The US ICF Ignition Program and the Inertial Fusion Energy Program

John Lindl - LLNL

Fusion Energy Program Leader

University of California
Lawrence Livermore
National Laboratory

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Outline of Talk

- The National Ignition Facility (NIF)
- Indirect Drive
- Direct Drive
- Fast Ignition
- IFE with Lasers
- IFE with Ion Beams

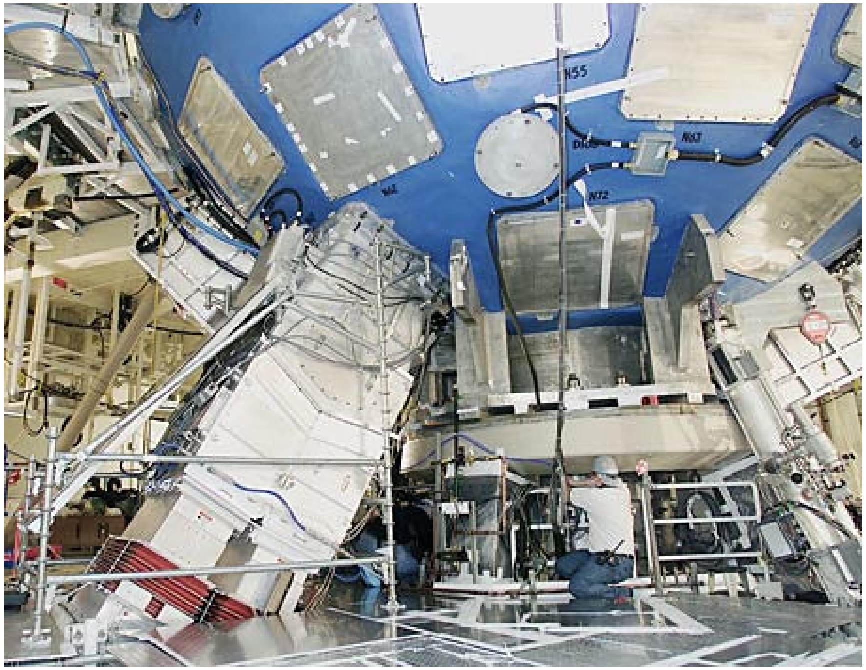
The National Ignition Facility

The beampath infrastructure for all 192 beams is complete and the first four beams have been activated for experiments

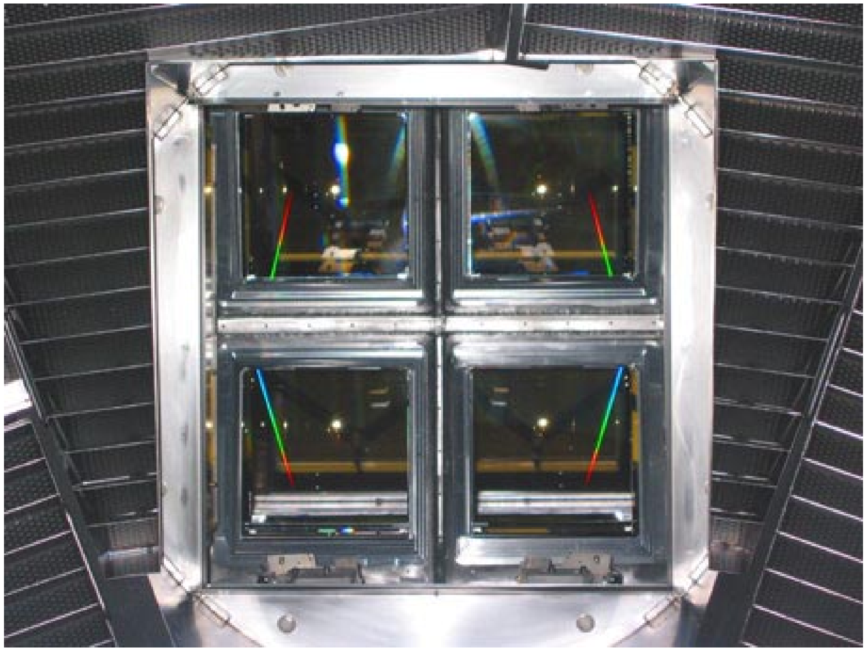
NIF Target Chamber upper hemisphere

The National Ignition Facility

First four NIF beams installed on the target chamber

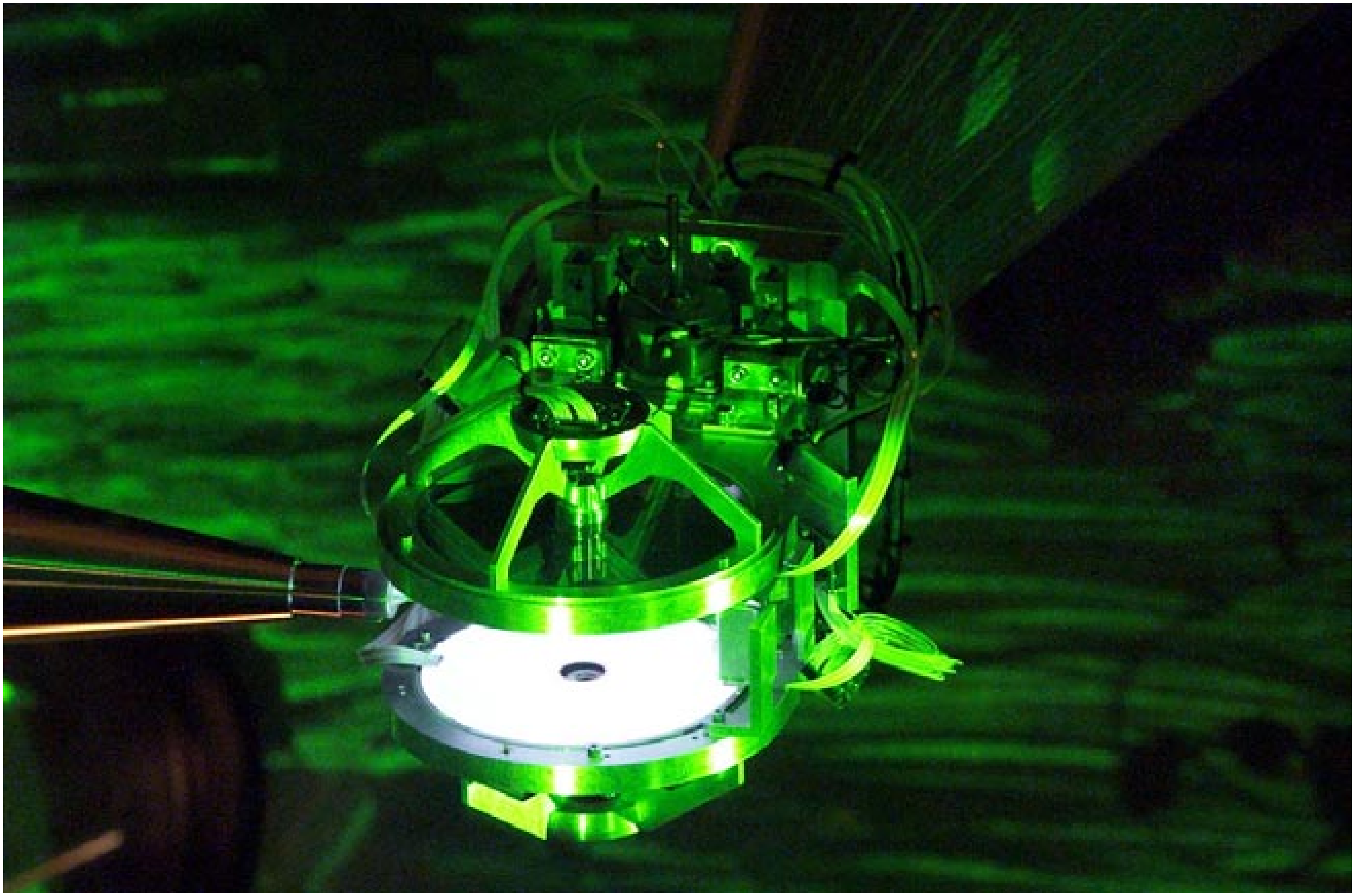


Quad 31b beamtubes and optics are installed and operational



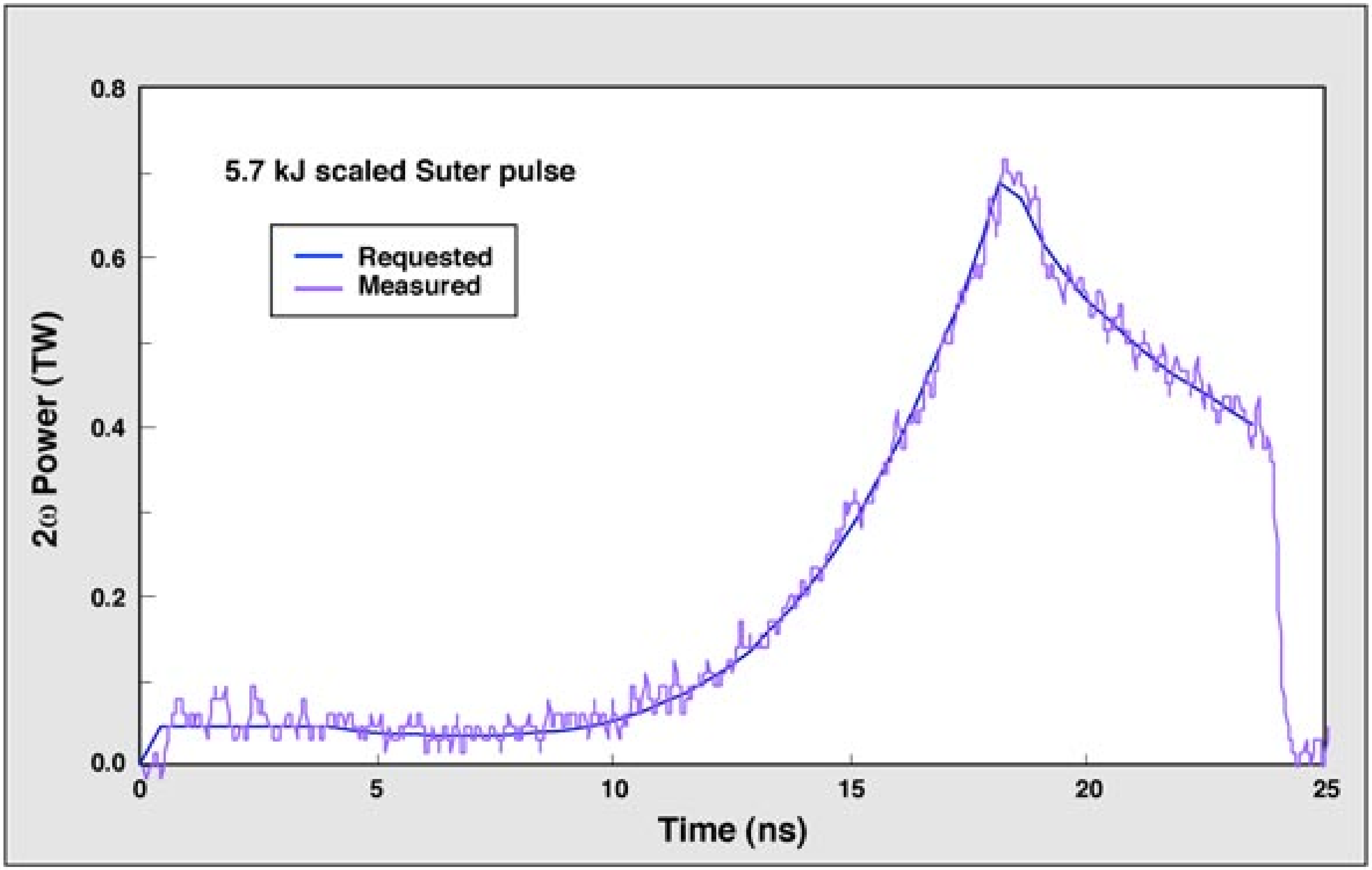
View from inside the target chamber

Target positioner and alignment system inside target chamber



Measured temporal profile of scaled Suter pulse closely replicates the requested pulse shape

The National Ignition Facility



NIF has begun to commission its experimental systems and will begin 4 beam (1 quad) experiments this summer

- The NIF Early Light (NEL) commissioning of four laser beams has demonstrated all of NIF's primary performance criteria on a per beam basis
  - 21 kJ of 1ω light (Full NIF Equivalent = 4.0 MJoule)
  - 11 kJ of 2ω light (Full NIF Equivalent = 2.2 MJoule) **(Non-optimal crystals)**
  - 10.4 kJ of 3ω light (Full NIF Equivalent = 2.0 MJoule)
  - 25 ns shaped pulse
  - < 5 hour shot cycle (UK funded)
  - Better than 6% beam contrast
  - Better than 2% beam energy balance
  - Beam relative timing to 6 ps
- Static x-ray imager and streaked x-ray detector operational and acquiring data at the target chamber

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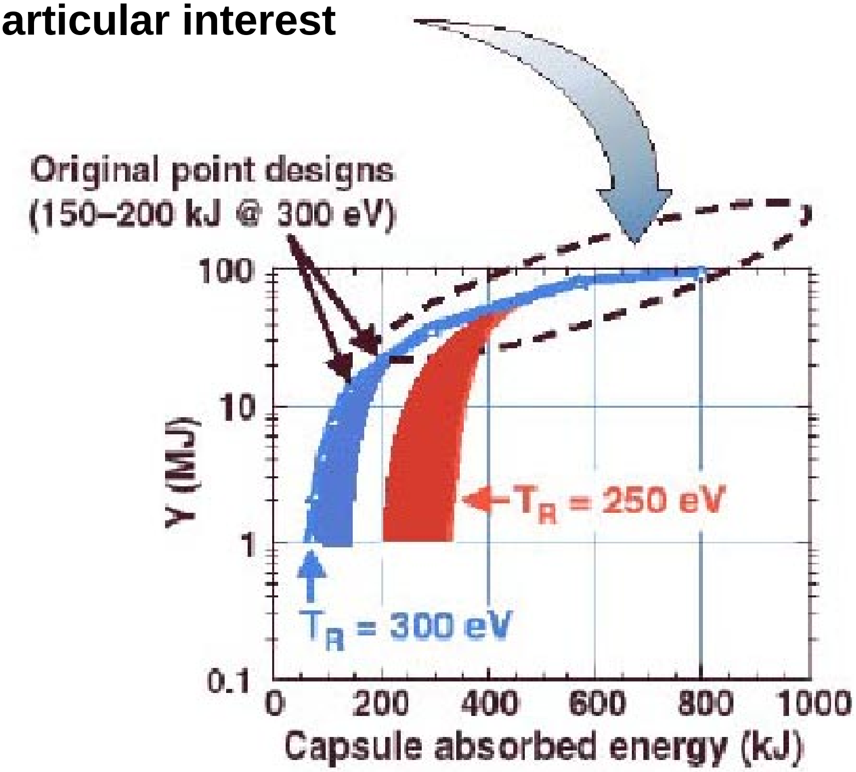
Recent ICF scientific interest has been in exploring the design space beyond the NIF baseline

- **Bigger ICF capsules are of particular interest**

- **Bigger capsules are more robust, less sensitive to experimental conditions**

  Bigger capsules offer:
  - **— Higher yield**
  - **— More options for experimentation**

- **Bigger capsules require energy above the 1.8 MJ NIF baseline**



Operation in the green, at 2ω, appears the best way to get to high energy

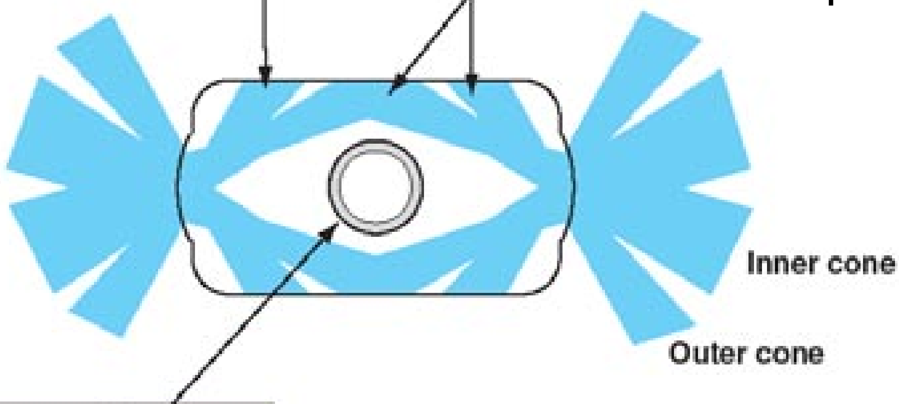
The choice of laser wavelength is central to the ICF Indirect Drive Ignition Program

Hohlraum Energetics

- Backscatter reduces laser absorption and energy coupled into the capsule

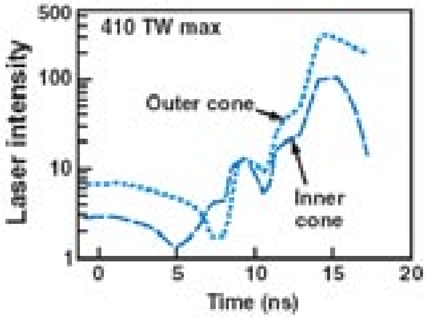
Indirect Drive Symmetry

- Unequal absorption between cones can spoil beam balance
- Beam bending, beam spray and cross beam effects can spoil symmetry



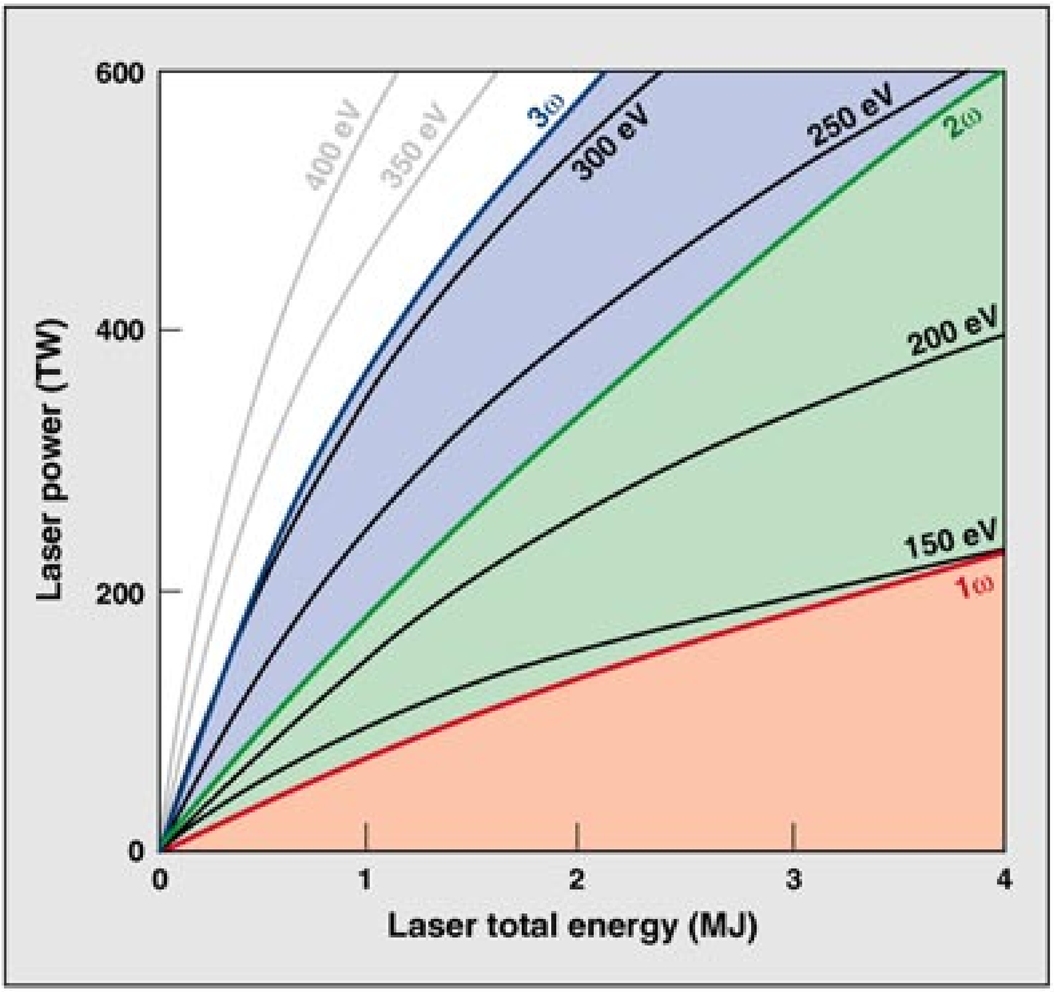
Implosion/compression to high density

- Time dependent scatter can spoil pulse shape
- Hot electrons from plasma waves can preheat the fuel making it less compressible



LPI interactions place limits on achievable hohlraum temperature

The National Ignition Facility



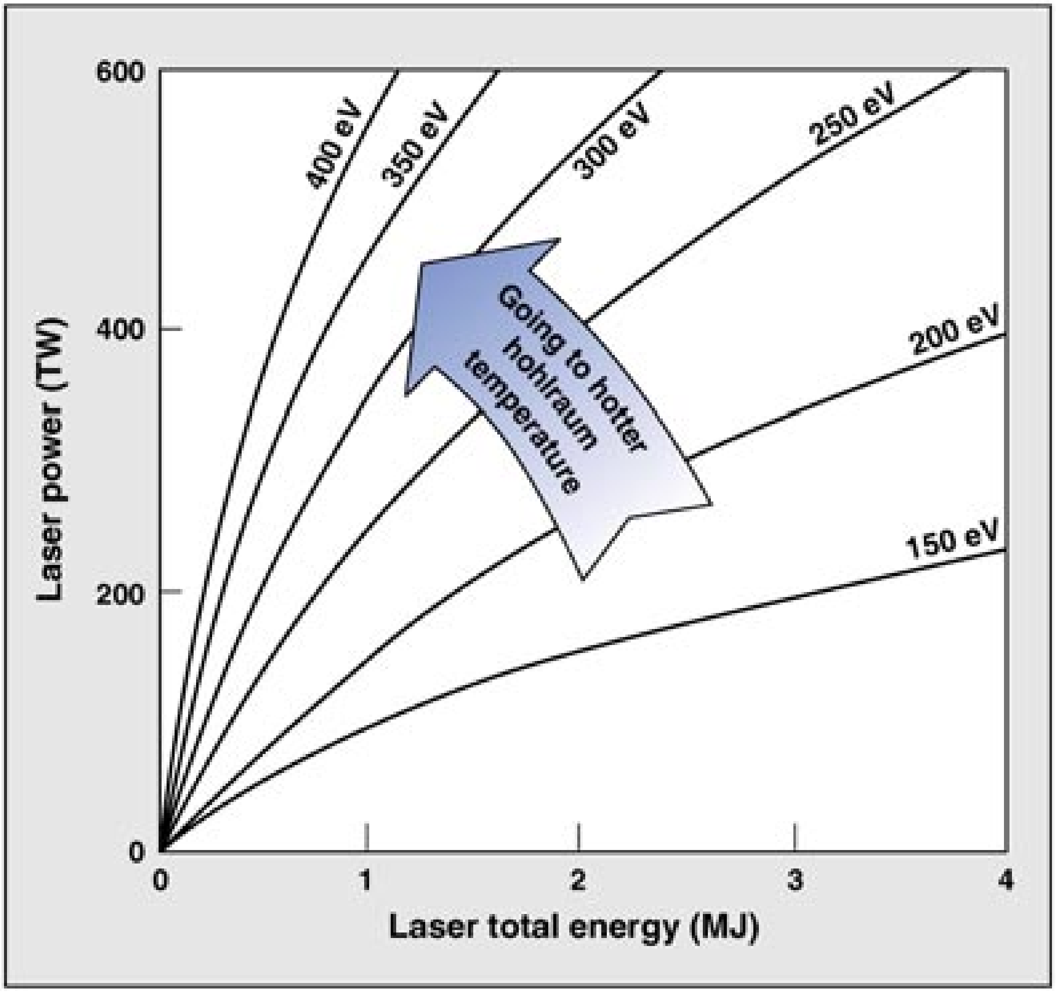
- LPI experience indicates that hohlraum plasma densities must be limited to $n/n_{crit} \approx 0.1$ to 0.2

- Because n_{crit} is proportional to $1/\lambda^2$, acceptable hohlraum densities and therefore, achievable hohlraum temperatures are lower for longer wavelengths

- The maximum expected T_R for 0.35μm (3ω) light is then ~300 eV

- From 1976 to 1980 hohlraum experiments on Shiva gave 1.06 μm (1ω) data that is again consistent with the simple LPI model
  - — Hohlraum temperature at 1ω was limited to 130 - 140 eV
- There is relatively little experience with green light

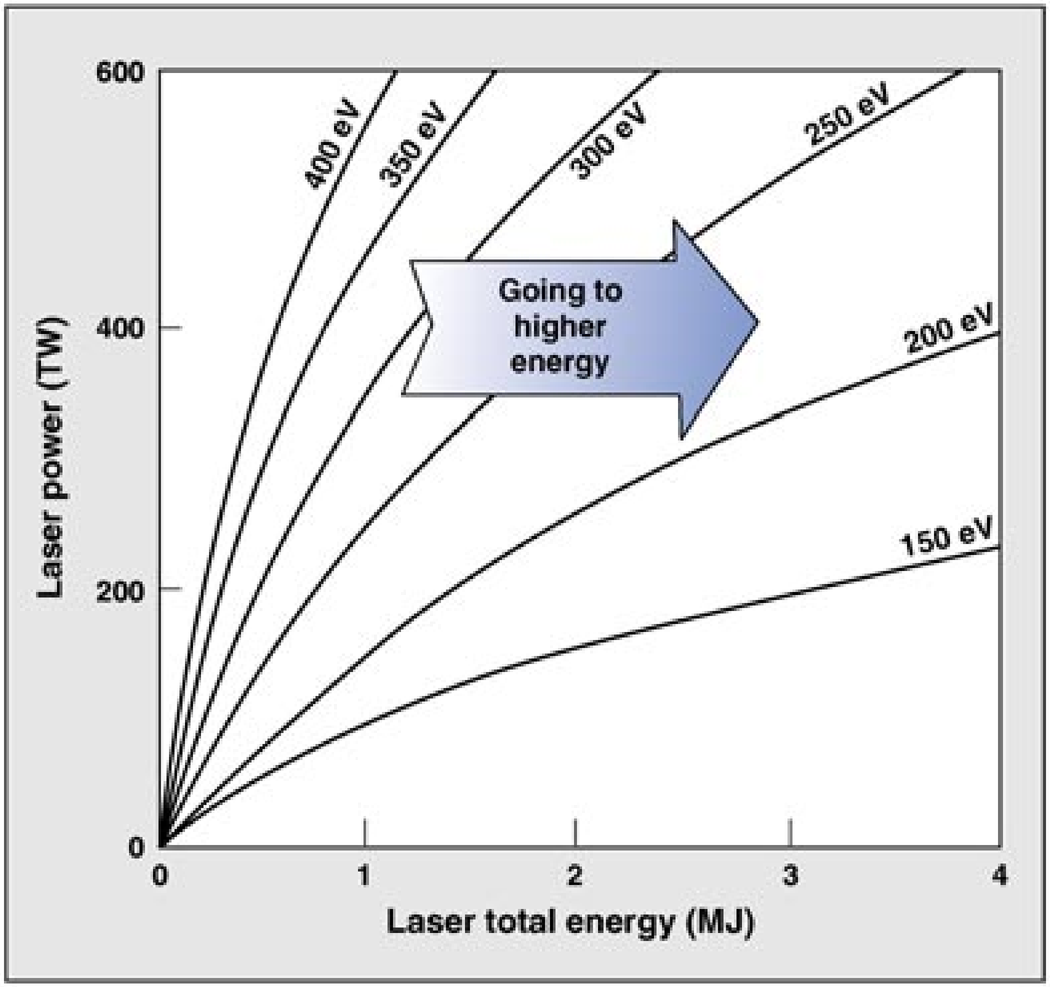
Higher hohlraum temperatures gives:



- Higher pressure on the capsule
- Higher implosion velocity
- Giving higher compression
- Allowing ignition with less energy into the capsule

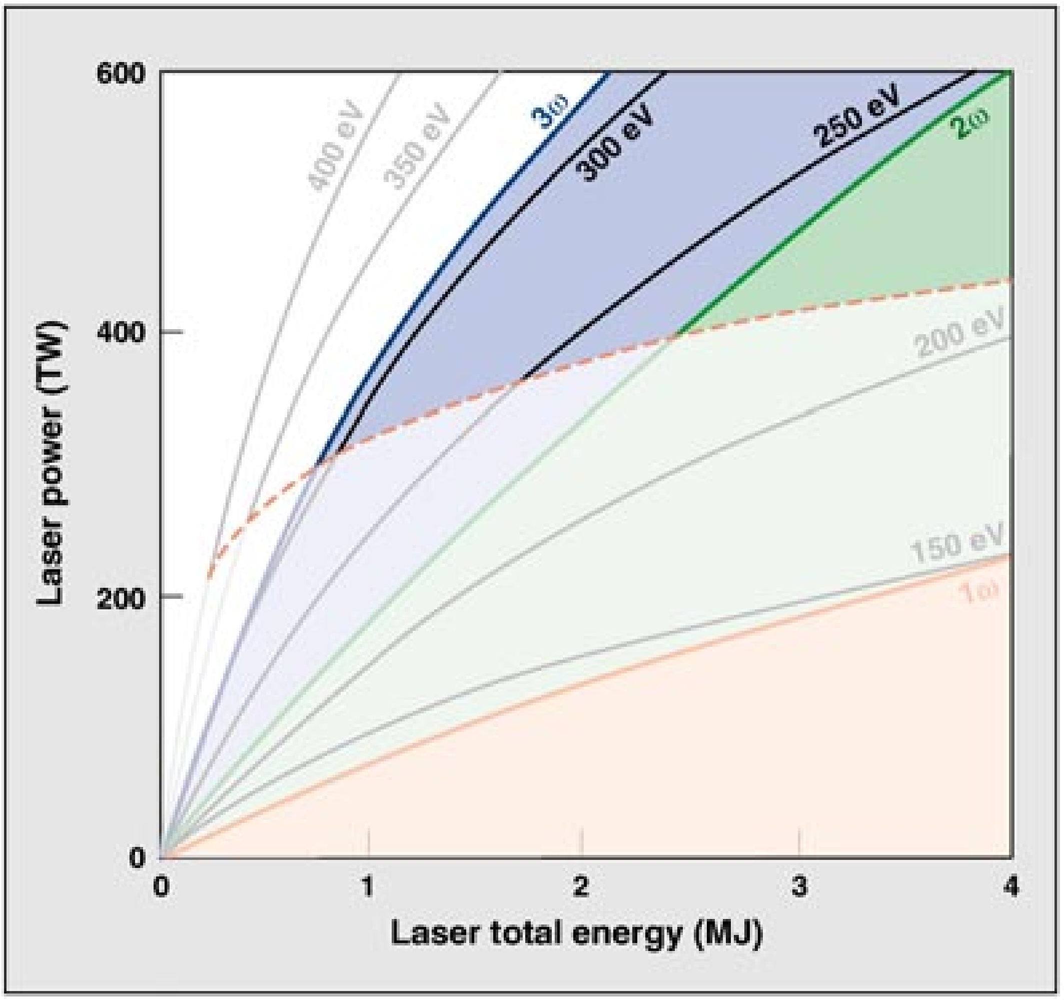
Higher energy allows you to drive larger capsules

The National Ignition Facility



- Larger capsules allow:
  - —Lower implosion velocity
  - —Lower radiation temperature
  - —Lower intensity
  - —Lower plasma density
- Reduced intensity and plasma density then allow longer laser wavelengths

The ICF ignition region in power and energy is based on constraints for LPI and hydrodynamic instabilities

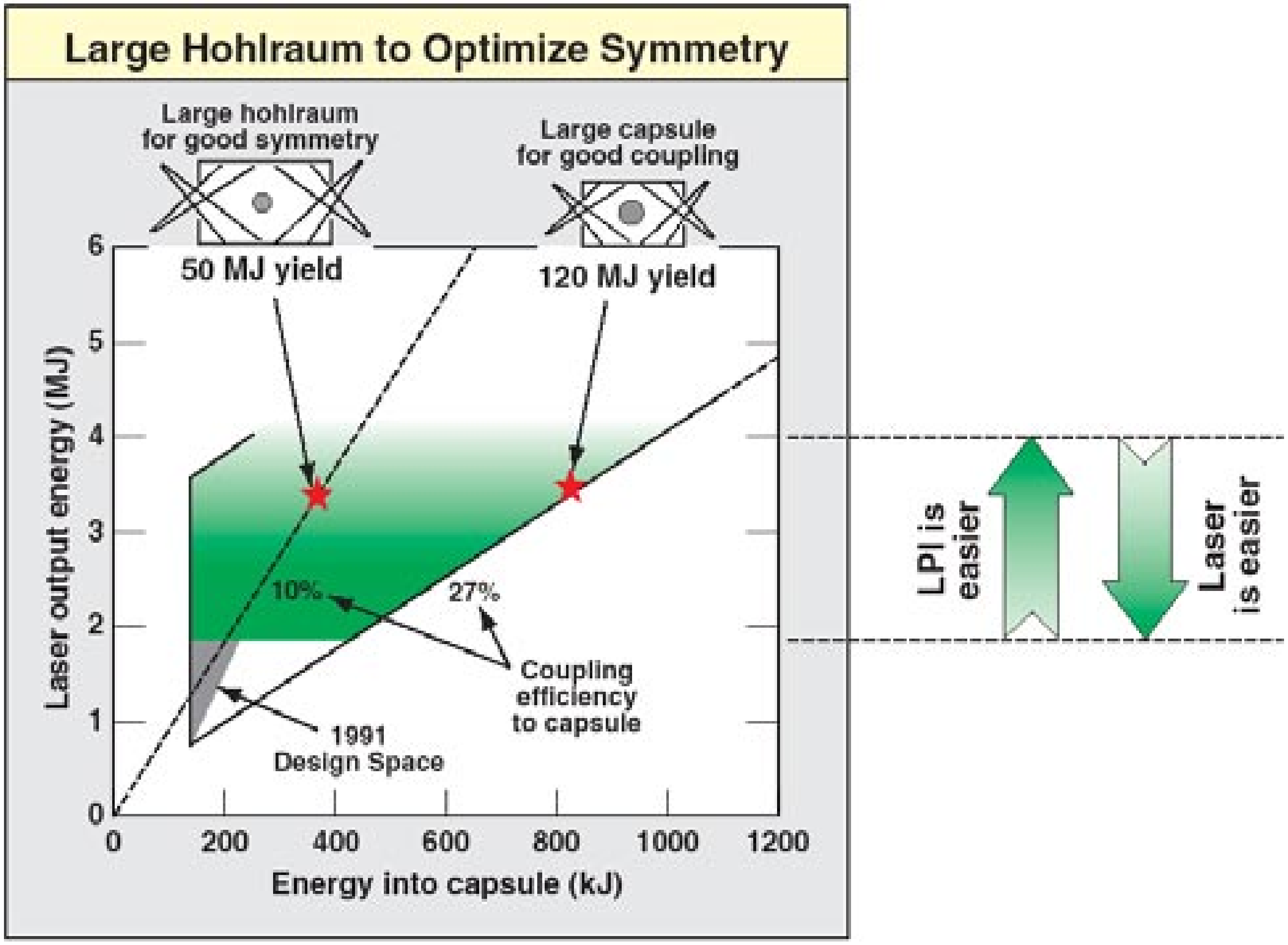


- The mechanical integrity of the capsule as it implodes can be degraded by hydrodynamic instabilities

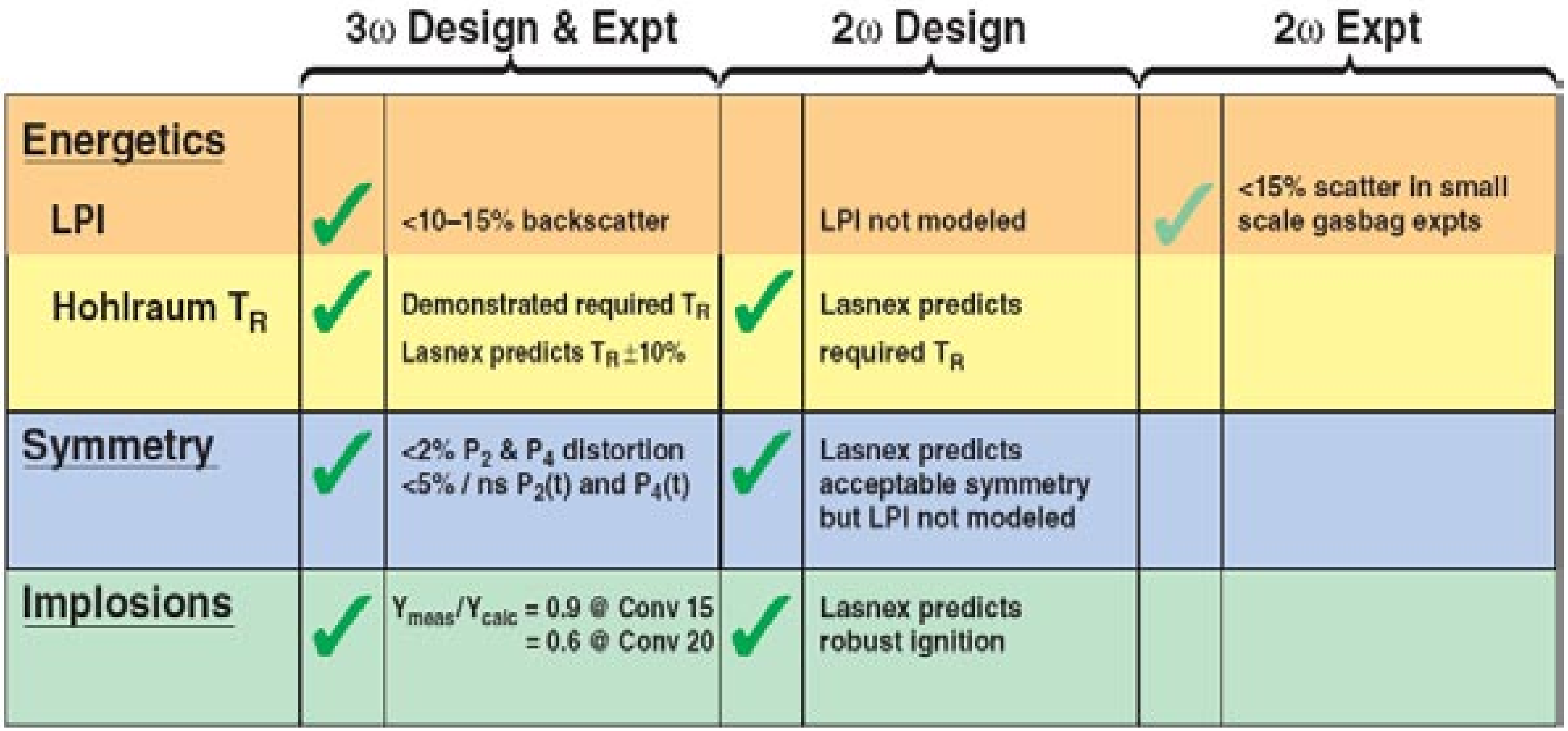
- There is a minimum T_R that is dictated by keeping these instabilities under control

- The red dashed line corresponds to those temperatures needed for a surface roughness of ~200Å

NIF’s 2w capability may provide an operating window for larger capsules with yields much greater than the baseline



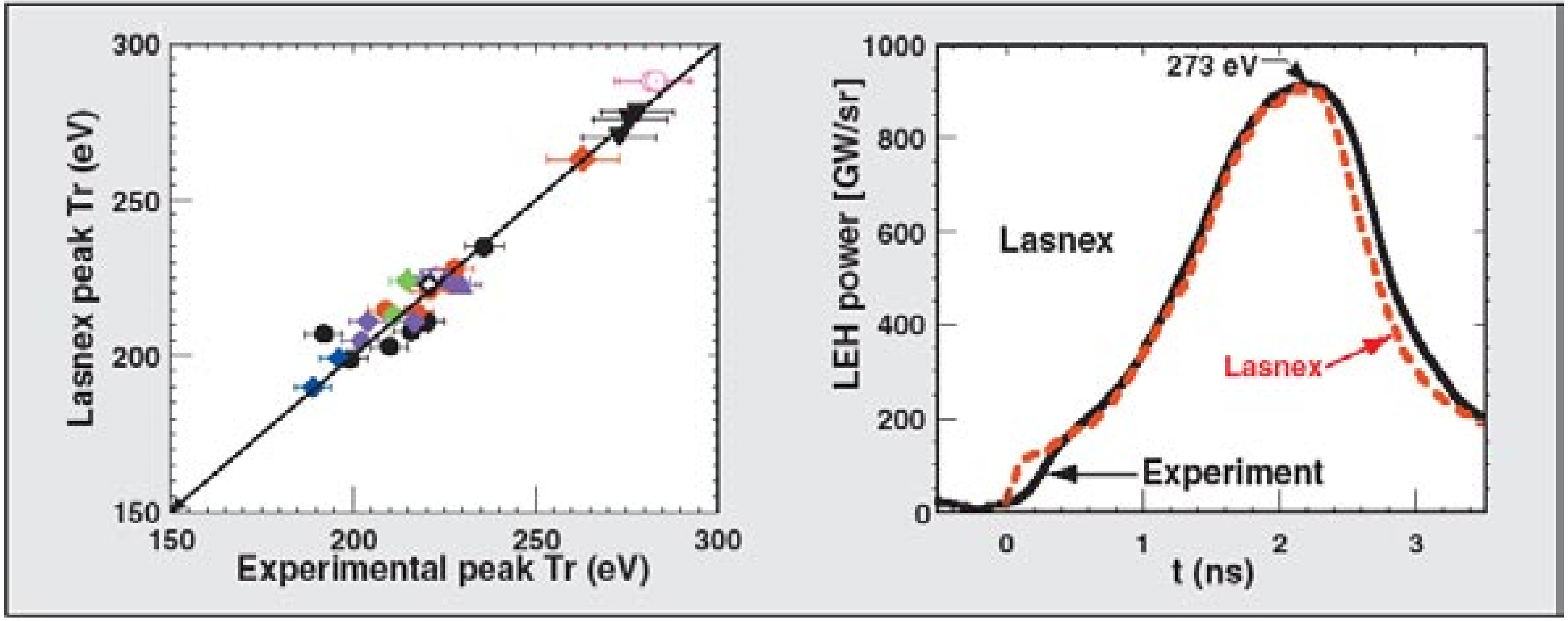
There is a well established physics basis for ignition at 3ω and experiments are beginning to address critical ignition requirements for 2ω



	3ω Design & Expt		2ω Design		2ω Expt	
Energetics						
LPI	✓	<10–15% backscatter		LPI not modeled	✓	<15% scatter in small scale gasbag expts
Hohlraum T_R	✓	Demonstrated required T_R Lasnex predicts $T_R \pm 10\%$	✓	Lasnex predicts required T_R		
Symmetry	✓	<2% P_2 & P_4 distortion <5% / ns $P_2(t)$ and $P_4(t)$	✓	Lasnex predicts acceptable symmetry but LPI not modeled		
Implosions	✓	Y_{meas}/Y_{calc} = 0.9 @ Conv 15 = 0.6 @ Conv 20	✓	Lasnex predicts robust ignition		

- 2ω looks very appealing in Lasnex designs
- Preliminary experiments are encouraging

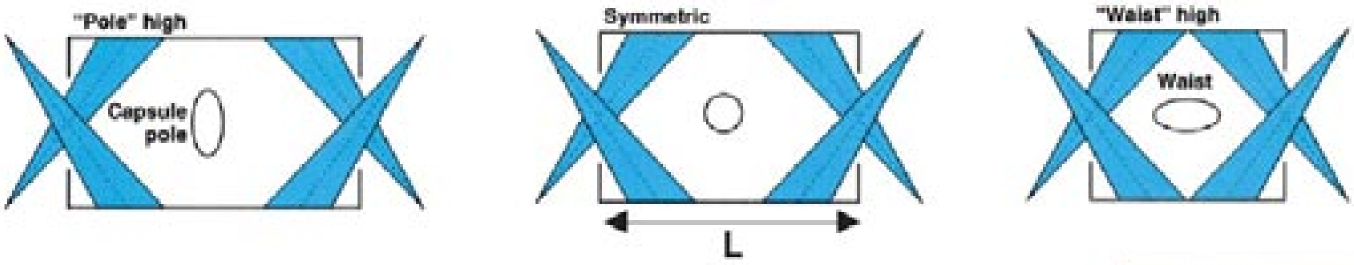
At 3ω, drive measurements and Lasnex simulations agree closely over >two orders of magnitude in T^4_R

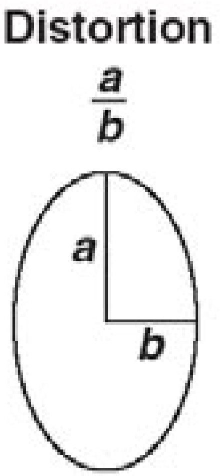


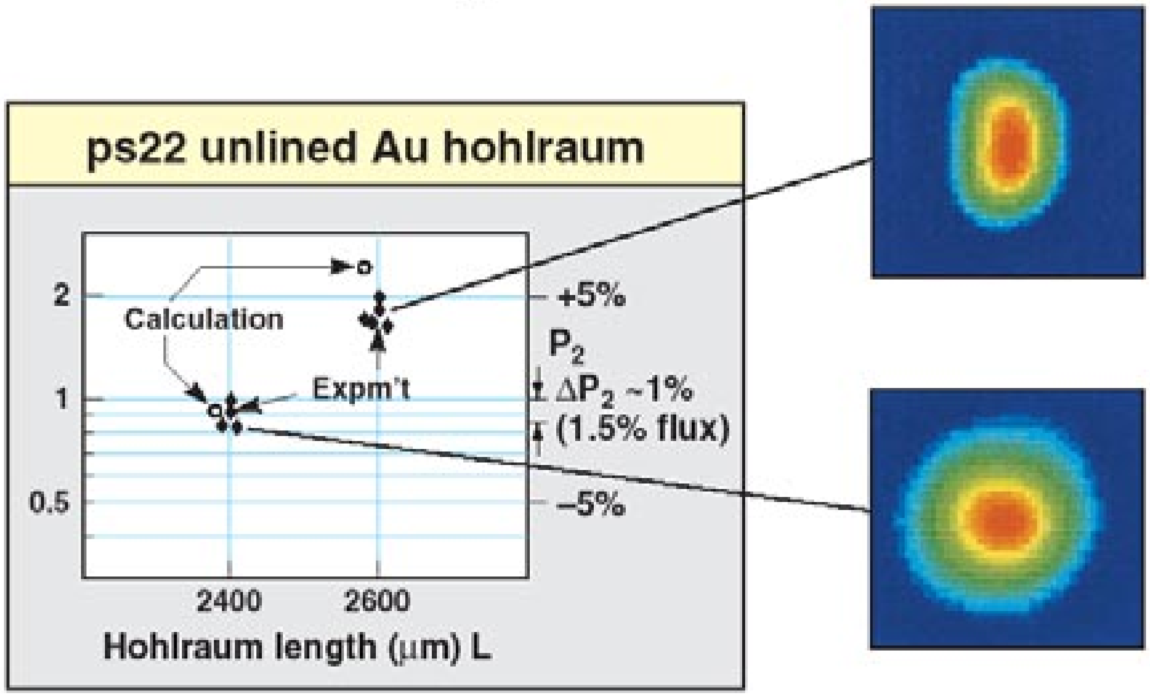
Vacuum and gas-filled hohlraums with 2.2 ns shaped pulses
(3:1 and 5:1 contrast ratio)

Lasnex can predict hohlraum drive to ±10%

On Nova and Omega, at 3ω we demonstrated control of symmetry by varying the hohlraum geometry

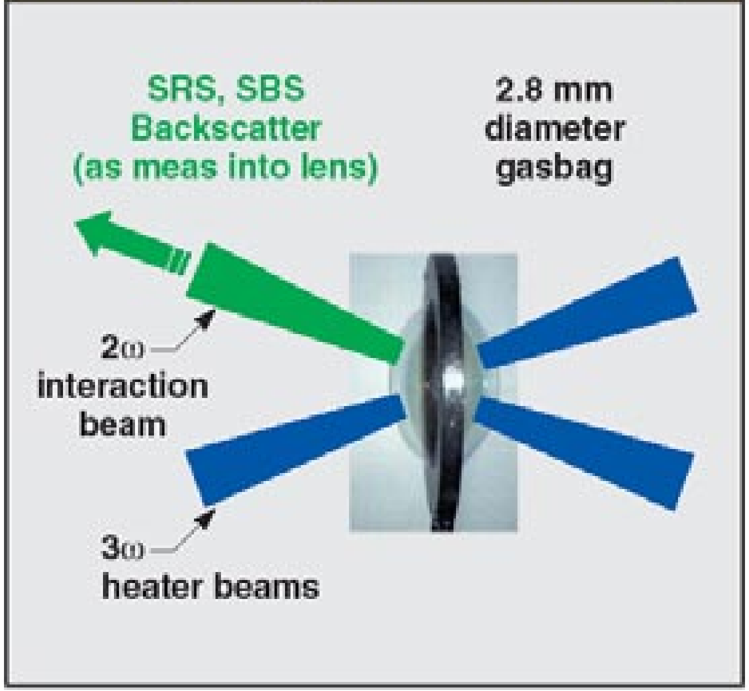




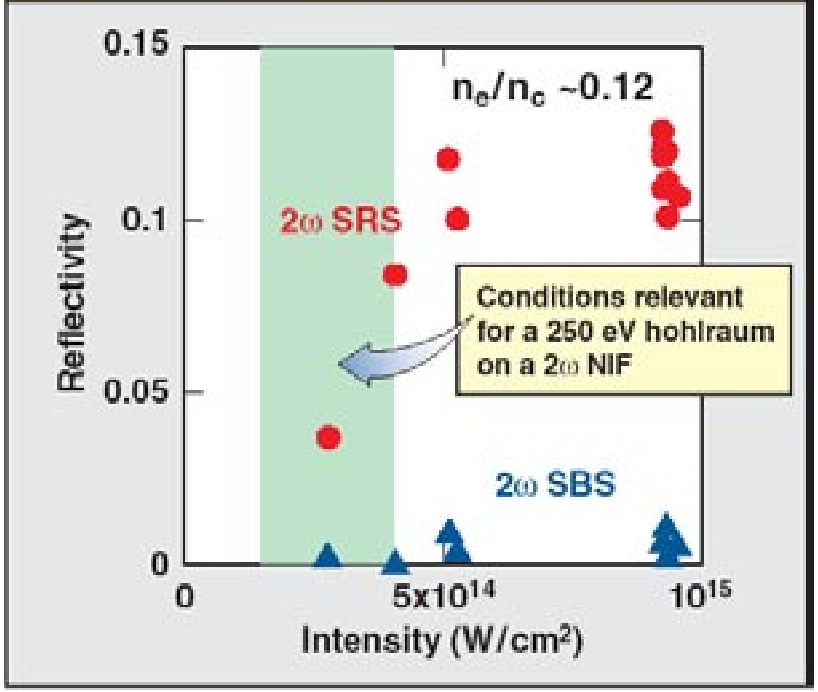


LPI backscatter at 2ω was measured on Omega

Gasbag configuration on Omega



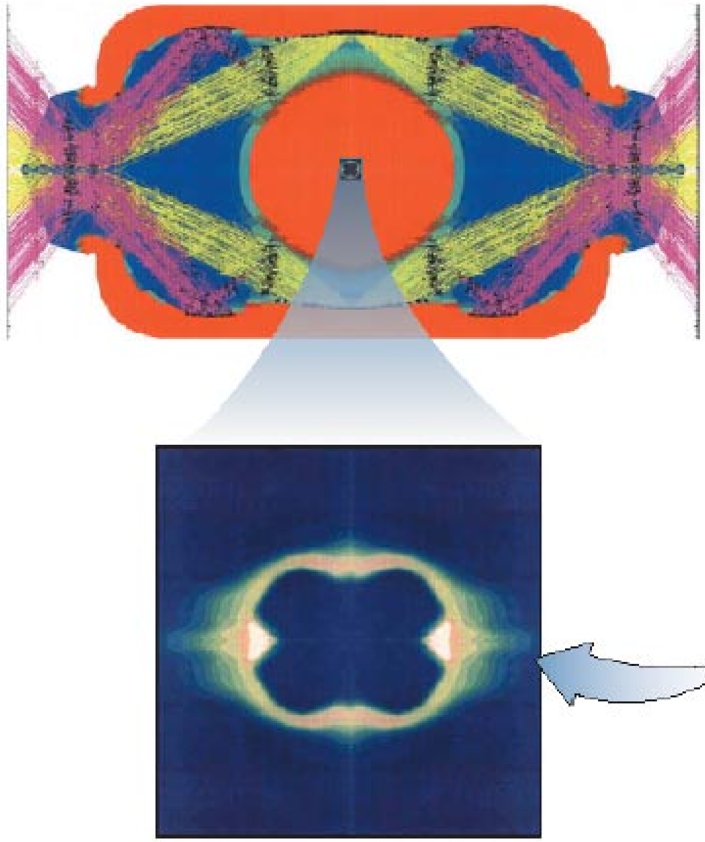
SRS, SBS Backscatter Measurements



LPI studies on Omega indicate acceptable levels of backscatter at 2ω for these conditions

- Upcoming experiments will check for backscattered light outside the lens

Lasnex calculations at 2ω indicate that symmetry can be controlled in the usual way.

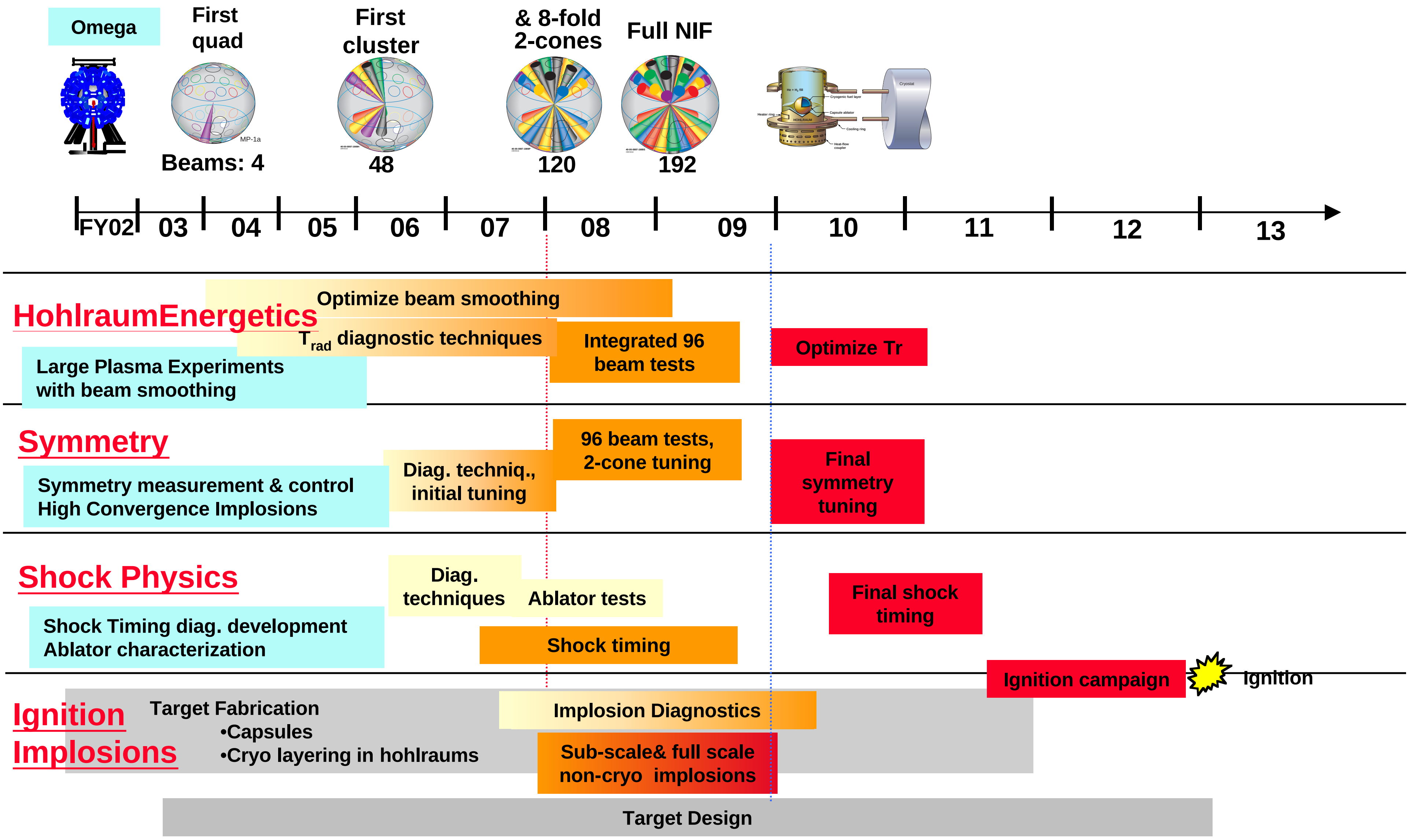


- Laser energy into hohlraum: 3.3 MJ
- Capsule absorbed energy: 400 kJ
- Calculated yield: 50 MJ

Fuel Density Profile at ignition

Symmetry can be controlled in the usual way by repointing beams and/or adjusting relative beam powers

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



Omega

First quad

Beams: 4

First cluster

48

& 8-fold 2-cones

120

Full NIF

192

FY02 03 04 05 06 07 08 09 10 11 12 13

HohlraumEnergetics

Optimize beam smoothing

T_{rad} diagnostic techniques

Integrated 96 beam tests

Optimize Tr

Large Plasma Experiments with beam smoothing

Symmetry

Symmetry measurement & control
High Convergence Implosions

Diag. techniq., initial tuning

96 beam tests, 2-cone tuning

Final symmetry tuning

Shock Physics

Shock Timing diag. development
Ablator characterization

Diag. techniques

Ablator tests

Shock timing

Final shock timing

Ignition campaign

Ignition

Ignition Implosions

Target Fabrication
- Capsules
- Cryo layering in hohlraums

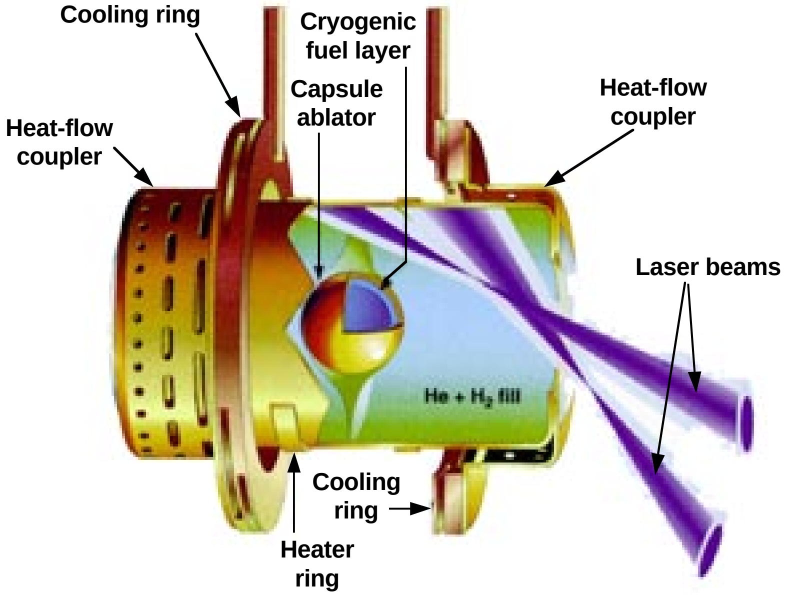
Implosion Diagnostics

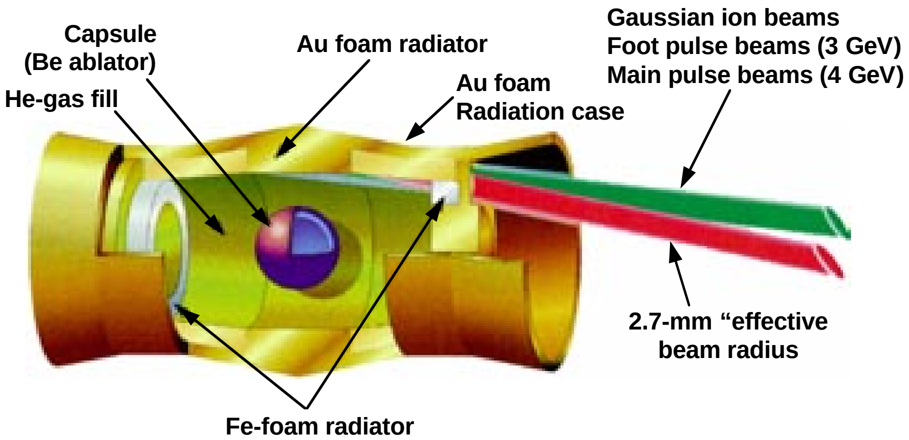
Sub-scale& full scale non-cryo implosions

Target Design

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

NIF target

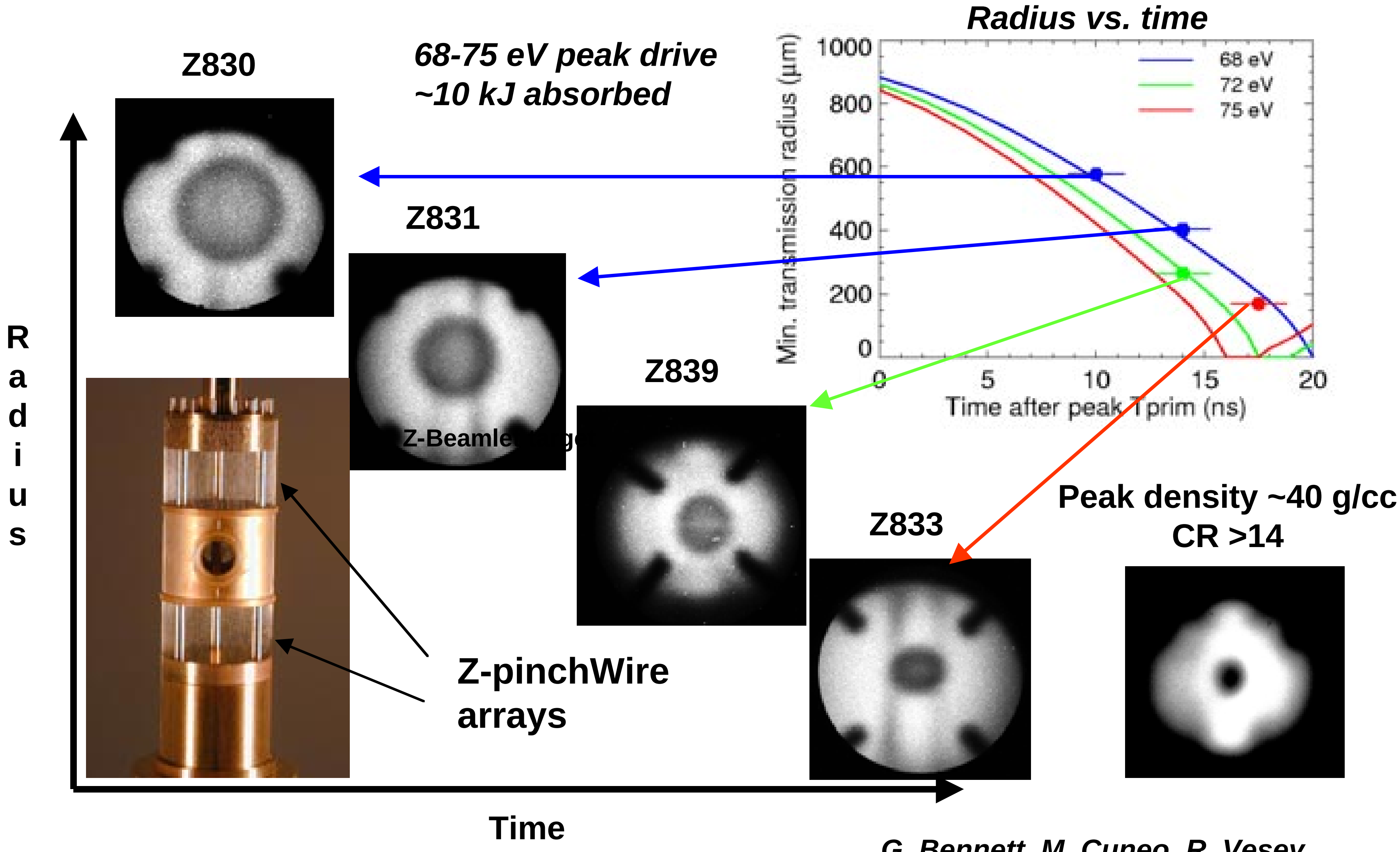




Yield = 400 MJ
Driver (using NIF-like hohlraum to capsule radius ratio)
  6 MJ of 4 GeV Pb ions → gain 67
  7.5 MJ of 8 GeV Pb ions → gain 53

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

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



68-75 eV peak drive
~10 kJ absorbed

Z-pinchWire arrays

Peak density ~40 g/cc
CR >14

G. Bennett, M. Cuneo, R. Vesey

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- → Direct Drive
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Control of hydrodynamic instabilities and laser imprint determine key features of laser direct drive targets

NIF BASELINE

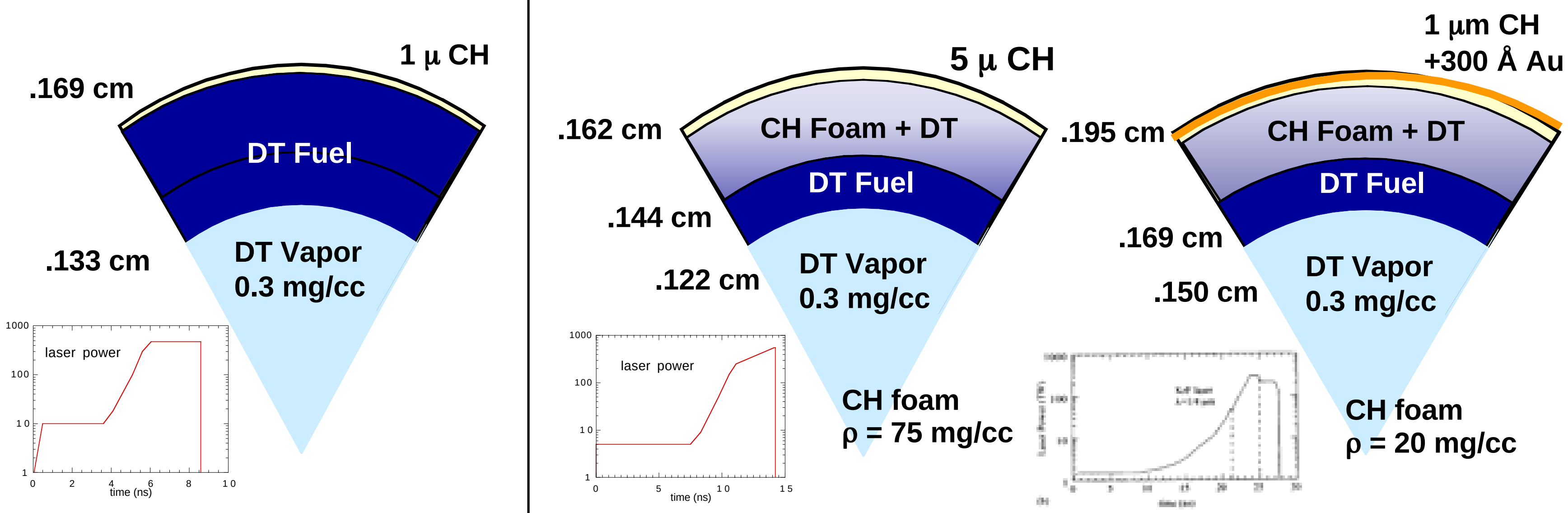
PURE DT

(shock heated)

ADVANCED DESIGNS

CH FOAM /DT+ DT

GOLD+ CH FOAM / DT + DT

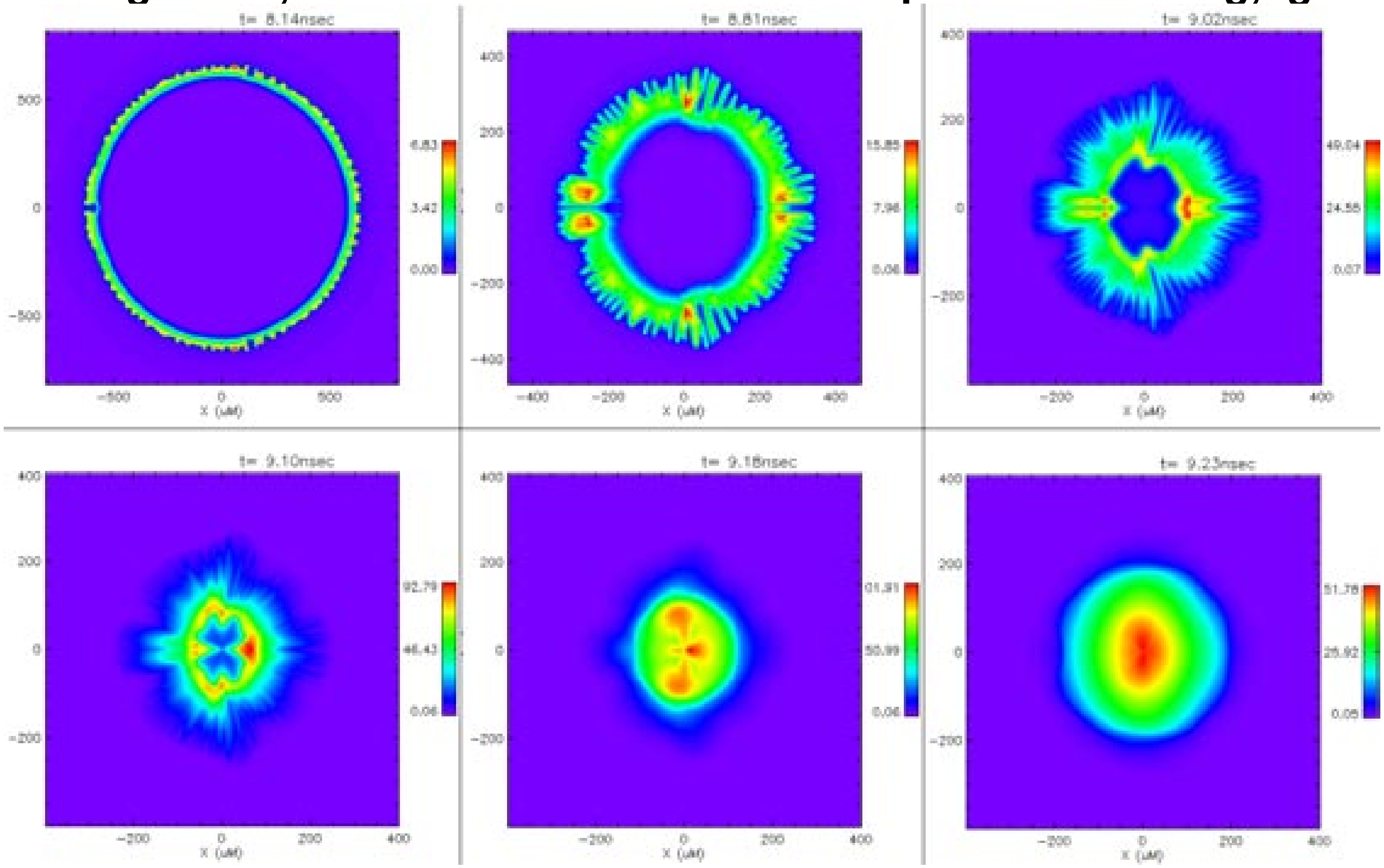


Laser Type	Glass	Glass	KrF	KrF (ISI)
Laser Energy	1.6 MJ (~60% absorbed)	1.6 MJ (90% absorbed)	1.6 MJ	1.3 MJ
1-D Gain	20-30	50-120	108	127
Zooming	No	No	Yes	Yes
ρR_{max}	1.2	1.86	2.11	1.8
e-folds$_{max}$	4.7	4.8	6.1	8
Ref:	C. Verdon UR	NRL, LLE	NRL	NRL

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)

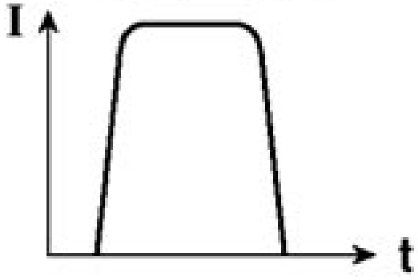
The target adiabat (α) determines both the target gain and stability

- The adiabat (α) is the ratio of the fuel to Fermi-degenerate pressure:

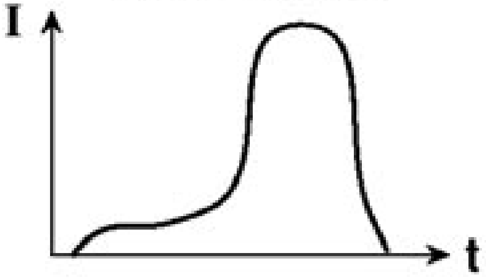
$$\alpha = \frac{P_{\text{fuel}}}{P_{\text{Fermi}}}$$

- The lower α, the higher the compressed density, increasing the target gain.
- The higher α, the more stable the target.
- A target designer's dilemma is to balance gain and stability:
  - choose an intermediate value of α;
  - tailor α in the target to optimize gain and stability.

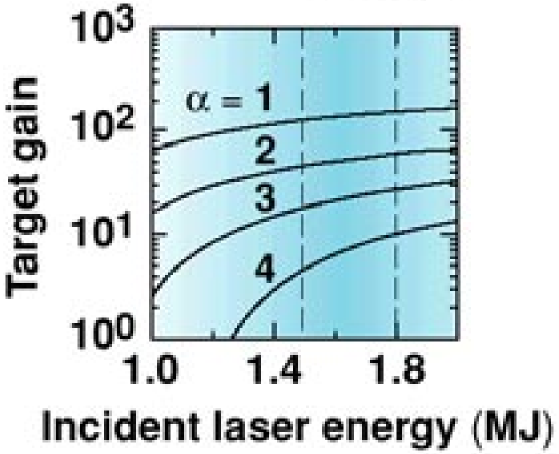
High α-pulse



Low α-pulse



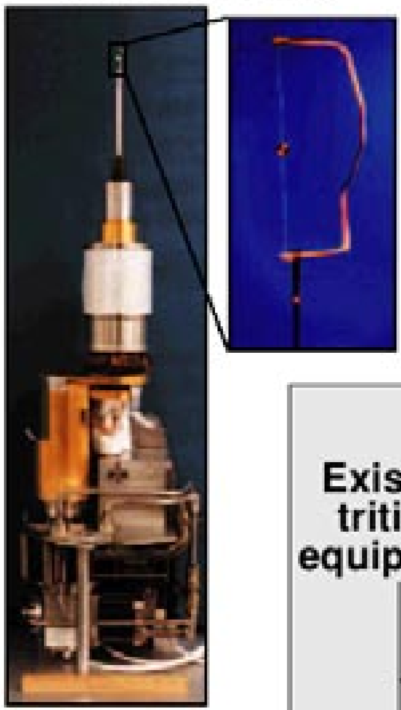
UR/LLE 351-nm direct-drive gain curves "all-DT" designs



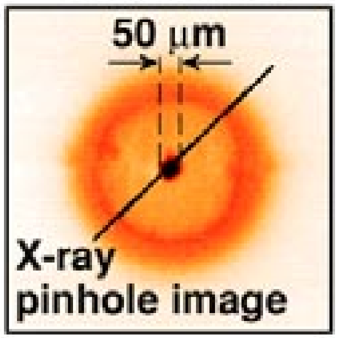
Implosions

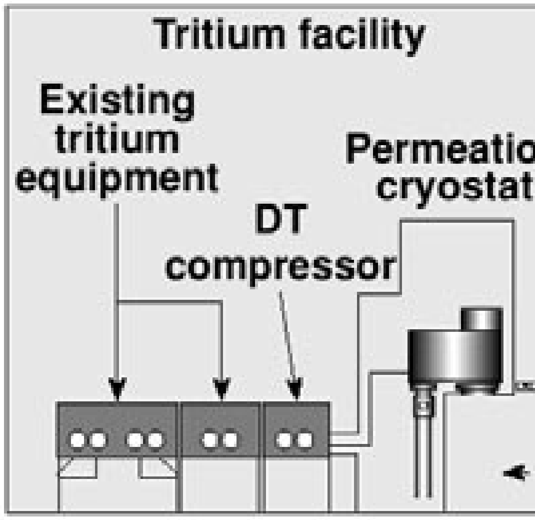
A multi-year science and engineering effort (with GA) was required to produce a reliable and precise cryogenic target experimental capability

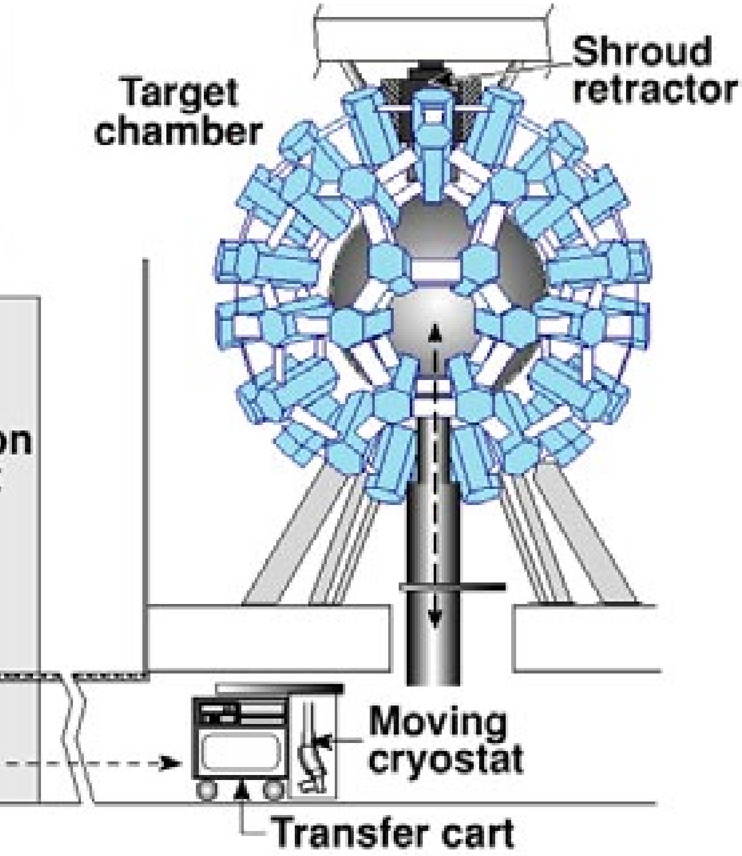
Target positioning and mounting



Target shot





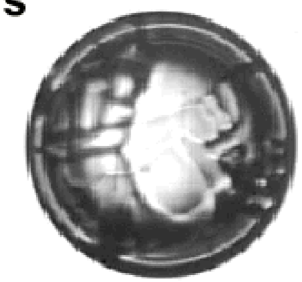


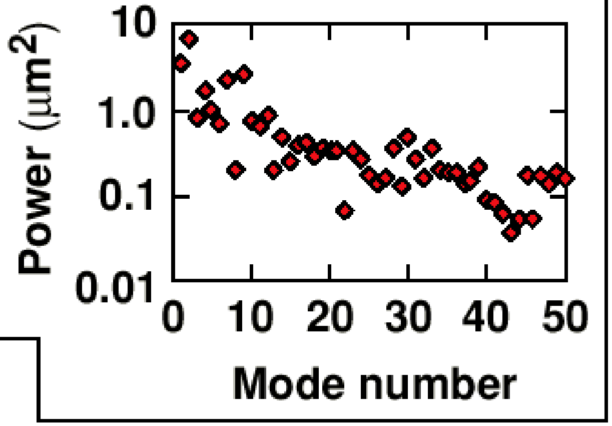
E11002c

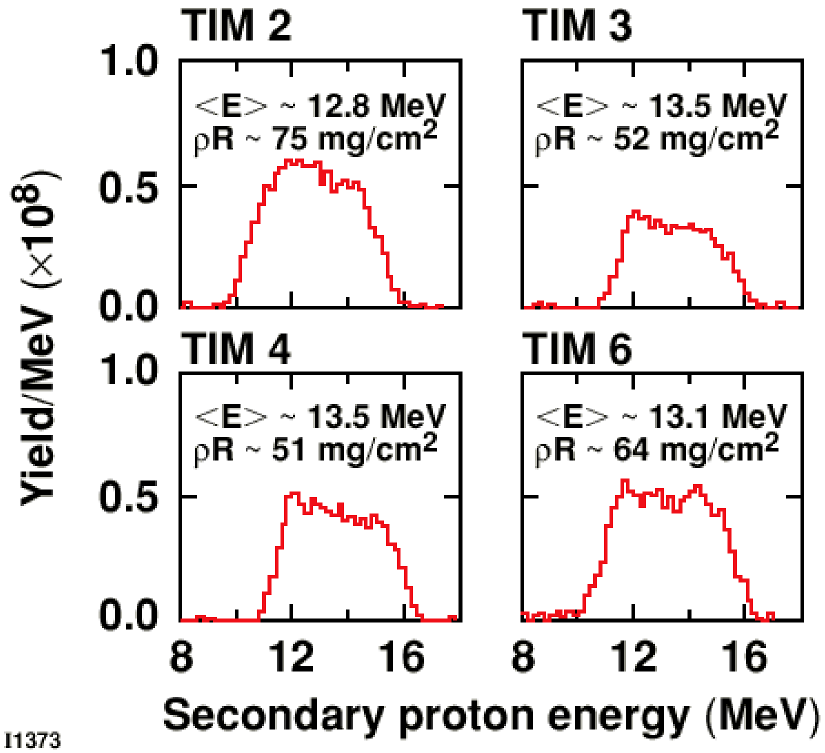
A well-centered, high-adiabat cryogenic target, even with an imperfect layer, can produce 1-D performance

Average ice + capsule rms smoothness is ~6 μm.

1-ns square
23.3 kJ
α = 25







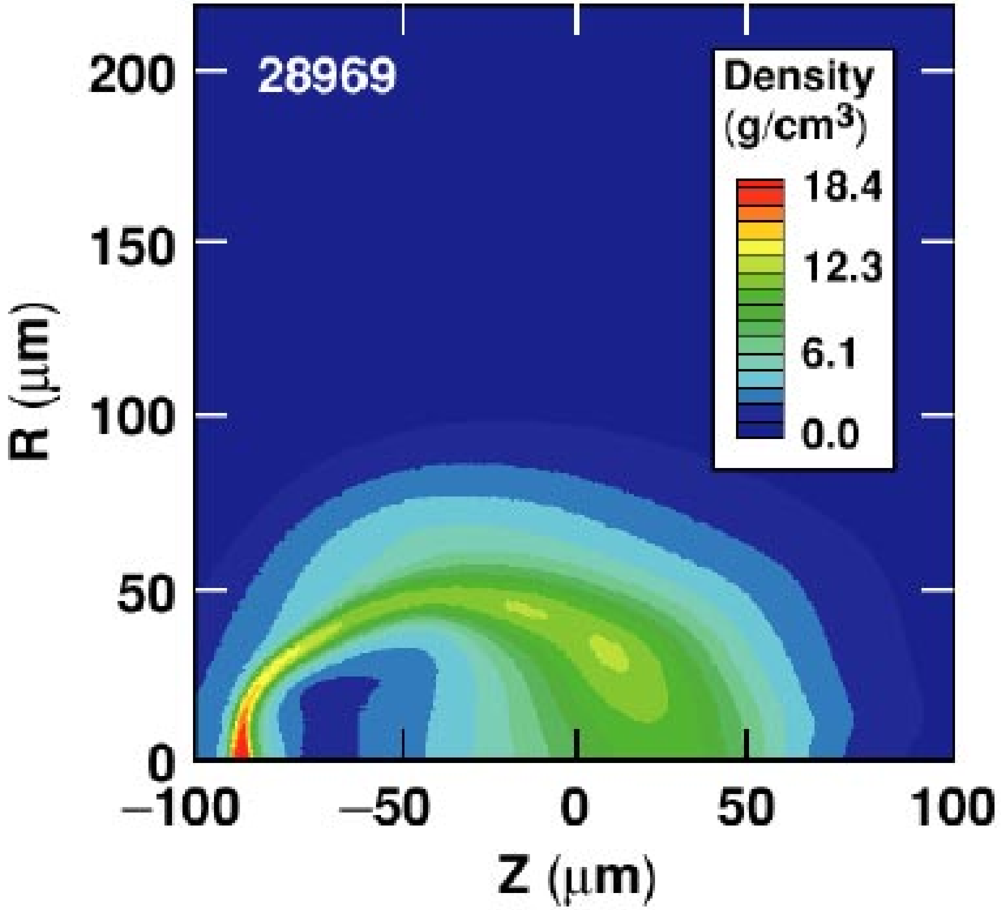
	Experimental	1-D *LILAC*
Yield (1n):	1.27×10^{11}	1.30×10^{11}
Yield (2n):	1.17×10^{9}	1.40×10^{9}
Yield (2p):	2.03×10^{8}	1.81×10^{8}
<ρR>:	61 mg/cm^2	45 mg/cm^2
T_{ion}:	3.6 keV	2.29 keV

Capsule offset from TCC: ~14±7 μm

Initial 2D hydrodynamic simulations show good agreement with experimental α=4 cryogenic target results

DRACO code simulated density contours

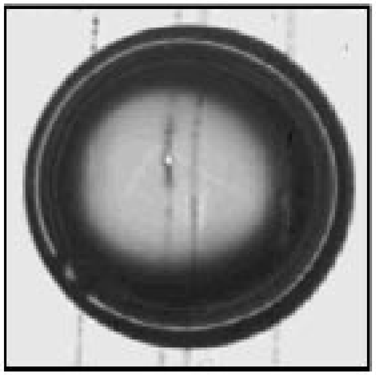
Density near peak burn



α = 4 pulse, 17 kJ

100-μm thick ice layer

8-μm rms ice roughness



	Expt	1-D	2-D
Y_{1n}	5.95×10^9	5.60×10^{10}	5.32×10^9
Y_2	6.75×10^7	6.94×10^8	6.31×10^7
$\langle\rho R\rangle$	67	80.0	58
T_{ion}	2.5	1.7	2.0

T.C.Sangster et al. Phys. Plasmas 10, 1937 (2003

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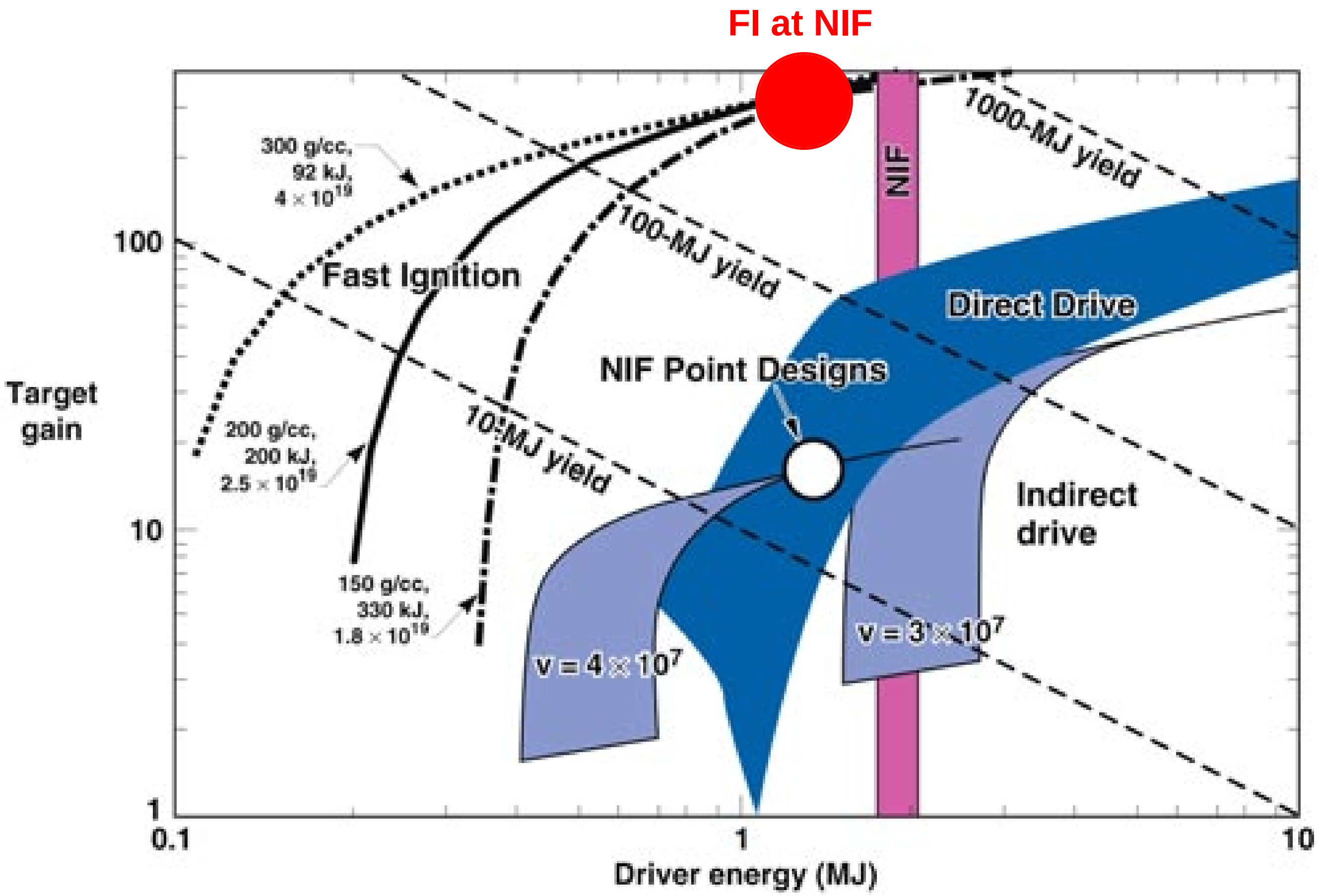
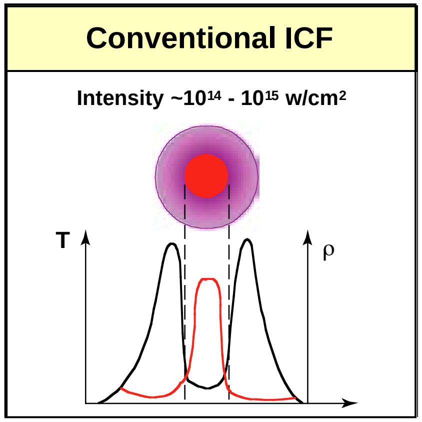
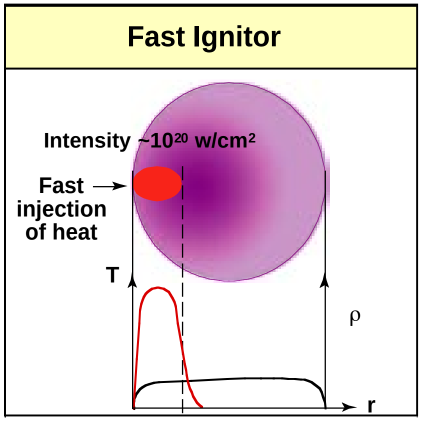
There is worldwide interest in fast ignition which potentially gives more gain and lower threshold energy than indirect or direct drive



Conventional ICF



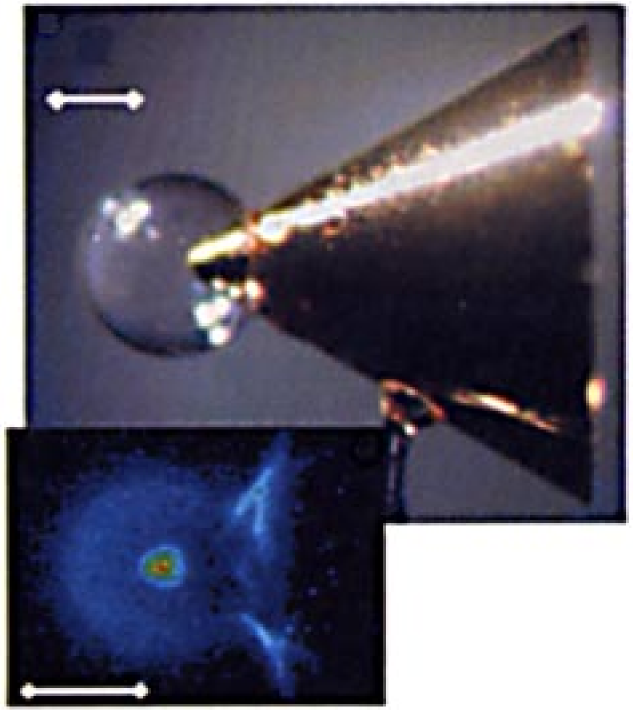
Fast Ignitor

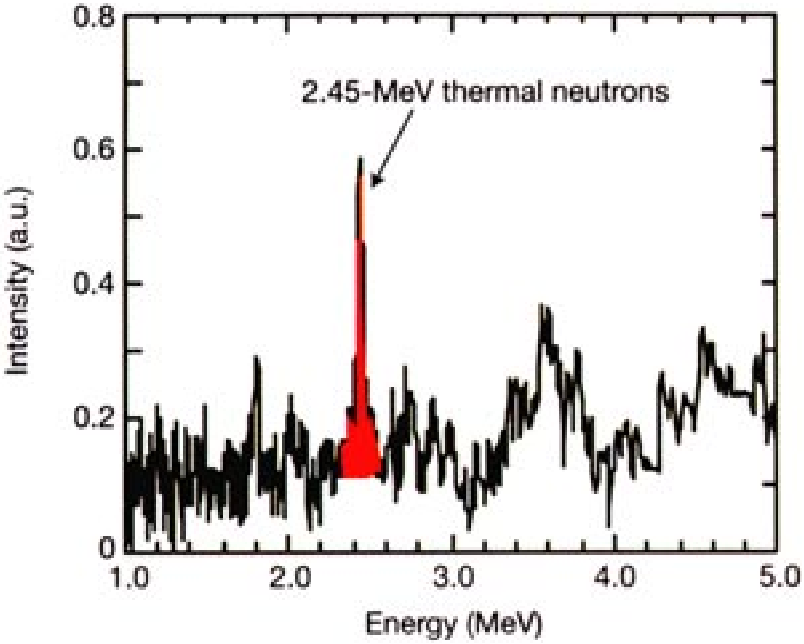


Higher gain is from reduced fuel density allowed by isochoric ignition

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)



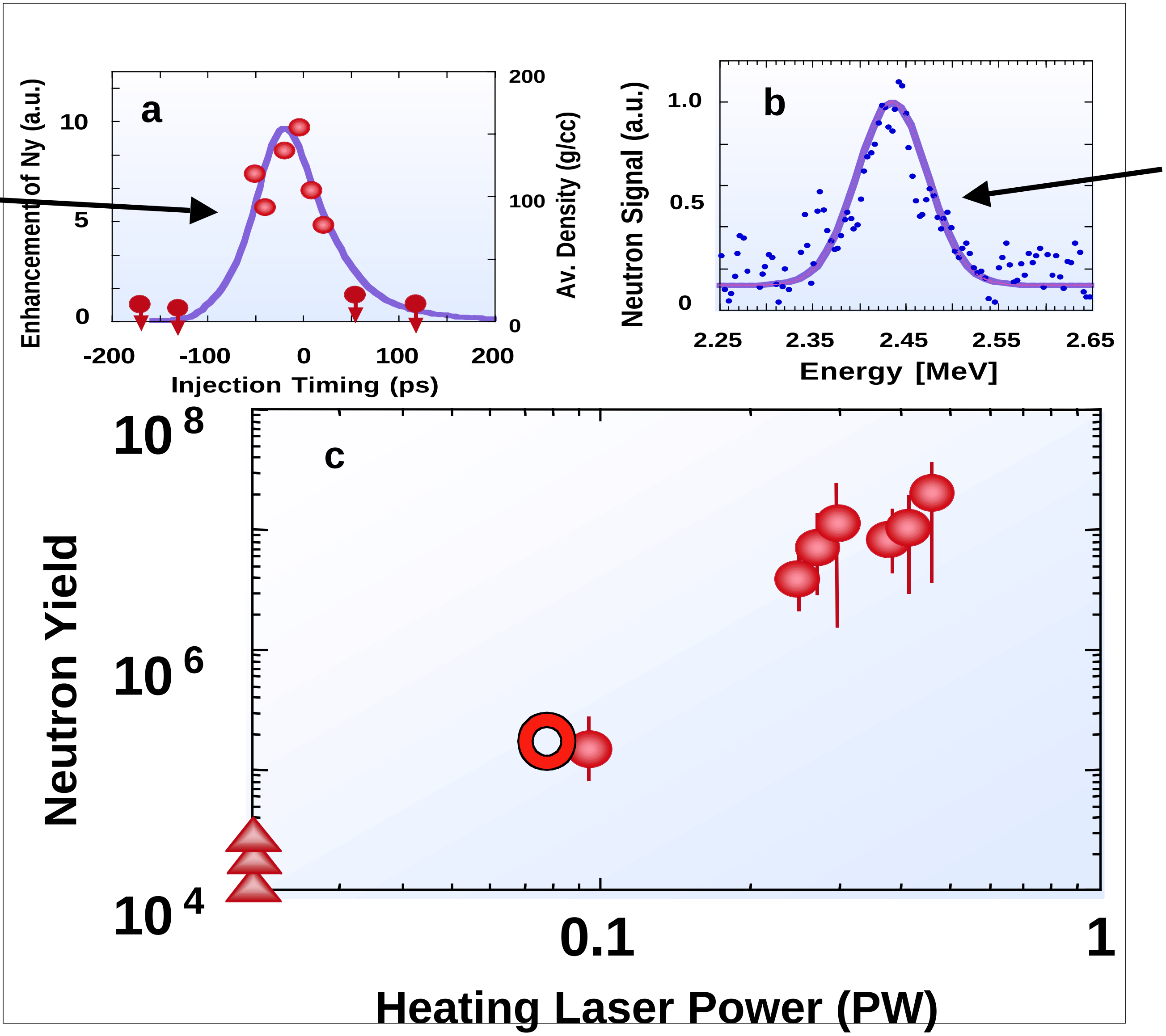


1.2 KJ compression pulse + 60 J, 100 tw fast heating pulse

Peta watt laser heating experimental results of cone guide target

ILE OSAKA

Required timing is 50ps



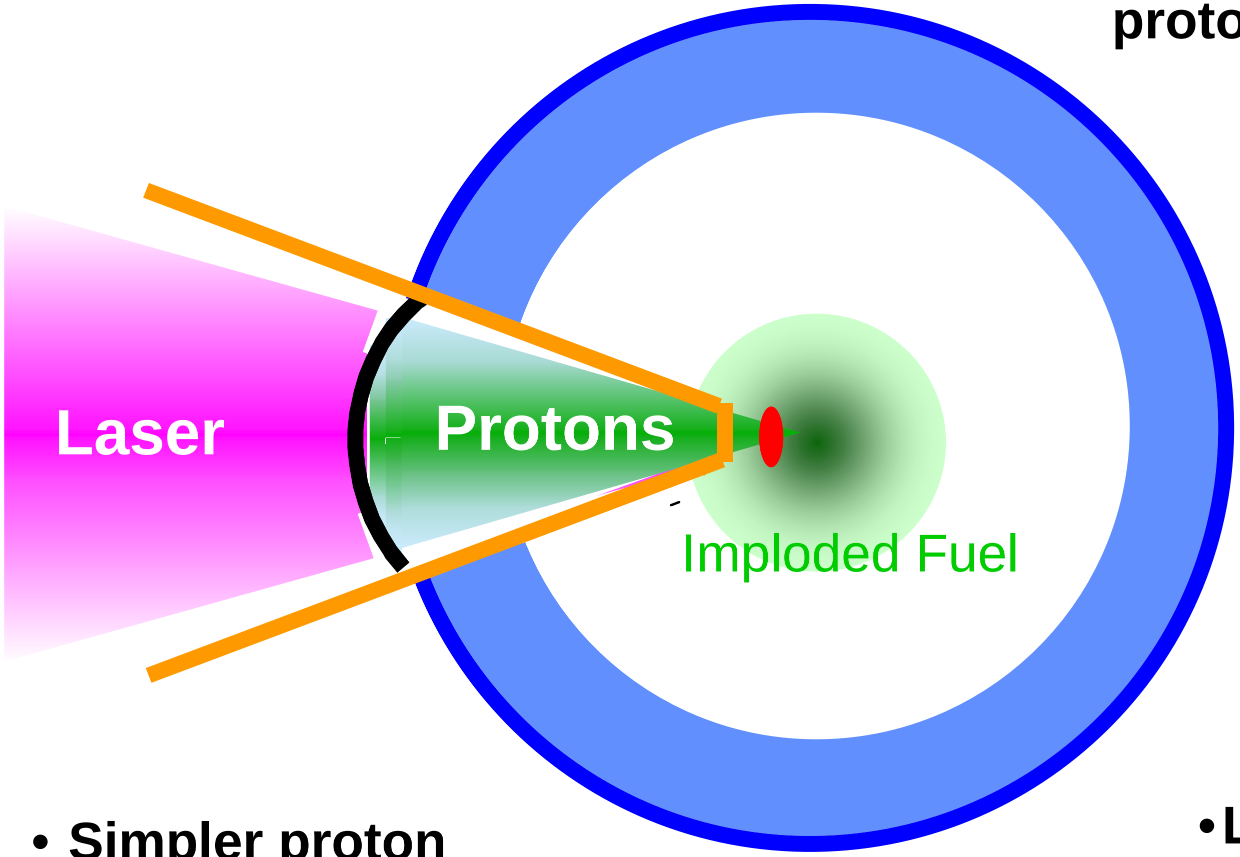
800keV

IF/OV1
T.Yamanaka

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).

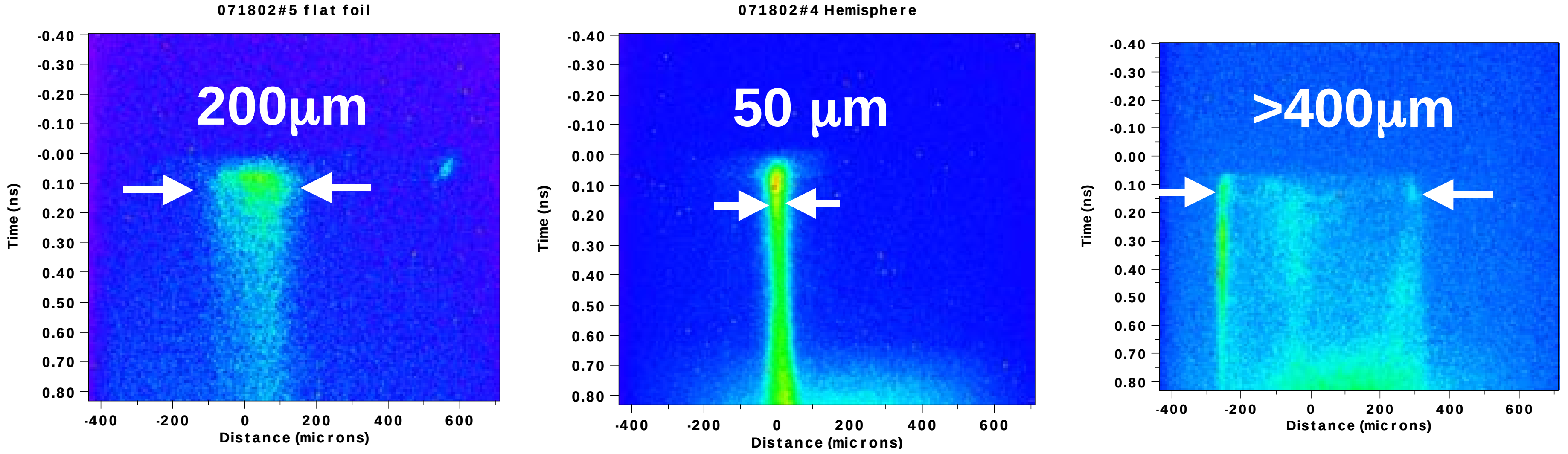
Ruhl et al. Plas. Phys. Rep. 27,363,(2001)

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

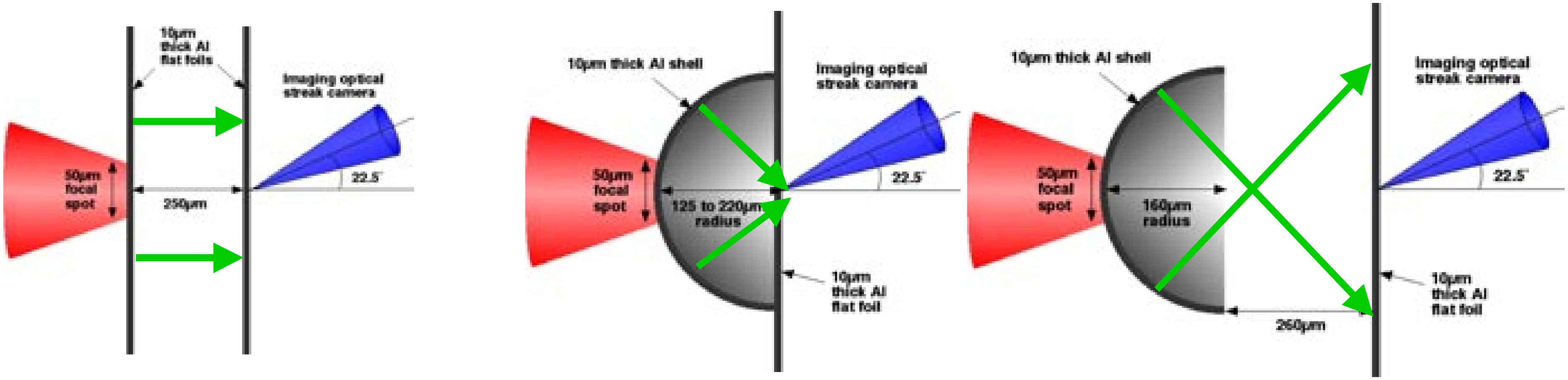
- Simpler proton energy transport by ballistic focussing

- Larger laser focal spot-easier to produce

Recent 100TW,100fs expt. shows first evidence of ballistic proton focusing (to 50 µm) and enhanced isochoric heating

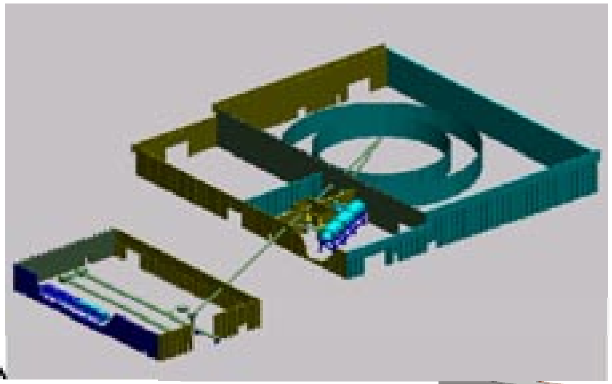


Streak images of Planckian emission

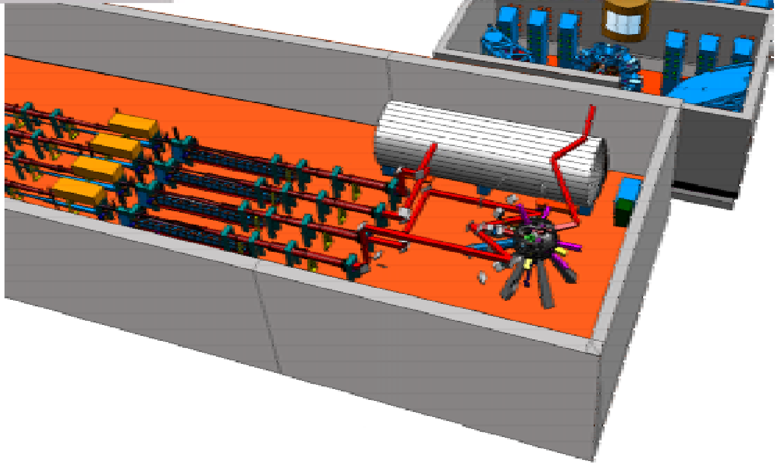


New U.S. facilities proposed for FY06/07 would support a ‘proof of principle’ study of fast ignition

SNL Z Beamlet / Z



HEPW at NIF

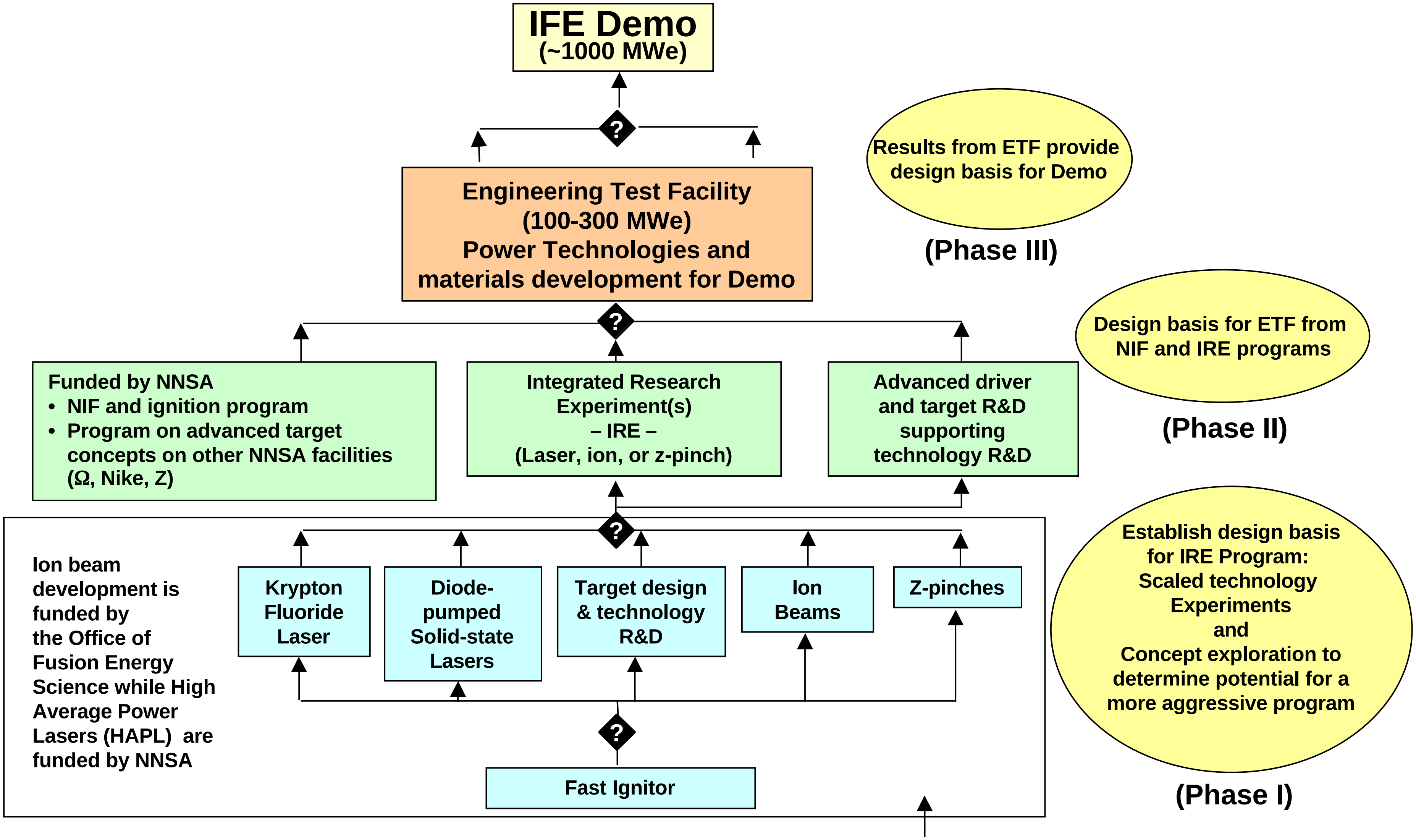


Omega EP

Outline of Talk

- The National Ignition Facility (NIF)
- Indirect Drive
- Direct Drive
- Fast Ignition
- IFE with Lasers
- IFE with Ion Beams

The US IFE Community Development plan proceeds in three phases to an Engineering Test Facility (ETF)



IFE Demo
(~1000 MWe)

?

Engineering Test Facility
(100-300 MWe)
Power Technologies and
materials development for Demo

Results from ETF provide design basis for Demo

(Phase III)

?

Funded by NNSA
- NIF and ignition program
- Program on advanced target concepts on other NNSA facilities (Ω, Nike, Z)

Integrated Research
Experiment(s)
– IRE –
(Laser, ion, or z-pinch)

Advanced driver
and target R&D
supporting
technology R&D

Design basis for ETF from NIF and IRE programs

(Phase II)

?

Ion beam development is funded by the Office of Fusion Energy Science while High Average Power Lasers (HAPL) are funded by NNSA

Krypton Fluoride Laser

Diode-pumped Solid-state Lasers

Target design & technology R&D

Ion Beams

Z-pinches

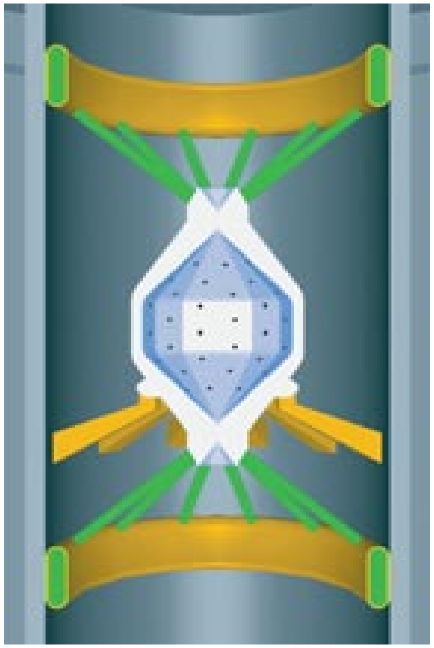
?

Fast Ignitor

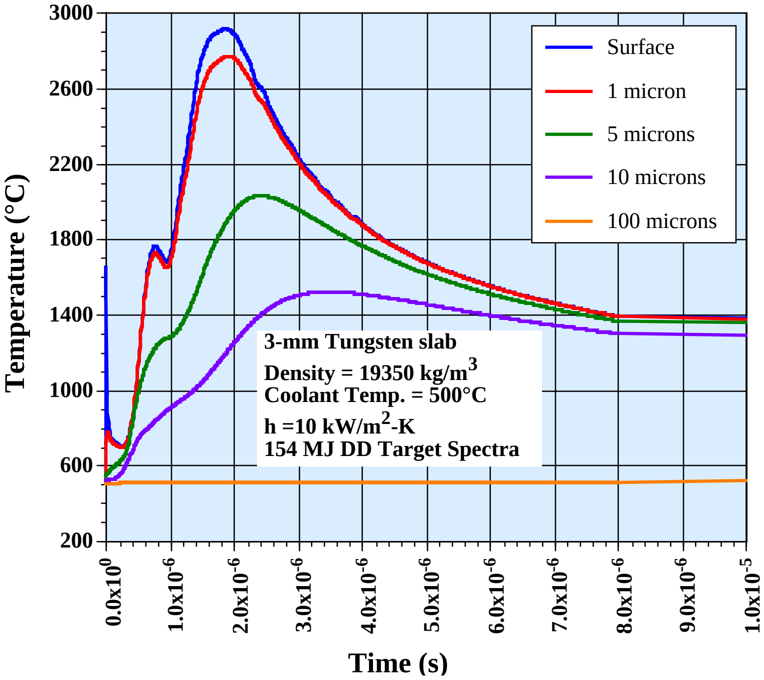
Establish design basis
for IRE Program:
Scaled technology
Experiments
and
Concept exploration to
determine potential for a
more aggressive program

(Phase I)

The U.S. Program in Laser IFE on Dry-wall chambers work is focused on first wall response to target emissions



The dry-wall Sombrero chamber uses low pressure gas and/or armor coating to protect the first wall from x-rays, ions and debris.

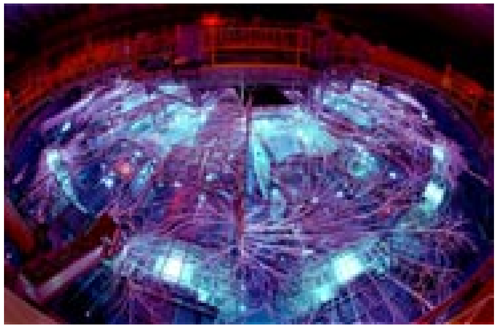


Temperature response of tungsten armored first wall indicates melting point will not be exceeded.

Materials evaluation:

Both the Z-machine and RHEPP produce near relevant threats and Measured ablations thresholds are close to code predictions

X-rays-
Z –machine
(Sandia)



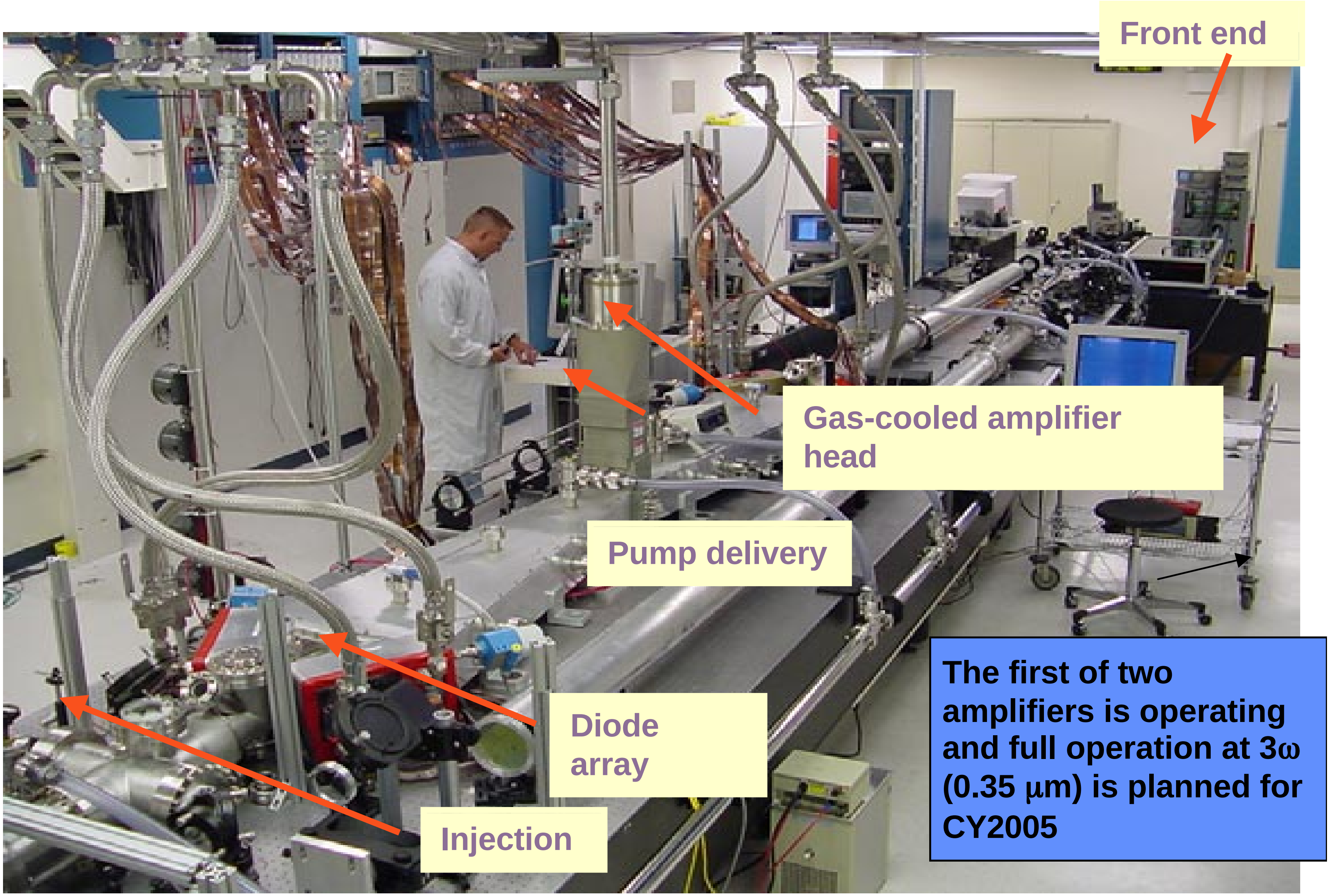
Ions-
RHEPP-1
(Sandia)

	Material	Predicted Ablation Threshold	Measured Ablation Threshold	Measured Roughening Threshold	Predicted Threat to wall*	
					154 MJ target	400 MJ target
X-rays (10 nsec exposure)	Pyrolitic Graphite	4.0 J/cm^2	3.5 - 4 J/cm^2	2.5 J/cm^2	0.40 J/cm^2	1.20 J/cm^2
	Tungsten	not done yet	2 J/cm^2	1.3 J/cm^2		
IONS (60 nsec exposure)	Pyrolitic Graphite	4.5 J/cm^2	3.5 - 4 J/cm^2	2.5 J/cm^2	8.5 J/cm^2 (1.41 J/cm^2)	21.1 J/cm^2 (3.52 J/cm^2)
	Tungsten (pure)	4.75 J/cm^2	5 J/cm^2	1.25 J/cm^2		
	Tungsten + 25% Re	Not yet modeled	5 J/cm^2	3.5 J/cm^2		

* Wall at 6.5 m, parenthesis are adjusted threat for time, $t^{1/2}$ scaling

SNL (Experiments)
Wisconsin (modeling)

The Mercury laser at LLNL is designed to be a 100J, 10Hz, 10ns DPSSL laser at 1/10th scale of a kJ-class beam line for Inertial Fusion Energy

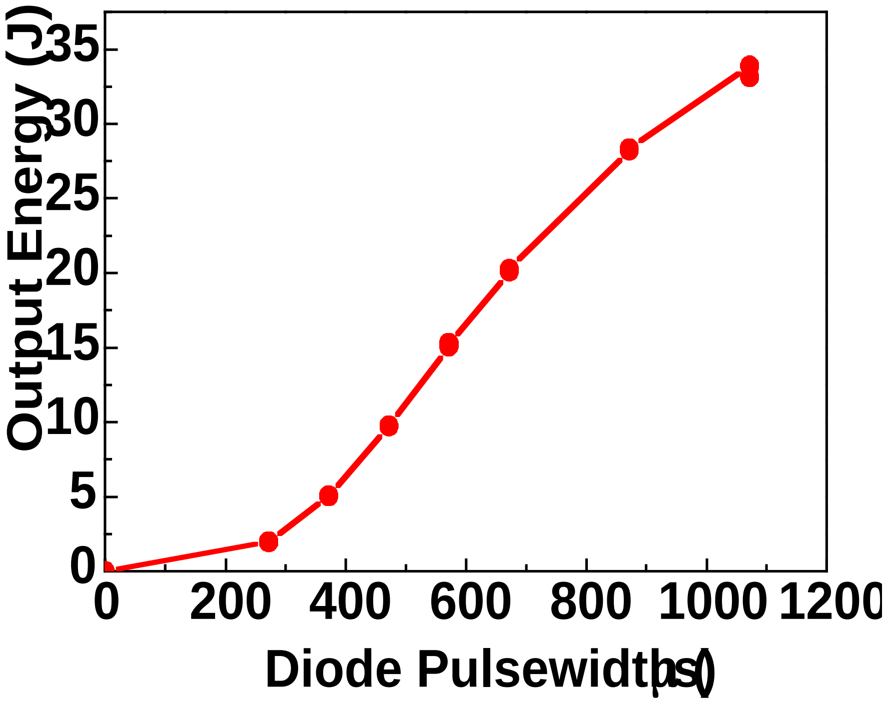


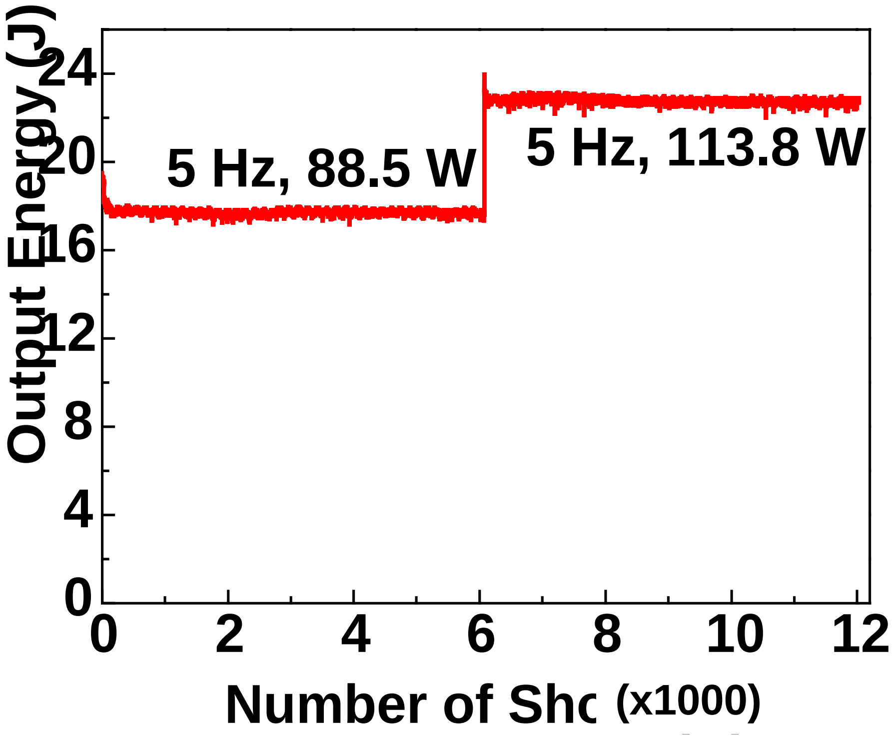
The first of two amplifiers is operating and full operation at 3ω (0.35 μm) is planned for CY2005

The Mercury Laser is operating reliably with the expected performance

Single shot energy of 34 J

> 10,000 shots without damage

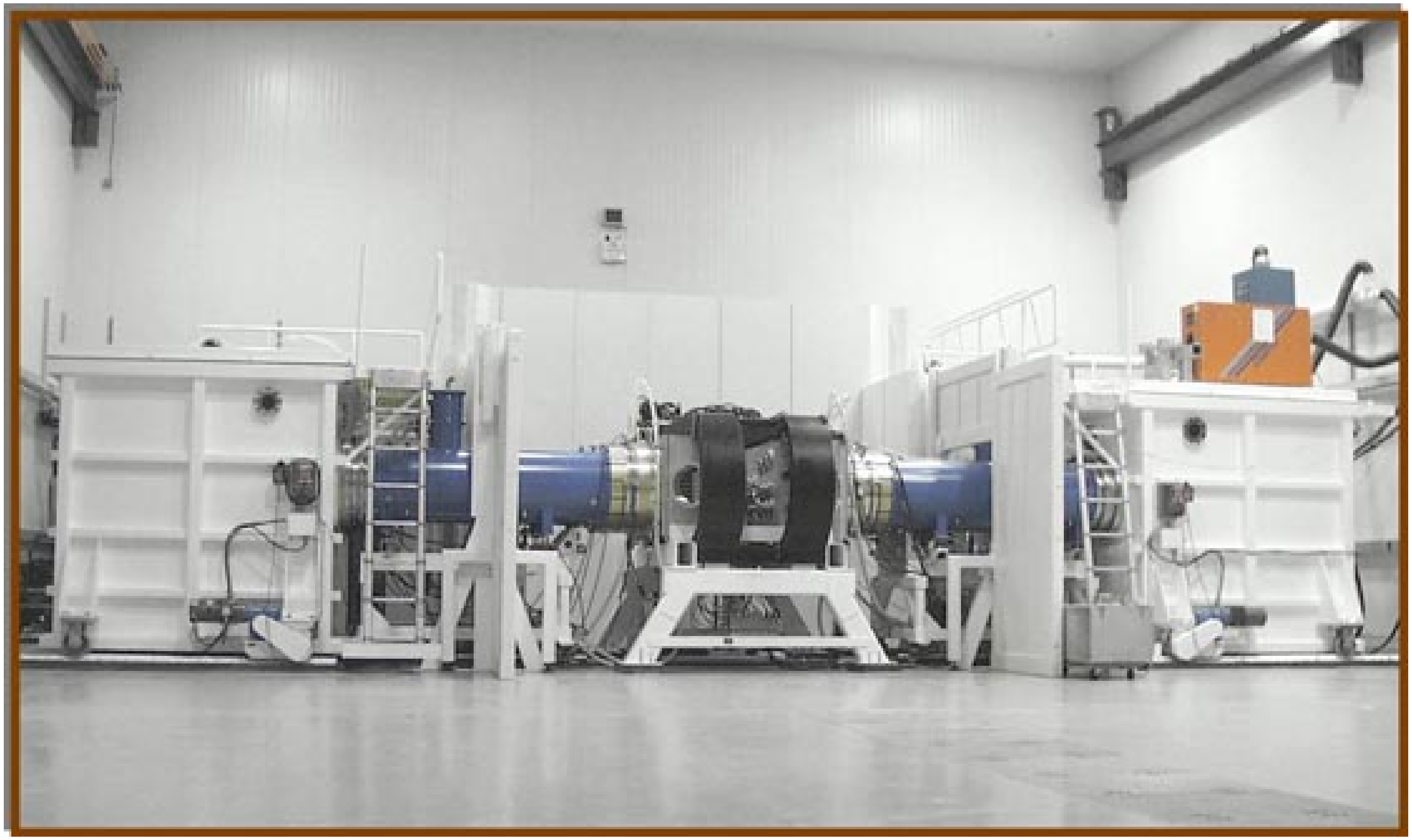




Implementation of second amplifier head will yield 100J from the system

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

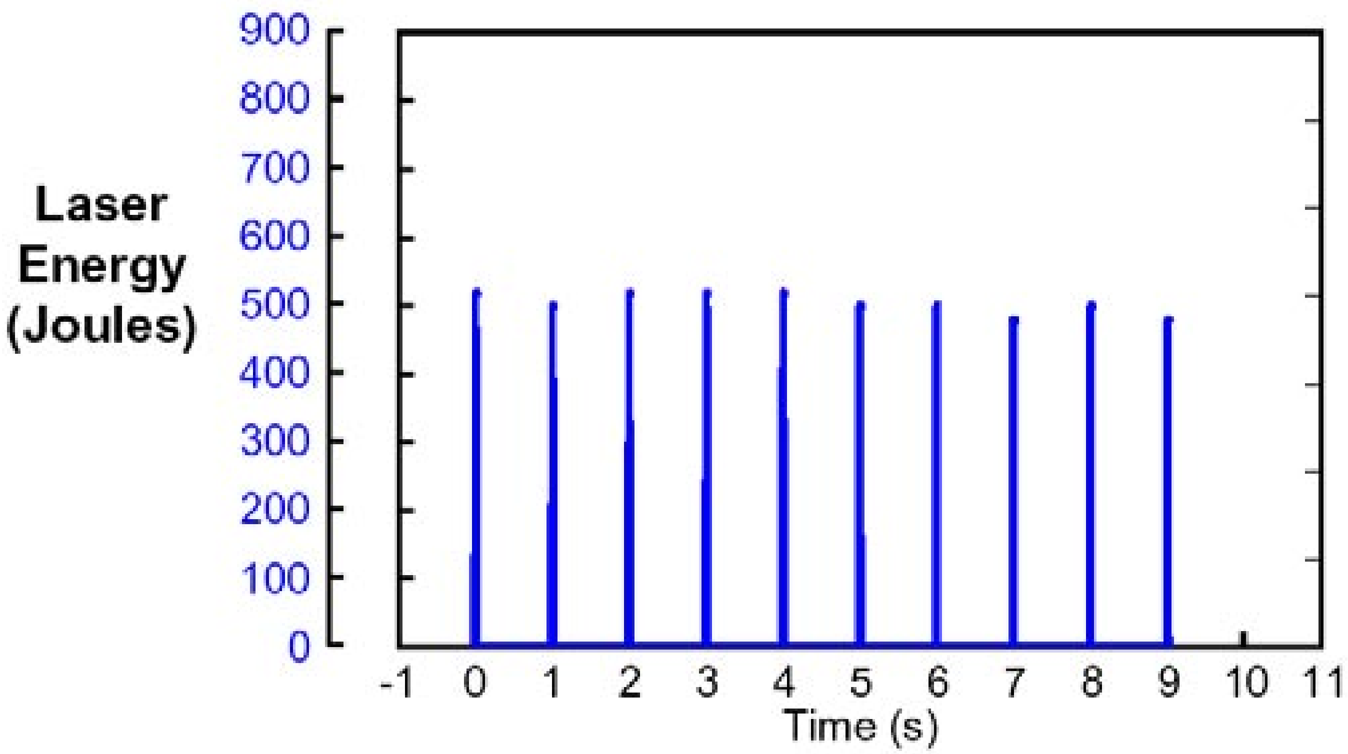
NRL



- 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

Achieved 500 J at 1 Hz bursts in oscillator configuration for 10 shots

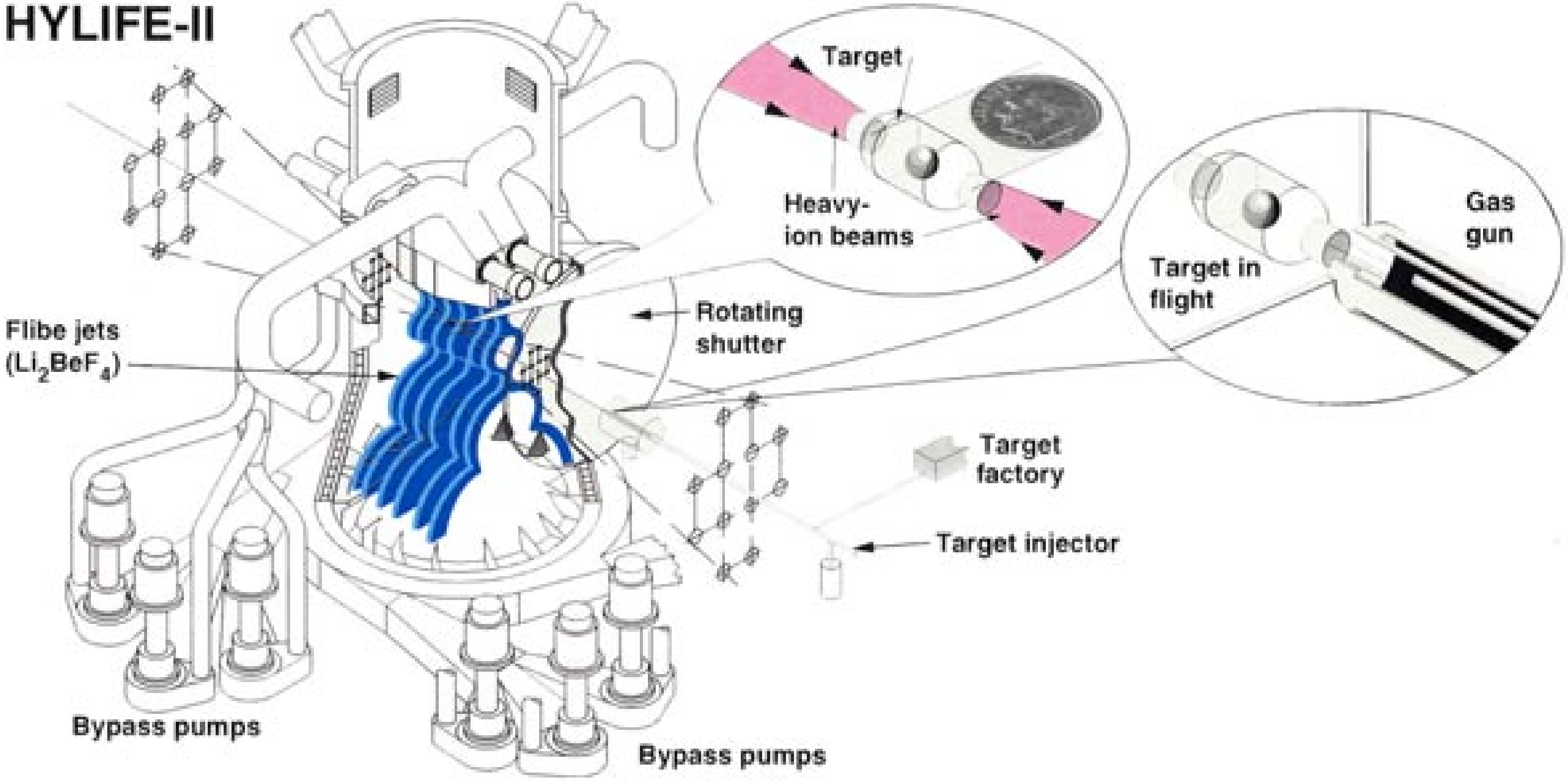
Oscillator Mode;
8% reflecting output coupler
10 shots, 1 Hz burst



Outline of Talk

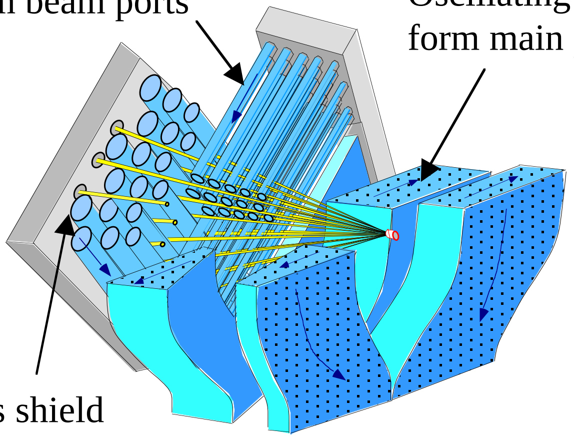
- **The National Ignition Facility (NIF)**
- **Indirect Drive**
- **Direct Drive**
- **Fast Ignition**
- **IFE with Lasers**
- **IFE with Ion Beams**

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



If successful, this approach to chambers can drammatically reduce the materials developments needs for fusion

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



Crossing cylindrical jets form beam ports

Oscillating jets form main pocket

Vortices shield beam line penetrations

Highly smooth cylindrical jets

Slab jet arrays with disruptions

Vortices

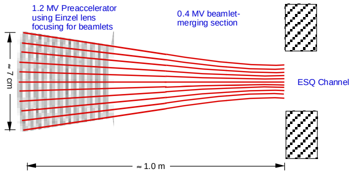
Flow conditions approach correct Reynolds and Weber numbers for HYLIFE-II

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

<u>NOW</u> (next three years) →

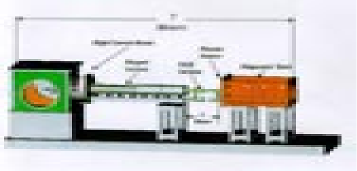
Brighter sources/

injector

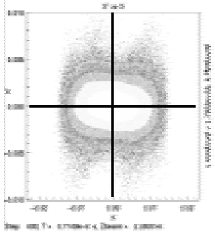


Maximum <J >, B_n
Transport

Beam neutralization →
min ε-limited focus r_f

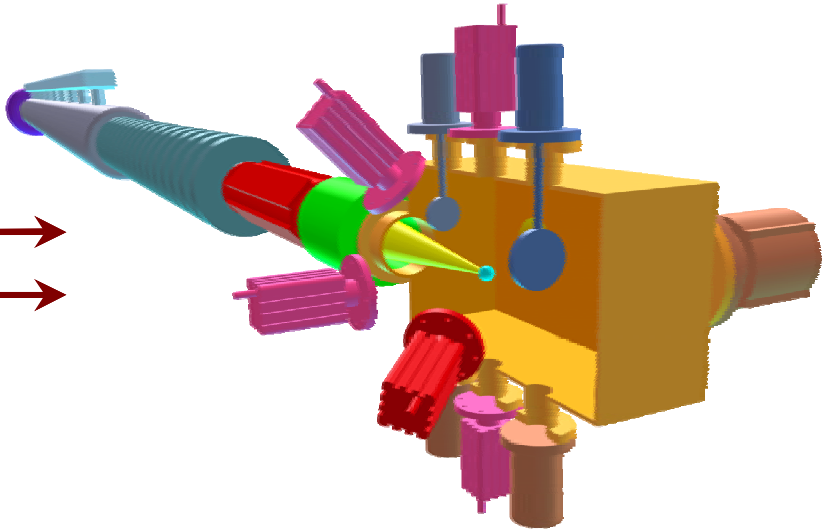


Theory/simulations



<u>NEXT STEP</u>

integrated beam experiments
(IBX)



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

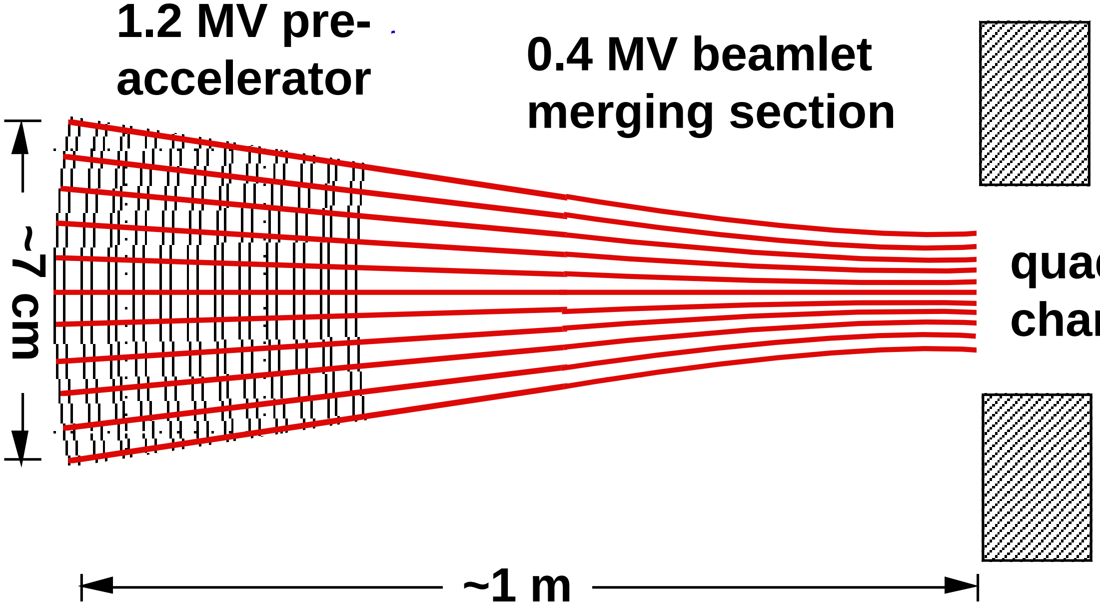
(Injection, acceleration, longitudinal compression and final focus)

Merging beamlets are main approach to a compact injector

Single beamlet channel was optimized to give desired beamlet size & convergence

Multi-beamlet arrangement was optimized to minimize emittance

The design ensures that the merged beam is "matched" to the quadrupole channel



1.2 MV pre-accelerator

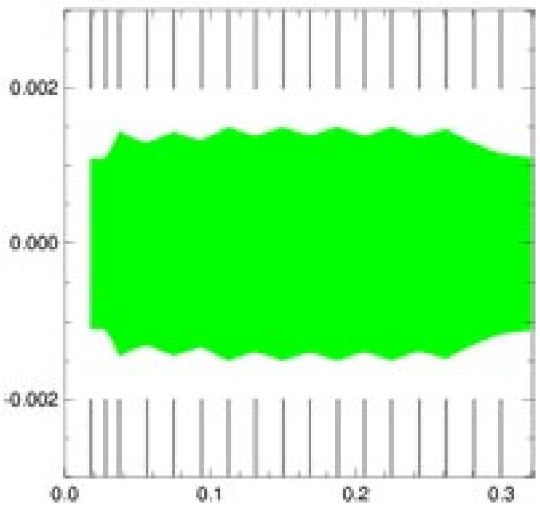
0.4 MV beamlet merging section

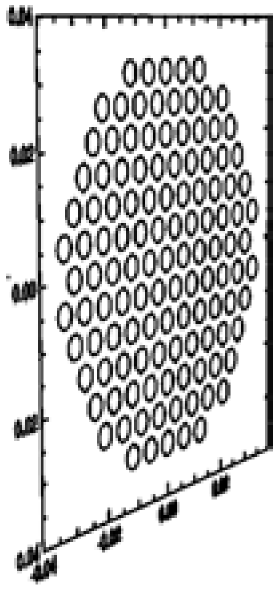
quad channel

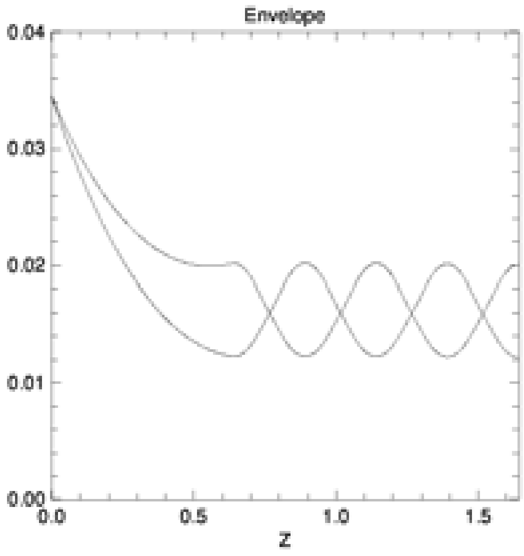
~7 cm

~1 m

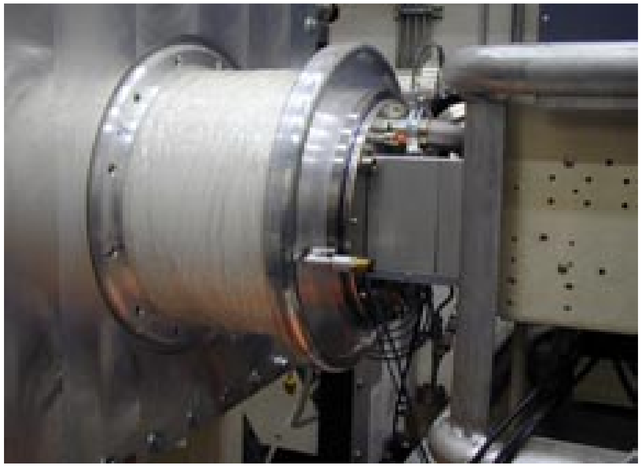
One beamlet







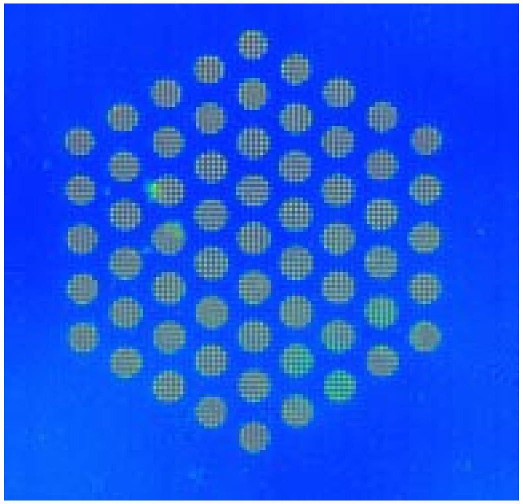
STS-100 is being used to characterize an Argon plasma source for a multi-beamlet injector concept



RF-driven multi-cusp source inside ceramic insulator

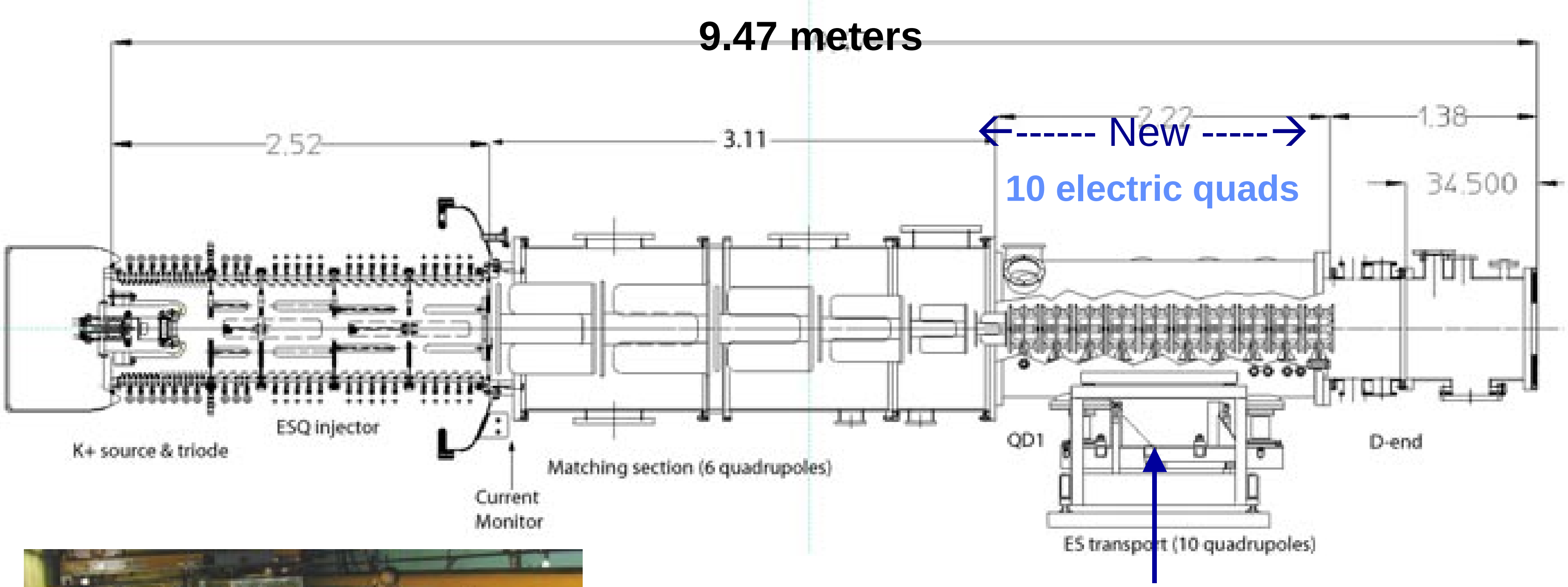
Obtained 5.0 mA from d=0.25 cm aperture ⇒ 100 mA/cm^2,(compared to 8.3 mA/cm^2 for hot-plate source)

→this meets the single beamlet goal



Initial image of 61 beamlets shows relatively uniform current density after first accelerating gap

The High Current Experiments (HCX) is exploring high fill factor and electron cloud effects in space charge dominated beams



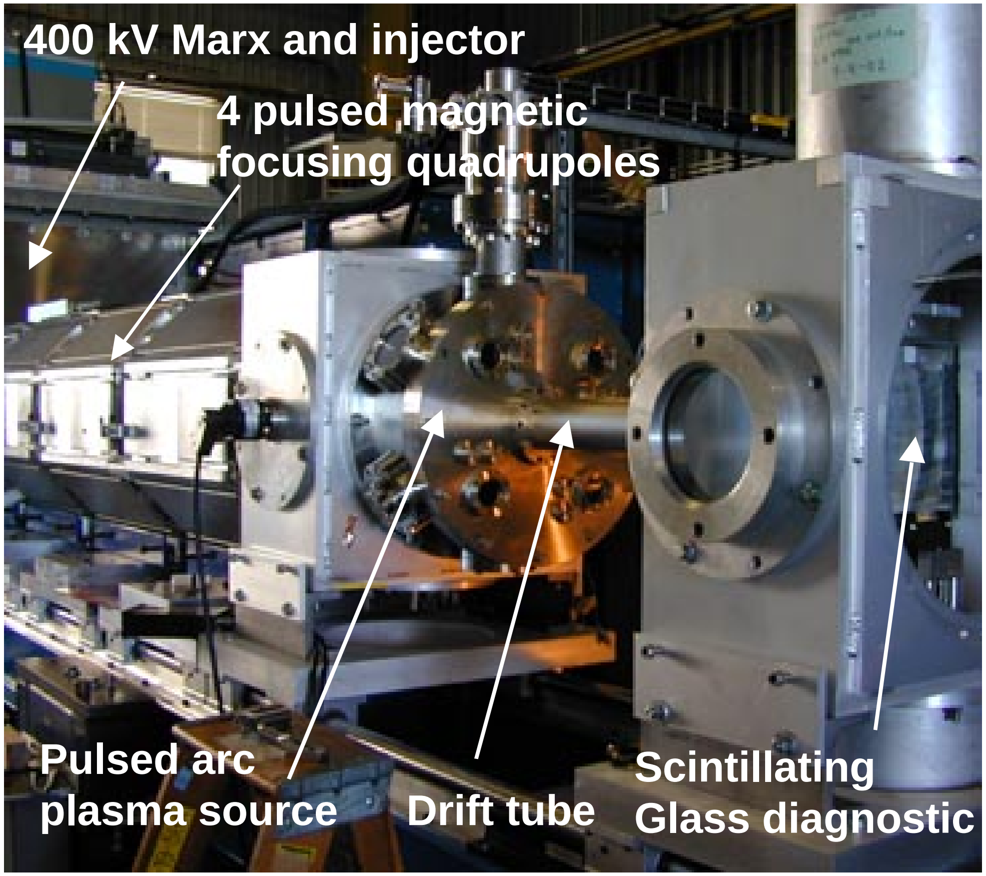
9.47 meters

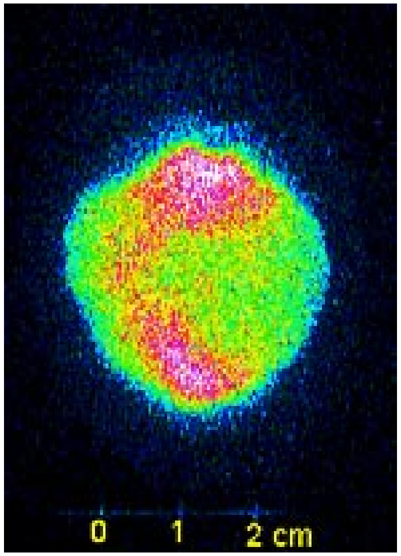
←------ New -----→

10 electric quads

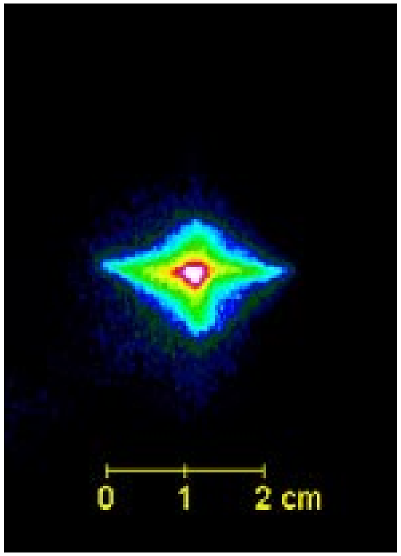
In initial experiments with up to 80% fill factor, there is no emittance growth within measurement uncertainty, (10 to 20 % in Δε) and little beam loss (< 2% in the middle of the beam pulse).

The Neutalized Transport Experiment (NTX) is exploring the effects of plasma neutralization on the focusing of space charge dominated beams





Focal spot Size without plasma



Focal spot size with plasma

Conclusions

- **The first 4 beams of NIF have been activated and will be available for experiments this summer. All the NIF primary criteria on a single beam performance basis have been achieved. Ignition experiments are expected to begin in about 6 years.**
- **There is steady progress in the target science and target fabrication in preparation for indirect drive ignition experiments on NIF.**
- **If further LPI experiments continue to show favorable results, NIF with green light may be capable of target designs with 5-10 times more yield than initial targets.**
- **There is excellent progress on direct-drive targets at the University of Rochester including very encouraging cryogenic implosions**
- **There has been substantial progress on z-pinch driven implosions**
- **There is world wide interest in the science of fast ignition and outstanding results from the Gekko Petawatt facility on heating and compression. Petawatt capability is being developed on the Omea laser, on the Z-Machine and on NIF**
- **A broad based program to develop lasers (KrF and DPSSL) and ions beams for IFE is under way with excellent progress in drivers, chambers, target fabrication and target injection**