Overview of IFE Status and Plans

John Lindl - LLNL
Fusion Energy Program Leader

University of California
Lawrence Livermore National Laboratory

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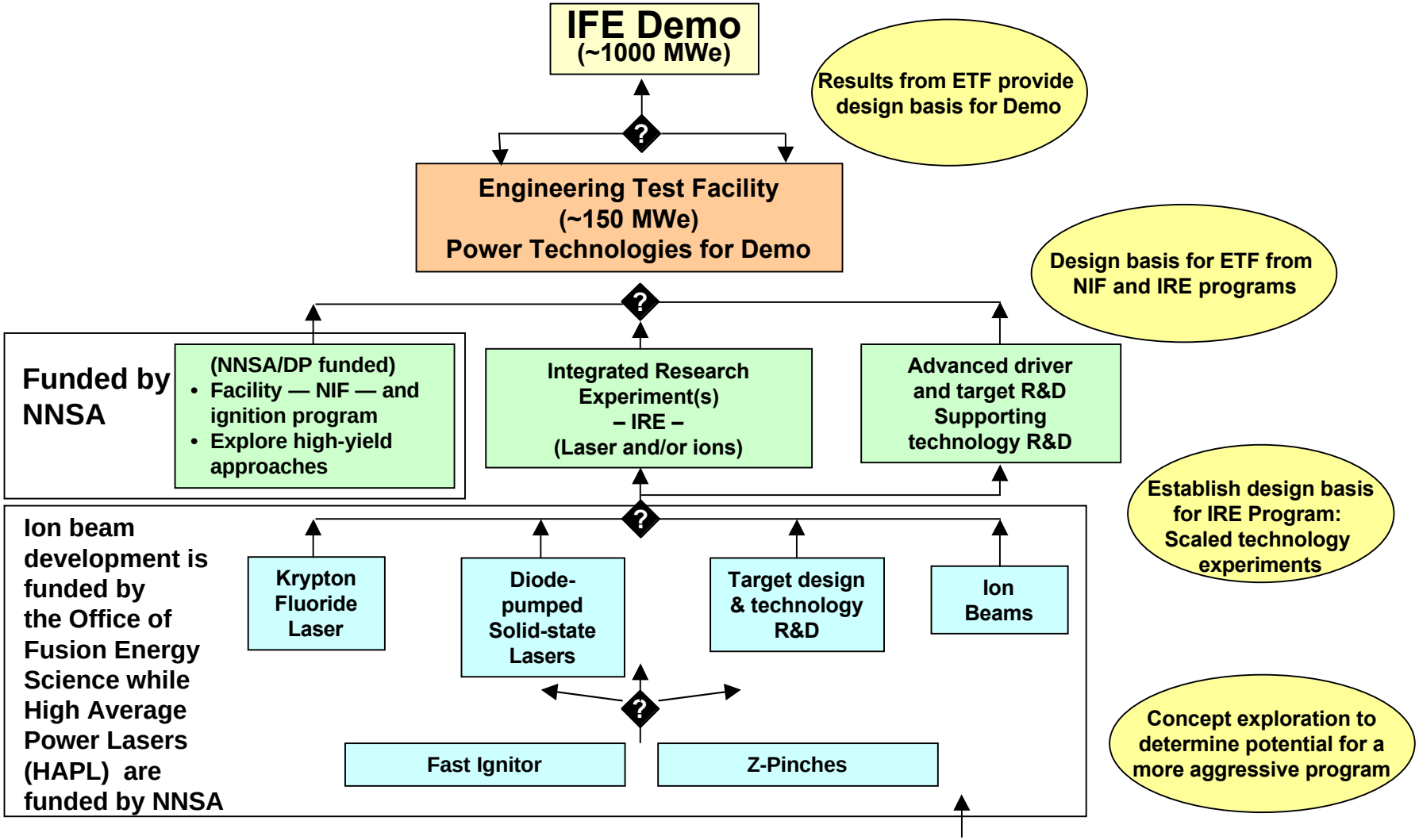
The U.S. IFE community is aggressively pursuing the integrated R&D program for lasers and ion beams developed in 1999



Outline/Summary

- NIF is back on track and will soon begin experiments with first 4 beams

- For Heavy Ion Fusion, experiments on ion sources, high current transport and neutralized focusing are now in operation or nearing completion. An Integrated Beam Experiments (IBX) at the PoP scale is proposed prior to construction of an IRE

- Most of the experiments needed to move the baseline NNSA funded laser IFE approaches to the next level are under construction. Assuming success an IRE will be proposed in FY05.

- Progress at the concept exploration level on fast-ignition targets and z-pinch drivers has been sufficient to warrant a more aggressive program

NIF Conventional Facilities were completed in September 2001

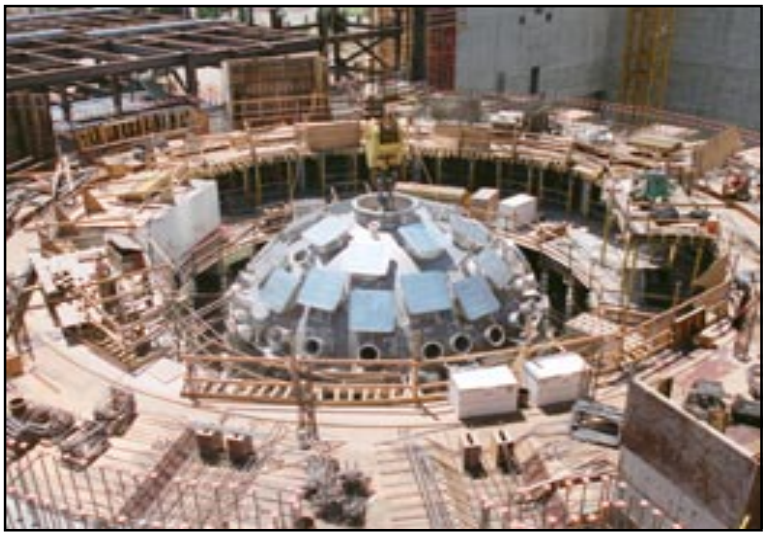
Installation of optical components in laser bay two for the first quad of beams is underway

Installation of Beamline infrastructure in 1st cluster (48 beams) was completed in October 2001

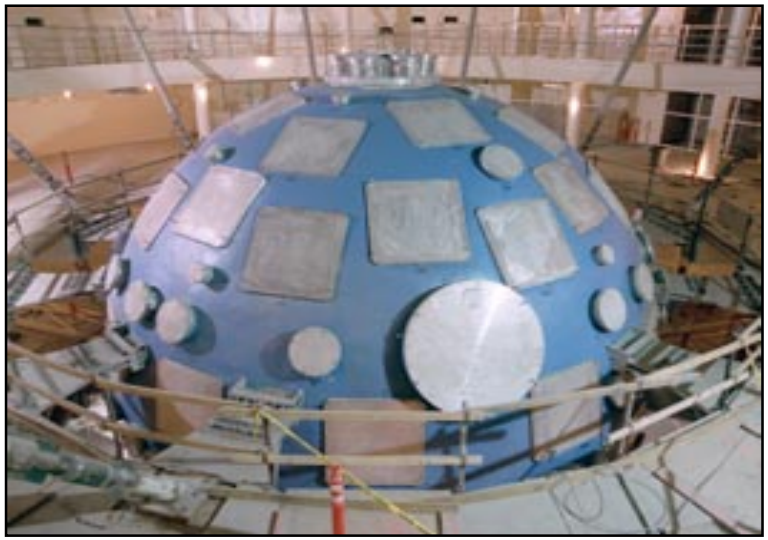
— First flashlamp light through the main amplifier for the first quad occurred in June 2002

The National Ignition Facility Target Chamber is complete

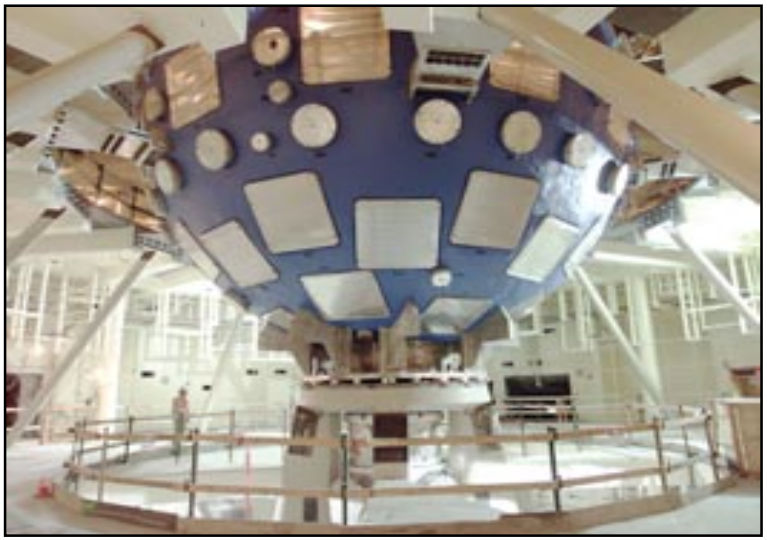
June 1999



June 1999



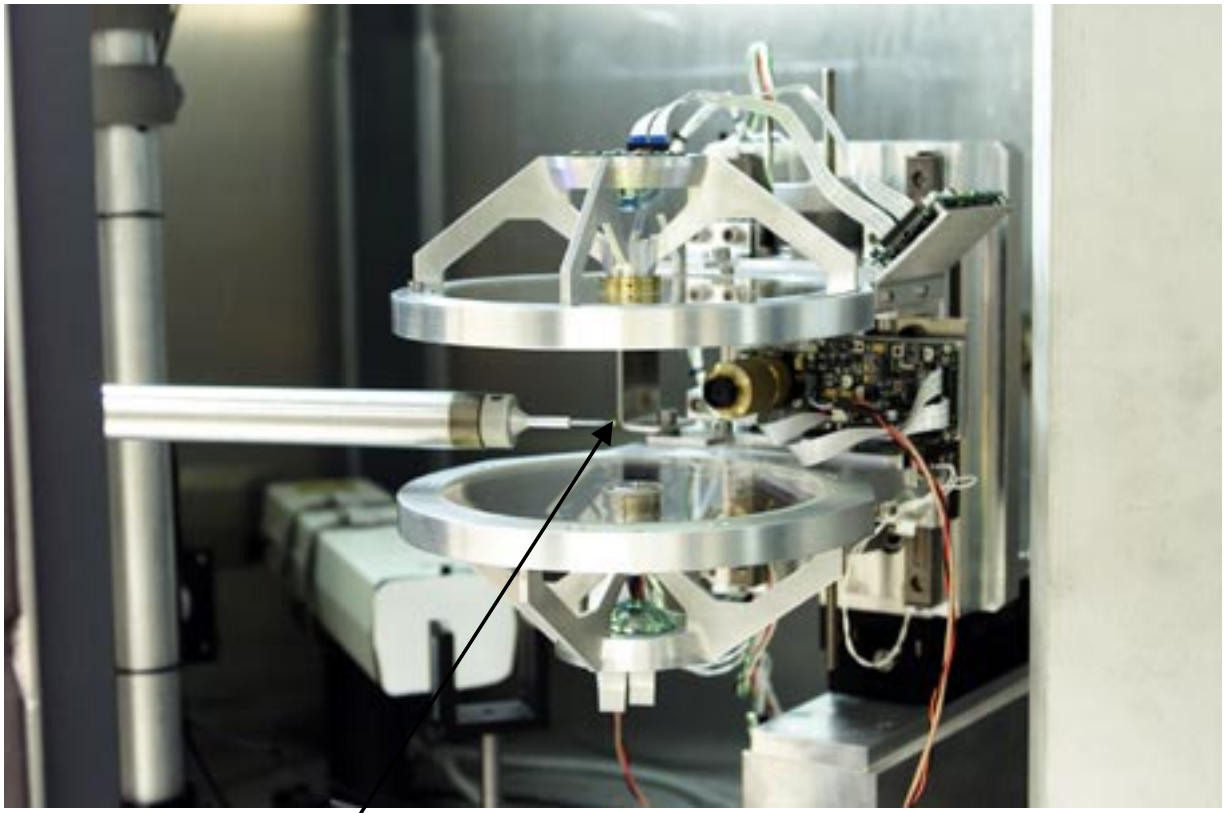
November 2000



March 2001

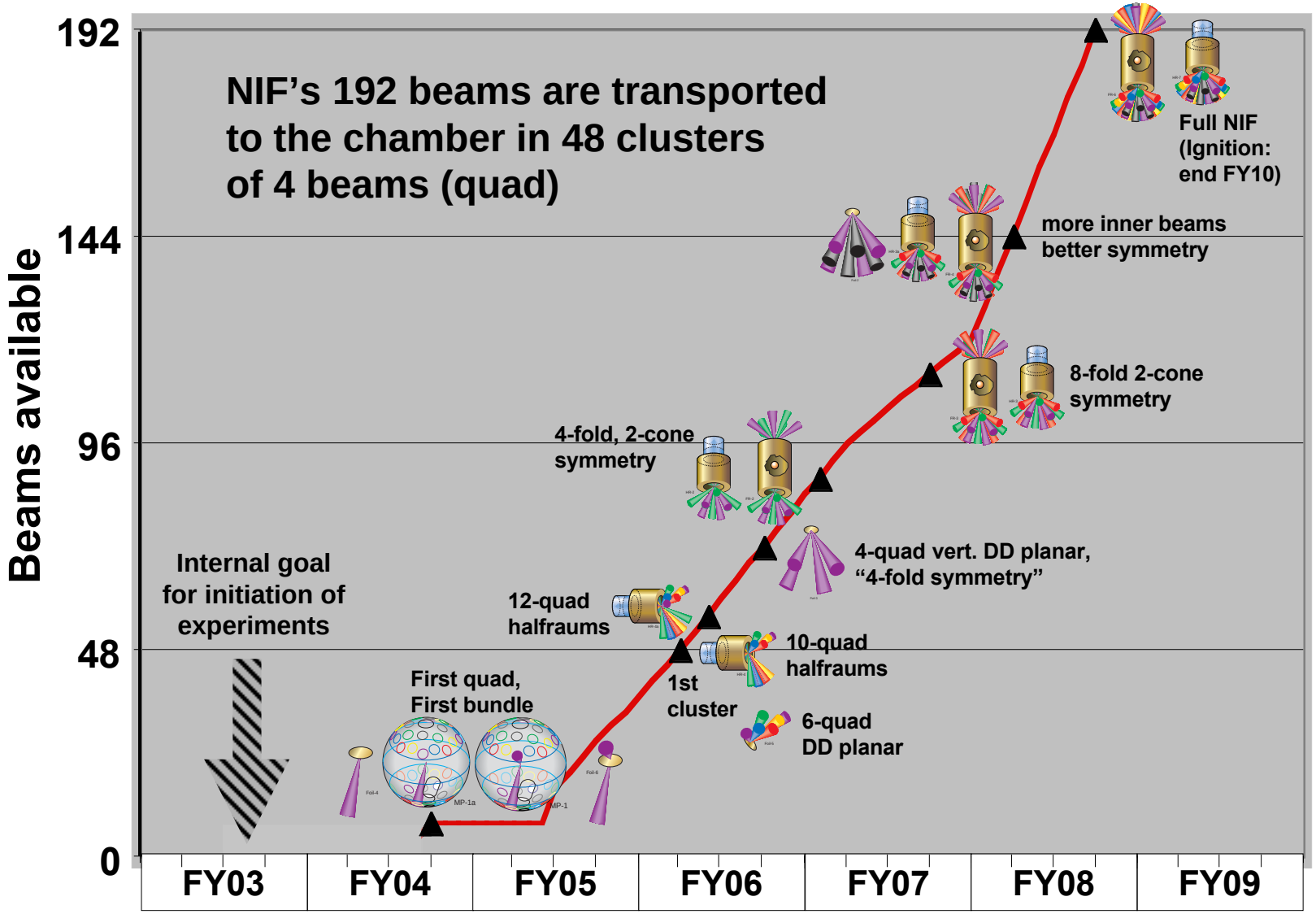
The NIF target positioner is being assembled and tested

The NIF Target Alignment Viewing system is being tested



NIF target

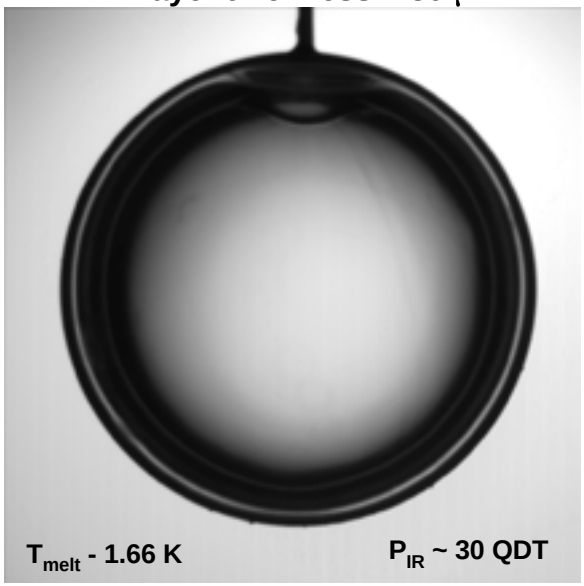
NIF's experimental program will begin soon after first light



Sufficiently smooth cryogenic fuel layers have been formed. Cryogenic hohlraum engineering has begun

Sufficiently smooth fuel layers of desired thickness have been produced using "IR layering"

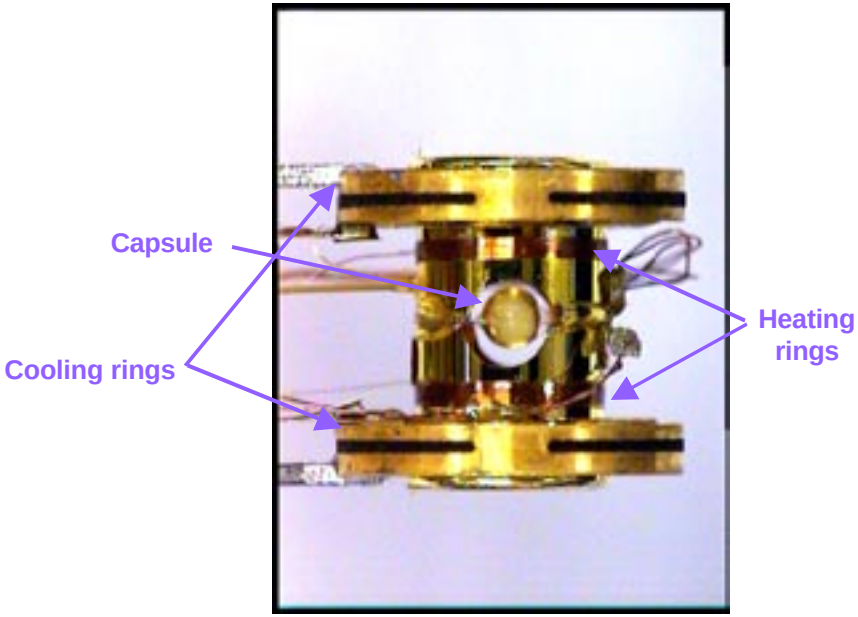
DD layer thickness = 80 μm



DD fuel layer formed inside capsule using symmetric IR illumination

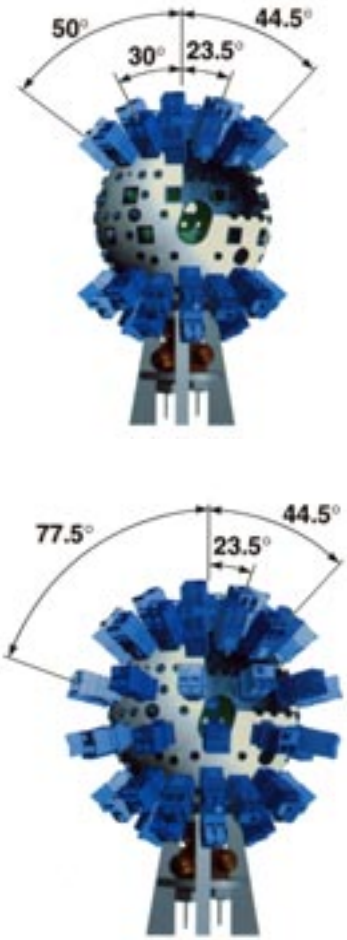
Layer smoothness 0.3 μm rms (modes 4-100)

Layering studies in cryogenic hohlraums are beginning

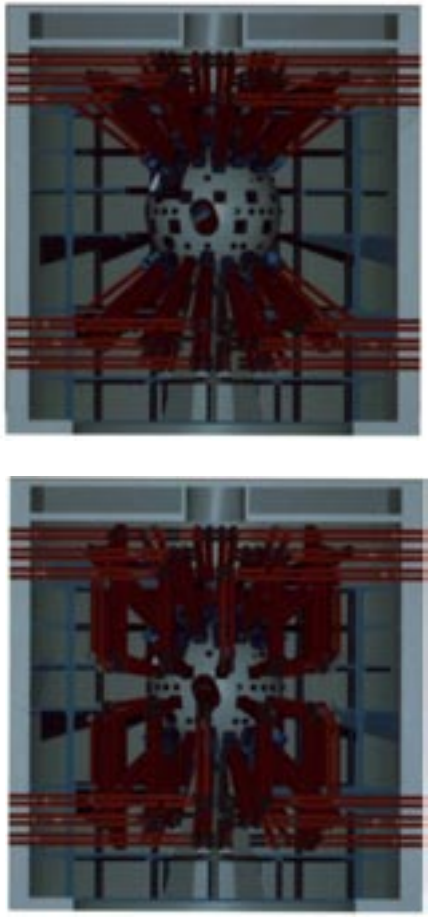


Studies will demonstrate thermal symmetry control

Both indirect drive and direct drive illumination geometries can be accommodated by the NIF design



Irradiation configurations



(Advanced technology for compact chirped pulse amplification (CPA) being pursued to allow fast ignition on NIF)

Outline/Summary

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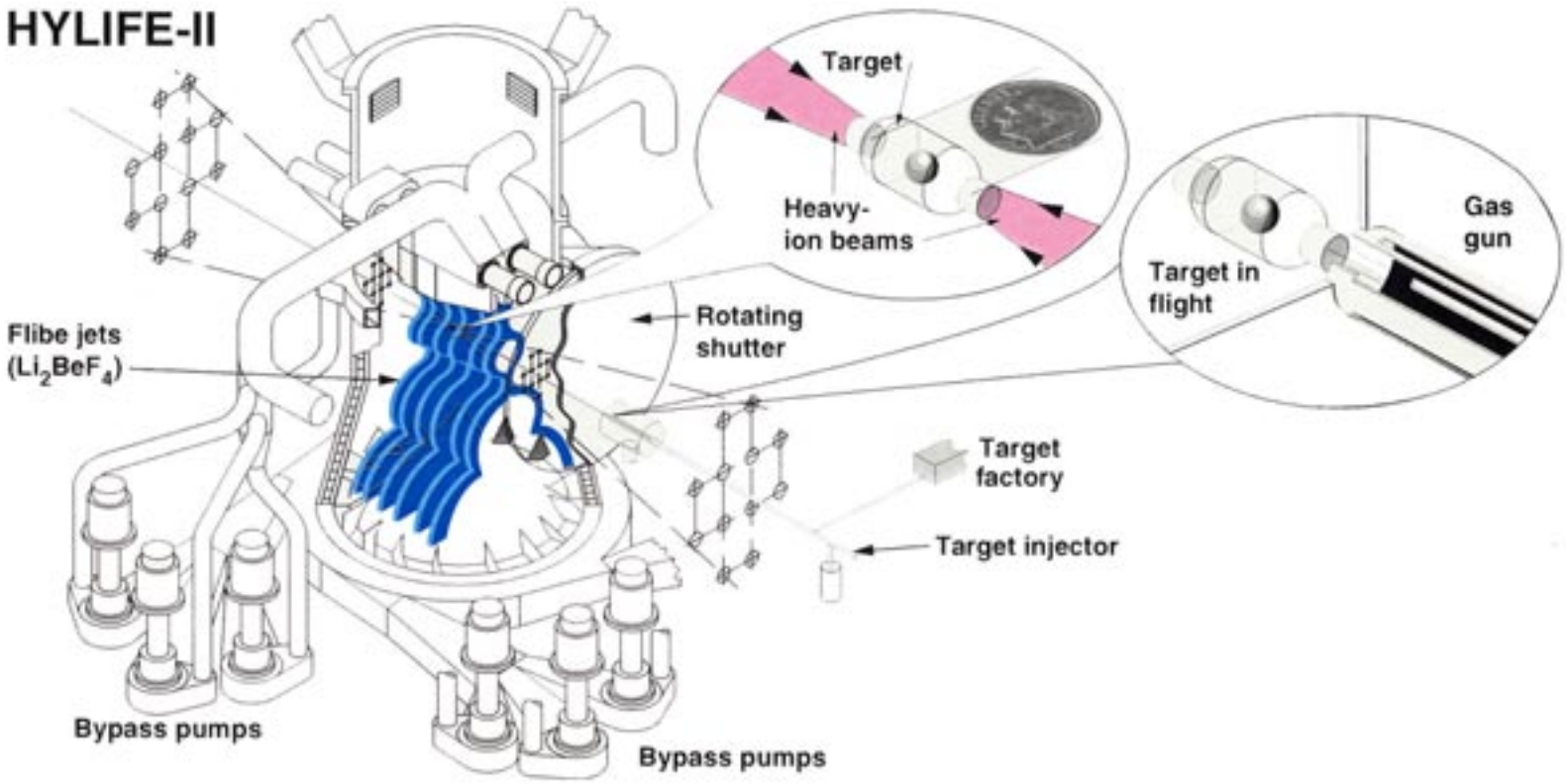
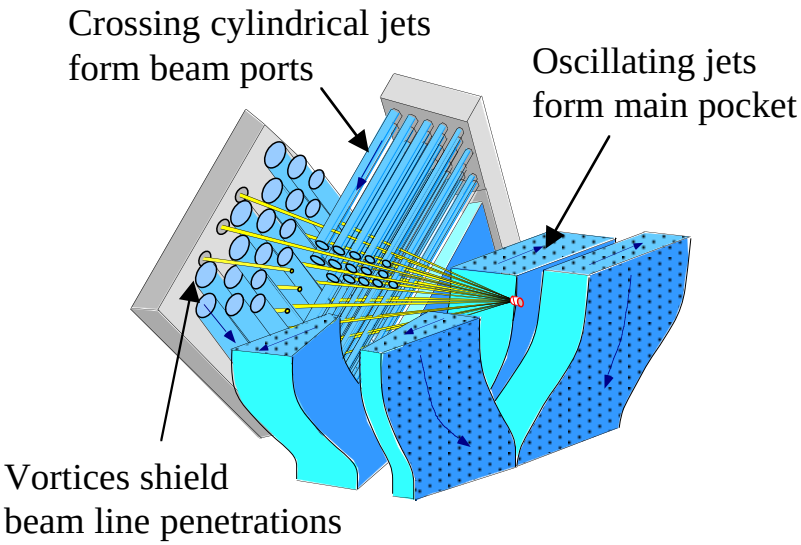
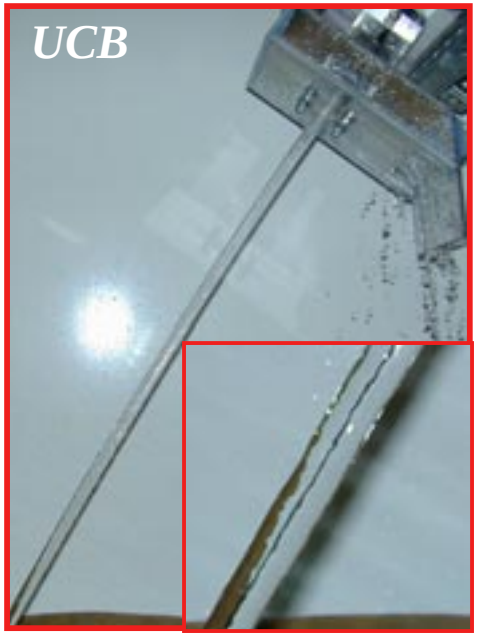
- Most of the experiments needed to move the baseline NNSA funded laser IFE approaches to the next level are under construction. Assuming success an IRE will be proposed in FY05.
- Progress at the concept exploration level on fast-ignition targets and z-pinch drivers has been sufficient to warrant a more aggressive program

The U.S. heavy ion fusion program is concentrating on liquid wall chambers and indirect drive targets



Scaled experiments have created the major classes of flows needed for thick-liquid-wall chambers being evaluated for Heavy Ion Beam driven fusion





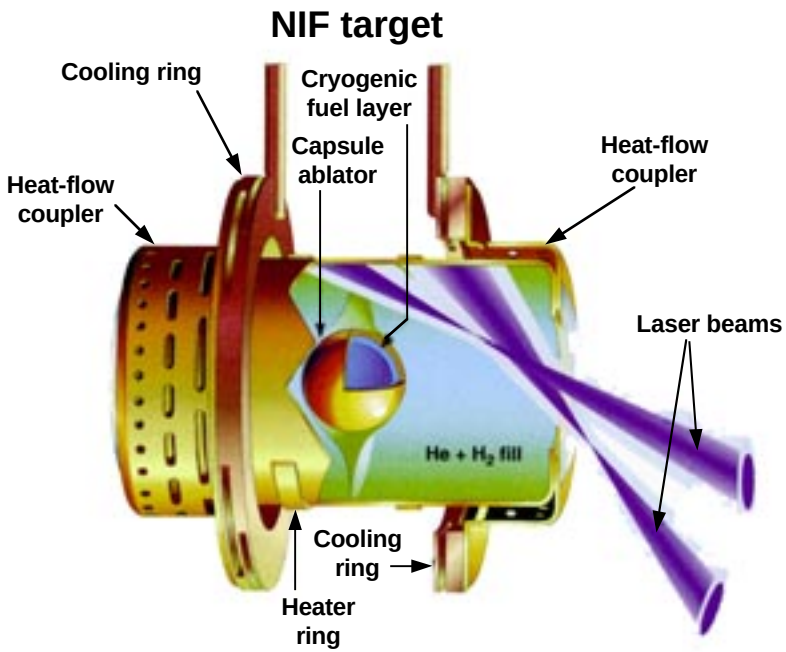
Highly smooth cylindrical jets

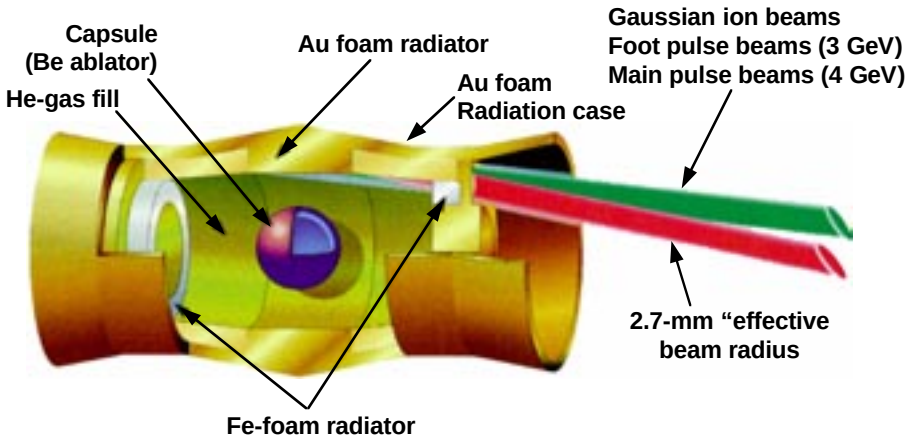
Slab jet arrays with disruptions

Vortices

Flow conditions approach correct Reynolds and Weber numbers for HYLIFE-II

The physics issues for ion beam target design for IFE and NIF targets have much in common



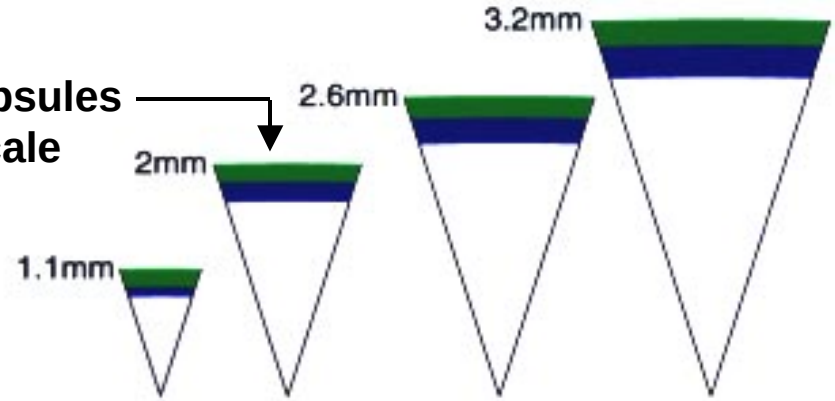


Yield = 400 MJ
Driver (using NIF-like hohlraum to capsule radius ratio)
6 MJ of 4 GeV Pb ions gain 67
7.5 MJ of 8 GeV Pb ions gain 53

- Capsule physics (hydrodynamics, ignition, and burn propagation)
- Symmetry control
- Hohlraum energetics

A wide range of capsules for Fusion Energy applications have comparable stability and symmetry requirements as NIF targets

- Enhanced NIF capsules may reach this scale



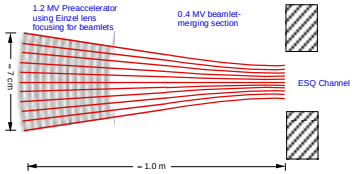
Scale	NIF	ETF	Reactor (6Hz)	Reactor (3Hz)
Peak T_R	300	246	223	203
IFAR	45	46	42	35
Convergence Ratio	36	37	36	40
Energy Absorbed (kJ)	150	631	1128	1841
Yield (MJ)	15	171	381	830

- The target size appropriate for the first average fusion power facility in the IFE development plan

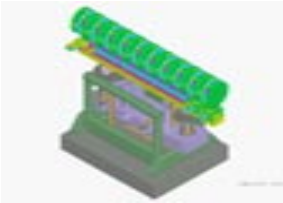
The heavy ion fusion program plans consists of distinct experiments on ion sources, beam transport, and focusing to be followed by an integrated beam experiment

NOW (next three years)

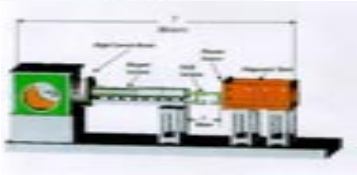
Brighter sources/ injector



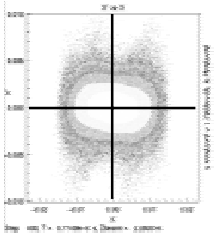
Maximum <J >, $\mathcal{E}_n$ Transport



Beam neutralization → min ε-limited focus r_f

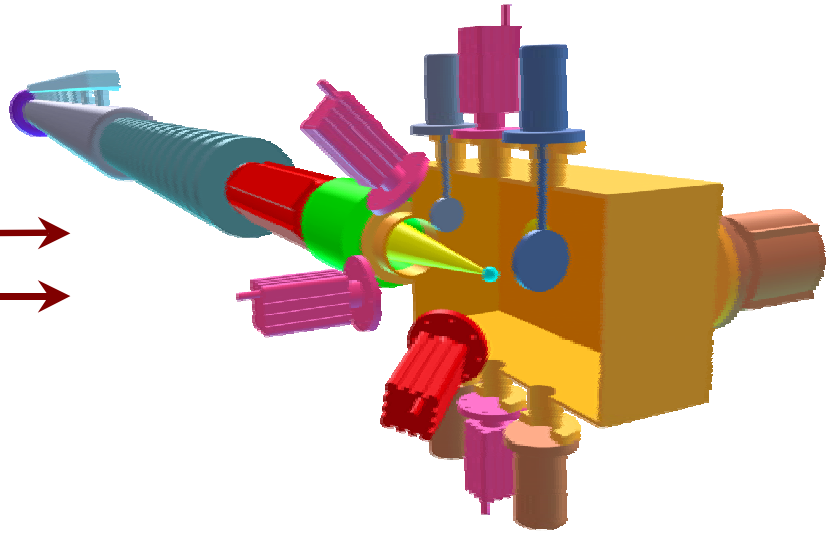


Theory/simulations



NEXT STEP

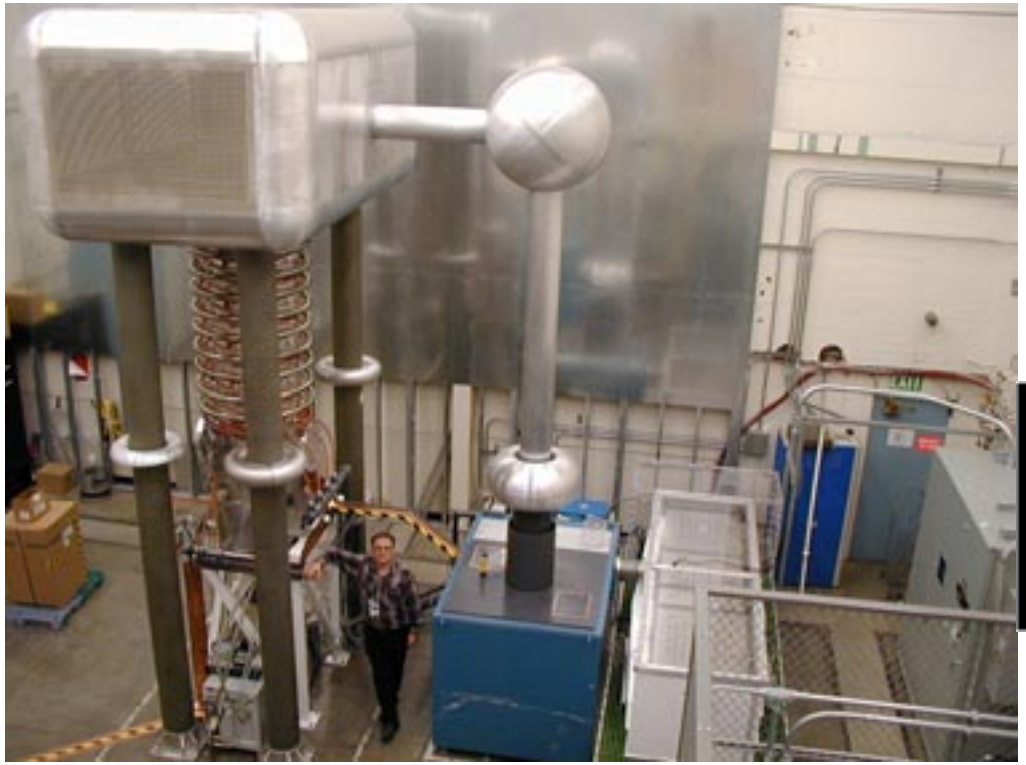
integrated beam experiments (IBX)

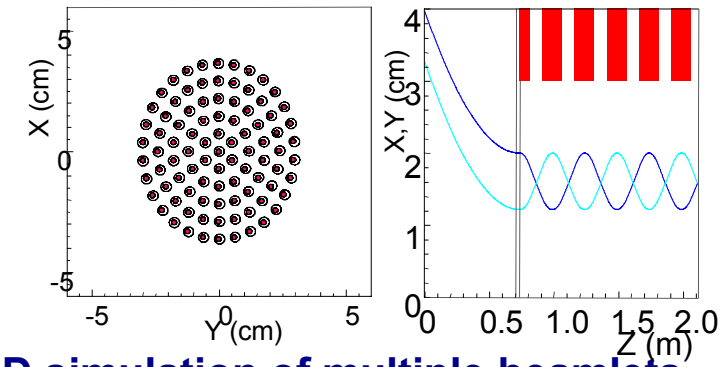


...to test source-to-target-integrated modeling

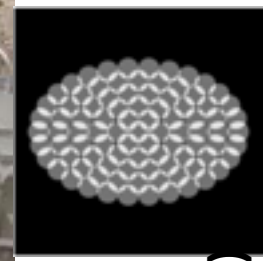
(Injection, acceleration, longitudinal compression and final focus)

Research on high-brightness sources and injectors commenced on LLNL test stand completed Dec 2001

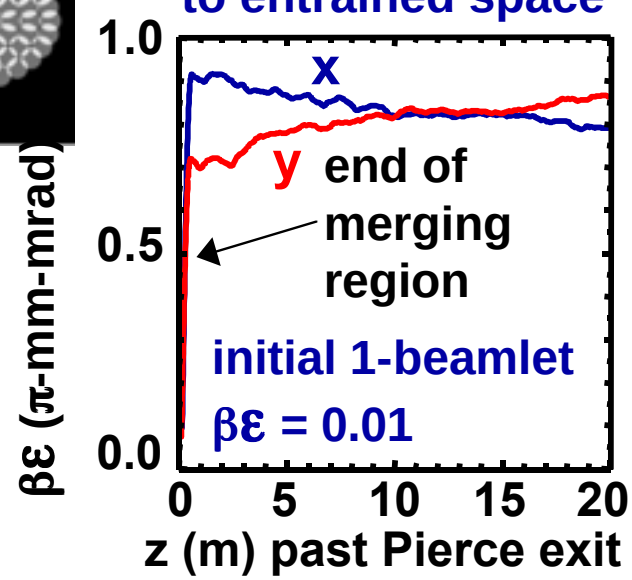




3-D simulation of multiple beamlets

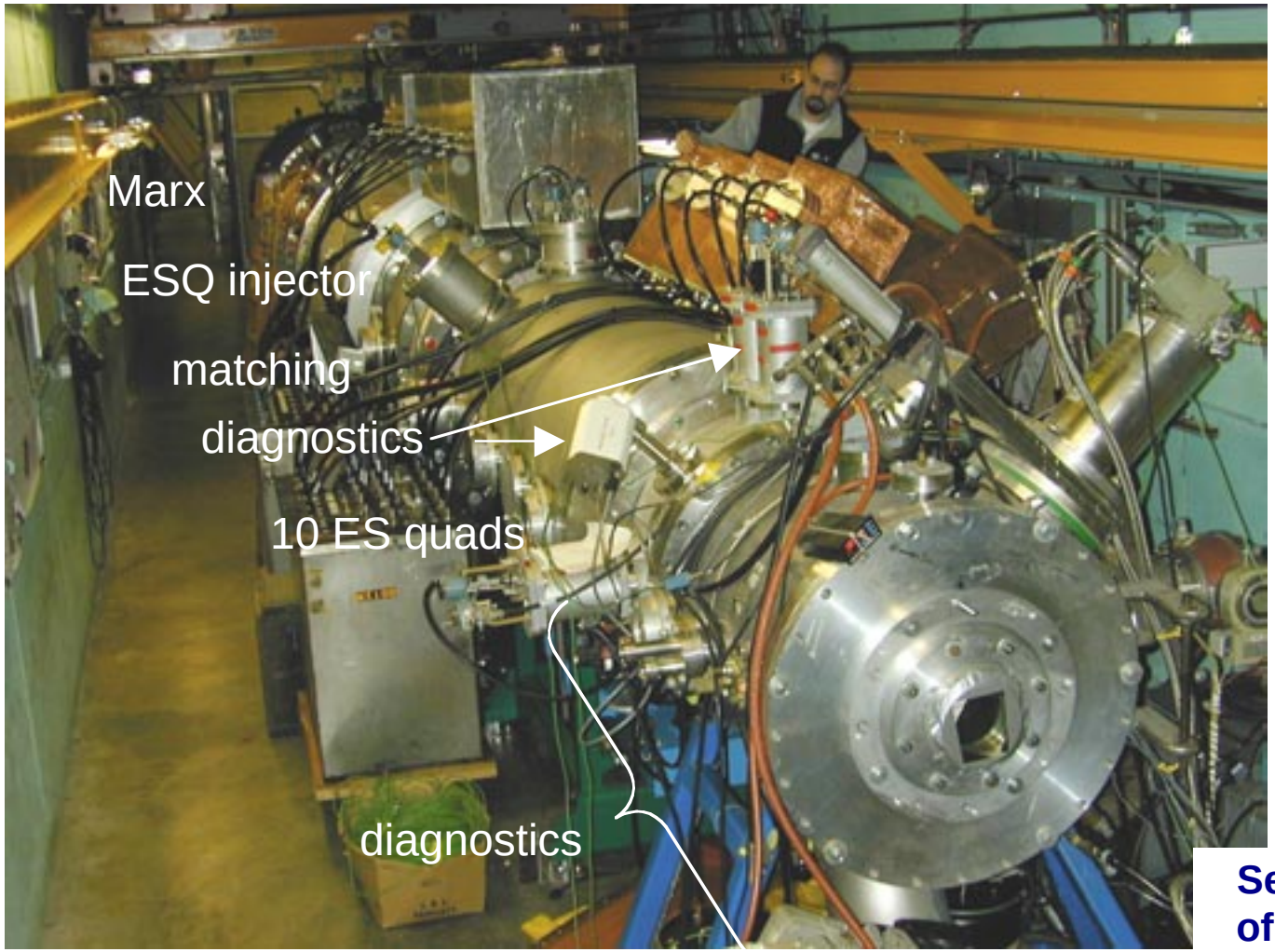


emittance grows due to entrained space



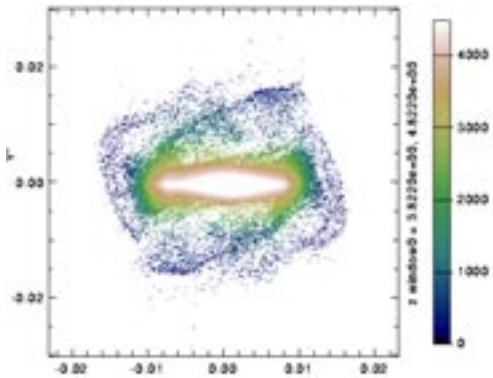
A new 500 KV facility at LLNL will explore a new compact injector concept useful for all future experiments, as well as feasibility of high-brightness plasma sources.

The High Current Experiment (HCX) at LBL began operation January 11, 2002.



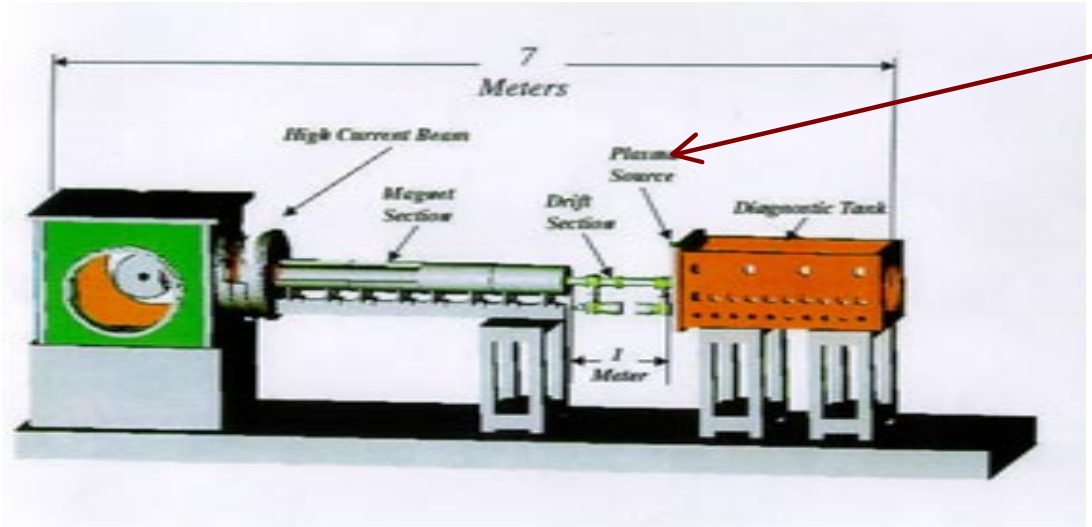
Transport

- **aperture limits**
- **electrons**
- **gas effects**
- **halo formation**
- **steering**

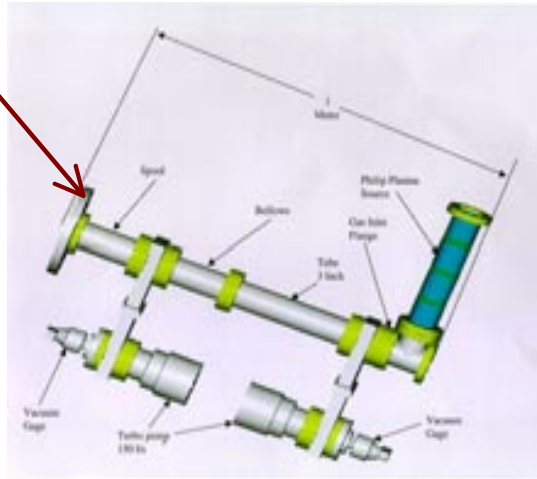


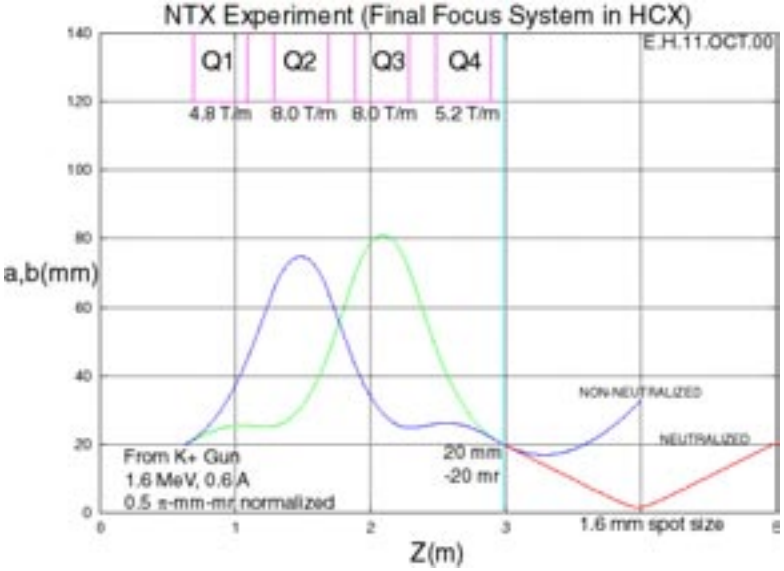
Self-consistent simulation of HCX beam phase space

The Neutralized Transport Experiment (NTX) will begin operating this year to study ballistic final focus with plasma neutralization



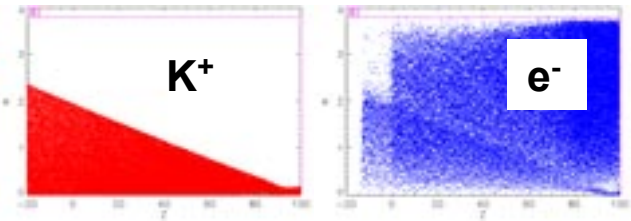
PPPL ECR plasma source





NTX gun has achieved design current 80mA @ 0.4 MeV and very low measured emmittance $\varepsilon_N \leq 0.1\ \pi$ mm-mr.

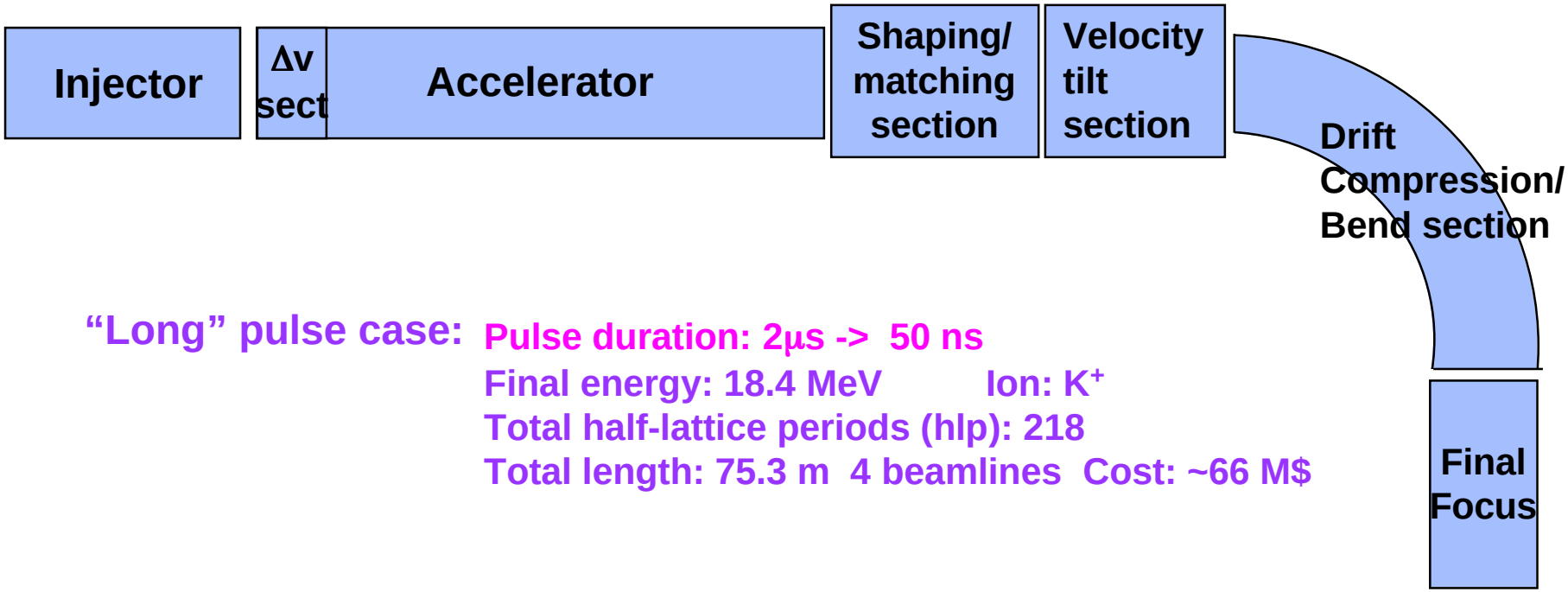
Simulations predict 99% neutralization



An Integrated Beam Experiment (IBX) at the PoP scale is proposed prior to construction of the more ambitious IRE

Short pulse case:

Pulse duration: 250 ns -> 25 ns
Final energy: 10 MeV Ion: K^+
Total half-lattice periods (hlp): 148
Total length: 64 m 1 beamline Cost: ~38 M$



"Long" pulse case:

Pulse duration: 2μs -> 50 ns
Final energy: 18.4 MeV Ion: K^+
Total half-lattice periods (hlp): 218
Total length: 75.3 m 4 beamlines Cost: ~66 M$

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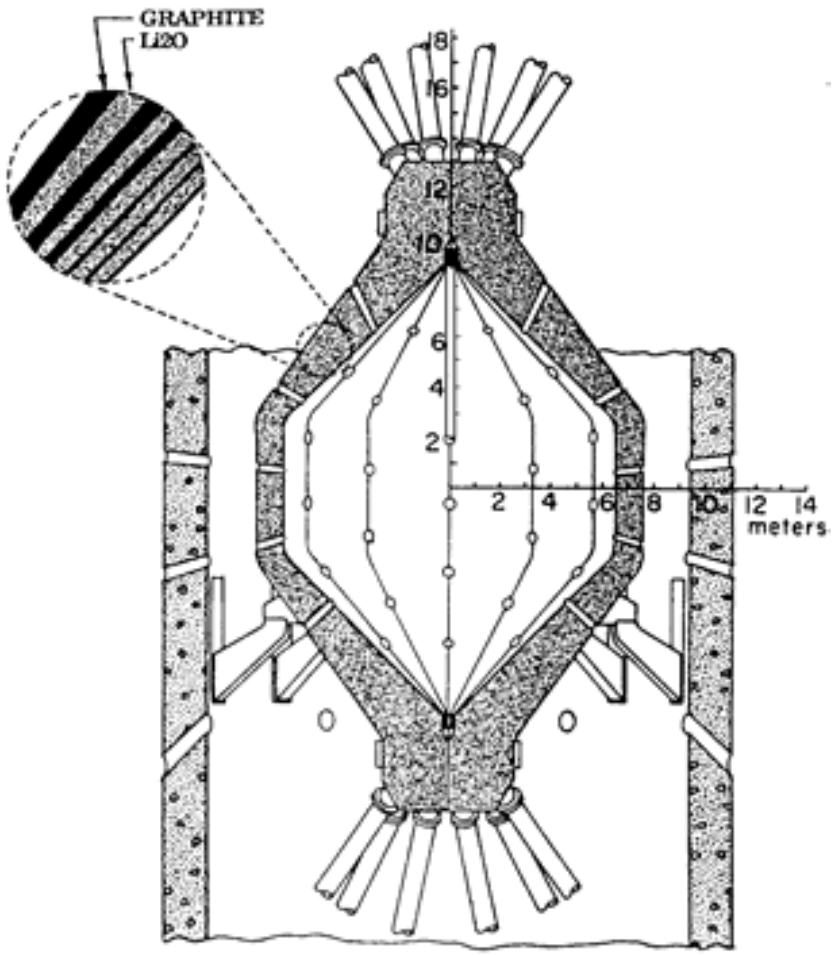
The laser-driven IFE program is concentrating on dry-wall chambers and direct drive targets



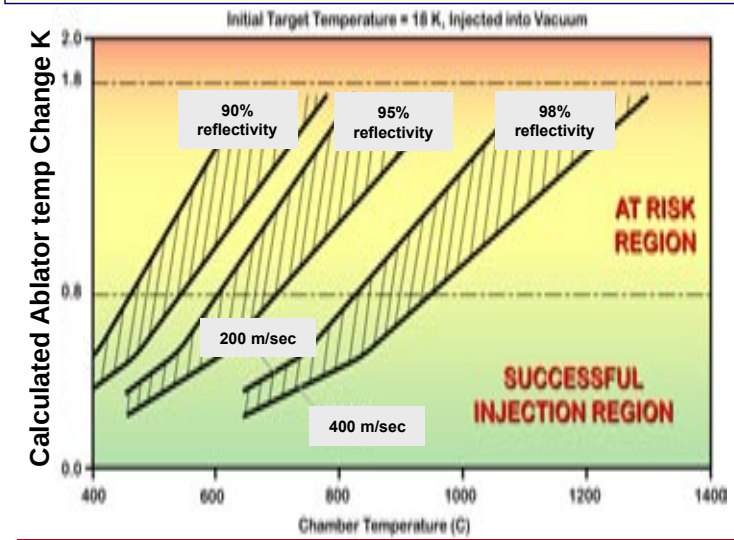
CROSS-SECTION OF SOMBRERO CHAMBER

Key Issue: Chamber Lifetime coupled to target injection requirements.

The U.S. Laser IFE Program is concentrating on identifying operating windows of dry wall chambers

NRL

Target survival conditions (*Goodin, GA*)



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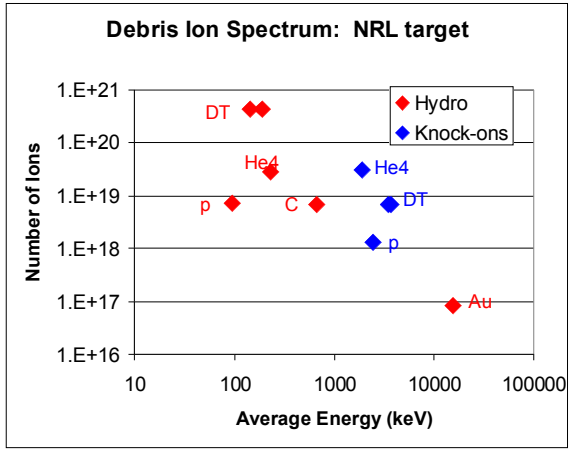
Target output (*Perkins, LLNL*)



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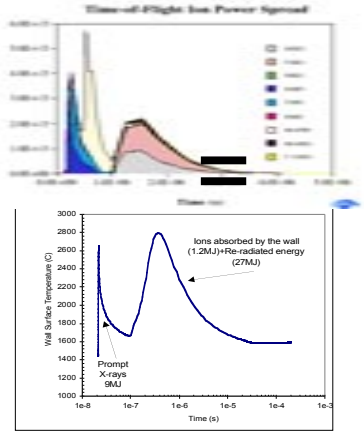
Time of flight (*Raffray, UCSD*) (Peterson, Wisconsin)



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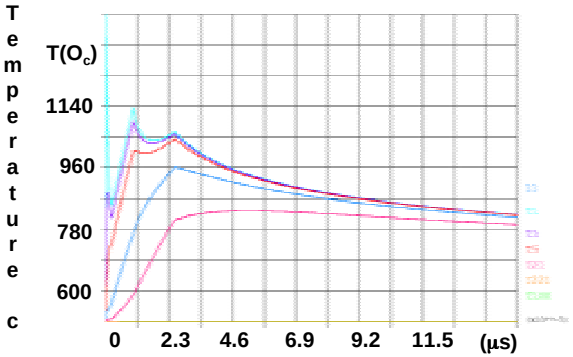
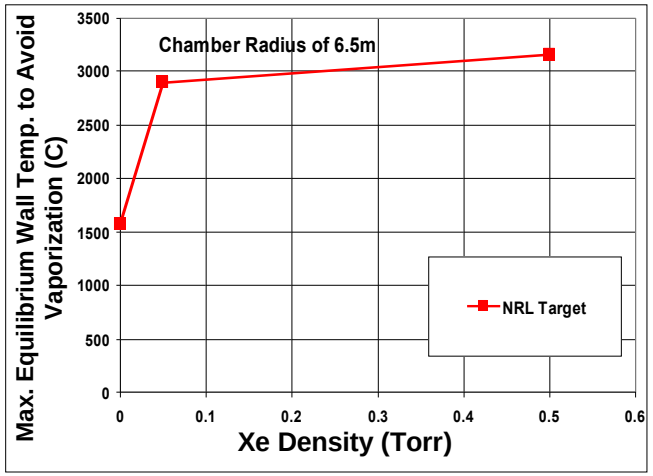
Tungsten First Wall (*Raffray, UCSD*)



- Coolant temperature = 500°C
- Chamber radius = 6.5 m
- Maximum temperature = 1438 °C

or

CFC (Graphite) First Wall (*Peterson, Wisconsin*)



The laser driven approach to IFE is progressing toward an IRE decision

- The first of two amplifiers of the Mercury DPSSL laser delivered its first pulses at the end of May
- Solutions to several of the key KrF laser technology issues has been identified and operation of Electra is expected in FY05
- Operating windows for dry wall chambers are being explored
- Instability growth for direct drive targets remains a challenge but substantial progress has been made in identifying targets with adequate gain and stability

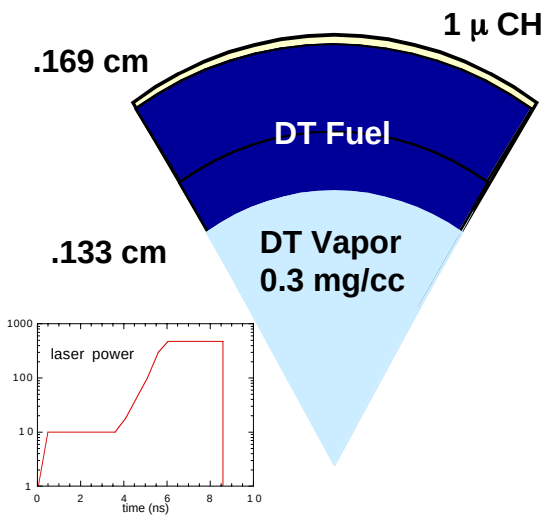
Assuming success of the current research program, an IRE start in FY05 is proposed

Control of hydrodynamic instabilities and laser imprint determine key features of laser direct drive targets

NIF BASELINE

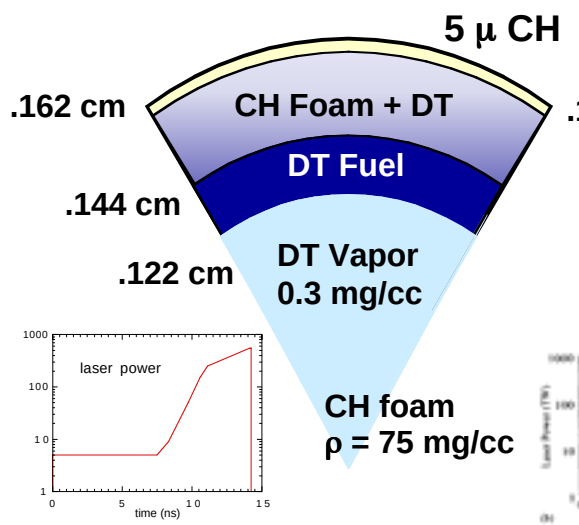
PURE DT

(shock heated)

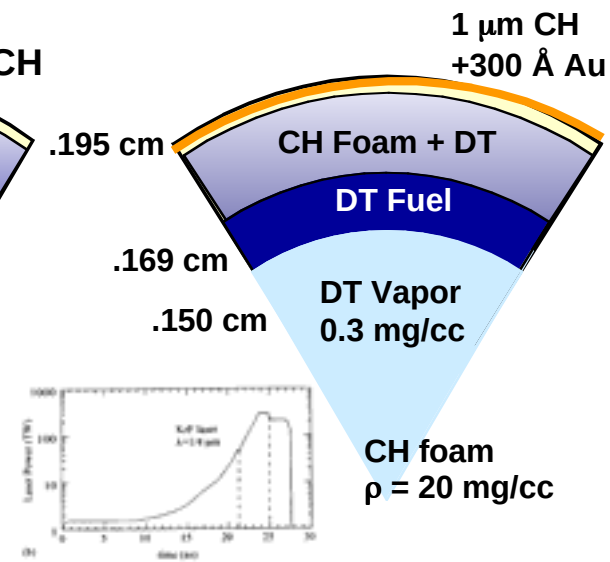


ADVANCED DESIGNS

CH FOAM /DT+ DT



GOLD+ CH FOAM / DT + DT

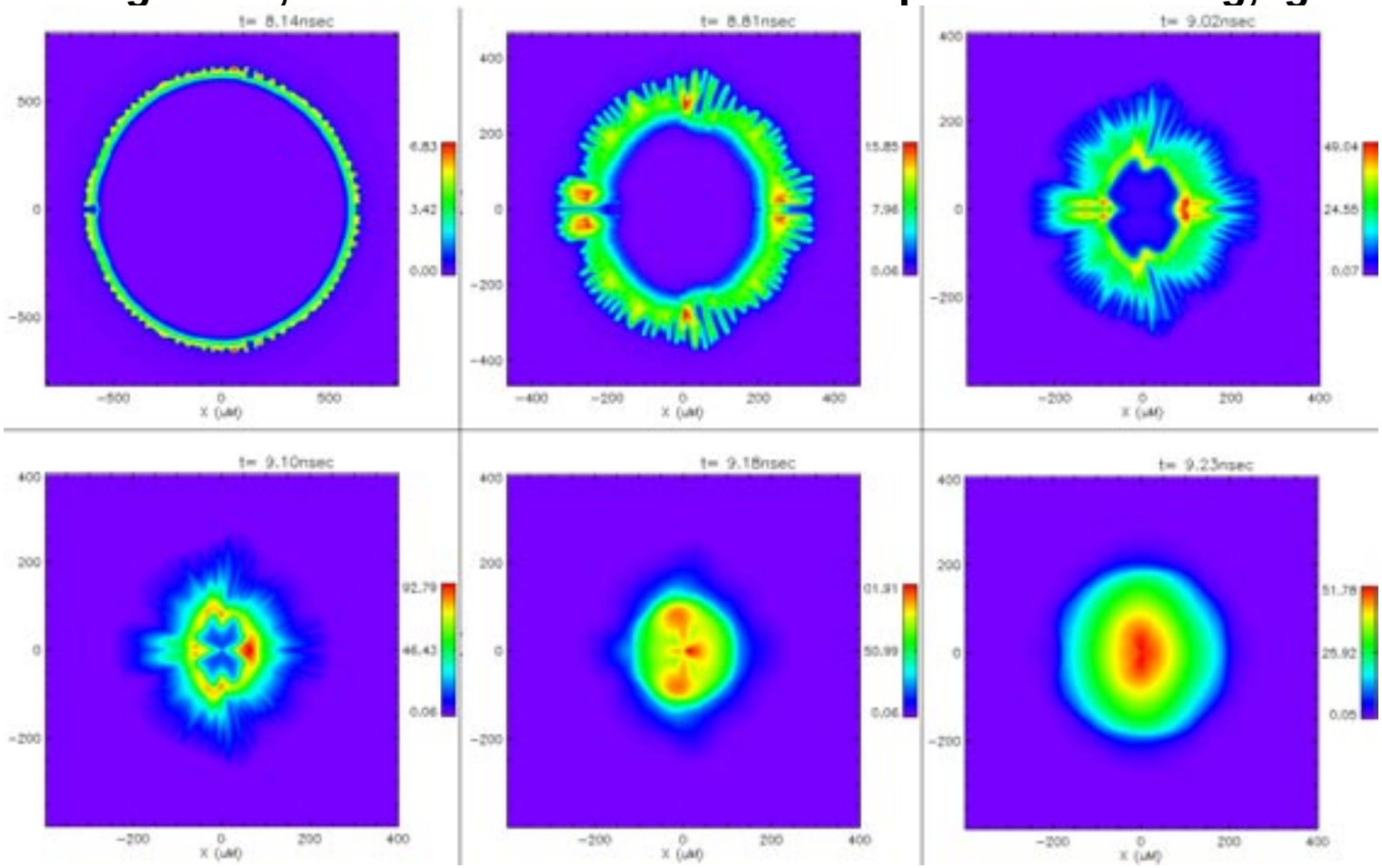


Laser Type	Glass	Glass	KrF	KrF (ISI)
Laser Energy	1.6 MJ (~60% absorbed)	1.6 MJ (90% absorbed)	1.6 MJ	1.3 MJ
1-D Gain	20-30	50-120	108	127
Zooming	No	No	Yes	Yes
ρR_{max}	1.2	1.86	2.11	1.8
e-folds$_{max}$	4.7	4.8	6.1	8
Ref:	C. Verdon UR	NRL, LLE	NRL	NRL

For NIF baseline, see S.V. Weber et al. Phys Plasmas 4, 1978 (1997), also S. E. Bodner, et al, Phys Plasmas 5, 1901 (1998)

NRL FAST 2D code integrated calculation of the effects of low and intermediate laser/target nonuniformity shows burn and gain for baseline NIF target

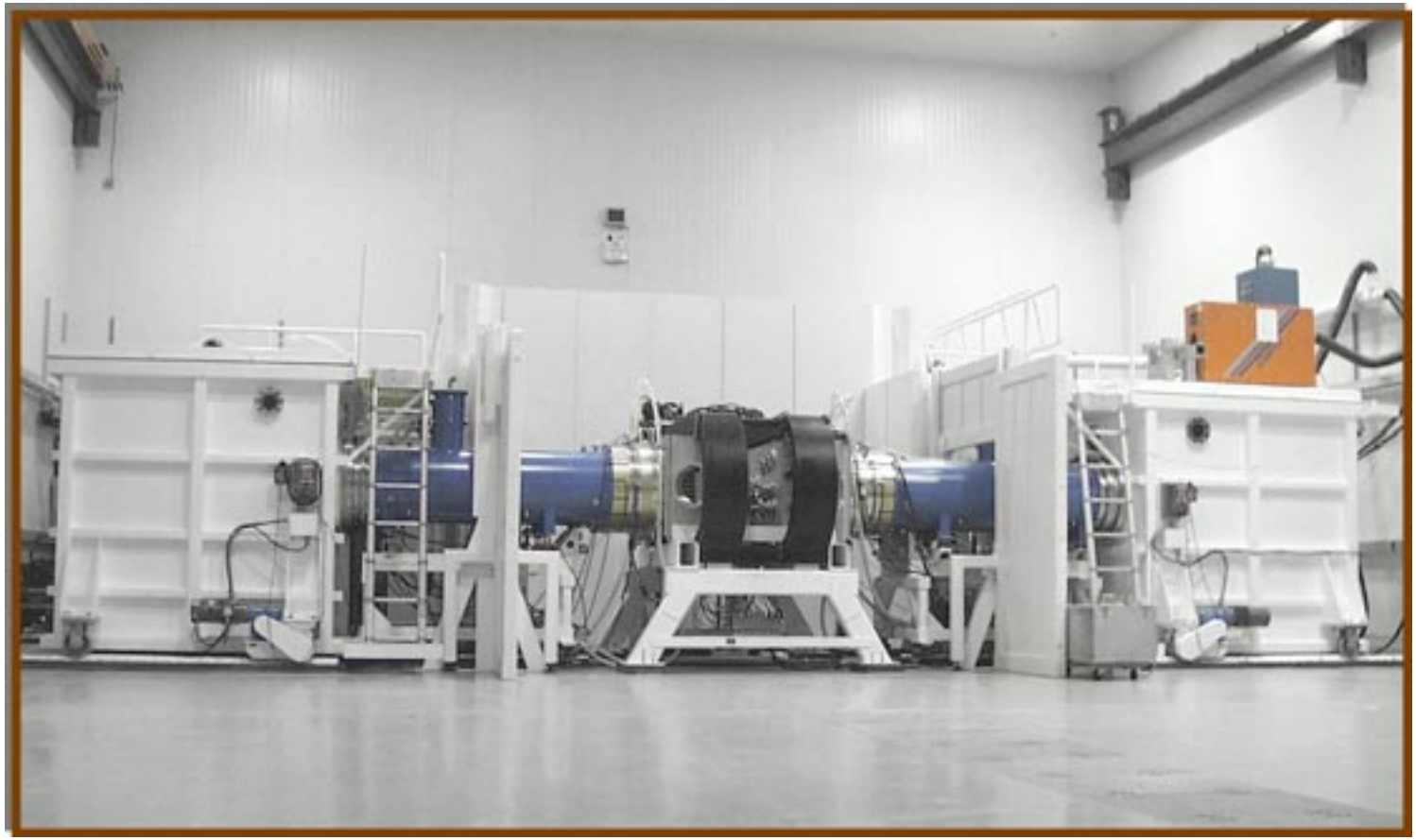
2D mode 2-128 calculation of NIF baseline DT pellet with inner and outer surface roughness, beam imbalance and 1 THz optical smoothing, gain=18



(NRL calculations with modes 2-256 are in progress)

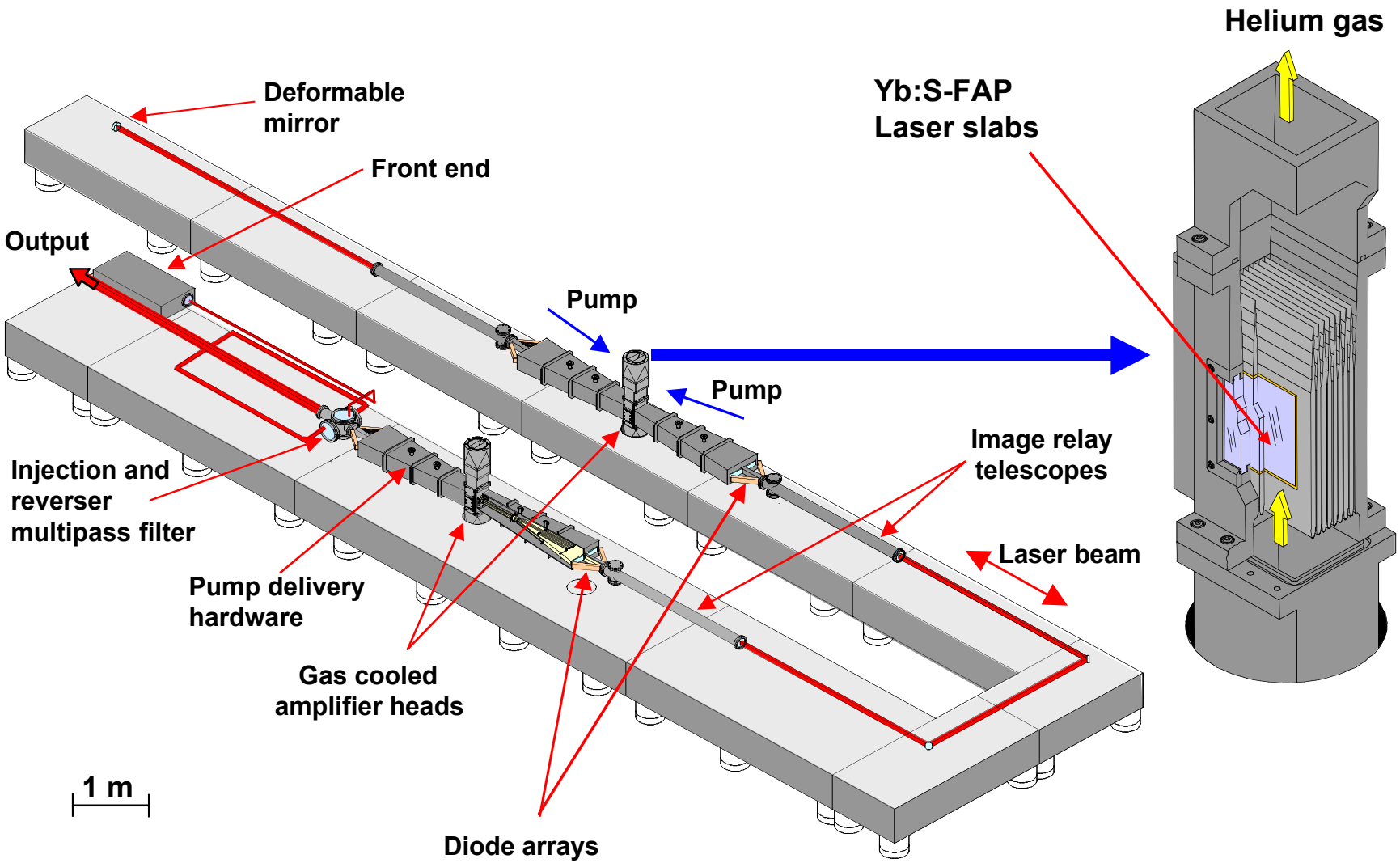
The major U.S. facility for KrF laser development for IFE will be the Electra laser at NRL, scheduled for completion in CY2005

NRL

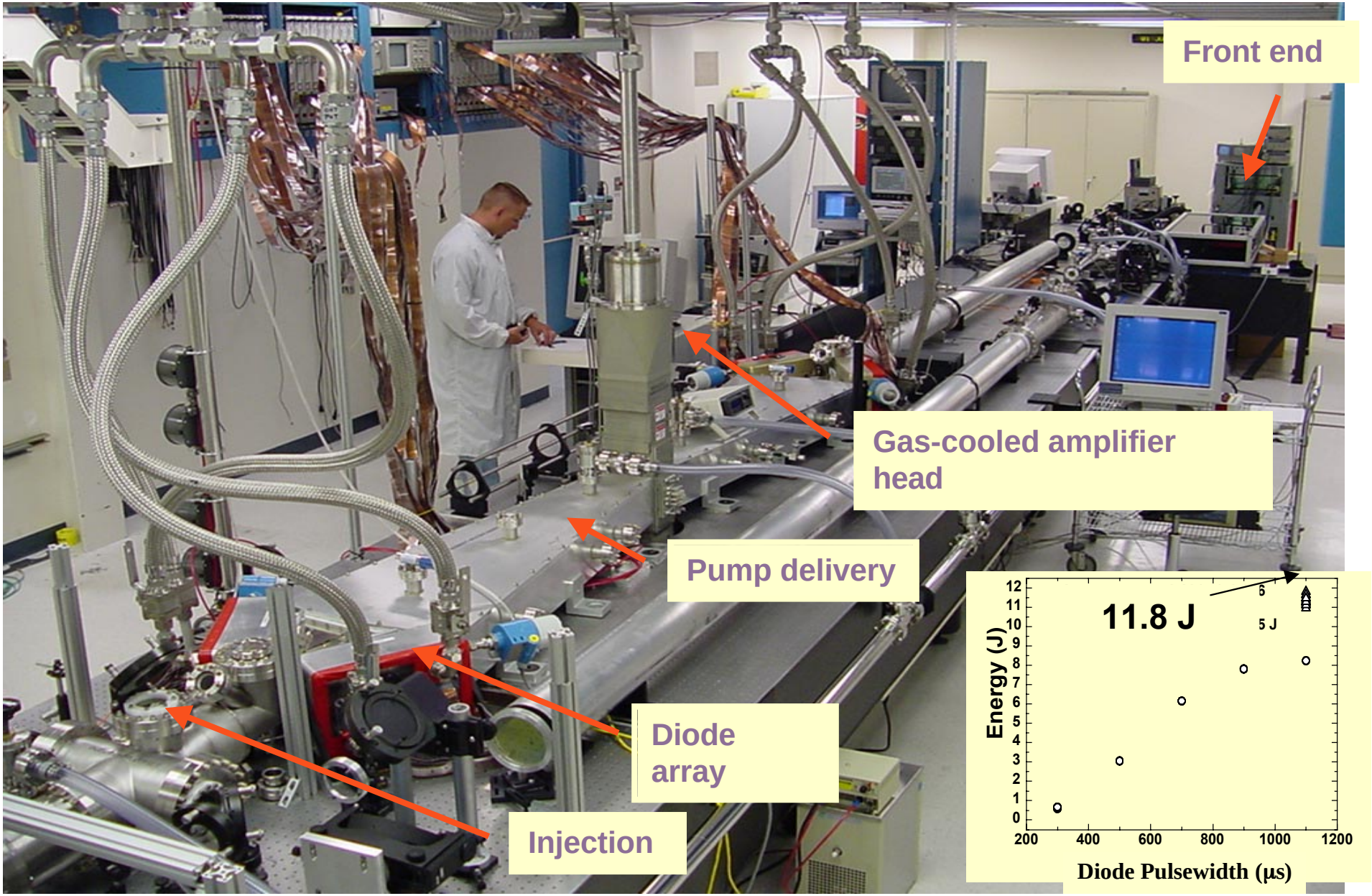


- First Generation pulse power system can run 5 Hz for 5 hours (500 keV, 100 kA, 100 nsec @ 5 Hz (25 kW))
- Excellent test bed for developing laser components

The Mercury laser at LLNL is a 100J, 10Hz, 10ns DPSSL laser being built to demonstrate energetics and rep-rate at 1/10th scale of a kJ-class beam line for Inertial Fusion Energy



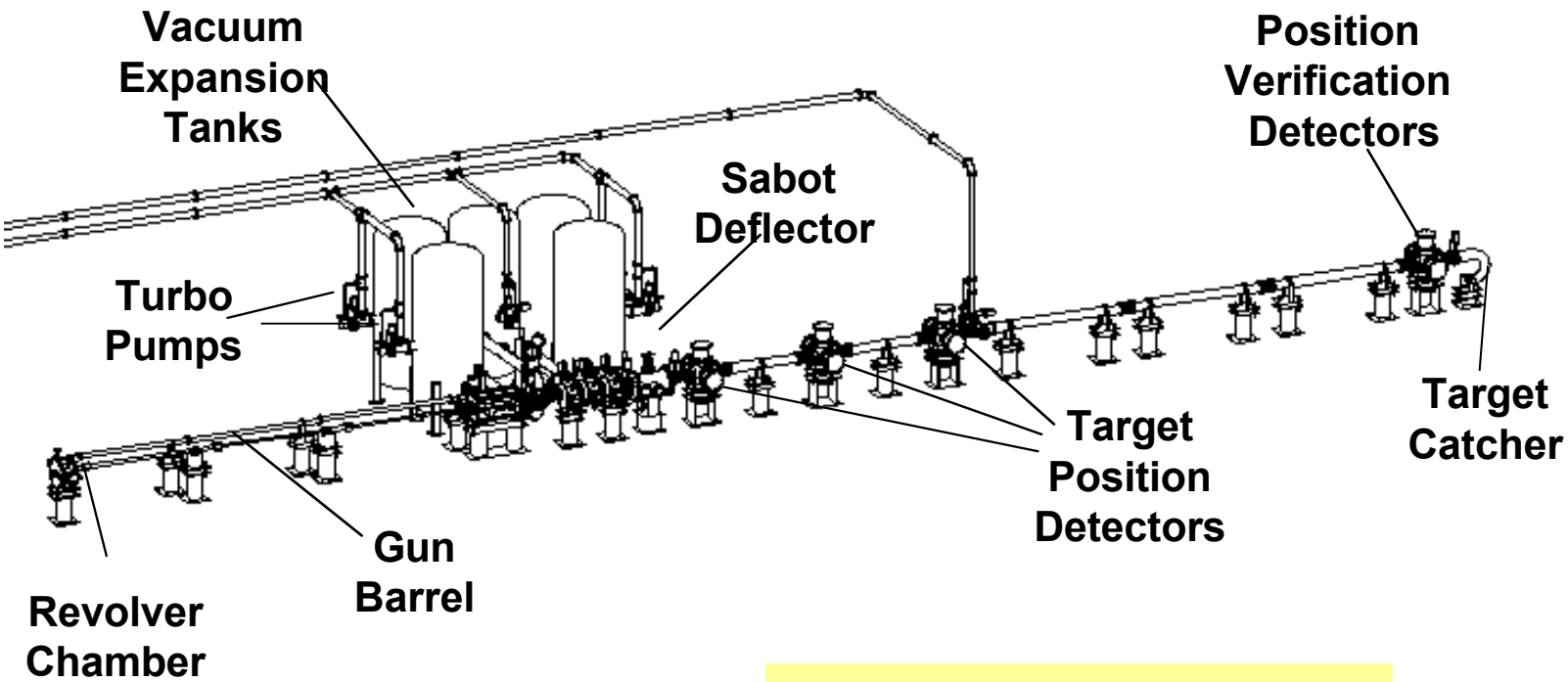
The first of two amplifiers has just begun operating and full operation at 3ω (0.35 μm) is planned for CY2005



The critical issues for target fabrication and injection are being addressed

- An injector for both direct and indirect drive is under construction
- Fabrication approaches for low-cost manufacturing have been identified

Injection System procurement is underway



Serves both heavy ion and laser driven target designs

Phased approach - single shot with single-axis tracking (CY02) then rep-rated and full tracking (CY03)

Targets will contribute about 10% of the COE if they are built for ~30¢/target for a 400 MJ yield

- Income for a 1 GW plant selling electricity for $0.05/KWH is $375M for 85% plant availability

- At 5Hz, and 85% availability, an IFE power plant will use 1.35×10^8 targets/year

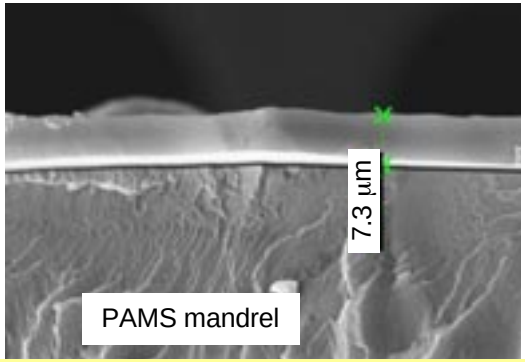
- At 5¢/KWH, these targets must cost less than ~$40M to contribute 10% to the COE or ($4 \times 10^7 / 1.35 \times 10^8$ targets) ~30¢/target (a gain 130 target driven by a 3.3 MJ driver produces about $3 worth of electricity)

- These goals can be met if a target factory can be build for $200M and be operated for $20M/year

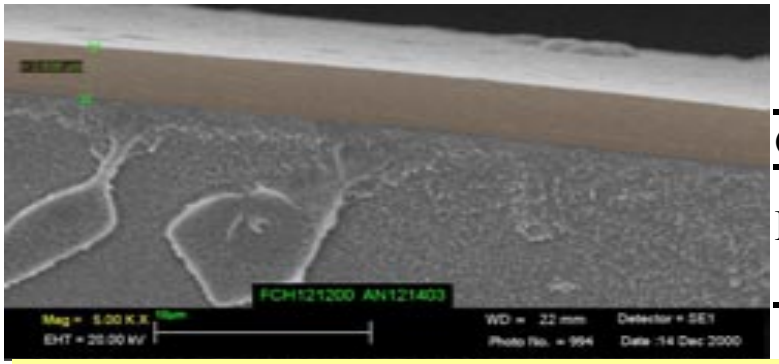
GENERAL ATOMICS
AND AFFILIATED COMPANIES

Target fabrication challenge: increase production from 2000 targets per year to 500,000 per day (at ~$0.25 each)

One solution: **Fluidized Beds**



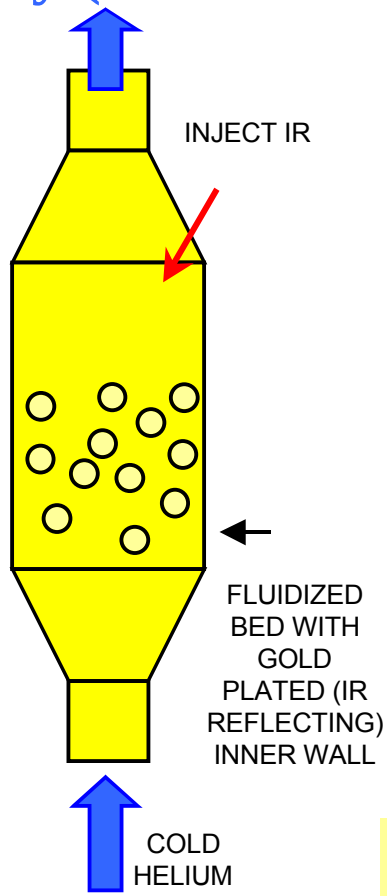
~ 7 micron thick PAA coating



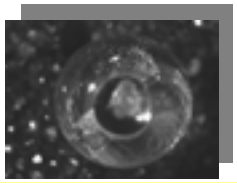
Coating

Mandrel

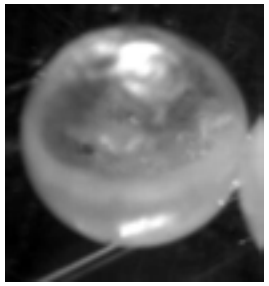
~ 3 micron thick GDP coating on PAMS



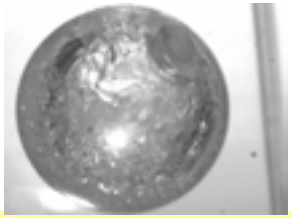
Cryo Fluidized Bed



Filled thru hole and sealed



Before



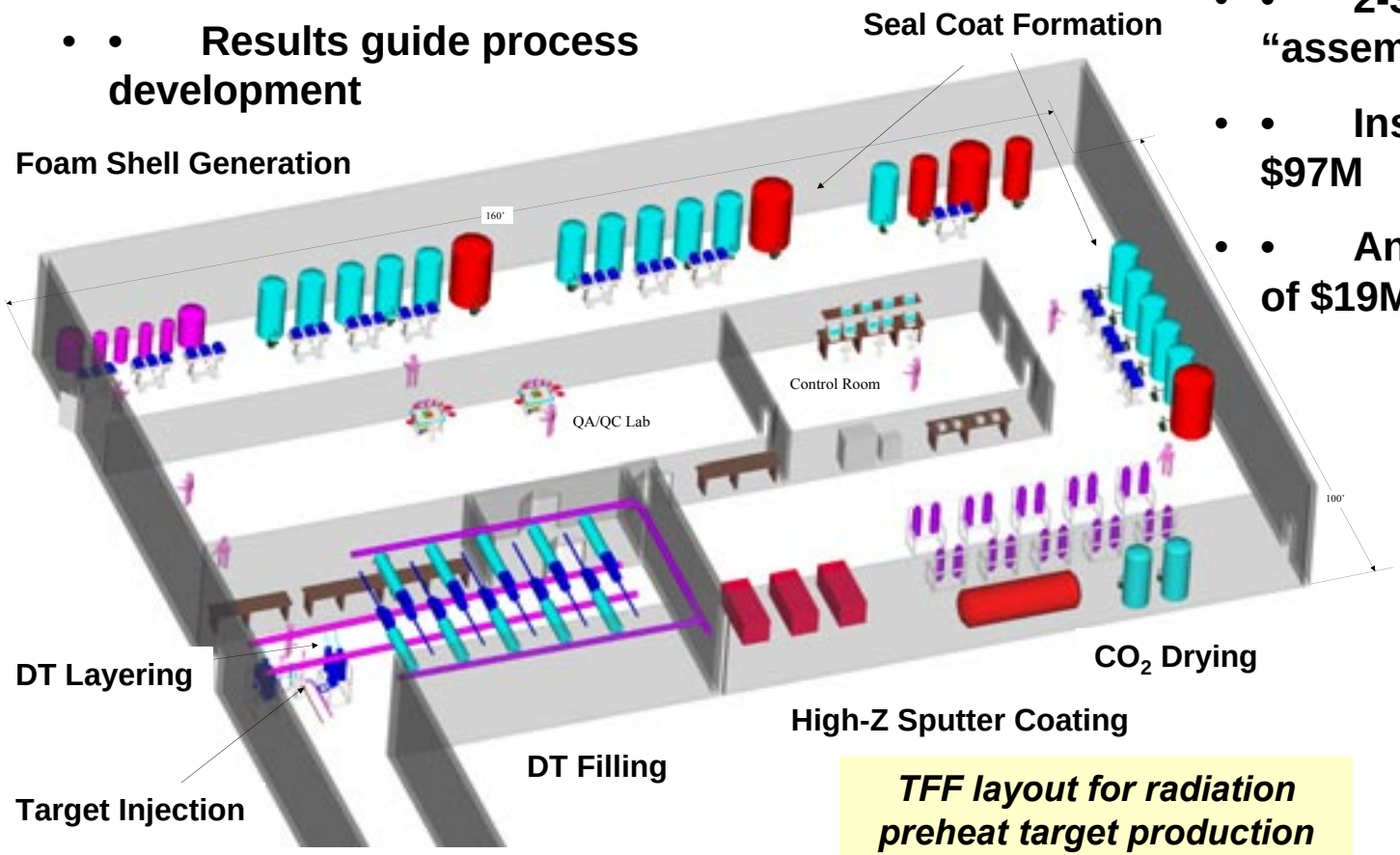
After

Layering demo with neopentyl alcohol in fluidized bed

Los Alamos
NATIONAL LABORATORY

Preliminary estimates of 16.6 cents/target for target production costs are encouraging

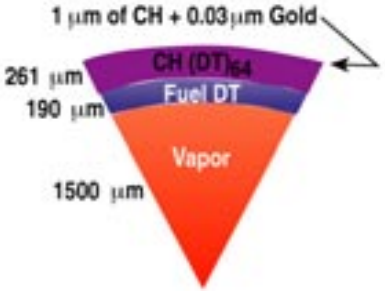
- • Chemical engineering approach to Target Fabrication Facility (TFF)
- • Costing is done for an "nth-of-a-kind" plant
- • Results guide process development



TFF layout for radiation preheat target production

- • <u>Major Parameters</u>
- • 500,000 targets per day
- • 2-3 weeks on "assembly line"
- • Installed capital of $97M
- • Annual operating cost of $19M

NRL radiation preheat target



Outline/Summary

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- Most of the experiments needed to move the baseline NNSA funded laser IFE approaches to the next level are under construction. Assuming success an IRE will be proposed in FY05.

- For Heavy Ion Fusion, experiments on ion sources, high current transport and neutralized focusing are now in operation or nearing completion. An Integrated Beam Experiments (IBX) at the PoP scale is proposed prior to construction of an IRE

- Progress at the concept exploration level on fast-ignition targets and z-pinch drivers has been sufficient to warrant a more aggressive program

Progress at the concept exploration level on fast-ignition targets and z-pinch drivers has been sufficient to warrant a more aggressive program

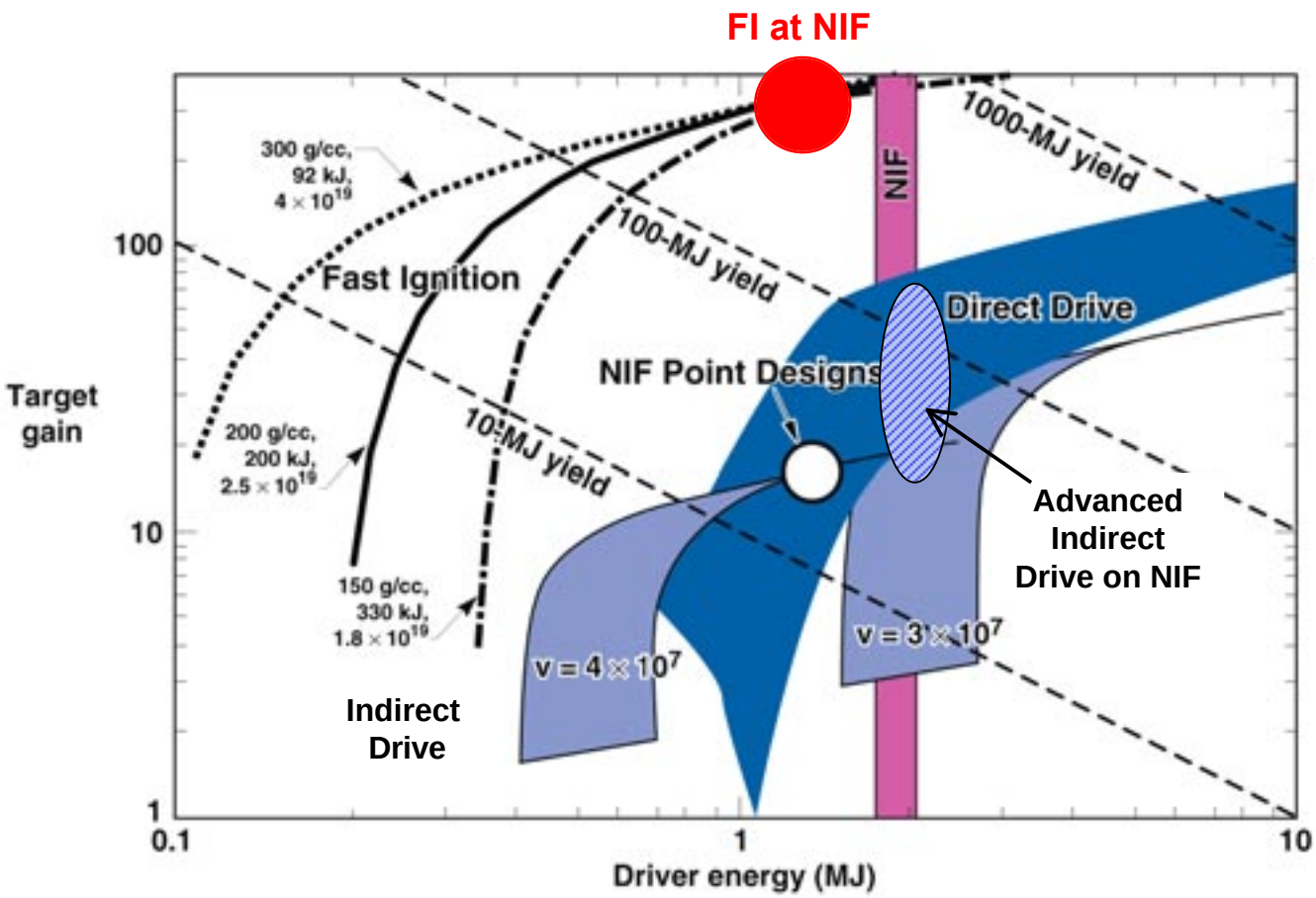
Fast ignition

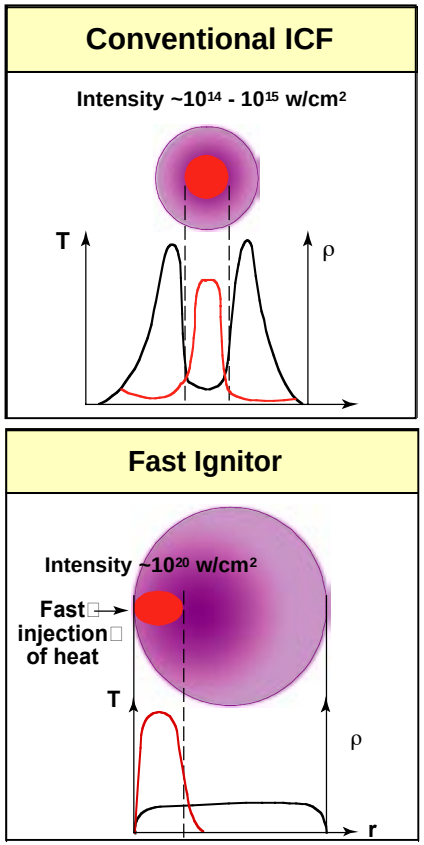
- There has been worldwide progress on key scientific issues
- DOE defense programs interest in high energy petawatt beams opens the possibility for moving to a proof of principle program

Z-pinch drivers

- There have been significant advances in z-pinch driven target experiments
- Concepts have been identified for rep-rated operation of z-pinches

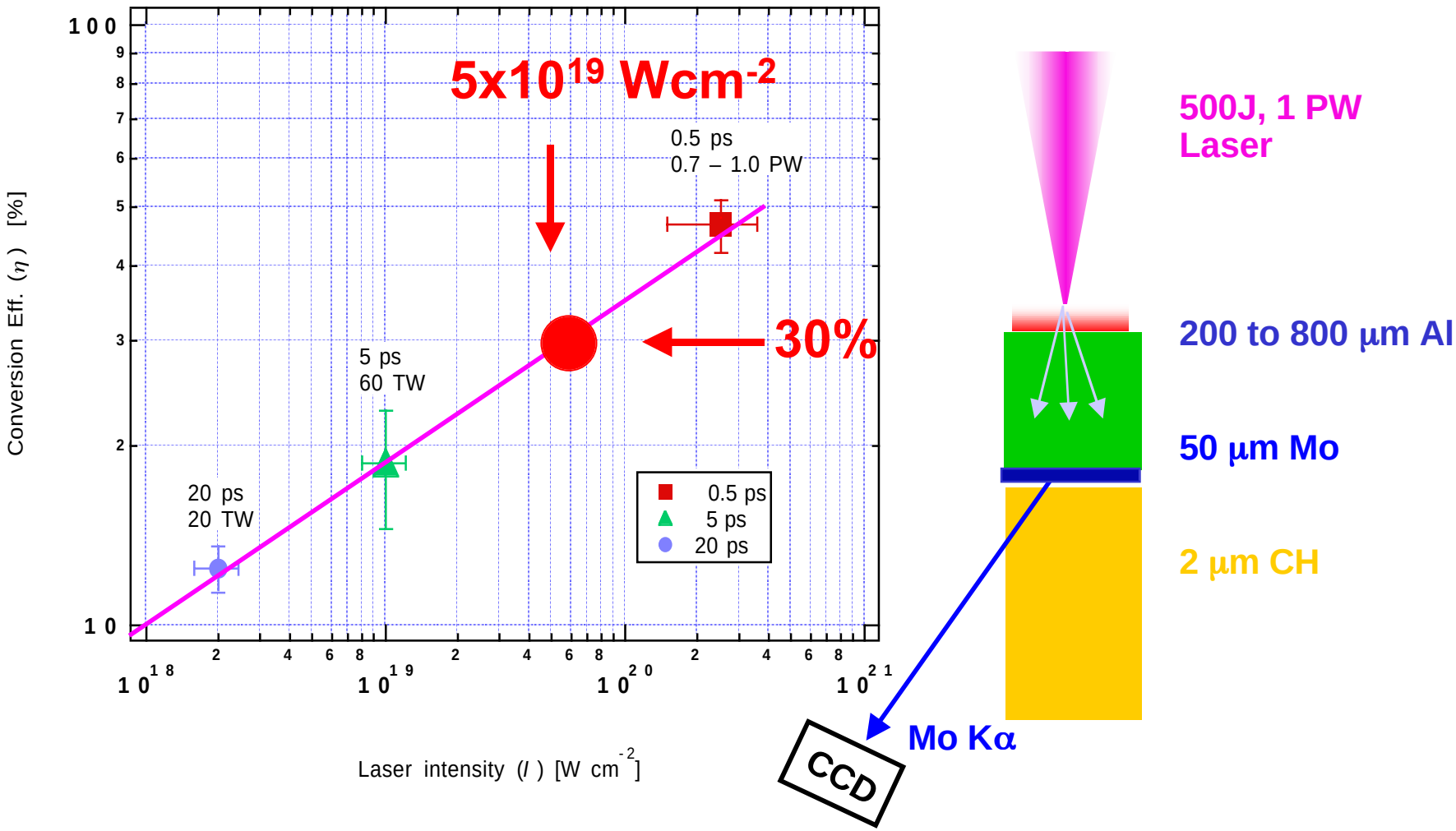
There is worldwide interest in fast ignition which potentially gives more gain and lower threshold energy than indirect or direct drive





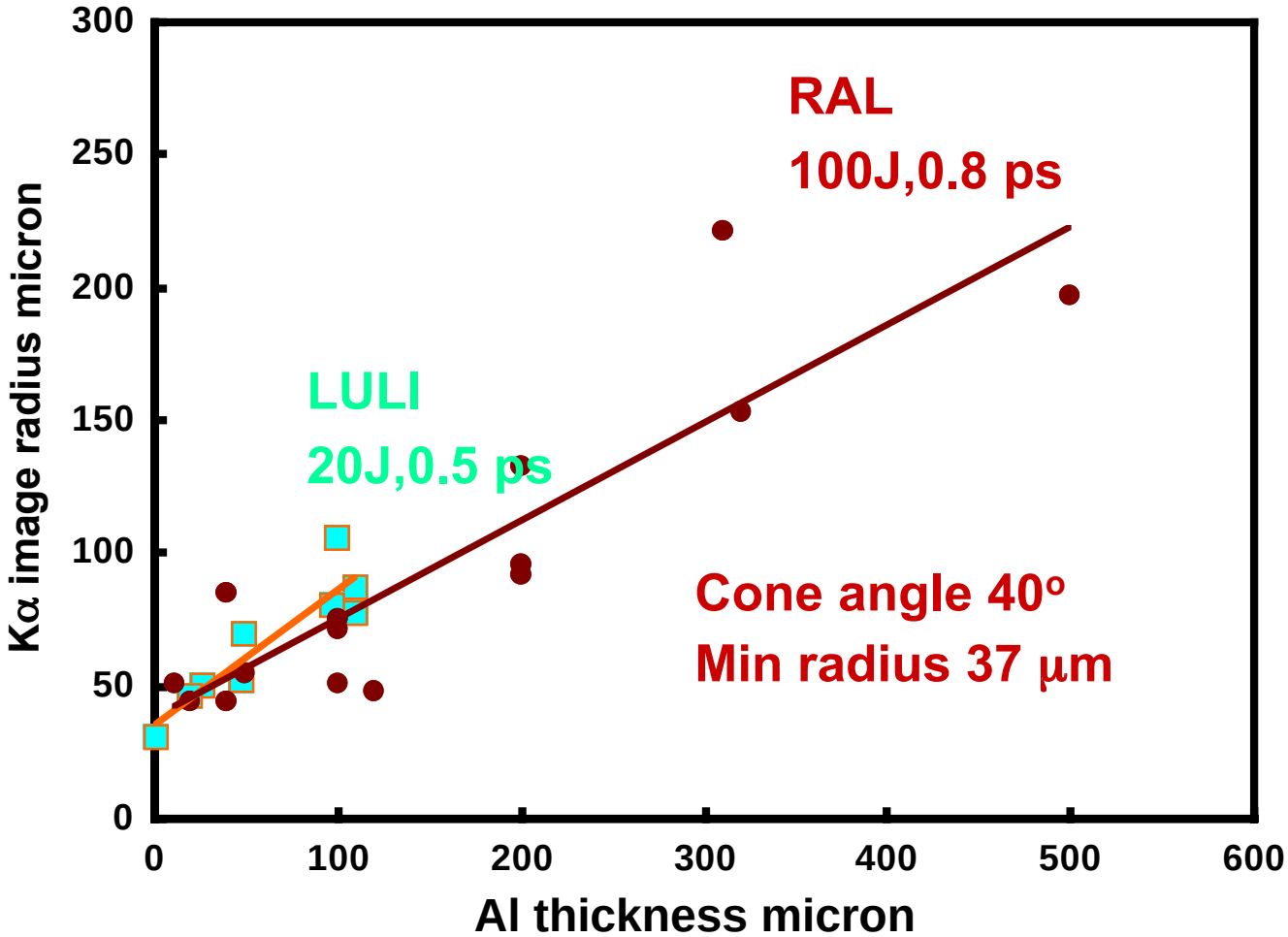
Higher gain is from reduced fuel density allowed by isochoric ignition

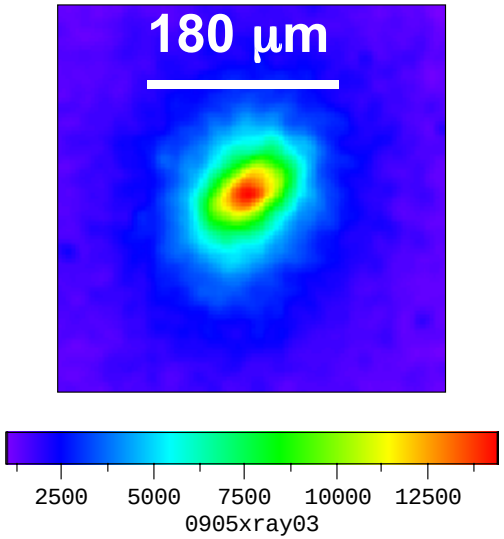
Efficient efficient conversion to electrons and penetration into solid matter have been demonstrated

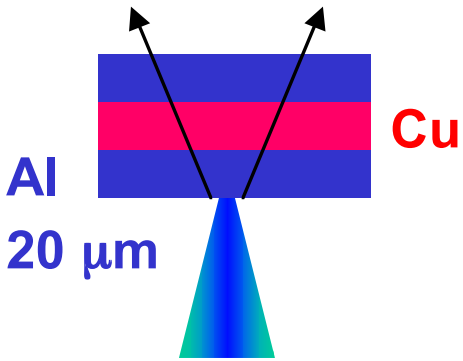


LLNL PW laser expts. K Yasuike et al. Rev Sci, Inst. 2001

Novel x-ray Kα imaging with spherically bent Bragg crystal shows cone angle of electron transport

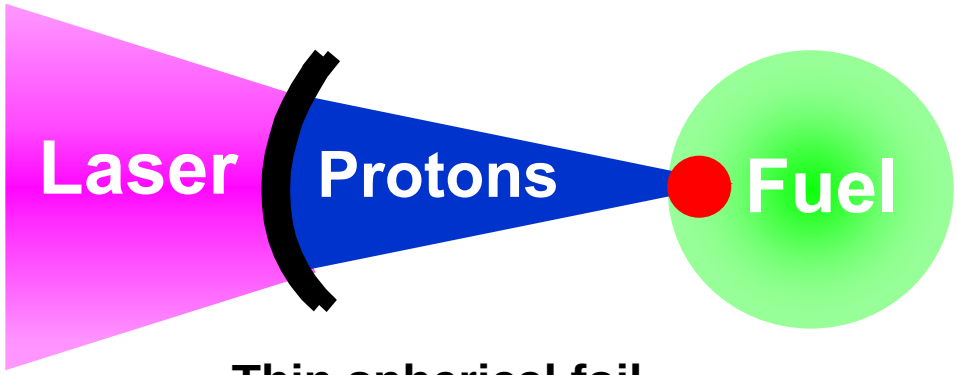






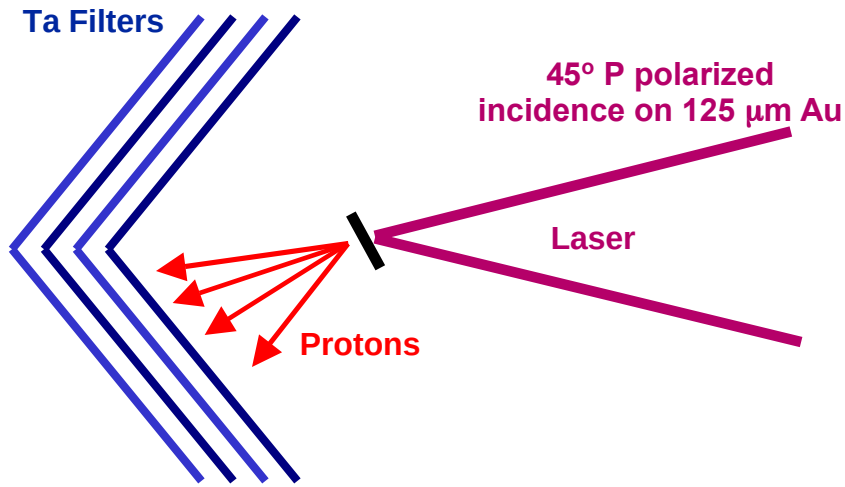
These data will benchmark new hybrid PIC modeling

A new FI concept is ignition using a ballistically focusing laser generated proton beam



Thin spherical foil

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



Cones of Radiochromic film

Up to 48J (12%) >10MeV and
kT_b=5MeV with 58 MeV cut off
Overall efficiency may be >45%

Nova Data

R Snavely et al. Phys. Rev. Lett. 85,2945 (2000)

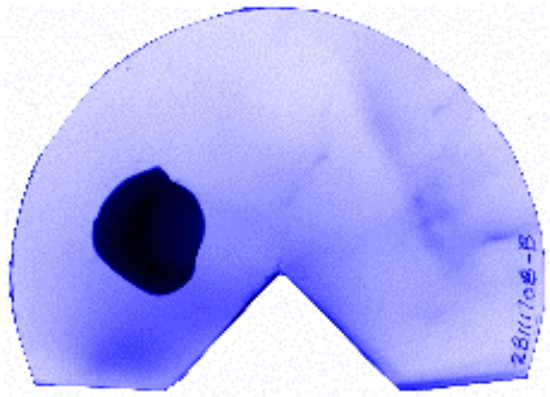
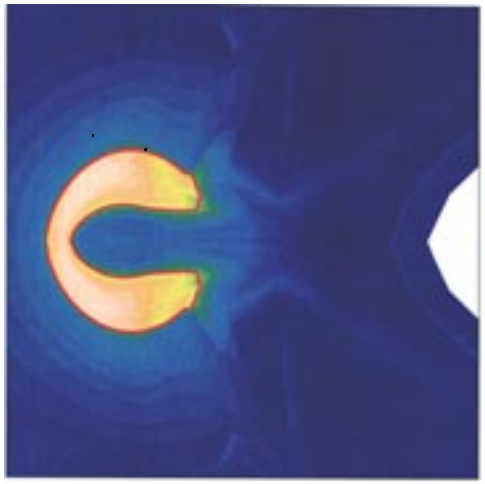
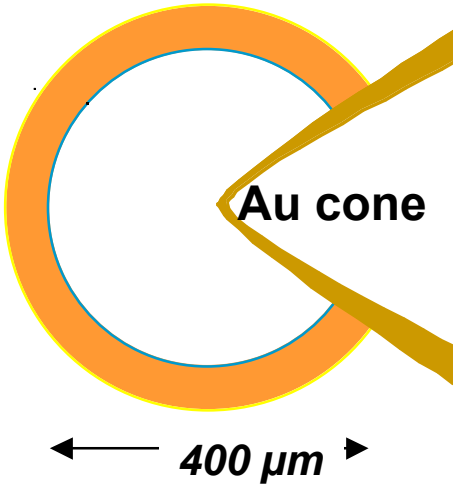


Image through 200μm Ta (Oct 1998)

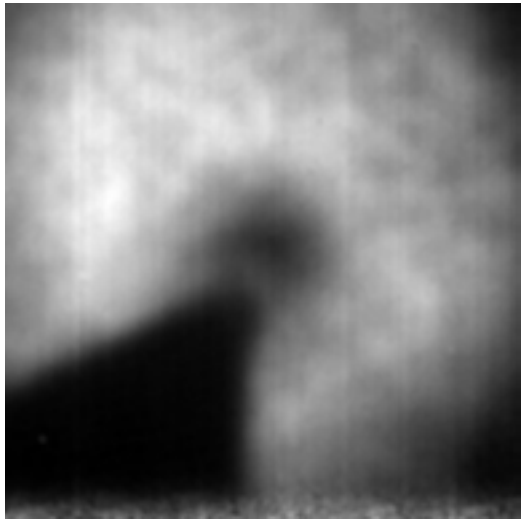
Joint GA/LLNL experiments have tested indirect drive cone focus target on the Omega laser



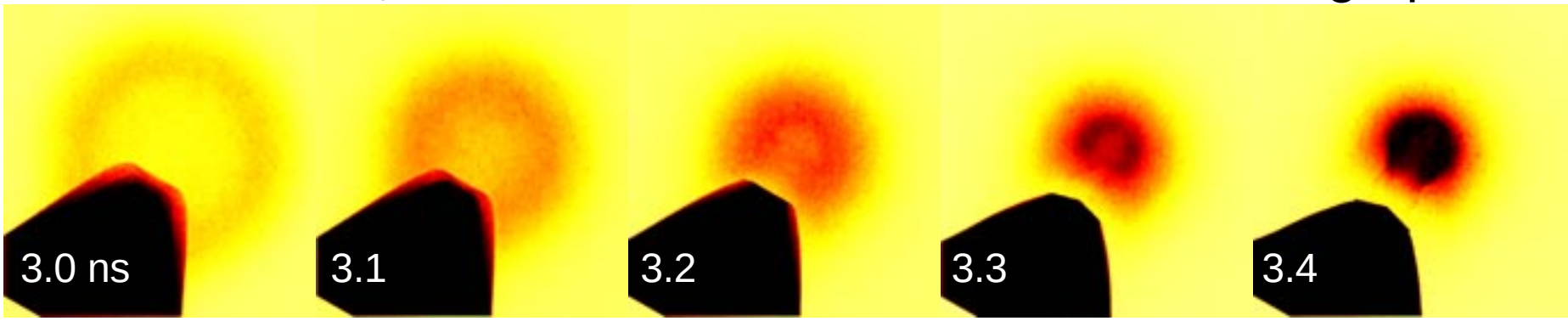
Lasnex model of Imploded density



Cone target at Omega



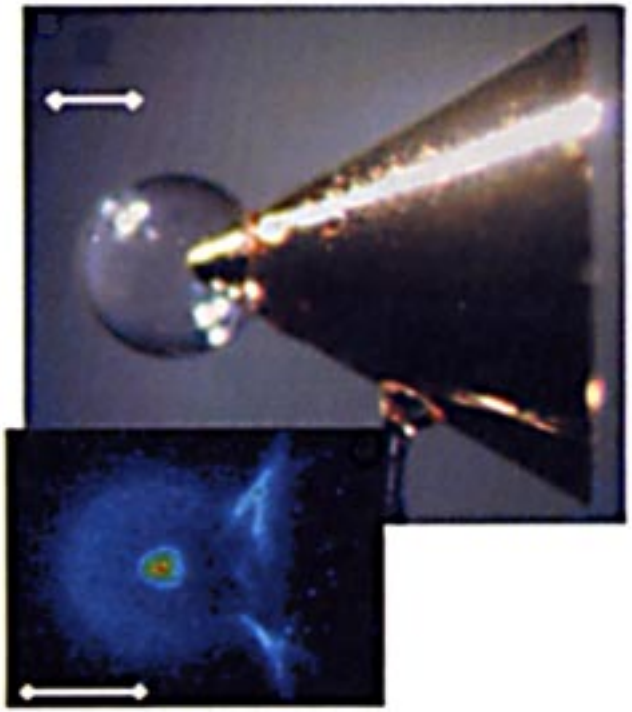
Radiograph

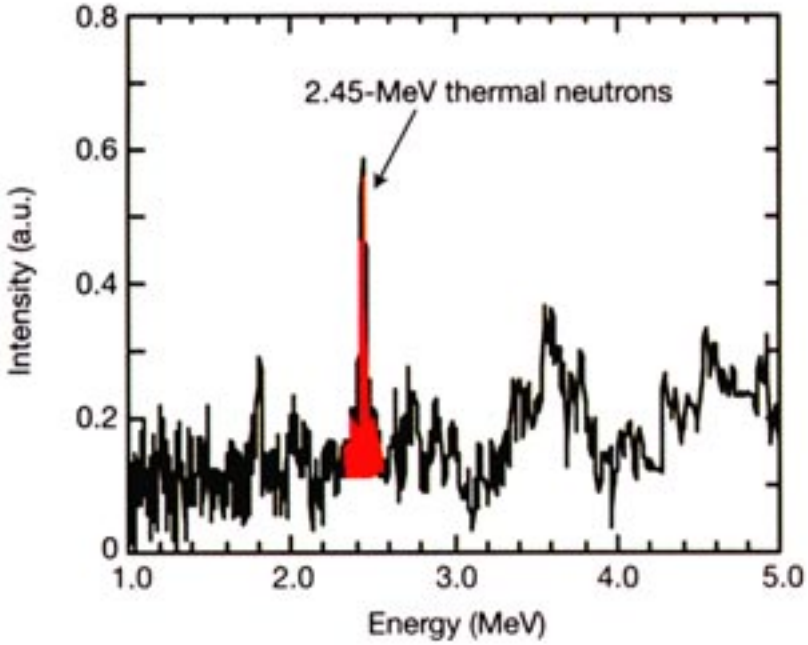


Simulated sequence of radiographs at Omega

Experiments on Gekko XII have seen enhanced neutron output from fast heating of a direct drive target with a reentrant cone

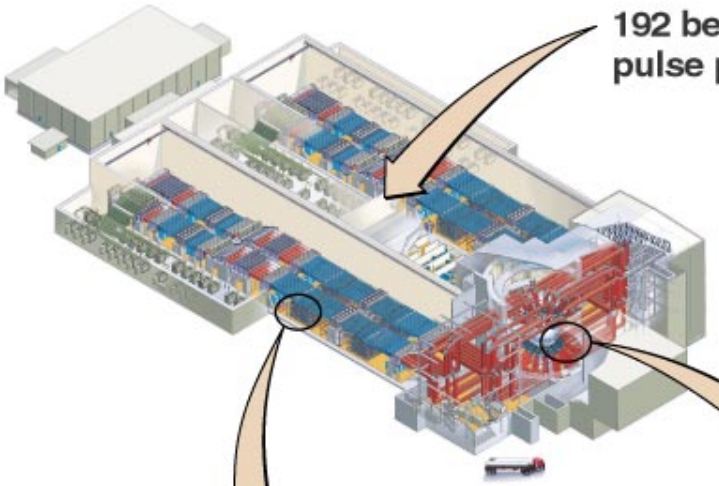
Enhanced neutron output from fast heating of deuterated direct drive shell implosion on Gekko XIII laser (Japan,UK) R. Kodama, et al., Nature 412, 798 (2001)





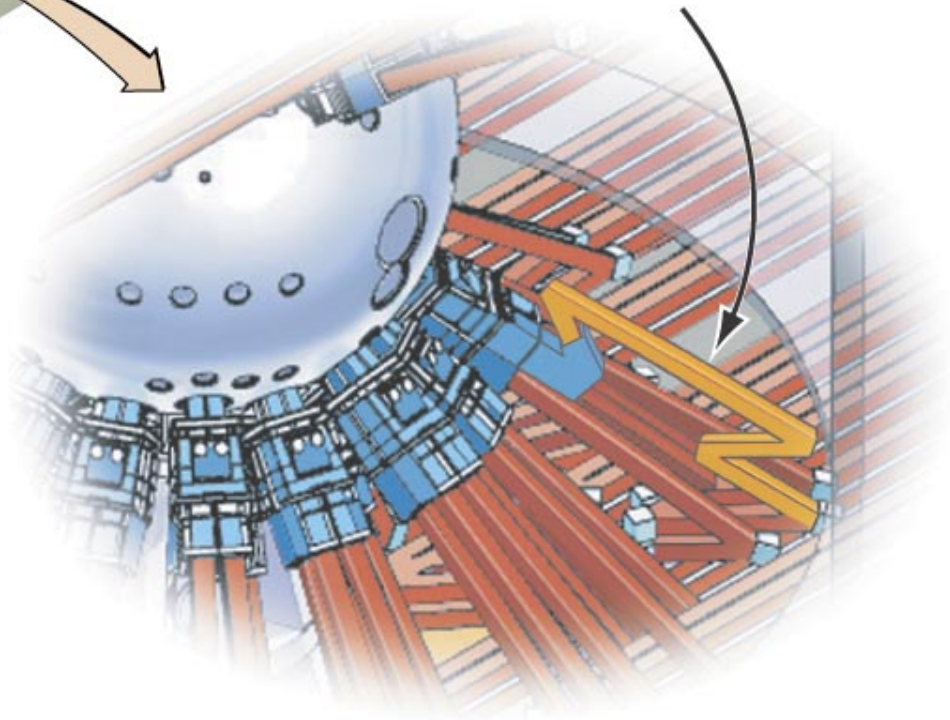
1.2 KJ compression pulse + 60 J, 100 tw fast heating pulse

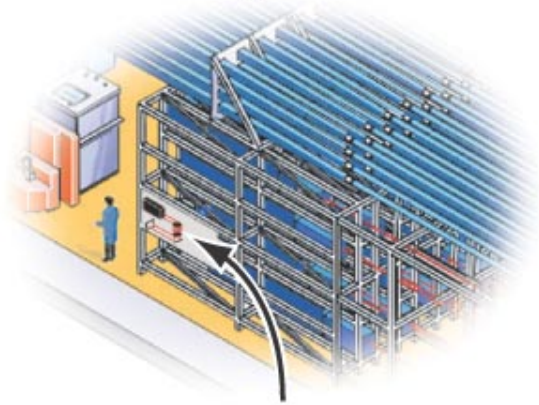
Advanced Technology will allow Multi-beamline HEPW deployment compatible with existing NIF architecture



192 beam National Ignition Facility has a short pulse potential of 0.2 Exawatts per beamline

Thin-optic pulse compressor and focusing lens are "plug and play" compatible with existing Final Optics Assembly (FOA)





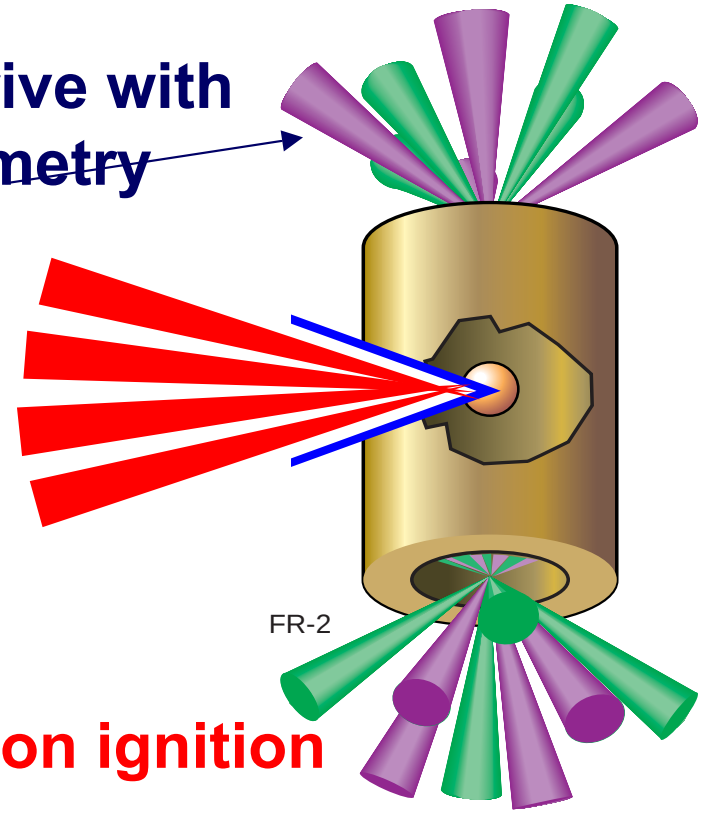
Front end modifications can fit within the existing NIF pre-amplifier module (PAM)

NIF-0801-02501(NNSA)
02CB/mcm

NIF could be used for 'proof of principle' studies of fast ignition in 2006/2007

NIF 'proof of principle' fast ignition expt.

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



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

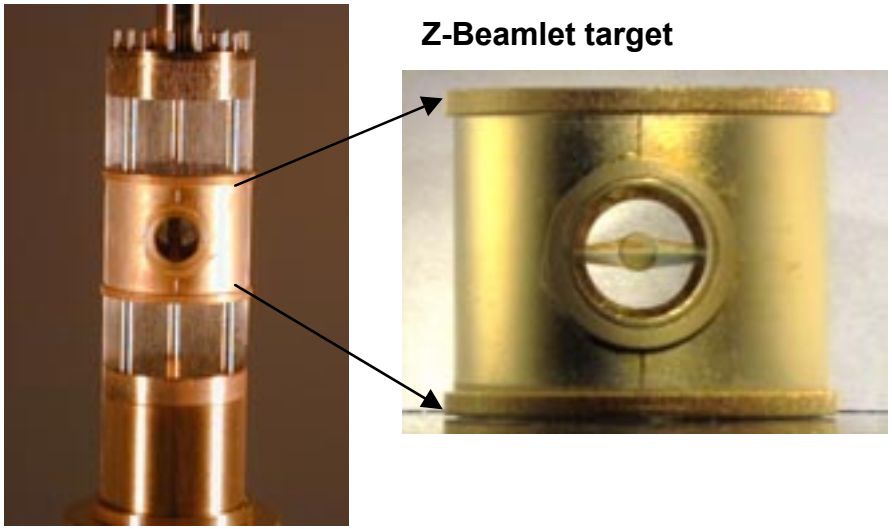
Full scale ignition would need about 20 HEPW beams

Substantial progress has been made on the symmetry of z-pinch driven indirect drive targets

The LLNL Beamlet laser - NIF's scientific prototype - is now operational as a diagnostic backlighter source on Z at Sandia Albuquerque

- **The intense x-ray backlighting available from Beamlet has imaged z-pinch implosions with a resolution not previously available on Z**

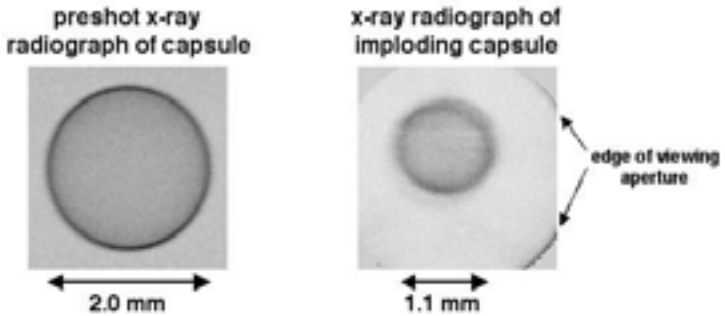
Z-Beamlet Laser



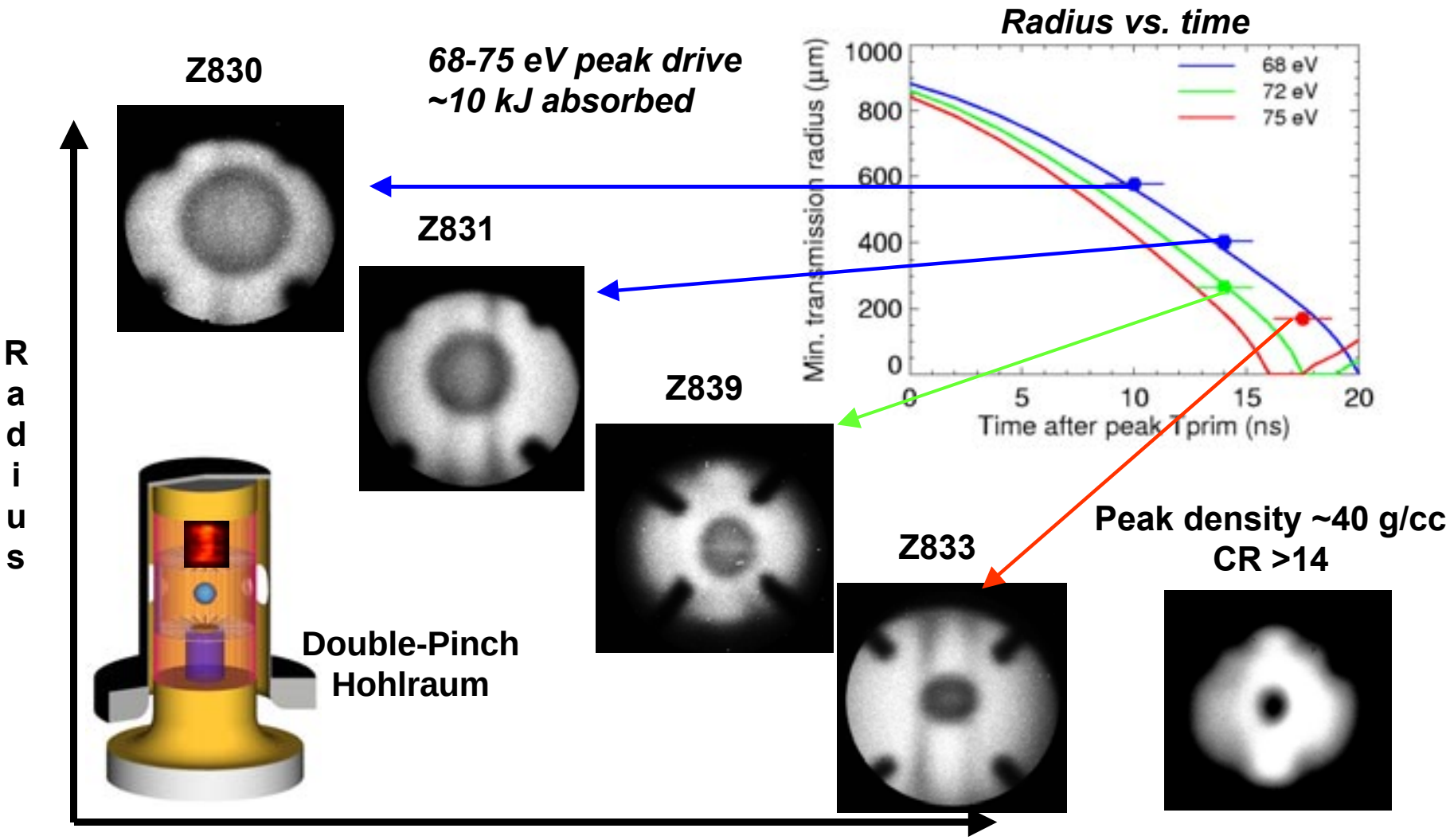
Z-Beamlet target

Concept for Z-pinch driven ICF target

Z-Beamlet radiograph

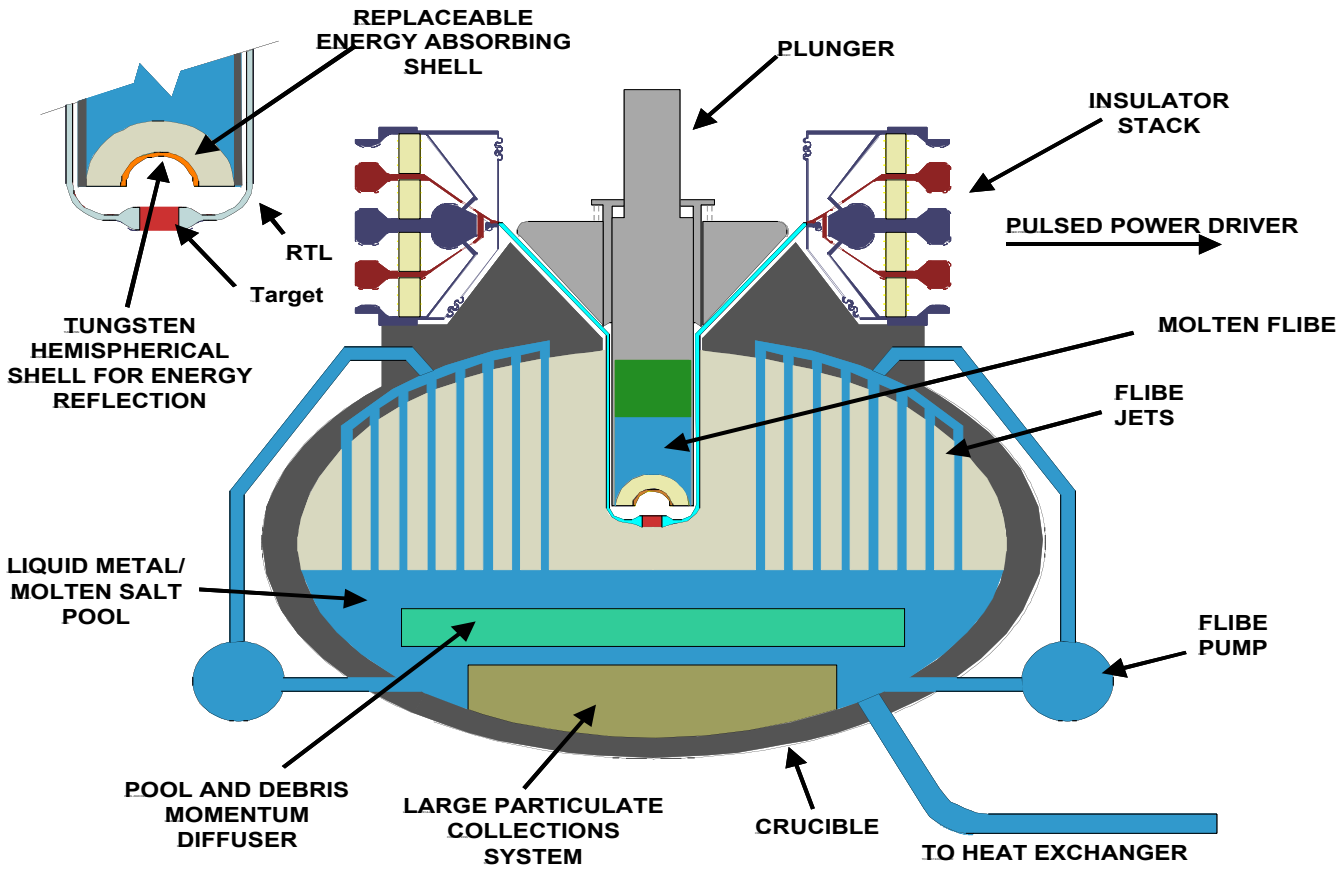


Double-pinch hohlraum on Z; capsule compression experiments demonstrate convergence ratio above 14; backlit capsule images agree with simulations



G. Bennett, M. Cuneo, R. Vesey

Concepts for z-pinch driven IFE envision high yield (~few GJ) low rep rate (~0.1 Hz) operation using recyclable transmission lines



RTL experiments on Saturn at the 10 MA level, with power plant level electrical stresses, have demonstrated uniform electrical turn-on, proper magnetically-insulated transmission line operation, high electrical conductivity, and low mass (results scale to 80 kg RTL with 90% electrical efficiency for power plant).

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