Z-Pinch Inertial Fusion Energy

Capsule compression experiments on Z
Z-Pinch Power Plant Chamber
Repetitive Driver LTD Technology

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Vienna, Austria
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Why Z-Pinch IFE?

**x-rays:** 1.8 MJ of x-rays on Z (demonstrated) available now

**low cost:** $30/J for ZR (demonstrated cost)
   $17/J goal for X-1 high yield study (1999)

**high efficiency:** wall plug to x-rays: ~15% on Z (demonstrated)
   can be optimized to: ~25% or more

**capsule compression experiments on Z:** (demonstrated)
   - double-pinchant hohlraum\(^1\): \(\text{Cr} \approx 14-20\), symmetry ~3%
   - dynamic hohlraum\(^2\): \(\sim 24 \text{ kJ x-rays absorbed, Cr} \approx 10\), DD neutrons
   - hemisphere compression for fast ignition\(^3\): \(\text{Cr} \approx 2\)


**repetitive pulsed power:**
   - RHEPP magnetic switching technology:
     2.5 kJ @ 120 Hz (300 kW ave. pwr. demonstrated)
   - LTD (linear transformer driver) technology:
     being developed (compact, direct, simple)
The long-range goal of Z-Pinch IFE is to produce an economically-attractive power plant using high-yield z-pinch-driven targets (∼3 GJ) at low rep-rate (∼0.1 Hz)

Z-Pinch IFE DEMO (ZP-3, the first study) used 12 chambers, each with 3 GJ at 0.1 Hz, to produce 1000 MWe
### Z-Pinch IFE Matrix of Possibilities

 чувство one from each category

<table>
<thead>
<tr>
<th>Z-Pinch Driver:</th>
<th>Marx generator/ water line technology</th>
<th>magnetic switching (RHEPP technology)</th>
<th>linear transformer driver (LTD technology)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTL (Recyclable Transmission Line):</td>
<td>Flibe/electrical coating</td>
<td>immiscible material (e.g., low activation ferritic steel)</td>
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<tr>
<td>Target:</td>
<td>double-pincho dynamic hohlraum fast ignition</td>
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<tr>
<td>Chamber:</td>
<td>dry-wall wetted-wall thick-liquid wall solid/voids (e.g., Flibe foam)</td>
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Z-Pinch Driver
Pulsed-power provides compact, efficient time compression and power amplification.

Electrical to x-ray energy
Conversion efficiency > 15%
Z-pinches offer the promise of a cost-effective energy-rich source of x-rays for IFE.

\[ E_k = \sqrt{3} L_p \frac{\mu_0}{4\pi} I_0^2 \]

ZR will be within a factor of 2-3 in current (4-9 in energy) of a High Yield driver.
Z-Pinch IFE Development Path

Facilities

- HY
- Baikal (Russia, proposed)
- EMIR (Russia, proposed)
- ZR
- Z
- Saturn
- Angara-5 (Russia)
- DEMO (~90 MA)
- ETF (~60 MA)
- IRE (10 MA)
- PoP (1 MA)
- RHEPP II

X-Ray Energy per Shot

Repetition Rate (Hz)
RTL
(Recyclable Transmission Line)
Z-pinch power plant chamber uses an RTL (Recyclable Transmission Line) to provide the standoff between the driver and the target.

Yield and Rep-Rate: few GJ every 3-10 seconds per chamber (0.1 Hz - 0.3 Hz)
Thick liquid wall chamber: only one opening (at top) for driver; nominal pressure (10-20 Torr)
Flibe absorbs neutron energy, breeds tritium, shields structural wall from neutrons
Eliminates problems of final optic, pointing and tracking N beams, high speed target injection
Requires development of RTL
RTL replacement requires only modest acceleration for IFE

\[
L = 0.5 a t^2, \text{ or } a \sim \frac{1}{t^2}
\]

Acceleration is \(10^4\) less than for IFE target injection for ions or lasers.
<table>
<thead>
<tr>
<th>RTL Research in last 3 years</th>
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<tbody>
<tr>
<td>RTL electrical turn-on</td>
<td><strong>Saturn experiments</strong> (2000) &lt;br&gt;tin, Al, stainless-steel all show negligible losses</td>
</tr>
<tr>
<td>RTL low-mass and electrical conductivity</td>
<td><strong>Saturn experiments</strong> (2001) &lt;br&gt;20(\mu) mylar; 50(\mu), 100(\mu), 250(\mu) steel &lt;br&gt;RTL mass could be as low as 2 kg &lt;br&gt;RTL mass ~ 50 kg has low resistive losses</td>
</tr>
<tr>
<td>RTL structural</td>
<td><strong>Calculations (U. Wisconsin)</strong> (2002) &lt;br&gt;full-scale RTL (~50 kg) of 25 mill steel ok for background pressure ~ 10-20 Torr</td>
</tr>
<tr>
<td>RTL manufacturing</td>
<td>(allowed RTL budget is a few $ for 3 GJ) &lt;br&gt;Flibe casting (<del>$0.70/RTL) &lt;br&gt;ferritic steel stamping (</del> $1.20-3.95/RTL)</td>
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</table>
Targets
Z-pinch-driven-hohlraums have similar topology to laser-driven-hohlraums, but larger scale-size.
The baseline DEH capsule yields 380 MJ with an ignition margin similar to a NIF capsule.

Capsule Performance Parameters

- Peak drive temperature: 223 eV
- In-flight aspect ratio: 37
- Implosion velocity: 2.9 x 10^7 cm/s
- Convergence ratio: 36
- Total RT growth factor: 420
- Peak density: 750 g/cm^3
- Total \( \rho_r \): 3.15 g/cm^2
- Driver energy: 16 MJ
- Absorbed energy: 1.12 MJ
- Yield: 380 MJ
- Burnup fraction: 31%

J.H. Hammer, et al., Phys Plasmas 6, 2129
Summary – Double-ended hohlraum ICF status

- Simulation codes and analytic modeling have been validated by measurements of time-dependent z-pinch x-ray production, z-pinch hohlraum temperatures, and capsule hohlraum temperatures.

- A reproducible, single power feed, double z-pinch radiation source with excellent power balance has been developed for ICF capsule implosion studies.

- The Z-Beamlet Laser (ZBL) is routinely used as an x-ray backlighter at x-ray energies up to 6.75 keV.

- Capsule symmetry (P2 and P4) in double-pinch hohlraums on Z can be systematically controlled with demonstrated time-integrated symmetry of $\leq 3\%$.

- Optimum hohlraums on Z should produce time-integrated radiation symmetry of $\leq 1\%$ for 5 mm diameter capsules and absorbed energies of 25 kJ.

- P4 shimming shots are scheduled in collaboration with LLNL and LBL HIF program.
Double-Ended Hohlraum Concept
Publications

**Concept**

**Hohlraum energetics**
Cuneo, Vesey, Porter et al., Phys. Plas. 8, 2257 (2001)
Cuneo, Vesey, Hammer et al., Laser Particle Beams, 19, 481 (2001)

**Foam ball radiation symmetry**
Hanson, Vesey, Cuneo et al., Phys. Plas. 9, 2173 (2002)

**Double pinch performance**

**Symmetric capsule implosions**
Bennett, Vesey, Cuneo et al., Phys. Plasmas (in press)

**Symmetry control**

**Pinch physics**
Stygar, Ives, Fehl, Cuneo et al., submitted to Phys. Rev. E
Waisman, Cuneo, Stygar et al., in preparation for Phys. Plasmas
The initial dynamic hohlraum high yield integrated target design produces a 527 MJ yield at 54 MA

Capsule Performance Parameters

- Peak drive temperature: 350 eV
- In-flight aspect ratio: 48
- Implosion velocity: $3.3 \times 10^7$ cm/s
- Convergence ratio: 27
- DT KE @ ignition: 50%
- Peak density: 444 g/cm$^3$
- Total $\rho r$: 2.14 g/cm$^2$
- Driver energy: 12 MJ
- Absorbed energy: 2.3 MJ
- Yield: 527 MJ
- Burnup fraction: 34%

J.S. Lash et al., *Inertial Fusion Sciences & Apps* 99, p583
Summary – Dynamic Hohlraum ICF status

• The primary radiation source is a thin radiating shock in the foam converter
• Demonstrated >200 eV x-ray drive temperatures in dynamic hohlraums on Z
• Measured $T_e \sim 1$ keV, $n_e \sim 1 \times 10^{23}$ from Ar K-shell spectra from imploded capsules
• Measured $2.6 \pm 1.3 \times 10^{10}$ thermonuclear D-D neutrons from ICF capsules absorbing >20 kJ
Dynamic Hohlraum Concept Publications

• Concept
  – Lash IFSA publication

• Energetics
  – publication on shock and temperature

• Temperature of imploded capsule core
  – publication on Ar spectra and temperature

• Neutron production
  – publication on neutron yield
Code calculations and analytic scaling predict z-pinch driver requirements for IFE DEMO

<table>
<thead>
<tr>
<th>Double-Pinch Hohlraum</th>
<th>current /x-rays $E_{\text{abs}}$ / yield</th>
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<tr>
<td></td>
<td>2 x 62-68 MA</td>
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<tr>
<td></td>
<td>2 x (16-19) MJ</td>
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<td></td>
<td>1.3 – 2.6 MJ</td>
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<td>400 – 4000 MJ</td>
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<table>
<thead>
<tr>
<th>Dynamic Hohlraum</th>
<th>current /x-rays $E_{\text{abs}}$ / yield</th>
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<tr>
<td></td>
<td>54 – 95 MA</td>
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<tr>
<td></td>
<td>12-37 MJ</td>
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<td>2.4 – 7.2 MJ</td>
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<td>530 – 4400 MJ</td>
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Based on these results, an IFE target for DEMO will require:

- **double-pinch hohlraum**
  - 36 MJ of x-rays (2x66MA)
  - 3000 MJ yield
  - (G = 83)

- **dynamic hohlraum**
  - 30 MJ of x-rays (86 MA)
  - 3000 MJ yield
  - (G = 100)

J. Hammer, M. Tabak, R. Vesey, S. Slutz, J. De Groot
Chambers/Power Plant
### Z-Pinch IFE and Heavy Ion IFE use thick liquid walls

Z-Pinches use simple waterfalls with a pressure requirement of 10-20 Torr.

#### Major drivers:

<table>
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<tr>
<th>Laser (KrF, DPSSL)</th>
<th>Heavy ion (induction linac)</th>
<th>Z-pinch (pulsed power)</th>
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<tr>
<td>GeV, kA</td>
<td>MV, MA</td>
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</table>

#### Targets:

| Direct-drive | Indirect-drive | Fast Igniter option (major driver + PW laser) |

#### Chambers:

| Dry-wall | Wetted-wall | Thick-liquid wall | Solid/voids |

Thick liquid walls essentially alleviate the “first wall” problem, and can lead to a faster development path.
Z-IFE DEMO produces 1000 MWe

**DEMO parameters:**

- yield/pulse: 3 GJ
- driver x-rays/pulse (86 MA) 30 MJ
- energy recovery factor: 80%
- thermal recovery/pulse: 2.4 GJ
- time between pulses/chamber: 3 seconds
- thermal power/unit 0.8 GWt
- thermal conversion efficiency 45%
- electrical output/unit 0.36 GWe
- number of units 3
- total plant power output 1.0 GWe

**Major cost elements:**

- LTD z-pinch drivers (3) $900 M
- RTL factory $500 M
- Target factory $350 M
- Balance of Plant $900 M
- Total Cost $2.65 G

ZP-3 (the first study) used 12 chambers, each with 3 GJ at 0.1 Hz

**Z-Pinch power plant studies:**

Z-Pinch IFE near-term plans
Z-IFE PoP is a set of four experiments (shown here) plus IFE target studies plus IFE Power Plant studies

**RTL experiments**
- issues: shape, inductance, mass, electrical/structural, manufacture, cost
- power flow: limits, optimal configuration, convolute location
- chamber/interface issues: vacuum/electrical, debris removal, shielding
- RTL experiment test on Z

**Repetitive driver- LTD (Linear Transformer Driver) experiment**
- 1 MA, 1 MV, 100 ns, 0.1 Hz driver design/construction/testing
- LTD is very compact (pioneered in Tomsk, Russia) no oil, no water
- LTD technology is modular, scalable, easily rep-ratable
- 1 MA, 100 kV cell is being developed this year (SNL/Tomsk)

**Shock mitigation scaled experiments**
- 3 GJ yield is larger than conventional IFE yields of 0.4-0.7 GJ
- coolant streams, or solids/voids, may be placed as close to target as desired
- shock experiments with explosives and water hydraulic flows
- validate code capabilities for modeling full driver scale yields

**Full RTL cycle @ 0.1 Hz experiment**
- integrated experiment (LTD, RTLs, z-pinch loads, 0.1 Hz)
- demonstrate RTL/z-pinch insertion, vacuum/electrical connections, firing of z-pinch,
  - removal of remnant, repeat of cycle
- z-pinches have 5 kJ x-ray output per shot

Cost: $14M/year for 3-5 years, $5M for FY04 to start