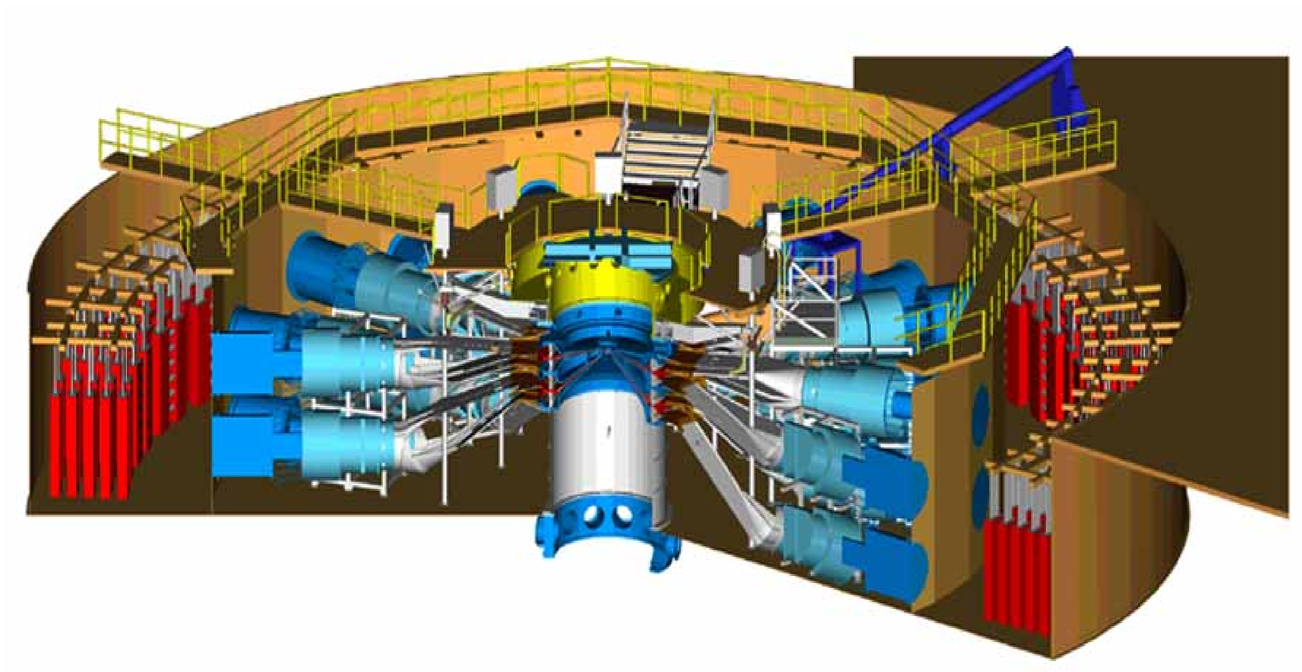
Indirect Drive Inertial Confinement Fusion Hohlraum Physics Using A 1-2 MJ Z-pinch X-ray Source



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Outline of the presentation

- Introduction to the hohlraum concept
- Description of Sandia National Laboratories' Z facilty
- Double-ended Z-pinch hohlraum experimental results
- Dynamic hohlraum experimental results
- Radiation science experiments on Z
- Summary of paper

Many people and institutions have contributed to the Z experiments reported in this presentation (partial list)

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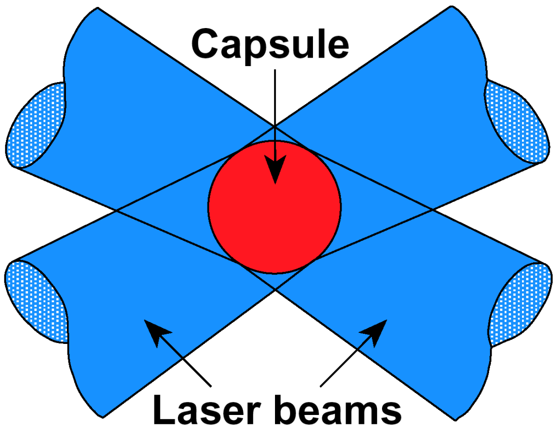
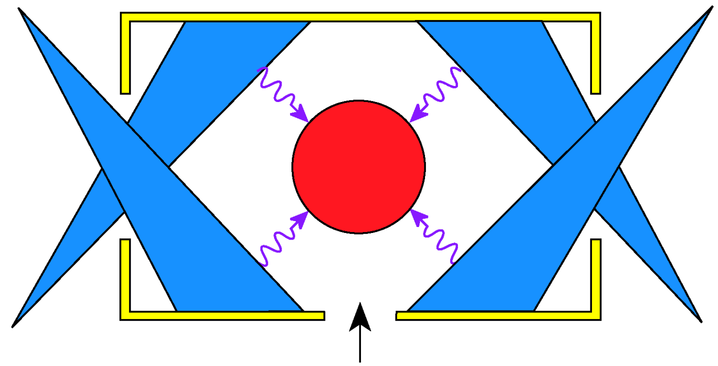
Bechtel Nevada-Neutron Detectors
Cornell University-Z-pinch Physics
General Atomics Corporation-Targets
Imperial College-Z-pinch Physics
Schaffer Corporation-Targets

In contrast to direct drive ICF, in indirect drive ICF the capsule is driven by soft x-rays generated in a hohlraum

Direct-drive target



Indirect-drive target



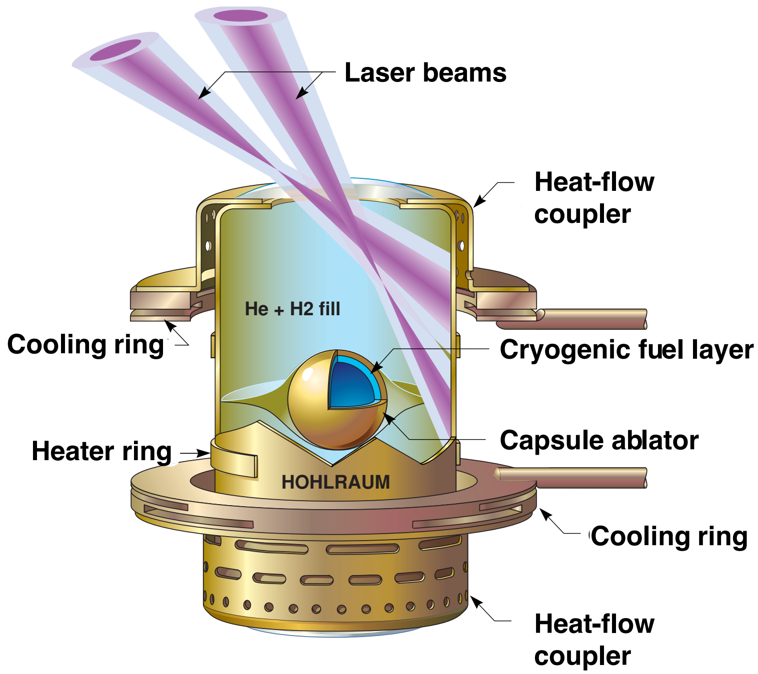
Hohlraum using
a cylindrical high-Z case

Features of indirect drive:

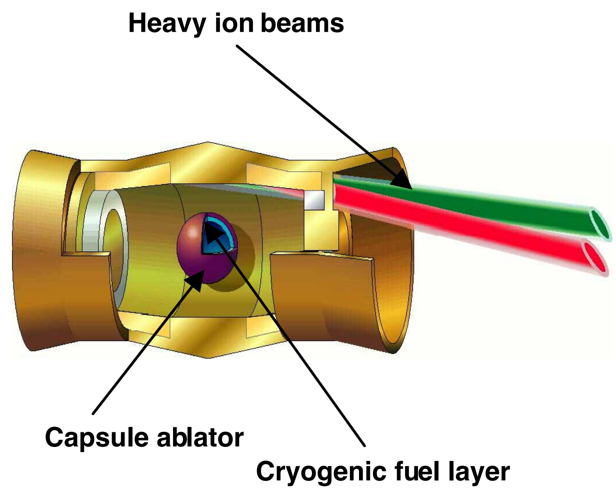
- Soft x-rays couple directly to capsule ablation front
- Beams or power sources originating in a restricted solid angle can be converted into a symmetric x-ray flux onto the capsule
- Symmetry can be tuned by variations in hohlraum to capsule radius ratio
- Ignoring hole losses, the x-ray power flux within a hohlraum is amplified over the input source power flux by a factor of $1/(1-\alpha)$ where α is the wall albedo
  - For a 200 eV Au wall hohlraum, a typical value of α is 0.8 yielding an amplification factor of 5

Hohlraums may be driven with a variety of radiation sources including lasers, heavy ions, and Z-pinches

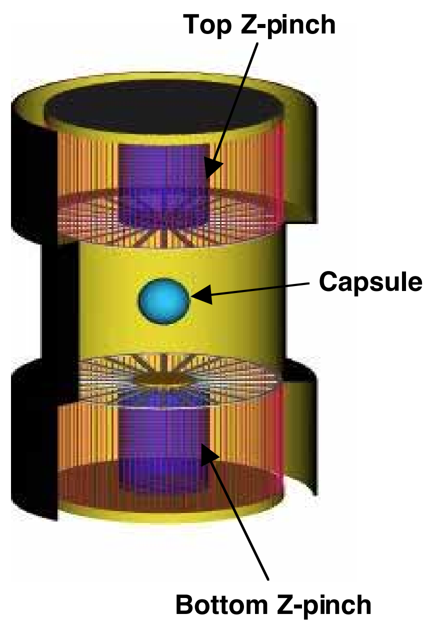
NIF Laser Ignition Hohlraum



Heavy Ion Hohlraum



Double-Ended Z-pinch Hohlraum



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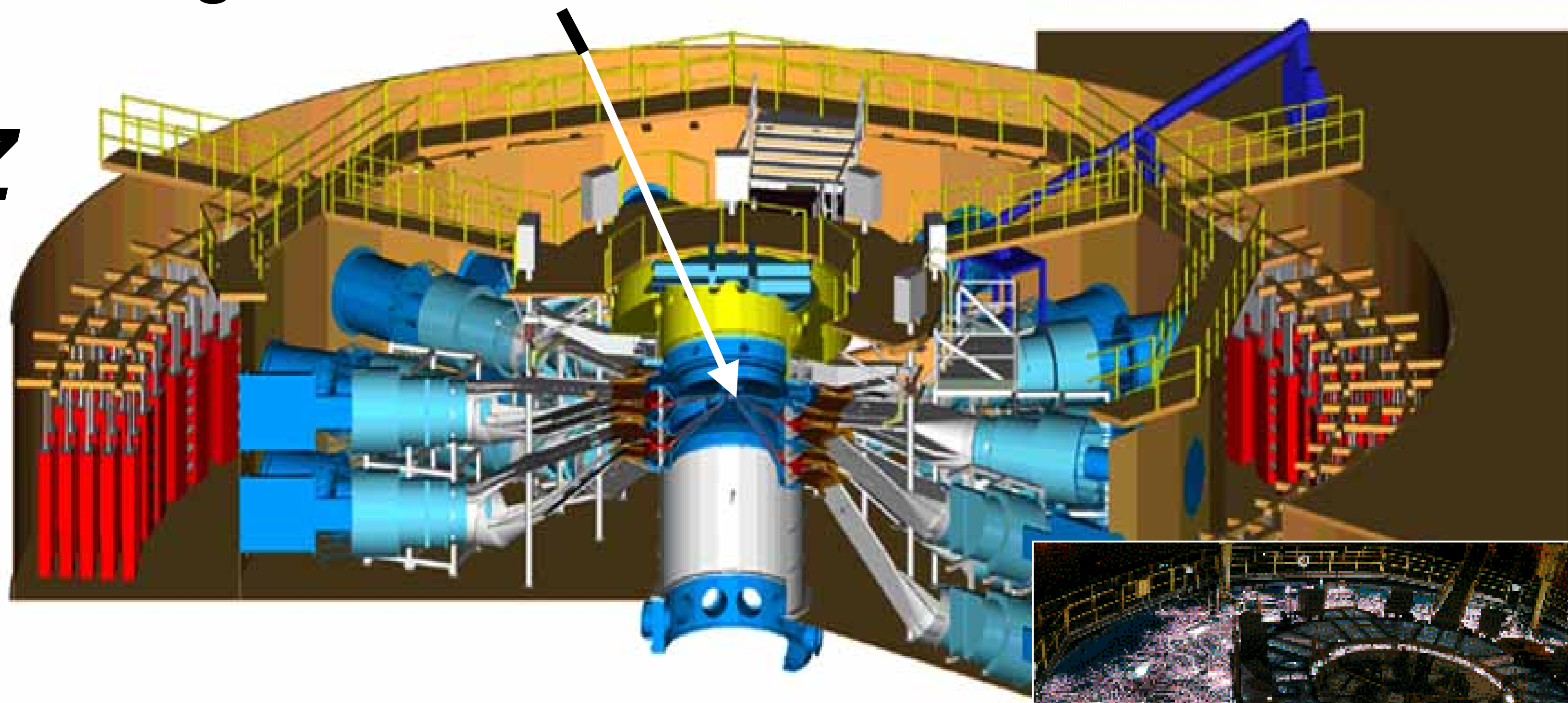
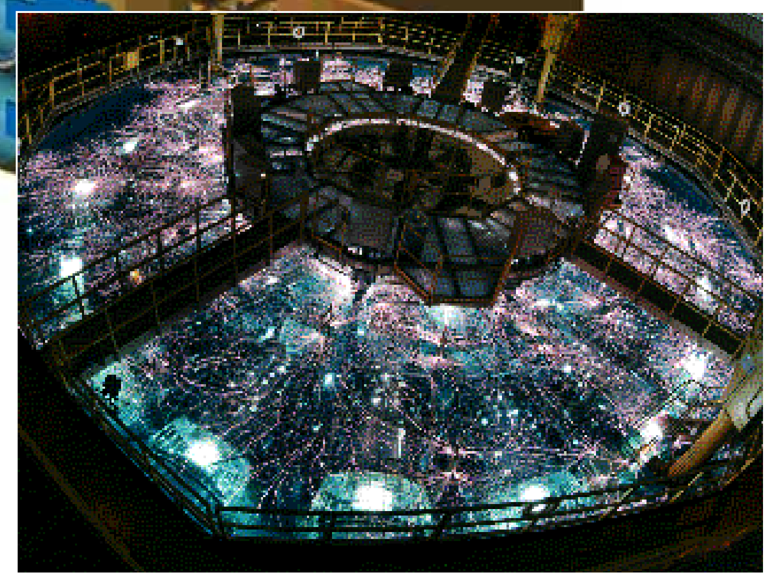
Pulsed-power accelerators with z-pinch loads provide efficient time compression and power amplification

Target Chamber

Z



11.5 MJ stored energy
19 MA peak load current
40 TW electrical power to load
100-250 TW x-ray power
1-1.8 MJ x-ray energy

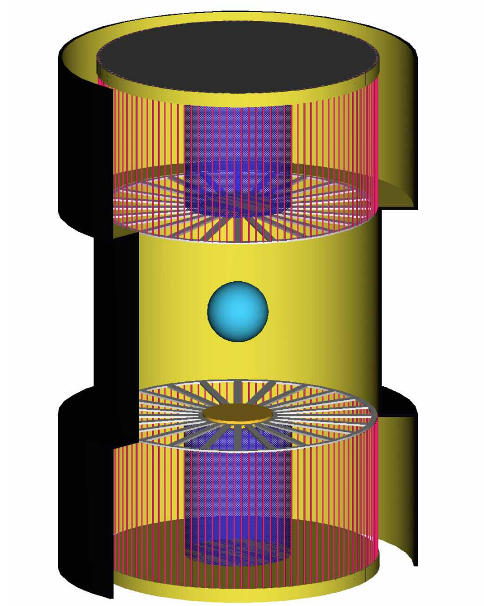


Two Complementary Approaches to Z-pinch-driven Fusion Are Being Studied at Sandia

Key issues

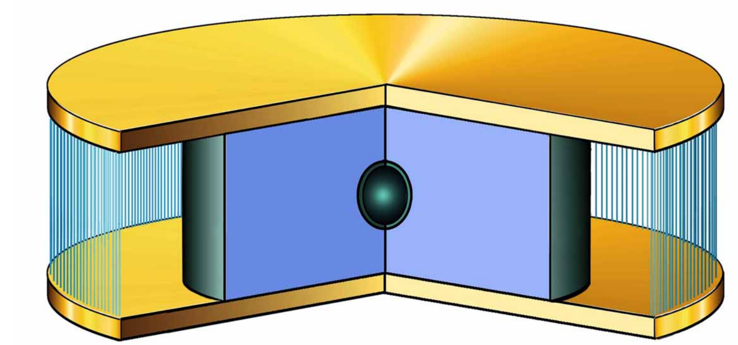
- hohlraum energetics
- radiation symmetry
- pulseshaping
- preheat
- capsule implosions

Double-ended hohlraum



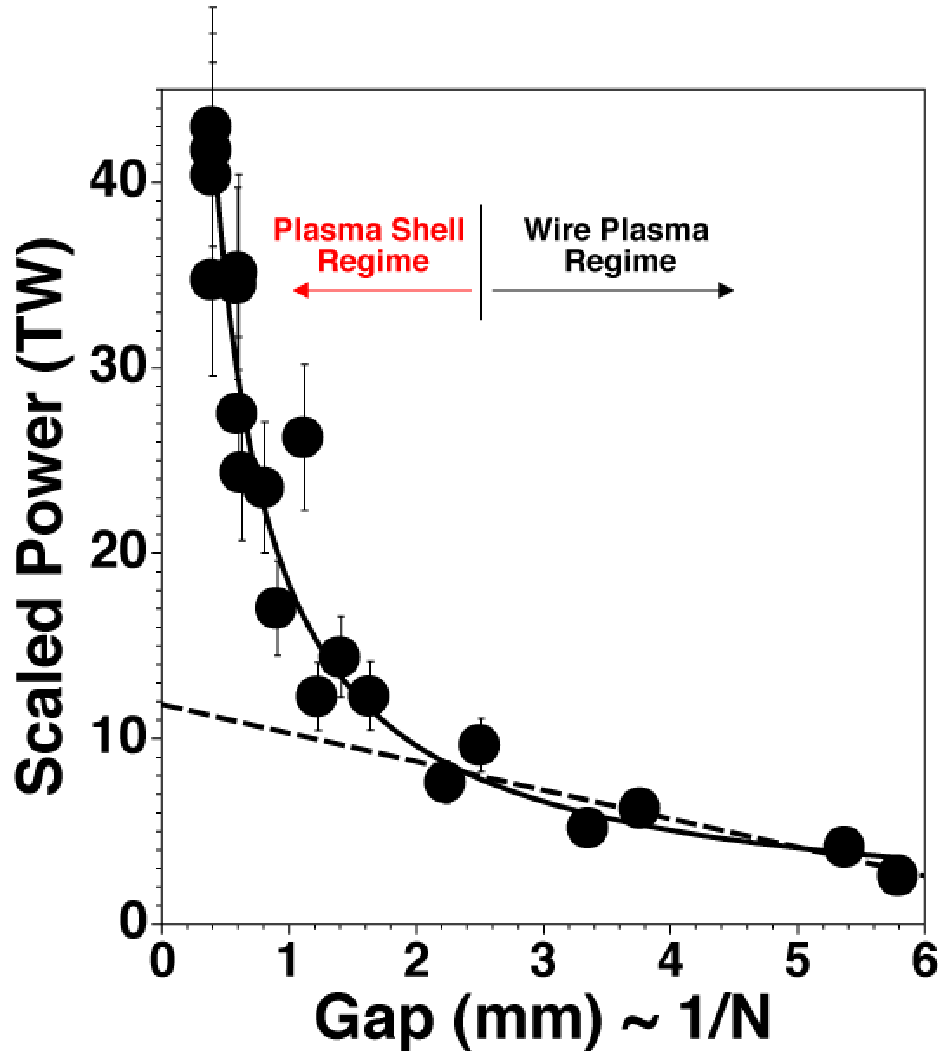
- Two 60 MA pinches
- 380 MJ yield

Dynamic hohlraum



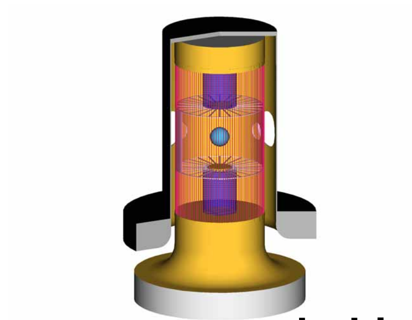
- 54 MA pinch
- 530 MJ yield

Increasing number of wires greatly increased x-ray power and the application on Z lead to a renaissance in z-pinch physics

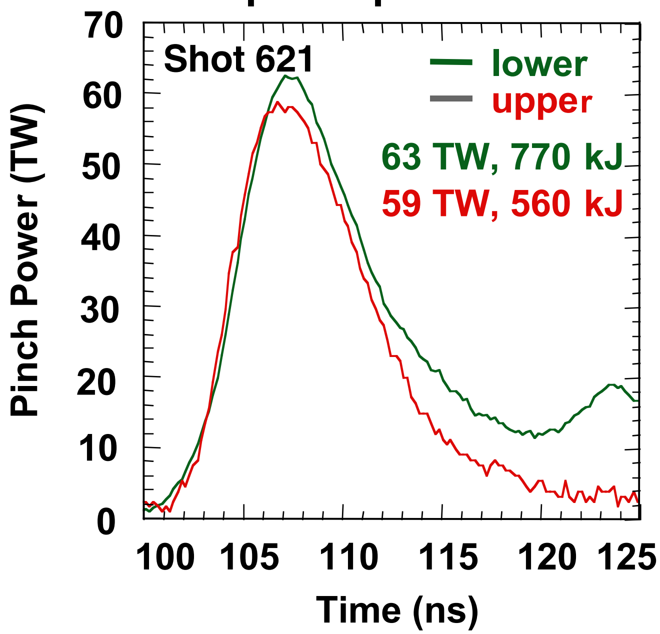


Sanford et al *Phys. Rev. Lett*. 77, 5063 (1996)

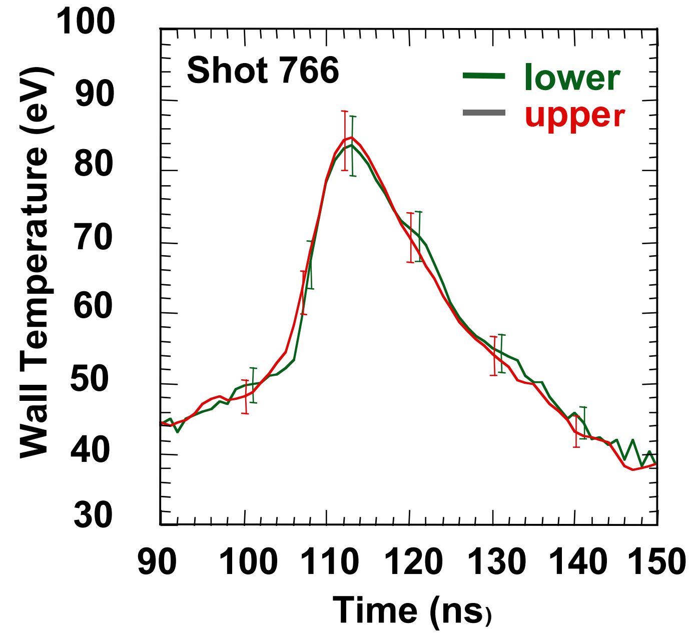
The double-pinch hohlraum power balance has been measured in experiments on Z



pinch power

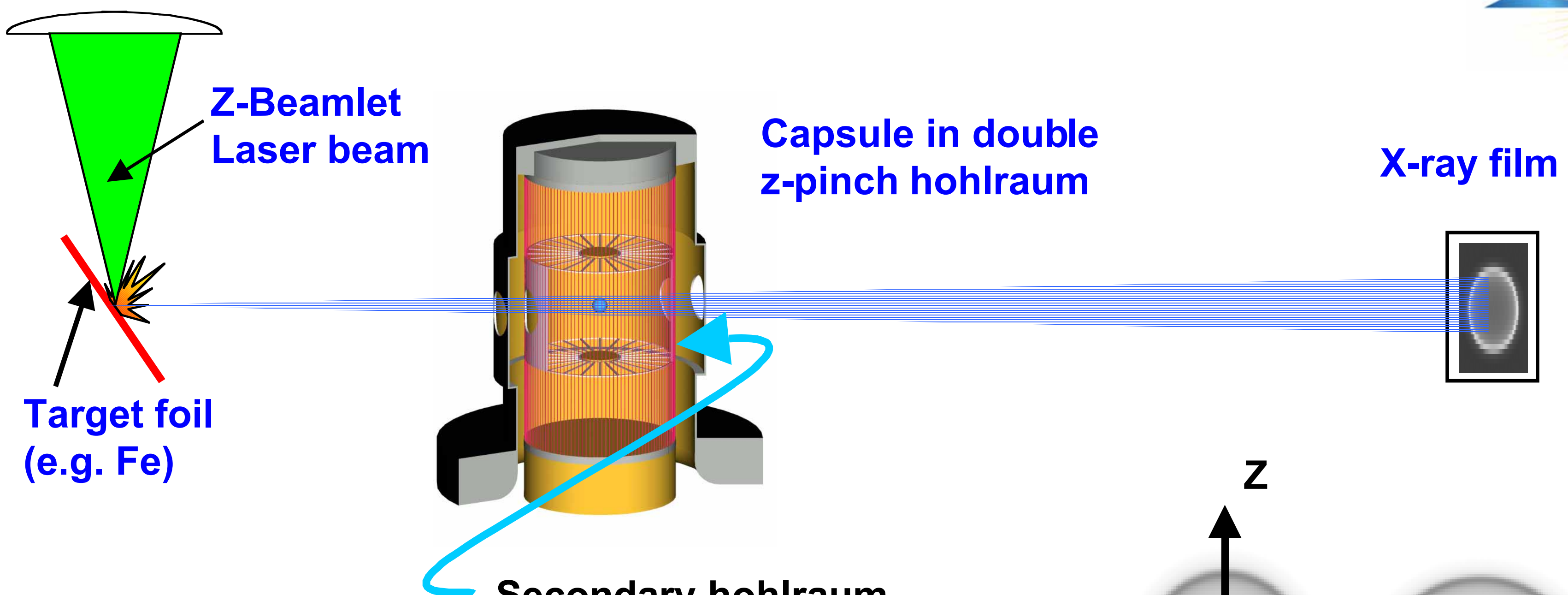


hohlraum temperature



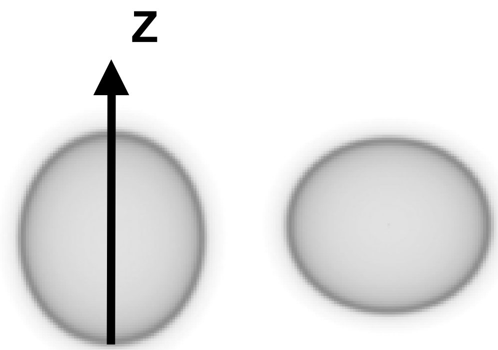
- From these measurements of top/bottom hohlraum T_r, P_1 is estimated to be $\leq$ 4% on most shots

We diagnose radiation asymmetry on Z with x-ray point-projection backlighting of an imploding capsule



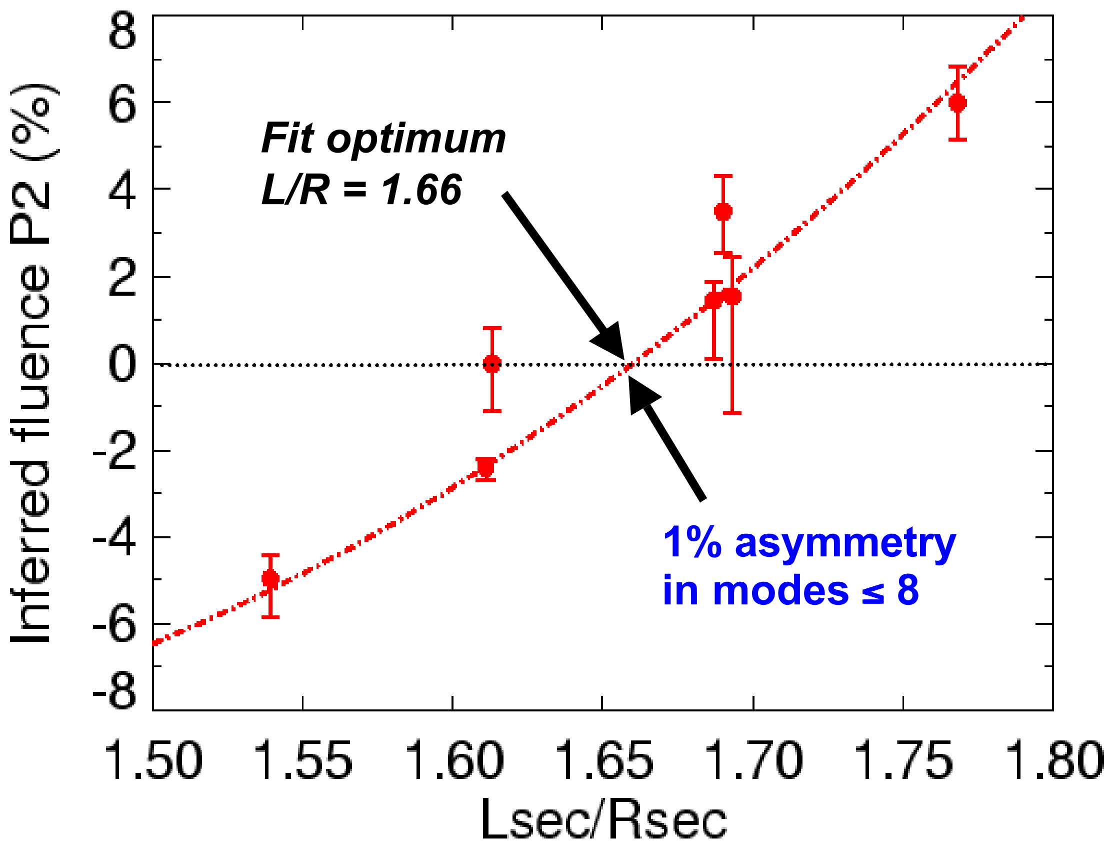
Secondary hohlraum
Radius ≡ R_{sec}
Length ≡ L_{sec}

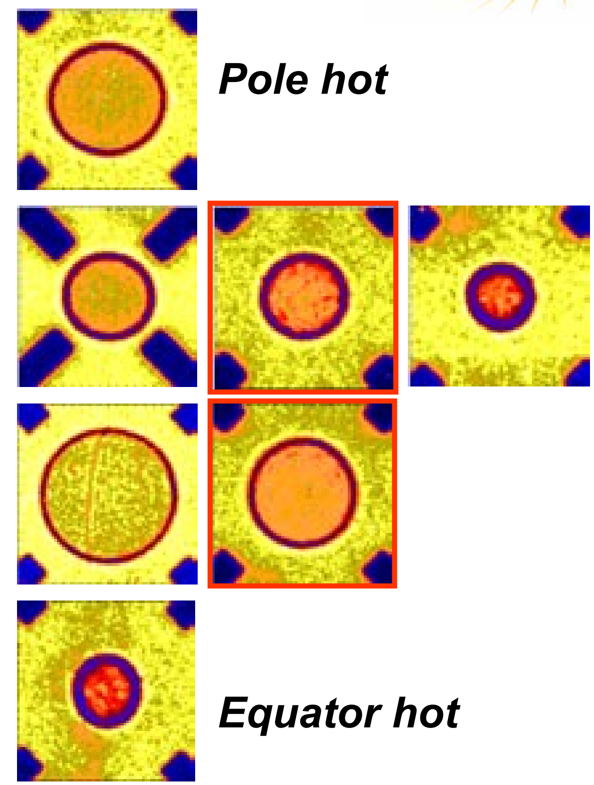
Example images of capsules driven by a dominant P_2 asymmetry:



$- P_2$	$+ P_2$
equator-hot	pole-hot

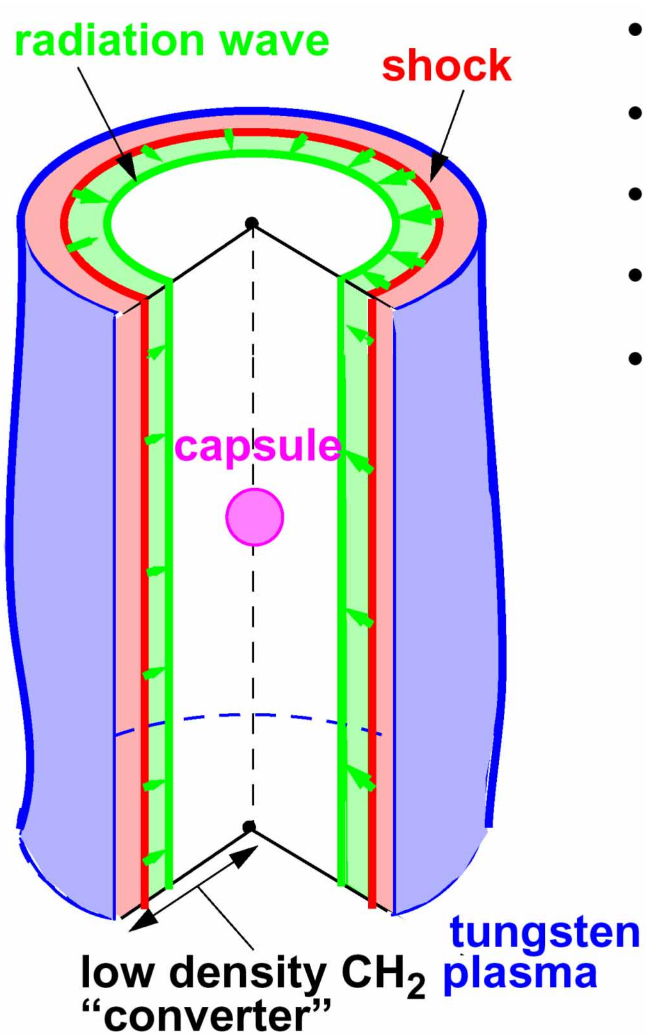
P_2 asymmetry can be controlled by varying hohlraum geometry as demonstrated experimentally on Z





The P_2 asymmetry is zero for a secondary hohlraum L/R = 1.66

Dynamic hohlraums efficiently couple x-rays to capsules



- Z-pinch plasma impacts foam converter
- The impact launches shocks in foam & W
- The foam shock is a main radiation source
- The z-pinch confines the radiation
- Capsule heated mainly by re-emission from tungsten hohlraum wall

issues:

1. interior diagnostics
2. symmetry, symmetry, symmetry
3. radiation production
4. radiation transport
5. radiation confinement
6. preheat

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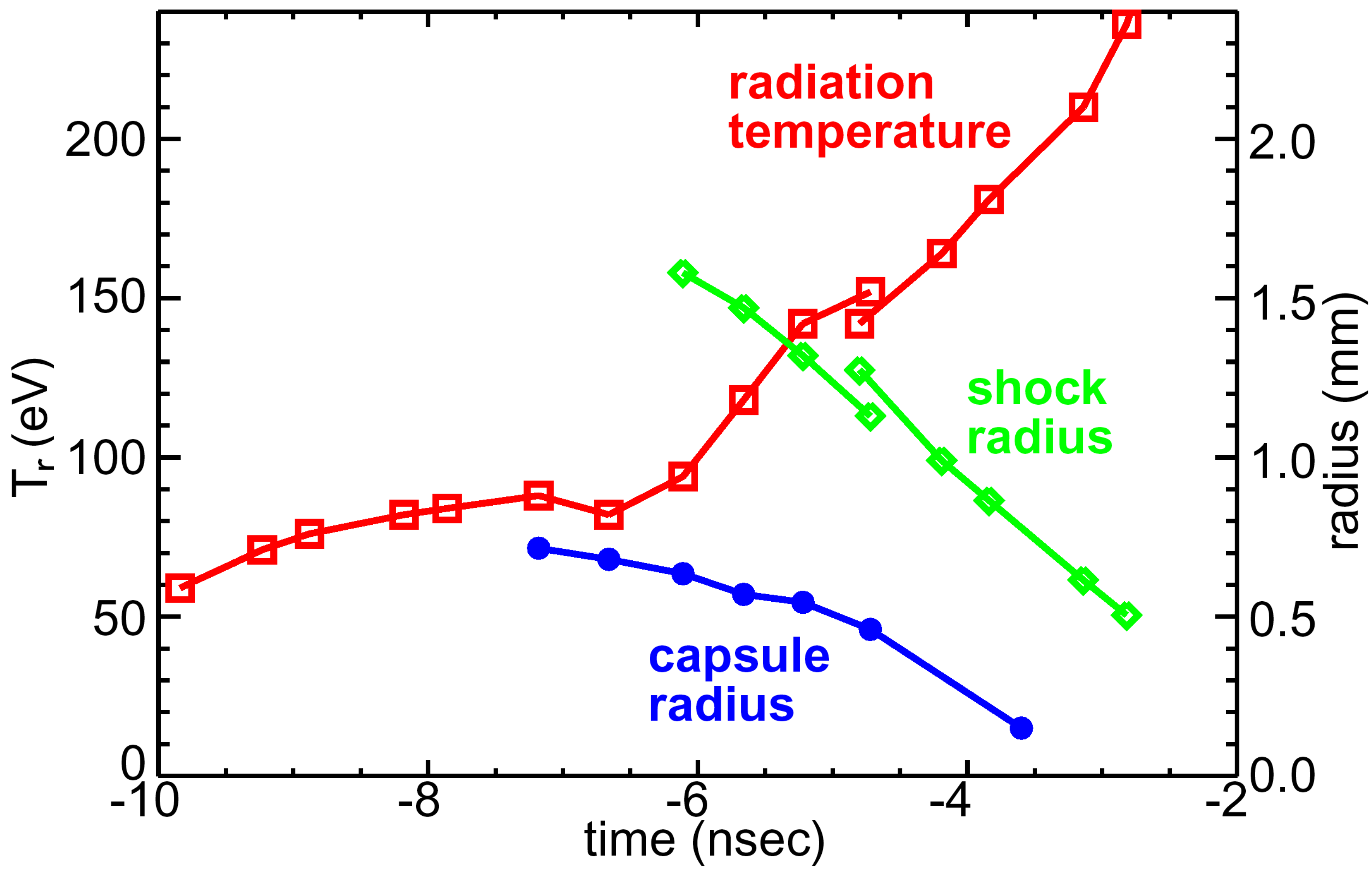
Hohlraum drive temperatures above 200 eV were measured for the Z dynamic hohlraum



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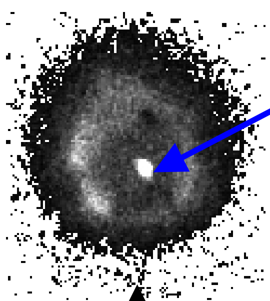
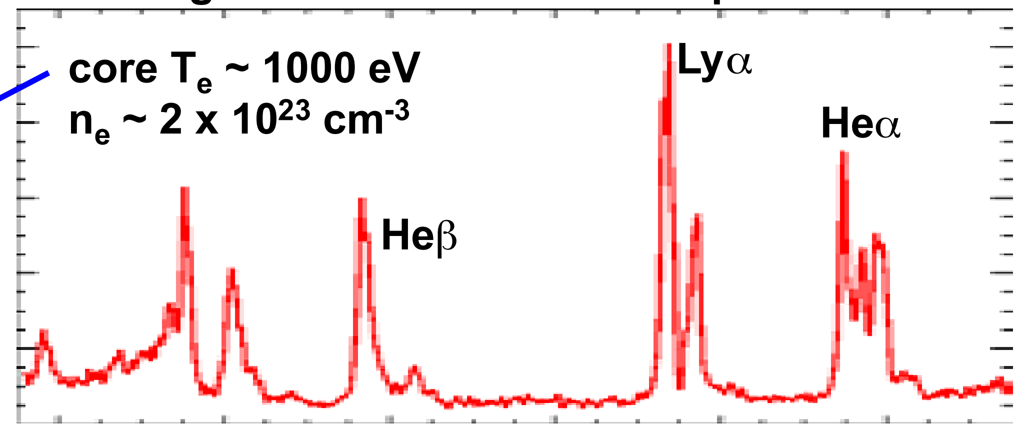
Core temperature, density, and symmetry diagnosed in dynamic hohlraum-driven ICF implosions

Capsule absorbs ~ 24 kJ x-rays
Implosion creates a 200 μm diameter hot core

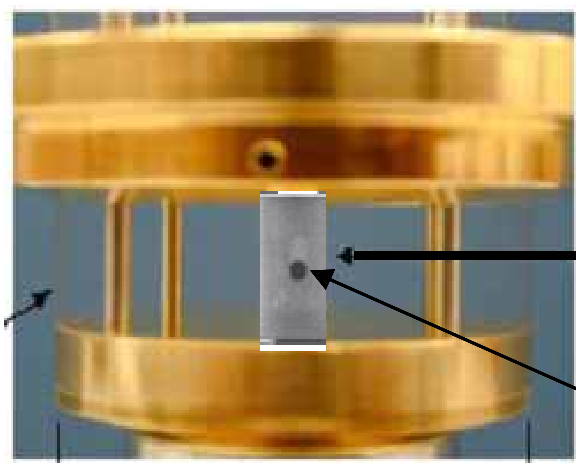


argon emission from ICF capsule

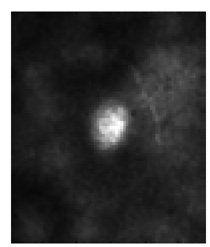


Wire impact on foam creates 200 eV dynamic hohlraum x-ray source

Wires



Imploded core (side-on image through pinch)



2.0 mm diameter, 50 μm CH wall D_2-filled capsule embedded in 14 mg/cc CH_2 foam

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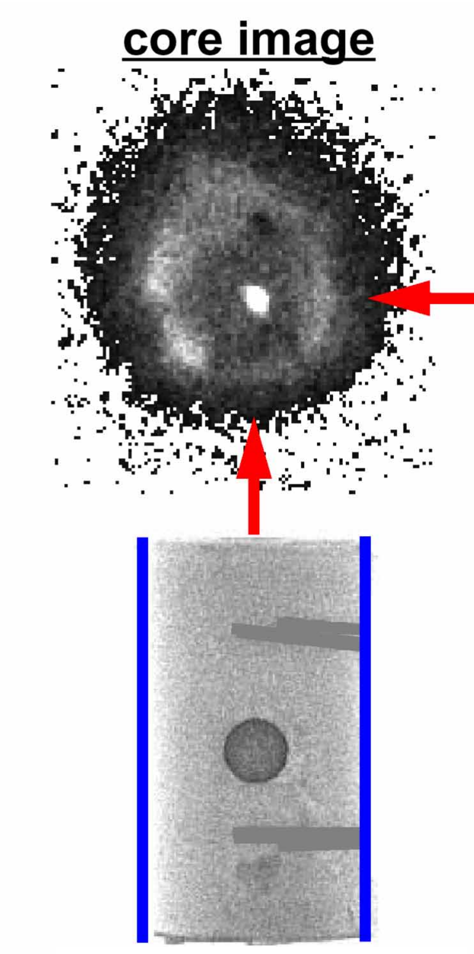
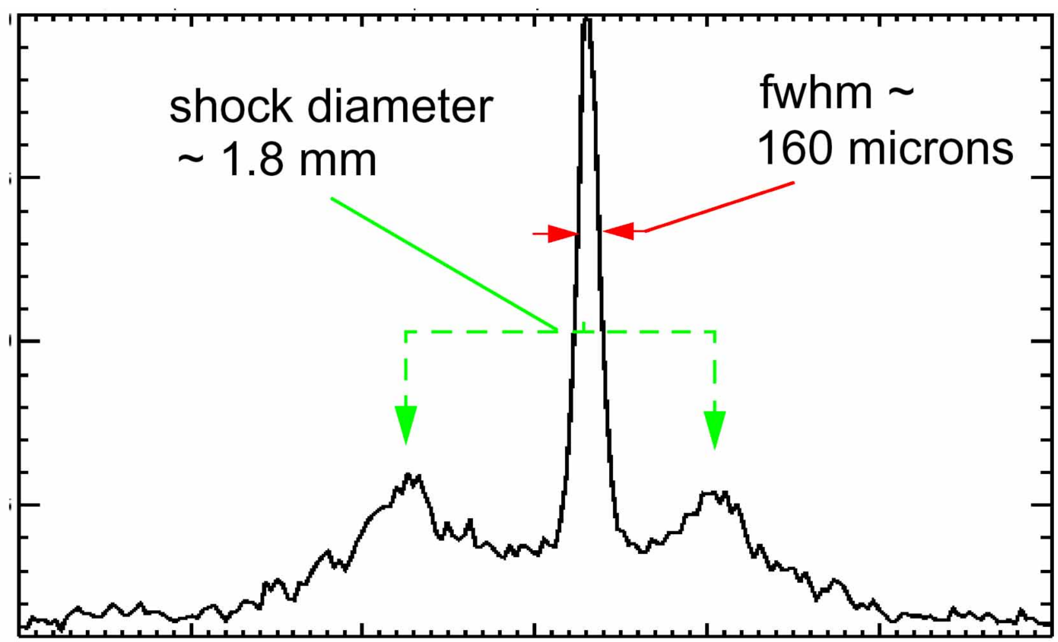
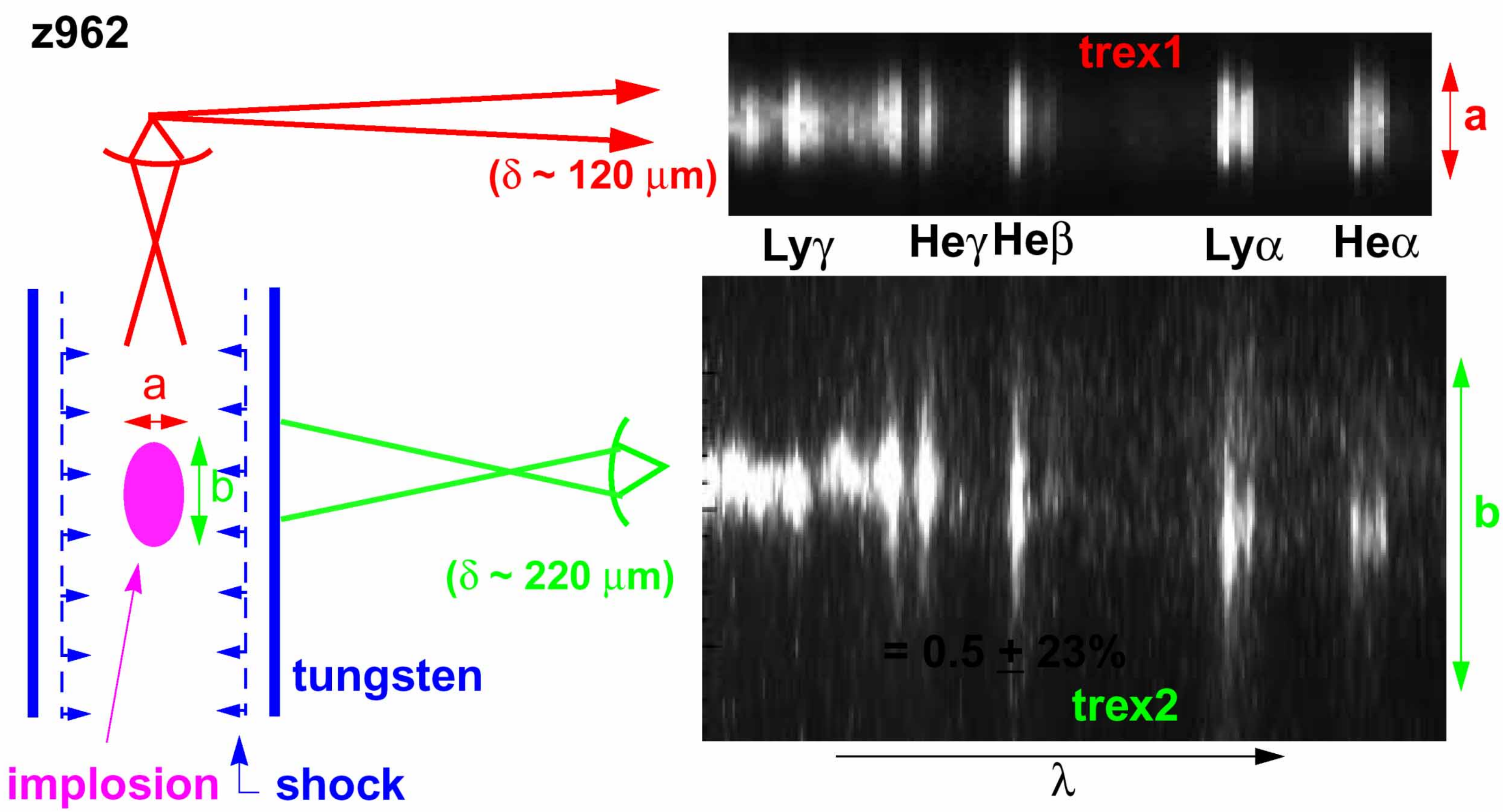
Time-resolved x-ray images demonstrate the capsule implosion is radiation driven





- **The implosion for this 40-μm-wall capsule occurs 2-3 nsec prior to shock reaching axis**
- **implosion image is simultaneous with spectrum**

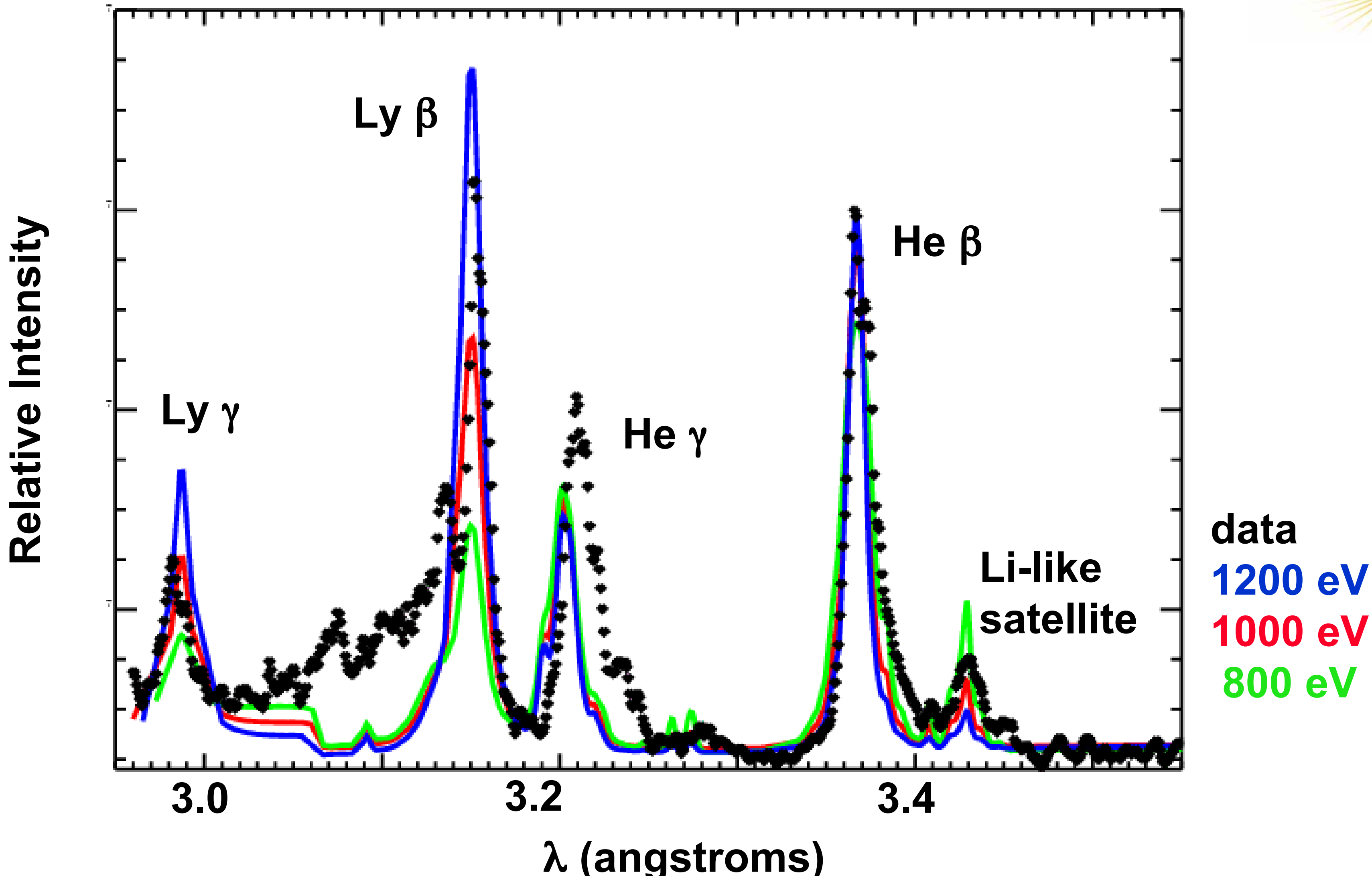
Initial time-resolved tomographic spectroscopy measurements have been performed



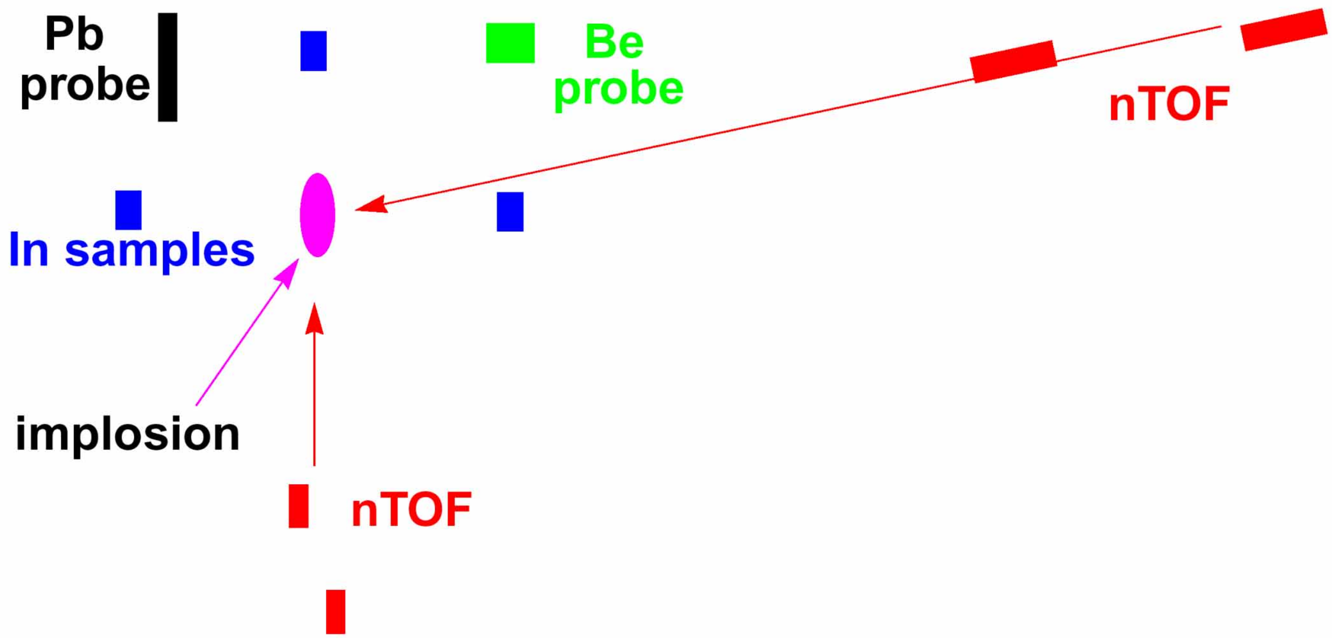
Spatial resolution was improved to 85 μm and 155 μm for the TREX1 and TREX2 spectrometers (Jan. 2003)

A third TREX (side view, radial resolution) is being fabricated

For shot z860 the electron temperature measured with line intensity ratios was ~ 1 keV at an electron density of 2 x 10^{23} cm^{-3} deduced from Stark broadening



Schematic of the neutron diagnostic arrangement used in these capsule experiments is shown here



Neutron yield measurements are a pre-requisite to extracting implosion physics from advanced neutron diagnostics

(ion temperature, bang time, shell and fuel ρr)

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A heavy Pb shield (9000 lbs.) and collimator is required for neutron time-of-flight measurements on Z

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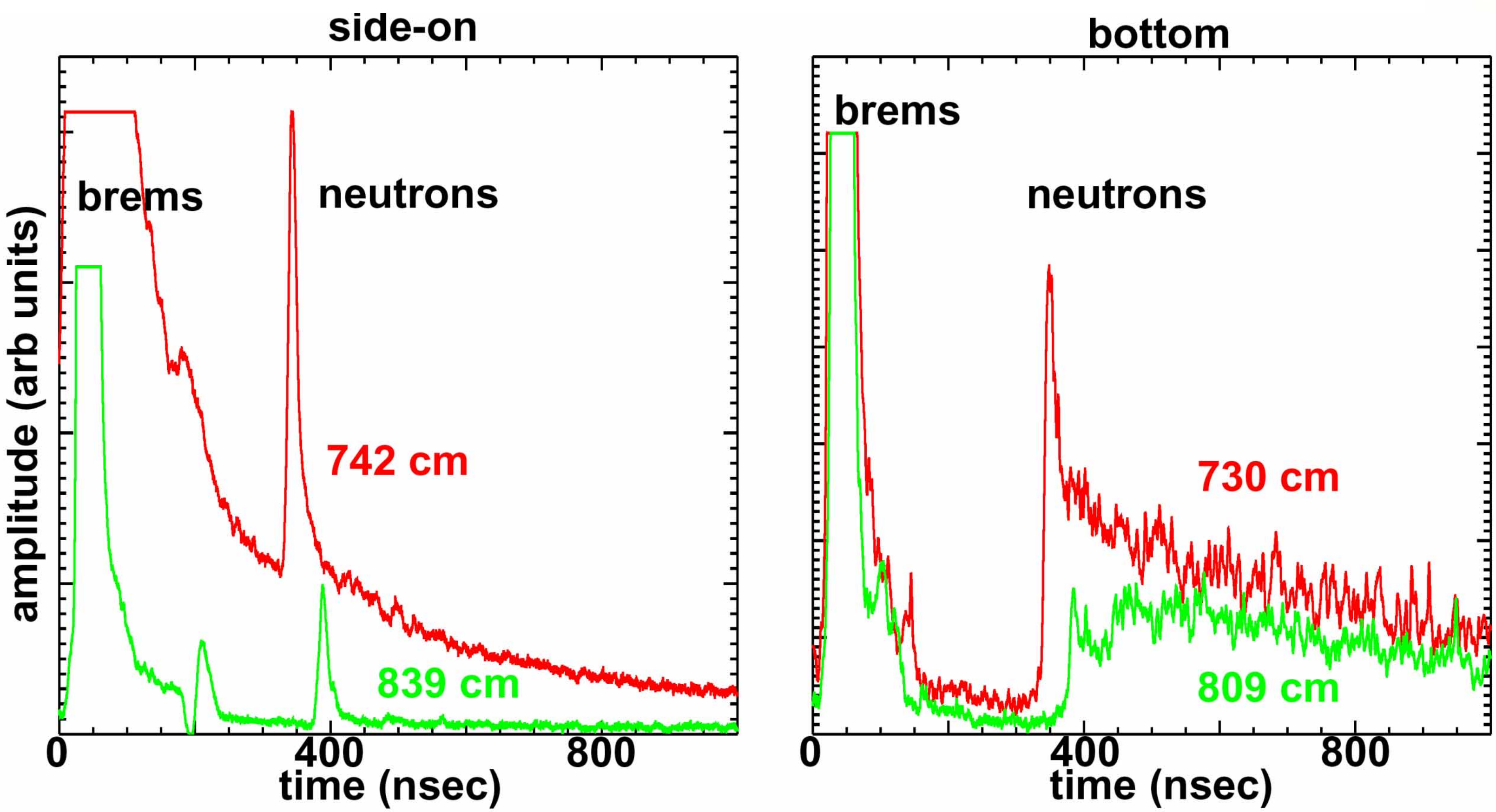
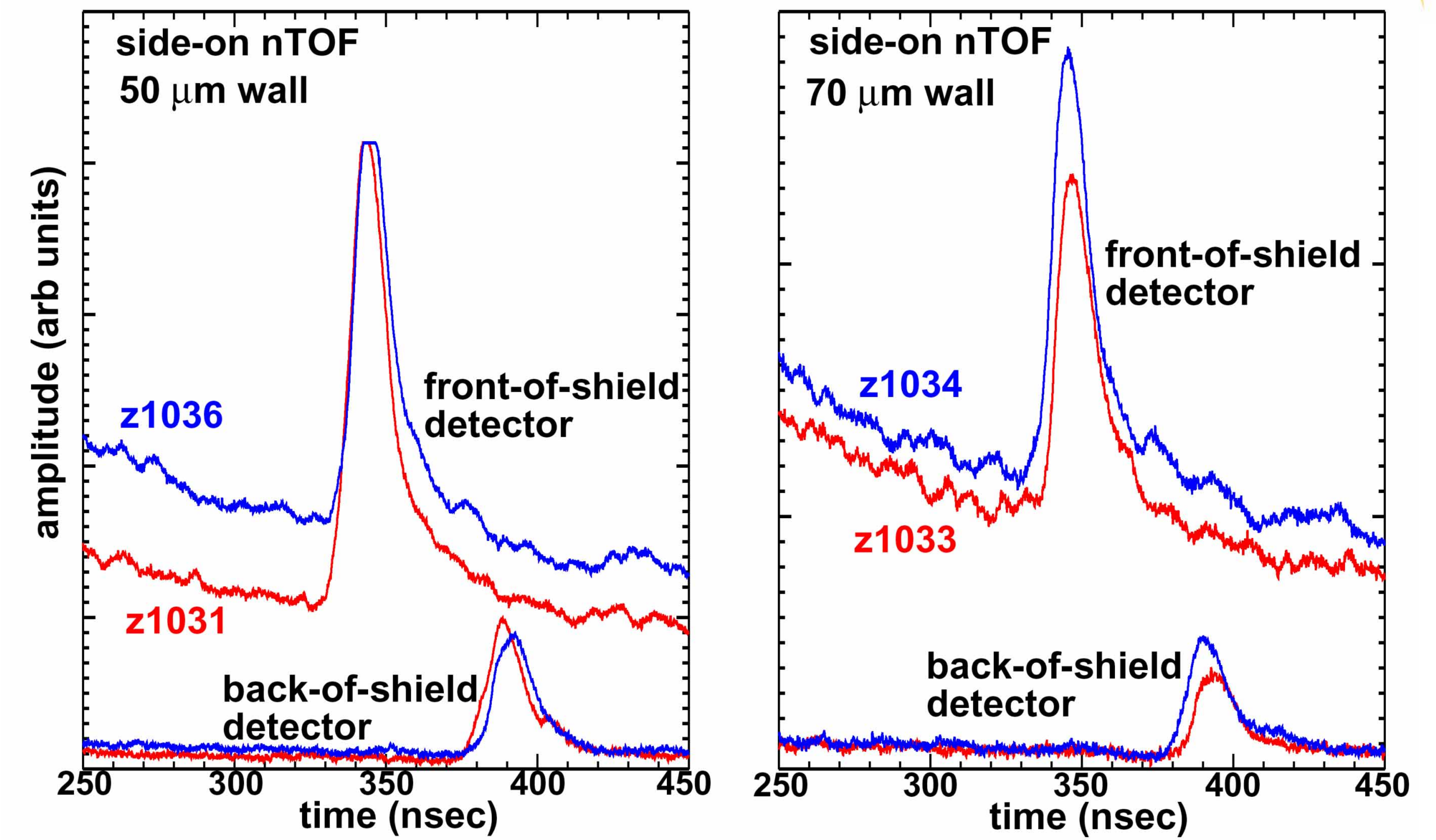
Fast signals are detected on both side-on and bottom neutron time-of-flight detectors



data is from z1031, 50 μm CH wall, 2 mm diameter
24 atm D2 + 0.085 atm Ar

The neutron time-of-flight signals exhibit respectable reproducibility



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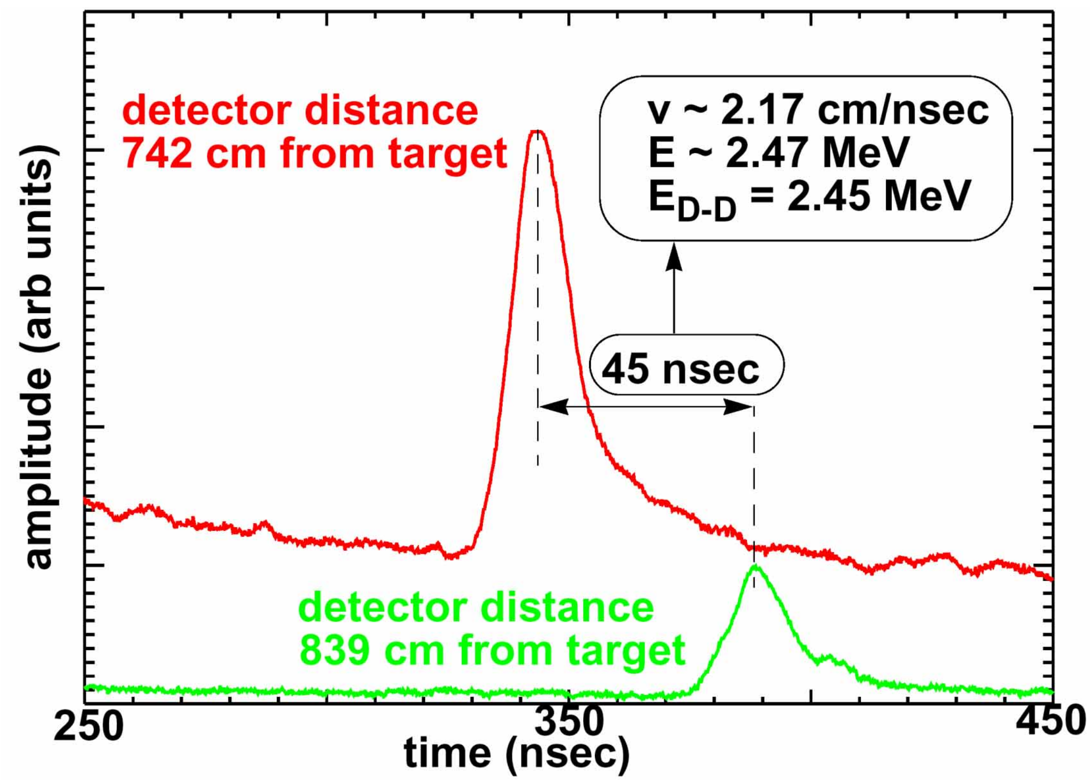
The neutron energy and yield are consistent with thermonuclear production



data is from z1031

50 μm CH wall,
2 mm diameter
24 atm D2 + 0.085 atm Ar

side-on detectors

- Measured neutron energy from two side-on detectors for z1031 was 2.47 ± 0.12 MeV
- Measured neutron energy from two bottom detectors for z1031 was 2.56 ± 0.13 MeV
- Neutron yield (Shot z1031) of (2.6 ± 1.3) $\times 10^{10}$ measured with In activation is consistent with calculated mass averaged T_i yield of ~2×10^{10}; 1-D predicted clean yield was ~ 2×10^{11}

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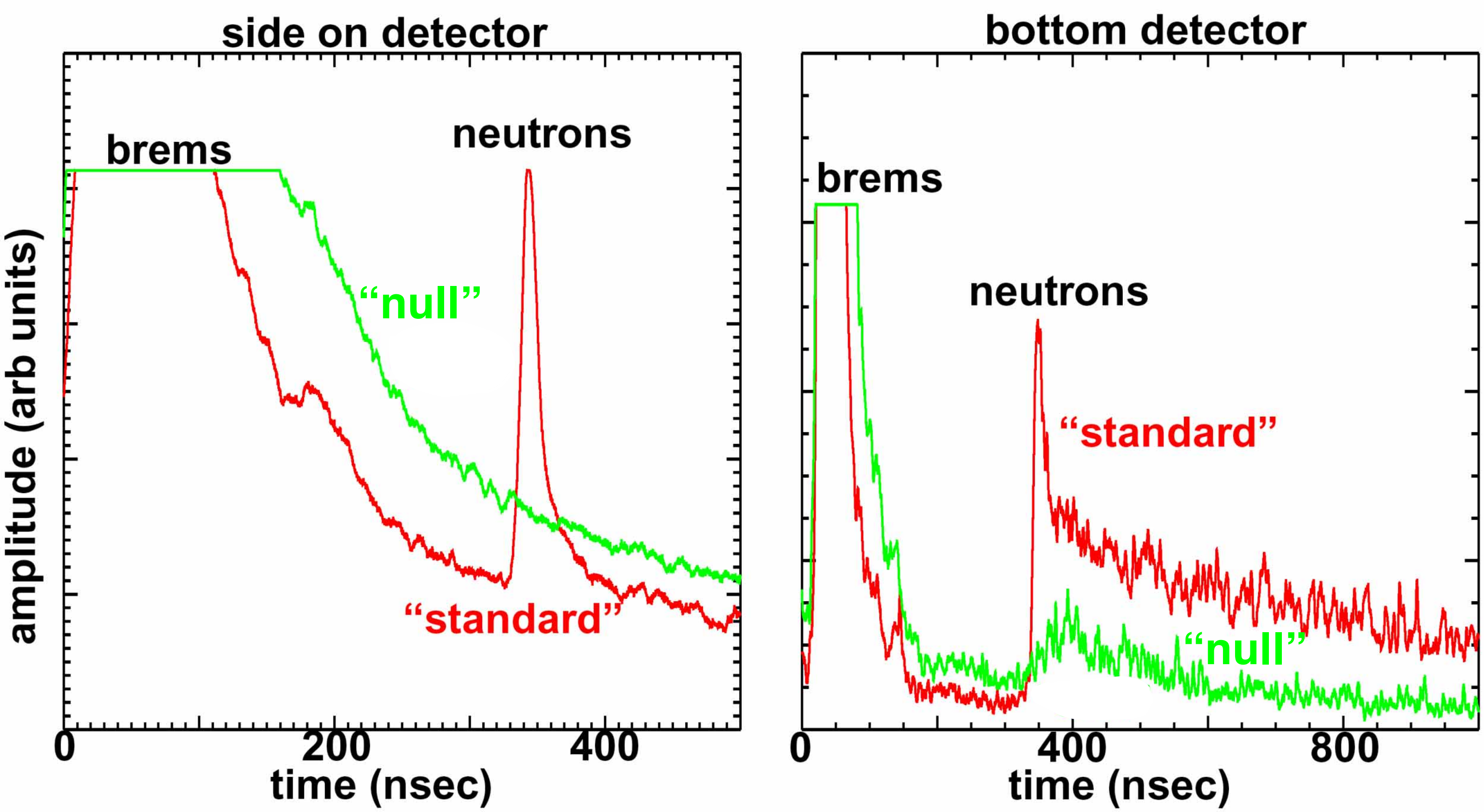
Neutron time-of-flight signal dramatically decreases when Xe fill gas is added to "null" the production of thermonuclear neutrons



z1031"standard" fill(24 atm D2 + 0.085 atm Ar)
z1032"standard" fill + 0.6 atm Xe

- On "null shots," neutron yield measured by Be activation decreased by more than an order of magnitude

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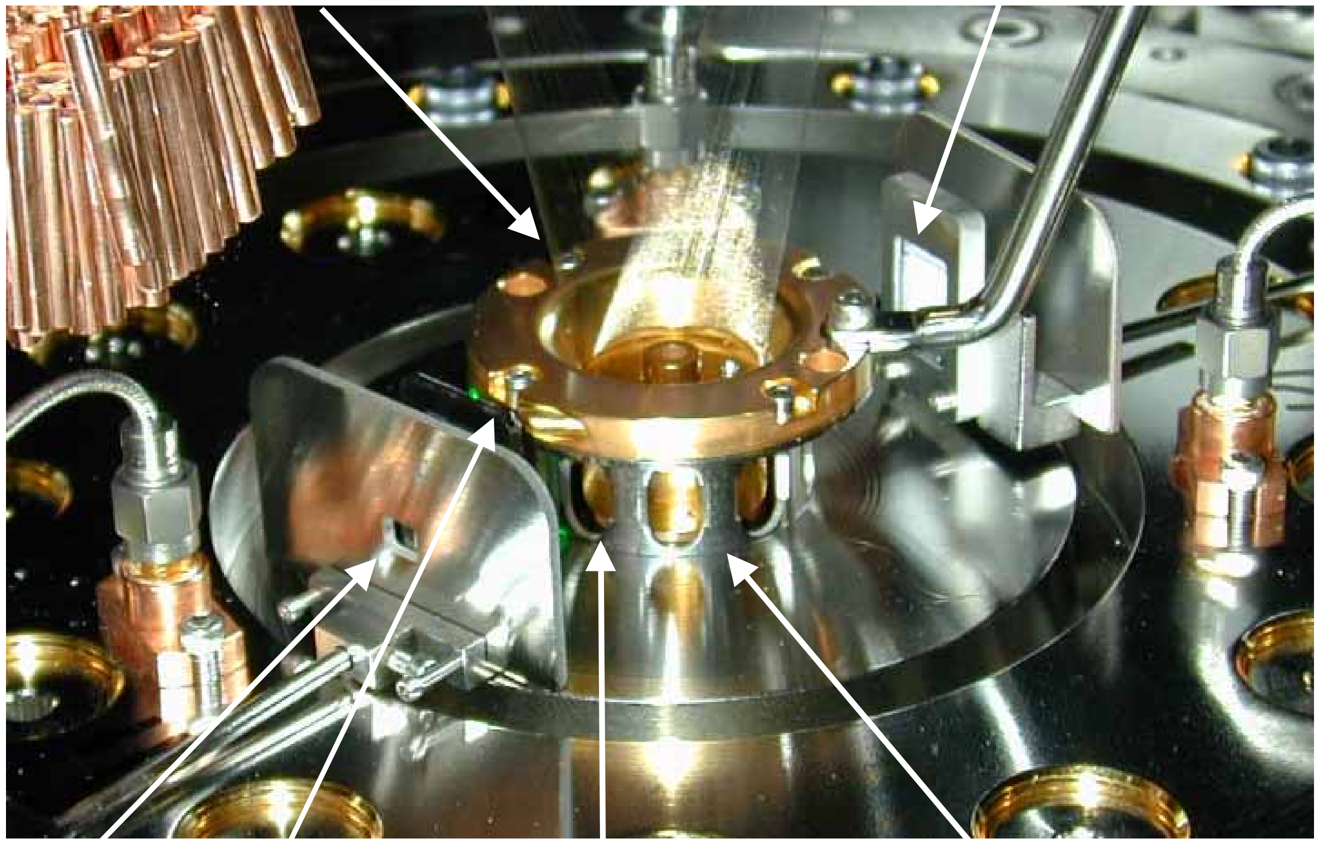
The evidence of thermonuclear neutron production in Z dynamic hohlraum experiments is convincing

- On "null shots" doped with 0.6 atm Xe gas, the fast neutron time-of-flight signal is substantially reduced on both side-on and bottom detectors in agreement with expectations from calculations
- On "null shots", the neutron yield decreased by more than an order of magnitude as measured by the Be activation detector in agreement with an expected decrease by a factor of ~ 20 from calculations
  - Any neutron yield from beam target interactions is at the level of the "null shots"
- On "null shots", Ar spectroscopy lines are not detected indicating a plasma of a much lower temperature in agreement with calculations that predict an electron temperature of 450 eV
- Measured neutron energy (Shot z1031) from side-on detectors was 2.47 ± 0.12 MeV and from the bottom detectors was 2.56 ± 0.13 MeV
  - If beam target interactions were responsible for the production of these neutrons, one would expect a shift in the neutron energy along the direction of the beam due to reaction kinematics
- The neutron yield (Shot z1031) measured by averaging the In activation detectors was $(2.6 \pm 1.3) \times 10^{10}$ to be compared to the calculated 1D clean yield of 2×10^{11}; 2D effects are expected to decrease this calculated yield by a factor of ~ 3-10

In the z-pinch geometry, many basic opacity and/or radiation science experiments can be conducted on a single shot

- Pinch x-rays both heat and backlight the sample
- The broad pinch x-ray spectrum backlights multiple elements over many nanoseconds
- Long pulse duration
- Multiple samples on a single shot
- Centimeter-scale samples



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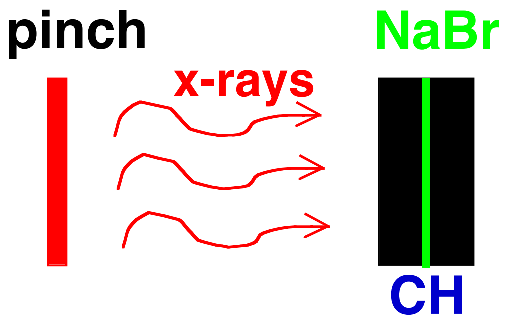
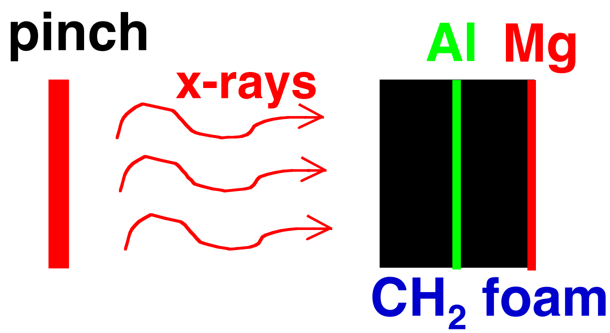
Such experiments have already been used to address a variety of radiation science issues



Opacity Measurements

- Na acts as a “thermometer”
- Measure open M-shell Br opacity under known T_e, n_e conditions

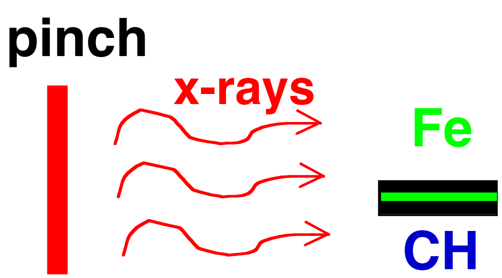
* J. E. Bailey et al., submitted to JQSRT (Jan. 2002)



Radiative Transfer Experiments

- Al and Mg provide Te (x, t)
- Infer radiation propagation through foam sample

* G. A. Rochau et al., Proceedings HTPD (2002)



Photoionization Measurements

- Fe ionization states probed by absorption and emission lines
- Infer photoionization in Fe

* R. F. Heeter et al., Rev. Sci. Instr. 72, 1224 (2001)
* R. F. Heeter et al., Proceedings ADNXA (2000)

Summary

- Indirect drive inertial confinement fusion employs hohlraums to drive capsule implosions
- These hohlraums may be driven by a variety of soft x-ray radiation sources that includes lasers, heavy ion beams, and z-pinches
- Capsule symmetry in double-ended z-pinch hohlraums can be controlled and diagnosed at the few per cent level
- Radiation drive temperatures T_r of ~ 200 eV have been achieved in dynamic hohlraum experiments on Z
  - This dynamic hohlraum drive delivers ~ 24 kJ absorbed energy to a 2-mm diameter, 50-μm-thick CH wall capsule
- From Ar emission spectroscopy, core electron temperatures of ~ 1000 eV and core electron densities of ~ 2 x 10^{23} cm^{-3} have been measured in Z dynamic hohlraum capsule experiments
- For the first time on a pulsed-power-driven facility, ~ 2 x 10^{10} thermonuclear neutrons have been produced in Z dynamic hohlraum experiments
- A large variety of fundamental radiation science experiments are being conducted on Z that include opacity, radiative transfer, and photoionization measurements

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