Fusion & High Energy Density Plasma Science Opportunities using Pulsed Power

Daniel Sinars, Sandia National Laboratories

Fusion Power Associates

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Sandia is the home of Z, the world’s largest pulsed power facility, and its adjacent multi-kJ Z-Beamlet and Z-PW lasers.
Using two HED facilities, we have demonstrated the scaling of magneto-inertial fusion over factors of 1000x in energy.
Our fusion yields have been increasing as expected with increased fuel preheating and magnetization.

Progress since 1st MagLIF in 2014
- Improved laser energy coupling from \( \sim 0.3 \text{ kJ} \) to 1.4 kJ
- Demonstrated 6x improvement in fusion performance, reaching 2.5 kJ DT-equivalent in 2018

Demonstrated platform on Omega
- Improved magnetic field strength from 9 T to 27 T
- Achieved record MIF yields on Omega of \( 5 \times 10^9 \) DD in 2018
We believe that Z is capable of producing a fusion yield of ~100 kJ DT-equivalent with MagLIF, though doing it with DT would exceed our safety thresholds for both T inventory & yield.

- 2D simulations indicate a 22+ MA and 25+ T with 6 kJ of preheat could produce ~100 kJ.
- Presently, we cannot produce these inputs simultaneously.

<table>
<thead>
<tr>
<th>Date</th>
<th>Liner</th>
<th>D2 Fill (mg/cc)</th>
<th>Current (MA)</th>
<th>Bfield (T)</th>
<th>Preheat (kJ)</th>
<th>Yield if DT fuel was used (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>AR=6</td>
<td>0.7</td>
<td>17-18</td>
<td>10</td>
<td>~0.5</td>
<td>0.2-0.4</td>
</tr>
<tr>
<td>Aug. 2018</td>
<td>AR=6</td>
<td>1.1</td>
<td>19-20</td>
<td>15</td>
<td>1-1.4</td>
<td>2.4</td>
</tr>
<tr>
<td>2020 Goal</td>
<td>TBD</td>
<td>1.5</td>
<td>20-22</td>
<td>20-30</td>
<td>2-4</td>
<td>~10</td>
</tr>
<tr>
<td>&gt;2020</td>
<td>TBD</td>
<td>1.5</td>
<td>21+</td>
<td>25+</td>
<td>6+</td>
<td>100</td>
</tr>
</tbody>
</table>

Preheat Energy = 6 kJ into 1.87 mg/cc DT

The Z facility is applied to a wide range of plasma science today, and further opportunities exist going forward.
The co-location of both laser and pulsed power facilities has been an enabling factor in our ability to do plasma science.

Developing plasma heating protocols for MagLIF.

X-ray backlighting for implosion physics.

X-ray diffraction for dynamic material science.

Over the next year, we will begin installing booster amps to bring Z-Beamlet to 6 kJ.
Today Z is routinely used to study a wide range of multi-Mbar material science questions—pulsed power can drive large samples at relevant strain rates

- **Key physics questions**
  - Role of microstructure
  - Kinetics and phase transitions
  - Strength
  - Transport properties
  - Radiation shock

Phase diagram of lithium showing a number of solid phases with a large degree of uncertainty

Image from electron backscattering diagnostic of grains in an additively-manufactured stainless steel. The different colors represent different grain orientations.

Image of Z explosive containment system used to contain debris from experiments with hazardous materials such as plutonium
Sandia and Lawrence Livermore National Laboratories are collaborating to produce record levels of >10 keV x rays. Z and NIF are developing advanced x-ray sources that provide unprecedented >10 keV yields. These x-ray sources are being used to study physics models for matter exposed to rapid, intense doses of x rays.

e.g., Studies of high-rate thermal degradation of polyethylene, where ~3 keV x-rays can heat ~100 microns of material at ~10^{12} K/s. 

Future high yield fusion facilities could provide even more powerful sources of 10-100 keV x rays.

Calculations done using MagLIF targets, but output curves are only weakly dependent on the specific target.
Some Z researchers use powerful soft x-ray sources to radiatively heat samples placed around the z-pinch up to $T_e \sim 200$ eV, allowing multiple simultaneous experiments on a Z shot.
Our radiation and materials platforms are heavily used by academic partners as part of Sandia’s Z Fundamental Science Program

- Scientists at Sandia partner with academic researchers to study cutting-edge high energy density science
- Competitive proposal process
- NNSA provides experimental time on Z, academic partners provide their own support and some equipment
- Has resulted in great science that benefits both academic and applied research efforts on Z!

Earth and super earths
Properties of minerals and metals

Jovian Planets
Water and hydrogen

Stellar physics
Fe opacity and H spectra

Photo-ionized plasmas
Range of ionization param. ξ
### Five major discoveries in Astrophysics and Planetary Science within the Z Fundamental Science Program

<table>
<thead>
<tr>
<th>Discovery</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>A higher-than-predicted measurement of iron opacity at solar interior temperatures</td>
<td>Jim Bailey, et. al., Nature 517, 14048 (2015)</td>
</tr>
<tr>
<td>Impact vaporization of planetesimal cores in the late stages of planet formation</td>
<td>Richard D. Kraus, Seth Root, et. al., Nature Geoscience, DOI:10.1038/NGEO2369 (2015)</td>
</tr>
</tbody>
</table>
We are exploring a modular architecture that might scale to 300-1000 TW and is twice as electrically efficient as Z. The architecture consists of modular components:

- **Brick** – “quantum” of the next gen systems
  - Single step pulse compression to 100 ns
  - 5.2 GW/800 J per brick
  - 100 kV per cavity

- **Cavity** – multiple bricks in parallel
  - 50 kA per brick
  - ~5 TW per module

- **Module** – multiple cavities in series
  - Linear Transformer Driver (LTD)

- **Machine** – multiple modules and levels in parallel

Next-gen machines: 20,000-200,000 bricks, 33-60 cavities/module, and 65-800 modules!

Bricks are a basis for other driver architectures, e.g., multi-MA arbitrary waveform generators for material science.

**Thor-72 (0.5 Mbar)**
- 4 MA, 200 ns
- 4,800 IMGs
- 48,000 bricks
- 800 Towers

**Thor-240 (1.2 TW, 2 Mbar)**
- 7 MA, 200 ns

**Neptune (50 TW, 20 MBar)**
- 23 MA, 750 ns
- 40-m diameter
- 4,800 IMGs
- 48,000 bricks
- 800 Towers

*Reisman et al., PRSTAB 18 (2015).*

*Stygar et al., PRSTAB 19 (2016).*
We have developed an extremely flexible pulsed power driver for materials science using cable pulser technology

- Up to 72 transit-time-isolated, independently triggered pulsed energy sources create unique pulse shapes at the load (today)
- 150-600 kbar pressures in mm-scale material samples (today)
- Recently signed a memorandum for collaborative research with UNM using this facility
LTD Cavity: We demonstrated >4000 shots over 6 months at full voltage (100 kV) with no major configuration change or component failure.

6th generation cavity

<table>
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<tr>
<th>Shots</th>
<th>Cavity Power</th>
<th>Module variation (42 cavities)</th>
<th>Variation per 100 modules (460 TW)</th>
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<tbody>
<tr>
<td>2000</td>
<td>107 ± 1.9%</td>
<td>±0.3%</td>
<td>±0.03%</td>
</tr>
<tr>
<td>3970</td>
<td>106 ± 3.2%</td>
<td>±0.5%</td>
<td>±0.05%</td>
</tr>
</tbody>
</table>


>20 years operation at 200 shots/year
We are also starting to investigate driver-target coupling physics, which is an uncertainty in going to larger machines.

Example driver uncertainties:
- Electrode plasma formation/expansion
- Current loss

Inertial Confinement Fusion Ignition
- ~3-5 PW 9 MJ electrical
- 1-30 PW DT neutrons
- 4-5 PW soft x-rays

Discovery Science Experiments
A terawatt-class power pulse generates plasmas within a vacuum transmission line section of a “vacuum” transmission line at small radius

- **Anode**
  - Heated ohmically, by electrons, neg. ions?, radiation
  - Anode-contaminant plasma (~2 eV) $10^{16-19}$
  - Electrons launched by MITLs located upstream (~MeV) 
  - Ions emitted by the anode plasma (~MeV) $10^{11-14}$
  - Electrons emitted by the cathode plasma (~100 keV)

- **Cathode**
  - Heated via breakdown, ohmically, by ions, radiation
  - Cathode-contaminant plasma (~2 eV) $10^{16-19}$

**Multi-scale and non-neutral plasmas crossing PIC and Continuum regimes**

**Improvements to modeling**

- $Z_{\text{inner MITL}}$
- $Z_{\text{outer MITL}}$
- $Z_{\text{post-hole convolute}}$

**New experimental platforms & diagnostic developments**

- $E \approx 10$ MV/cm
- $B \approx 100$ T
We are exploring the idea of a next-generation pulsed power facility to address multiple scientific opportunities

- **Opportunities: A Z-Next facility capable of coupling ~10 MJ to targets could address key physics gaps**
  - Achieve ~30 MJ yield; demonstrate scaling to >100 MJ
  - Provide combined neutron and x-ray environments at record fluences on test objects
  - Achieve higher-pressure capabilities for actinide dynamic material properties
  - Address critical nuclear weapon primary and secondary physics issues

- **To realize these opportunities, we are making a number of investments through 2025**
  - Demonstrating key target physics and scaling
    - Seek to increase the shot rate of Z
    - Improving our diagnostic capabilities on Z
  - Demonstrating driver technology options
  - Understanding driver-target coupling and scaling
    - Advanced models and simulations

China’s 10 MA Primary Test Stand
END
We are halfway through a full-aperture upgrade to Z-PW

Z-Petawatt optics before upgrade

Z-Petawatt after full-aperture upgrade

Design: Spare parts from ZBL were assembled into a 2-pass main amplifier cavity with a sub-apertured 15cm round beam
- Reduced the cost and infrastructure at the time
- Modest beam energy/size and grating technology matched
- Only top half of the 2x1 amplifiers used (as with ZBL)

- Full-aperture HEPW (1-2kJ/1054nm/500fs to 200ps)
- High x-ray energies (>15keV) for backlighting and diffraction
- Full-aperture co-injection (1.5-2.5kJ/527nm/2ns)
- Lower x-ray energies (<15keV) for backlighting and diffraction
- Additional energy for heating with ZBL on MagLIF