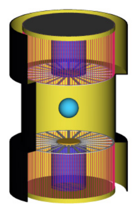
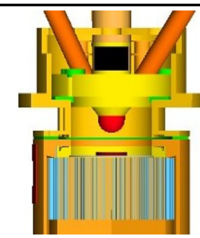
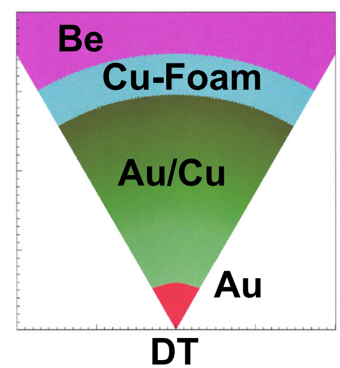
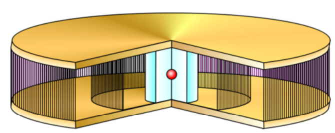
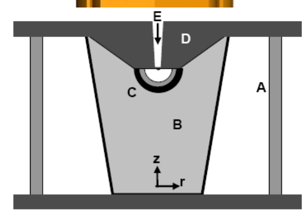
Status of Z-Pinch ICF Research

ICF Target

Driver		Cryogenic		Non-cryogenic
		Hot spot ignition	Fast ignition	Double shell
X-ray drive	Vacuum hohlraum			
	Dynamic hohlraum			

Fusion Power Associates Meeting
September 27, 2006

Keith Matzen
Sandia National Laboratories

GENERAL ATOMICS

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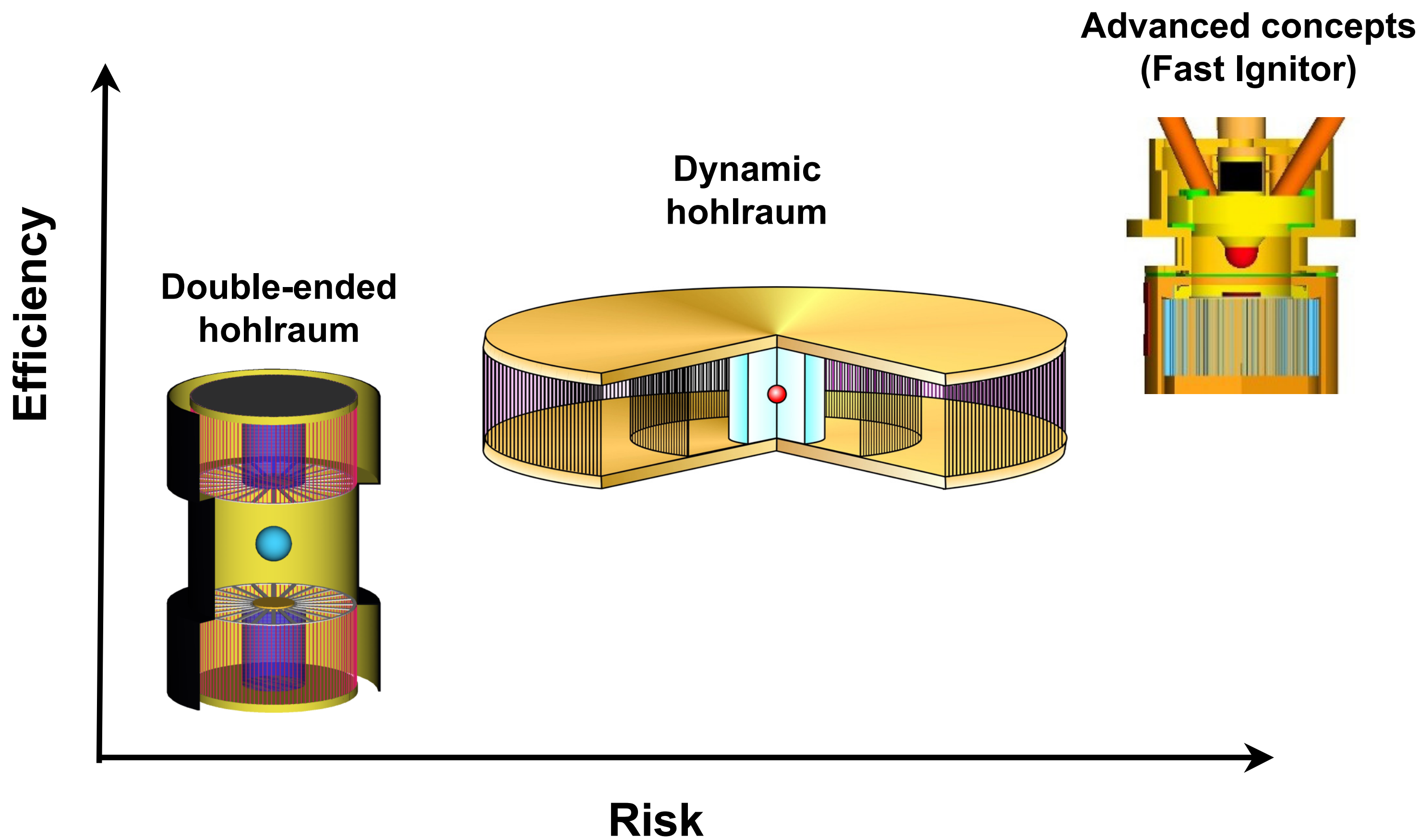
National Nuclear Security Administration

The goal of the Pulsed Power ICF program is to validate a High Yield target design



We are presently studying 3 High Yield target concepts

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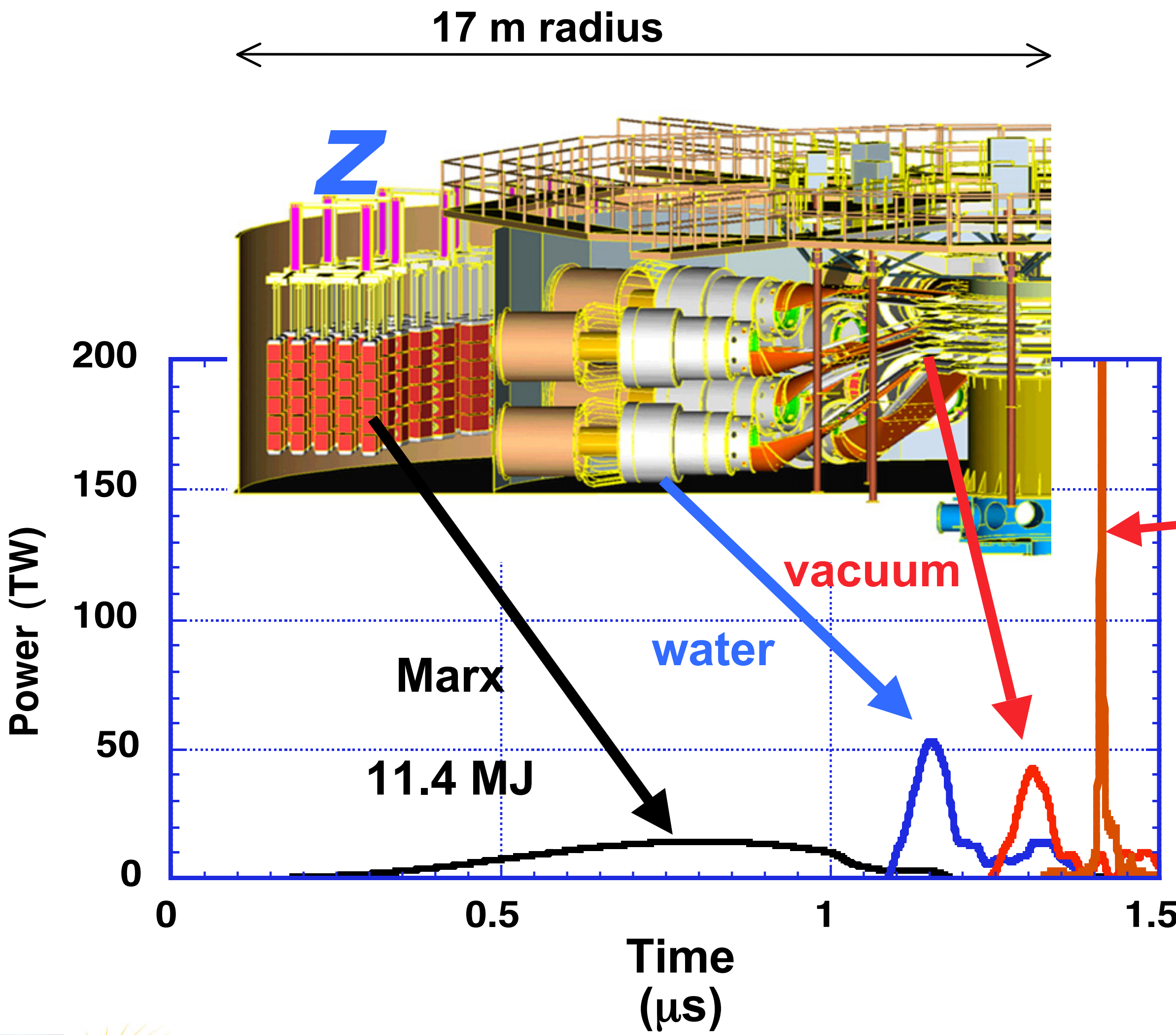
Pulsed-power provides compact, efficient, power amplification

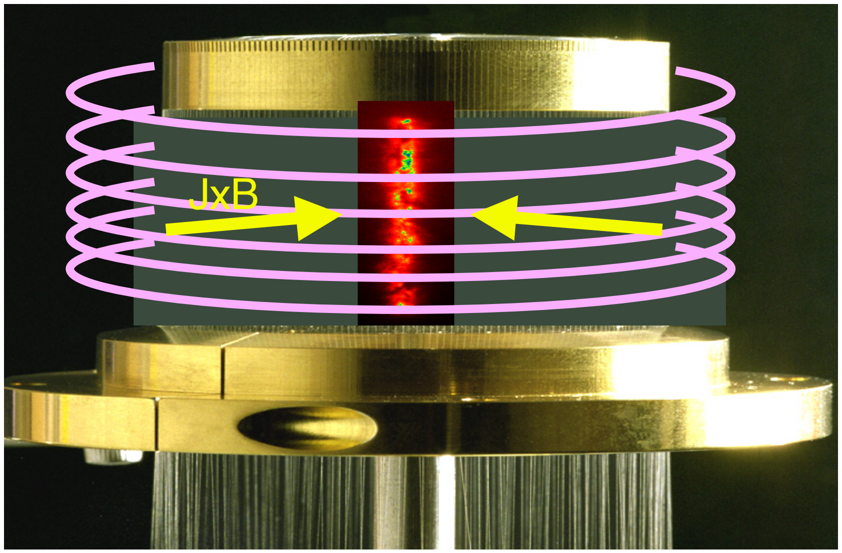


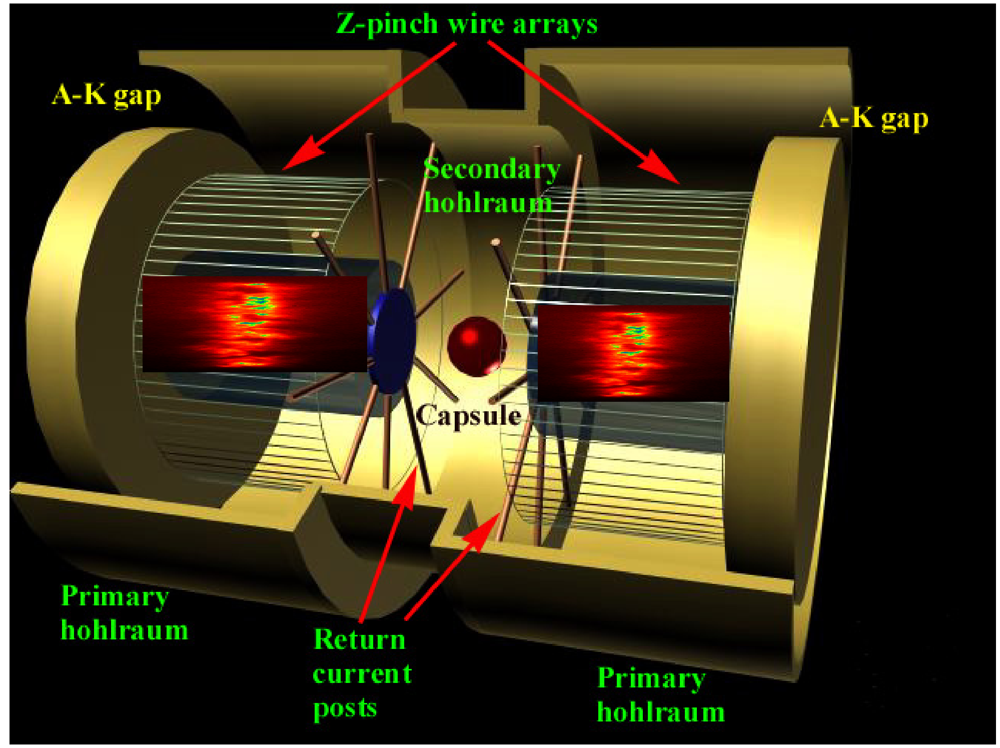
x ray output
~1.6 MJ
~200 TW

Electrical to x-ray energy
Conversion efficiency ~ 15%

Efficiency ⇒ Low Cost

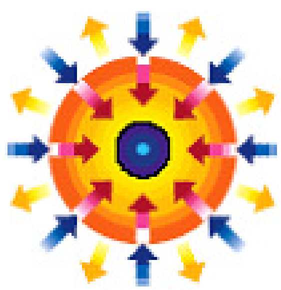
Indirect drive ICF: a spherical capsule is imploded by z-pinch-produced x-rays contained in a hohlraum



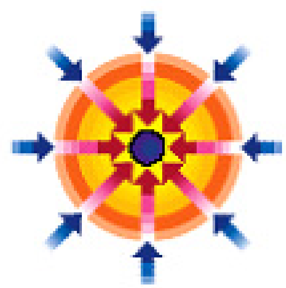


Target heating

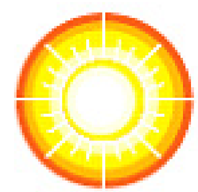
Compression



Ignition



Burn



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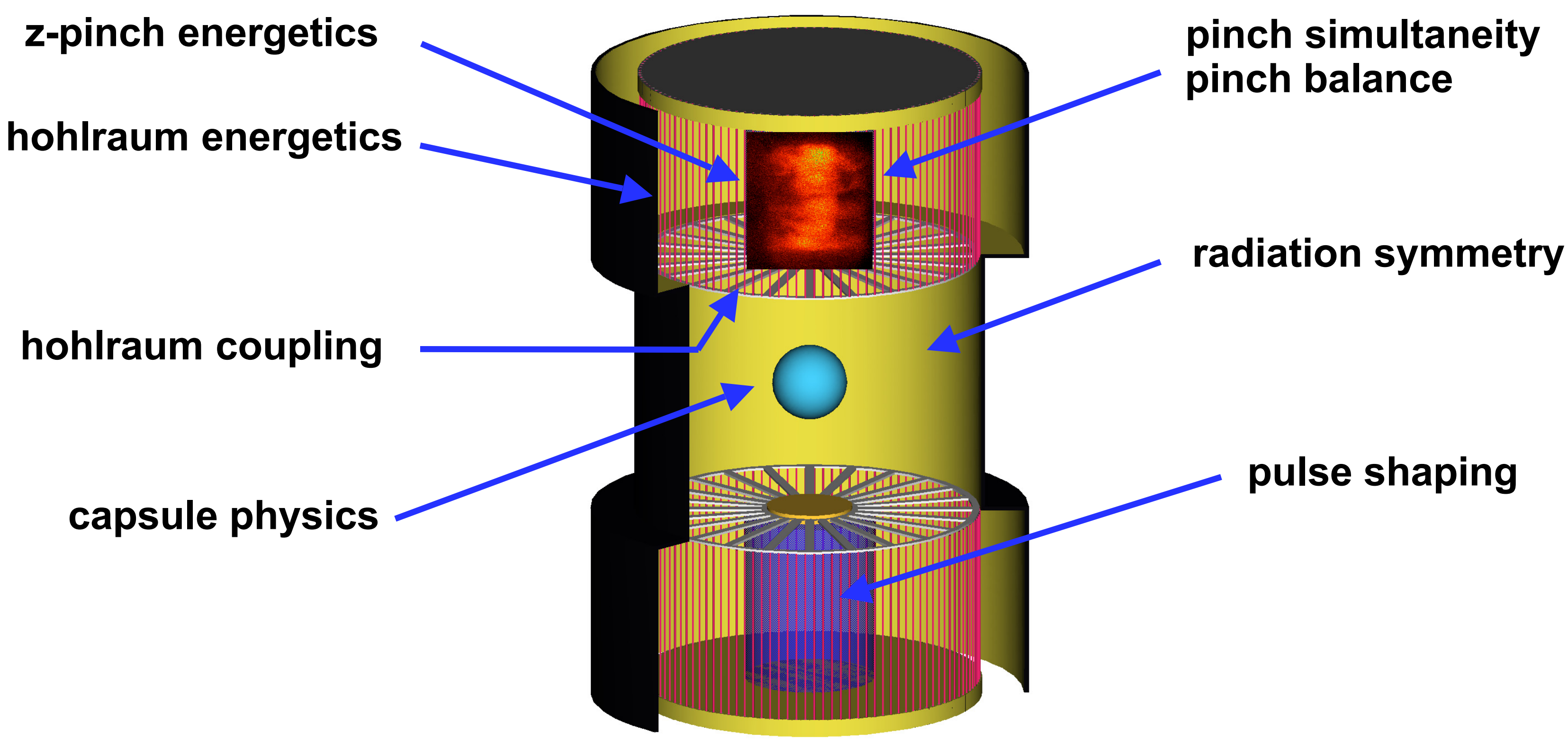
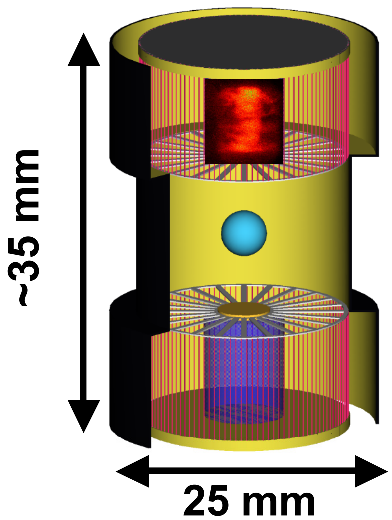
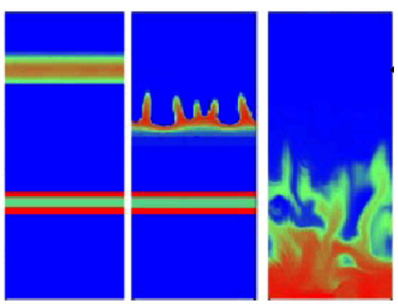
The double-ended hohlraum high yield concept separates capsule, hohlraum, and z-pinch physics issues



A focused effort began in Sept 2005 to create a modern reference design for the double-ended hohlraum (DEH)





PHYSICS OF PLASMAS VOLUME 6, NUMBER 5 MAY 1999

High yield inertial confinement fusion target design for a *z*-pinch-driven hohlraum*

James H. Hammer,† Max Tabak, Scott C. Wilks, John D. Lindl, David S. Bailey, Peter W. Rambo, Arthur Toor, and George B. Zimmerman
Lawrence Livermore National Laboratory, Livermore, California 94551

John L. Porter, Jr.
Sandia National Laboratories, Albuquerque, New Mexico 87185-1191

Key results of initial scoping study:

- **400 MJ yield capsule**
- **16 MJ total x-ray energy output from 2 pinches**
- **2 x 62 MA currents required with 100 ns rise time**
- **Pulse shaping via multi-shell z-pinch load design**
- **Spoke x-ray transmission of > 60% required**
- **Pinch power balance of 7% required**

Integrated 2D simulations with capsule implosion/ignition/burn were not achieved in the 1999 study, mainly due to symmetry issues

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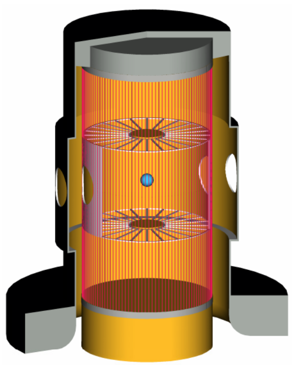
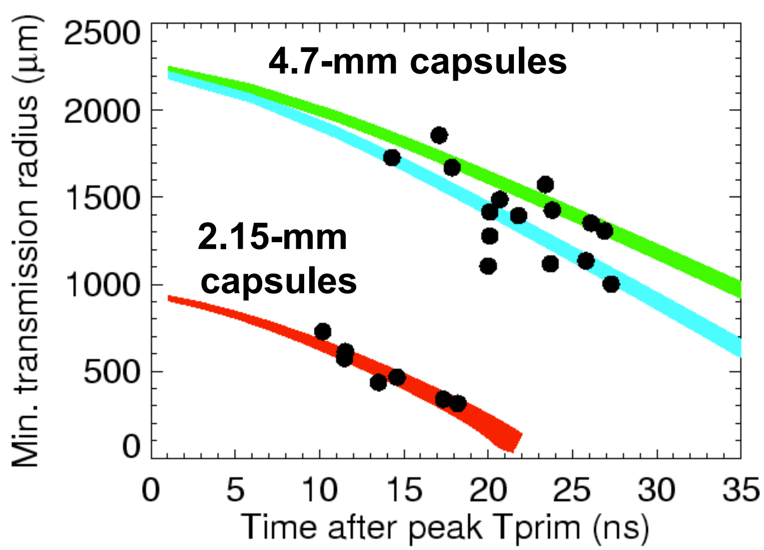
2D Lasnex simulations of hohlraum energetics and symmetry have been validated in DEH experiments on Z



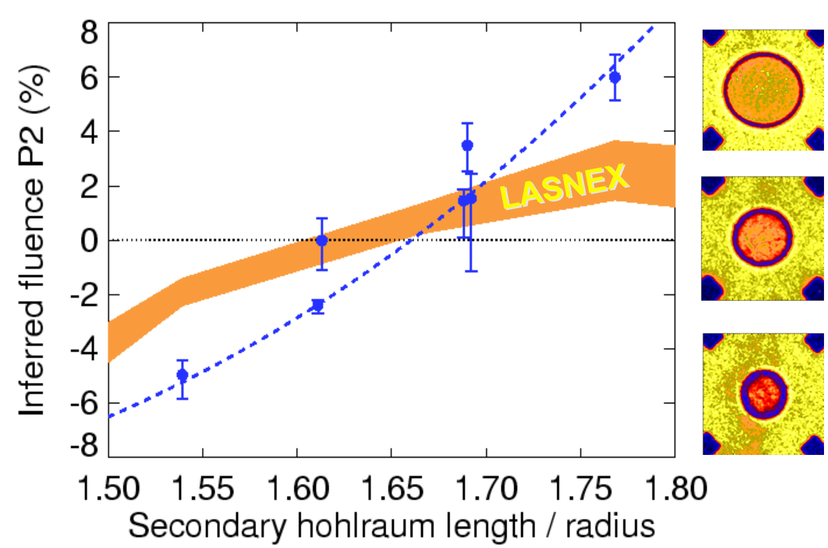
- **Consistency of z-pinch and hohlraum energetics documented at ± 20% level in flux**
- **Spoke transmission measured to be > 70%**

M. Cuneo et al., Phys. Plasmas 2001
G. Bennett et al., Phys. Plasmas 2003
R. Vesey et al., Phys. Plasmas 2003
R. Vesey et al., proc. IFSA 2005

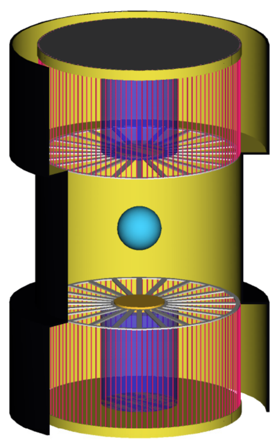
Backlit capsule trajectories confirm hohlraum coupling



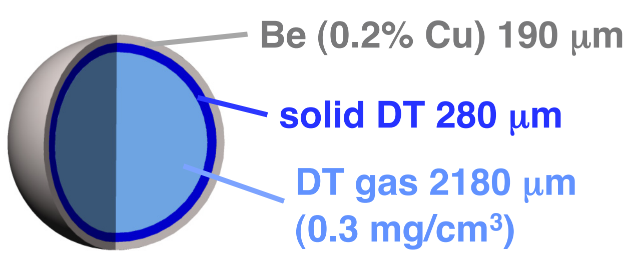
Backlit capsules confirm equator/pole symmetry tuning vs. length



Baseline DEH capsule uses a 0.2% Cu-doped Be ablator, absorbing 1.2 MJ of x-rays, yielding 520 MJ



DEH capsule design

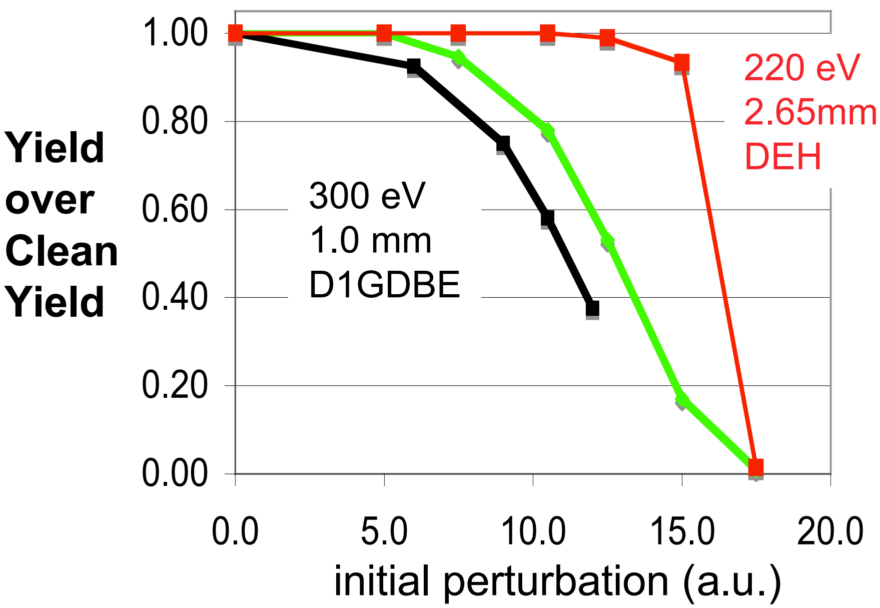


Outer radius = 2.65 mm

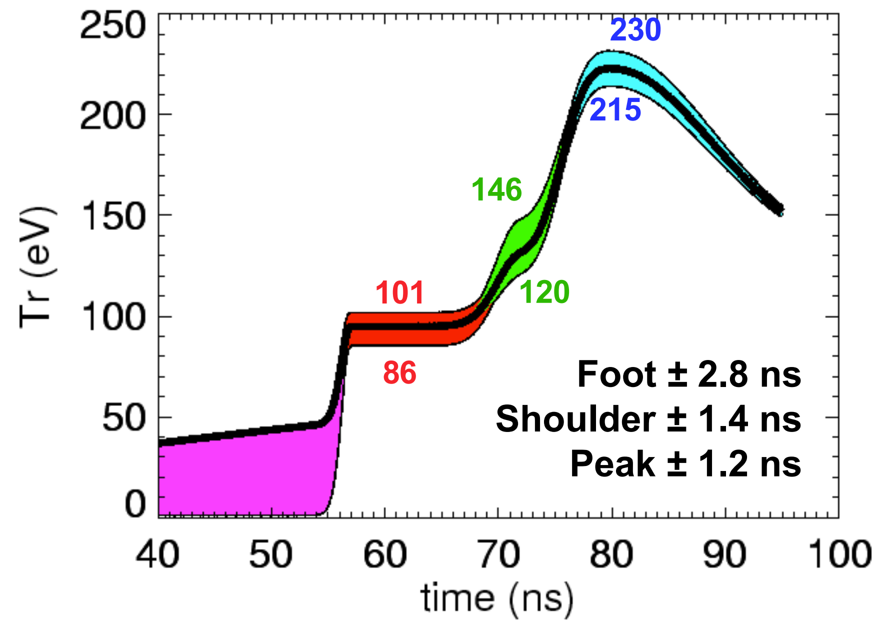
Capsule	NIF GDBE	DEH
Ablator thickness (µm)	160	**190**
DT fuel thickness (µm)	80	**280**
Absorbed energy (MJ)	0.14	**1.21**
Yield (MJ)	13	**520**
Peak ρr (g/cm^2)	1.9	**3.1**
Implosion velocity (cm/µs)	37.0	**26.0**
α_{if}	0.93	**0.73**
Fuel fraction at >1.5 α_{if}	0.06	**0.07**
Drive pressure (MB)	160	**60**
Inflight aspect ratio	19	**35**
Fuel KE margin	33%	**29%**
Hot spot convergence ratio	36	**35**

Although not optimized, the 220 eV DEH capsule robustness compares well with the NIF GDBe capsule

Surface perturbation tolerance due to RT instability (mode 12)



Pulse shape tolerances (>90% full yield)



Work is underway to define a more robust 220 eV capsule:

- **radially-dependent level of Cu dopant in Be shell**
- **optimization of capsule AND pulse shape**

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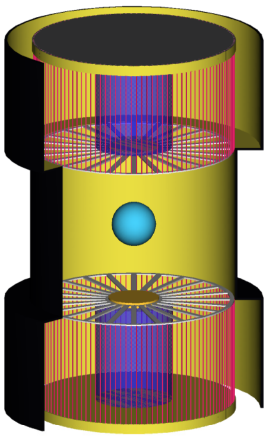
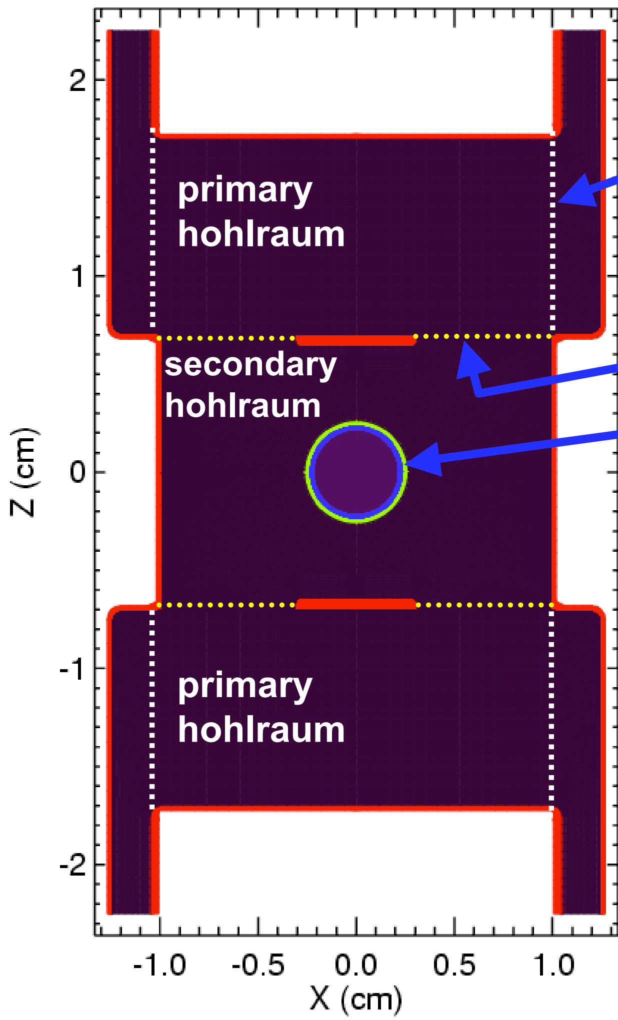
2D Lasnex hohlraum/capsule simulations capture the essential physics of radiation coupling and symmetry

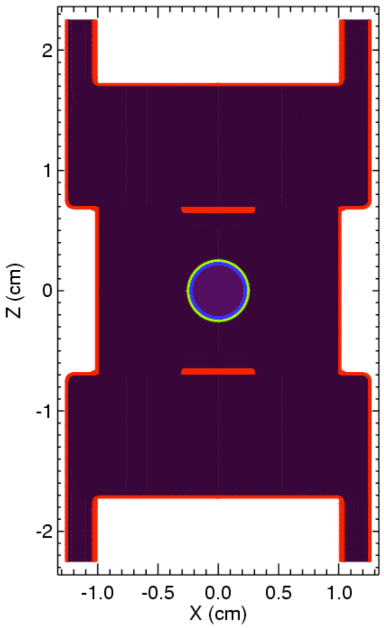




Included:
- Moving x-ray source pinch model r(t), P(t)
- Radiation transport
- Hohlraum wall radiation-hydrodynamics
- Magnetic tamping of primary hohlraum
- Spoke transmission as radiation b.c.
- Capsule implosion and asymmetry
- Capsule ignition and burn

Not included:
- Self-consistent z-pinch implosion (yet)
- 3D asymmetry
- High-mode RT instability in capsule

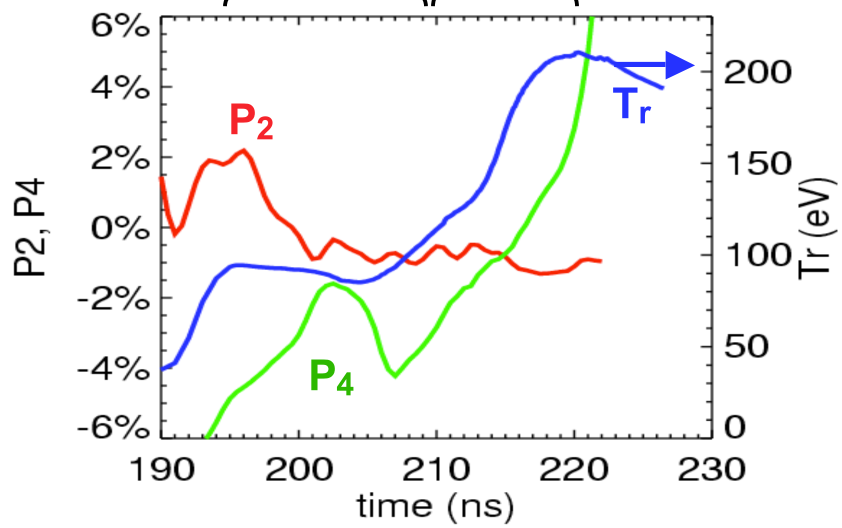
Low-mode symmetry control in the "baseline" hohlraum configuration is not adequate for ignition capsules



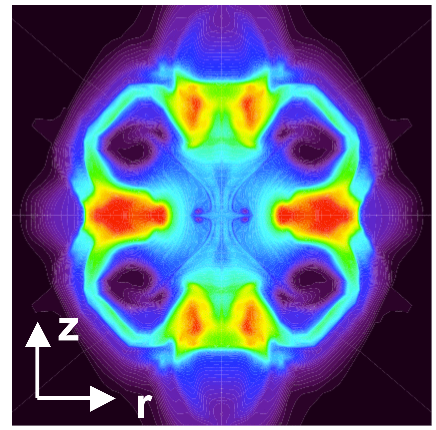
All walls $Au_{50}Gd_{50}$

Ablation pressure asymmetry

Foot	Main
⟨ P_2 ⟩ = -0.2 %	⟨ P_2 ⟩ = -1.0 %
⟨ P_4 ⟩ = -3.3 %	⟨ P_4 ⟩ = -0.3 %
⟨ P_6 ⟩ = +0.0 %	⟨ P_6 ⟩ = -0.4 %
⟨ P_8 ⟩ = +0.2 %	⟨ P_8 ⟩ = 0.0 %



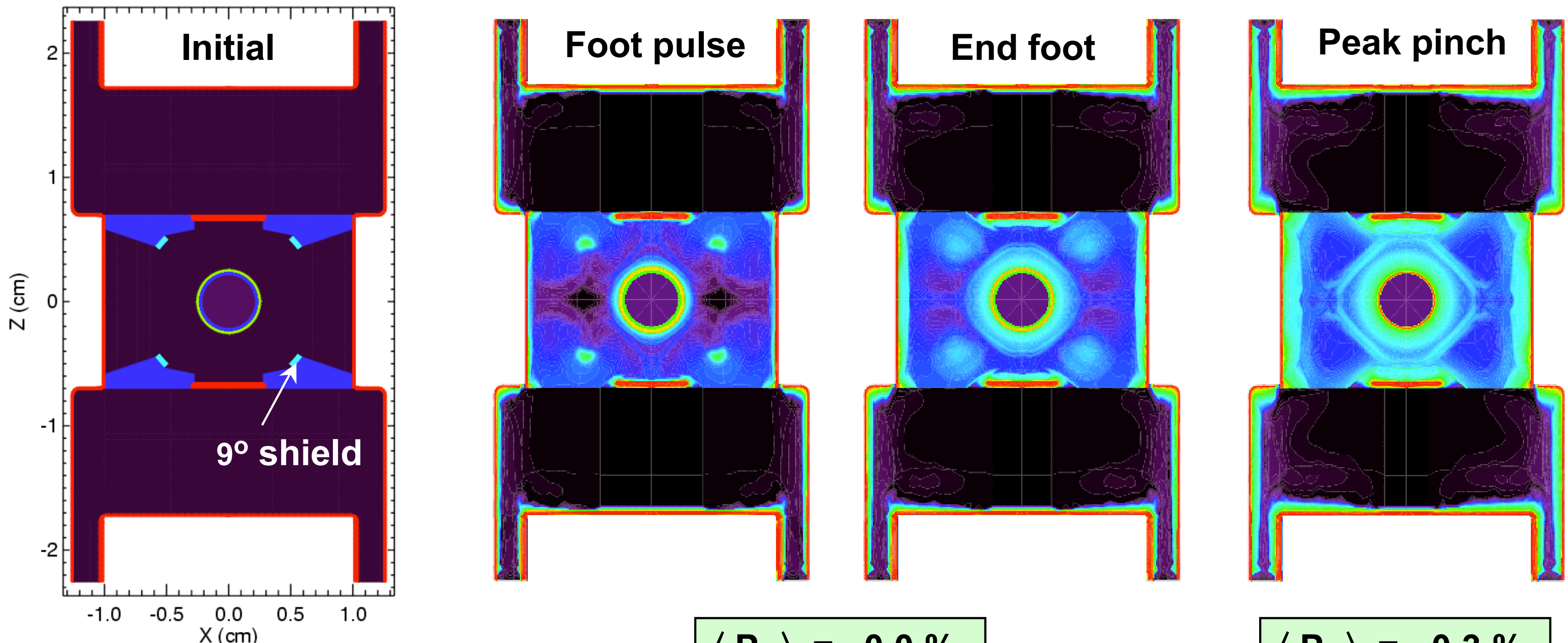
Fuel density contours at peak convergence



Yield = 0.040 MJ
ρ_{max} = 310 g/cc

Similar level of P_4 asymmetry measured in foot-like Z experiments

Secondary entrance foams and P_4 shields give low time-dependent P_2, P_4, P_6, and P_8 asymmetry

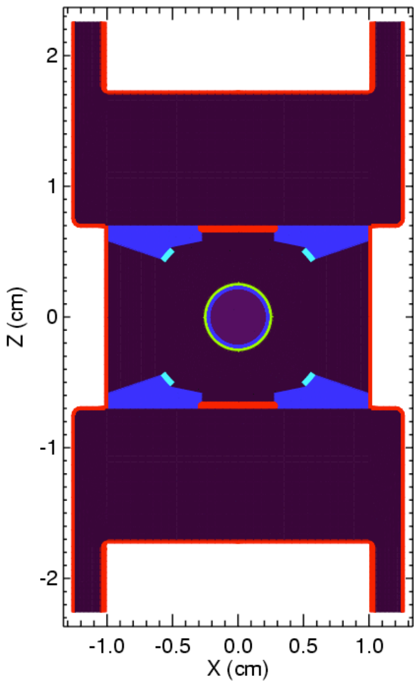


P_4 shield :
100 mg/cc CH_2 (3% Ge)
Sec. entrance foam :
5 mg/cc CH_2

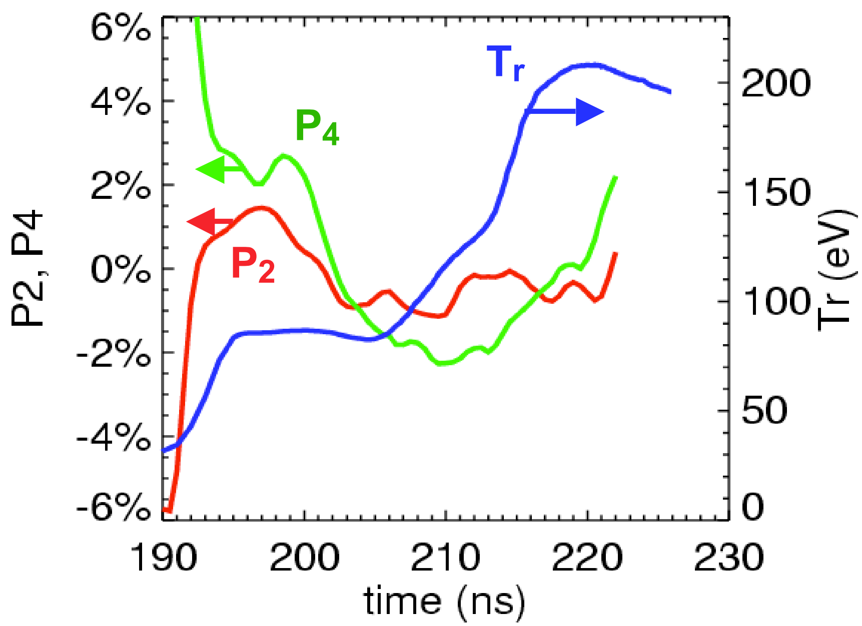
$\langle P_2 \rangle = 0.0\ \%$
$\langle P_4 \rangle = +0.2\ \%$
$\langle P_6 \rangle = +0.1\ \%$
$\langle P_8 \rangle = +0.1\ \%$

$\langle P_2 \rangle = -0.3\ \%$
$\langle P_4 \rangle = -0.8\ \%$
$\langle P_6 \rangle = +0.1\ \%$
$\langle P_8 \rangle = +0.4\ \%$

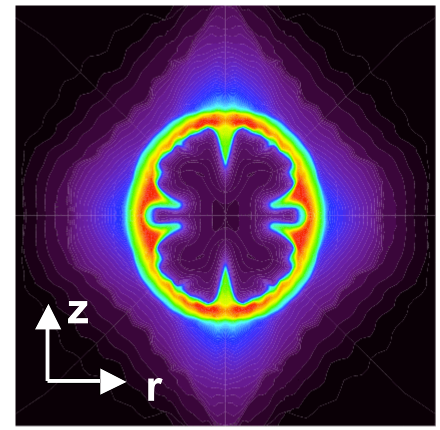
Secondary entrance foams and P_4 shields have resulted in highly symmetric capsule implosions that yield nearly 500 MJ



Ablation pressure asymmetry
P_4 shield: 4.4°, 200 mg/cc



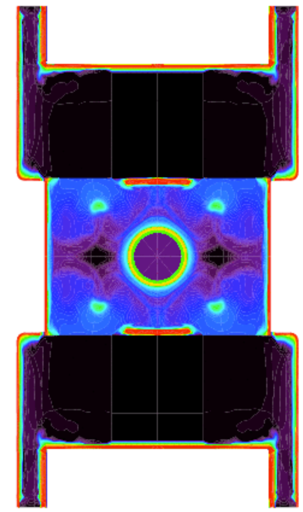
Fuel density contours near ignition



Yield = 470 MJ
ρr = 2.7 g/cm^2
ρ_{max} = 580 g/cc

Initial P_4 control set by shield angular range, duration set by density ($\rho\Delta x$)
Resolution convergence studies are underway

Hohlraum / capsule simulation summary



2 main goals of hohlraum/capsule simulations have been met:

Demonstrated ignition and burn in best available 2D models

Developed strategy to control time-dependent symmetry

Identified a new technique for mode-selective symmetry control with small angular range shields

P_4 is tunable with negligible effect on P_6 and P_8 at capsule

Solutions exist with 2 shields per side that should tune P_4 with exactly zero effect on P_2, P_6, and P_8 (to be tested)

Work is in progress (Herrmann) to define more robust capsule designs

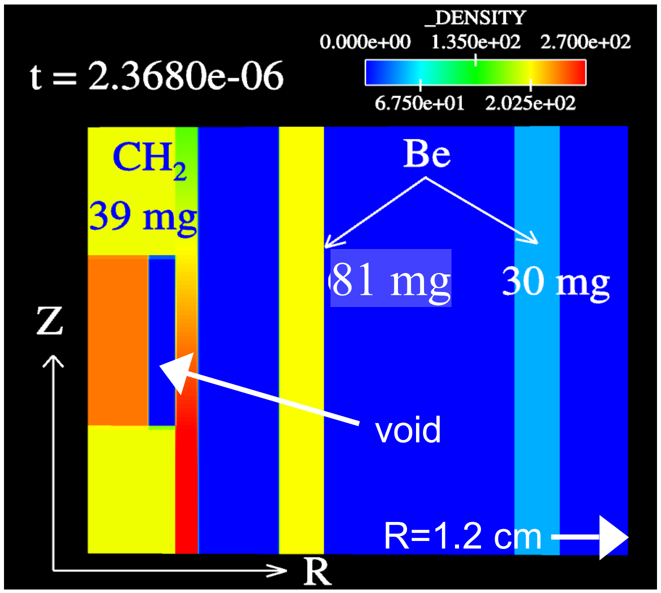
Concept separates z-pinch from capsule – design z-pinch load in parallel

Each pinch should provide 9 MJ total, with 0.5 MJ foot pulse 20-25 ns prior to peak

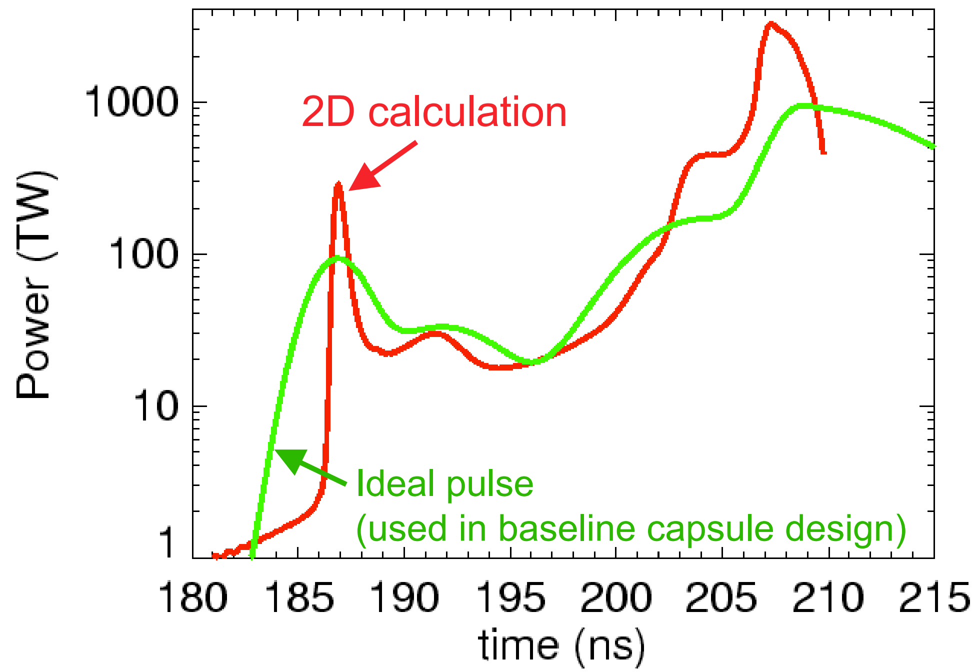
Design work is in process with Alegra (2D & 3D) and Lasnex (1D & 2D)…

Recent z-pinch simulations produced an x-ray pulse shape capable of igniting a capsule

Alegra simulation
Nested Be-Be-CH_2 shells
Z voltage x 5.3



Z-pinch x-ray power history



Load design has evolved to provide good foot – shoulder – peak timing
The total x-ray energy output is more than adequate at ~10 MJ

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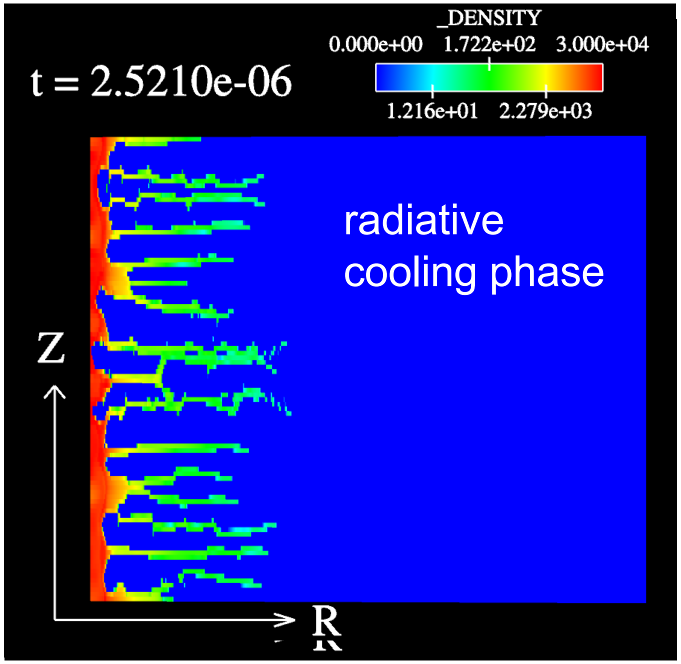
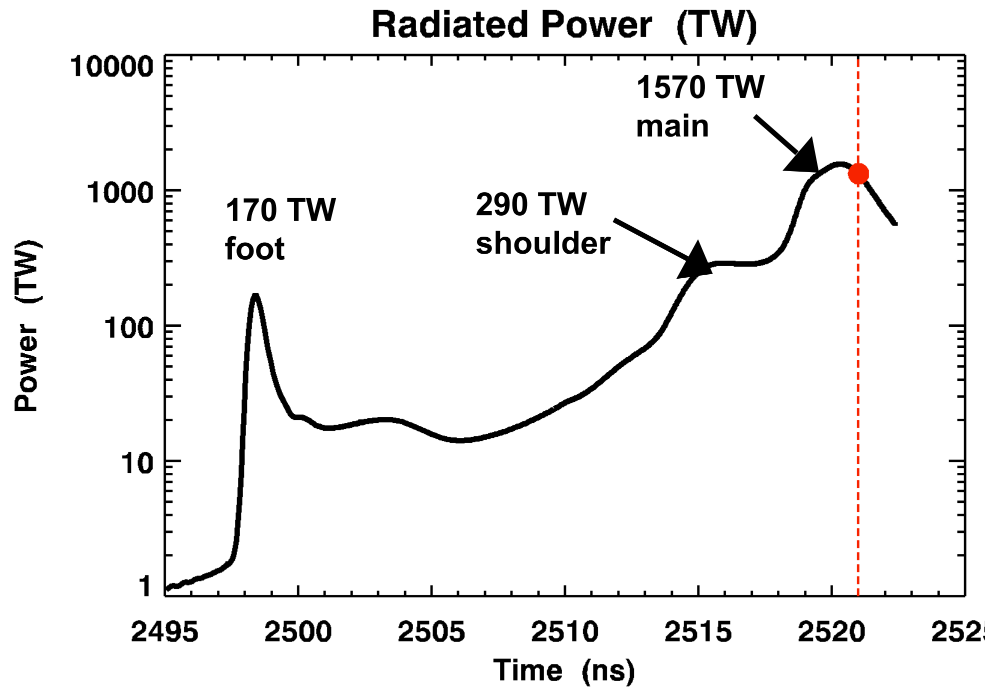
Radiation pulse features are produced by shock heating when z-pinch components collide

Z-Pinch density ρ(r,z)





Amplitude of radiation pulse feature produced by shock event depends on kinetic energy flux of impactor and opacity (optical depth).

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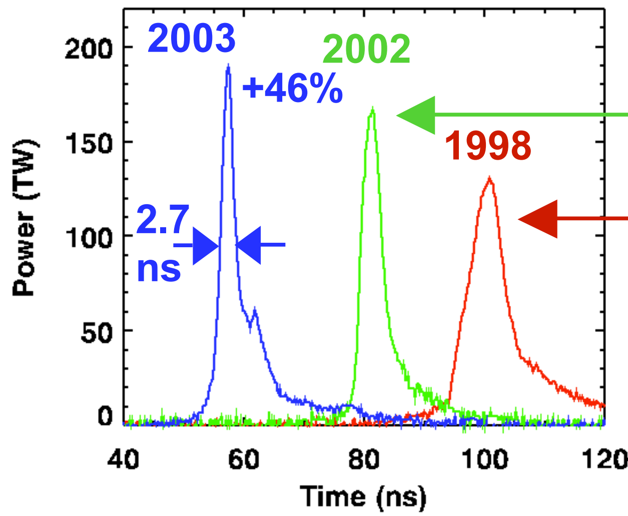
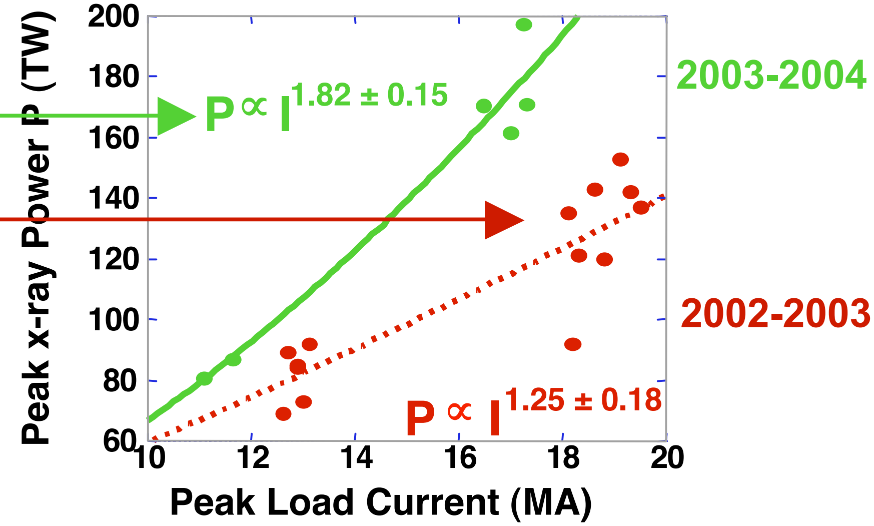
We have made significant progress in power scaling, reproducibility, and pulse shaping of wire array z-pinches

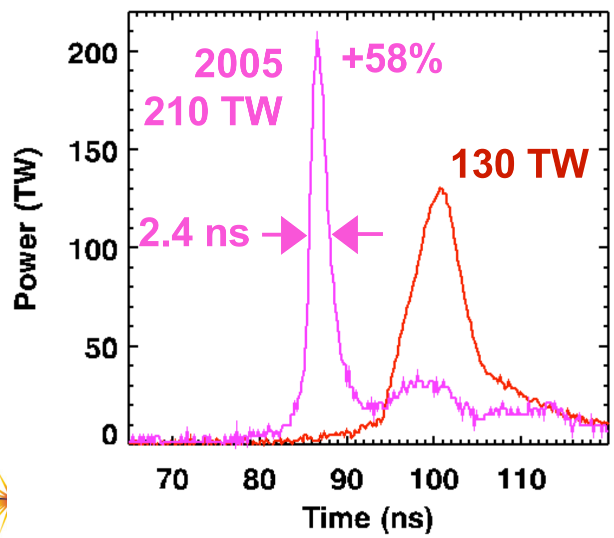
Pulse compression with single arrays



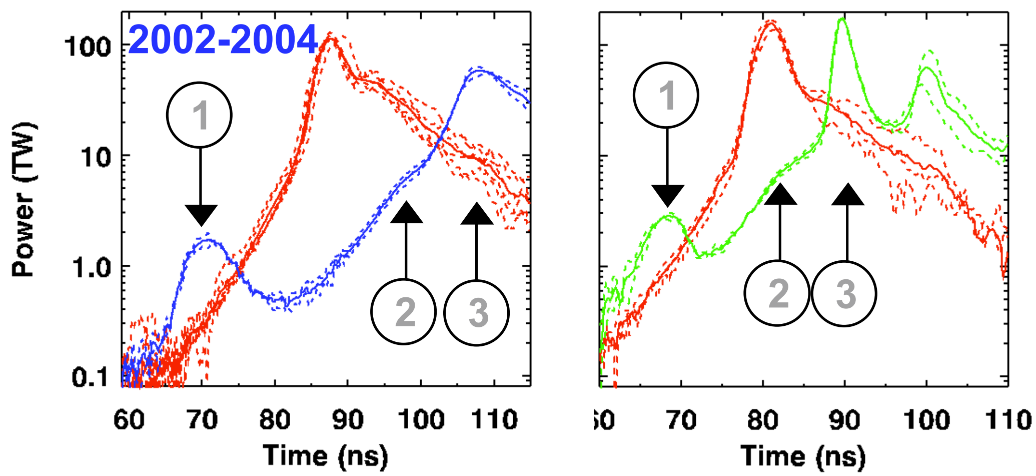
Current scaling of single arrays



Pulse compression with nested arrays

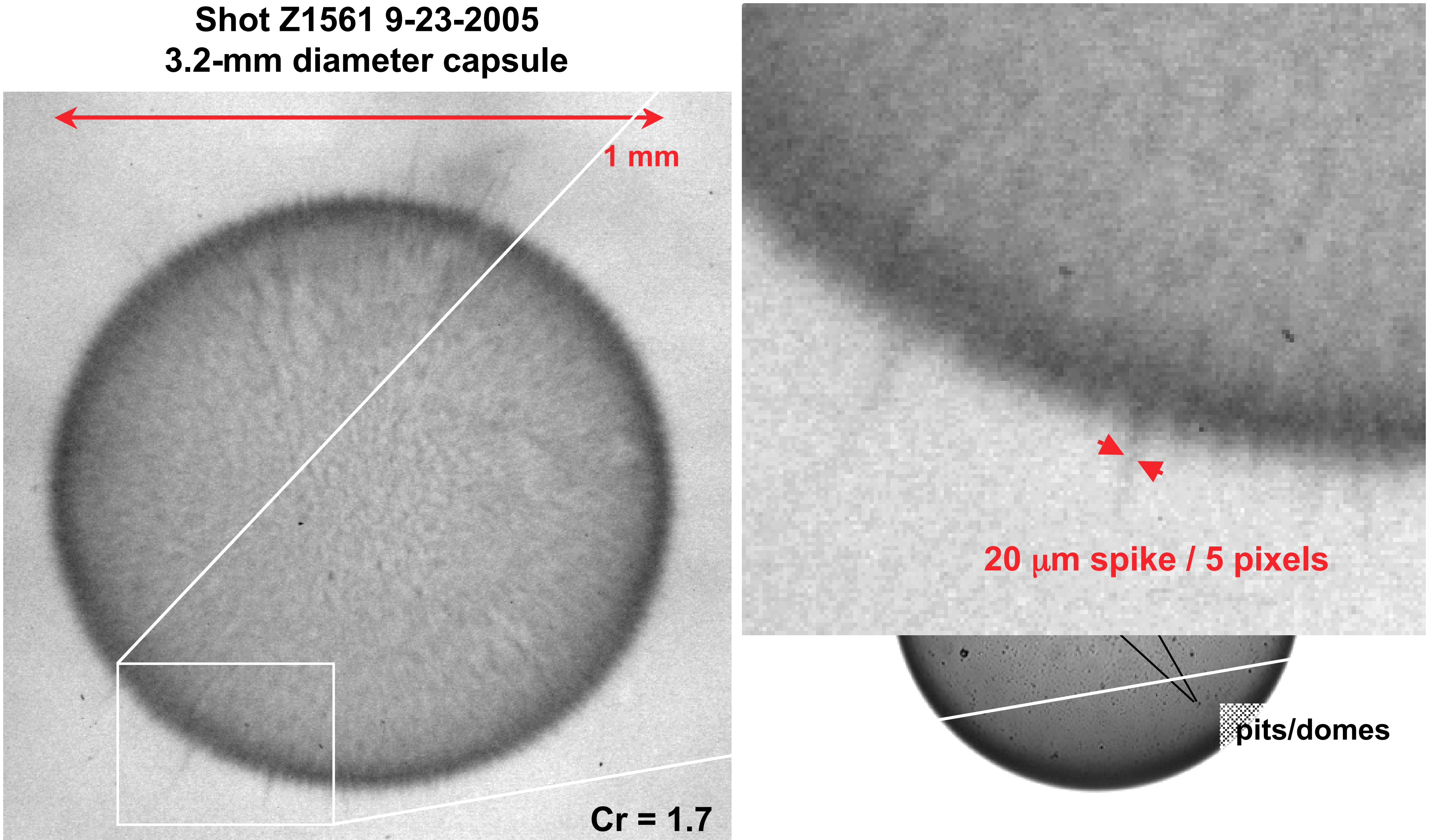


Reproducible, controllable shapes with nested arrays



20 μm resolution radiography provides new opportunities for capsule implosion studies

Shot Z1561 9-23-2005
3.2-mm diameter capsule



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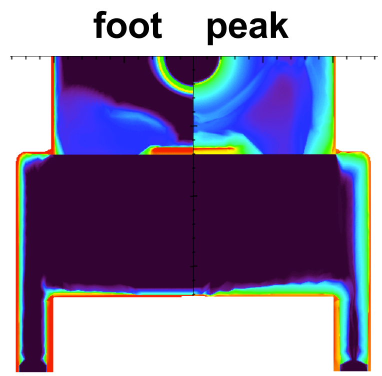
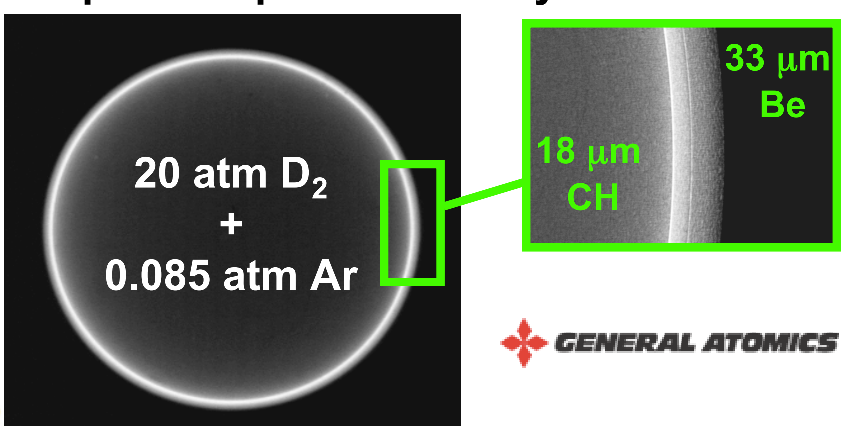
Progress in pulsed-power hot-spot ignition

- **Integrated LASNEX hohlraum/capsule simulations predict ignition and burn in double-ended hohlraum configuration**
- **Achieved dramatic advances in our ability to experimentally control the radiation output of Z-pinches**
- **Designed power pulse shapes for high yield capsules through z-pinch engineering with ALEGRA-HEDP**
- **Record x-ray driven D-D neutron yields with Be capsules in dynamic hohlraums**



1D yield 520 MJ
2D yield 470 MJ (currently)

Be capsule imploded with Dynamic Hohlraum



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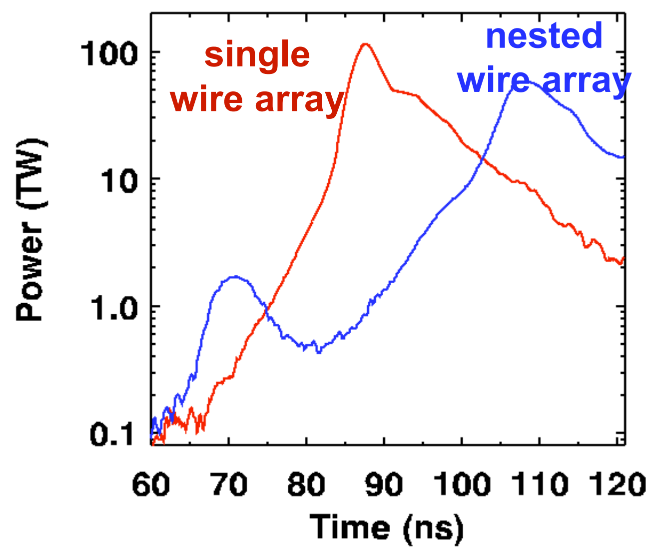
Radiation pulse shaping



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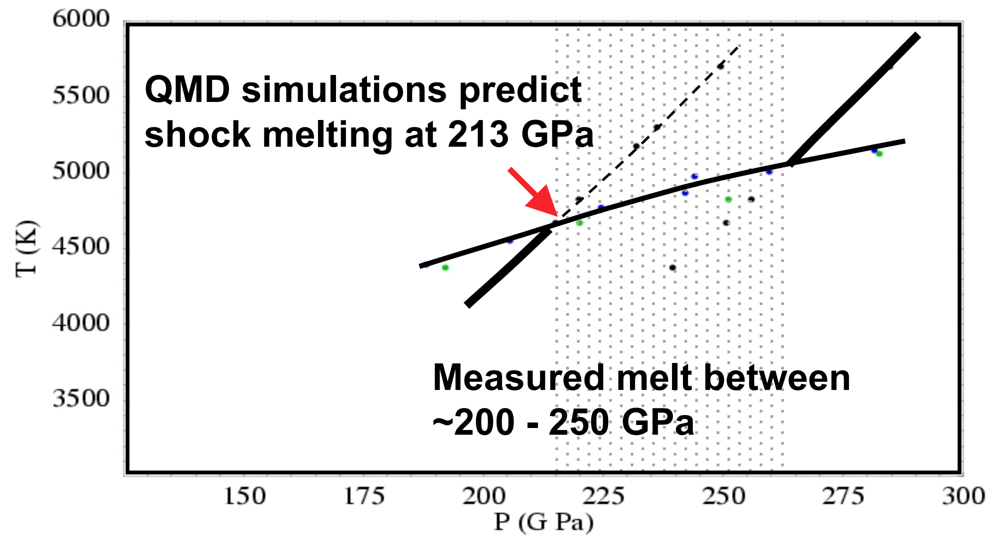
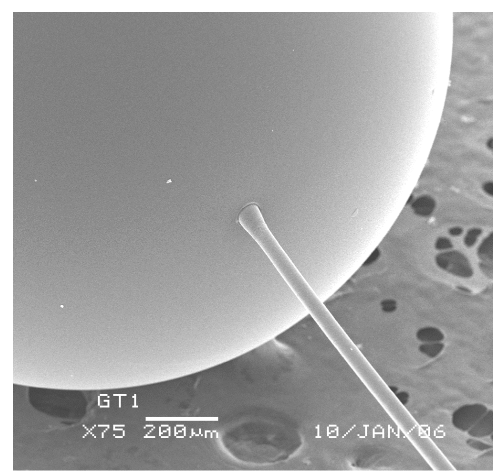
We are using our experience from several science campaigns to support the National ICF Program

- Measured Be melt pressure
- Delayed ZR shutdown to enable diamond melt experiments
- Fielded fill tube hydro experiments (collaboration with GA and LLNL)
- Performed experiments with LANL and LLNL on Omega
- Developing NIF cryogenic target system x-ray blast shield
- Assessing EMP shielding for NIF diagnostics





GENERAL ATOMICS

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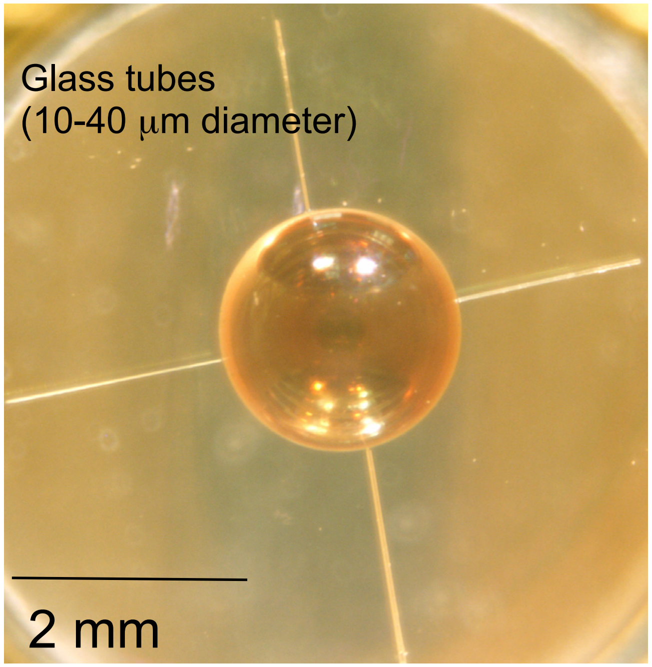
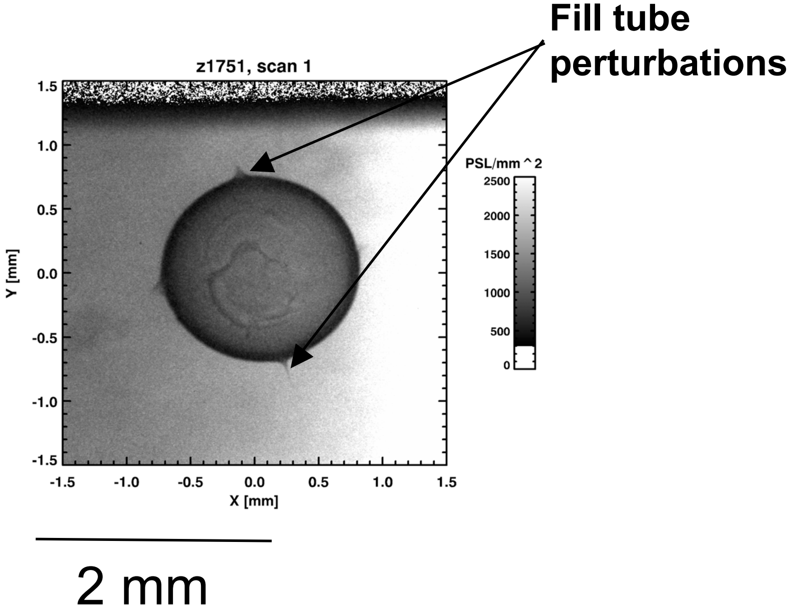
Recent experiments used Z's unique capabilities to assess the effects of fill tubes on capsules

Optical image

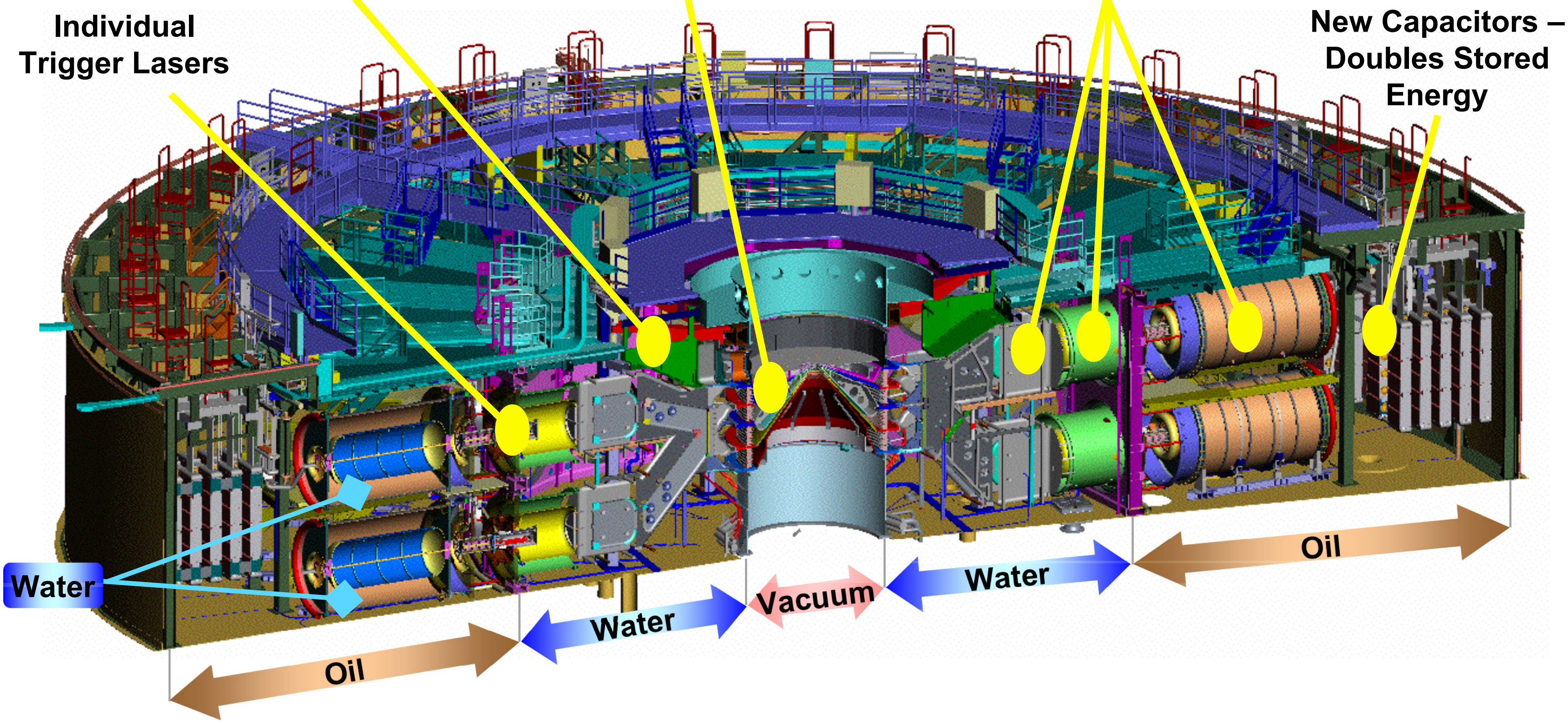


X-ray image during implosion
(1 nanosecond snapshot)



- **Fill tube calculations are some of the most challenging calculations that have been done in support of inertial confinement fusion ignition**
- **Need data to validate the computational tools used to simulate fill tubes**
- **Capability to do experiments on NIF-scale objects coupled with high resolution radiography allows high utility experiments**

ZR: Refurbishment of the Z Pulsed Power Generator



Refurbishment

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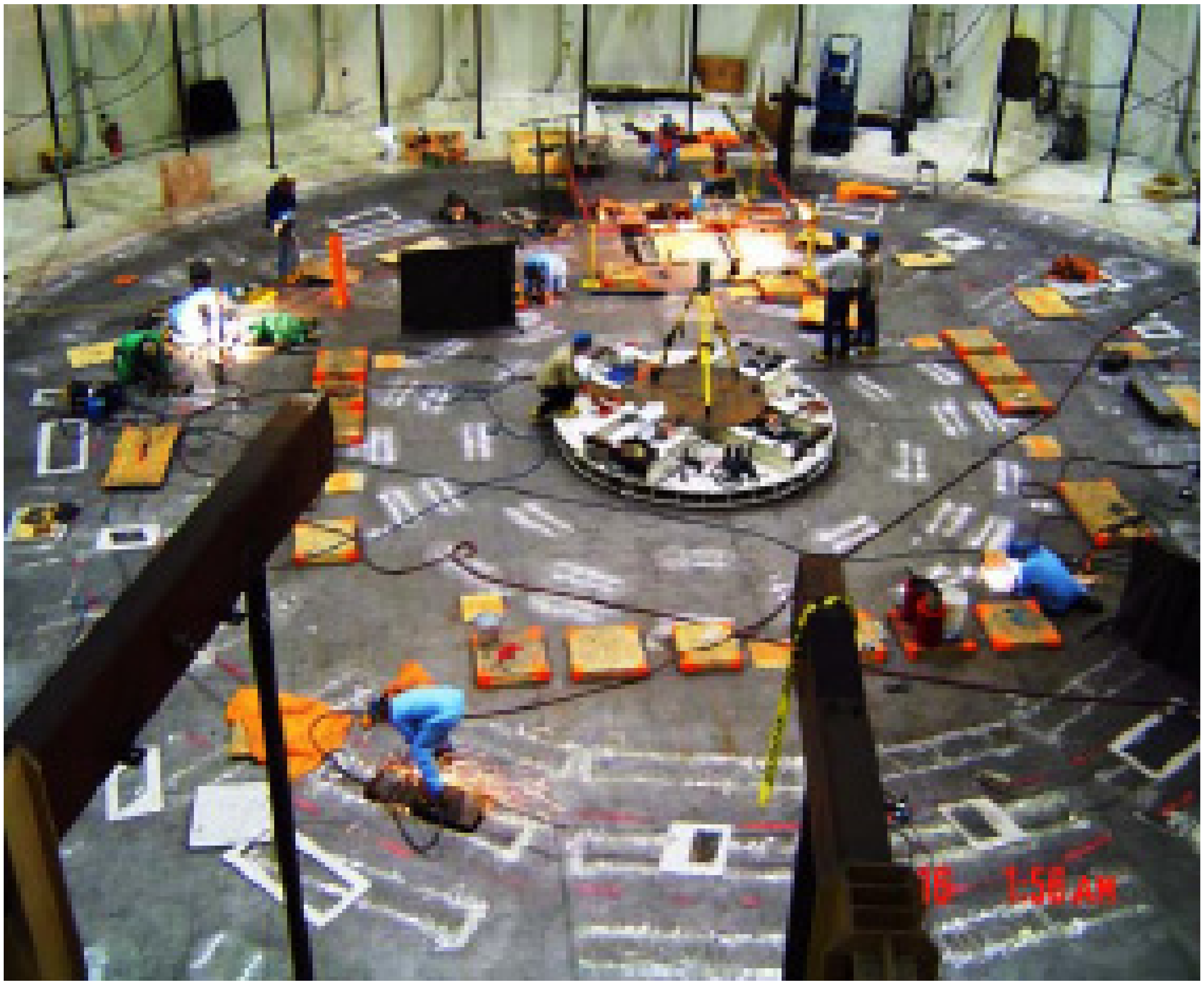
Some assembly is required



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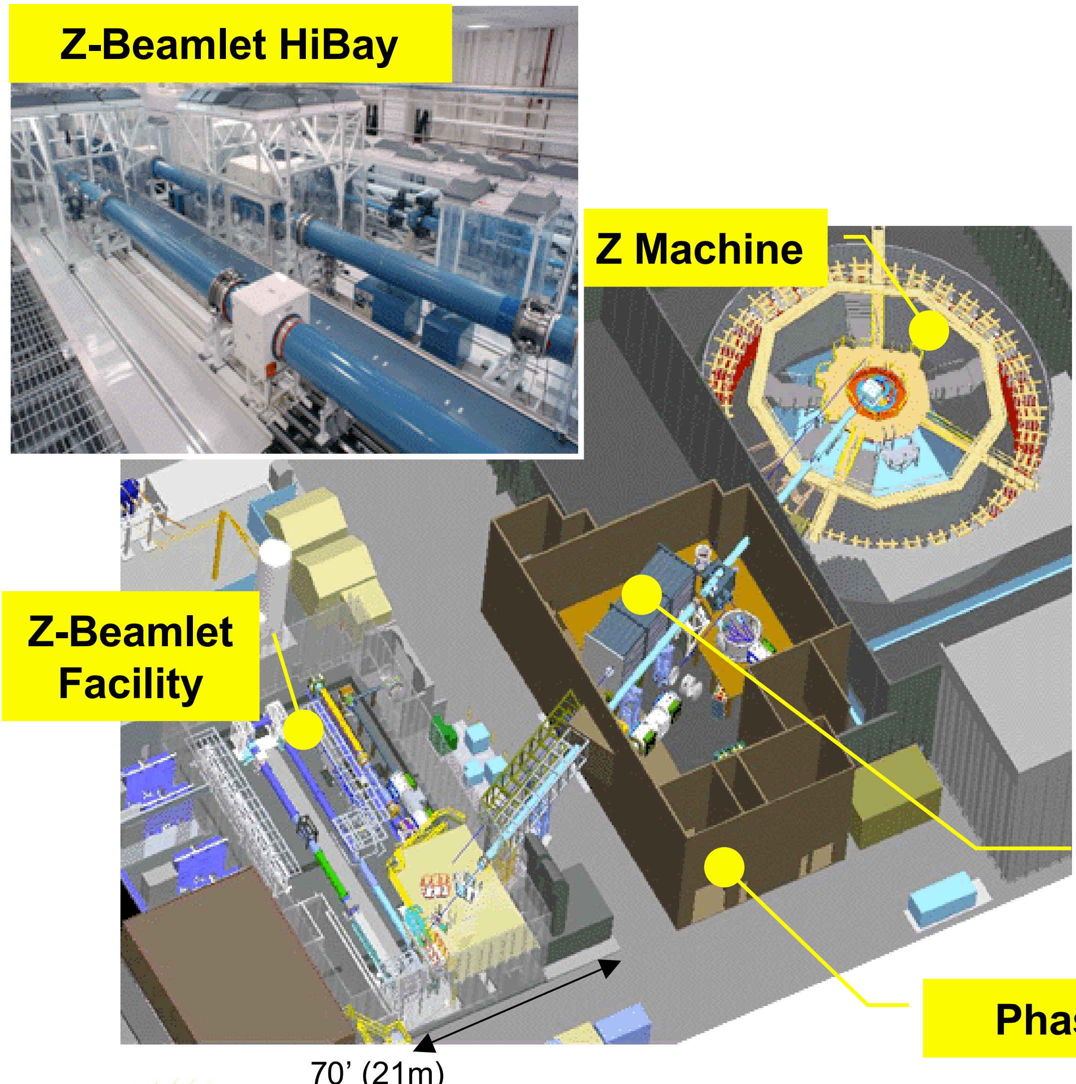
The Z-Petawatt Laser System will provide new capability for radiography and fast ignition research



- **Terawatt-class Z-Beamlet provides 1-10 keV x-ray backlighting on Z**
- **Petawatt-class enhancement allows new radiography options (X-rays over 10-100 keV; protons) and Fast Ignitor research on Z**
- **System operational in 2007 at 500 J / 500 fs with Nova gratings, ramping up to 2 kJ in 5-10ps**