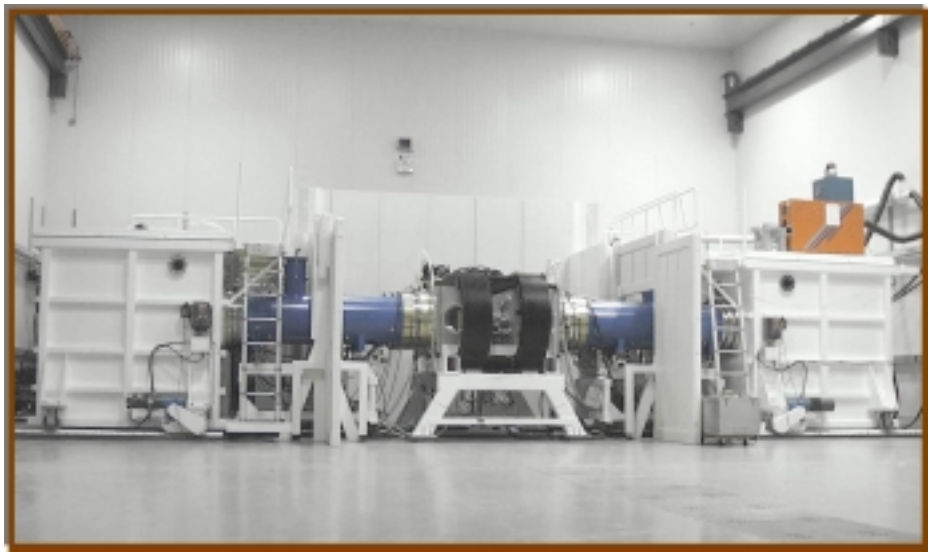
1. 1999 $. Sombrero (1992) gave $180/J and $4.00/J
2. Shots between major maintenance (2.0 years)
3. Not Applicable: Different technology
4. Not Applicable: Nike shoots planar targets

1. 1-D gain. S.E. Bodner et al, .“Direct drive laser fusion; status and prospects”, *Physics of Plasmas* **5,** 1901, (1998).
2. Sombrero: 1000 MWe, 3.4 MJ Laser, Gain 110; Cost of Electricity: $0.04-$0.08/kWh; Fusion Technology, **21**,1470, (1992)

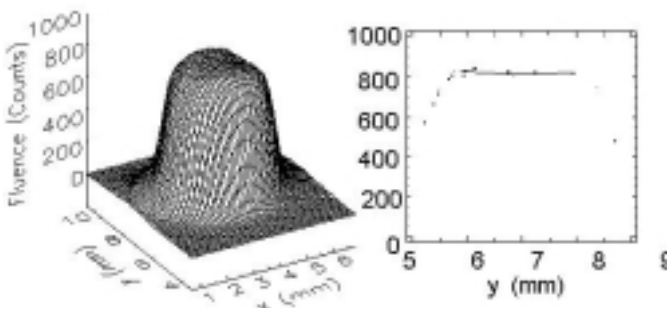
The key issues for KrF are being addressed with the Electra and Nike Lasers at NRL

Electra: 700 J, 30 x 30 cm aperture, 5 Hz
Develop technologies for Rep-Rate, Durability, Efficiency, and Cost

(Build laser by integrating each component as it is developed)



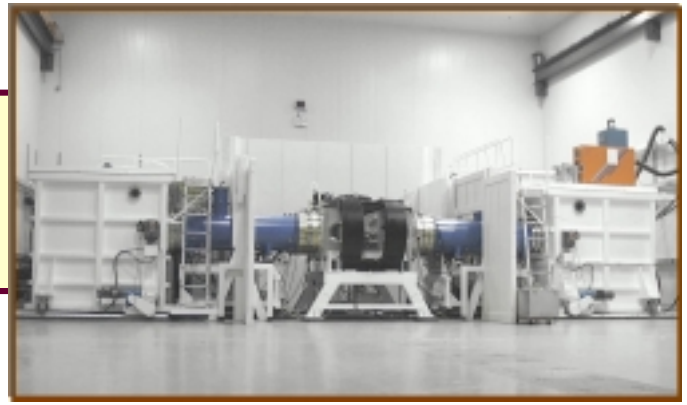
Nike: 2-3 kJ, 100 x 100 cm, single shot
Electron beam physics on near full scale diode



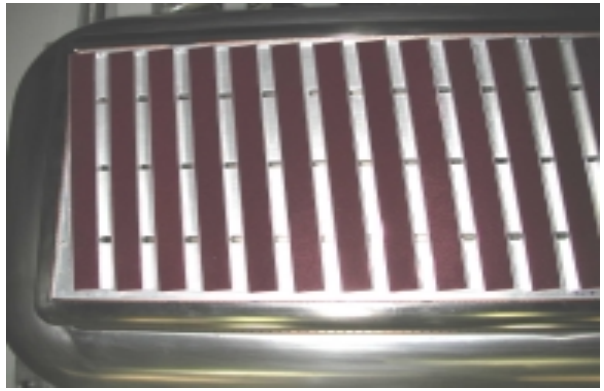
Demonstrated outstanding beam uniformity:
1.2% spatial non-uniformity per beam
0.3% non-uniformity, overlapped beams

Progress in KrF Laser Development

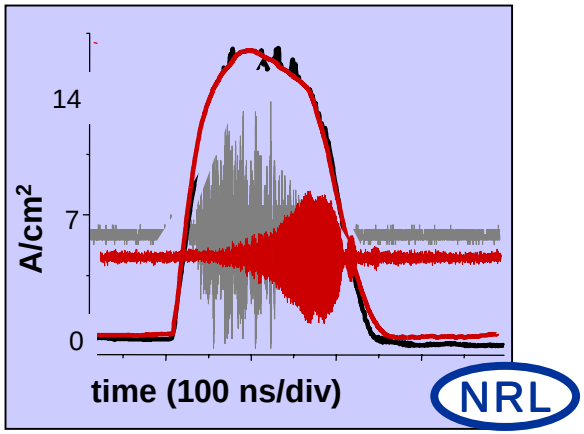
Built Electra First Generation Pulsed Power System: 500 keV, 100 kA, 100 nsec @ 5 Hz for 5 hours. Excellent platform to develop laser components



Demonstrated on Electra beam can be patterned to "miss" hibachi ribs—increase efficiency

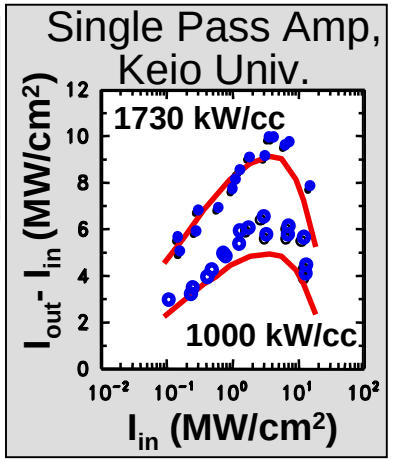


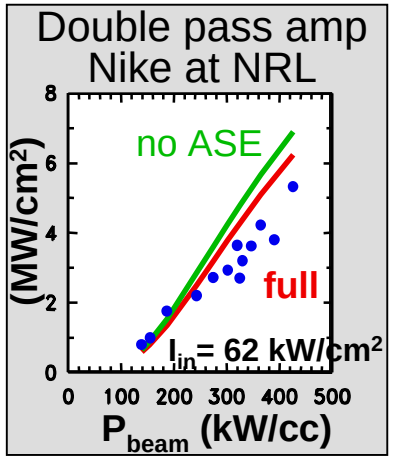
Used 3-D simulations plus Nike experiments to identify and mitigate "transit time" instability in large area diodes. Enhances efficiency



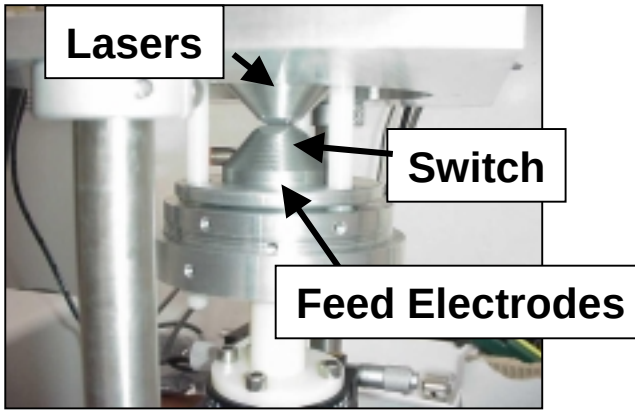
Progress in KrF Laser Development – Continued

Developed "Oresetes" KrF Kinetics model
Accurately predicts wide range of KrF lasers.
Now used as design tool for future systems.

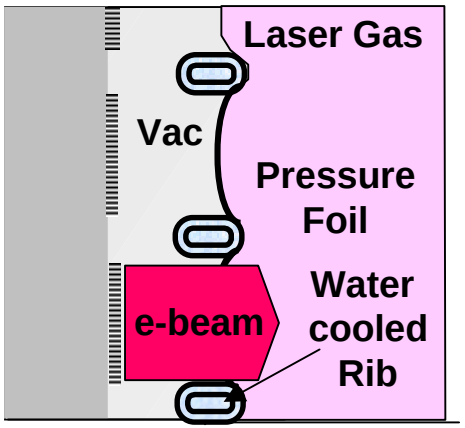




Demonstrated prototype solid state laser switch.
Will be basis for IFE pulsed power system.



Hibachi: Evaluating concept to deflect laser gas to cool foil.



KrF R&D will follow our program to develop Laser Fusion Energy

NRL

Phase III
Engineering Test Facility ETF
start ~2014, operating 2020

- ***2-3 MJ, 60 laser beam lines***
- High gain target implosions
- Optimize chamber materials & components.
- Generate ~ 300 MW electricity from fusion

?

Establish: Target physics, Full scale Laser technology, Power Plant design

Phase II
Integrated Research Expt (IRE)
start ~2005

- ***Laser facility*** **– 5 Hz full energy beam line, hits injected targets**
- ***Target facility-*** inject Cryo pellets into chamber environment
- ***Power Plant Design***

NIF Experiments
- Target Physics
- Implosions

?

Develop Viable: Target designs, scalable laser tech, target fab/ injection, final optics, chamber

Phase I:
Mission Oriented R&D
2001

We are here

Lasers
- ***Electra KrF***
- Mercury DPPSL

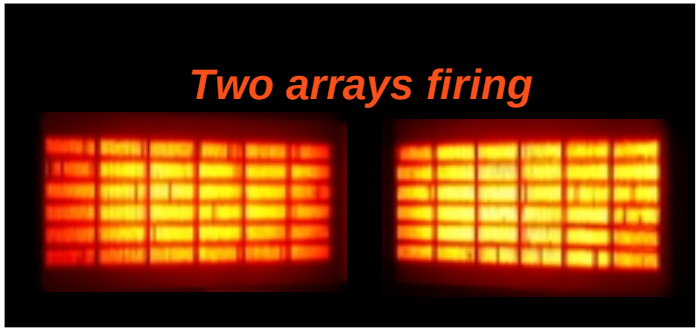
Other Components
- target fabrication
- target injection
- final optics
- chamber & materials

Target Design
- Modeling
- Laser/Target Expts @1-30 kJ

Diode-Pumped Solid-State Lasers (DPSSL)

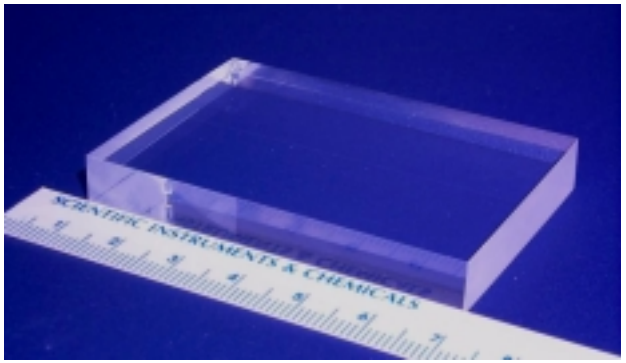
We are deploying advanced technologies in Mercury

Laser diodes



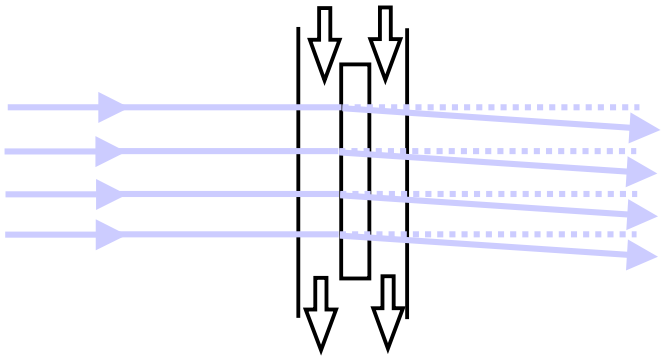
High efficiency and long lifetime

Yb:S-FAP crystals



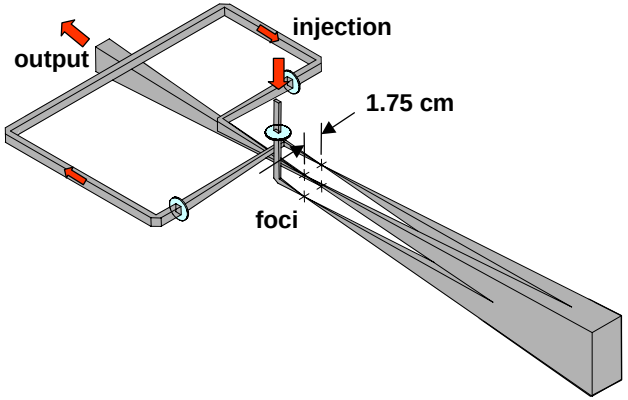
Large energy storage and thermal conductivity

Gas-cooling



Longitudinal heat removal allows 10-Hz operation

Architecture



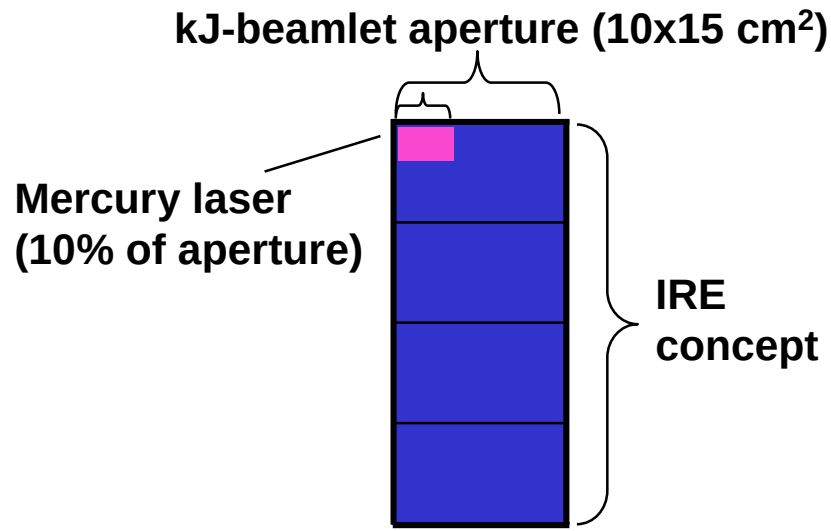
Angular multiplexing for a compact multi-pass architecture

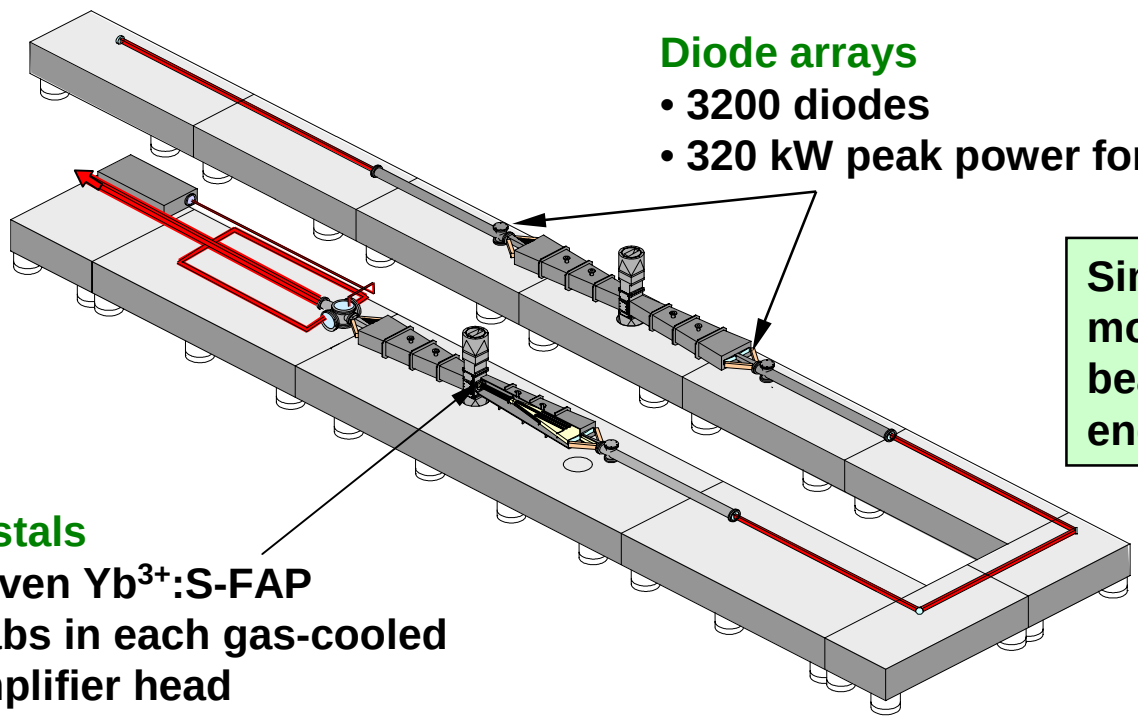
Attributes and progress for solid state lasers

Attributes and Progress	***Comments***
➢ **Optical architecture**	**Uses relay imaging like NIF, adapted to minimize modulation in gain slabs and with a reverser**
➢ **Yb:S-FAP crystal slabs**	**Producing adequate size for Mercury, further scale-up needed for IRE and IFE driver**
➢ **Diode pump source**	**Fabricated largest arrays in the world for Mercury, pathway defined for IRE, IFE needs cost reduction**
➢ **>10% efficiency**	**Achievable with attention to laser components**
➢ **Pulse shaping and beam smoothing**	**Front-end pre-compensates for amplifier distortions**
➢ **>10^9 shot reliability**	**Diode reliability demonstrated at small scale, will test system-level performance with Mercury laser**
➢ **Scalability**	**Nearly all physics parameters same as Mercury, ASE will need to be managed in full-size aperture**

Mercury is a 1/10 aperture diode-pumped gas-cooled crystalline laser for IFE

Energy:	100 J
Reliability:	> 10^8 shots
Pulse length:	2-10 ns
Efficiency:	10 %
Rep rate:	10 Hz
Beam quality:	< 5x diff. limit
Scalability:	Scales to > kJ aperture



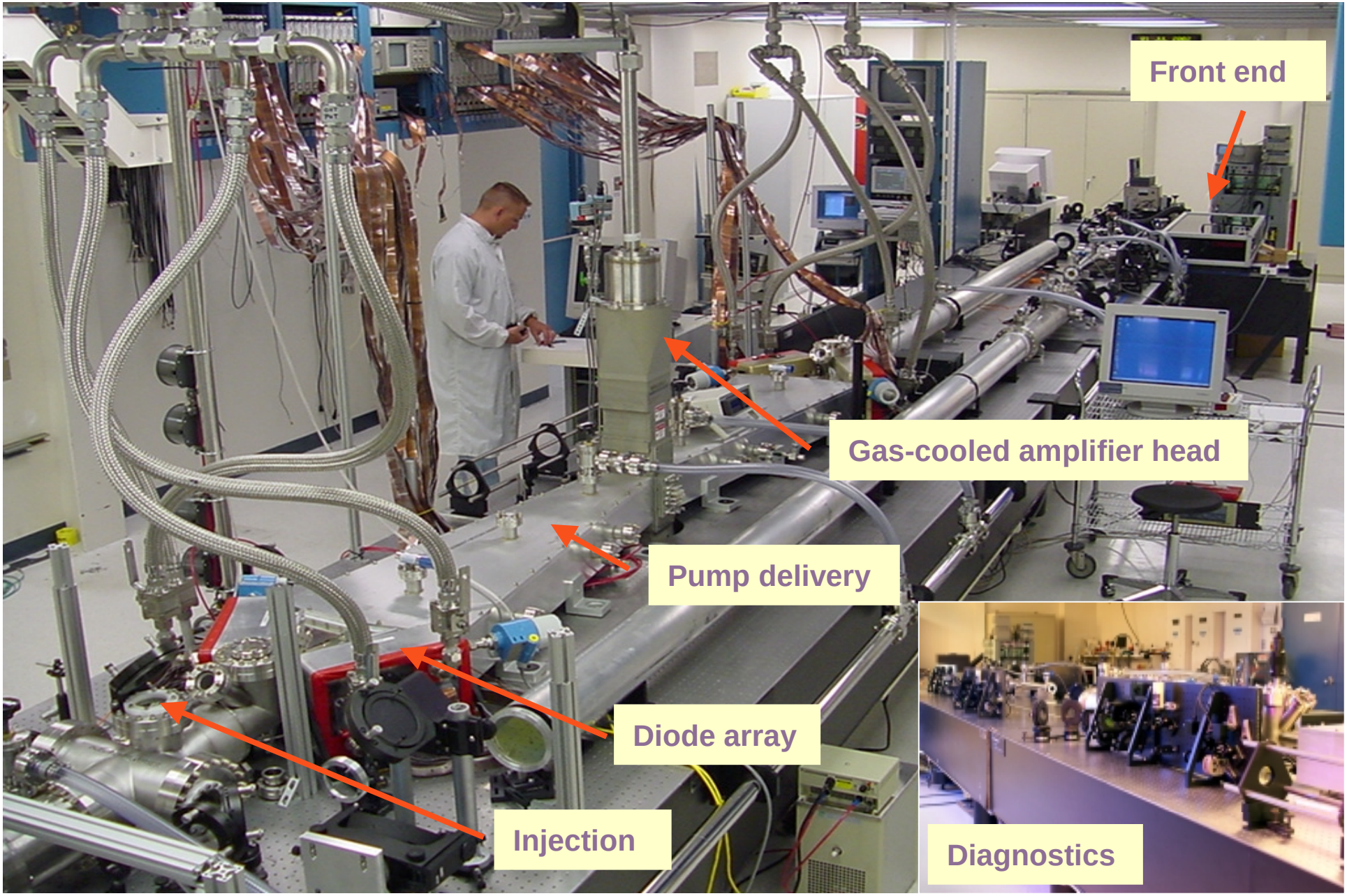


Diode arrays
- 3200 diodes
- 320 kW peak power for each amplifier

Crystals
- Seven Yb^{3+}:S-FAP slabs in each gas-cooled amplifier head

Similar laser parameters and modularity assure that sub-scale beamlines address physics and engineering issues of IRE

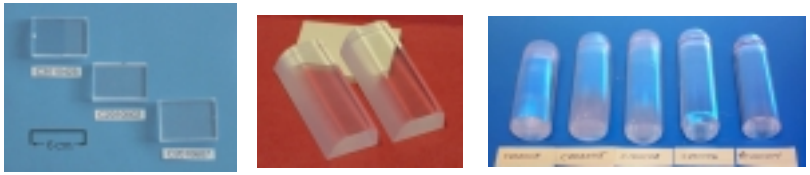
We have conducted experiments on the Mercury laser



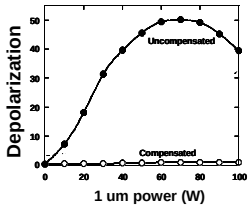
Summary of results

- Four 80 kW diode backplanes completed, +50 tiles towards four more

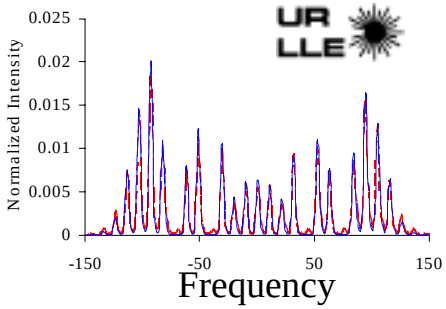
- 5 Yb:S-FAP slabs fabricated, 3 in the que, boules for 5 more slabs



- Half aperture Pockels cell assembled and tested up to 100 W average power



- Spectral sculpting demonstrated for broadband operation and SSD

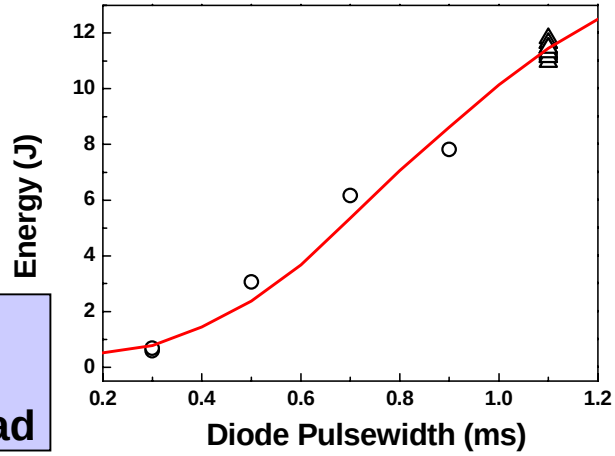


- Control system activated and diode pulsars functional

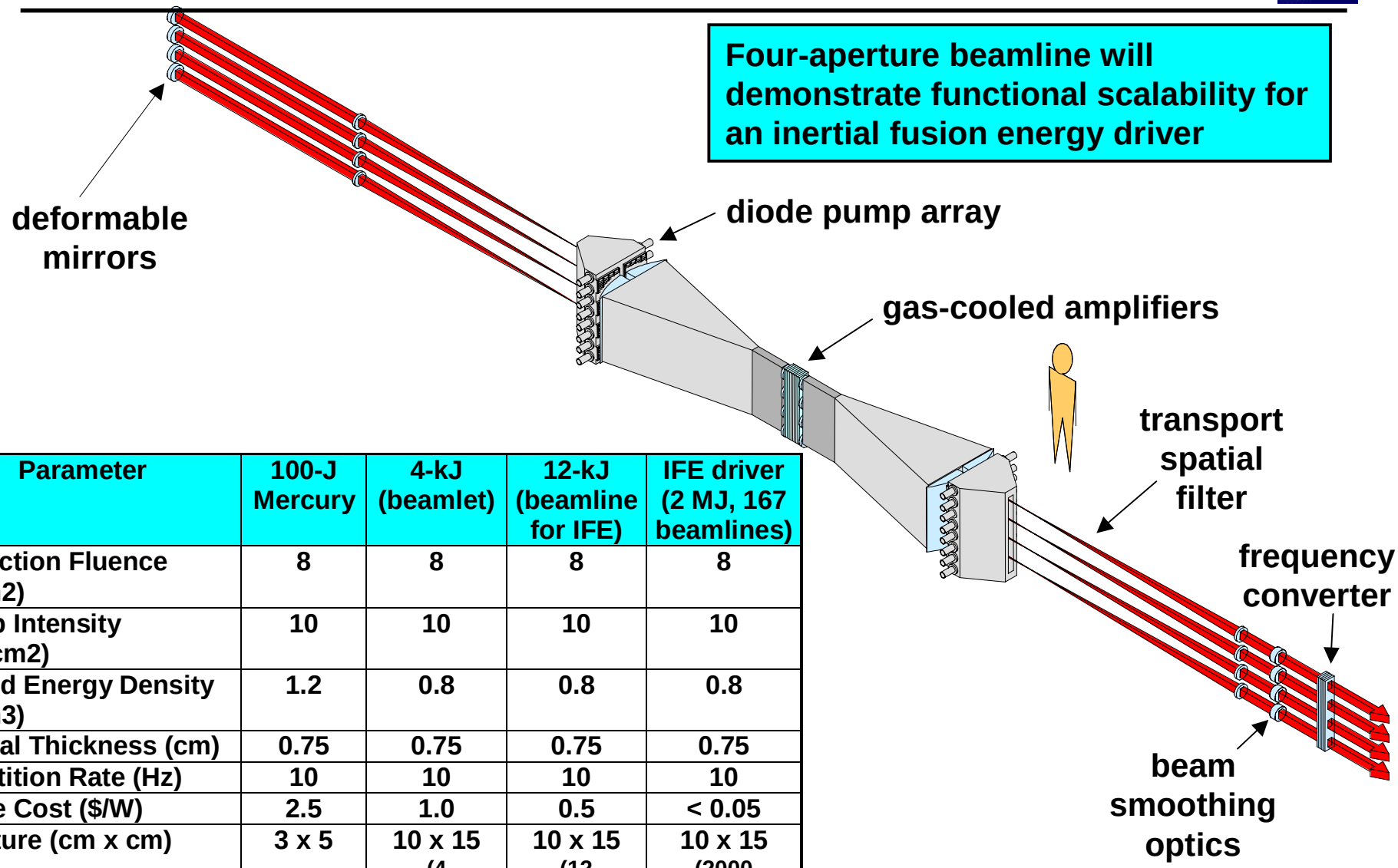
- System aligned and monitored using beam diagnostic packages

- Energy and gain experiments performed with 4 Yb:S-FAP slabs in one amplifier

First integrated operation of the 4-pass amplifier head

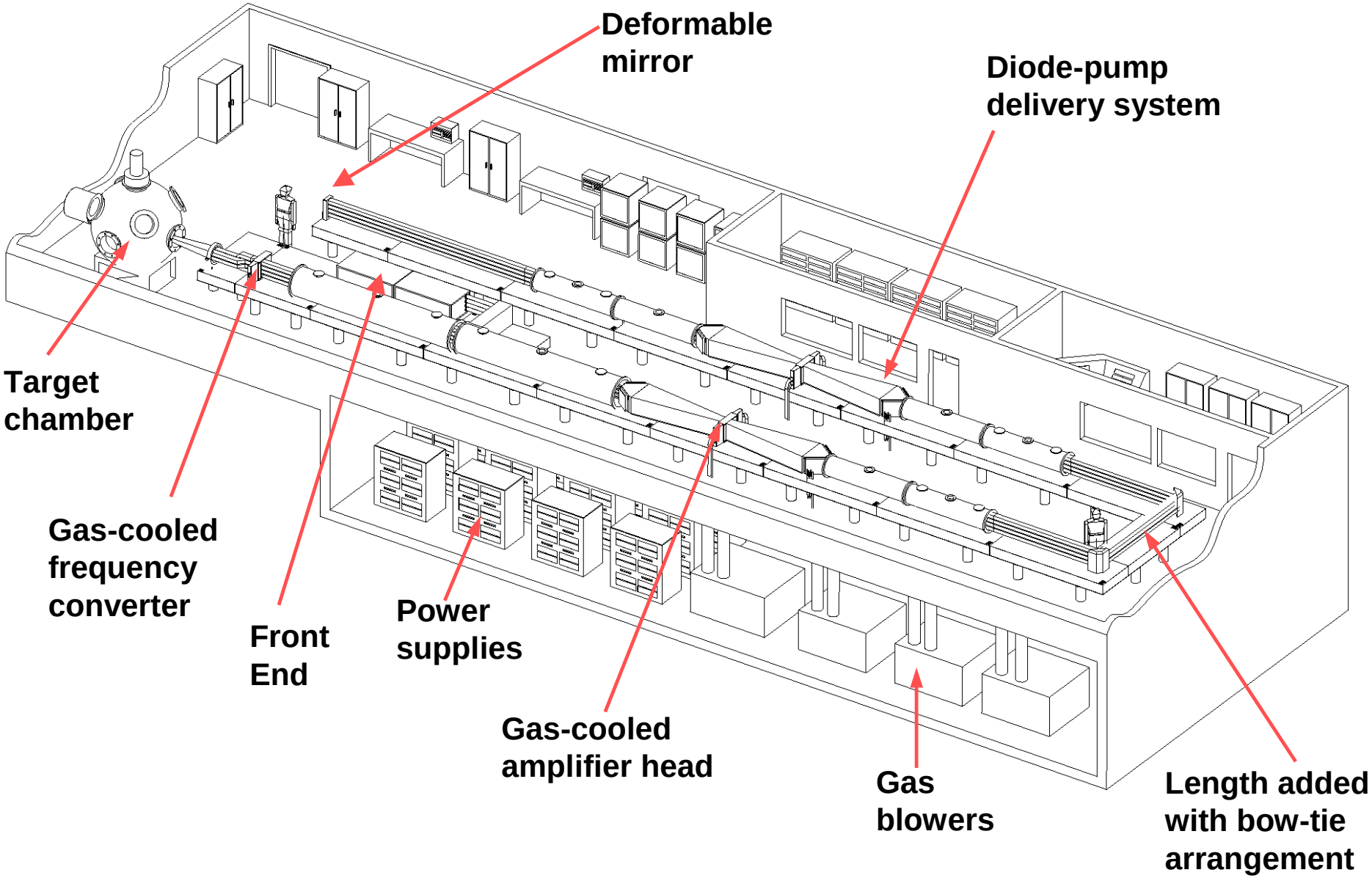


IRE laser is envisioned as a 4x1 beam bundle (>4 kJ) which will demonstrate functional scalability for an IFE driver



Parameter	100-J Mercury	4-kJ (beamlet)	12-kJ (beamline for IFE)	IFE driver (2 MJ, 167 beamlines)
Extraction Fluence (J/cm2)	8	8	8	8
Pump Intensity (kW/cm2)	10	10	10	10
Stored Energy Density (J/cm3)	1.2	0.8	0.8	0.8
Crystal Thickness (cm)	0.75	0.75	0.75	0.75
Repetition Rate (Hz)	10	10	10	10
Diode Cost ($/W)	2.5	1.0	0.5	< 0.05
Aperture (cm x cm)	3 x 5	10 x 15 (4 segments)	10 x 15 (12 segments)	10 x 15 (2000 segments)
Wall plug efficiency (%)	10 (1ω)	10 (3ω)	>10 (3ω)	>10 (3ω)

The “Venus Laser” IRE will be comprised of four 1-kJ apertures

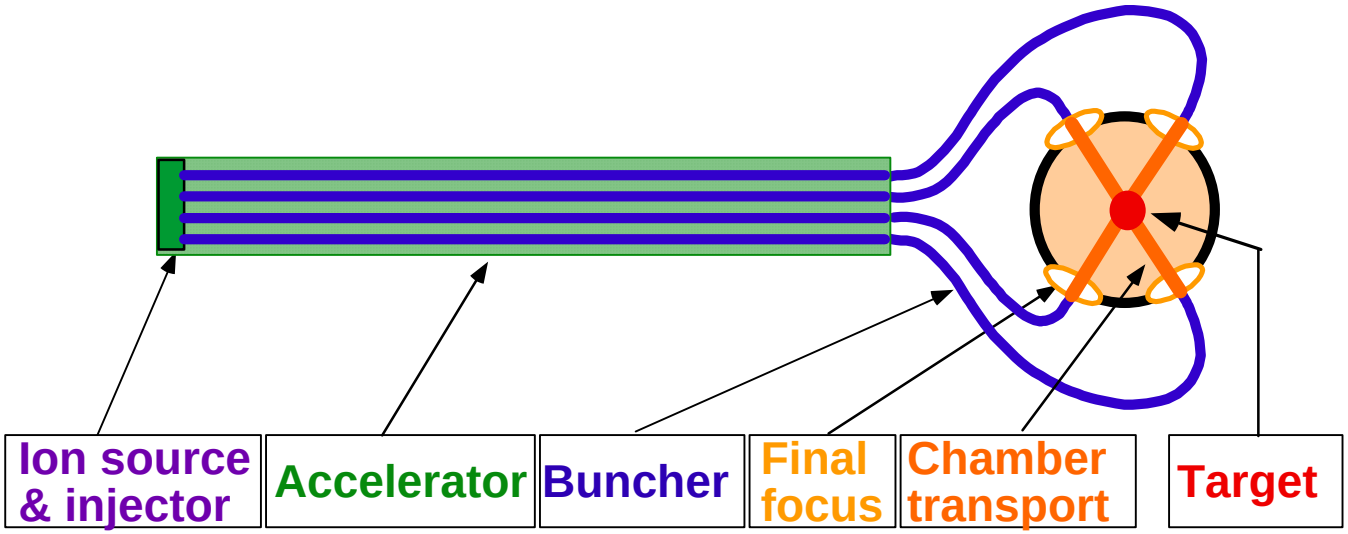


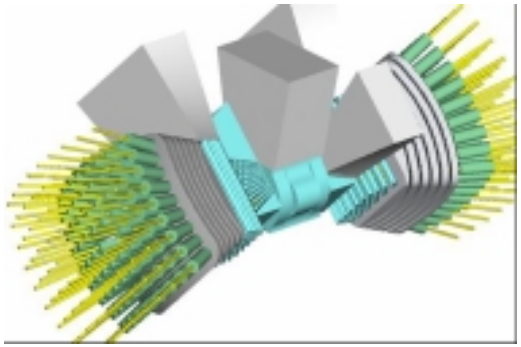
Heavy Ion Accelerators

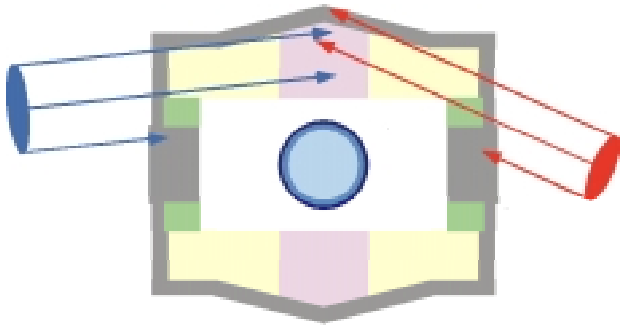
Heavy ion accelerators have many attractive features

- **High energy accelerators with MJ class beam energies exhibit efficiency, pulse rate and durability needed for IFE**
- **Indirect-drive HIF targets benefit in many ways from the large ICF target physics research effort**
- **Thick-liquid protected chambers with potential 30-year lifetimes are compatible with the indirect-drive target illumination geometry**
- **Cryogenic-DT fuel capsules are protected by the surrounding hohlraum when injected into the hot fusion chamber**
- **Clear bore magnets used to focus the beams can tolerate target debris and radiation (no direct line of sight)**

Success of heavy-ion fusion depends on an integrated program to achieve accelerators, chambers and targets that work together







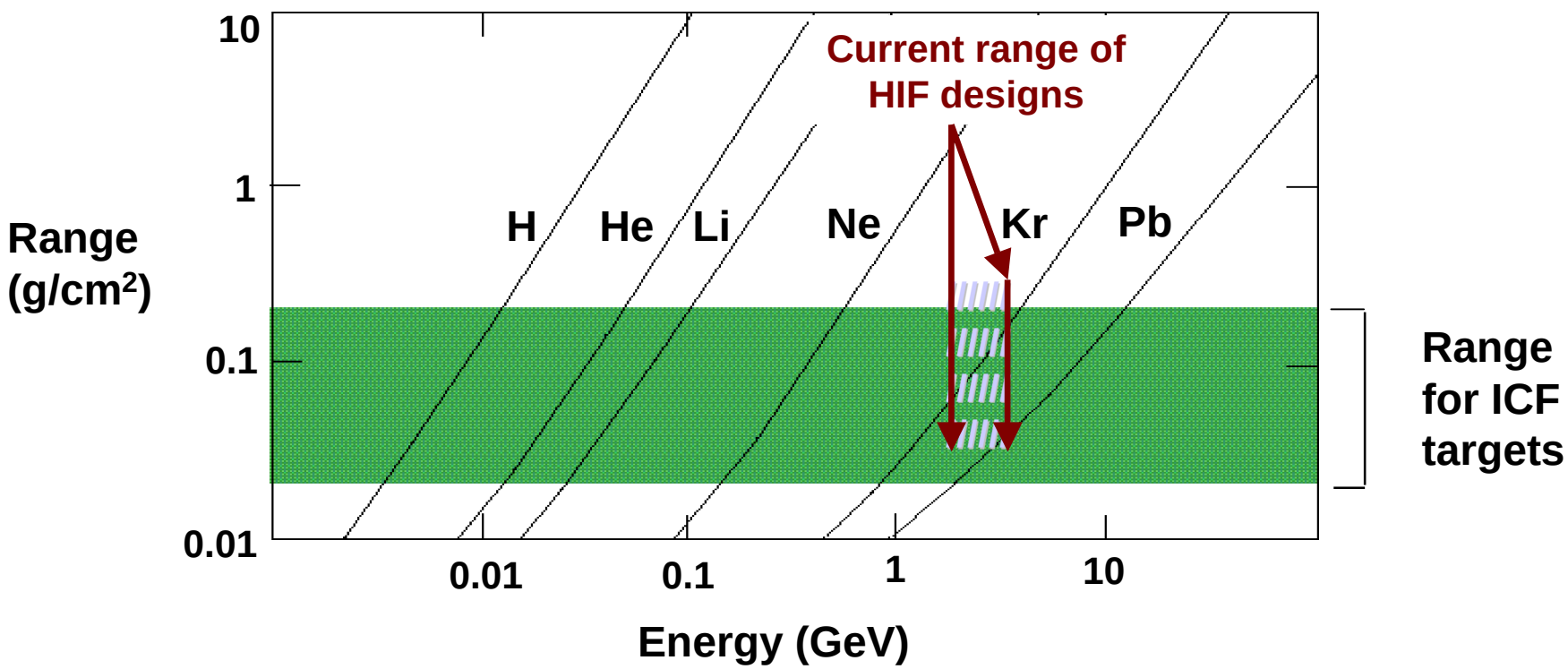
Beams at high current and sufficient brightness to focus

Long lasting, low activation chambers that can withstand 400 MJ fusion pulses @ 6 Hz

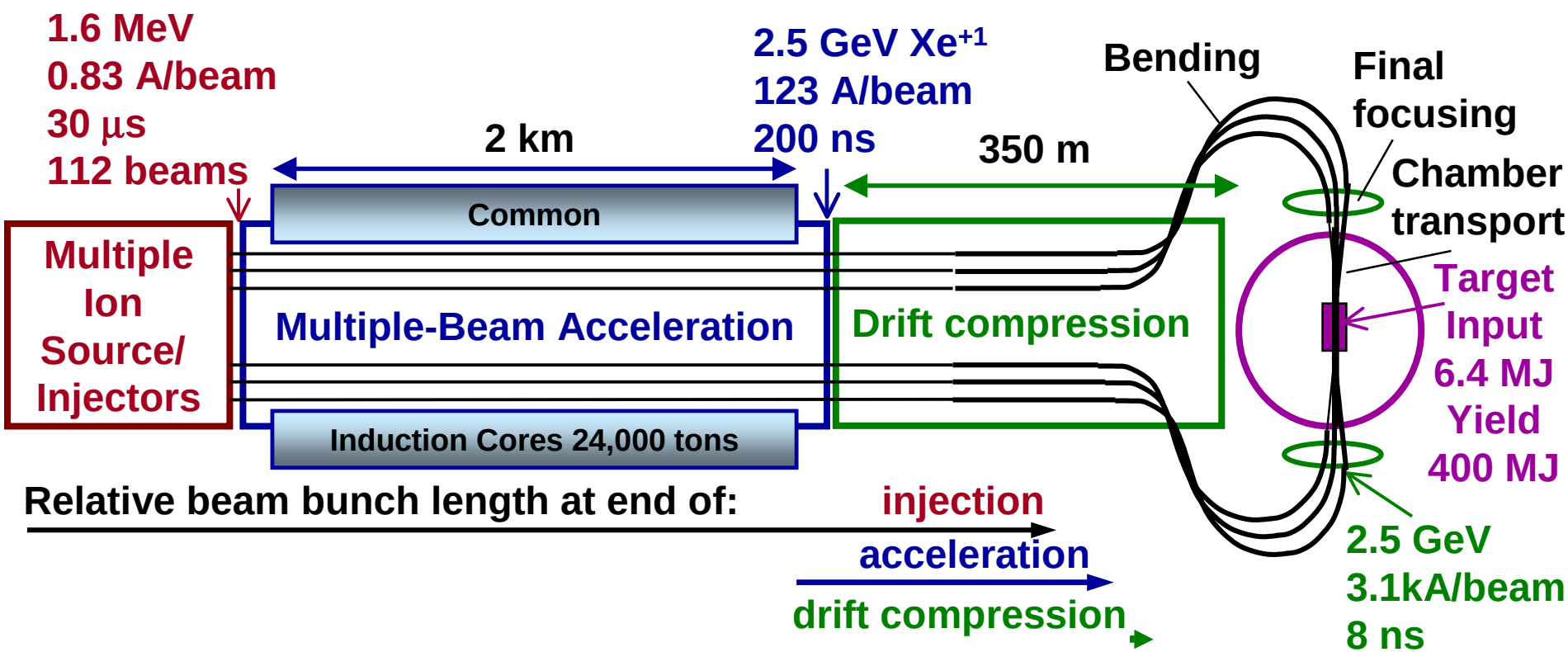
High gain targets that can be produced at low cost and injected

A variety of ions can be used for a HIF driver

- Collective effects are reduced with heaviest ions →more energy/particle →fewer particles (~10^{15} total ions).
- Cost tradeoff with lower mass ions →lower voltage, lower cost accelerators. Compromise with 2.5 GeV Xenon.
- Modern superconducting magnets can adequately confine the beam against its space charge forces during acceleration.



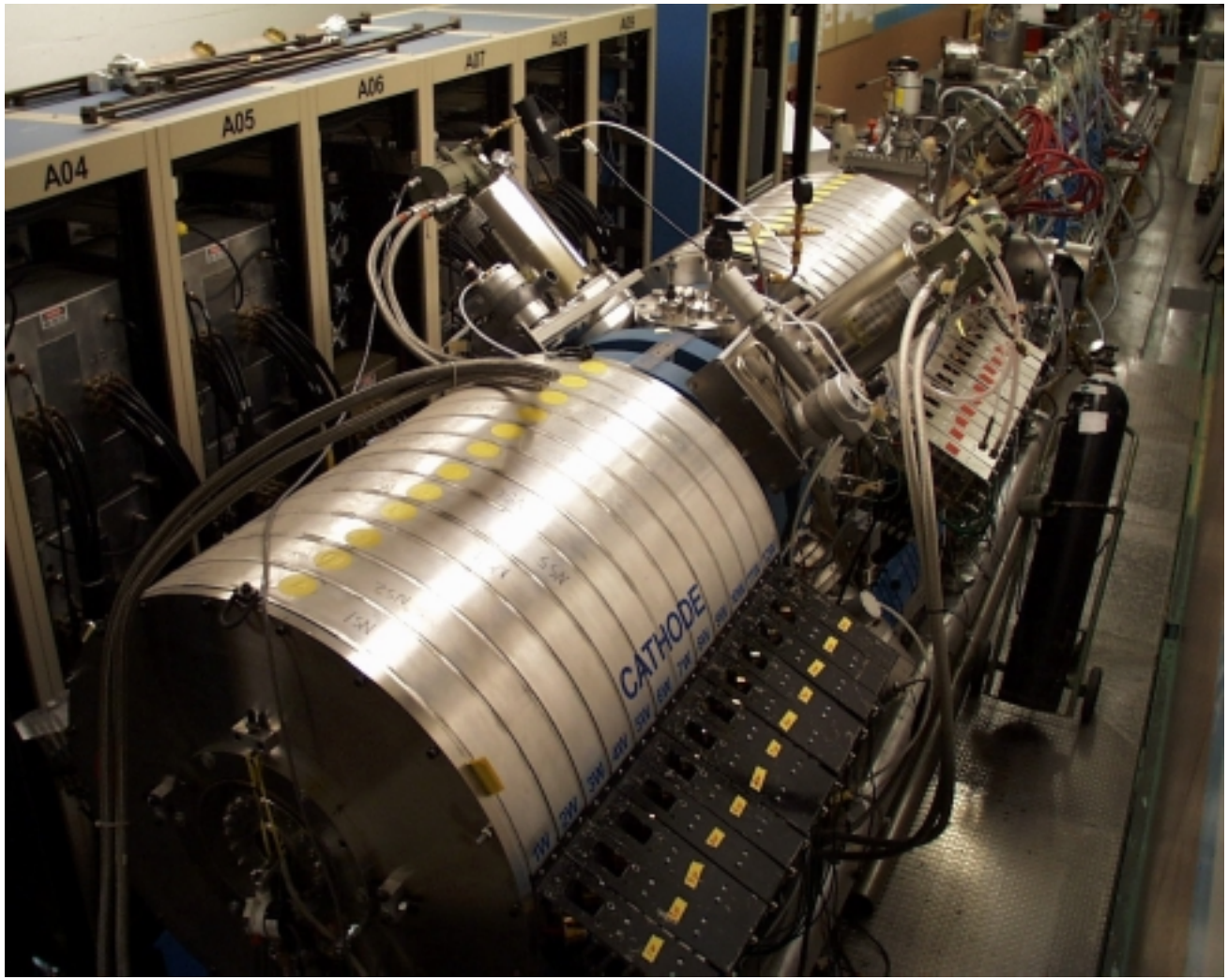
Reference 6.4 MJ, 112-beam, quad-focused driver



Bunch length compression is integral part of HIF concept

Driver efficiency ~ 45% → very low recirculating power fraction

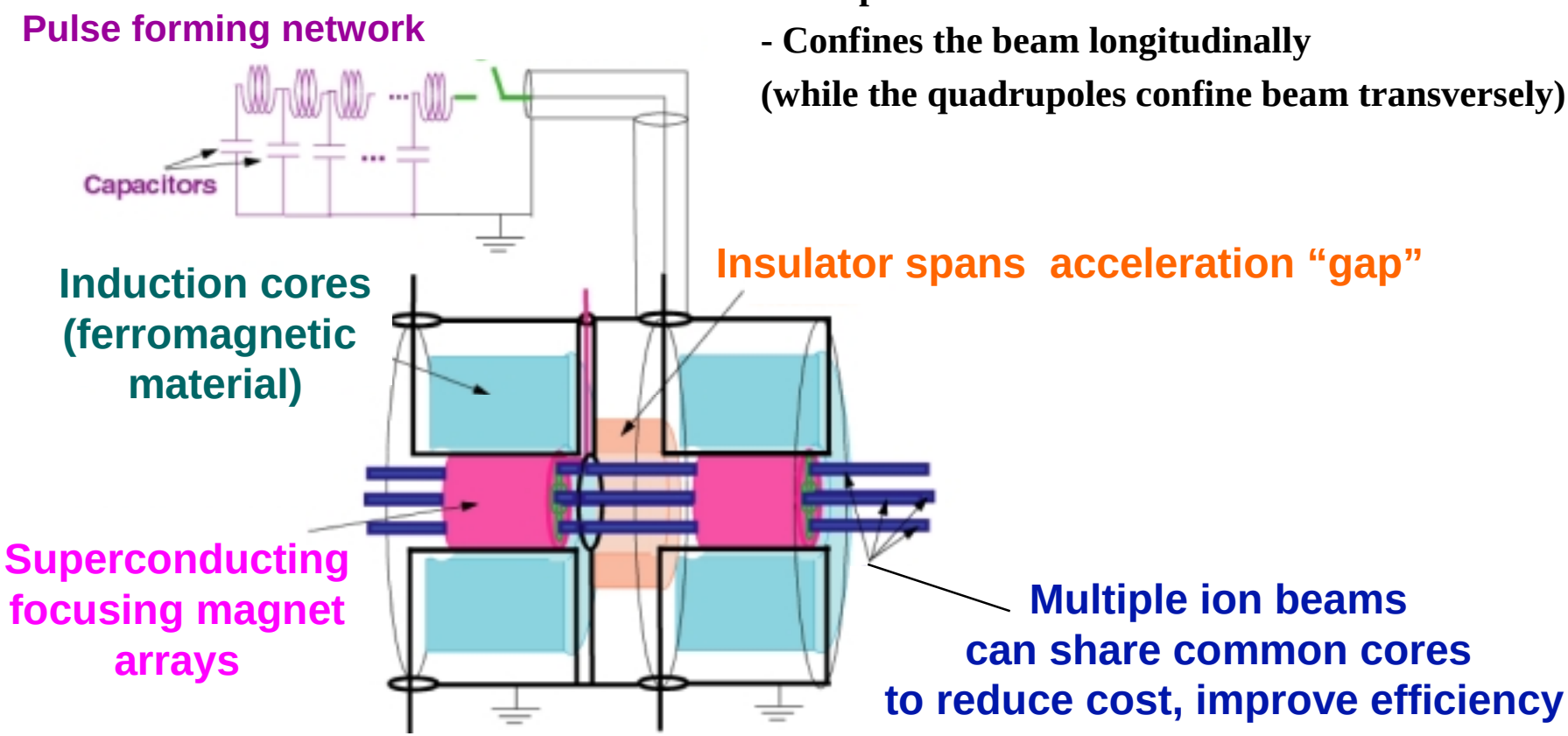
The RTA Injector (1 MeV, 1 KA, 375 ns) is a working example of a short-pulse induction-driven injector



Induction is used to accelerate kA currents of ions by inducing longitudinal electric fields in a sequence of gaps

- The electric field in the gap does three things:
- Accelerates the beam
- Compresses the beam
- Confines the beam longitudinally

(while the quadrupoles confine beam transversely)



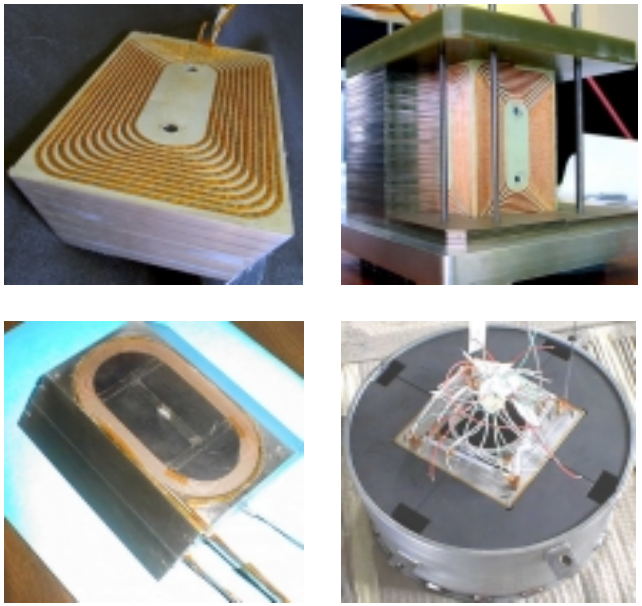
Assembly of 2μsec Induction Accelerator Cell for DARHT

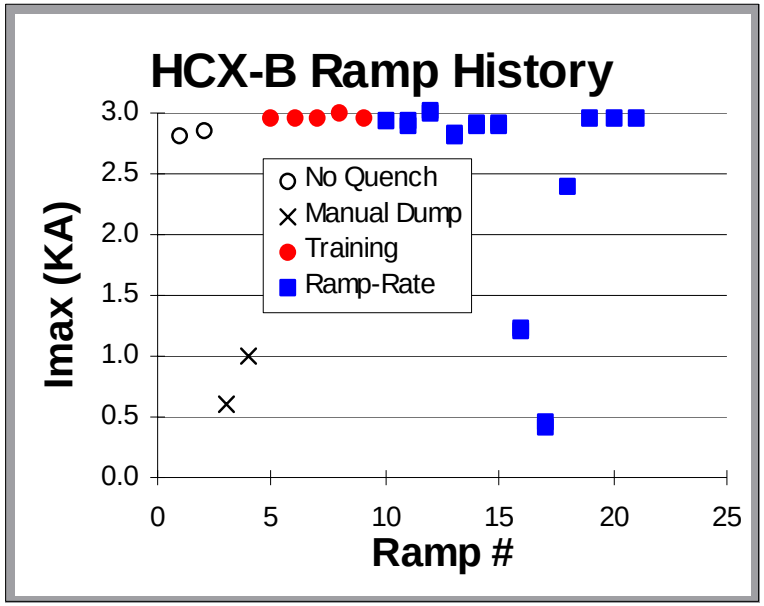
Superconducting magnet development FY01-02

Four prototypes fabricated and tested

AML

LLNL

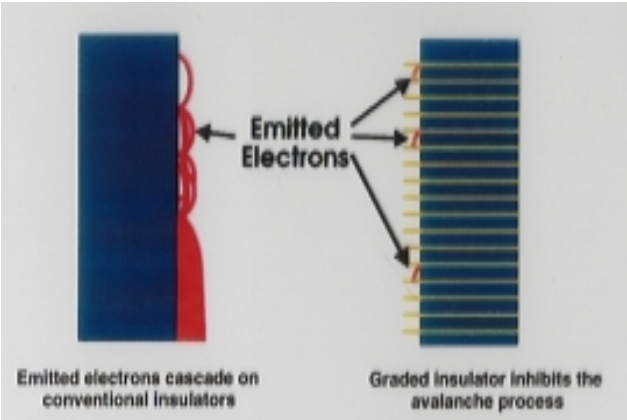




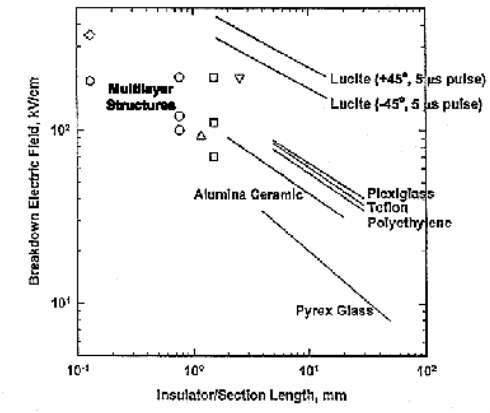
The LLNL design was selected for further development (December 2001)

A cryostat housing two quads, and one optimized prototype magnet are being fabricated in FY02

LLNL and Allied Signal Insulator Development



Closely spaced conductors are believed to inhibit the breakdown process



The effect scales inversely with spacing of the conductive planes

The ability to manufacture these structures is being perfected

Insulator Test Cell

Beam Dump

The technology has been demonstrated with beam on ETA-II (175 kV/cm in a high radiation field with no breakdowns)

Challenges and Main Issues

- **HIF requires well-focused beams of sufficient power for driving heavy-ion IFE targets.**

- **Sufficient power *of focusable and affordable* beams requires understanding:**
  - emittance growth, electron/gas interactions at high current/space charge potential, and accelerator aperture limits
  - maximum-average beam current densities achievable in injection, transport and acceleration experiments for future multi-beam arrays
  - power amplification limits to longitudinal bunch compression with velocity-tilt after acceleration
  - maximum beam perveance and neutralization limits to final focus and chamber transport

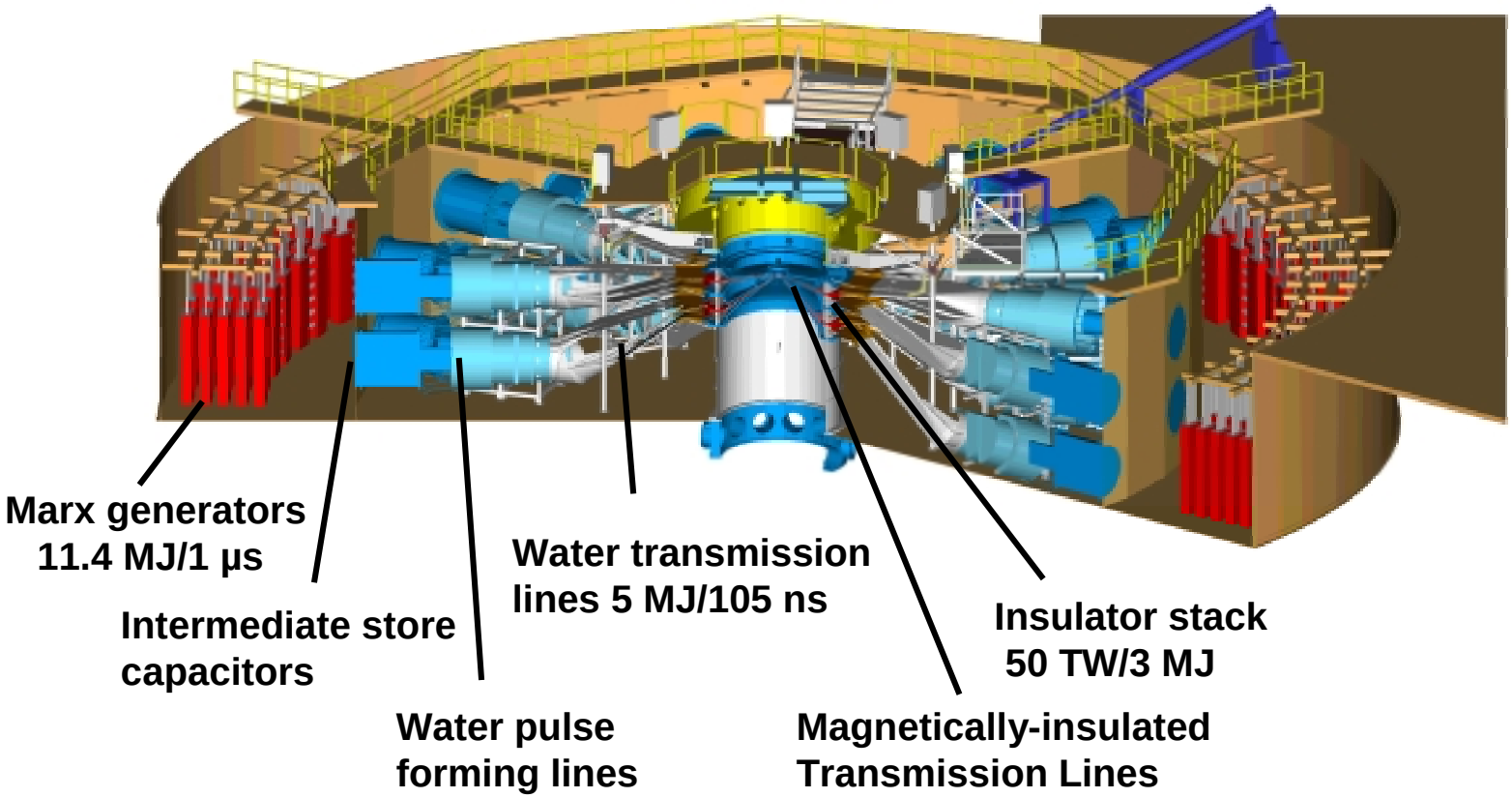
Challenges and Main Issues (Continued)

- **Many issues are more economic than basic feasibility: e.g. emittance growth and halo ion losses may be reduced with larger vacuum gaps between the beam and transport channels, at the expense of larger focusing magnets and induction core size.**

- **Most uncertain issue is achievable focal spot size consistent with bunch compression, focal length, target gain, chamber gas, ion stripping, and plasma neutralization.**

Z-Pinch

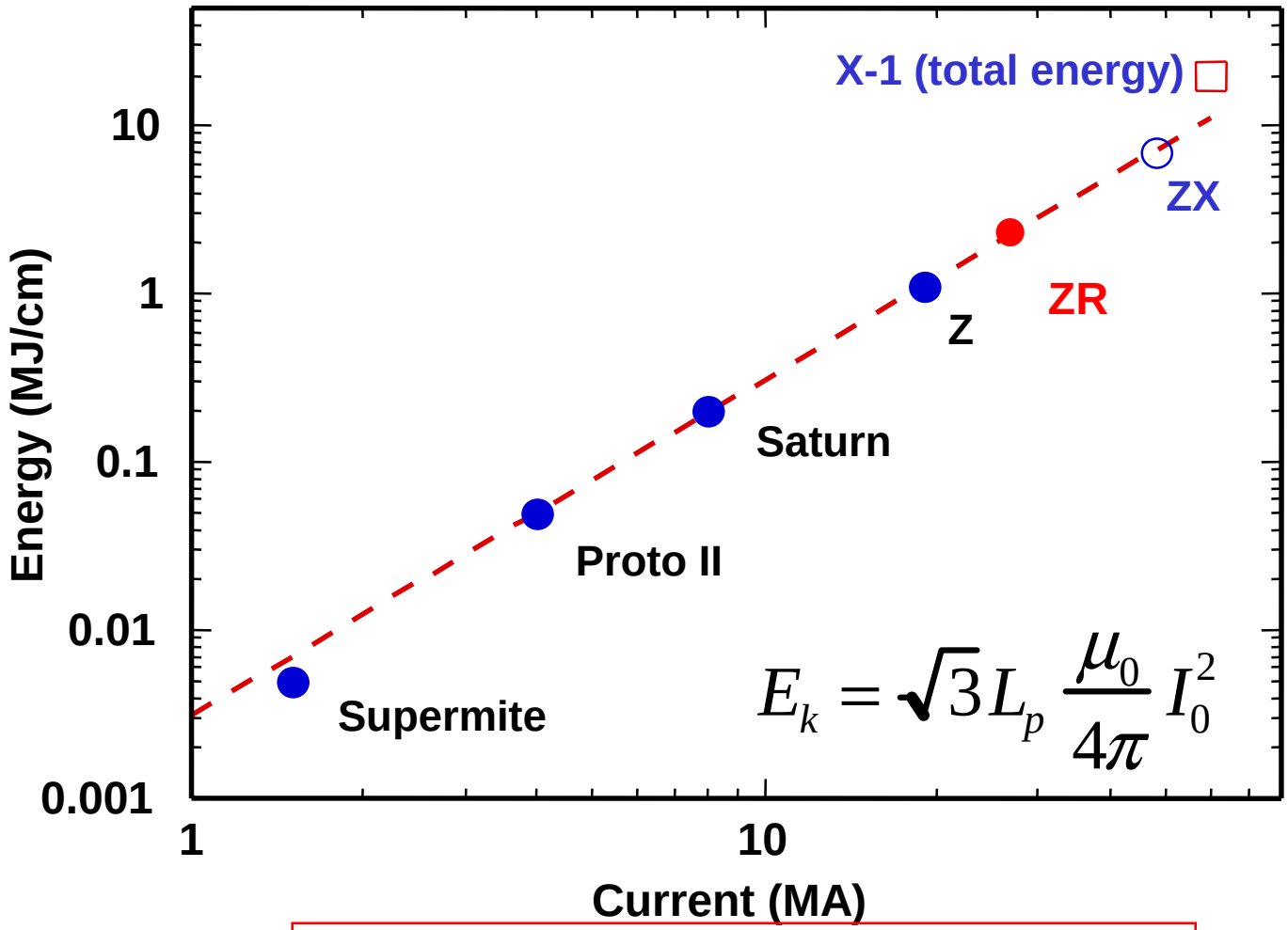
Z , the world's most powerful x-ray source for z-pinch-driven targets, is on the pathway to z-pinch IFE



X-rays from z-pinch wire array: ~ 6 ns, ~ 1.6 MJ, ~ 230 TW
High efficiency (wall-plug to x-rays): ~ 15%

Sandia National Laboratories

Z-pinches offer the promise of a cost-effective energy-rich source of x-rays for IFE



ZR will be within a factor of 2-3 in current (4-9 in energy) of a High Yield driver

Sandia National Laboratories

Rep-rated pulsed power is being studied for the z-pinch power plant concept

Status: Z (20 MA) at ~ 1 shot/day is ~ 10^{-5} Hz
Z-Pinch IFE needs ~ 1 shot/10 seconds is 0.1 Hz
RHEPP has demonstrated 2.5 kJ at 10^2 Hz (0.25 MW ave. pwr.)

Survey of possible rep-rated pulsed power scenarios for 0.1 Hz :
- Fast charging MARX (like Z)
- RHEPP (magnetic pulse compression)
- Linear Transformer Driver (LTD)

Tentative choice: LTD
- LTD is very compact, very fast (pioneered in Tomsk, Russia)
- Direct charging of compact capacitors
- IVA (inductive voltage adder)
- MITL (magnetically-insulated transmission line)
- Modular, scalable, easily rep-rateable

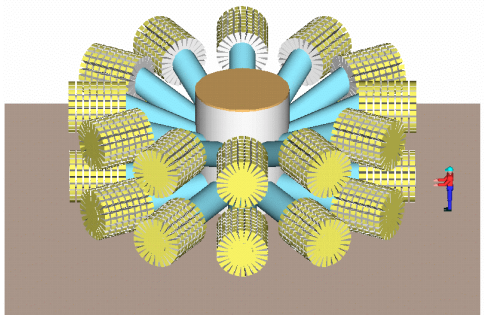
Planned scaled facilities:
- PoP scale experiment: 1 MA, 1MV, 100 ns, 0.1 Hz
- IRE: 10 MA, 2 MV, 100 ns, 0.1 Hz
- ETF: 60 MA, 5-10 MV, 100 ns, 0.1 Hz

LTD studies for a 1 MA driver (PoP scale) and a 10 MA driver (IRE scale) are in progress

Sandia National Laboratories

Comparison of existing Saturn assembly with the proposed new LTD

Saturn	LTD Z-Pinch IRE
30-m diameter	14.8-m diameter
6 -m height	5-m height
250,000-gallon oil tank.	None
250,000-gallon water tank.	None
2 m diameter insulating stack.	None



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Scaled Recyclable Transmision Line (RTL) cycle experiments

PoP (Proof of Principle):

1 MA, 1 MV, 100 ns, 0.1 Hz
Scaled RTL
Integrated experiment for N shots
~ 5 kJ x-ray output per shot

IRE (Integrated Research Experiment):

10 MA, 2 MV, 100 ns, 0.1 Hz (rep-rated Saturn scale)
Scaled RTL
Integrated experiment for N shots
~ 0.5 MJ x-ray output per shot

ETF (Engineering Test Facility):

Extension of Z-pinch HY Facility
~ 60 MA, 5-10 MV, 100 ns, 0.1 Hz
Full-scale RTL
~ 0.5 GJ fusion yield per shot

Sandia National Laboratories

Z-Pinch IFE is being developed as an integrated system

	CE	PoP	IRE
Targets (capsule compression, symmetry experiments, etc. on Z,ZR, etc.) (DP) Z-Pinch Driven Target Dynamic Hohlraum Target Fast Ignition, Advanced Targets	(X)	(X)	(X)
Driver (Rep-Rated) Fast cycling Marx RHEPP technology LTD technology		X	X
Standoff (Recyclable Transmission Line - RTL) RTL material choice, optimum shape, low inductance, etc. Electrical turn-on, conductivity, low mass, mechanical strength, etc. RTL/Chamber interface issues, etc.	X	X	X
Chamber and Power Plant Thick liquid walls, solid/voids, containment, etc. Power Plant design Manufacturing, target fabrication, costing, etc.	X	X	X
Integrated, Rep-Rated, Scaled RTL Cycle Experiment @ 0.1 Hz Model RTL cycle Couple with z-pinch load Automated, rep-rated, demonstration experiments		X	X

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Key Issues for Z-Pinch IFE are being addressed

- **Driver requirements for high yield targets (double pinch hohlraums and dynamic hohlraums require ~ 60 MA or more; fast ignition requires considerably less + PW) (ZR will be at 26 MA)**
- **Rep-rated pulsed power optimization, development of LTD drivers for PoP, IRE, and ETF, …**
- **Recyclable Transmission Line (RTL) optimization (shape, inductance, power flow, structural properties, …)**
- **RTL/interface issues (electrical, vacuum, shielding, …)**
- **Shock mitigation, effects on first wall and accelerator, …**
- **Scaled, rep-rated, RTL cycle experiments at 0.1 Hz (PoP, IRE, ETF, …)**
- **Power plant optimization (driver cost, RTL manufacturing, COE, …)**

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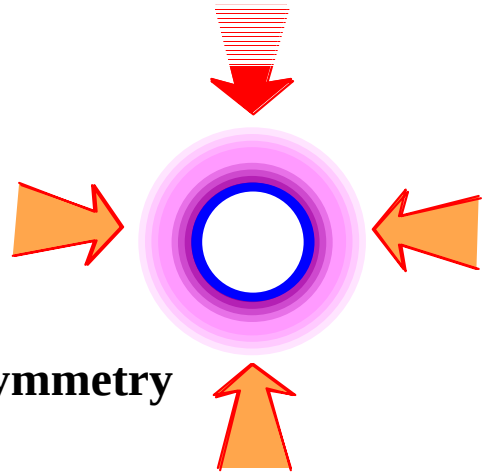
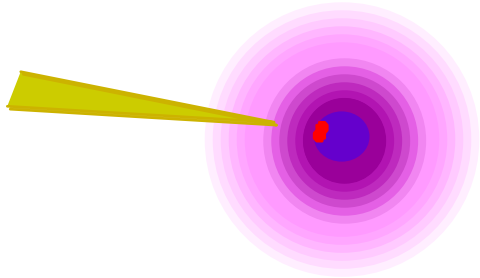
Drivers for Fast Ignition

Fast Ignition concept separates compression and ignition

- **Driver assembles fuel**
  - **200 - 400 g/cm^3**
  - **Compact shape**
  - **No need for spherical symmetry**



- **Ignitor heats minimal volume of DT**
  - **Must be pure DT**
  - **Surface must be accessible**
  - **High density ignition minimizes ignition mass**



Minimal ignition mass and reduced compression → higher gain

Fast Ignition requires two drive systems

- **Compression Driver to compress the fuel to 200-400 g/cm^3**
  - **~1 MJ, 10 ns pulse**
  - **Could be any of the previously described drivers**
  - **Compression requirements are more relaxed - lower brightness, less demanding uniformity**
  - **Must allow access for ignitor laser**

Driver requirements somewhat relaxed for FI targets

- **Short-pulse Ignitor Beams**
  - **~100 kJ, ~20 ps pulse**
  - **Only sufficiently bright candidate is high avg. power laser with pulse compression optics**
  - **$I\lambda^2$ determines electron energy, 1 μm looks good at FI levels of intensity**

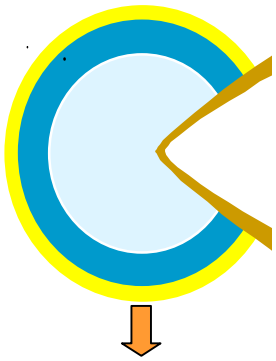
Ignitor Beam pointing, timing, propagation into target chamber, survival of optics are challenges

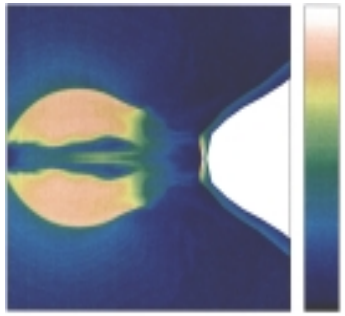
Compression Driver Issues are different for FI

- **Higher gain → efficiency less important for COE; relaxed brightness**
- **RT unstable targets → relaxed beam smoothness, relaxed imprint***
- **No central core → relaxed beam placement (simple shimming for correction)**
- **Longer wavelength → higher damage threshold→ smaller aperture→ lower cost**

*Pending confirmation by FI-target studies

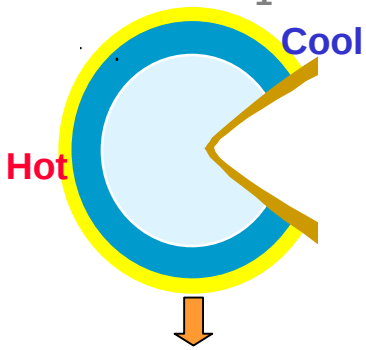
symmetric drive

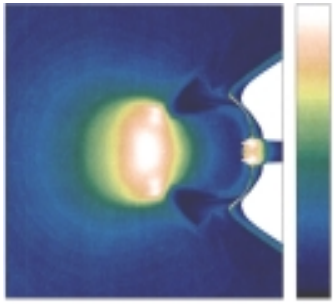




$\langle\rho R\rangle$=2.03 g cm^{-2}

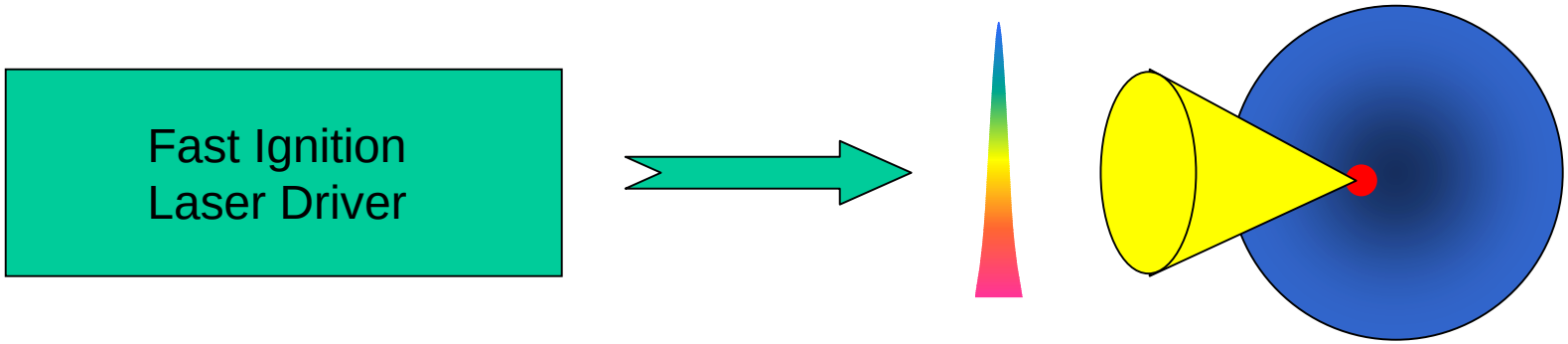
drive asym: 10% P_1





$\langle\rho R\rangle$=2.10

Fast Ignition Driver Rough Specifications

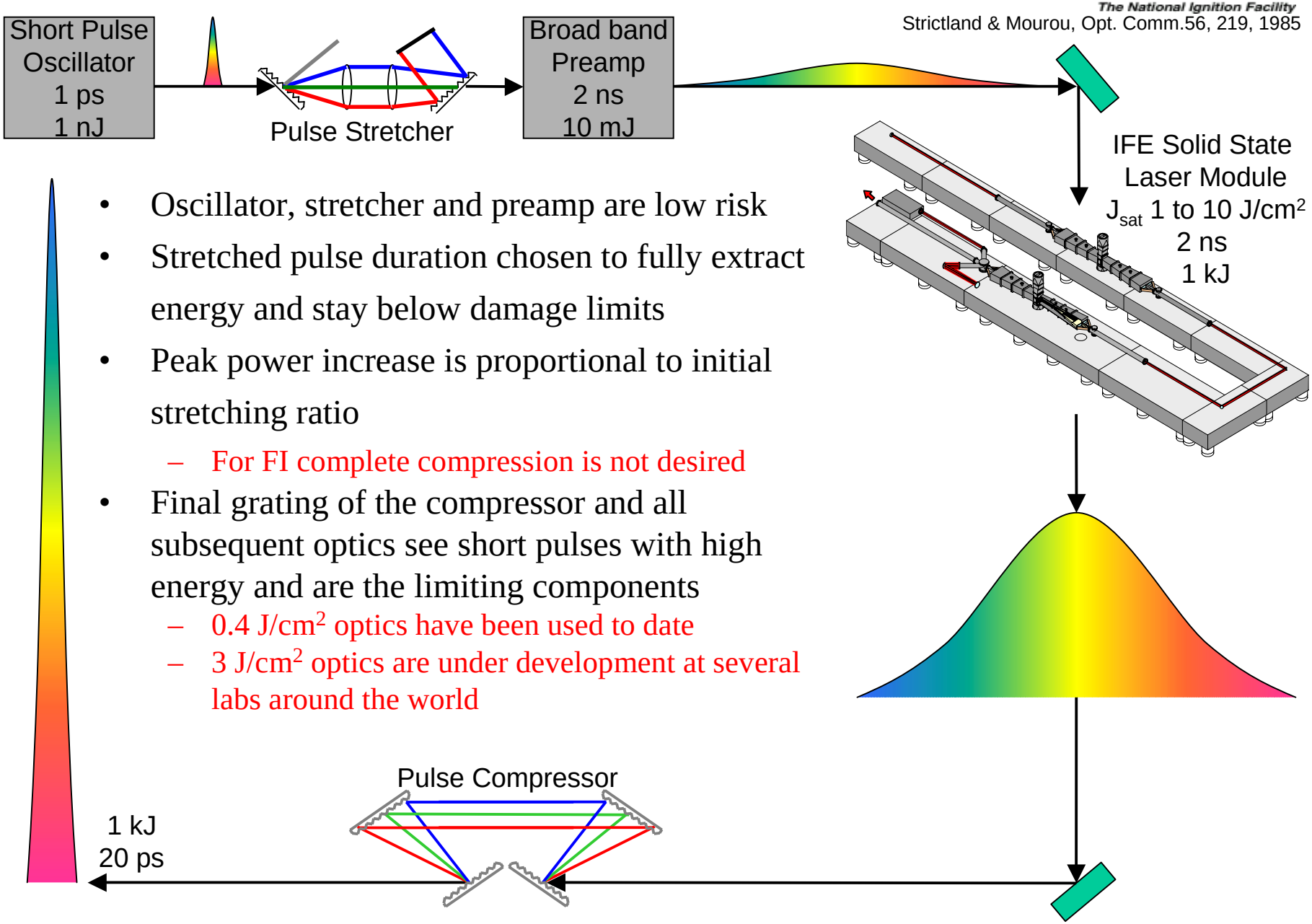


- How much energy is needed? ~100 kJ
- How short a pulse is needed? 20 ps
- How small a spot is needed? <50 μm
  - Could be significantly relaxed if cone concentrates input light
- How big is the beam? 20 cm x 20 cm per kJ
  - Assumes 3 J/cm^2 compatible final optics
- What timing accuracy is needed? ~5 ps
- What pointing accuracy is needed? ~10 μm
  - Could be significantly relaxed if cone concentrates input light

Chirped Pulse Amplification

The National Ignition Facility

Strictland & Mourou, Opt. Comm.56, 219, 1985



- Oscillator, stretcher and preamp are low risk
- Stretched pulse duration chosen to fully extract energy and stay below damage limits
- Peak power increase is proportional to initial stretching ratio
  - For FI complete compression is not desired
- Final grating of the compressor and all subsequent optics see short pulses with high energy and are the limiting components
  - 0.4 J/cm^2 optics have been used to date
  - 3 J/cm^2 optics are under development at several labs around the world

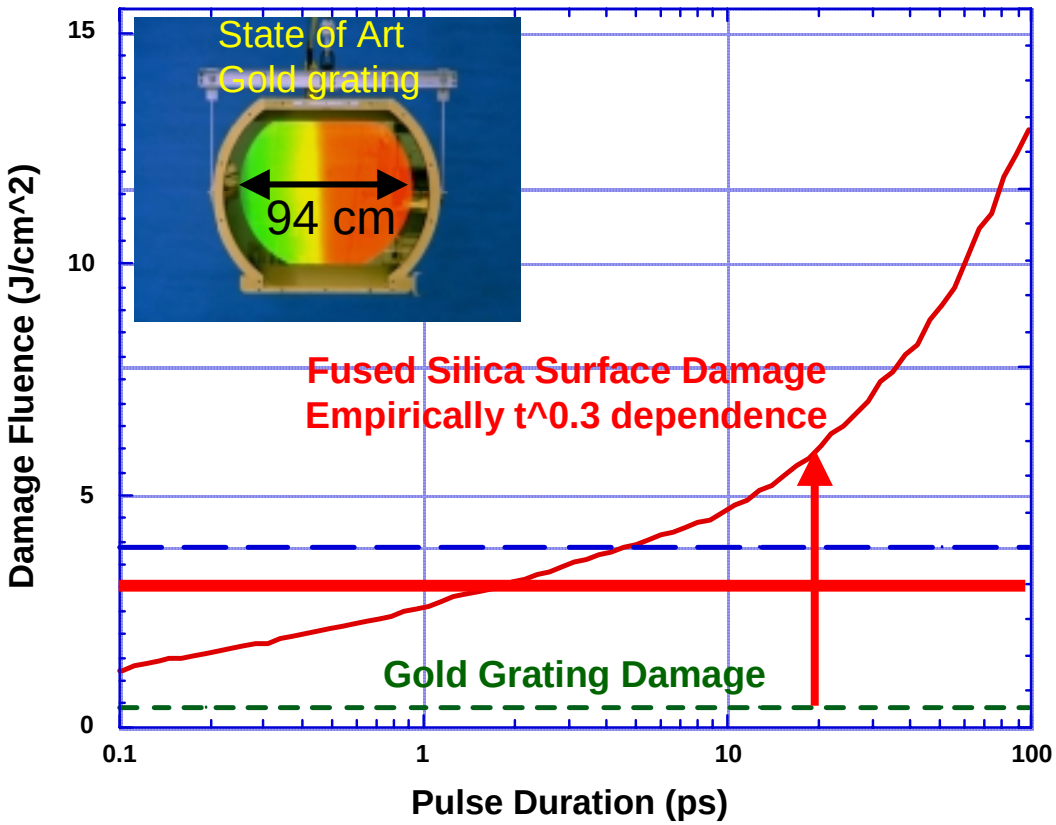
Ignitor Beam Options

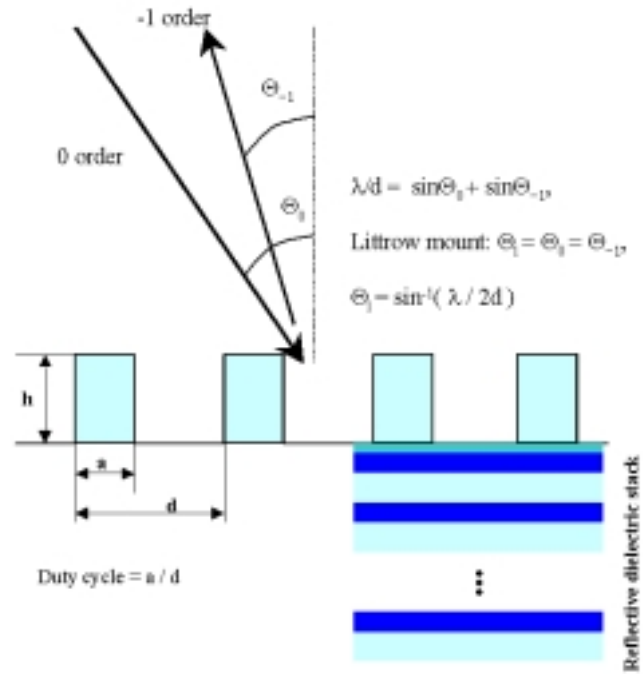
- **DPSSL (λ = 1 µm) is first choice**
  - **Has bandwidth, saturation energy and storage time compatible with single pulse, CPA extraction**
  - **Efficient use of optics operating at damage fluence limit**
  - **Could frequency double if shorter λ needed**
- **KrF (λ = 0.25 µm) is much more difficult**
  - **Cannot be efficiently use as a single short pulse, CPA (saturation fluence is too low)**
  - **Angular multiplexing requires too many pulses**
  - **Raman beam combined KrF may be possible**
- **Others?**

E_L ~100 kJ
$I\lambda^2$ ~10^{20} W/cm^2-µm^2
τ_L ~ 20 ps
Focus dia <50 µm

Ignitor beam development can be a derivative part of existing HAPL program

Dielectric Final Optics for ps HEPW pulses





- Increased damage resistance of fused silica suggests moving away from traditional gold coated gratings to multilayer dielectric (MLD) gratings
- For fixed aperture, higher energy is obtained at increased pulse duration
- Exact MLD performance will depend on electric field strength within the grating structure. Present designs should provide ~3 J/cm^2 at 20 ps

Summary: Several driver options for IFE are being developed and will be discussed at Snowmass

- **Lasers – both KrF and DPSSL**
- **Heavy ion accelerators**
- **Z-pinch**
- **Drivers for Fast Ignition**

Near term development plans for these drivers (and other IFE power plant subsystems) will be reviewed and perhaps refined through a series of meetings that will include members of the Driver, Target Physics and Technology Working Groups.

Extras / Back-up

Why Heavy Ions?

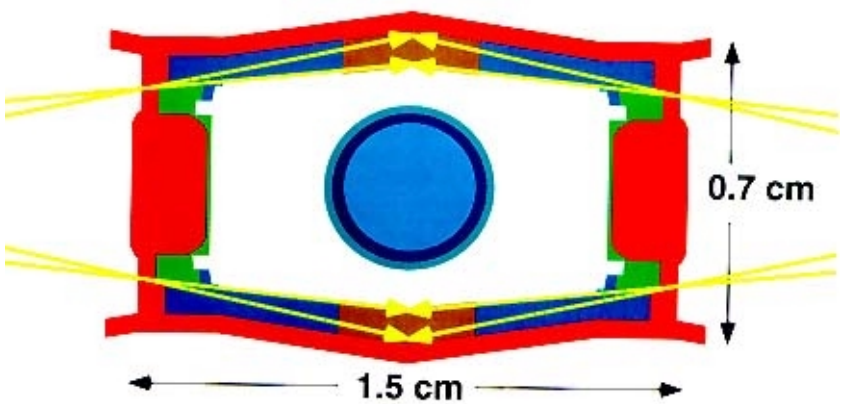
→ High energy accelerators with MJ class beam energies exhibit efficiency, pulse rate and durability needed for IFE

→Clear bore magnets used to focus the beams can tolerate target debris and radiation.

Need for high power + need to minimize current (for focusability) → High ion kinetic energy

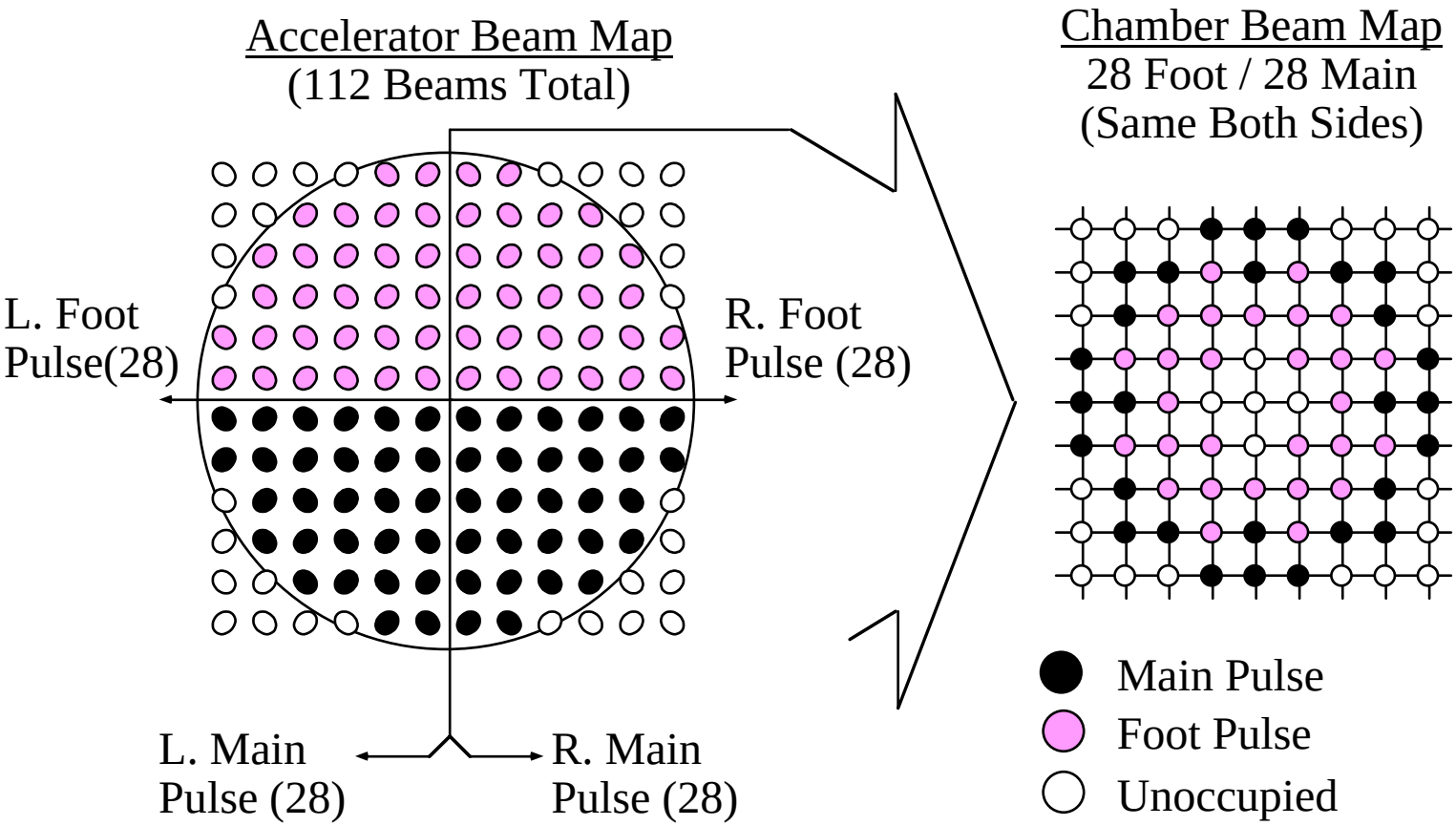
↓

High Z ions for dE/dx (or else range too long)



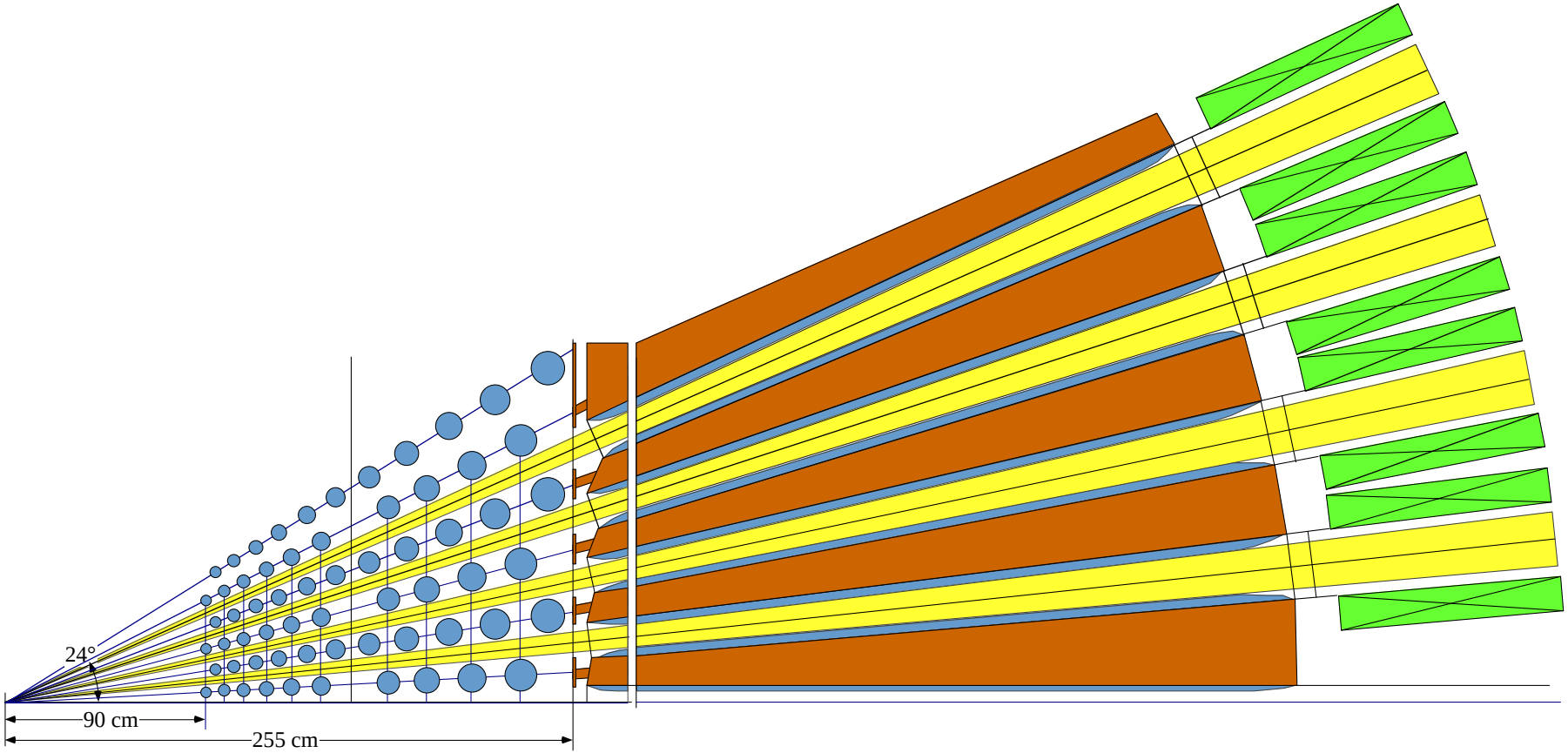
For focusability we use high Z, high kinetic energy ions.

A 112-beam configuration (56 foot-pulse / 56 main pulse)



Array Angles: $\theta_{min} = 8.5°$, $\theta_{max} = 24.7°$

9x9 array showing beam tubes and magnets at 6 meters

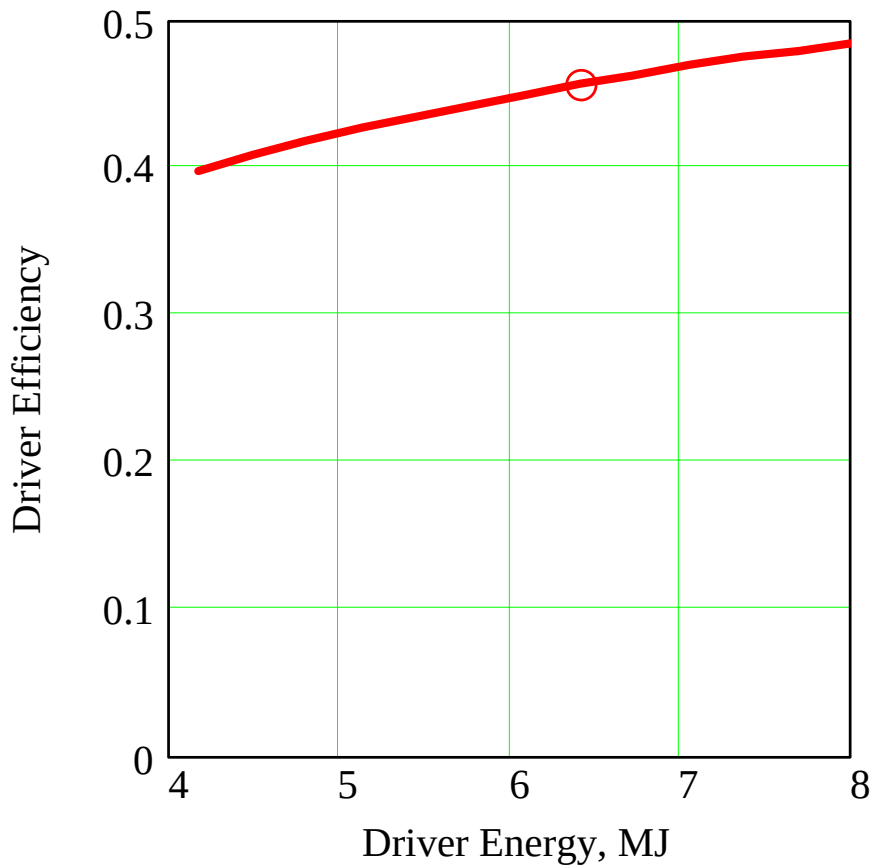


Detailed mechanical design of the beam tubes is needed to determine where steel, coolant, voids, and other materials will be located to allow injection/ extraction of vortex flow and optimize shielding

Reference induction linac accelerator requirements for HIF drivers

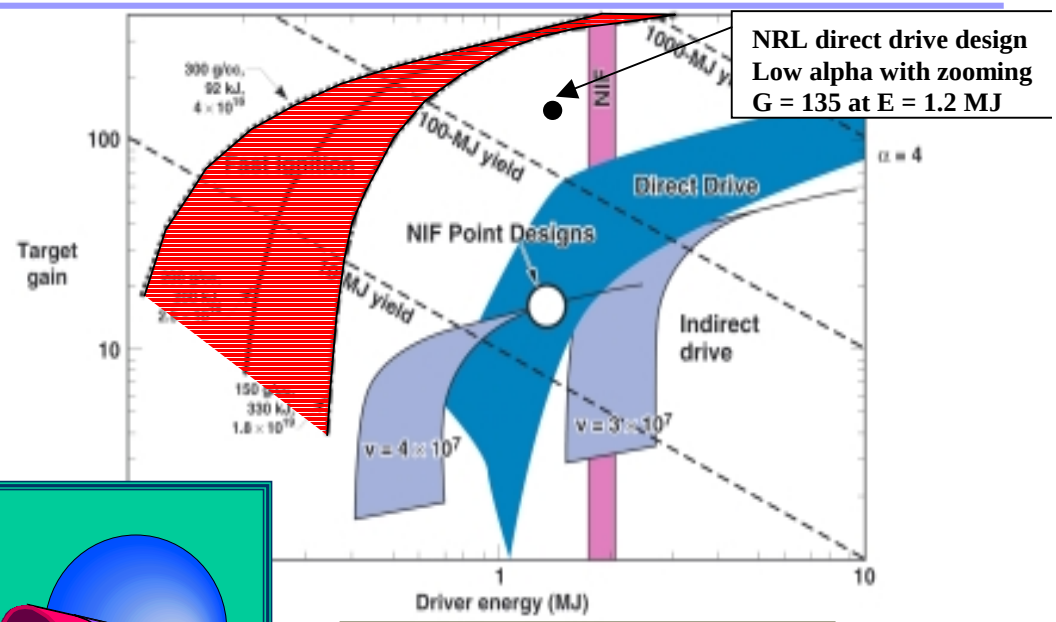
Requirement	Range
Ion mass	131 amu (for lower cost) to 238 (only if more margin needed on focusing spot)
Ion kinetic energy	2.5 to 5 GeV for mass 131 to 238
Number of beams	> 50 (to avoid excessive electric fields in final focus to ~ 100 for minimum cost based on SC quad transport
Beam energy to target	5 to 7 MJ total depending on desired yield/rep rate, ~ 30-50% of beams @ 75% full energy for pre-pulse, 70-50% of beams @ full energy for main pulse
Ion source current/emittance/pulse	> 0.5 A/beam, < 2 π mm-mr normalized /, > 10 μsec
Transverse emittance growth at focus	< 5 π mm-mr normalized to meet focal spot size
Parallel momentum spread at focus	delta p/p < 5 x 10^{-3} to meet focal spot size
Electric-to-beam efficiency @ >5 Hz	> 20% for ηG > 10, > 40% for minimum CoE
Ferritic core material cost	< 5 $ /kg
Switching cost for >10^9 shot life	<10^{-5} $/Watt
Insulator cost	< 0.01 $ Volt @ meter diameter
Durability/reliability	> 10^9 shots between maintenance periods, sufficient for >75% overall plant availability

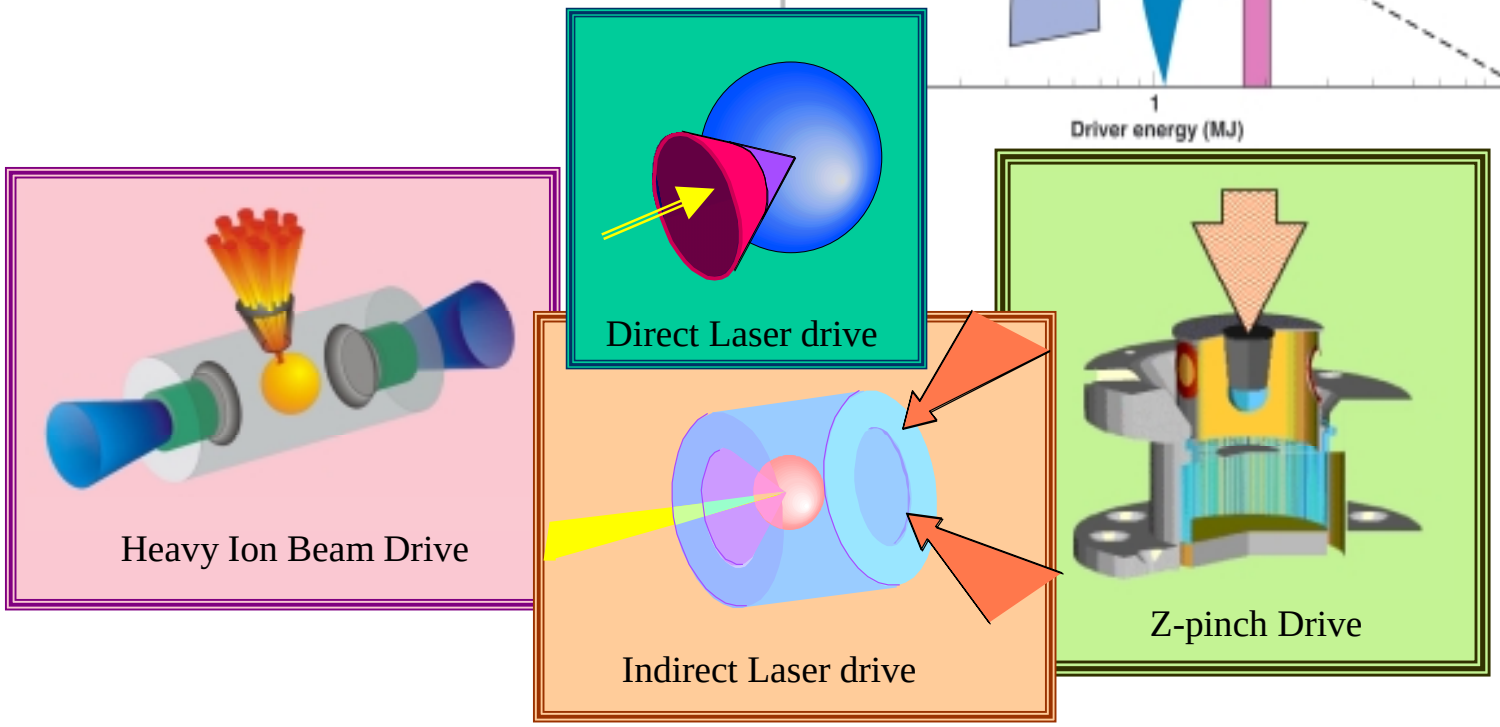
HI driver efficiency is over 40%.



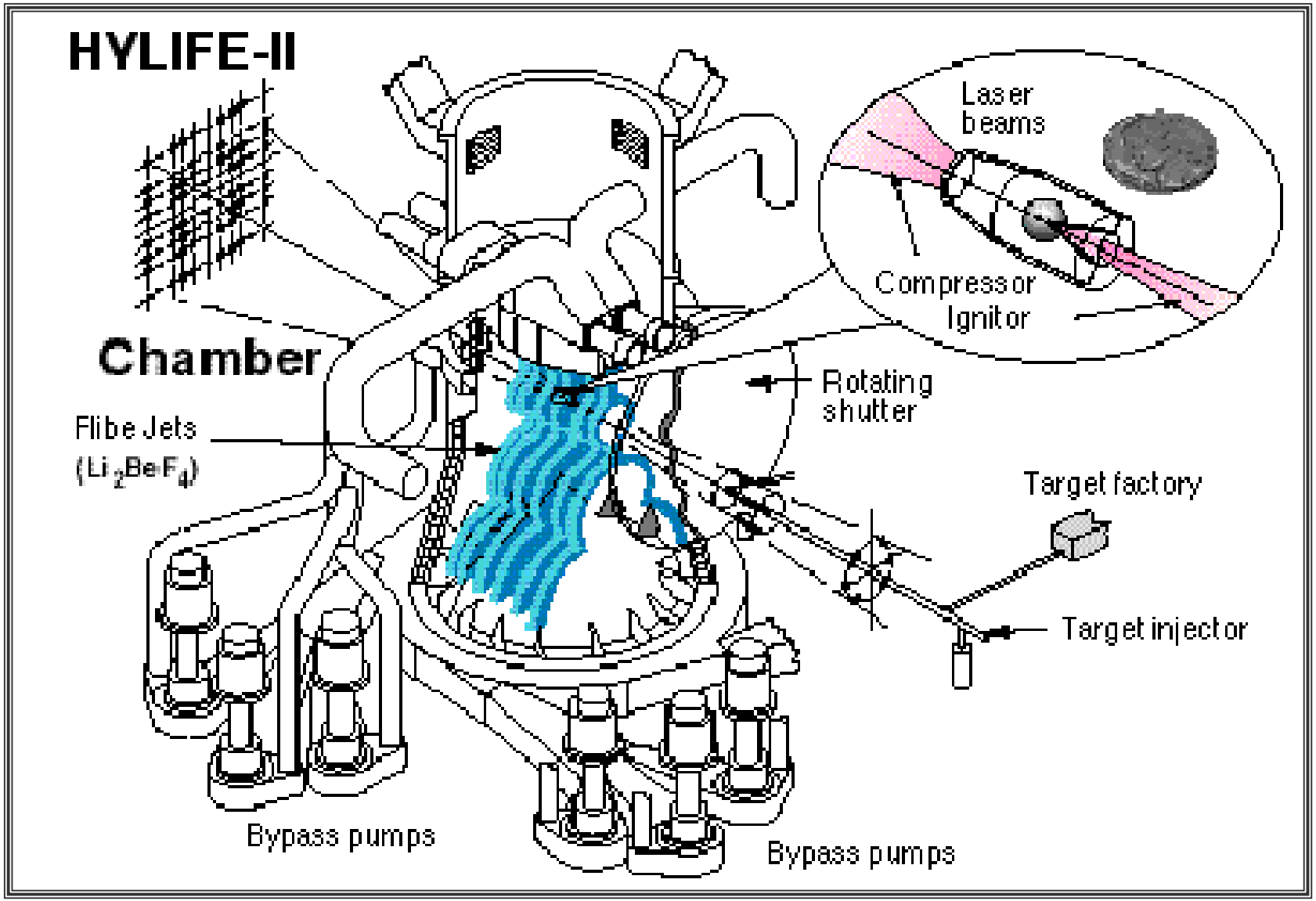
Fast Ignition concept leads to an attractive system

- **Low threshold to reach ignition**
- **High gain for efficient power plant**
- **Compatible with any driver**



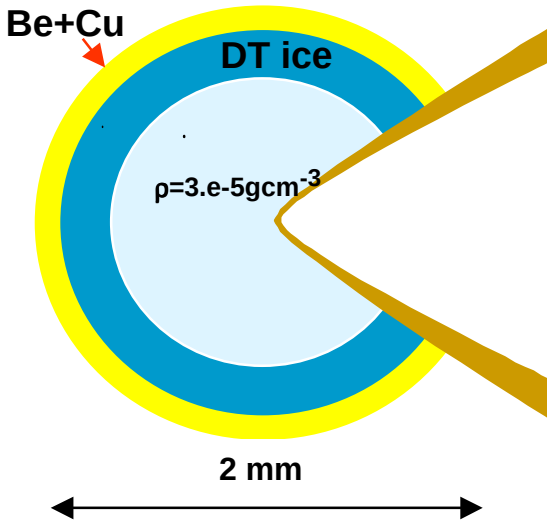


FI Concept permits driver location along target axis



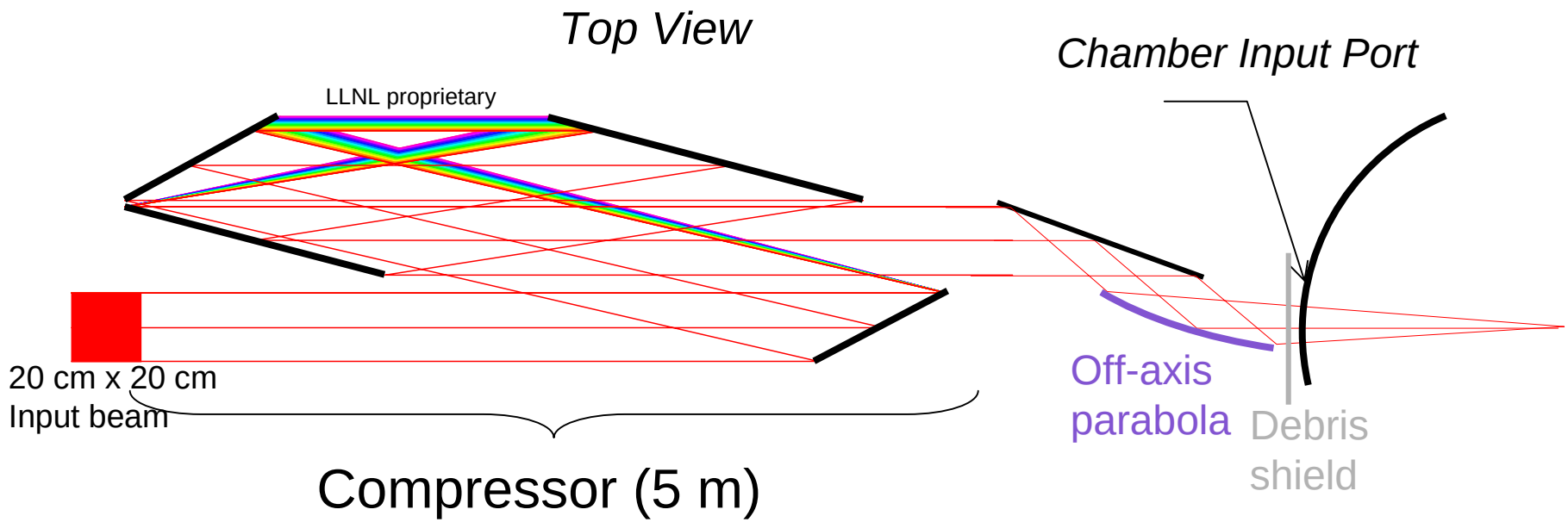
Fast Ignition will allow innovative target design

- CONS
  - Need complex geometry to accommodate Ignitor Beam
  - Adds mass (and potential projectile)
- PROS
  - Central hot spot not required
  - Large aspect ratio, low acceleration targets desired (RT unstable)
  - Relaxed surface specifications
  - Cheaper fabrication technologies (stamped)
  - Easier cryo system, faster production -> less inventory



Target design studies needed to determine driver specifications

Compact compressor design



- Compressor foot print is determined primarily by stretched pulse duration and bandwidth
- Size of gratings is determined by input beam size and angle of incidence
  - High damage gratings operate at high angle of incidence, 77 degrees
- 3 J/cm^2 operating fluence and 20 ps pulse duration determines acceptable thickness of debris shield
  - B=1 for 370 micron thickness
- Standoff from target will depend strongly upon ability of cone target to concentrate input radiation