Self-Consistent, 2D Magneto-Hydrodynamic Simulations of Magnetically Driven Flyer Plates

Ray Lemke


Sandia National Laboratories
Albuquerque, NM 87185-1186

44th Annual Meeting of the Division of Plasma Physics
November 11-15, 2002, Orlando, FL
Introduction

- Magnetically accelerated flyer plates are used to drive shock physics experiments on Z.

- Accurate modeling requires 2D MHD simulation.
  - Have used time resolved measurements to validate/develop physics models.
  - Accurate material models.
  - Self-consistent coupling of pulsed power machine to load.

- Time dependent VISAR measurements accurately predicted.

- State of flyer is accurately predicted.

- 40 km/s shockless flyer predicted for ZR.
1D illustration of magnetically driven flyer and isentropic compression experiments

- Magnetic field compresses cathode and anode, and diffuses into material. Joule heating modifies material. Load inductance increases.

R. W. Lemke, SNL Dept. 1674, 11/13/2002
Sample frame from flyer movie shows geometry

600/200 μm Al/Ti flyer, 28 km/s final velocity

R. W. Lemke, SNL Dept. 1674, 11/13/2002
Late time movie frame showing bowed flyer

Density @ 2.67002e-06 s

target

Al/Ti flyer

cathode

void

600/200 μm Al/Ti flyer, 28 km/s final velocity

R. W. Lemke, SNL Dept. 1674, 11/13/2002
Simulation code is **ALEGRA**: 2d, 3d, radiation magneto-hydrodynamics

- **Physics capabilities:**

<table>
<thead>
<tr>
<th>MHD</th>
<th>HYDRODYNAMICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQUATION OF STATE</td>
<td>SOLID DYNAMICS</td>
</tr>
<tr>
<td>ELECTRICAL CONDUCTIVITY</td>
<td>STRUCTURAL DYNAMICS</td>
</tr>
<tr>
<td>EXTERNAL CIRCUIT DRIVE</td>
<td>MATERIAL MODELS</td>
</tr>
<tr>
<td>THERMAL CONDUCTIVITY</td>
<td>ELASTIC PLASTIC</td>
</tr>
<tr>
<td>RADIATION MHD</td>
<td>OPACITY</td>
</tr>
</tbody>
</table>

- 1D useful for validating physics models.
- 2D, circuit driven MHD necessary to produce/predict measurements.

R. W. Lemke, SNL Dept. 1674, 11/13/2002
Cross section of Z machine showing central convolute and load region
Predictive MHD requires accurate circuit for $Z$

Z MITLs, Convolutes, and Load

Circuit Driven MHD Simulation

$$V_z = Z_{flow} \sqrt{I_u^2 - I_d^2}$$

MHD: Slab Electrode/Flyer Configuration

R. W. Lemke, SNL Dept. 1674, 11/13/2002
Machine dependent loss impedance and crowbar necessary for accurate modeling

Model suggests steady loss of current at convolute resulting in short circuit.
2D, circuit driven, MHD simulation accurately produces measured flyer velocity & load current

flyer velocity & load current vs. time

Results for 850 μm Al flyer.

R. W. Lemke, SNL Dept. 1674, 11/13/2002
MHD simulation yields realistic flyer state: density, temperature & magnetic field at impact

State of flyer at impact determines pressure drive for EOS measurement.

R. W. Lemke, SNL Dept. 1674, 11/13/2002
Joule heating & measurement accuracy place constraint on minimum flyer thickness

location pressure/diffusion fronts vs. time

magnetic diffusion rate vs. peak current

minimum flyer thickness \sim \frac{U_s U_r}{(U_s + U_r)} t_{dmin} + R_B I_0 t_a

R. W. Lemke, SNL Dept. 1674, 11/13/2002
Flyer bowing and post impact shock structure accurately determined by 2D simulation

Shock Breakout Visar Measurement

Simulation at Impact

Comparison - Simulation & Exp

Shock Arrival Time (300 μm)
Inductance increase during current pulse is a major impediment to achieving large pressures.

- Inductance increases due to electrode deformation.
- Hydrodynamic optimization minimizes early time electrode motion.
  - Stiff materials for electrode(s).
  - Isentropic compression.
- Electrical optimization of load maximizes pressure on sample.
Electrical optimization of load: reduce alternative current paths; maximizes magnetic flux on sample.

Slab Electrode Configuration

One-Sided Electrode Configuration

Make inductance of current path under sample small compared to alternative paths; yields large increase in magnetic pressure.

R. W. Lemke, SNL Dept. 1674, 11/13/2002
Electrical optimization yields large increase in magnetic field (pressure) for same current.

Magnetic Field on Anode Surface per Unit Current vs. AK-gap: slab & one-sided configurations

B / I (Tesla/MA) vs. ak-gap (cm)

- B/I one-sided
- B/I slab

R. W. Lemke, SNL Dept. 1674, 11/13/2002
Hydrodynamic optimization of load minimizes electrode motion & avoids shock formation

Stiff (large shock impedance) materials: reduce mechanical motion of electrodes.

Isentropic compression: avoids early time shock formation; further reduces mechanical motion. Requires shaped voltage waveform.
Very high velocities via multi Mbar isentropic compression requires voltage pulse shaping.

Voltage rise shaped for isentropic compression of Al to 6 Mbar.

R. W. Lemke, SNL Dept. 1674, 11/13/2002
40 km/s shockless flyer predicted for optimized one-sided geometry on refurbished Z machine

- Results for 600/200 μm thick Al/Ti flyer with 6 Mbar drive.
- Would extend $D_2$ EOS data up to ~3 Mbar. Could get 40 Mbar in Cu.
Self-consistent 2D MHD simulation yields realistic details of magnetically accelerated flyer plates

- Results validated using time resolved measurements.
- Velocity waveform determined by magnetic drive, shocks, reverberations, and ablation.
- Results sensitive to model of electrical conductivity.
- Joule heating places constraint on minimum flyer thickness.
- Inductance increase due to electrode deformation a serious impediment to achieving very high pressures.
- Predictions for high pressure material science loads on ZR:
  - 40 km/s flyer velocity; 3 Mbar in D₂.
  - Peak ICE pressures of ~10 Mbar in tungsten.