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

Presented at:
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Outline of the presentation

- Introduction to the hohlraum concept
- Description of Sandia National Laboratories’ Z facility
- 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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<tr>
<td>R. G. Adams</td>
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<td>J. E. Bailey</td>
<td>C. L. Ruiz</td>
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<td>G. R. Bennett</td>
<td>T. W. L. Sanford</td>
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<td>M. E. Cuneo</td>
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<td>J. S. Lash</td>
<td>R. A. Vesey</td>
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<td>R. W. Lemke</td>
<td>D. F. Wenger</td>
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<td>M. K. Matzen</td>
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<td>T. A. Mehlhorn</td>
<td>Bechtel Nevada-Neutron Detectors</td>
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<tr>
<td>T. J. Nash</td>
<td>Cornell University-Z pinch Physics</td>
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<tr>
<td>J. L. Porter</td>
<td>General Atomics Corporation-Targets</td>
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<tr>
<td>P. K. Rambo</td>
<td>Imperial College-Z pinch Physics</td>
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<td>G. E. Rochau</td>
<td>Schaffer Corporation-Targets</td>
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In contrast to direct drive ICF, in indirect drive ICF the capsule is driven by soft x-rays generated in a hohlraum.

**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 $\alpha$ is the wall albedo.
  
  - For a 200 eV Au wall hohlraum, a typical value of $\alpha$ 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.
Pulsed-power accelerators with z-pinch loads provide efficient time compression and power amplification.

Target Chamber

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

- Two 60 MA pinches
- 380 MJ yield

- 54 MA pinch
- 530 MJ yield

Key issues:
- Hohlraum energetics
- Radiation symmetry
- Pulseshaping
- Preheat
- Capsule implosions
Increasing number of wires greatly increased x-ray power and the application on Z lead to a renaissance in z-pinch physics.

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

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.

Example images of capsules driven by a dominant $P_2$ asymmetry:

- $P_2$ equator-hot
- $P_2$ 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-pinched plasma impacts foam converter
- The impact launches shocks in foam & W
- The foam shock is a main radiation source
- The z-pinched 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
Hohlraum drive temperatures above 200 eV were measured for the Z dynamic hohlraum.
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

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

Imploded core (side-on image through pinch)

argon emission from ICF capsule

core $T_e \sim 1000\,\text{eV}$
$n_e \sim 2 \times 10^{23}\,\text{cm}^{-3}$

Wires

2.0 mm diameter, 50 μm CH wall D₂-filled capsule embedded in 14 mg/cc CH₂ foam
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.

Shock diameter: ≈ 1.8 mm

FWHM: ≈ 160 microns

200 eV hohlraum
Initial time-resolved tomographic spectroscopy measurements have been performed.

Spatial resolution was improved to 85 μm and 155 μm for the TREA1 and TREA2 spectrometers (Jan. 2003)
A third TREA (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 $2 \times 10^{23}$ 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 $\rho r$)
A heavy Pb shield (9000 lbs.) and collimator is required for neutron time-of-flight measurements on Z
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.
The neutron energy and yield are consistent with thermonuclear production

- Measured neutron energy from two side-on detectors for z1031 was $2.47 \pm 0.12$ MeV
- Measured neutron energy from two bottom detectors for z1031 was $2.56 \pm 0.13$ MeV
- Neutron yield (Shot z1031) of $(2.6 \pm 1.3) \times 10^{10}$ measured with In activation is consistent with calculated mass averaged $T_i$ yield of $\sim 2 \times 10^{10}$; 1-D predicted clean yield was $\sim 2 \times 10^{11}$
Neutron time-of-flight signal dramatically decreases when Xe fill gas is added to “null” the production of thermonuclear neutrons.

On “null shots,” neutron yield measured by Be activation decreased by more than an order of magnitude.

- z1031 “standard” fill (24 atm D2 + 0.085 atm Ar)
- z1032 “standard” fill + 0.6 atm Xe
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 $(2.6 ± 1.3) \times 10^{10}$ to be compared to the calculated 1D clean yield of $2 \times 10^{11}$; 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
Such experiments have already been used to address a variety of radiation science issues

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**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)

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**Radiative Transfer Experiments**
- Al and Mg provide $T_e (x, t)$
- Infer radiation propagation through foam sample

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**Photoionization Measurements**
- Fe ionization states probed by absorption and emission lines
- Infer photoionization in Fe
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 $\sim 200$ eV have been achieved in dynamic hohlraum experiments on Z
  – This dynamic hohlraum drive delivers $\sim 24$ kJ absorbed energy to a 2-mm diameter, 50-µm-thick CH wall capsule
• From Ar emission spectroscopy, core electron temperatures of $\sim 1000$ eV and core electron densities of $\sim 2 \times 10^{23}$ cm$^{-3}$ have been measured in Z dynamic hohlraum capsule experiments
• For the first time on a pulsed-power-driven facility, $\sim 2 \times 10^{10}$ 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