Magnetically driven implosions for nuclear fusion, radiation source development, laboratory astrophysics, and high-pressure material properties

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Overview

- What are magnetically driven implosions?
- What is pulsed power?
- How are magnetically driven implosions and pulsed power used to create HED matter?
- What is high-energy-density (HED) matter?
- What are some applications for magnetically driven implosions in HED physics?
- What research is presently underway at U-M and at the National Laboratories?
Basic Pulsed Power Experimental Setup

\[ (r = 0) \]
Basic Pulsed Power Experimental Setup

\[ r = 0 \]

\[ \mathcal{C}_L \]

\[ (r = 0) \]
Basic Pulsed Power Experimental Setup

\[ V \quad L \quad (r = 0) \quad L \quad V \]
Basic Pulsed Power Experimental Setup

\[ I'(t) = \frac{V(t)}{L} \]

\[ (r = 0) \]
Basic Pulsed Power Experimental Setup

\[ I'(t) = \frac{V(t)}{L} \]

\[ B(r) = \frac{\mu_0 I}{2\pi r} \]

\( r = 0 \)
Basic Pulsed Power Experimental Setup

\[ I'(t) = \frac{V(t)}{L} \]

\[ B(r) = \frac{\mu_0 I}{2\pi r} \]

\[ P_{mag}(r) = \frac{B^2(r)}{2\mu_0} \propto \frac{I^2}{r^2} \]
Basic Pulsed Power Experimental Setup

\[ P_{mag}(r,t) \]

\[ P_{mag}(r,t) \]

\[ C_L \]

\[ (r = 0) \]
Imploding Geometry for Highest Pressures

\[ P_{mag}(r,t) \]

\[ (r = 0) \]
Imploding Geometry for Highest Pressures

\[ P_{mag}(r,t) \quad (r = 0) \]
Imploding Geometry for Highest Pressures & Diagnostic Access

Used for cylindrically converging experiments to achieve highest pressures

\[ P_{\text{mag}}(r,t) \]

\[ C_L \]

\( (r = 0) \)
Exploding Geometry for Material Properties Experiments & Diagnostic Access

$P_{mag}(r,t)$

Used in Planar Dynamic Materials Experiments

$(r = 0)$
Apply Voltage using Capacitors and Switches

\[ P_{\text{mag}}(r,t) \]

\[ P_{\text{mag}}(r,t) \]

\[ P_{\text{mag}}(r) = \frac{B_\theta^2(r)}{2\mu_0} \propto \frac{I^2}{r^2} \]

\((r = 0)\)
The Z Machine at Sandia National Laboratories

1–4 kJ Z Beamlet Laser (ZBL) for radiography and MagLIF fuel preheating

Up to 22 MJ stored
15% coupling to load
1–3 MJ delivered to load
26 MA in 100 ns
>100 Mbar drive pressures

10,000 ft²
Pulsed-power is about energy compression in space and time.

Energy compression achieved by a sequence of storage and switching techniques (energy stored over longer time scales and discharged over faster time scales):

- Voltages are combined in series for voltage addition
- Currents are combined in parallel for current addition
- Voltages and currents are increased together for power amplification
The Z Machine at Sandia National Laboratories: Overall Facility Scale Size

The Z-Beamlet (ZBL) and Z-Petawatt (ZPW) lasers at Sandia can be used to heat fusion fuel, radiograph experiments on Z, and perform standalone laser-only HEDP experiments.

ZBL was originally a prototype laser for the National Ignition Facility (NIF).

ZBL recently upgraded from 2 kJ in 2 ns to 4 kJ in 4 ns.
The Z Machine at Sandia National Laboratories: Accelerator Scale Size (~100 feet)
The Z Machine at Sandia National Laboratories: Load Hardware Scale Size (~1 foot)
The Z Machine at Sandia National Laboratories: Fusion Target Scale Size (~1 cm)
Z is a fun place to conduct experiments

- Harsh environment makes experiment design and diagnostics development challenging
- Debris must be carefully managed
- Several MJ energy release equivalent to few sticks of dynamite
Magnetically-Driven Cylindrical Implosions are Efficient: Implosion Drive Pressure is Divergent!

\[ P = \frac{B^2}{2\mu_o} = 140 \cdot \left( \frac{I_{[\text{MA}]} / 30}{R(t)_{[\text{mm}]}} \right)^2 \text{ [Mbar]} \]

140 Mbar is the radiation drive pressure produced on the NIF!

1 bar ≈ 1 atmosphere
Z can access a large portion of the energy density phase-space for stockpile stewardship applications and high-impact fundamental science.
Z & ZBL are used to create HED matter for stockpile stewardship applications and fundamental science.

**Dynamic Material Properties**

Sample

Isentropic Compression

Flyer Plate

**Z-Pinch X-ray Sources (RES, Rad. Physics)**

**Inertial Confinement Fusion**

Current

$B$-Field

$J \times B$ Force

Magnetization

Laser Heating

Compression

CY13 Z shot distribution

- Inertial Confinement Fusion: 26%
- Dynamic Material Properties: 38%
- Radiation Physics: 9%
- Radiation Effects Testing: 15%
- Other National Security: 1%
- Pulsed Power: 6%
- Fundamental Science: 5%

~150-200 shots/year
Sandia has established a fundamental science program on Z and has awarded time to university users.

- Use high magnetic pressures and intense x-ray bursts to create unique matter and plasmas on Z that can help address astrophysical questions.
- Addressing exciting scientific questions like:
  - Do we understand the structure of the sun?
  - Can we use white dwarfs as cosmic chronometers?
  - How does the accretion disk around a black-hole behave?
  - What is the structure of the planets in our solar system (and beyond)?
  - How did the Earth and the Moon form?
The Z Fundamental Science Program engages a broad international community and has advanced HED science

- **Resources/shots on Z over 5 years**
  - 50+ dedicated ZFS shots (~5% of all Z shots)
  - Ride-along experiments on program shots

- **Science with far-reaching impact**
  - 1 Nature, 1 Nature Geoscience, 1 SCIENCE

- **Popular outreach**
  - MIT Technology review, 10/4/2012
  - Discover Magazine, 9/16/2012
  - Local TV coverage (7-KOAT, 13-KRQE) in early 2015

- **New external funding won**
  - DOE/OFES/HEDLP

- **Students and postdocs**
  - 4 M.Sc. Exam, 2 Ph.D. exams
  - 5 postdocs
The Z Fundamental Science Program is resulting in high-impact scientific publications:

**White Dwarf Photospheres**  

**Active Galactic Nuclei & X-ray Binary Systems**  
*M. Hall et al. Phys. Plasmas 2014*

**Black Hole Accretion Disks**  
*G. A. Rochau et al. Phys. Plasmas 2014*

**Earth and Super Earths**  
*R. G. Kraus et al. Nature Geoscience 2015*

**Solar Opacity for Structure of Sun**  
*J. E. Bailey et al., *Nature* 2015*

**Gas Giant Planets/Metallic Hydrogen**  
*M. D. Knudson, *Science* 2015*
Z experiments are informing and challenging the interpretation of spectral data from the world’s multi-billion dollar x-ray observatories.

“Laboratory-based experiments are sorely needed to complement the rapidly proliferating spectral data originating from the latest [~$1B] space telescopes”

Nuclear fusion: traditionally, two approaches:

**Inertial Confinement Fusion (ICF):** Laser-driven

- National Ignition Facility (NIF), USA; Omega laser, USA
- Laser Megajoule (LMJ), France
- Typically associated with Nuclear Weapons (NW) & Stockpile Stewardship Program (SSP)

**Magnetic Confinement Fusion (MCF):**

- ITER (EU, India, Japan, China, Russia, South Korea, and the USA)
- JET (UK/EU), DIII-D (USA/Int.), etc.
- Typically associated with fusion energy

NIF ~ $4 billion

ITER ~ $20 billion
Recent big news in ICF: NIF

Scientific breakeven in late 2013 – first time in history!

The New York Times

Giant Laser Complex Makes Fusion Advance, Finally

The Wall Street Journal

A Star Is Born: U.S. Scores Fusion-Power Breakthrough

LETTER

doi:10.1038/nature13008

Fuel gain exceeding unity in an inertially confined fusion implosion

O. A. Hurricane¹, D. A. Callahan¹, D. T. Casey¹, P. M. Celliers¹, C. Cerjan¹, E. L. Dewald¹, T. R. Dittrich¹, T. Döppner¹, D. E. Hinkel¹, L. F. Berzak Hopkins³, J. L. Kline², S. Le Pape¹, T. Ma¹, A. G. MacPhee¹, J. L. Milovich¹, A. Pak¹, H. -S. Park¹, P. K. Patel¹, B. A. Remington¹, J. D. Salmonson¹, P. T. Springer¹ & R. Tommasini⁶

400 MJ stored in NIF, ~10 kJ into fuel, ~20 kJ out in fusion yield (good, but should be ≥1 MJ yield if capsule ignites)
Other recent big news: MagLIF (Nature, 12/31/13)

Triple-threat method sparks hope for fusion

The secrets to its success are lasers, magnets and a big pinch.

By W. Wayt Gibbs

The Z machine at Sandia National Laboratories in New Mexico discharges the most intense pulses of electrical current on Earth. Millions of amperes can be sent towards a metallic cylinder the size of a pencil eraser, inducing a magnetic field that creates a force — called a Z pinch — that crushes the cylinder in a fraction of a second. Since 2012, scientists have used the Z pinch to implode cylinders filled with hydrogen isotopes in the hope of achieving the extreme temperatures and pressures needed for energy-generating nuclear fusion. Despite their efforts, they have never succeeded in reaching ignition — the point at which the energy gained from fusion is greater than the energy put in. But after adding two more components, physicists think they are at last on the right path.

Researchers working on Sandia’s Magnetized Liner Inertial Fusion (MagLIF) experiment added a secondary magnetic field to thermally insulate the hydrogen fuel, and a laser to preheat it (see ‘Fueling the pinch’). In late November, they tested the system for the first time, using 16 million amperes of current, a 10 tesla magnetic field and 3 kilojoules of energy from a green laser.

“We were excited by the results,” says...
Recently, the U.S. National ICF Program added pulsed-power and magnetically driven implosions (energy rich & efficient)

<table>
<thead>
<tr>
<th>Indirect-drive ICF (NIF)</th>
<th>Direct-drive ICF (OMEGA)</th>
<th>Magnetic-drive ICF (Z)</th>
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</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram of ICF process" /></td>
<td><img src="image2.png" alt="Diagram of ICF process" /></td>
<td><img src="image3.png" alt="Magnetic-drive ICF" /></td>
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Z ~ $0.1$ billion
Sandia National Labs is using the Z facility to study the **Magnetized Liner Inertial Fusion (MagLIF)** concept.

1. **Magnetization**: 10–50 T $B_z$ applied (ms timescale) to insulate hot fuel from cold liner wall and to trap charged fusion products in the fuel.

2. **Preheating**: ZBL laser preheats fuel to 100–250 eV to reduce required compression ratio to CR≈20–30.

3. **Implosion & Flux Compression**: Z drive current & $B_\theta$ field implode liner (via z-pincho) at 50–100 km/s, compressing fuel and $B_z$ field by 1000x.

With DT fuel, simulations indicate scientific breakeven may be possible on Z (fusion energy out = energy deposited in fusion fuel).

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HYDRA Simulation MagLIF Movie
time = 0.0 ns

The image shows the results of a HYDRA simulation with MagLIF technology, displaying the time evolution of various plasma properties for a given time (time = 0.0 ns). The simulation data is presented in four panels:

1. Density: The left panel in the upper row shows the density distribution, indicated by different colors representing varying density levels.
2. Ion Temperature: The right panel in the upper row illustrates the ion temperature with color coding for temperature values.
3. Pressure: The lower left panel shows the pressure distribution, with colors indicating different pressure levels.
4. Electron Temperature: The lower right panel depicts the electron temperature, with color coding for temperature values.

Key components labeled in the image include:
- **Anodes**: Indicated on the diagram with a label.
- **Liner**: Also labeled on the diagram.
- **Cathode**: Labeled within the fuel region. The fuel region is highlighted in yellow.

The data visualization provides a detailed representation of the plasma behavior under the specified conditions.
HYDRA Simulation MagLIF Movie
time = 120.0 ns
HYDRA Simulation MagLIF Movie
time = 123.0 ns

- **Laser has fully penetrated the fuel**

![Graphs showing various properties such as density, ion temperature, pressure, and electron temperature.](image)
HYDRA Simulation MagLIF Movie

time = 144.0 ns

- Density
- Ion Temperature
- Pressure
- Electron Temperature

Labels:
- Anodes
- Liner
- Cathode
- High-Temp Compressed Fuel

HYDRA Simulation MagLIF Movie

time = 153.0 ns

- Anodes
- Liner
- Cathode

Liner wraps around the fuel
MagLIF Timing Overview:

~ 60–100-ns implosion times
~ adiabatic fuel compression (thus preheating the fuel is necessary)
~ 5-keV fuel stagnation temperatures (60 million degrees K)
~ 1-g/cc fuel stagnation densities
~ 5-Gbar fuel stagnation pressures

\[ T \approx T_0 \left( \frac{\rho}{\rho_0} \right) \approx T_0 C_R^{4/3} \]

\[ (C_R = R_0 / R_{\text{stagnation}}) \]

- Typically for ICF (e.g., NIF), faster implosions shock-heat the fuel, not so for MagLIF
- Magnetization is used to keep the preheated fuel from cooling off during the implosion

Anatomy of a MagLIF Experiment:

- **Field Coils**: Helmholtz-like coil pair produce a 10-30 T axial field w/ ~3 ms rise time

- **ZBL**: 1-4 kJ green laser, 1-4 ns square pulse w/ adjustable prepulse (prepulse used to help disassemble laser entrance window)
Anatomy of a MagLIF Target:

- **Be Liner**: OD = 5.63 mm, ID = 4.65 mm, h = 5–10 mm
- **LEH Window**: 1-3 μm thick plastic window. Supports 60 PSI pure D2 gas fill.
- **Washer**: Metal (Al) washer supporting LEH window
- **Channel**: Al structure used to mitigate the “wall instability.” Also reduces LEH window diameter to allow thinner windows
- **Return Can**: Slotted for diagnostic access
Many diagnostics used and continually being developed to study MagLIF and HEDP on Z

Z Target Diagnostics

- **Power & Energy**
  - X-ray Diodes
  - Photo Conducting Diamonds
  - Silicon Diodes
  - Bolometer

- **Spectroscopy**
  - Time-integrated 0.8-10 keV
  - Time-resolved 0.8-10 keV
  - Time-integrated 7-25 keV
  - Streaked Visible

- **X-ray Imaging**
  - 1.9 or 6.1 keV Backlighting
  - 277 or 528 eV Time-Gated Self-Emission
  - Filtered Self-Emission

- **Motion / Velocity**
  - VISAR
  - Photonic Doppler Velocimetry (PDV)
  - Passive Shock Breakout

- **Neutrons**
  - D-D Activation
  - D-T Activation
  - Time-of-Flight
  - Imaging
Implosion instabilities like the Magneto-Rayleigh-Taylor (MRT) instability could cause MagLIF to fail.

Thus we use liners with thick walls to mitigate MRT feed-through.

Beryllium Liner

0.58 mm

3.47 mm

5–6.5 mm
To study liner implosion instabilities, penetrating radiographs are taken to piece together implosion “movies”:
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![Diagram showing axial and transverse displacement](image-url)
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![Graph showing axial displacement vs. transverse displacement]
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To study liner implosion instabilities, penetrating radiographs are taken to piece together implosion “movies”:

- These experimental data are compared with detailed numerical simulations to understand the seeding and evolution of liner implosion instabilities.
Images of the hot and compressed fusing fuel (on axis inside of the imploding liner) are also collected

- This high-resolution image was produced by an x-ray crystal optics system

- FWHM is 50-110 μm (this reacting plasma is less than the thickness of a human hair)

- Experimental data like these are compared with detailed numerical simulations to unfold plasma conditions

MagLIF Status and Year 2020 Goals for the MagLIF Program at Sandia

- In short, MagLIF is working
- Sandia now needs to demonstrate how MagLIF scales with driver power & energy to justify building a next-step/next-generation pulsed-power facility (i.e., Z-Next)
- Demonstrate scaling with modest upgrades to present Z facility:
  - DT fuel (presently use DD fuel)
  - 8 kJ preheat (presently a 4-kJ laser)
  - 30 T B\textsubscript{20} (presently 15–20 T)
  - 27 MA (we presently 18–20 MA)
  - 95-kV Marx Charge (typically use 80 kV)
  - 25 MJ stored (typically store 18 MJ)
  - 50-million-K plasma (have achieved 35 million degrees K, or 3 keV)
  - 0.1–1 MJ fusion yield (have achieved 500 J of DT-equivalent fusion yield)
Pulsed Power at U-M: MAIZE

\[ P_{\text{mag}}(r,t) = \frac{B_\theta^2(r)}{2\mu_0} \propto \frac{I^2}{r^2} \]

\((r = 0)\)
The Michigan Accelerator for Inductive Z-pinchof Experiments (MAIZE)

In the NERS Plasma, Pulsed Power, and Microwave Laboratory

MAIZE is a Linear Transformer Driver (LTD):
- ~1 MA in 100 ns
- ~100 kV
- ~10 kJ, 0.1 TW
- ~3-m-diameter cavity
Use MAIZE to:

- Study implosion instabilities*
- Develop diagnostic instruments and techniques, which can then be transferred to Z and NIF
- Study power-flow issues
- Study the coupling of LTDs to HED matter
- Study magnetized plasma flows for laboratory astrophysics
- Create and study pulsed fusion/neutron sources as well as pulsed x-ray and gamma-ray sources

MagLIF/Z Beyond 2020: Z300 & Z800

Z300:
- 48 MA, 320 TW delivered
- 48 MJ stored
- 30–80 MJ fusion yield
- 35 m in diameter (size of Z today)
- 2970 LTD cavities!

Z800:
- 60 MA, 890 TW delivered
- 130 MJ stored
- 0.2–1 GJ fusion yield
- 52 m in diameter
- 5400 LTD cavities!

LTD-based architectures
(Linear Transformer Driver)

(MAIZE is a single LTD cavity!)

So, is “fushion” \((h \to 0)\) really 140 years away?
Concluding Remarks

• Pulsed power and magnetically driven implosions for fusion and HEDP are fun and exciting projects to be involved with
• Lots of U-M grads working on these projects at Sandia and elsewhere
• BBC Z Machine Clip: https://www.youtube.com/watch?v=eaopaLJk3-Y
• Thank you for your time!
• Questions?