

Update on IFE Research at LLNL

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**IAEA Research Coordination Meeting
CRP on Elements of IFE Power Plants
November 4-7, 2003
Vienna, Austria**

Work performed under the auspices of the U.S. Department of Energy by the University of California,
Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

Outline



- **Introduction**
- **National Ignition Facility**
- **Targets**
- **Drivers (heavy ion accelerators and lasers)**
- **Chambers and power plant assessments**

LLNL conducts a wide variety of IFE related R&D activities



- **The National Ignition Facility is being constructed at LLNL and had started experiments.**
- **Target physics activities include target designs and experiments for direct drive with lasers, indirect drive with heavy ions, and fast ignition.**
- **A high average power Diode Pumped Solid State Laser (DPSSL) is being developed at LLNL.**
- **LLNL is a partner in the development of a heavy ion driver. LLNL work includes magnet development, source/injector experiments, and beam and systems modeling.**
- **We also have activities on chamber design, fusion materials, safety and environment, and systems modeling.**

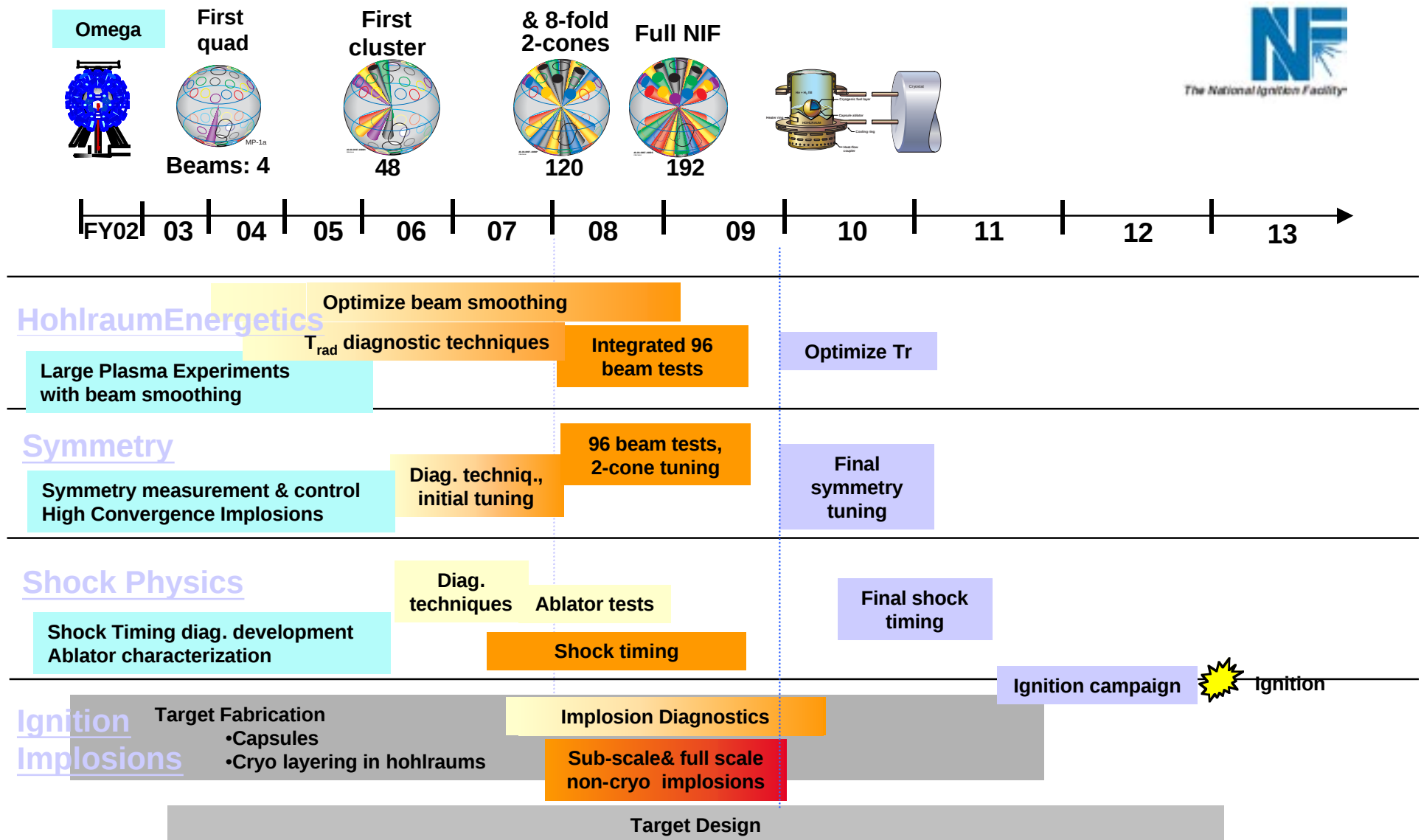
The National Ignition Facility (NIF) will prove the scientific feasibility of ignition and energy gain in the laboratory



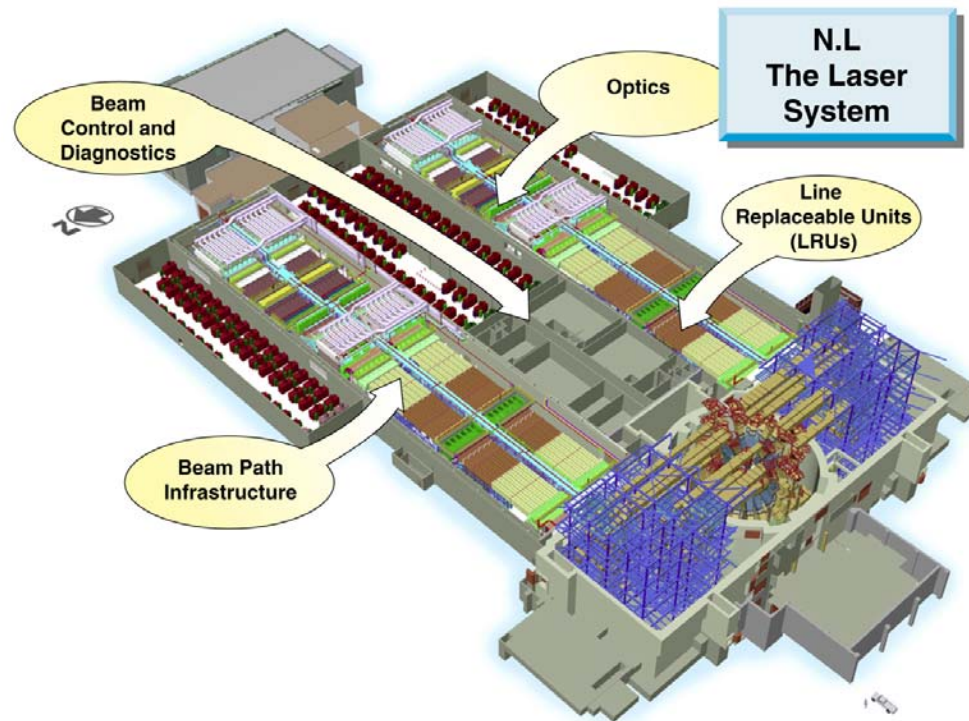
1st Beam line – 12/02
Full NIF – FY08-09
Ignition – FY11-12



The indirect drive Ignition Plan makes use of existing facilities, and early NIF, to optimize the ignition design



One critical mission for the National Ignition Facility (NIF) is to compress a DT target to fusion ignition



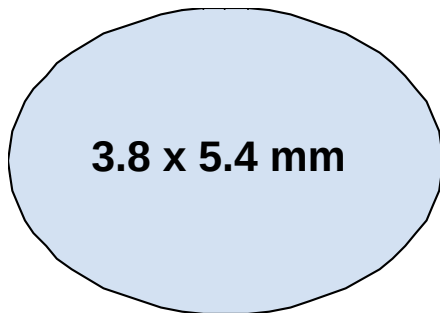
NIF laser has been optimized for maximum Joules per shot in several nanoseconds

- Architecture: Flash lamp pumped Nd:glass oriented at Brewster's angle

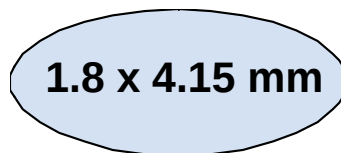
Inertial Fusion Energy (IFE) will require much higher shot rate and efficiency

- Efficiency: 0.5 % $\rightarrow$ >5 %
- Shot rate: 1 shot / 4 hours $\rightarrow$ 10 shots / second

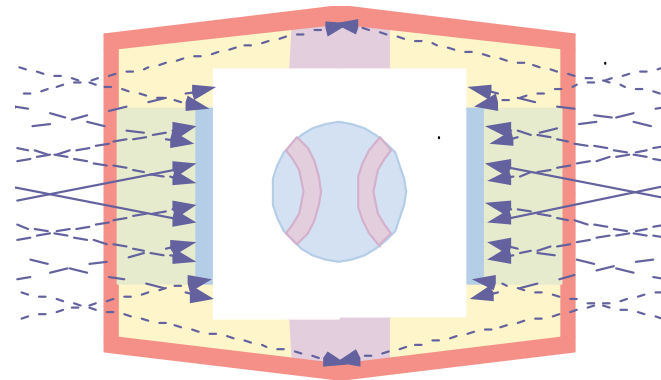
The hybrid target allows much larger beam spots than previous designs but requires shims to get adequate symmetry



Hybrid target
6.7 MJ, G~ 60



Distributed radiator target
5.9 MJ, Gain ~ 70

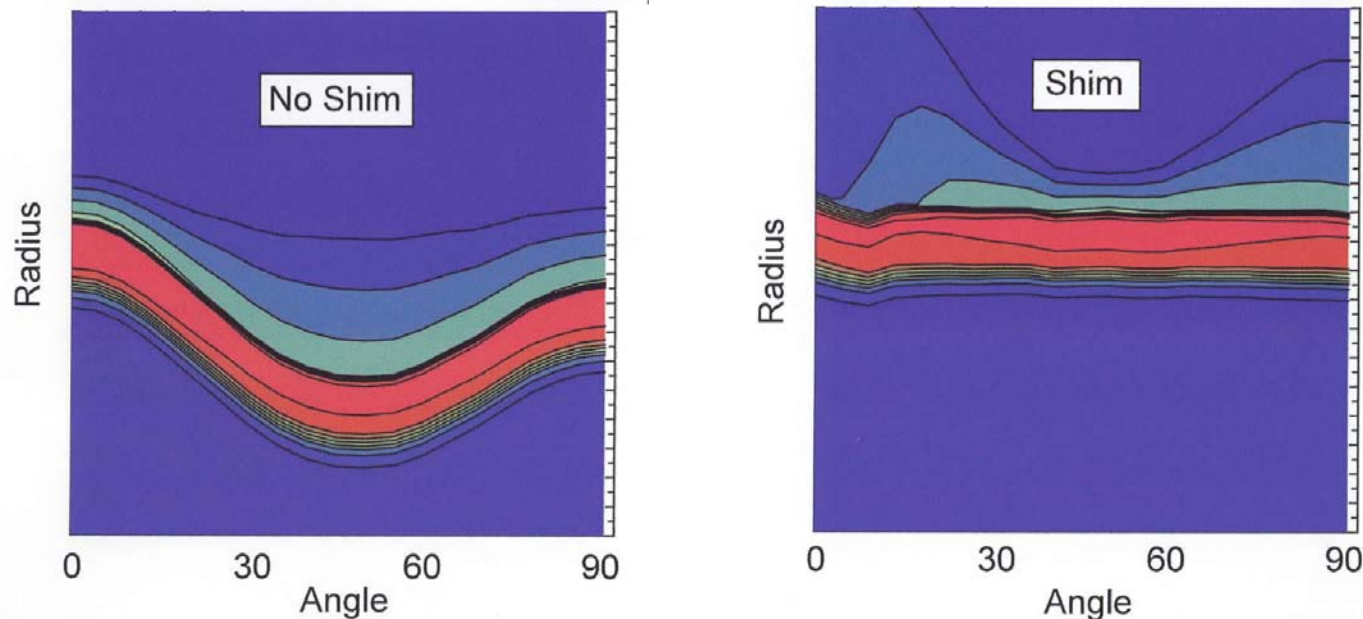


- For Gaussian beams, > 50% of the energy is deposited behind the shine shield
- Radiation flow around the shine shield results in a bright source near the peak of P_4
- A shim layer was used to fix this asymmetry

We are planning an experiment on Z to test that a shim can take out the P_4 asymmetry

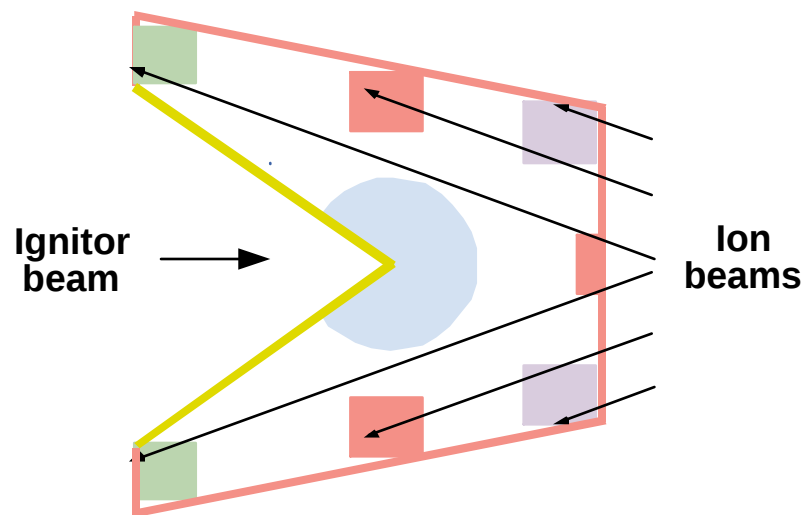


Density contours



If shims are successful, they can also be used in indirect drive targets for Z-pinchs or lasers

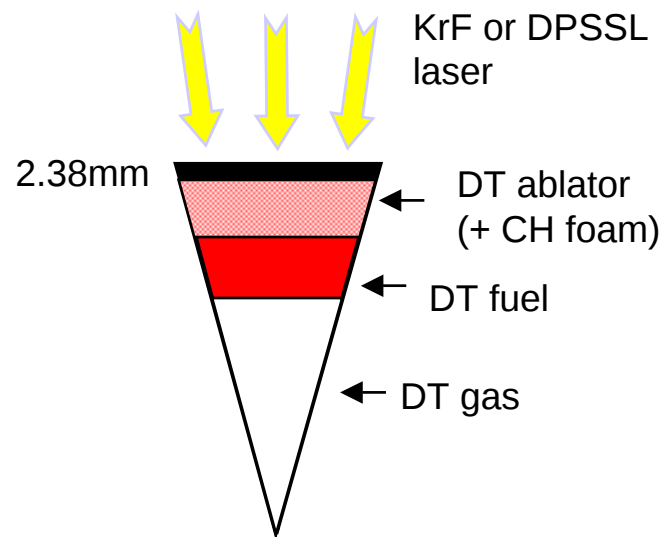
Simple estimates suggest that using ions to compress fuel for fast ignition drops the ion peak power to 70-160 TW



	150 eV	120 eV	Distributed Radiator
E_{beam}	2.7 MJ	1.9 MJ	5.9 MJ
Power	160 TW	68 TW	550 TW
E_{ign} (@30%)	150 kJ	600 kJ	---
Gain	160	140	68

A first estimate of driver cost suggests that the 150 eV case reduces the driver cost by 40% and the COE by 25%

Through Innovative Laser Pulse Shaping we have Significantly Improved the Stability of High-Gain Direct-Drive Targets for Inertial Fusion Energy



Yield **350MJ**

E_{laser} **2.9MJ**

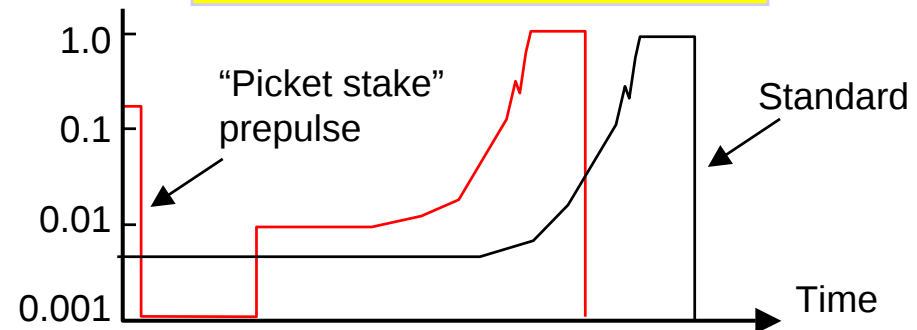
Gain **120**

Shell breakup fraction:

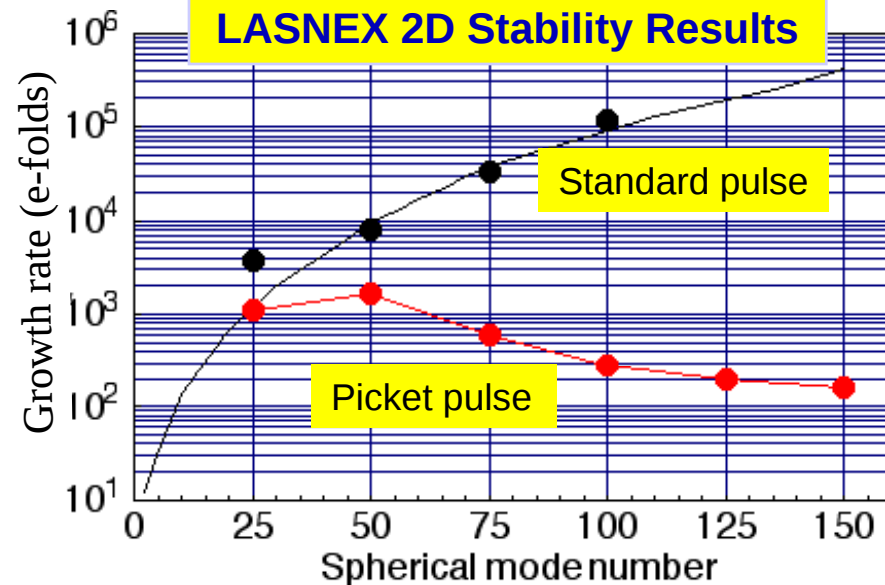
- *Standard pulse* **~1.8**

- *Picket pulse* **~0.15**

Laser Power Pulse Shape



LASNEX 2D Stability Results





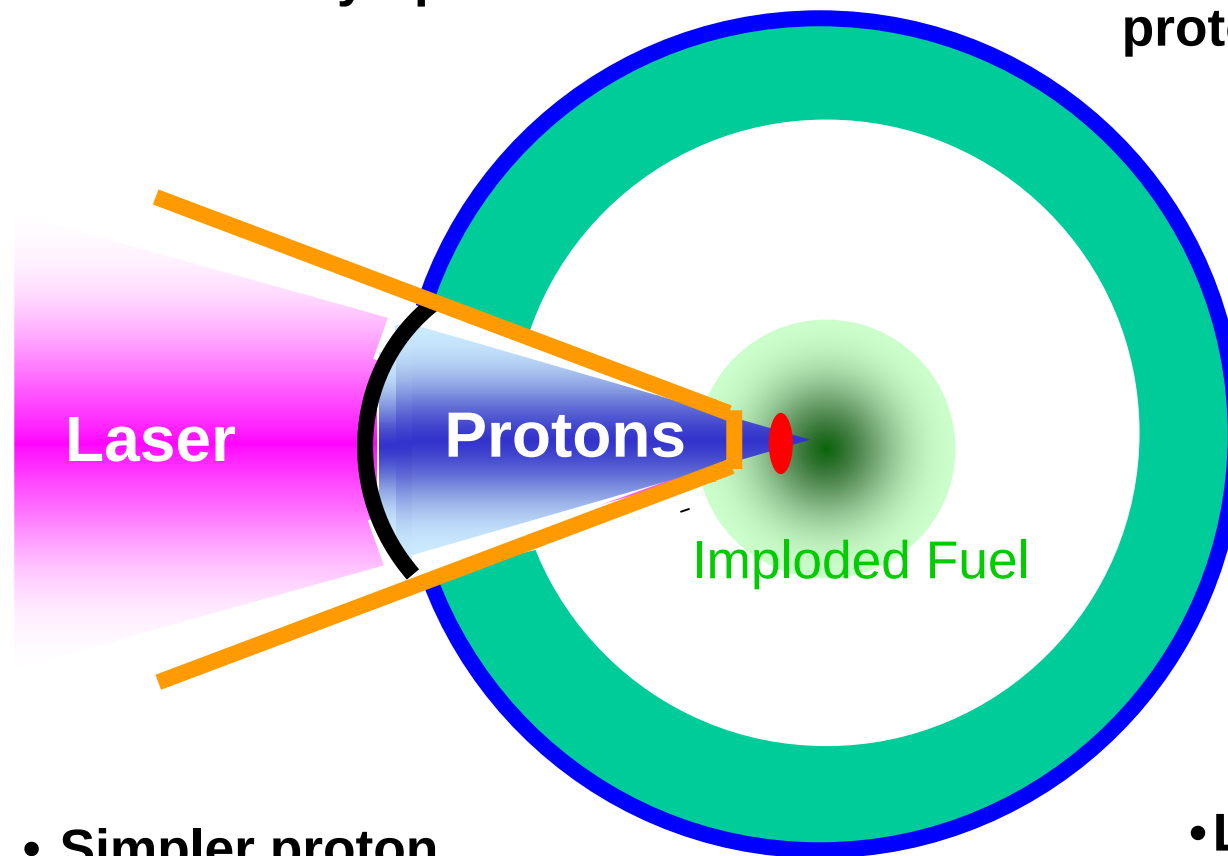
**Atzeni. Phys. Plas. 6 3316
(1999)**

ICC2003

Proton ignition is a newer concept avoiding the complexity of electron energy transport

- Same driver and fuel assembly options

- Novel physics of Debye sheath proton acceleration



M. Roth *et.al.*
Phys Rev. Lett
86,436 (2000).

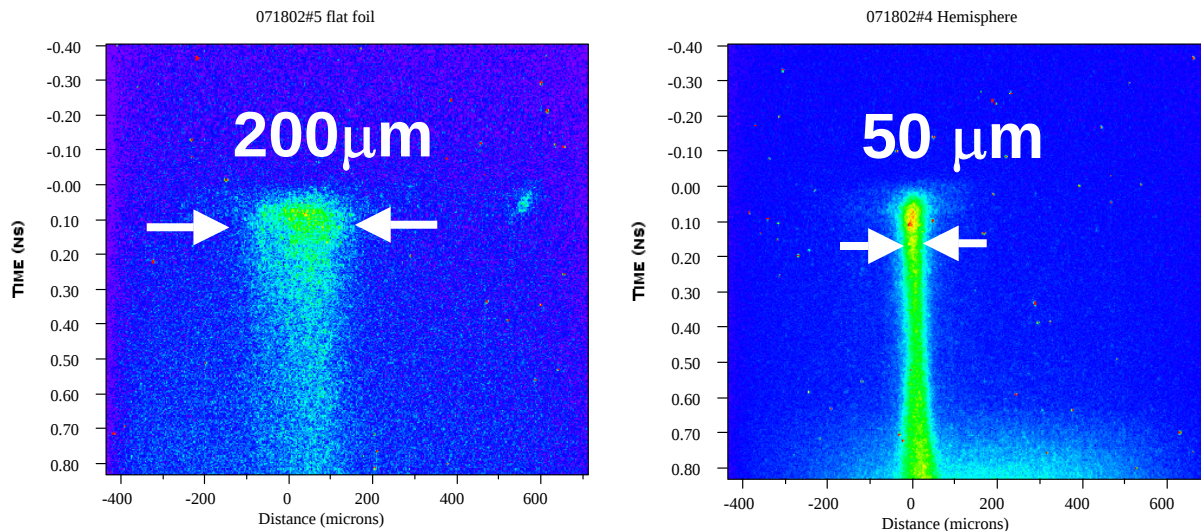
Ruhl et al. Plas.
Phys. Rep.
27,363,(2001)

Temporal, et al.
Phys Plasmas
9, 3102, 2002

- Simpler proton energy transport by ballistic focussing

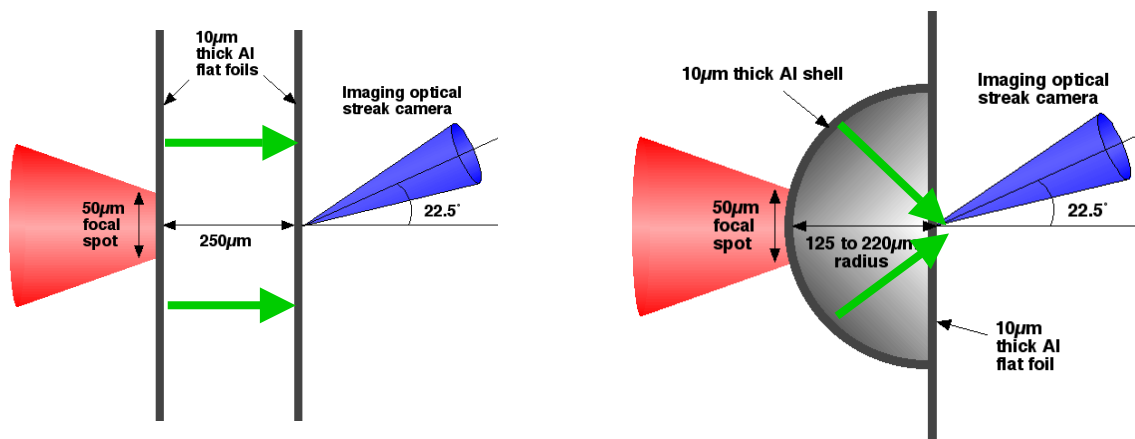
- Larger laser focal spot-easier to produce

First demonstration of ballistic proton focusing was made recently with the LLNL JanUSP laser

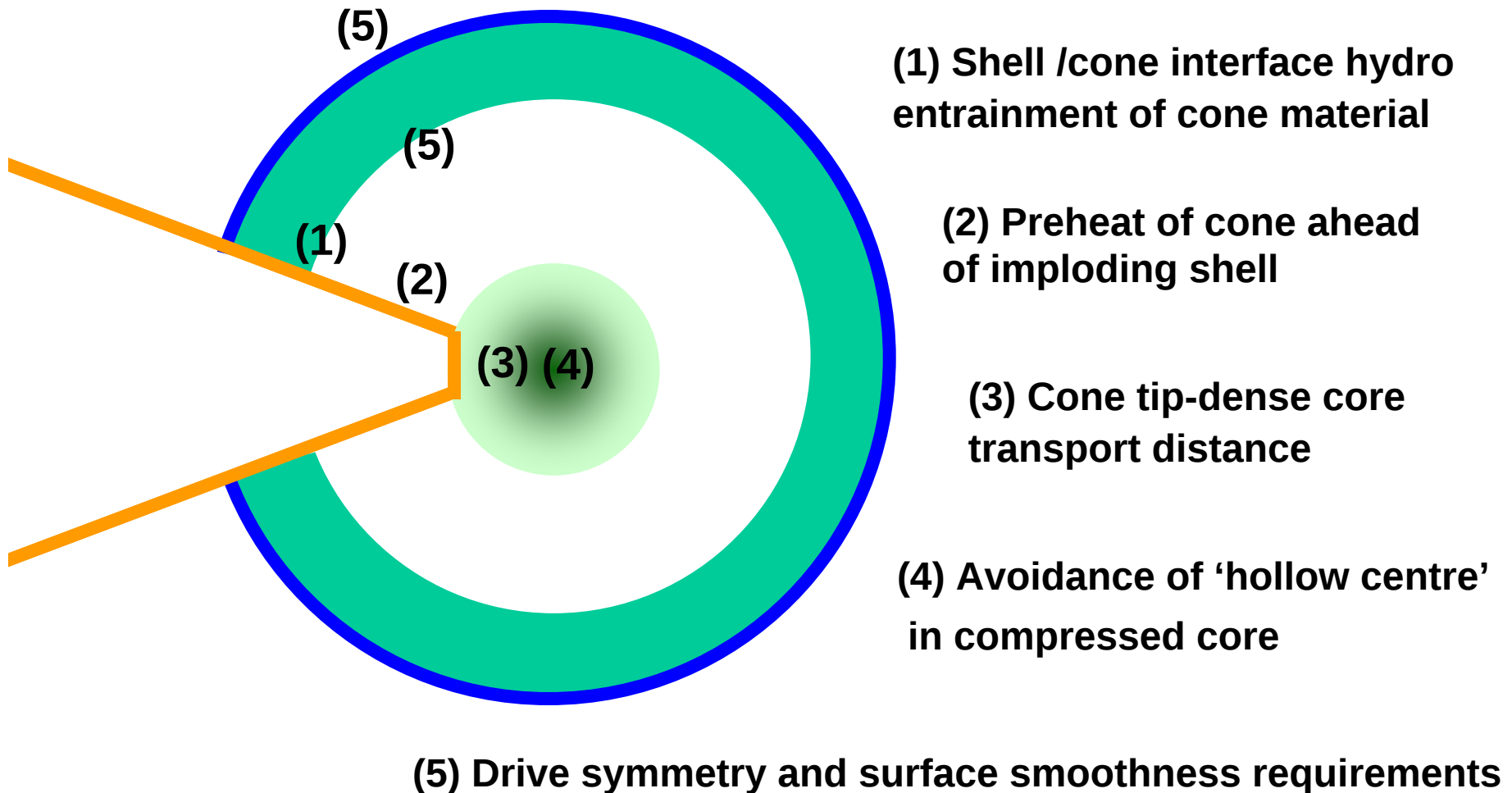


Streak images of Planckian emission

- Focused beam gives 7.7x more temp rise (20 eV) than unfocused
- Focused protons give 2 to 3 x more heating than direct heating by electrons

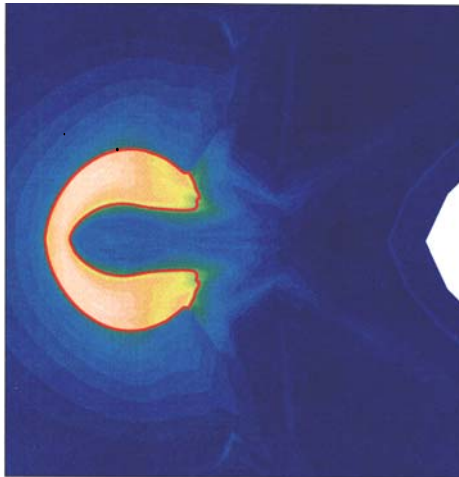


Fast ignition targets are designed with radiation /hydro- codes and tested at the Omega laser

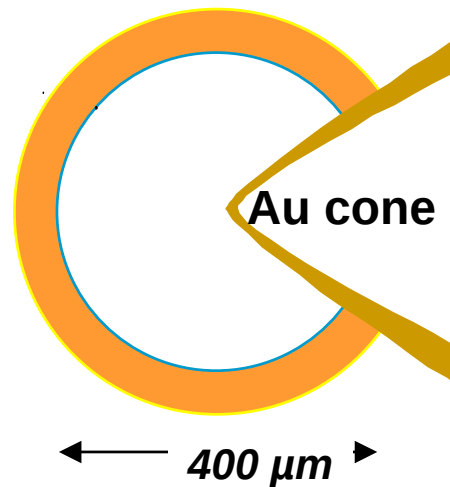


Validate fuel assembly concepts in 'hydro- equivalent' targets

Design of cone targets was developed using modeling with Lasnex



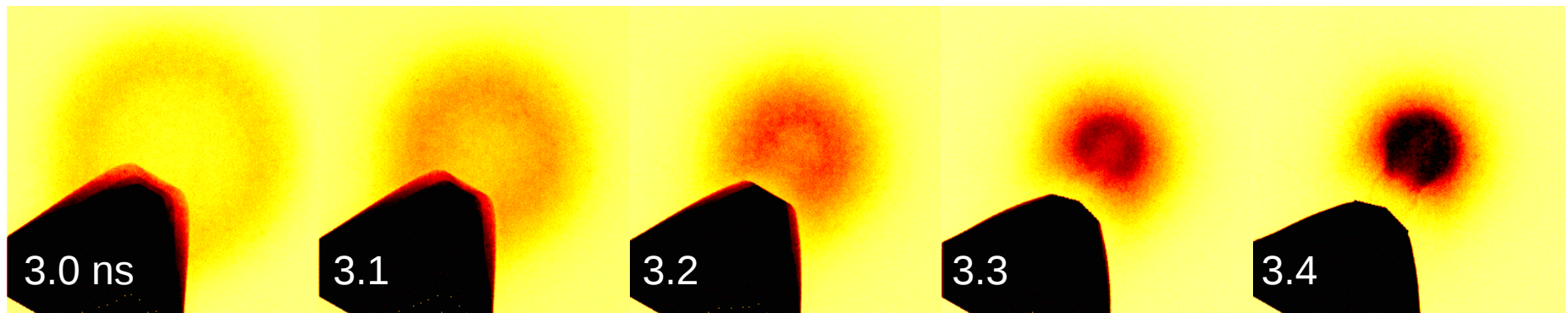
Lasnex model of
Imploded density



Cone target at Omega

"Design and Analysis
of Cone-Focussed
Fast Ignition Experiments",
Hatchett, S.P., et al.
2002, *Bull. Am. Phys. Soc.*,
47, 85.

Radiograph



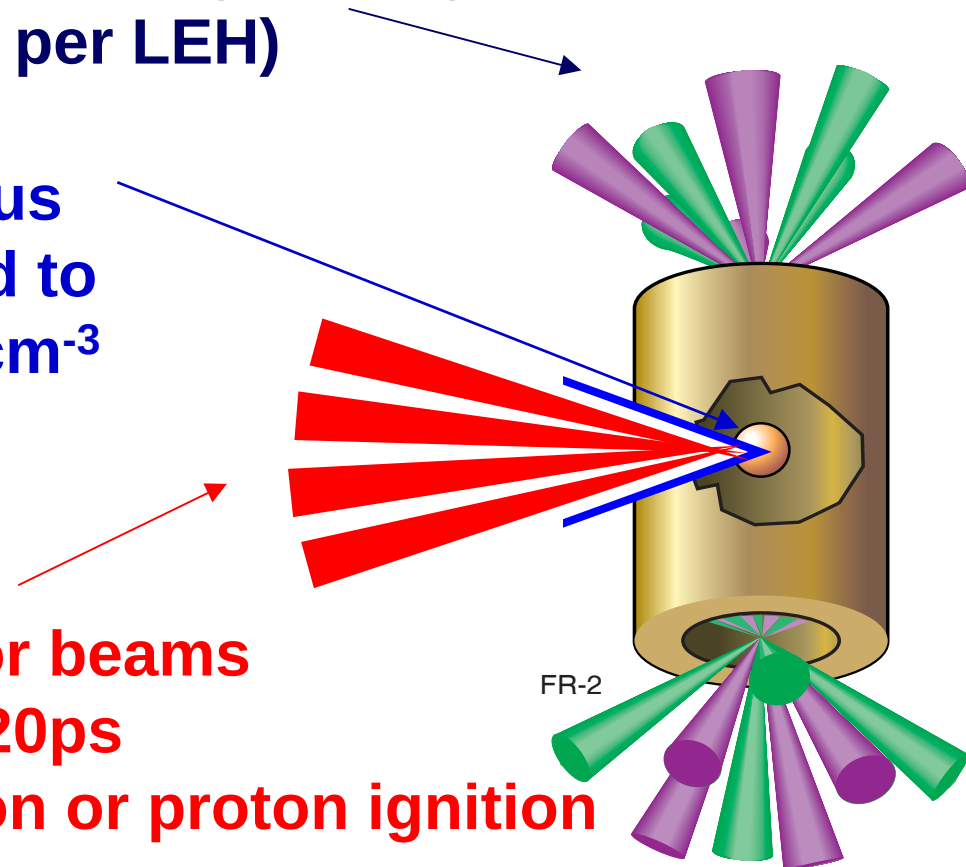
Simulated sequence of radiographs at Omega

A 'proof of principle' FI experiment at NIF has been designed using Lasnex modeling

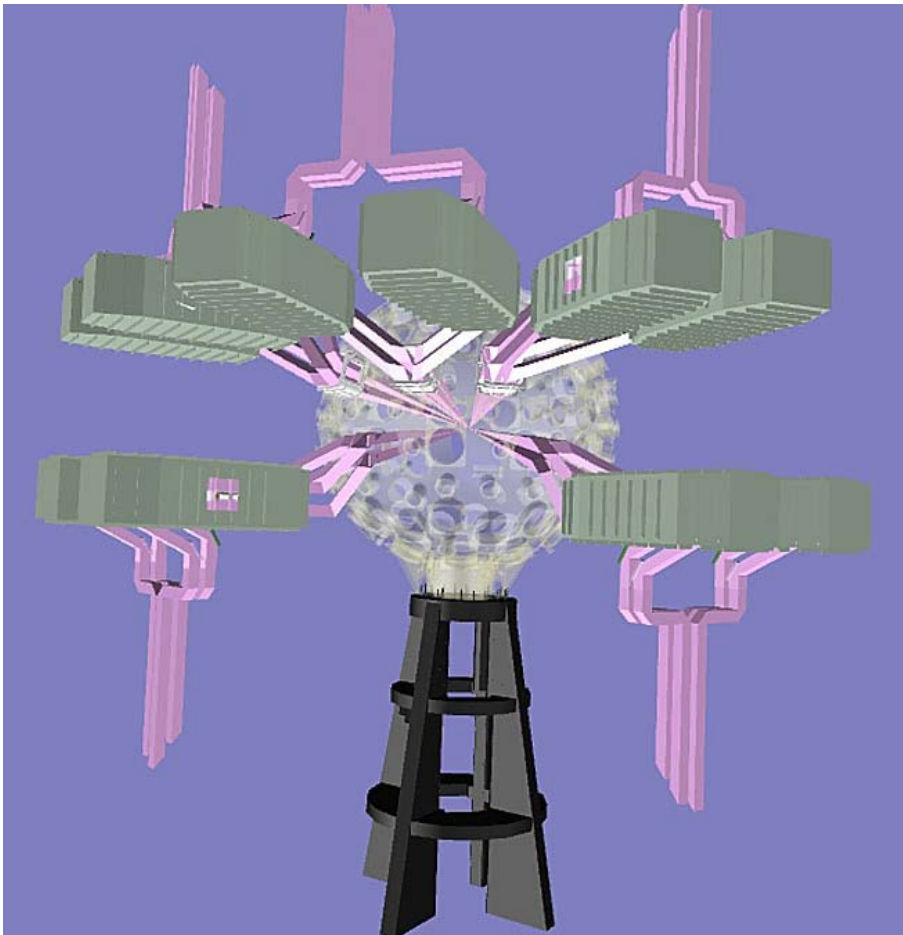
250kJ Hohlraum drive with
8 fold 2 cone symmetry
(8 quads per LEH)

CD shell 740 μm radius
160 μm wall Imploded to
45 μm radius, 250 gcm^{-3}
 $\rho r = 1.0 \text{ gcm}^{-2}$

4 HEPW ignitor beams
total of 20kJ, 20ps
driving electron or proton ignition



High gain fast ignition experiments using 100 kJ of HEPW would require 5 quads of HEPW beams



NIF could be adapted to demonstrate high gain fast ignition

Solid state laser driver requirements for inertial fusion energy (IFE)



1) Efficiency > 5 - 10 %, including cooling

- Key issue is recycled power in power plant for laser driver

2) Overall cost < \$500/J for 2 MJ laser driver

- Requires diode price of 5¢/W_{pk} (< \$0.5B for 2 MJ driver)

3) Repetition rate of 5 - 10 Hz

- Limited by clearing rate of chamber

4) Reliability of >10⁸ shots

- ~10¹⁰ needed for diode arrays; >10⁸ shots for other components

5) Pulse width of 3 nsec and wavelength of < 0.4 μm (I.e. use tripling)

- Needed to compress target to ignition

6) Beam smoothness of $\sigma < 0.1$ % in 1 nsec on-target

- Beam quality must be < 12 xDL to allow for smoothing to be applied

7) Architecture scalable to multi-kilojoule class per beam line

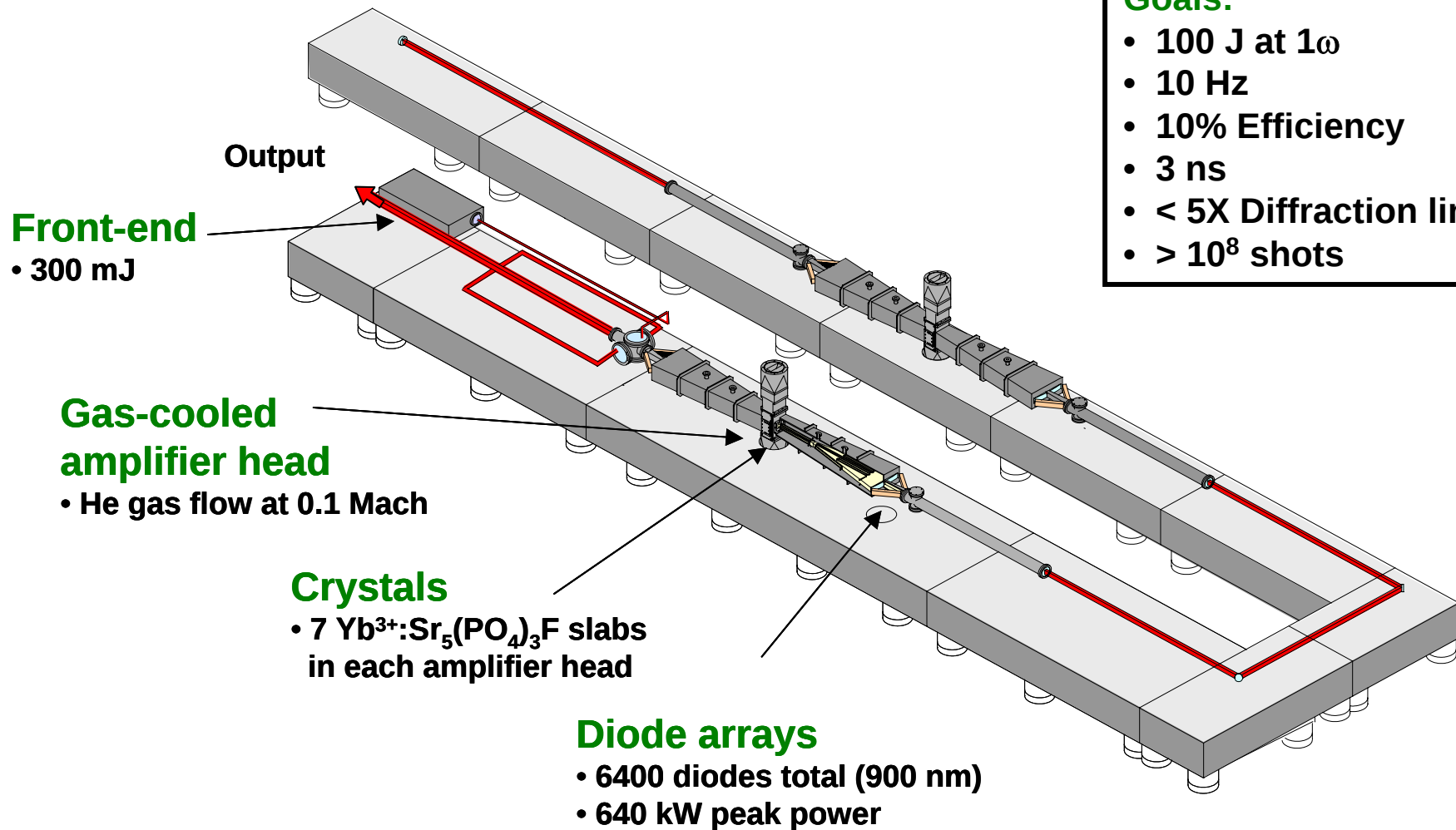
- Beam energy impacts brightness and coherence, and system integration

Mercury Laser is proceeding toward its goals - one amplifier head of the laser has been activated thus far



Goals:

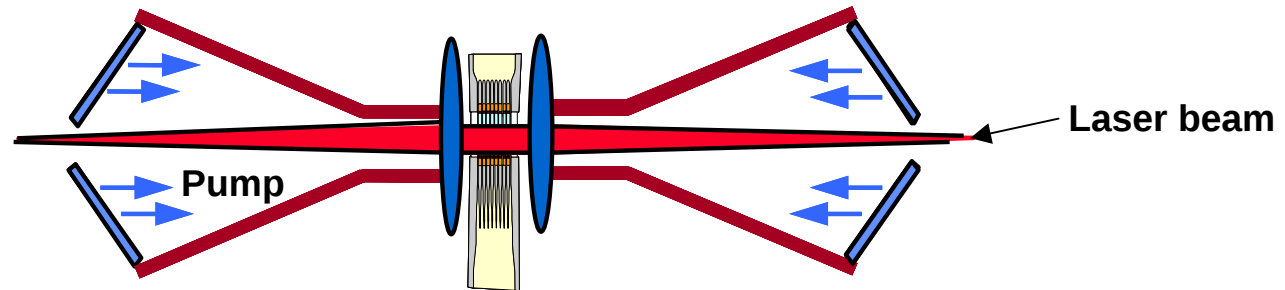
- 100 J at 1ω
- 10 Hz
- 10% Efficiency
- 3 ns
- $< 5X$ Diffraction limit
- $> 10^8$ shots



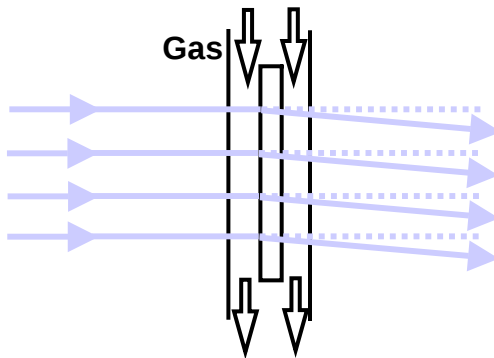
Components of the Mercury Laser will allow rep-rated, efficient operation



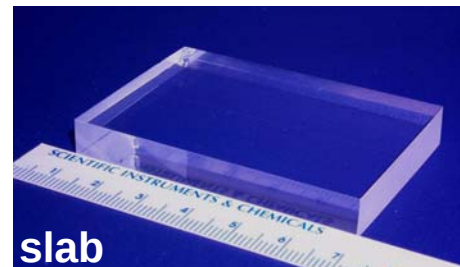
Brewsters angle → Normal incidence amplifier
Compact optical arrangement



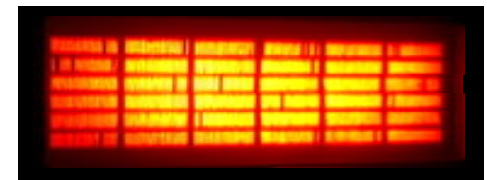
Convective cooling → Forced gas
Allows 10-Hz operation



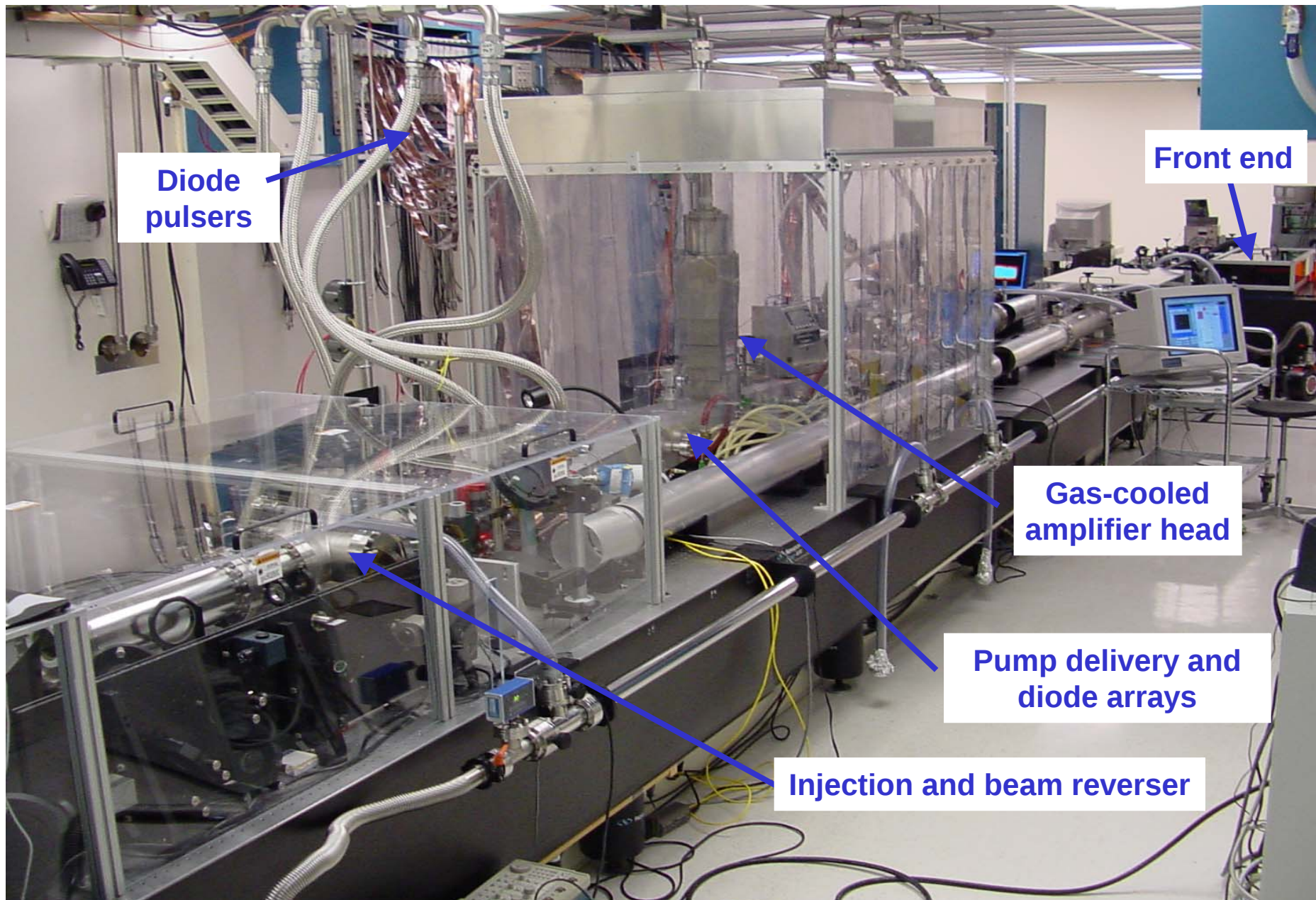
Nd:glass → Yb:crystals
Increased energy storage and efficiency



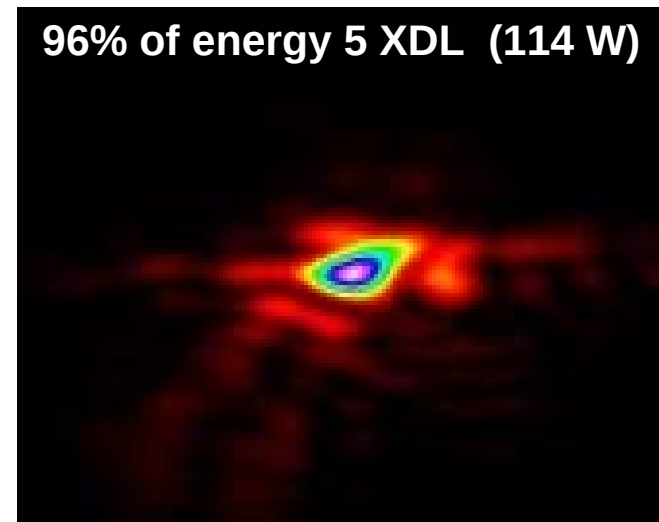
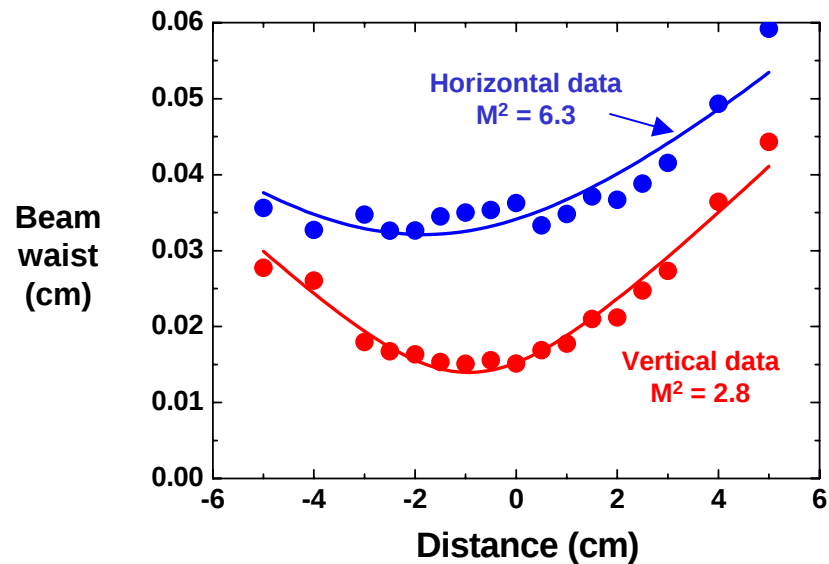
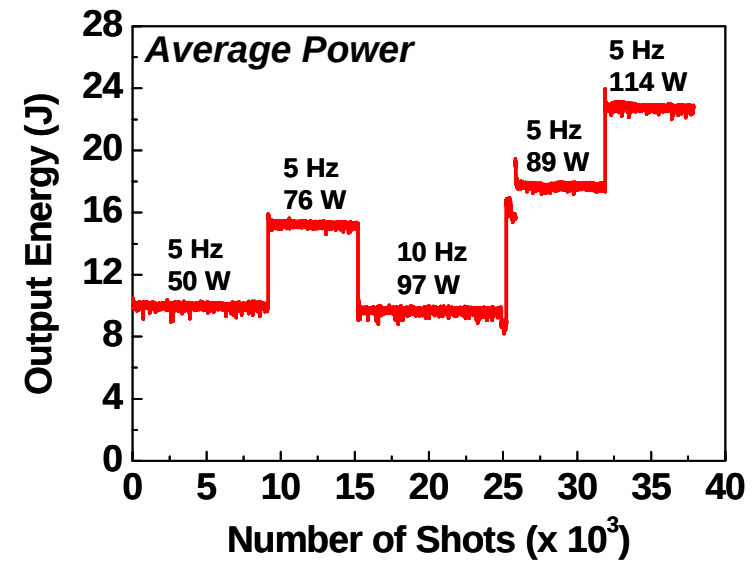
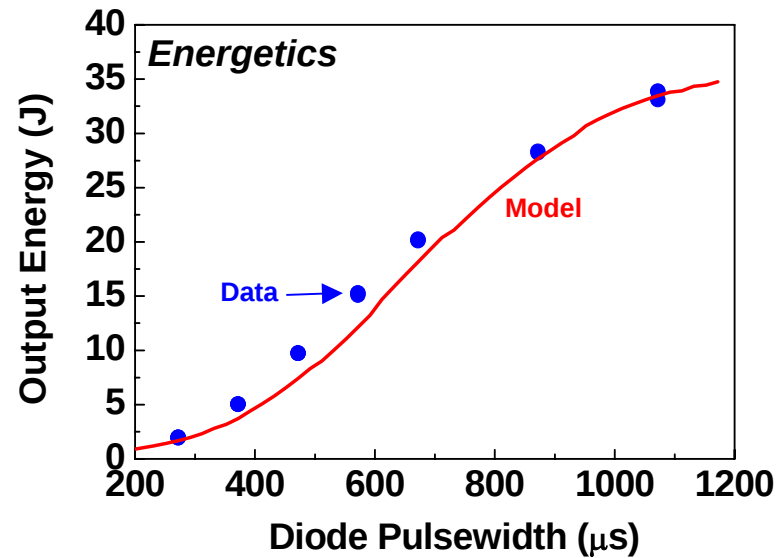
Flash lamps → Laser diodes
Higher efficiency and reliability



Mercury Laser has been operated reliably in single-shot and rep-rated modes 



With a *single* amplifier, Mercury was operated at up to 34 J single shot, and 114 W average power at 5 Hz



The 2-amplifier system will enable 100 J operation

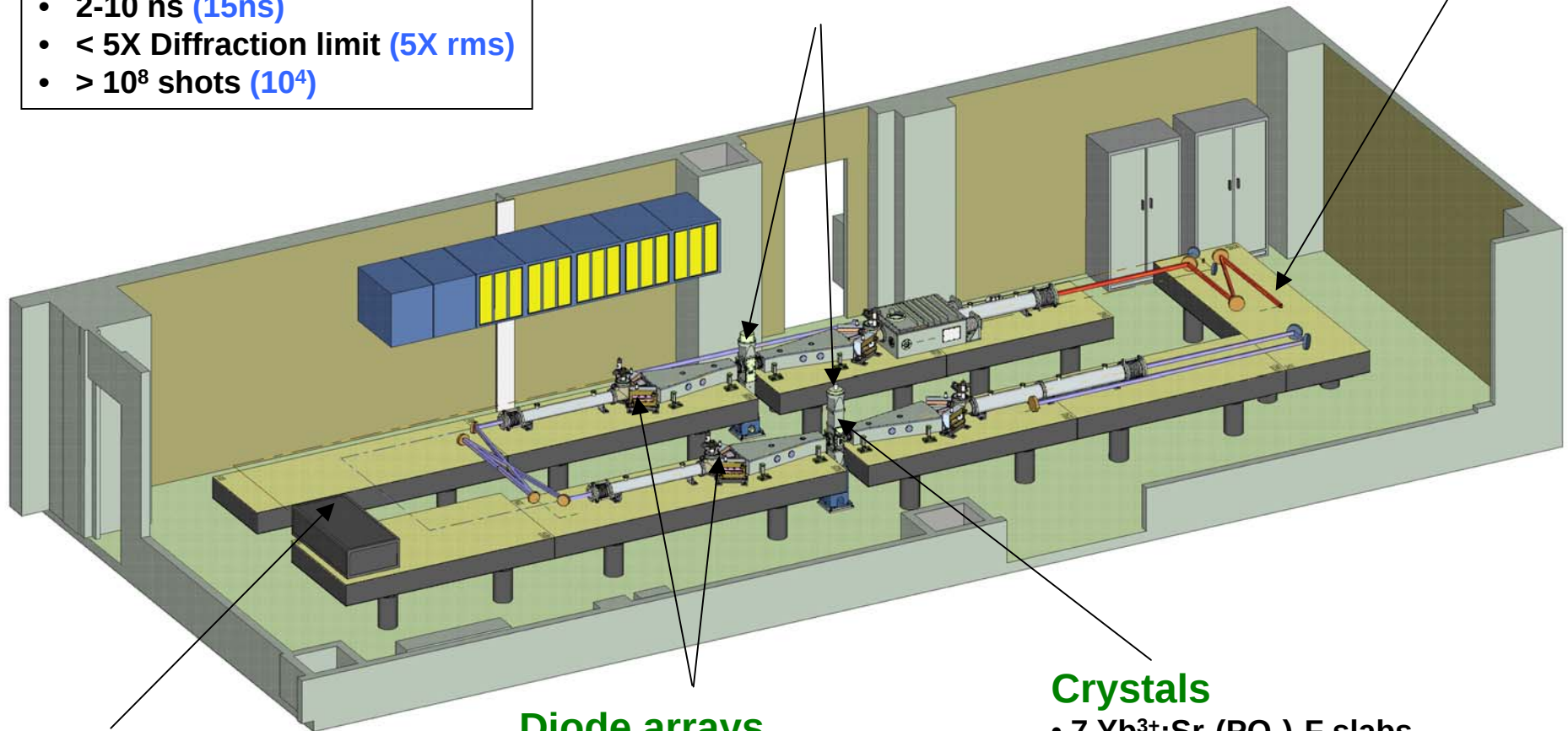
Goals: (performance to date)

- 100 J at 1 ω (24J, 34J SS)
- 10 Hz (5-10Hz)
- 10% Efficiency (4%)
- 2-10 ns (15ns)
- < 5X Diffraction limit (5X rms)
- > 10⁸ shots (10⁴)

Gas-cooled amplifier heads

- Helium gas flow at 0.1 Mach

Output



Front-end

- 300 mJ

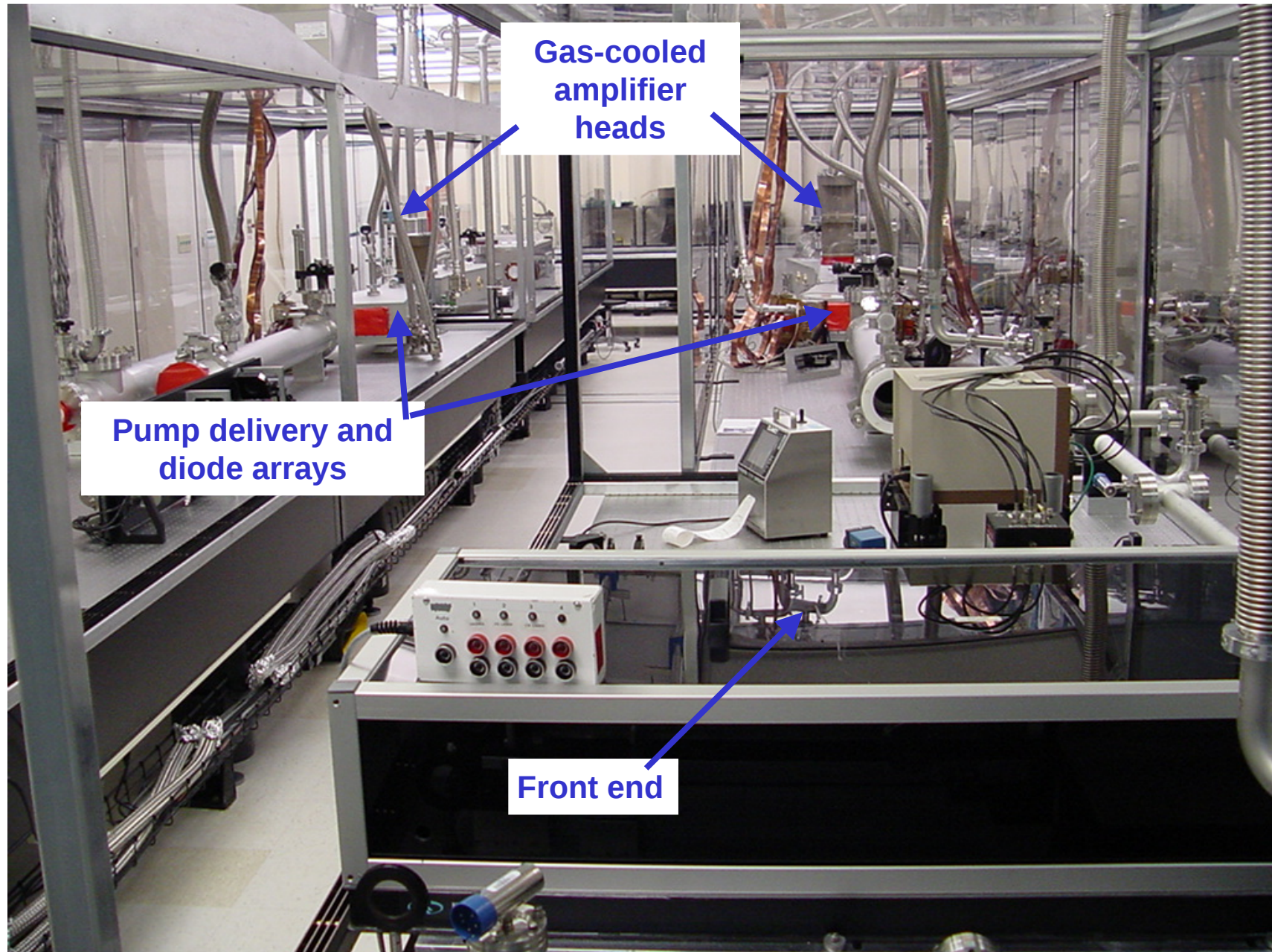
Diode arrays

- 8 diode arrays
- 6624 diodes total (900 nm)
- 730 kW peak power (110W/bar)

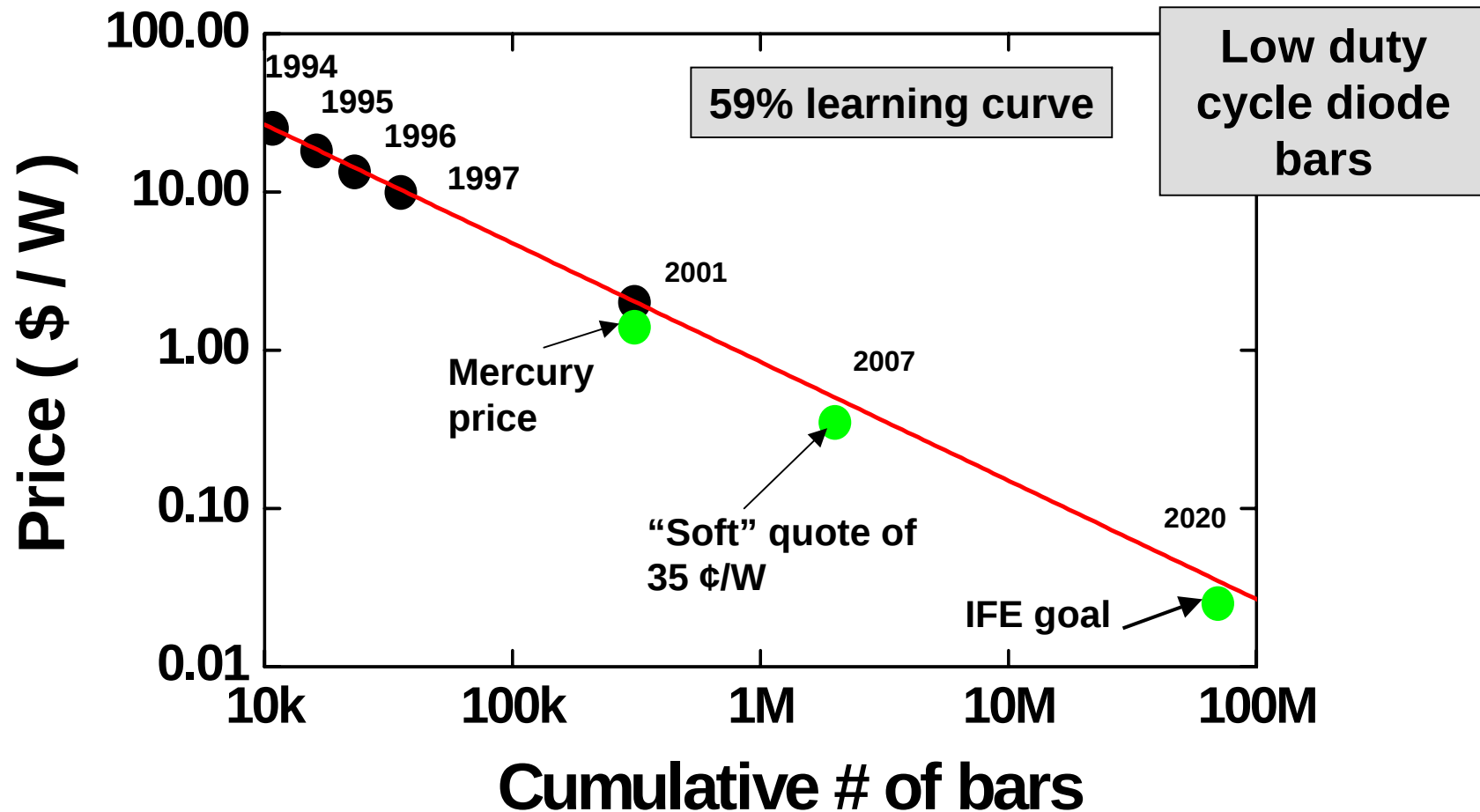
Crystals

- 7 Yb³⁺:Sr₅(PO₄)₃F slabs in each amplifier head

We are currently commissioning the second amplifier needed to achieve 100 J



Learning curve analysis suggests that diode bar prices will drop as the market grows, and can reach price of $< 5 \text{ ¢} / \text{W}$ for a fusion economy

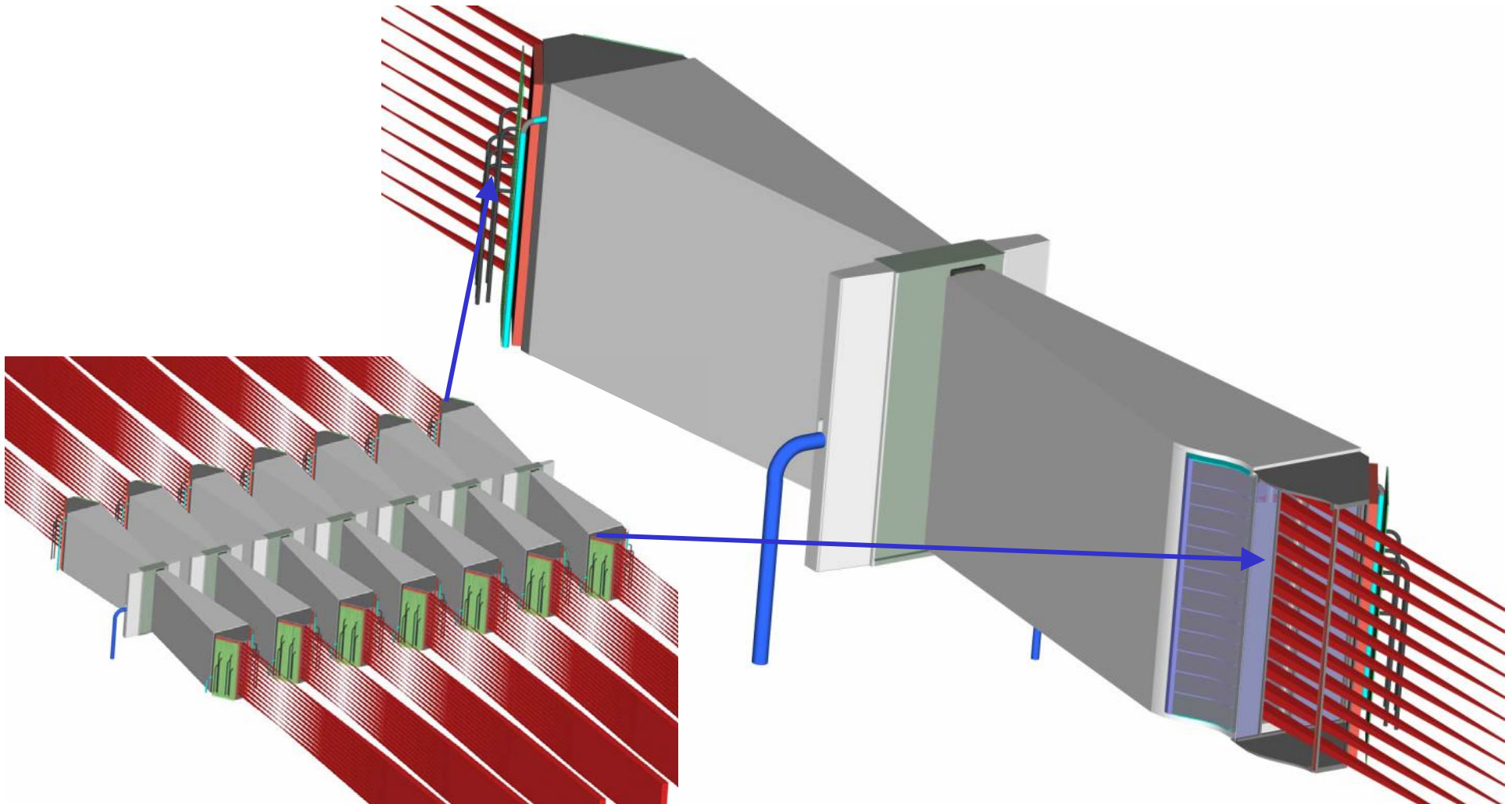


- IFE plant uses ~25,000,000 bars operating at 400 W / bar
- "Bottoms-up" estimate of diode bars is ~3 ¢/W
- Semiconductor industry "minimum function" can have ~60% learning curve
 - *IEEE Spectrum*, June 1980, p.45

IFE beamline involves linear bundling of 12 apertures

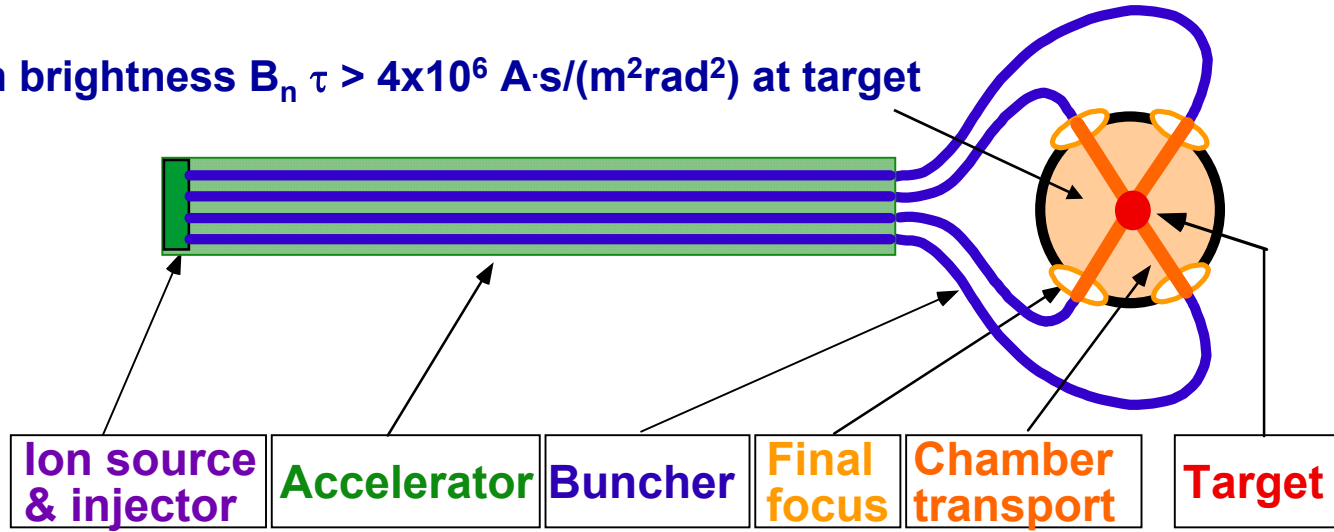


- 12 aperture beamline fed by cooling lines (water and helium), and mounted on space frame structure
- 7 beamlines can be serviced by each water and helium utility
- Beams are re-formatted to a nearly square beam for transport to chamber



Heavy-ion beam requirements flow from designs of accelerators, chambers and targets *that work together*

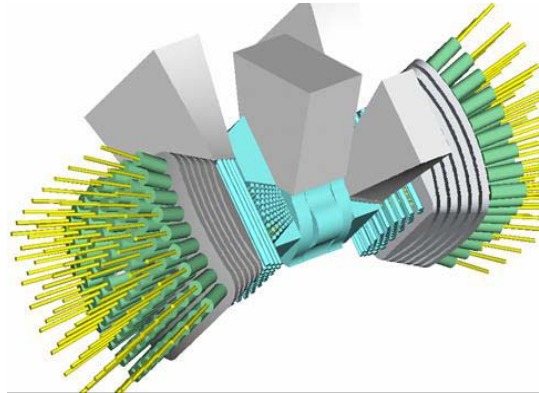
Beam brightness $B_n \tau > 4 \times 10^6 \text{ A}\cdot\text{s}/(\text{m}^2\text{rad}^2)$ at target



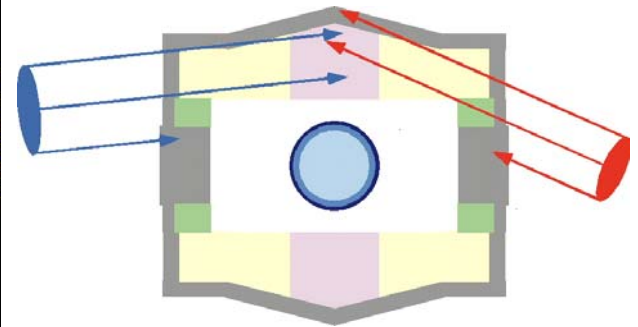
A self-consistent HIF power plant study was recently published in Fusion Science and Technology, 44, p266-273 (Sept. 2003)



Beams at high current and sufficient brightness to focus



Long lasting, thick-liquid protected chambers for 300 MJ fusion pulses @ 5 Hz (See talk by Tillack)



High gain targets that can be produced at low cost and injected (See talks by Lindl, Nobile, Campbell)

Heavy ions can apply to a variety of targets, chambers, and focusing schemes, but a key motivation is the desirability of using thick liquid-protected fusion chambers with much reduced materials development

Approaches emphasized in the U.S. program

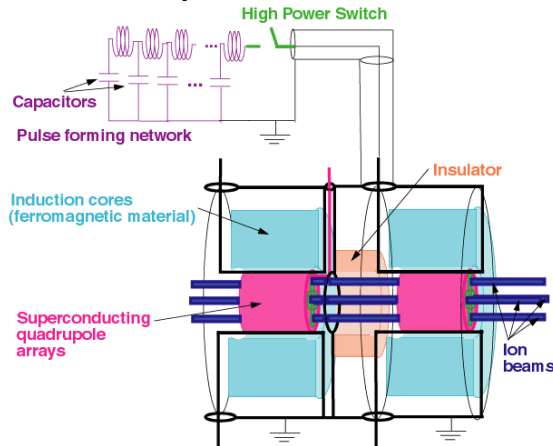
(primary emphasis)

(secondary)

Accelerator	Target	Focusing	Chamber
Induction Linac	Indirect Drive, Distributed Radiator	Ballistic, Neutralized	Thick-Liquid-Protected Wall
RF Linac + Storage Ring	Indirect Drive, Hybrid Target	Ballistic, Vacuum	Thin-Liquid-Protected Wall
Induction Recirculator	Indirect Drive, Fast ignition	Pinch Modes	Solid Dry Wall
High Gradient Line Linacs	Direct Drive, Aspherical		Granular-Solid Flow Protected Wall

Example of critical physics issue: drift compression of bunch length by factors of 10 to 30

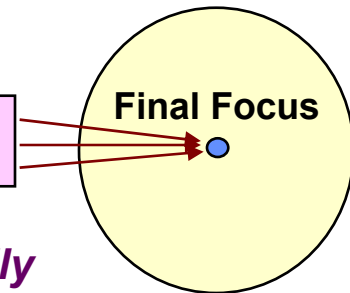
Induction acceleration is most efficient at $\tau_{\text{pulse}} \sim 100$ to 300 ns



Bunch tail has a few percent higher velocity than the head to allow compression in a drift line

Target capsule implosion times require beam drive pulses ~ 10 ns

Drift compression line



The beam must be confined radially and compressed longitudinally against its space-charge forces

Issues that need more study and experiments:

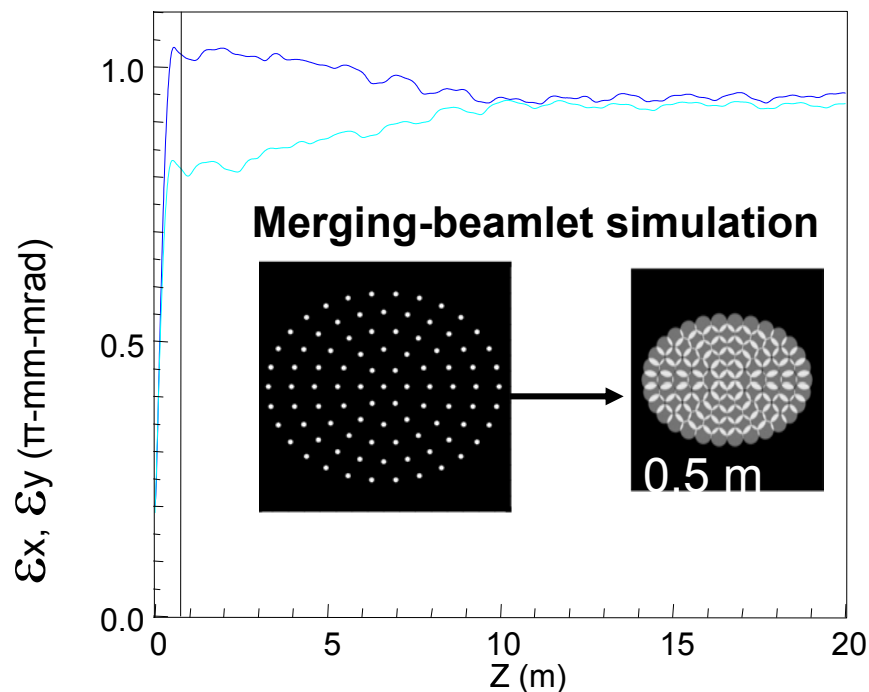
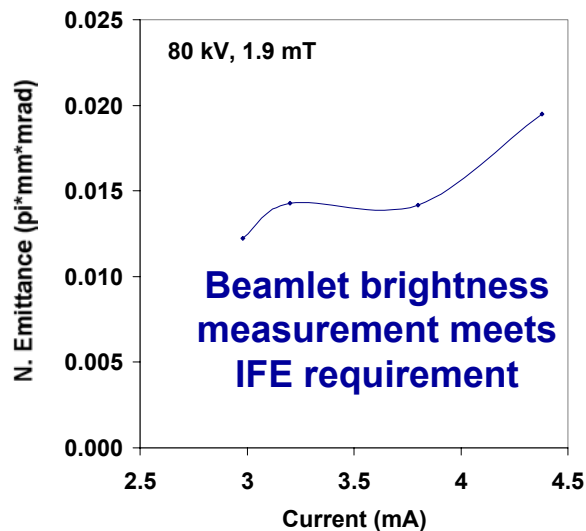
1. Matching beam focusing and space-charge forces during compression.
2. Beam heating due to compression (conservation of longitudinal invariant)
3. Chromatic focus aberrations due to velocity spread

Source-Injector Test Stand (STS – operating at LLNL)

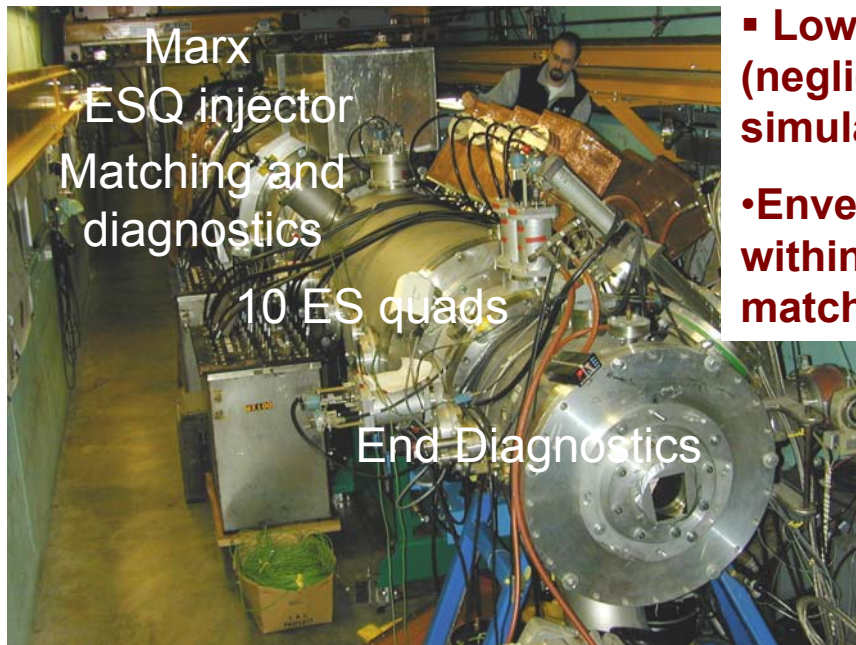


Injector Brightness:
source brightness,
aberration control with
apertures, beamlet
merging effects

(Recent paper submitted
for publication in Review
of Scientific Instruments.
Simulation published Jan
2003 Phys. Rev Special
Topics-Accelerators and
Beams)

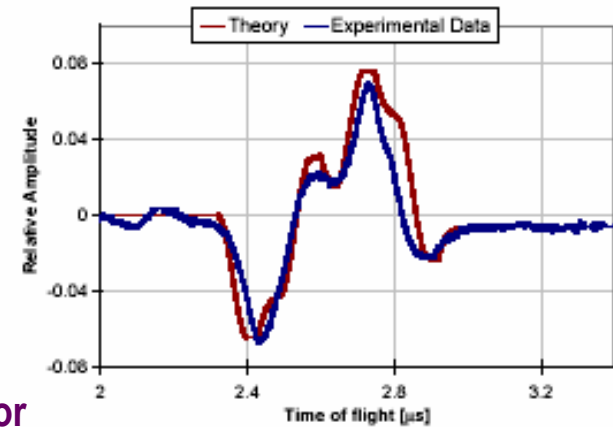


High Current Experiment (HXC- operating at LBNL)



- Low $\varepsilon_n \sim 0.5 \pi$ mm-mr (negligible growth as simulations predict)
- Envelope parameters within tolerances for matched beam transport

(Recently submitted for publication in Physical Review Special Topics- Accelerators and Beams)

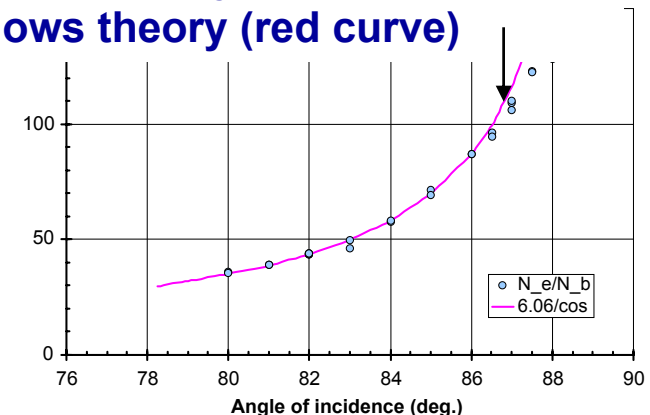


↑ Propagation of longitudinal perturbation launched at $t = 0$.

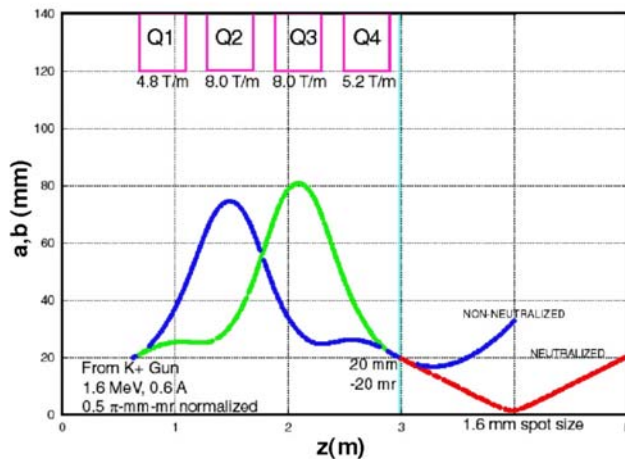
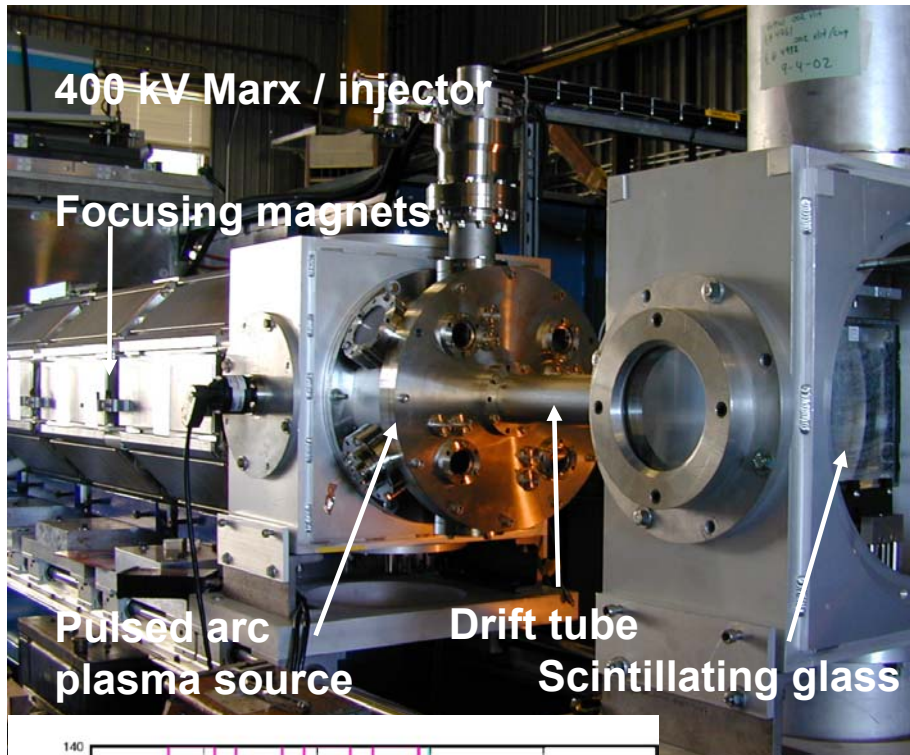
New Gas-Electron Source Diagnostic (GESD) shows secondary electrons per ion lost follows theory (red curve)



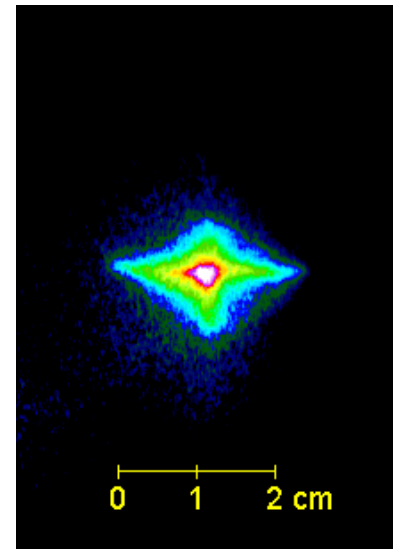
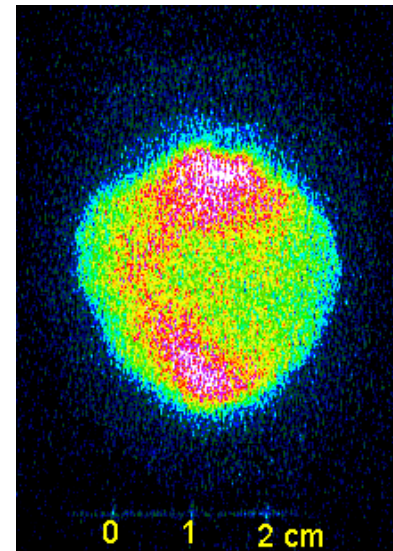
Four magnetic quadrupoles and additional diagnostics have been recently added to study gas and secondary electron effects



Neutralized Transport Experiment (NTX- operating at LBNL)



Envelope simulation of NTX focusing with and without plasma

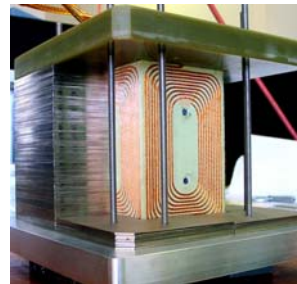


Superconducting magnet development

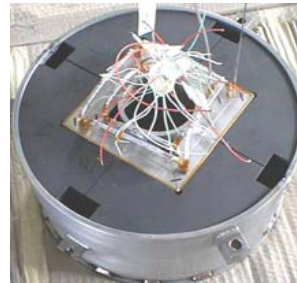
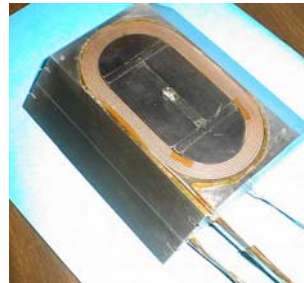


Four prototypes were fabricated and tested

AML



LLNL



- The LLNL design was selected for further development (December 2001)
- A cryostat housing two quads, and one optimized prototype magnet was fabricated in FY02

Understanding how the beam distribution evolves passing sequentially through each region requires an integrated experiment

- The beam is collisionless, with a “long memory”
- Its distribution function --- and its focusability --- integrate the effects of applied and space-charge forces along the entire system

NOW

STS-
injection



HCX-
transport



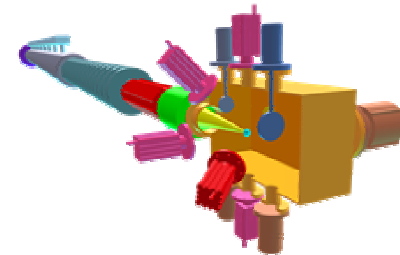
NTX-
focusing



Combine these
elements and add
acceleration and
drift compression

NEXT

A source-to-target
integrated beam experiment
(IBX) which sends a high
current beam through
injection, acceleration, drift
compression, and final
focus





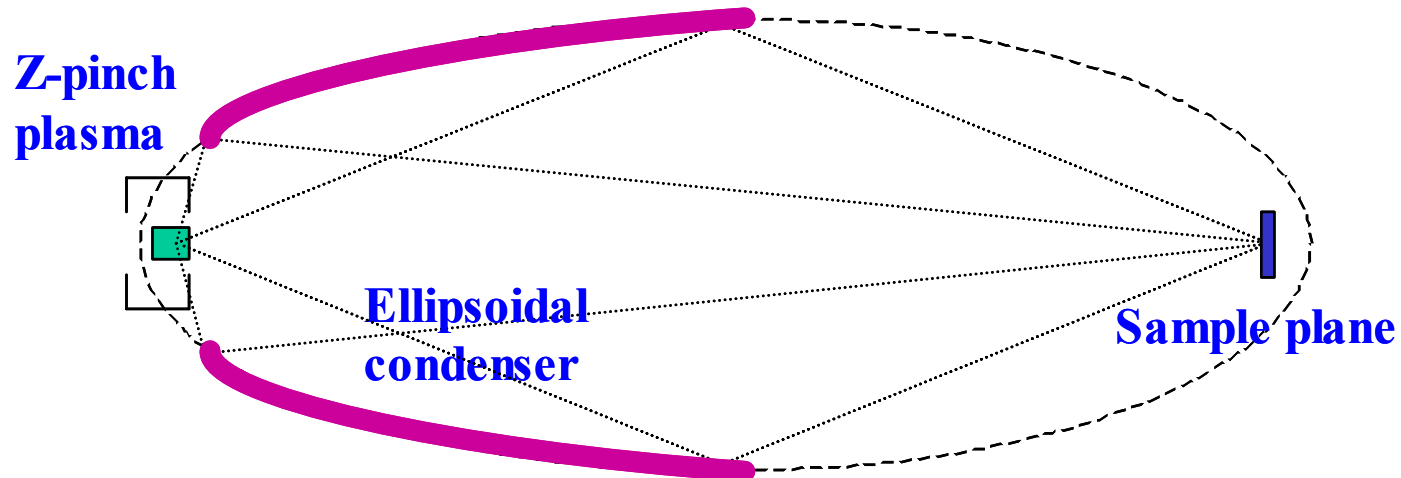
XAPPER Mission

- ❑ XAPPER is to perform rep-rated, x-ray exposures to look for “sub-threshold” effects such as roughening and thermomechanical fatigue.
- ❑ XAPPER provides large doses of soft (100-400 eV) x-rays;
Dose is a reasonable figure of merit, not fluence.
- ❑ XAPPER cannot match exact x-ray spectrum, but it can replicate a selected figure of merit. For example, the peak surface temperature, dose, stress, etc. that would occur in a real IFE system can be matched on XAPPER.
- ❑ XAPPER will be used in the study of x-ray damage to optics and chamber wall materials.

PLEX LLC produces a source that meets our needs



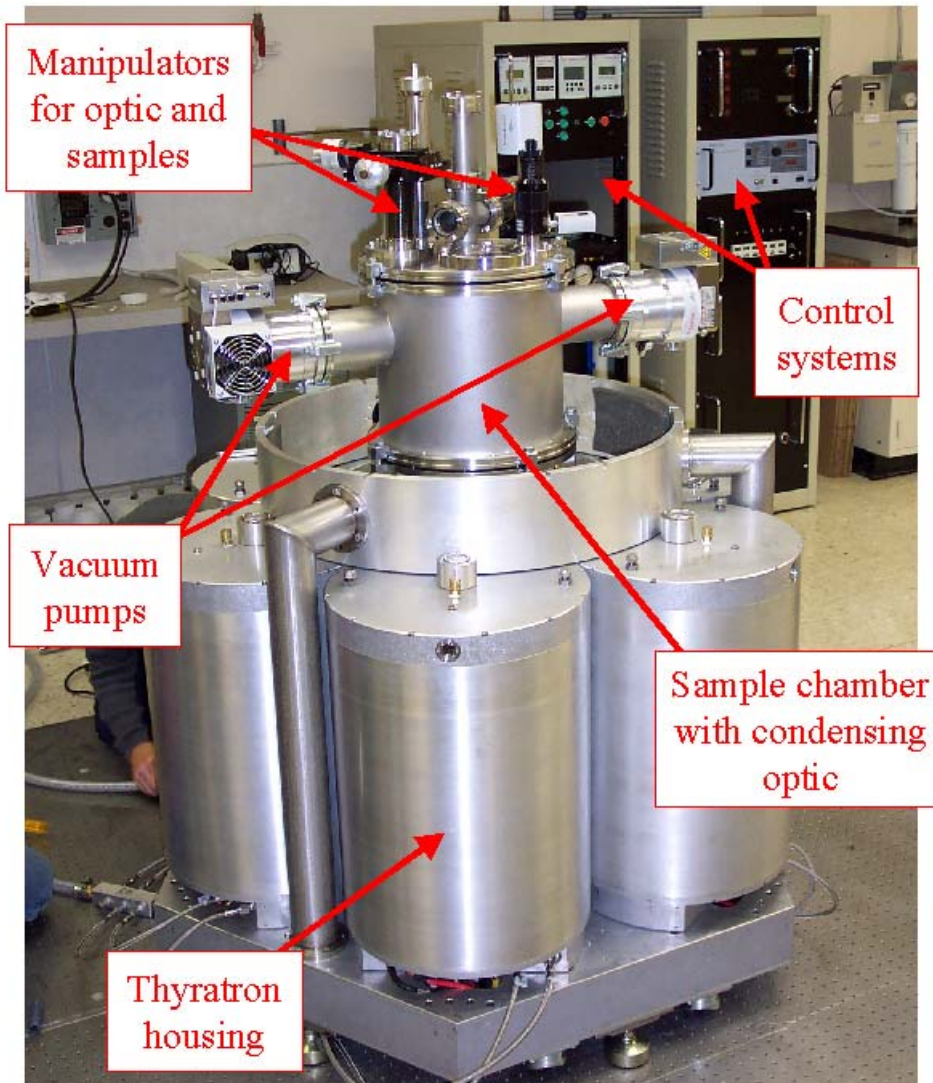
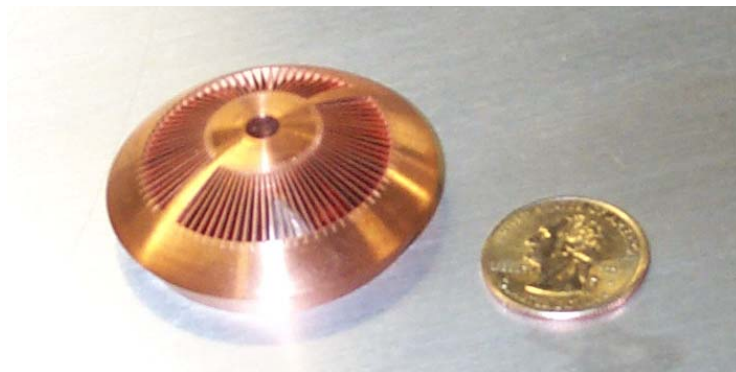
- ❑ Uses a Z-pinch to produce x-rays:
 - Pinch initiated by ~ 100 kA from thyratrons
 - Operation single shot mode up to 10 Hz
 - Use of a focusing optic helps keep debris off samples
 - Several million pulses before minor maintenance



The XAPPER experiment is used to study damage from rep-rated x-ray exposure



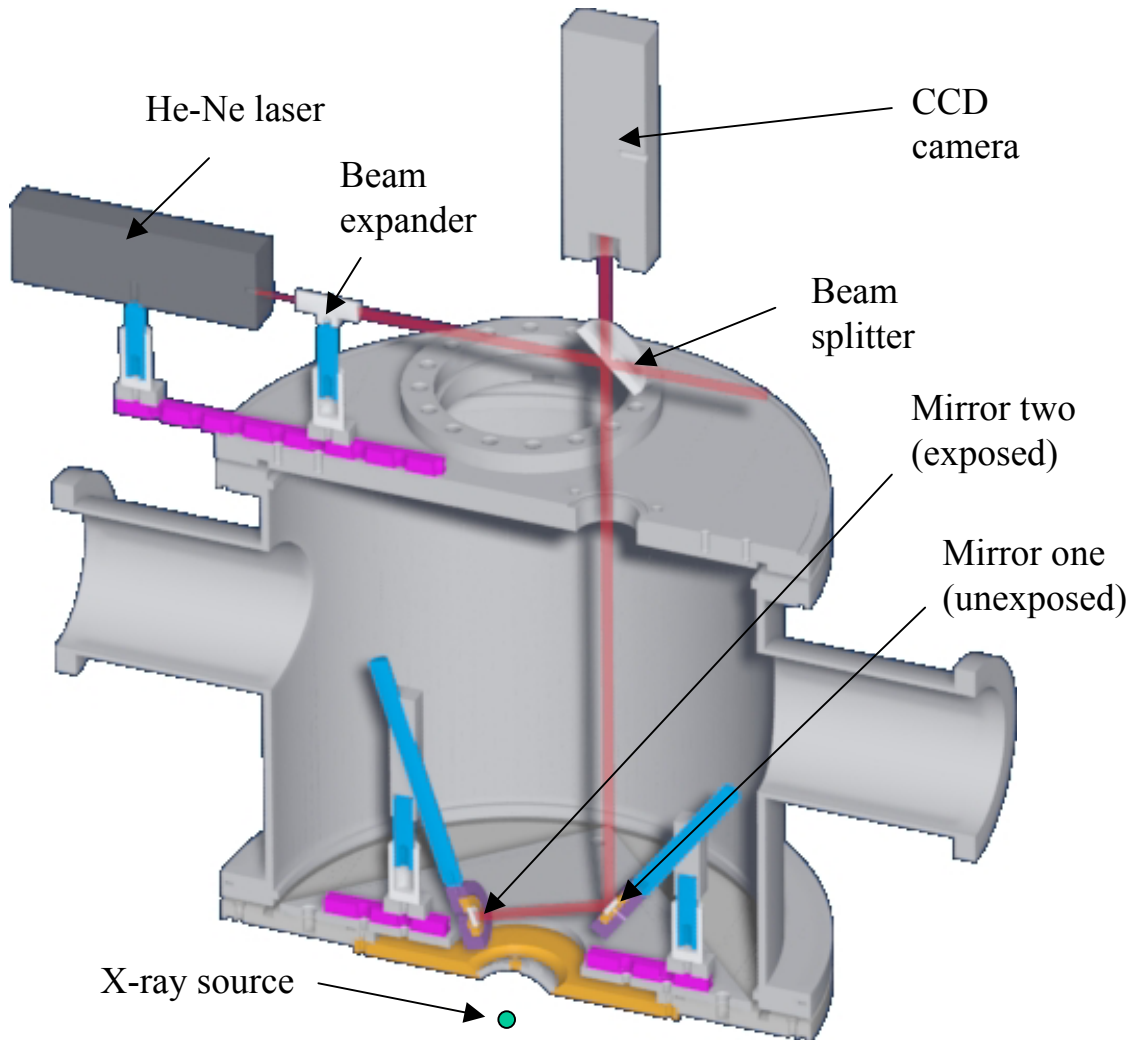
- ❑ Source built by PLEX LLC; delivered 10/02; operational 11/02; system testing and characterization now complete
- ❑ Operates with Xe (113 eV), Ar (250-300 eV), N₂ (430 eV)
- ❑ Use of foil comb helps keep debris from optic and samples



In-situ optics damage testing is underway



Goal: Observe optic being damaged in real time and in-situ



Concept: Following x-ray pulse, interrogation beam (HeNe) injected, sent off auxiliary mirror, strikes sample mirror, returns, and is sent to CCD

Neutrons can cause damage that leads to optical absorption

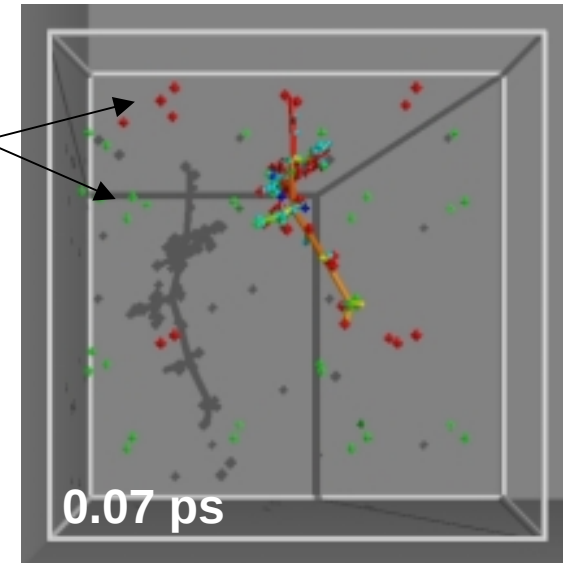


- Neutrons alter the structure of the optical material; defects absorb a portion of the laser energy during subsequent pulses
- Effect measured experimentally and modeled computationally; two items work in our favor:
 - Concentration of damage saturates at relatively low doses
 - Damage can be thermally annealed
- Still, optical absorption in transmissive optics pushes design towards reflective or very thin transmissive optics

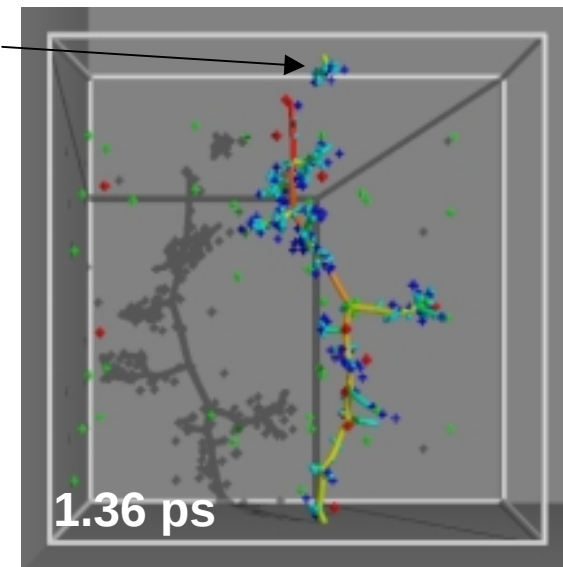
2 keV Recoil in Fused Silica (0.4% OH Content)

Structural Defects

- ODC
- NBOHC



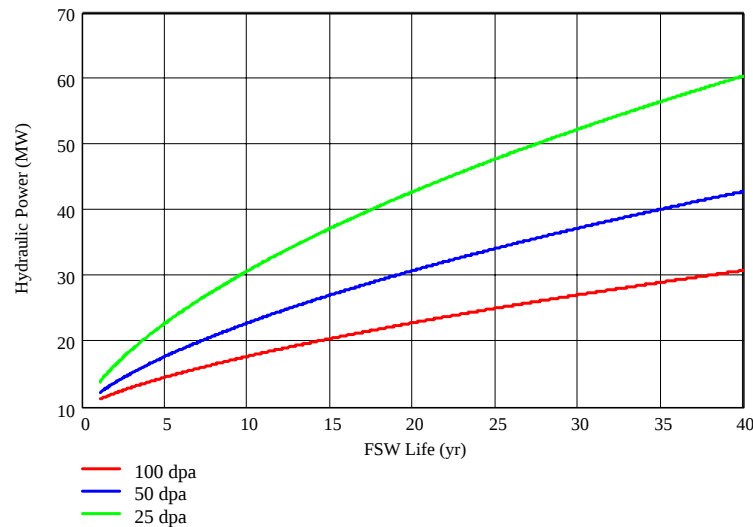
Replacement



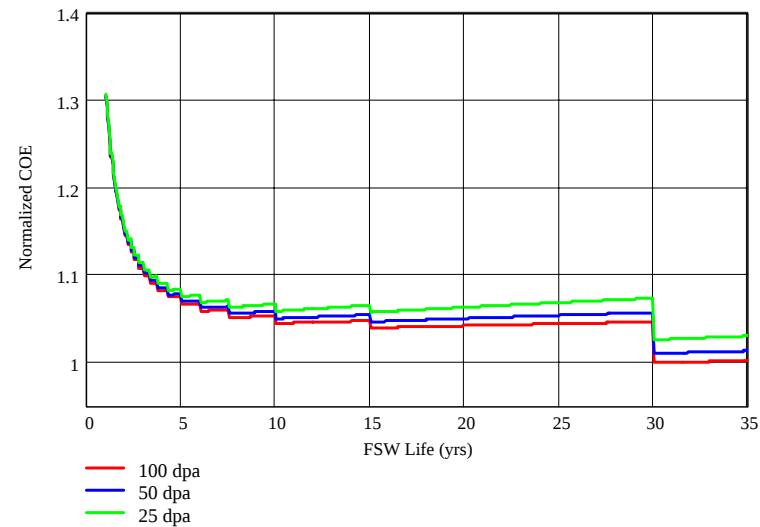
Effects of lower neutron damage limit were investigated for the HYLIFE-II chamber



Pumping Power



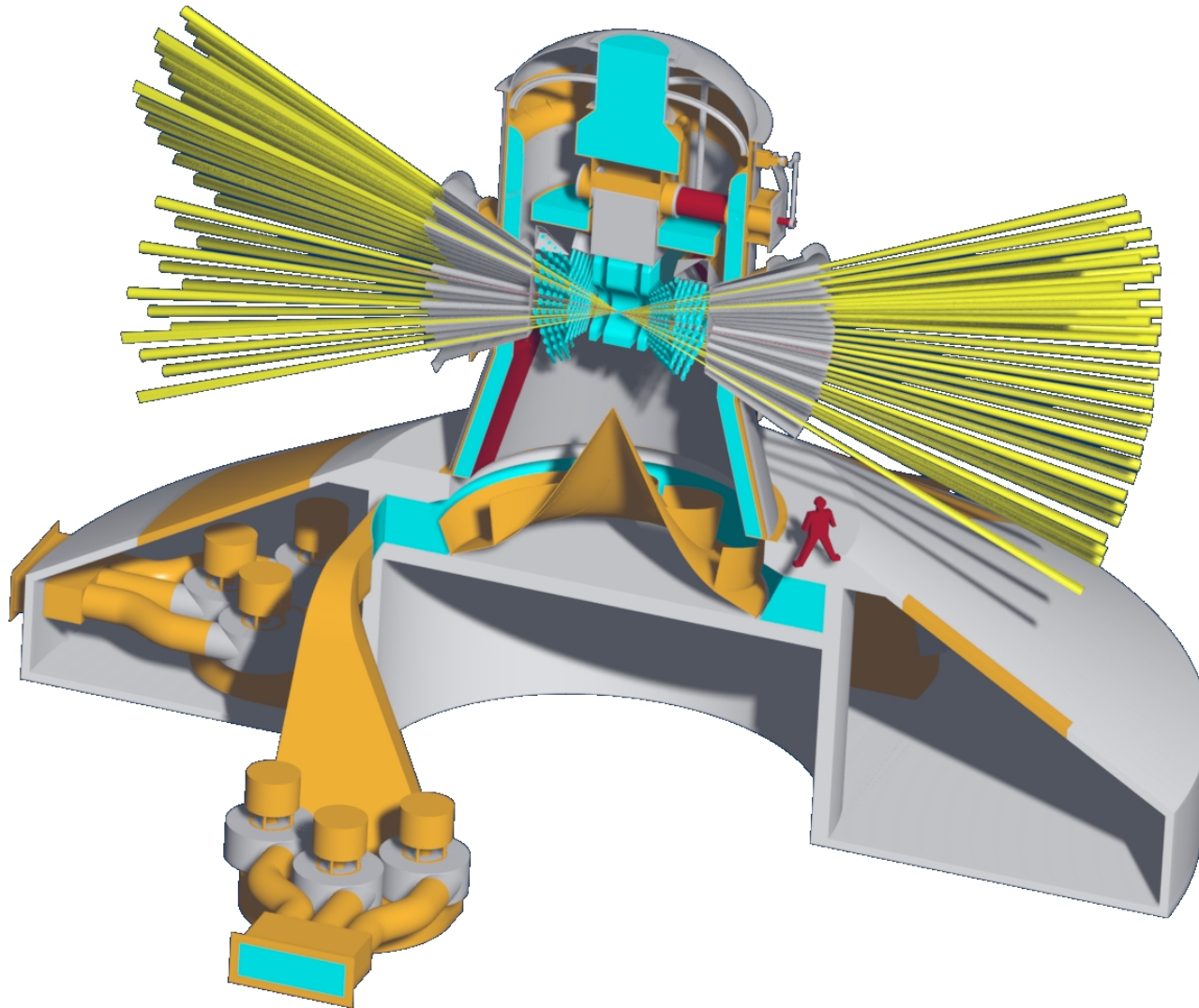
Normalized COE



- **Pumping power increases with decreasing damage limit for a fixed wall life.**
- **Longer lifetimes require a thicker fluid layer and higher pumping power.**
- **A wall life greater than 10 years gives a cost of electricity within ~5% of full 30 year wall life.**



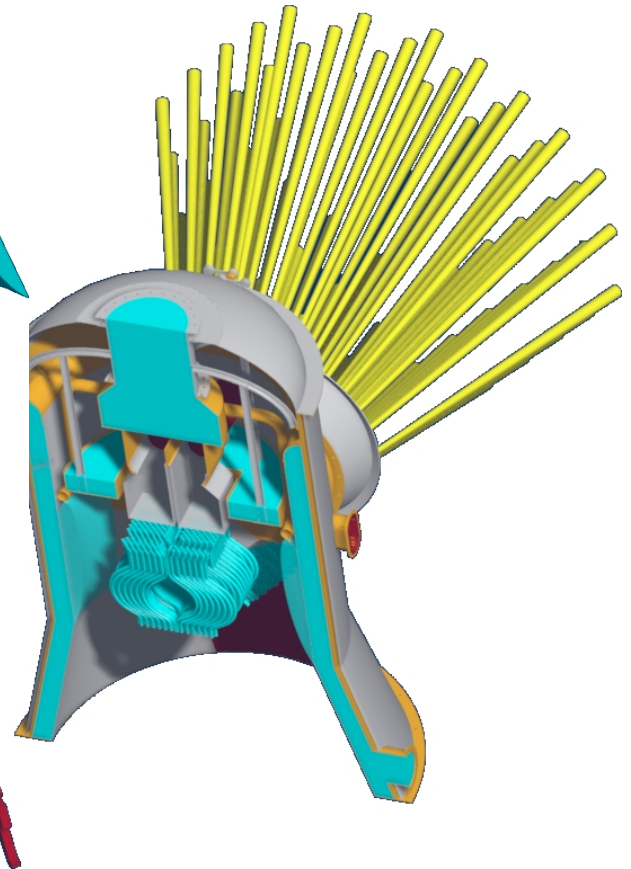
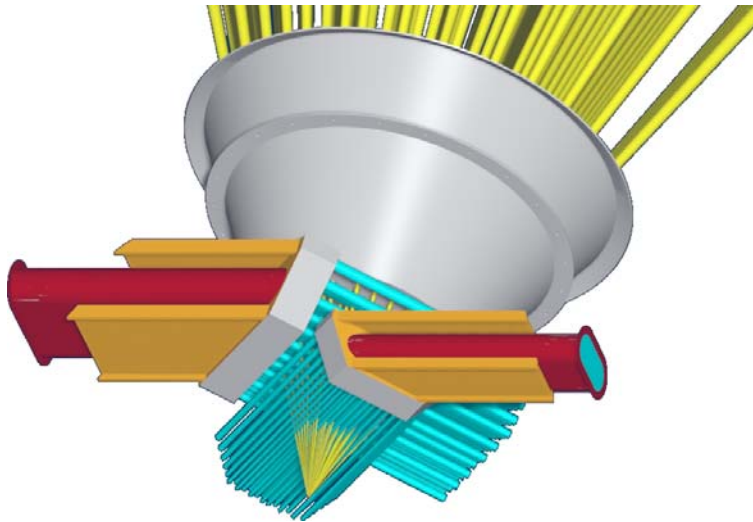
Detailed HYLIFE-II parametric CAD has been developed



Physics &
Advanced Technologies



Chamber construction features were developed to allow for ease of maintenance



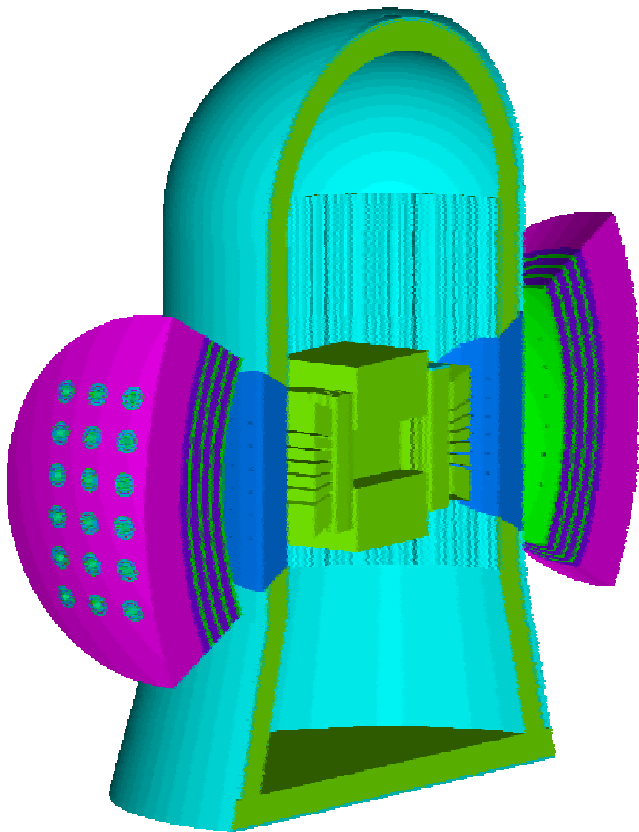
- **Broad features of maintenance scheme**
 - Depends only on vertical cranes and simple robotic manipulators
 - Does not compromise any functional capability of previous chamber
 - Most internal components assembled as a single modular unit to be replaced in entirety
 - All structures down to first-wall easily accessible



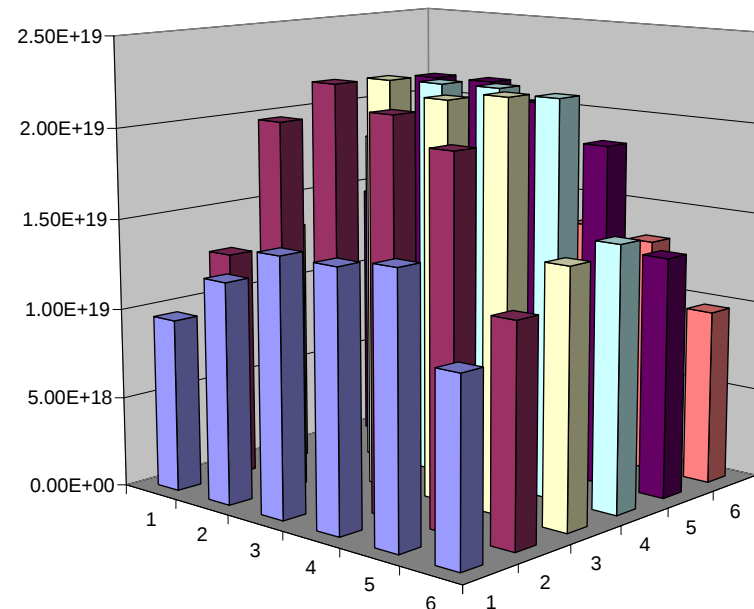
Work has progressed to detailed 3D neutronics models - predicting >30 year magnet lifetime



3D Tart model for HYLIFE-II



Fast neutron flux for 36 magnet array



- There is a strong peaking of the fast neutron fluence at the center of the magnet array due to neutron scattering between neighboring penetrations.
- Estimated magnet life is 40-90 years depending on beam-to-structure clearance.

Accident analyses have been completed for HYLIFE-II and SOMBRERO

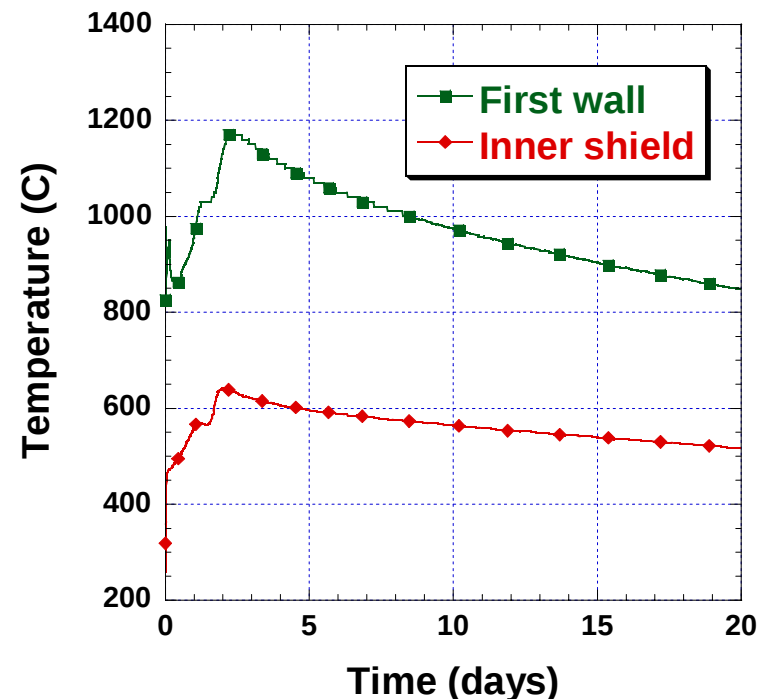


HYLIFE-II

- Loss-of-flow and loss-of-coolant accidents analyzed
 - Key Result: Accident dose = 0.5 rem (average weather conditions and ground release) which meets no-evacuation criteria
-

SOMBRERO

- Loss-of-flow with simultaneous loss-of-vacuum accident analyzed (worst case accident)
- Key Result: Simple modifications reduce off-site dose to acceptable level. Graphite oxidation is an issue.



Temperature history with decay heat and oxidation

Summary



- **LLNL is conducting R&D in many areas related to the development of IFE**
- **Work covers many approaches including**
 - **Direct-drive, indirect-drive and fast-ignition targets**
 - **Laser and heavy-ion drivers**
 - **Thick-liquid-wall and dry-wall chambers**
- **Other activities include**
 - **Material issues for first walls and optics**
 - **Systems modeling and integration**
 - **Neutronics, activation, safety and environmental assessments**