Current-adder pulsed power generators for high-pressure dynamic material studies


Presented at
Megagauss 2016
Shock and isentropic compression experiments access different material regimes

- **Shock compression**: higher-temperature, high-pressure
- **Isentropic compression**: low-temperature, high-pressure
- Valuable for Equation of State (EOS) studies

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**Pressure Input**

- **Hugoniot Jump Conditions**
- **Differential Conservation Equations**

**Stress-density (EOS)**

- **Single Point Non-reversible**
- **Continuous Isentrope Reversible**

**Aluminum phase diagram**

- **Hugoniot**
- **Liquid**
- **Solid**
- **Isentrope**

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- Shock compression: higher-temperature, high-pressure
- Isentropic compression: low-temperature, high-pressure
- Valuable for Equation of State (EOS) studies
Z and other pulsed-power machines are used to drive material-physics experiments.

- The magnetic pressure generated within a short-circuit load drives the experiment.
- A smooth pressure profile can be guaranteed by the circuit.
- Velocity measurements are used to determine the isentrope.

\[
P_{\text{magnetic}} = \frac{\mu_0 I^2}{2w^2}
\]

\(I = \text{current}\)

\(w = \text{width of the conductor}\)

ICE on ZR have been performed on a variety of materials

<table>
<thead>
<tr>
<th>Velocity (cm/µs)</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Experiment</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
<td>0.04</td>
</tr>
</tbody>
</table>


Validated Void-Collapse Model


Tantalum: quasi-isentrope to 4 Mbar

Thor Specifications for a Megabar-class pulsed power accelerator

- Peak current: 7 MA
- Current rise time: 200-500 ns
- Pulse shaping through independent, decoupled switches
- Megabar+ (100 GPa) peak magnetic pressures
- Enables a variety of experiments:
  - Soft Materials: Cerium, Lithium
  - Flat Top Pulse: Strength
  - Shock-Ramp: Iron
- High throughput – 2+ shots per day
- Cost-effective university-scale machine
- Conditions relevant to geophysics
The Thor concept meets the requirements for a compact, megabar-class ICE driver

- Each Brick
  - \( V = 200 \text{ kV} \)
  - \( C = 40 \text{ nF} \)
  - Total Energy (\( n = 200 \))
    \[ E = \frac{1}{2} nCV^2 = 160 \text{ kJ} \]
- Drive circuit, or “brick” (96-288 total)
- 300-ns-long coaxial transmission lines (288 total)
- Four water-insulated radial transmission lines
- Anode
- Cathode
- Water-insulated double-post-hole convolute (DPHC)
- Rexolite line
- Kapton-insulated stripline load
- Bricks – 2x80 nF caps, 1 HCEI switch
- Thor-XX = Thor-# of bricks
- 100-ns basis function pulses for ICE
- Veloce-type stripline loads
Each Thor brick consists of two capacitors and a switch.

Cables are impedance-matched to bricks.

C = 40 nF, L = 240 nH, R = 0.37 Ω

\[ Z = 1.1 \sqrt{\frac{L}{C}} + 0.8R = 3.00\Omega \]

4 x 200 ft. 11.2 Ω Cables
DS-X 1.25 in diameter
Z = 2.8 Ω

Brick “basis function”
The central power flow (CPF) section is 2 meters in diameter.
The central power flow (CPF) combines current from the cables into transmission lines.

- Maximum 288 cables
- Load Region
- Cable Header
- Water Line
- ICE Panel
- Kapton
- 40 DPHC posts
- Rexolite
Current is delivered to a strip-line ICE load to maximize magnetic pressure for ICE

Panel on plate

\[ B \text{ concentrated into stripline} \]

\[ P \sim \left( \frac{I}{w} \right)^2 \]

Connector bolt
Sample
Top panel
0.5 mm Kapton insulation
Shorting current contact
Bottom panel
Thor can produce pressures of well over a Mbar

- 4 triggers spaced 50 ns apart
- Current rise time ~ 200 ns
- 10 mm X 20 mm (WxL) Cu panels

<table>
<thead>
<tr>
<th>Brick #</th>
<th>Cables per brick</th>
<th>Etot (KJ)</th>
<th>Peak I (MA)</th>
<th>Peak P (Mbar)</th>
<th>Eload (kJ)</th>
<th>Eff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>96</td>
<td>3</td>
<td>76.8</td>
<td>4.1</td>
<td>0.65</td>
<td>27.0</td>
<td>35</td>
</tr>
<tr>
<td>144</td>
<td>2</td>
<td>115</td>
<td>5.4</td>
<td>1.1</td>
<td>56.1</td>
<td>49</td>
</tr>
<tr>
<td>288</td>
<td>1</td>
<td>230</td>
<td>6.9</td>
<td>1.7</td>
<td>111</td>
<td>48</td>
</tr>
</tbody>
</table>

Thor-96
10 mm Cu panels

![Graph showing current and pressure over time]
Thor-24 was commissioned in September

CPF

Load region

Brick Voltage (±50 kV Charge)

Current (MA)

Time (ns)

Load Current (±55 kV Charge)

Current (MA)

Time (ns)
Thor-48 will be commissioned in FY17

Thor-48: 3.3 MA, 440 kbar

Thor-72: 4 MA, 650 kbar
Thor-144 will fit comfortably within the building 961 high bay at Sandia
Pressure pulse tailoring enables study of many materials of interest in relevant regimes

Pulse tailoring is required to maintain shockless loading.

**Ideal Pressure Profiles**

- **Cu**
- **Pb**

**Shock up thickness**

**Velocity Waveforms**

- **Cu**
  - $X_C=1.5\ mm$

- **Pb**
  - $X_C=0.7\ mm$
We have developed a circuit-free method to tailor the current pulse

Ideal pulse for Cu/LiF Window: Xc=2400 µm

Find desired current and voltage

Find optimized forward-going current $I_+$

Form forward-going current

Express current as brick sum*

Optimize to find trigger times:

$$F(\bar{\tau}) = \int_0^T dt [I_+(t) - I_{0+}(t)]^2$$

$$\bar{\tau} = (\tau_1, \ldots, \tau_n)$$

*IResult of transit-time isolated transmission lines
Optimization results are verified with the MHD code

- Use open circuit voltage to drive load:
  - $V_{OC} = 2ZI_+$
- Circuit model can be expressed as LR series circuit
- We are now using this approach in ALEGRA 3D MHD modeling

$$V_D = 2ZI_+ - L_C \dot{I}_D - ZI_D$$

Optimization procedure is used to design 1.1 Mbar Cu/Ta strength experiments

1.5 mm Cu, 0.8 mm Ta, 4 mm LiF

Desired voltage and current

Optimization to determine triggering

Compare optimized and desired pressures

We are able to design Thor “virtual experiments” using the circuit/MHD capability of ALEGRA 3D

- All circuit elements are modeled, down to the brick level
- Circuit is self-consistently coupled to the 3D MHD simulation
- Simulation performed with brick timing
  \[ \vec{\tau} = (\tau_1, \ldots, \tau_n) \]
- Allows us to accurately predict ICE load performance with a single physics code
Thor-72 point design for Cerium: pulse tailoring

~300 kbar pressure pulse

Phase diagram

Cerium pressure history

Pulse-shaping with 72 bricks
We have extended the current-adder architecture to the megajoule-class Neptune machine.

- 600 “Marxed” Bricks
- 600 Coaxial Lines
- CPF

$E_{\text{TOTAL}} = 4.8 \text{ MJ}$
$I_{\text{MAX}} = 31 \text{ MA}$
$E_{\text{LOAD}} = 1 \text{ MJ}$

Neptune can reproduce ZR performance

6 Mbar Ta ICE

31 km/s shockless Al flyer

Optimized and desired current
Neptune can reach 1 TPA (10 Mbar) for ICE

Magnetic Field and FS velocity for 1.8 mm Cu

ALEGRA 3D simulation

Over 1 TPa (10 Mbar) pressure

Conclusions

- We have developed a compact, low-cost platform for performing dynamic material experiments in the megabar (100 GPa) regime
  - Precise pulse tailoring with gradient-based optimization technique
  - Ability to explore shockless-loading regime for equation of state (EOS), dynamic strength, and phase transition studies
  - Capability for XRD being developed
- A physics campaign on Thor will be conducted in FY17. This will include:
  - Validation of ICE on Thor
  - Pulse tailoring
  - First pulsed power driven X-ray diffraction experiments
  - Flyer plate experiments
- We have developed the Neptune machine
  - 1 TPA (10 Mbar) ramp wave experiments possible in a variety of materials (Cu, Ta, Pb).
The ultimate performance of Thor depends on the number and type of coaxial cable

- The Thor CPF can accommodate 288 cables
- With the present cable (4 cables/brick), this limits the number of bricks to 72
- An effort is underway to reduce cable number and length
  - Increase dielectric constant $\varepsilon_r \rightarrow$ reduce $Z$ and $c \rightarrow$ reduce no. of cables and length
  - Nano-ceramic-poly: 1 (2) cable/brick, 46 (75) foot length, 144 (288) brick system
  - Water (DI) cable: 2 cables/brick, 30 foot length, 144 brick system
- We will be manufacturing a high-epsilon cable next year
There are compelling reasons why Thor/ICE is important to the materials community

- Sample size – cm scale width, mm scale in thickness, many grains across propagation direction
- Strain rate – $10^6$ – $10^7$
- Ability to tailor pulses – required to avoid shocks, tunable for different phase paths.
- A standard driver – A validated technique for high pressure measurement, valuable to the high-pressure community:
- Capable of obtaining dynamic XRD data with a compact source:
- Vertical orientation allows placement at a synchrotron facility.
Thor-24 shot series in September: copper at 200 kbar

- Time (ns)
- Current (MA)
- Pressure (Mbar)

- 10 mm copper panel
- 0.5 mm kapton insulation

- 10 mm
- 20 mm

- Velocity profiles
- Velocity (km/s)

- 400 µm
- 1000 µm

- I
- P

- 0 50 100 150 200 250 300 350 400
- Time (ns)
- 0 0.05 0.1 0.15 0.2 0.25
- Current (MA)
- 0 0.05 0.1 0.15 0.2 0.25
- Pressure (Mbar)

- 100 200 300 400
- Time (ns)
- 0 0.1 0.2 0.3 0.4 0.5
- Velocity (km/s)