Status of Z-Pinch Research

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.
Outline

• Status of Z-pinch IFE
  – No funding; IFE science and technology research “on hold”

• Update on refurbished Z

• Update on pulsed power ICF

• Advances in pulsed power technology

Z is focused on single-shot ICF & HED research; fusion energy is the goal
The Z-pinch IFE concept uses low rep-rate recyclable transmission lines, high yield targets, thick liquid walls
Many of the important issues and systems have been studied within the Z-IFE program.

A pre-conceptual Z-pinch power plant design has established baseline parameters:

1. **Recyclable Transmission Lines (RTLs)**
   - Simulations (> 5 MA/cm works)
   - Experiments (> 5 MA/cm works)
   - Fabrication of PoP-size RTLs and pressure testing

2. **LTD repetitive driver**
   - 0.5 MA, 100 kV LTD cavity fires every 10 seconds
   - 1.0 MA, 100 kV LTD cavities (5) voltage-adder tests
   - Full IFE driver architectures

3. **Shock mitigation**
   - Theory/simulations
   - Experiments: water ring/explosives foamed liquids shock tube/foams

4. **Z-PoP planning**
   - Vacuum/electrical connections
   - Overhead automation animations
   - Costing

5. **Z-IFE targets for 3 GJ yields**
   - Gains ~ 50-100
   - Double-pinch/dynamic hohlraum
   - Scaling studies

6. **Z-IFE power Plant**
   - RTL manufacturing/costing
   - Wall activation studies: 40 year lifetime
   - Power plant design +GNEP, transmutation

*Results documented on 3 CDs*
Sandia’s ITER activities are within the Pulsed Power Sciences Center

*The US is providing 20% of ITER’s first wall modules and two port limiters*

**Sandia’s role:**
- lead design and R&D
- develop US industrial team
- perform R&D on joining of Be & evaluate performance at the PMTF facility
- develop QA procedures and test FW panels

**Cooled port limiters**
- Retractable, Be/Cu armor, articulation

**First Wall modules**
- Shield blocks (90)
- FW panels (360)
Outline

• Status of Z-pinch IFE

• Update on refurbished Z
  – Project completed in September
  – Have delivered 26 MA to ICE load

• Update on pulsed power ICF

• Advances in pulsed power technology
The \textbf{Z} Refurbishment Project Concluded in Sep ’07

14 Month Facility Outage

- Last Shot Old \textbf{Z}
  - July ’06

- Demolition Completed
  - Sept ’06

- Tank Modifications Completed
  - Jan ’07

- Center Section Installed
  - July ’07

- Installation Completed
  - Aug ’07

- First System Test – New \textbf{Z}
  - Sept ’07
Z-shot #1775 achieved a load current of 26.4 MA

The measured load current is slightly higher than the MITL current, and the MITL is slightly higher than the stack, as expected.

<table>
<thead>
<tr>
<th>Z-shot number</th>
<th>Marx-Charge voltage</th>
<th>Peak load current</th>
</tr>
</thead>
<tbody>
<tr>
<td>1770</td>
<td>70 kV</td>
<td>20.6 MA</td>
</tr>
<tr>
<td>1772</td>
<td>75 kV</td>
<td>22.8 MA</td>
</tr>
<tr>
<td>1773</td>
<td>80 kV</td>
<td>23.8 MA</td>
</tr>
<tr>
<td>1774</td>
<td>85 kV</td>
<td>25.6 MA</td>
</tr>
<tr>
<td>1775</td>
<td>90 kV</td>
<td>26.4 MA</td>
</tr>
</tbody>
</table>
Experimental benefits of Refurbished Z

Precision & pulse flexibility will enable:
- New experimental regimes
- Improved timing with Z Backlighter & Z Petawatt

More current than on Z will enable up to:
- 50% increase – x-ray power radiated
- 70% increase – x-ray energy radiated
- 15-20% increase - temperature
- 3x increase - peak ICE pressure
- 40% increase - flyer plate velocity
Z-Petawatt will enable high photon energy backlighting and fast ignition physics experiments on Z

**Compression chamber installation**

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**Z Backlighter**

- \( \lambda = 527 \text{ nm} \)
- June 2001:
  - \( \tau = 0.3 - 8 \text{ ns} \)
  - \( \phi \sim 75 \mu\text{m spotsize} \)
  - \( E < 2 \text{ kJ} \)
  - \( I < 10^{17} \text{ W/cm}^2 \)
- Goal in 2008
  - Multi-frame @ 6.151 keV

- \( \lambda = 1054 \text{ nm} \)
- December 2007:
  - \( \tau = 500 \text{ fs min} \)
  - \( \phi \sim 30 \mu\text{m spotsize} \)
  - \( E < 500 \text{ J} \)
  - \( I > 10^{20} \text{ W/cm}^2 \)
- Goal in 2009
  - 2 kJ/10 ps
Outline

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• Update on refurbished Z

• Update on pulsed power ICF
  – Experimentally demonstrated symmetry, pulsed shaping, energy coupling, and capsule implosions
  – Integrated 2D high fusion yield designs

• Advances in pulsed power technology
**Z and Z-Beamlet/Petawatt support a diverse research portfolio of ignition & high yield ICF options**

<table>
<thead>
<tr>
<th>Driver</th>
<th>ICF Target</th>
<th>Cryogenic</th>
<th>Non-cryogenic</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray drive</td>
<td>Hot spot ignition</td>
<td>Fast ignition</td>
<td>Double shell</td>
</tr>
<tr>
<td>Vacuum hohlraum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic hohlraum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct drive</td>
<td>Magnetic field</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The double-ended hohlraum concept separates capsule, hohlraum, and z-pinch physics issues

- Demonstrated ignition in 2D hohlraum + capsule simulations for the first time
- Robustness of 220 eV capsules is suitable for Z-pinch driven hohlraum
- Developed strategy to control time-dependent hohlraum symmetry
- Capsule absorbs 7% of the z-pinch-generated x-ray energy
The integrated target design builds on several years of validation experiments on Z.

**Double pinch development**

**Z-Backlighter development**

**Symmetry**

**Pulse shaping**

- Double pinch development
- Z-Backlighter development
- Pulse shaping
We have developed a modern high-yield target design for the z-pinch-driven double-ended hohlraum.

- Demonstrated ignition in 2D LASNEX hohlraum+capsule simulations for the first time
- Developed strategy to control time-dependent hohlraum symmetry
- Robustness of 220 eV capsules is suitable for z-pinch driven hohlraum
- Defining Z-pinch and accelerator requirements based on the capsule and hohlraum requirements
- Extending target design work to smaller scale vacuum hohlraums including advanced compact x-ray sources


2D LASNEX hohlraum + capsule simulations capture the essential physics of radiation coupling and symmetry.

log(ρ)
The current high yield target design centers around a beryllium ablator capsule with 500 MJ fusion yield.

### 1D capsule parameters

<table>
<thead>
<tr>
<th>Capsule</th>
<th>NIF Rev1</th>
<th>DEH capsule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ablator outer radius (mm)</td>
<td>1.0</td>
<td>2.65</td>
</tr>
<tr>
<td>Peak drive temperature (eV)</td>
<td>300</td>
<td>220</td>
</tr>
<tr>
<td>Ablator thickness (µm)</td>
<td>160</td>
<td>190</td>
</tr>
<tr>
<td>DT fuel thickness (µm)</td>
<td>75</td>
<td>280</td>
</tr>
<tr>
<td>DT fuel mass (mg)</td>
<td>0.15</td>
<td>4.74</td>
</tr>
<tr>
<td>Absorbed energy (MJ)</td>
<td>0.14</td>
<td>1.21</td>
</tr>
<tr>
<td>Yield (MJ)</td>
<td>13</td>
<td>520</td>
</tr>
<tr>
<td>Peak ρr (g/cm²)</td>
<td>1.9</td>
<td>3.1</td>
</tr>
<tr>
<td>Implosion velocity (cm/µs)</td>
<td>36.4</td>
<td>26.0</td>
</tr>
<tr>
<td>Fuel KE margin</td>
<td>33%</td>
<td>29%</td>
</tr>
<tr>
<td>Hot spot convergence ratio</td>
<td>36</td>
<td>34</td>
</tr>
</tbody>
</table>

¹NIF ignition point design layered Be capsule Rev 1.
Recent Publications Relevant to the Double Z-Pinch Target Design:

Issue: How well do simulations model the perturbations arising from the presence of fill tubes on inertial confinement fusion capsules?

Ignition scale capsules with multiple ignition-scale tubes attached were made and characterized.

Experiments on Z imaged the perturbation growth with ~10 µm resolution using 6.151 keV backlighting.

HYDRA simulations are within ~ 30% of the experimental measurements.

This level of agreement increases our confidence that perturbations from fill tubes will not be a problem for the first ignition experiments.
Accurate material models are critical to the success of the National Ignition Campaign.

300 eV graded-dopant Be design:

- Beryllium and diamond capsule ablators both have microstructure that could seed instabilities that would prevent ignition.
- The risk reduction strategy is to ensure that both ablators are melted, significantly reducing the seed for instabilities.
- Strong shocks, created through pulse shaping to maintain the DT on a low adiabat, can also be used to melt the beryllium and diamond ablators.
- Accurate, experimentally verified models are needed.
- NIC requested Z experiments for both beryllium and diamond to develop these models.

Sputtered Be has grains

This is predicted to be of no consequence when the Be melts.
Z answered important questions about the properties of Be and diamond for the National Ignition Campaign.

- Z data was obtained in 1 week
- Measurements on Z have an accuracy of ≤ 1%

Stress versus density for diamond

- Z data
- Pavlovskii
- Gekko
- Omega
- Luli
- QMD

QMD predicted region of melt
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• Advances in pulsed power technology
  – Demonstrated improved efficiency and reliability
Linear Transformer Drivers (LTDs) are a major advance in pulsed power technology

- Rise time $\geq 70$ nsec
- Rep rate = 1 shot every 10 seconds
- Timing jitter = 2 ns ($1\sigma$)
- Voltage and current reproducibility = 0.3% ($1\sigma$)
- Peak power = 0.1 TW
- Output energy = 11.3 kJ
- Electrical efficiency = 70%

LTD cavity

- LTDs compress stored electrical energy to the desired pulse length in a single stage
- LTDs are composed of simple modules of fast capacitors and 200-kV switches
- LTDs have an efficiency of 70% and can be fired once every 10 seconds

LTD switch
LTD capacitor

Sandia National Labor
We have developed an architecture that can be applied to the design of petawatt-class z-pinch drivers*

\[ E_{\text{stored}} = 180 \text{ MJ} \]
\[ P_{\text{electrical}} = 1050 \text{ TW} \]
\[ V = 24 \text{ MV} \]
\[ L = 29 \text{ nH} \]
\[ I = 68 \text{ MA} \]
\[ \tau_{\text{implosion}} = 95 \text{ ns} \]
\[ E_{\text{radiated}} \sim 20 \text{ MJ} \]

Diameter = 104 m

Summary

- The Z-Pinch IFE research program is presently on hold due to lack of funding.

- Integrated 2D calculations predict fusion yields in excess of 500 MJ and define the pulsed power generator design requirements for high fusion yield.

- The **Z** Refurbishment Project was completed in September and the **Z** facility has delivered over 26 MA to ICE loads.

- LTDs are a promising next generation pulsed power driver with demonstrated improvements in efficiency and reliability with the capability to be repetitively pulsed.