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

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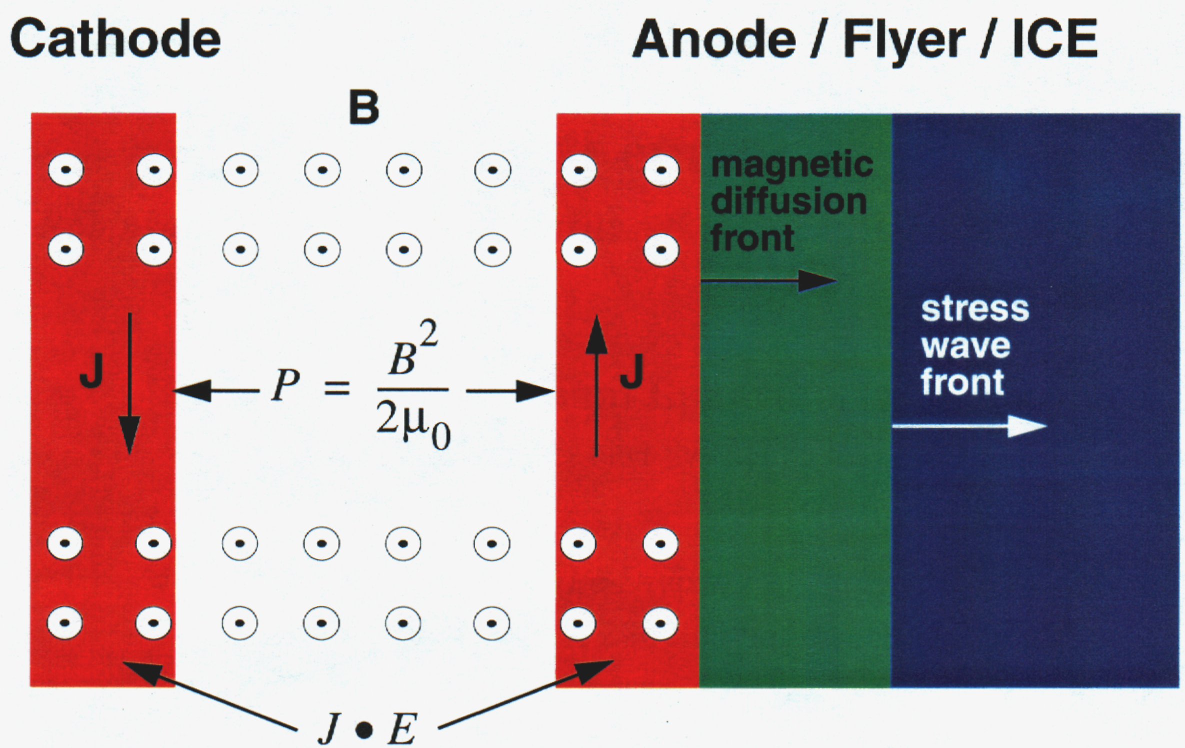
Introduction

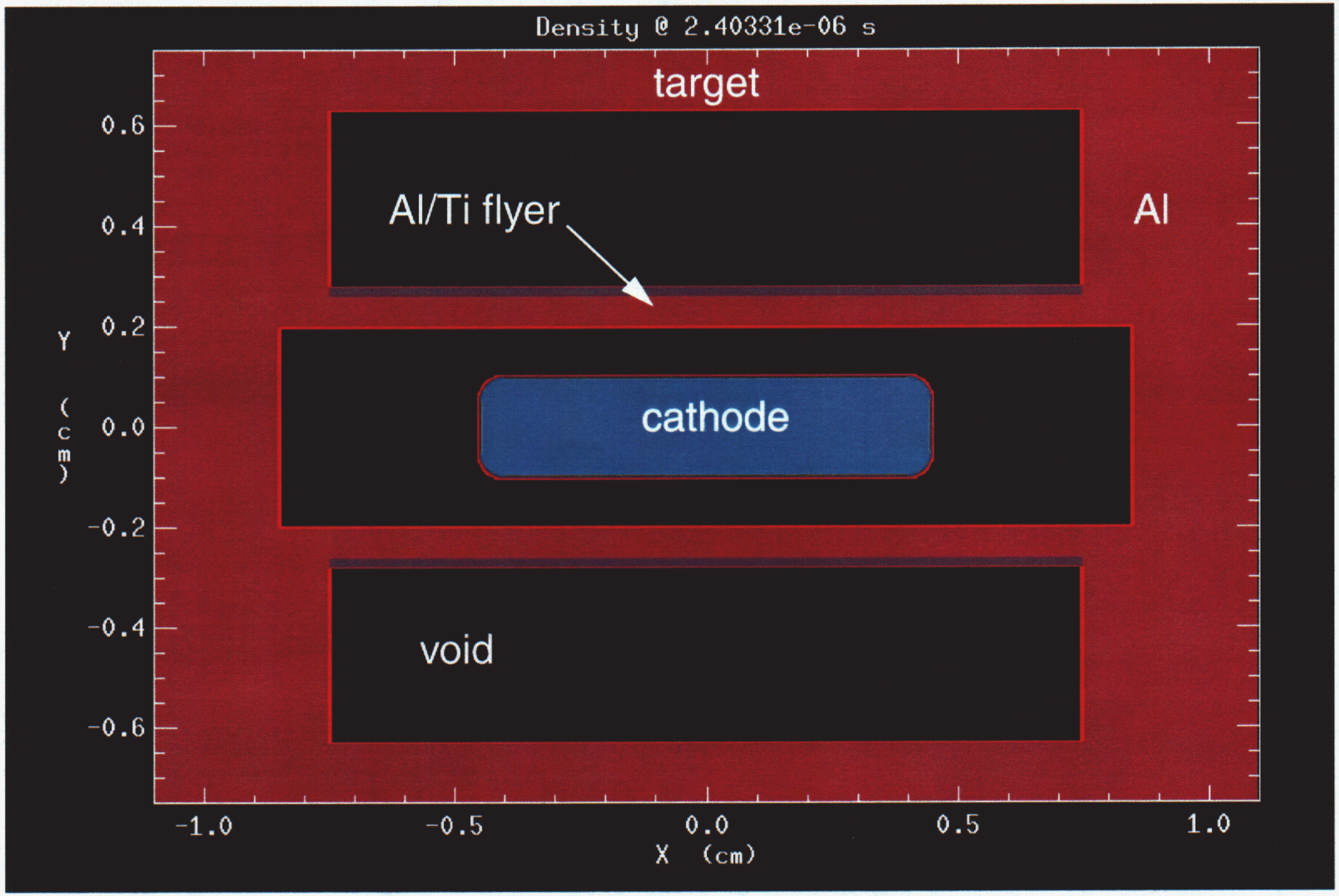
- Magnetically accelerated flyer plates are used to drive shock physics experiments on Z.
- Accurate modeling requires 2D MHD simulation.
  - Have used time resolved measurements to validate/develop physics models.
  - Accurate material models.
  - Self-consistent coupling of pulsed power machine to 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.

Sample frame from flyer movie shows geometry



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

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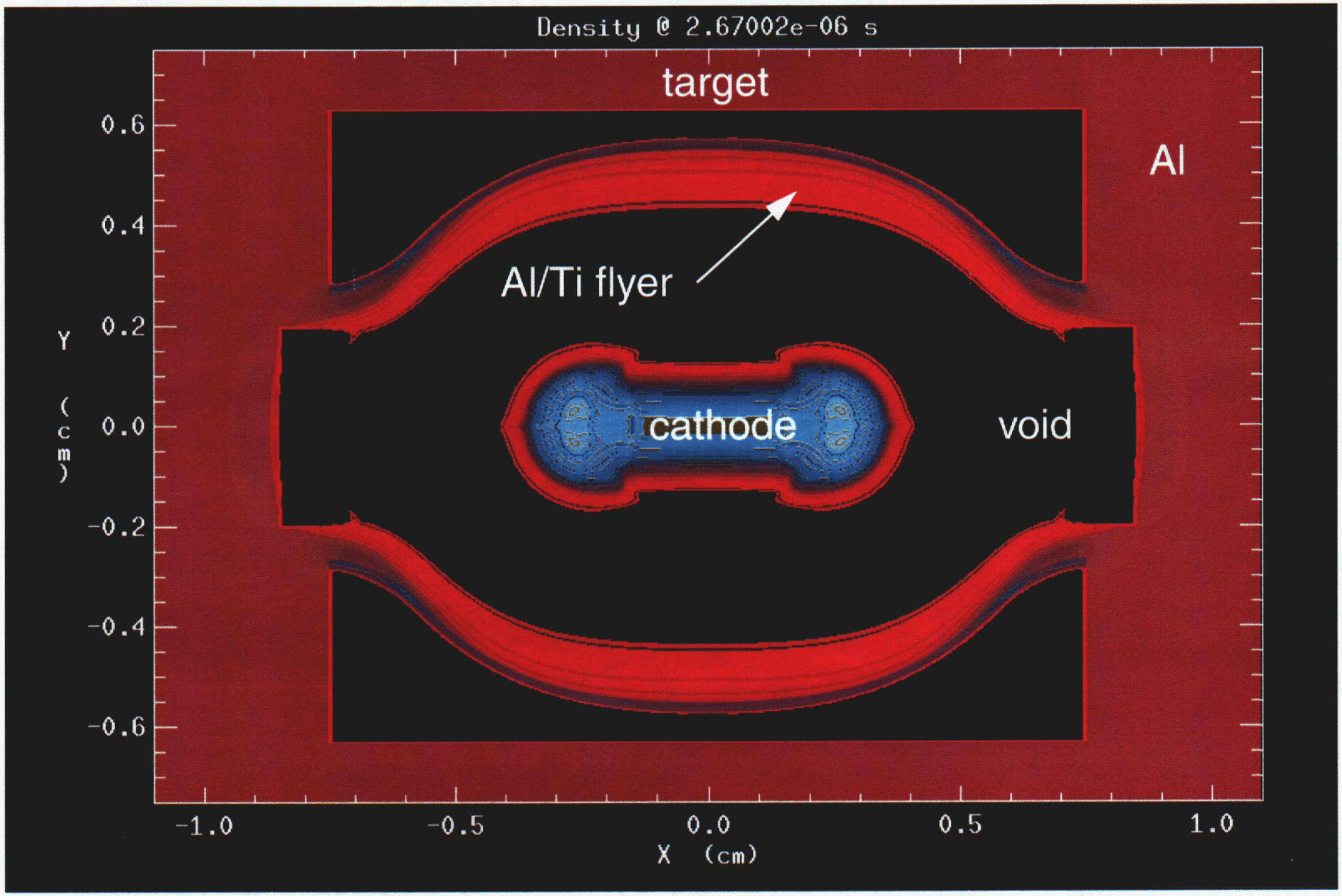
Late time movie frame showing bowed flyer



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

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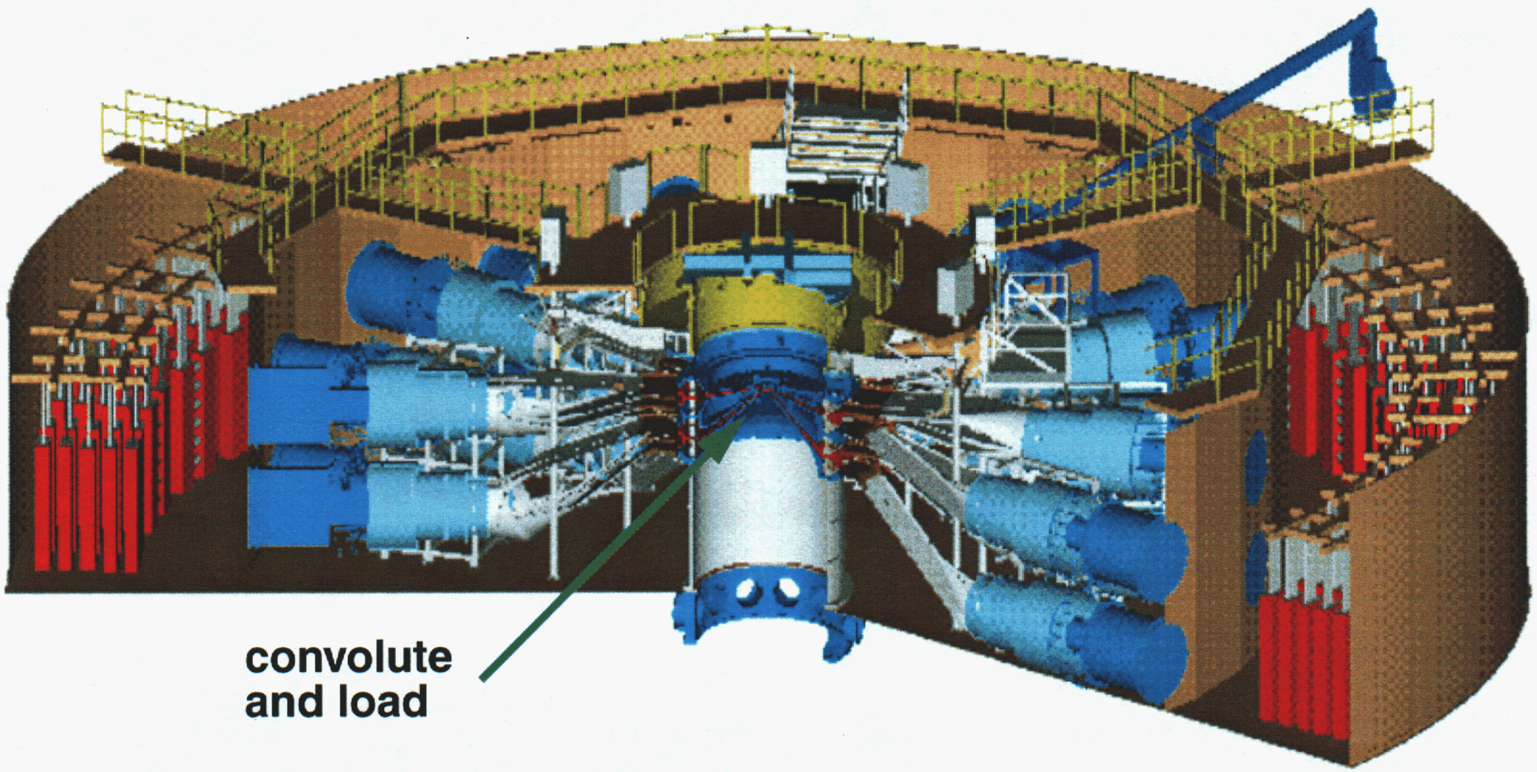
Simulation code is ALEGRA: 2d, 3d, radiation magneto-hydrodynamics

- Physics capabilities:

MHD	*HYDRODYNAMICS*
EQUATION OF STATE	*SOLID DYNAMICS*
ELECTRICAL CONDUCTIVITY	*STRUCTURAL DYNAMICS*
EXTERNAL CIRCUIT DRIVE	*MATERIAL MODELS*
THERMAL CONDUCTIVITY	*ELASTIC PLASTIC*
RADIATION MHD	*OPACITY*

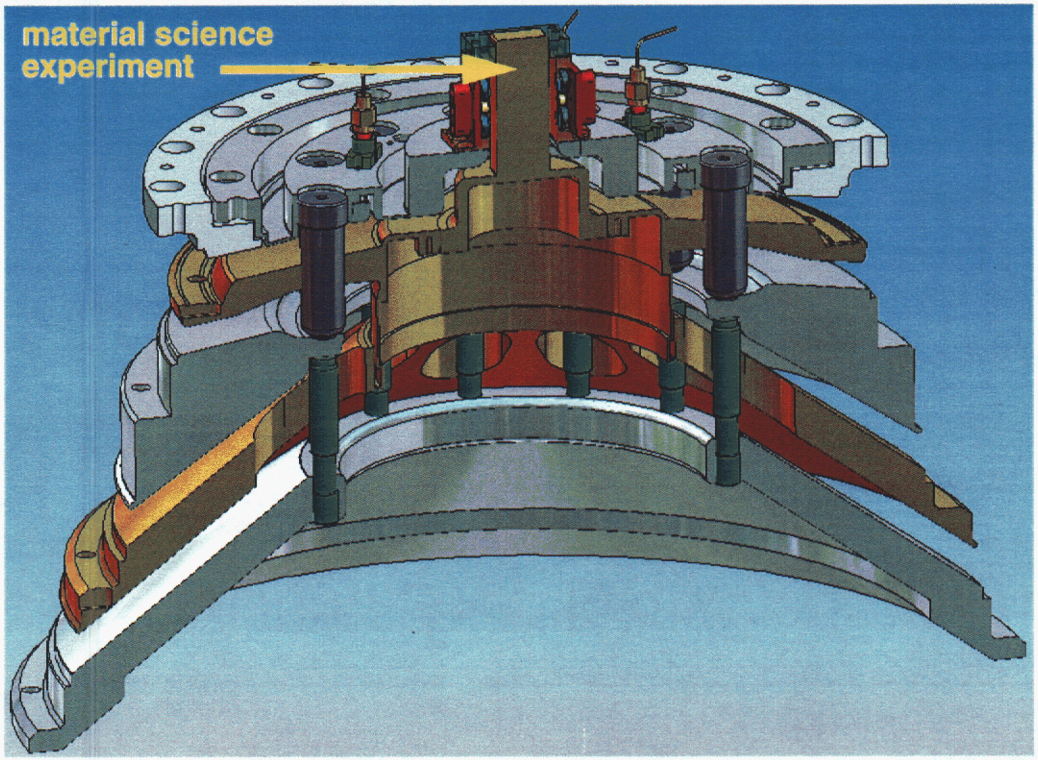
- 1D useful for validating physics models.
- 2D, circuit driven MHD necessary to produce/predict measurements.

Cross section of Z machine showing central convolute and load region

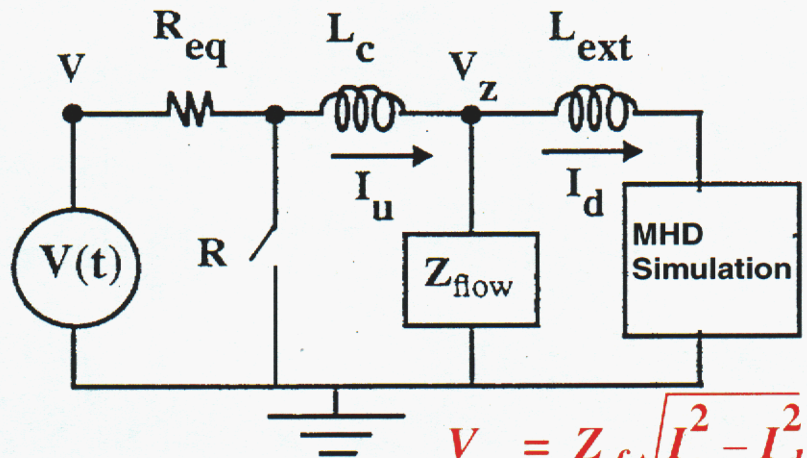


Predictive MHD requires accurate circuit for Z

Z MITLs, Convolutes, and Load

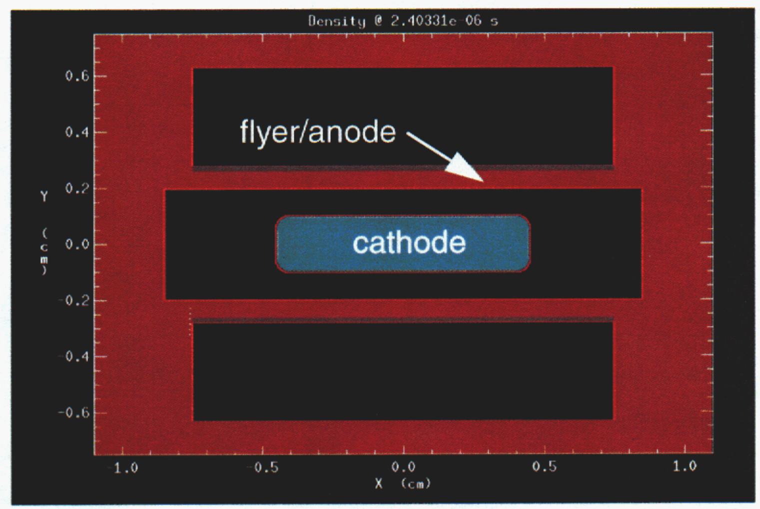


Circuit Driven MHD Simulation



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

MHD: Slab Electrode/Flyer Configuration



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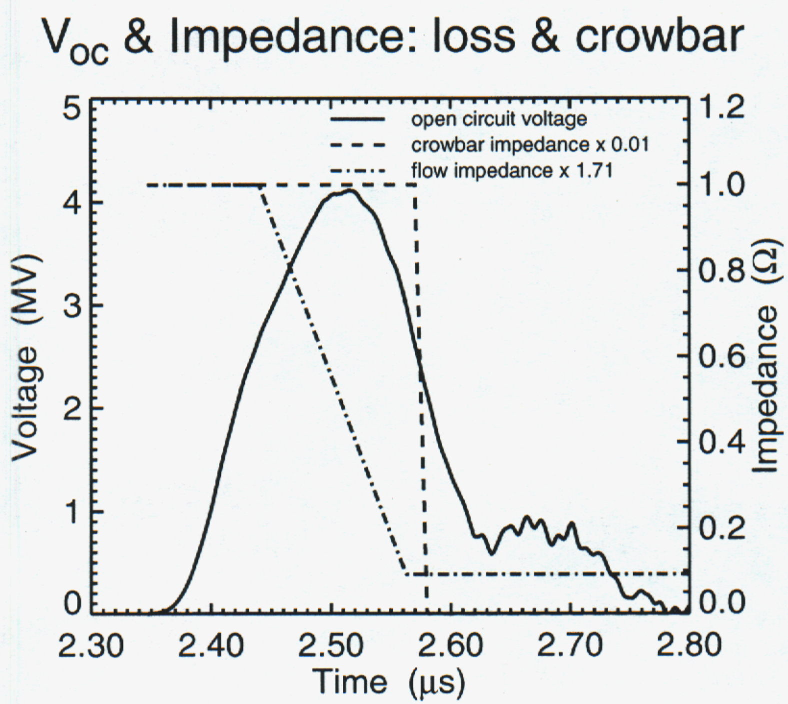
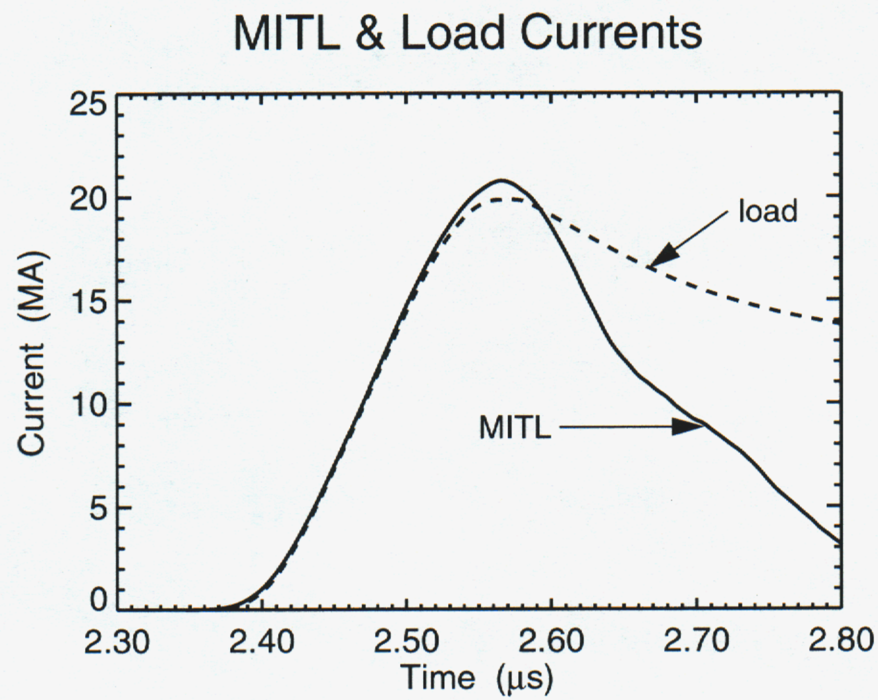
Machine dependent loss impedance and crowbar necessary for accurate modeling





Model suggests steady loss of current at convolute resulting in short circuit.

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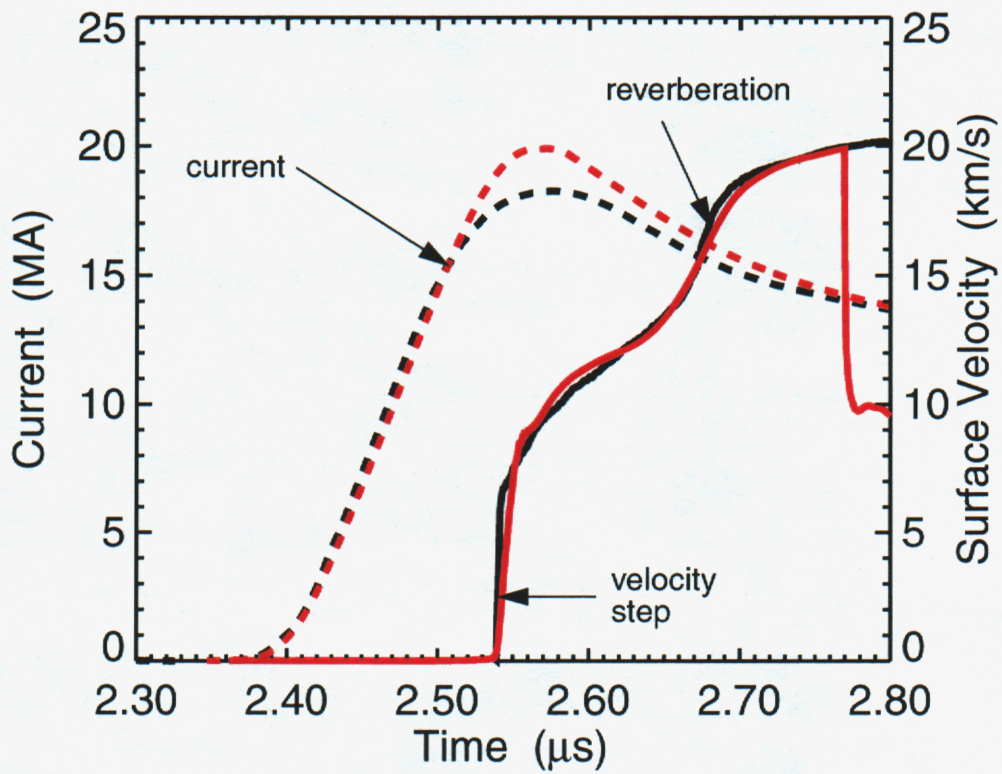
2D, circuit driven, MHD simulation accurately produces measured flyer velocity & load current

flyer velocity & load current vs. time



Results for 850 μm Al flyer.

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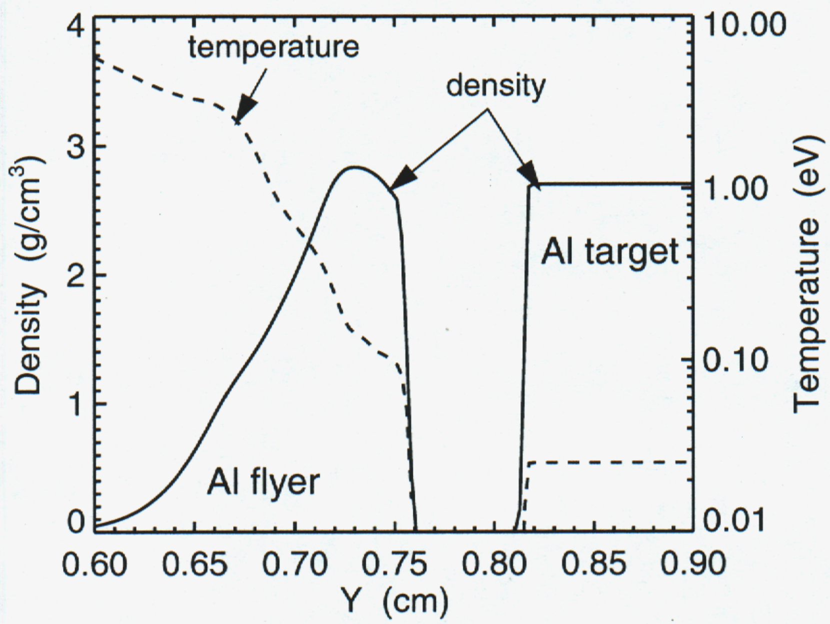
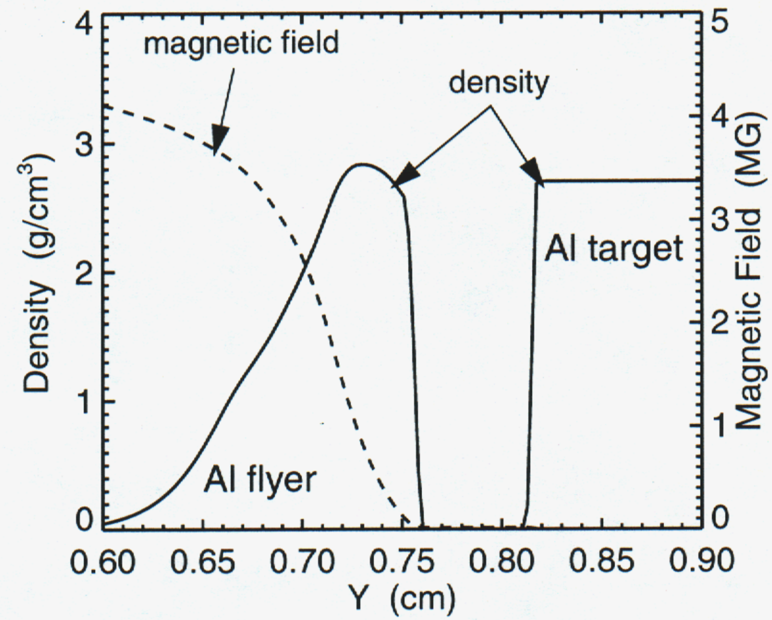
MHD simulation yields realistic flyer state: density, temperature & magnetic field at impact

density & temperature vs. position



density & magnetic field vs. position



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

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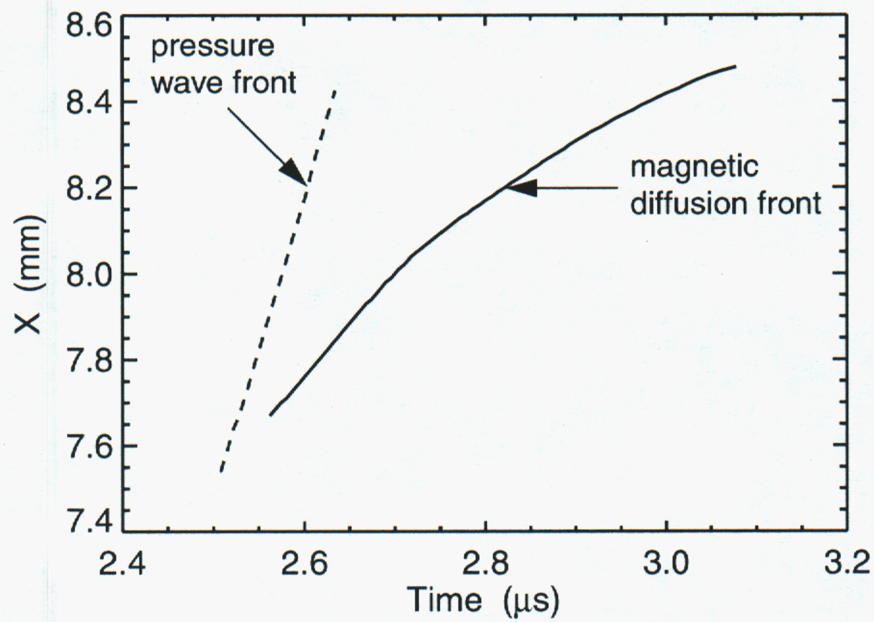
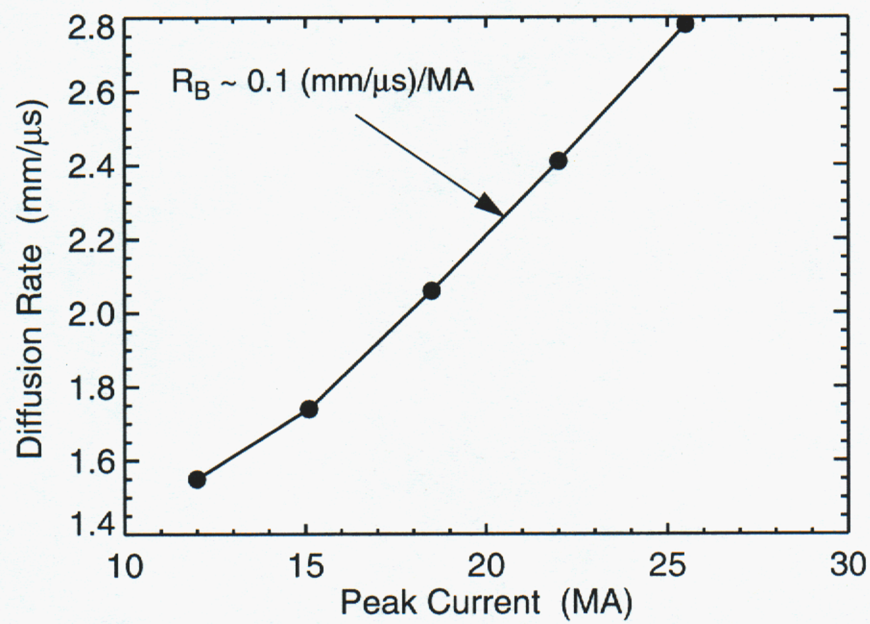
Joule heating & measurement accuracy place constraint on minimum flyer thickness

location pressure/diffusion fronts vs. time



magnetic diffusion rate vs. peak current



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

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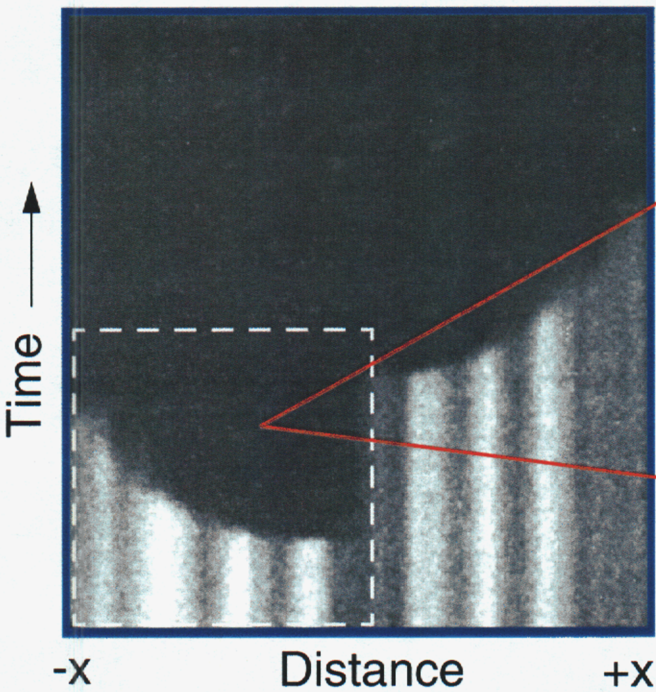
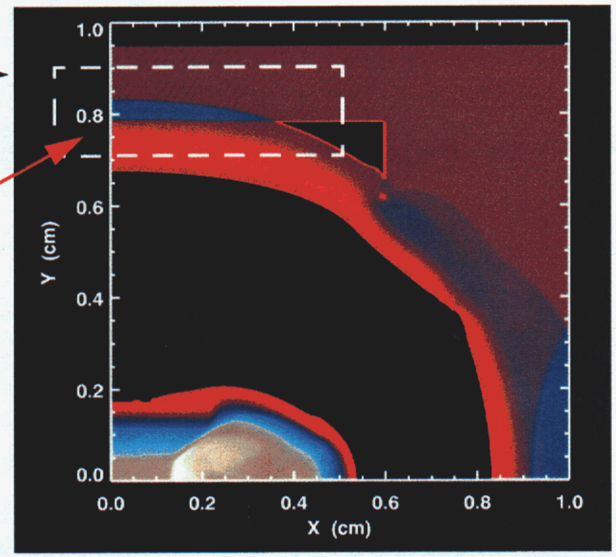
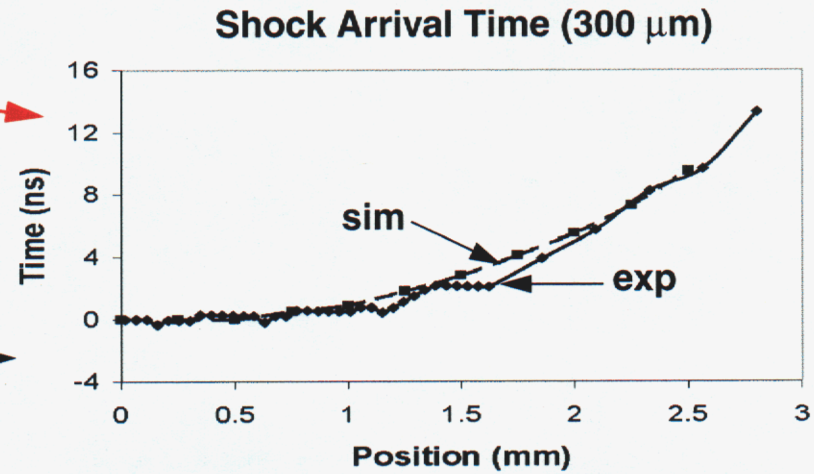
Flyer bowing and post impact shock structure accurately determined by 2D simulation

Shock Breakout
Visar Measurement



Simulation
at Impact





Comparison
Simulation & Exp

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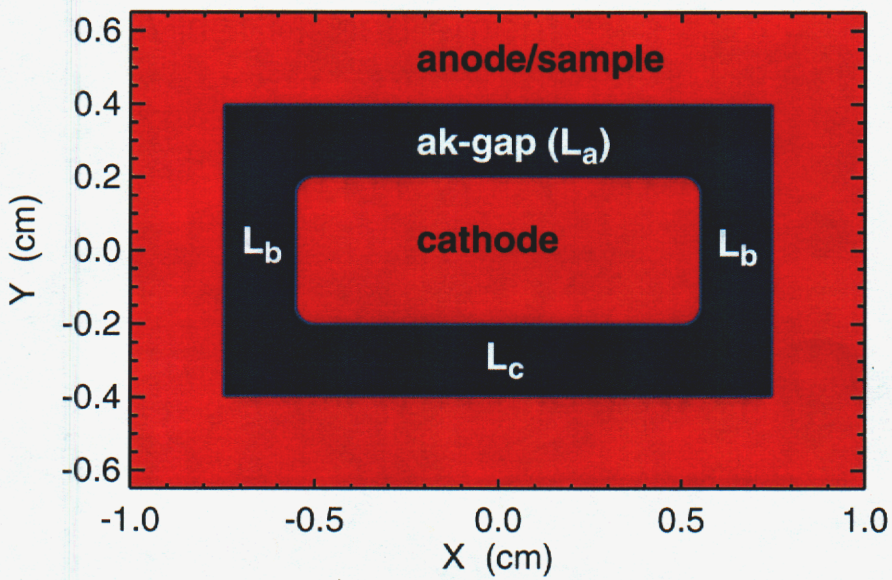
Inductance increase during current pulse is a major impediment to achieving large pressures

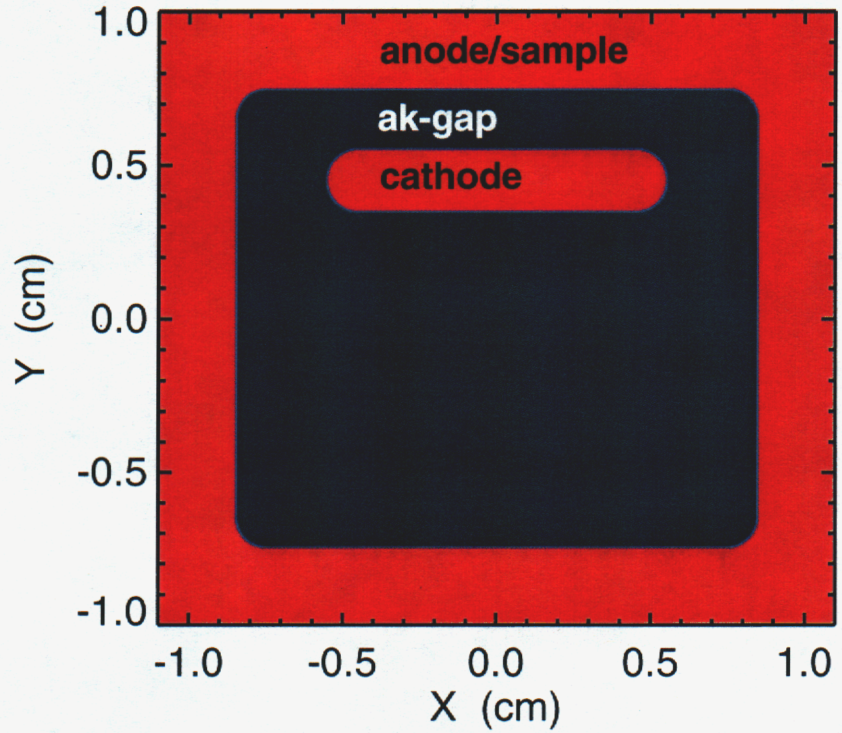
- Inductance increases due to electrode deformation.
- Hydrodynamic optimization minimizes early time electrode motion.
  - Stiff materials for electrode(s).
  - Isentropic compression.
- Electrical optimization of load maximizes pressure on sample.

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.

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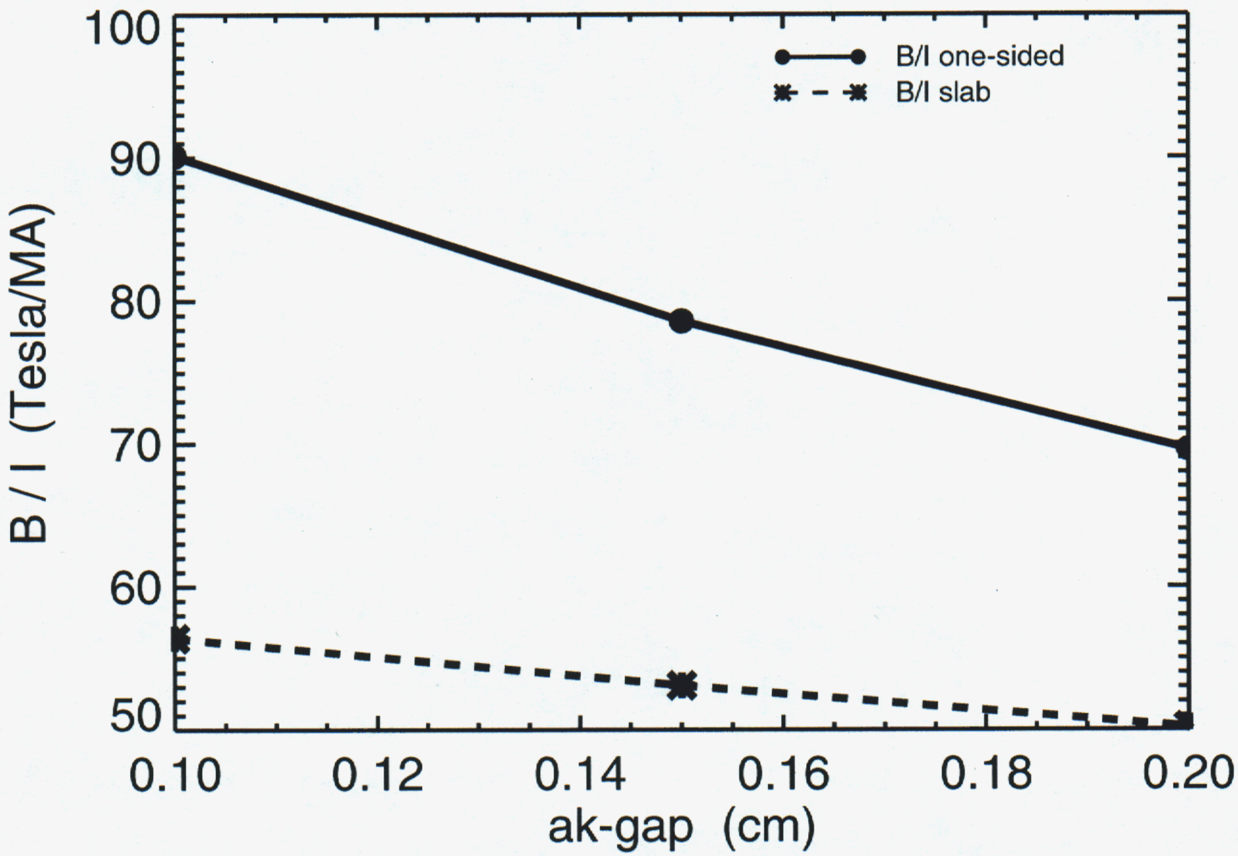
Electrical optimization yields large increase in magnetic field (pressure) for same current

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



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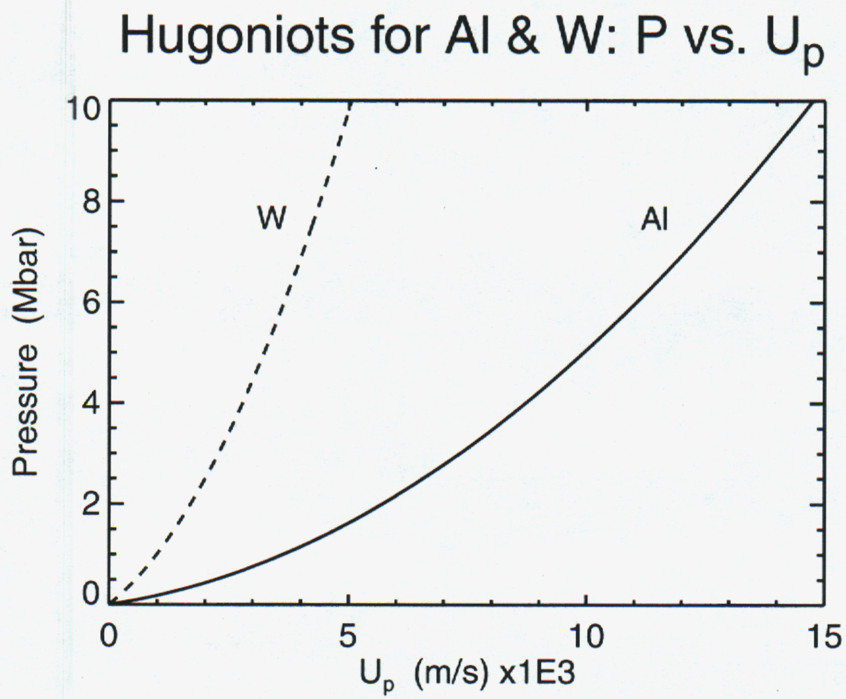
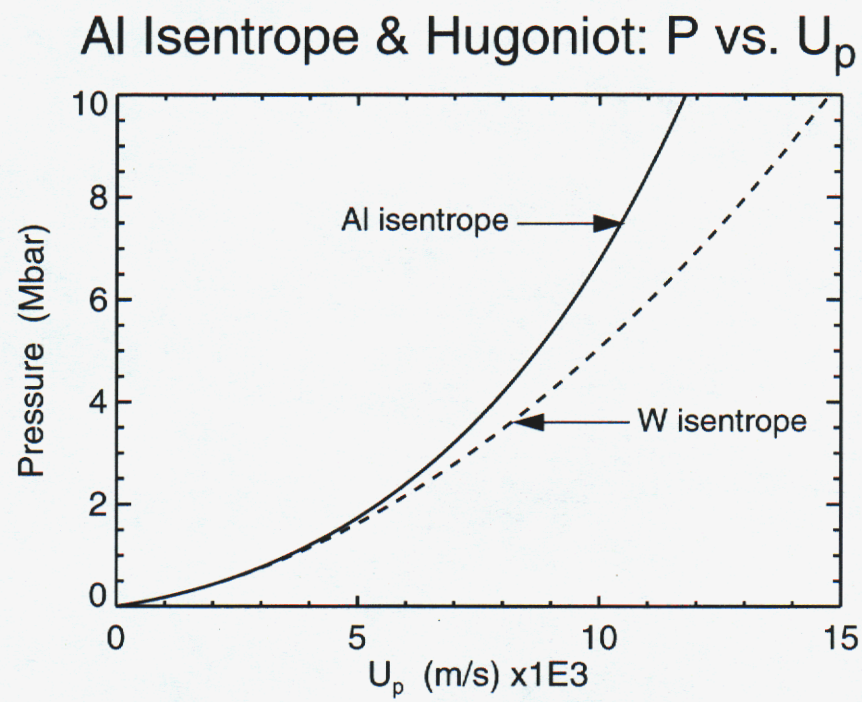
Hydrodynamic optimization of load minimizes electrode motion & avoids shock formation





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.

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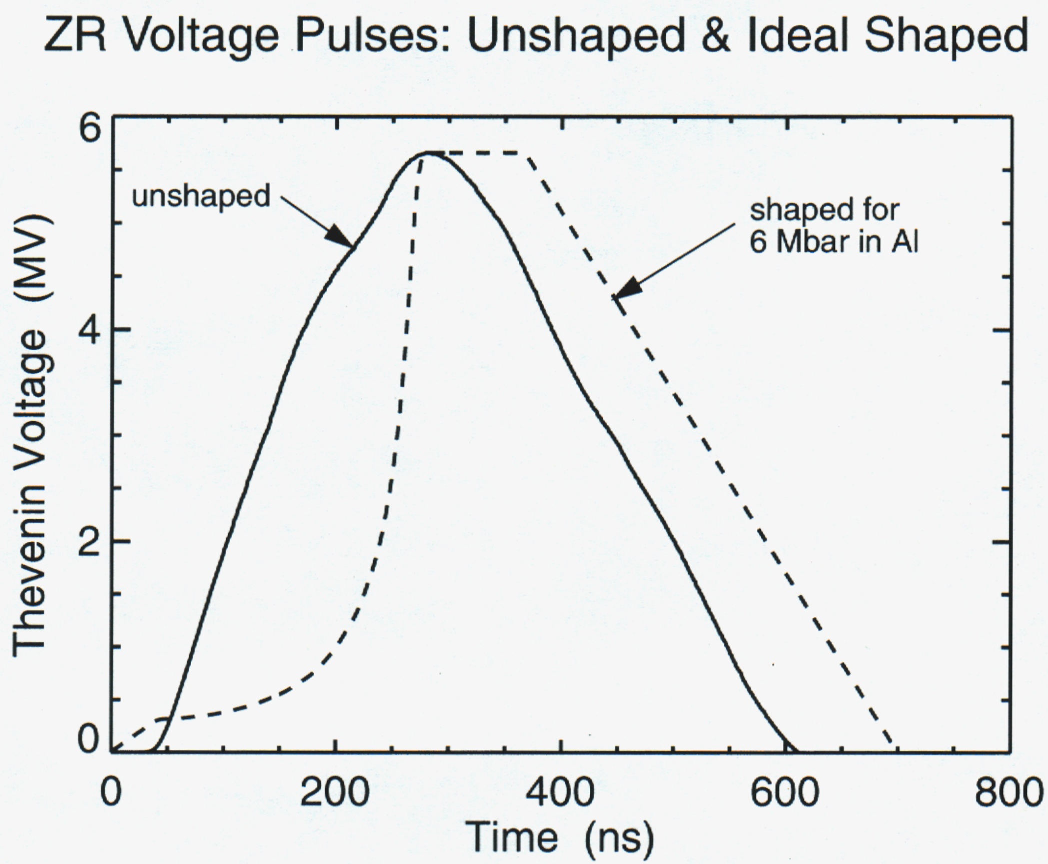
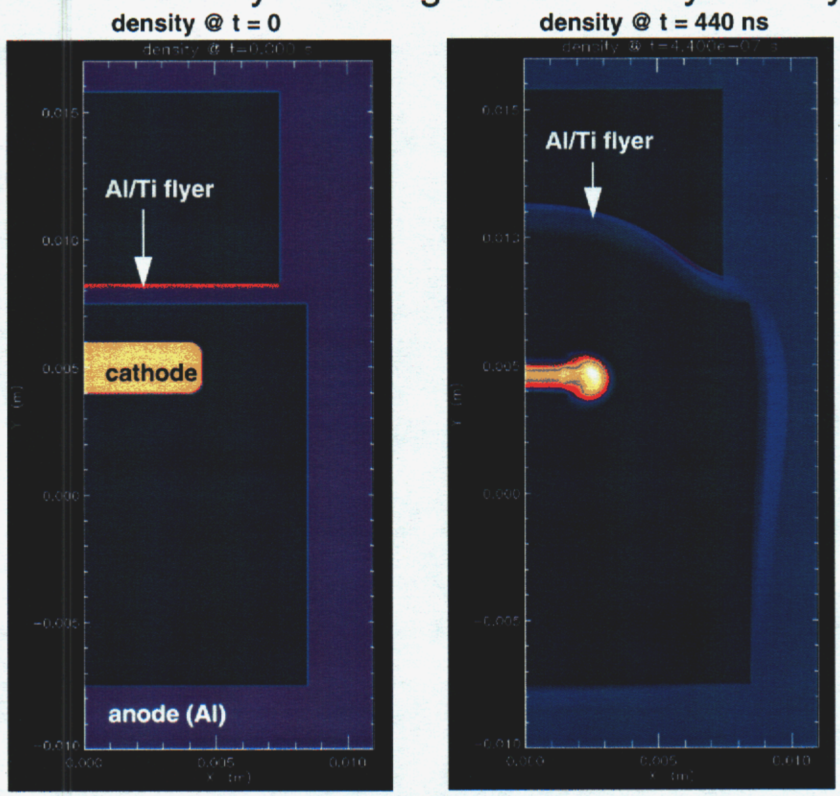
Very high velocities via multi Mbar isentropic compression requires voltage pulse shaping



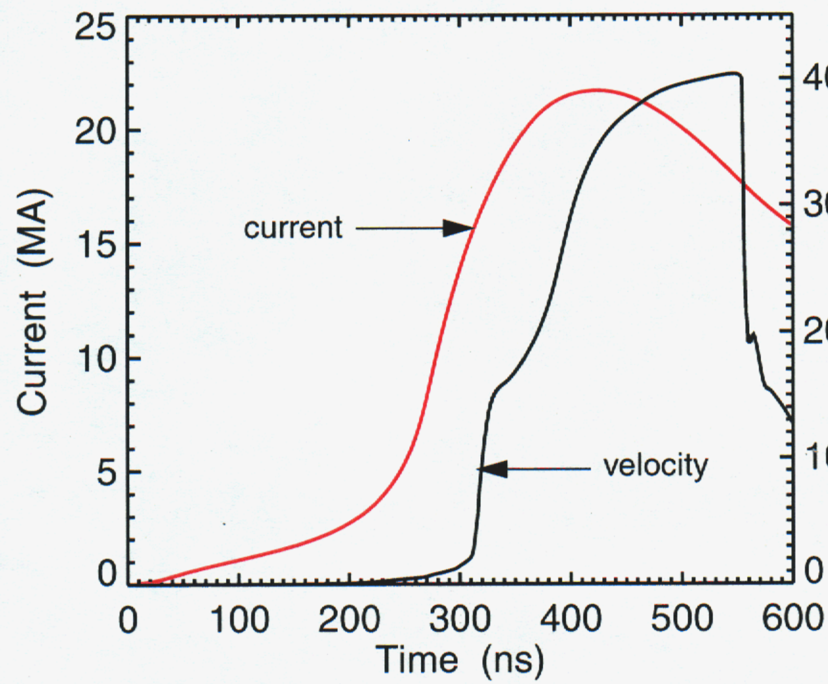
Voltage rise shaped for isentropic compression of Al to 6 Mbar.

40 km/s shockless flyer predicted for optimized one-sided geometry on refurbished Z machine

One Sided Flyer Configuration 1/2 Symmetry



Load Current & Flyer Surface Velocity



- *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.***

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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 D_2.
  - Peak ICE pressures of ~10 Mbar in tungsten.