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Considerations for Generating Up To 10 Mbar Magnetic Drive Pressures With The Refurbished Z-Machine

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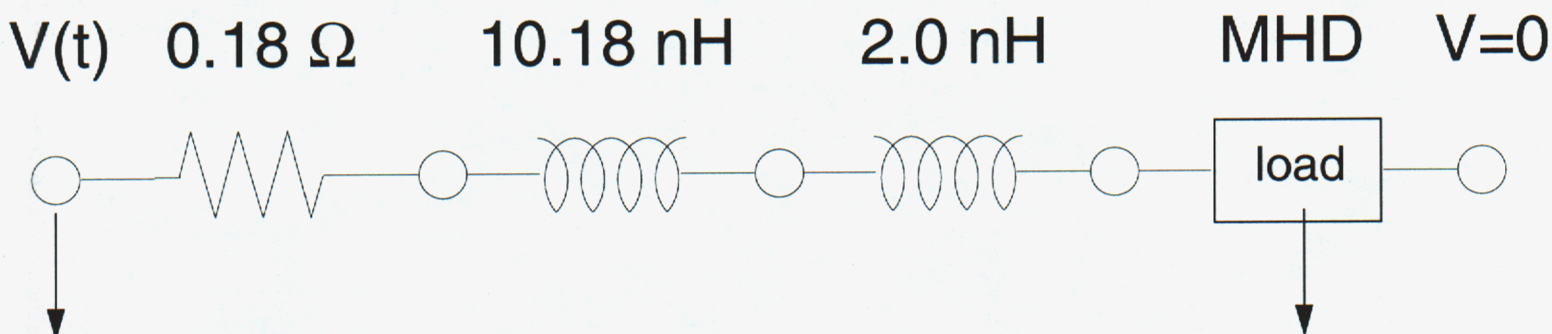
Introduction

- *The refurbished Z-machine, called ZR, is expected to deliver ~28 MA to a variety of loads. We are interested in determining the peak magnetic drive pressure that can be generated in a load that would typically be used in EOS experiments on ZR (involving either shocks, or isentropic compression).*
- *In this context, a typical load is formed by a rectangular slab cathode enclosed by a hollow rectangular duct, the anode. The electrodes are shorted at one end. The magnetic pressure at the anode serves as the driving pressure for the EOS experiment.*
- *The load undergoes significant deformation during the current pulse, which changes both it's inductance and the functional dependence of the magnetic field on geometry. These effects significantly reduce the peak magnetic pressure that can be achieved relative to a static geometry, and depend on: (1) details of the load [such as initial geometry and electrode material] and (2) the machine voltage (current) waveform.*
- *We have used the* ALEGRA *code to perform 2D, MHD simulations of shock physics loads that include the effects of dynamic geometry to determine the peak magnetic pressure that might be achieved on ZR. An external circuit model for ZR is used to drive the MHD simulation. Effects of the drive voltage waveform, and electrode materials were explored. Results are presented.*

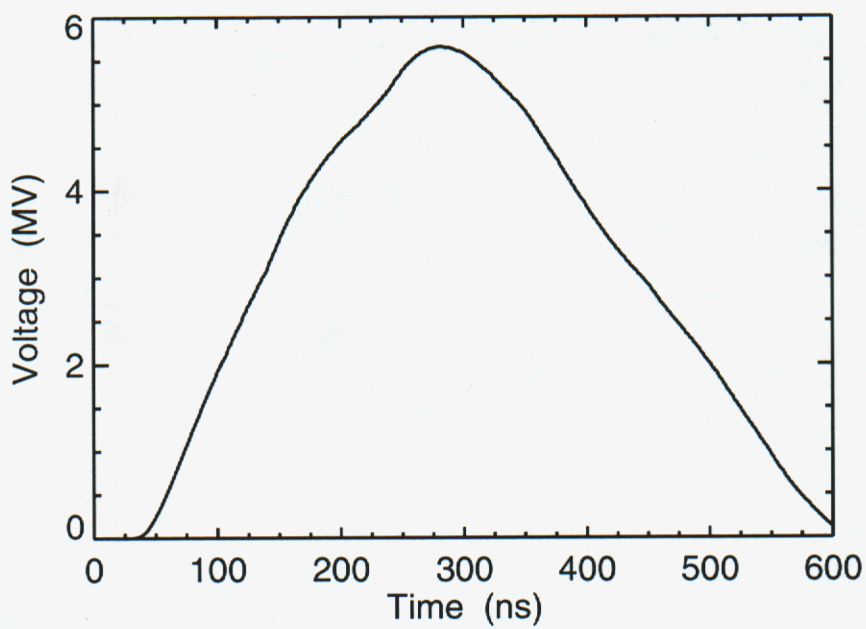
Summary of results

- *The magnetic pressure at a point on the anode can be expressed as $P(t)=0.5\mu_0[I(t)/S(t)]^2$, where I(t) and S(t) are the time-dependent current and magnetic field scale length, respectively. The deformation of the geometry that occurs during the current pulse increases the load inductance significantly, which reduces the peak current ~10-20% relative to a static geometry. The deformation of the electrodes also changes the way in which S(t) depends on the spatial coordinates. These two effects combine to substantially reduce the peak magnetic pressure that can be achieved relative to a static geometry.*
- *The effects of dynamic geometry can be offset somewhat using stiffer materials for one or both of the electrodes, and by shaping the current waveform so that significant deformation is delayed until near peak current (this is also a requirement to produce isentropic compression and shockless flyers). However, the shaped current pulse must contain the same energy as the unshaped or peak pressure is reduced.*
- *2D MHD simulations using the anticipated ZR circuit parameters predict that ~10 Mbar peak pressure can be generated in a shock physics load comprised of tungsten electrodes, and with a tapered voltage pulse. Pressures of ~6 Mbar and ~9 Mbar are predicted for aluminum and copper electrodes, respectively.*

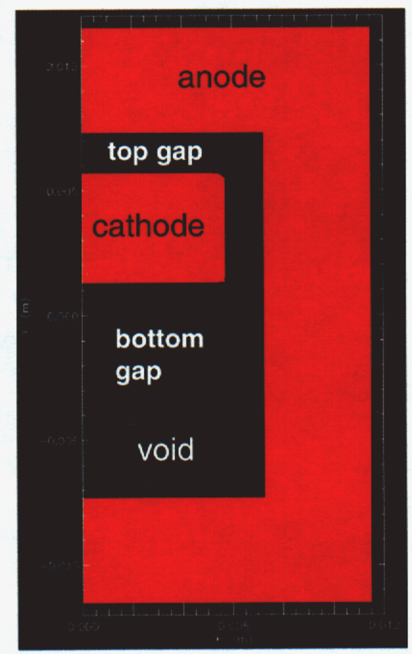
ZR circuit model coupled to ALEGRA 2D MHD



Predicted ZR Voltage Waveform (85 kV)



Load Geometry; Half-Symmetry



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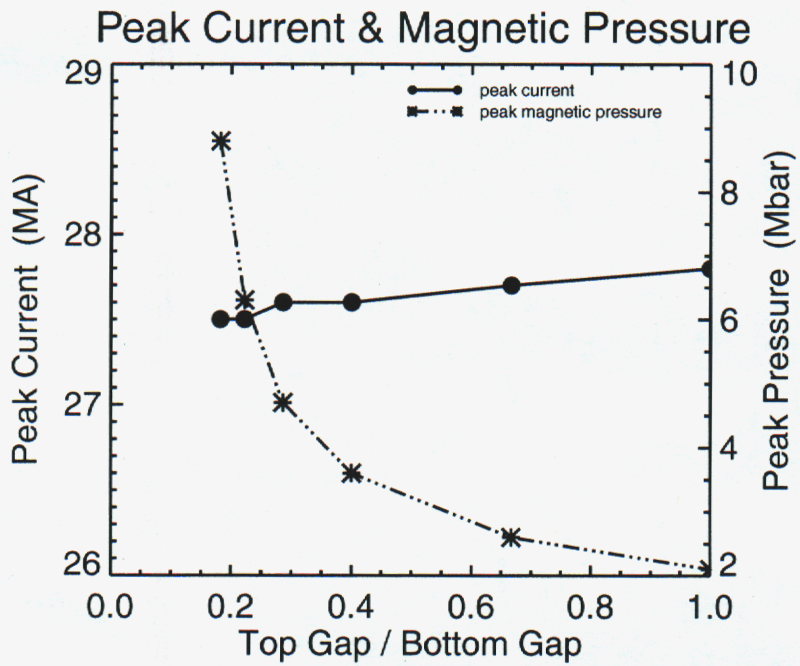
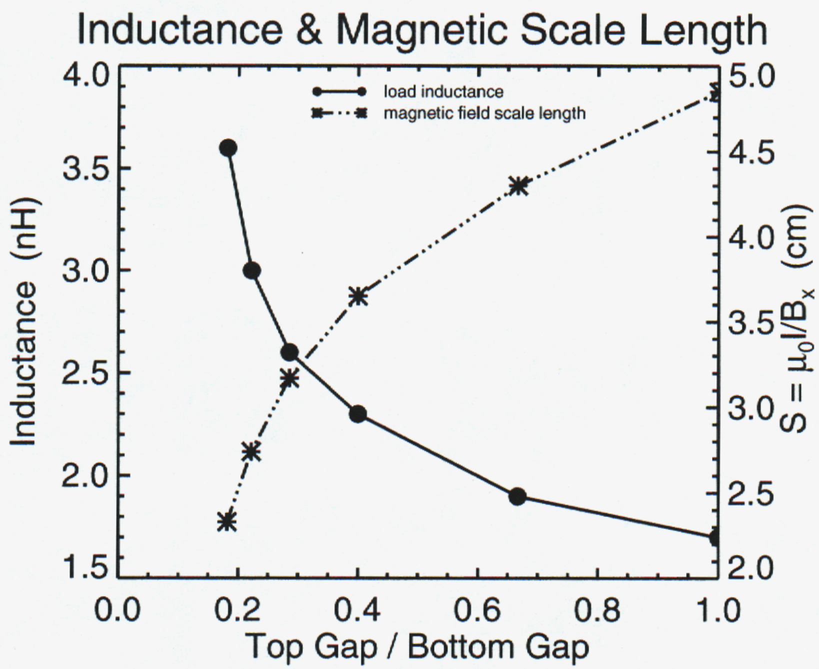
Predictions of maximum possible peak current & magnetic pressure: ideal conditions (no hydro motion & minimal magnetic diffusion)

- Results for ZR circuit & voltage waveform (85% maximum charge); aluminum electrodes; 2 mm top gap; 3.6 cm length in z-direction (affects inductance).
- Peak current ~27.7 MA; $2.1 \leq B^2/2\mu_0 \leq 8.8$ Mbar. Increasing bottom gap for fixed top gap increases magnetic pressure on anode surface.





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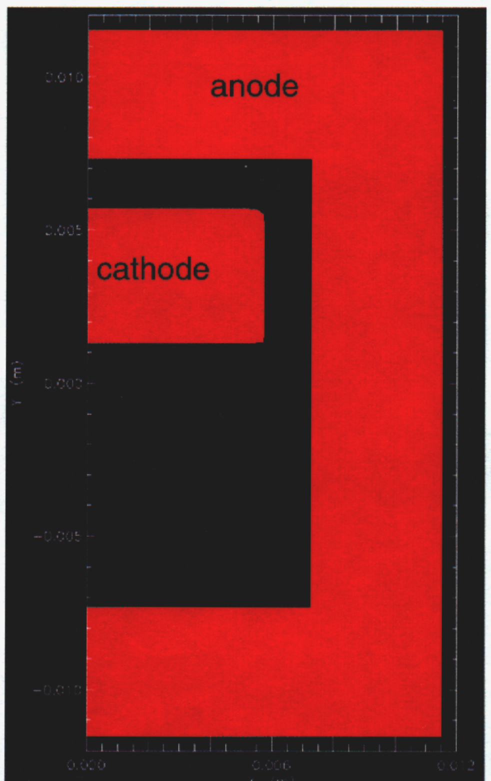
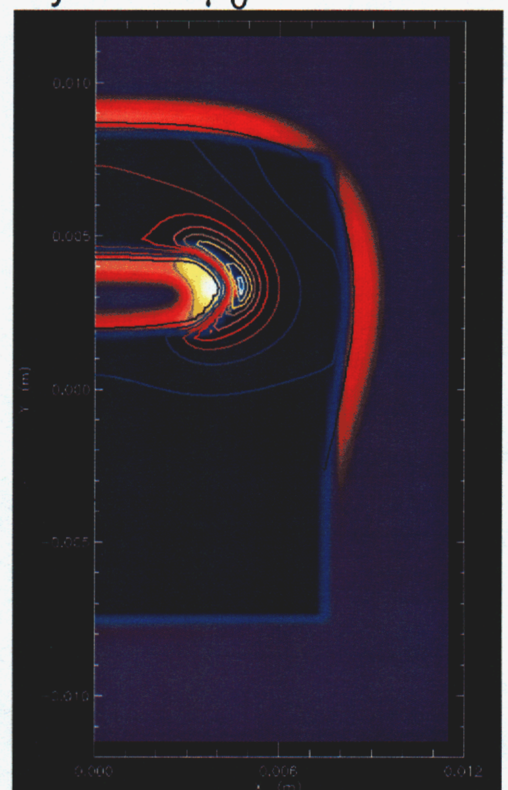
Full MHD simulation reveals significant electrode deformation during rise to peak current

- With Al electrodes, top and side gaps more than double in size due to compression of anode and cathode: produces inductance increase that lowers peak current relative to static geometry.

Density t=0



Density & $B^2/2\mu_0$ @ Peak Current



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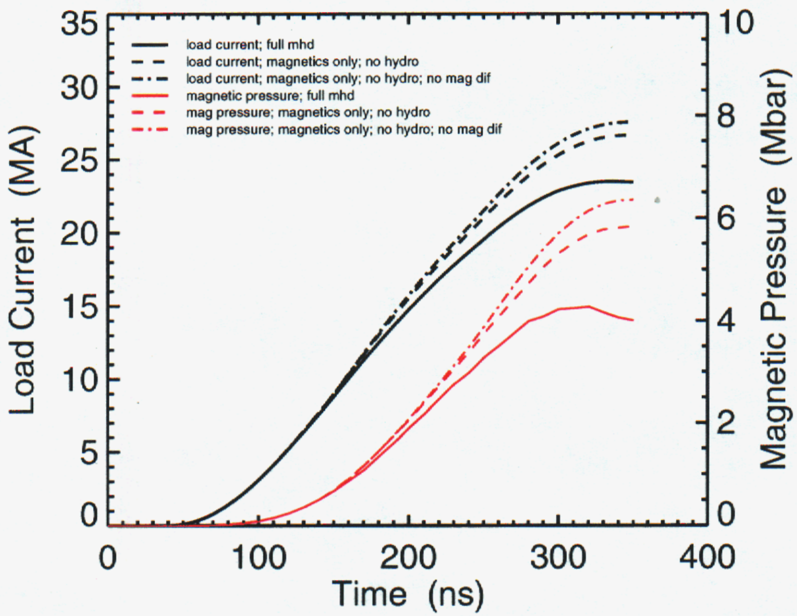
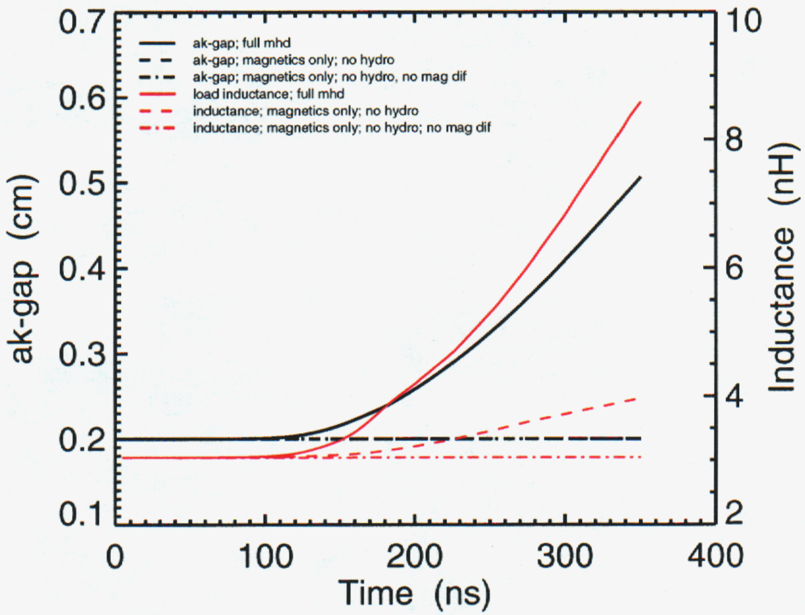
Electrode deformation causes significant inductance increase: reduces current and pressure

- Results for ZR circuit & voltage waveform; aluminum electrodes; 2 mm top gap; 4 mm thick cathode; 3.6 cm length in z-direction (affects inductance).
- Peak pressures: ideal case 6.3 Mbar; no hydro with magnetic diffusion 5.8 Mbar (8% reduction, 33% inductance increase); full mhd 4.3 Mbar (32% reduction, inductance increases by factor of 2.8 by peak current).

Load Current & Magnetic Pressure



AK-Gap & Load Inductance



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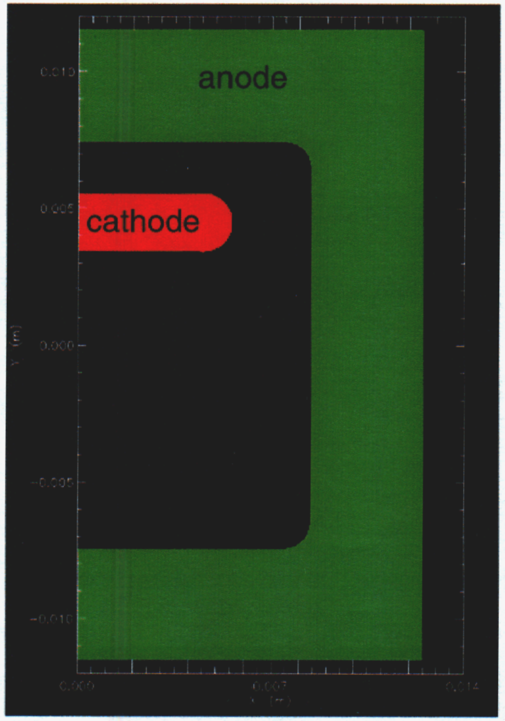
Effect of dynamic gap can be offset: requires pulse shaping, optimum load geometry, & stiff materials

- Load can be constructed to concentrate magnetic flux in sample area (minimize alternative parallel current paths). Use stiff material for cathode or both electrodes (smaller ak-gap possible, yields maximum pressure).
- Tapering rise of voltage (current) pulse as shown minimizes electrode deformation (inductance increase) until peak current (also required for ICE).

Semi-optimized Load



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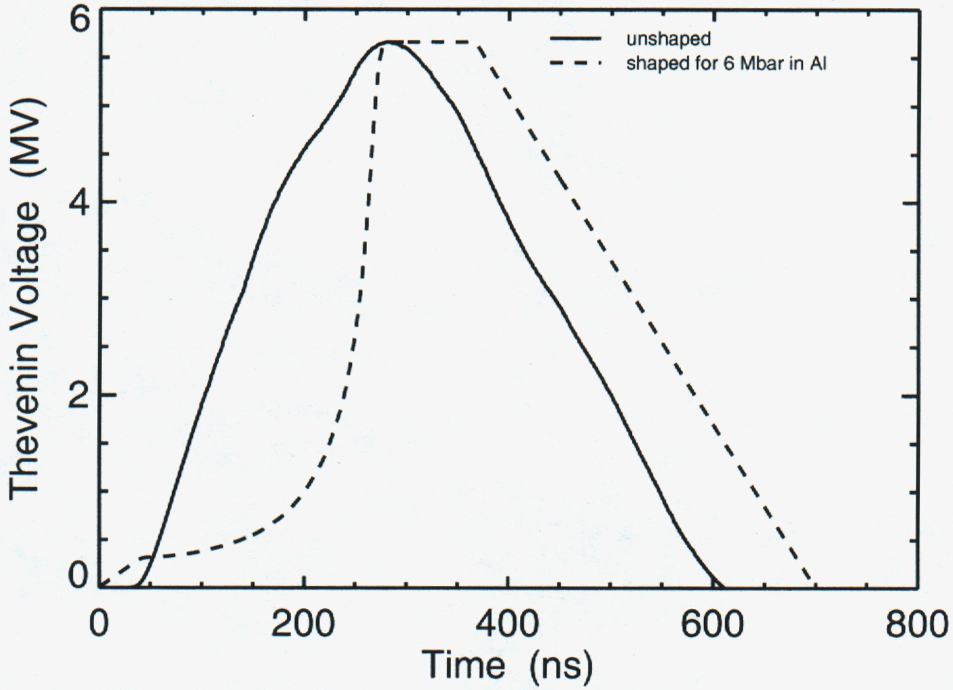
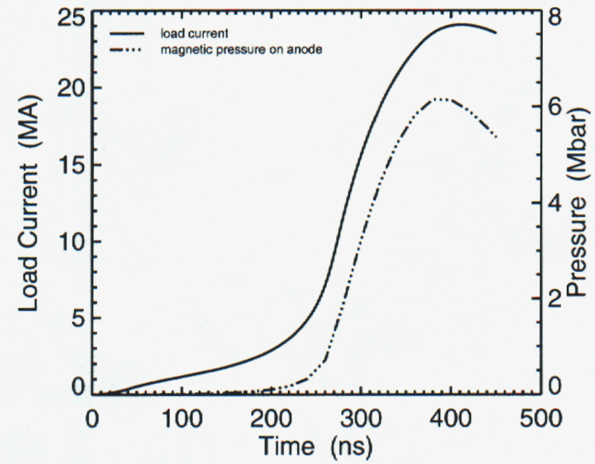
ZR Voltage Pulses: Unshaped & Shaped



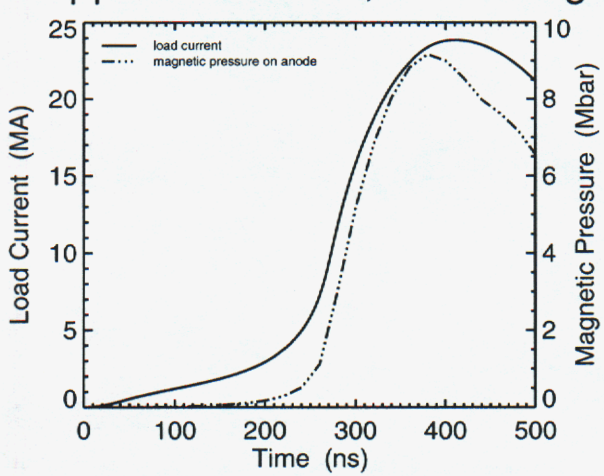
Optimized load configuration: simulations predict 6.2 Mbar in Al, 9.2 Mbar in Cu, & 10.2 Mbar in W

- All cases full MHD; ZR circuit model (85 kV charge); shaped voltage waveform; semi-optimum load geometry; 2 mm thick cathode.
- With proper design large pressures can be achieved.

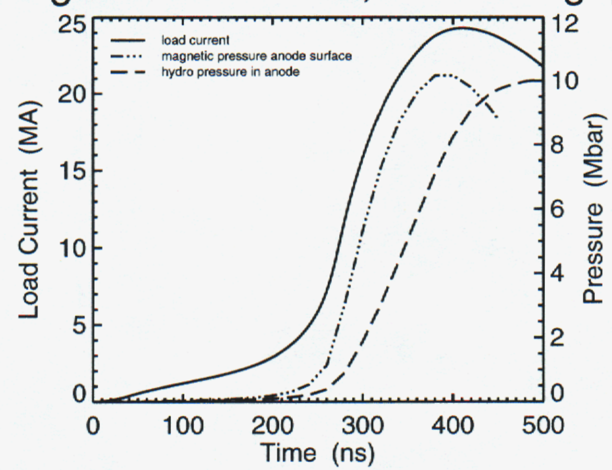
W cathode; Al anode; 2 mm ak-gap



Copper electrodes; 1 mm ak-gap



Tungsten electrodes; 1 mm ak-gap



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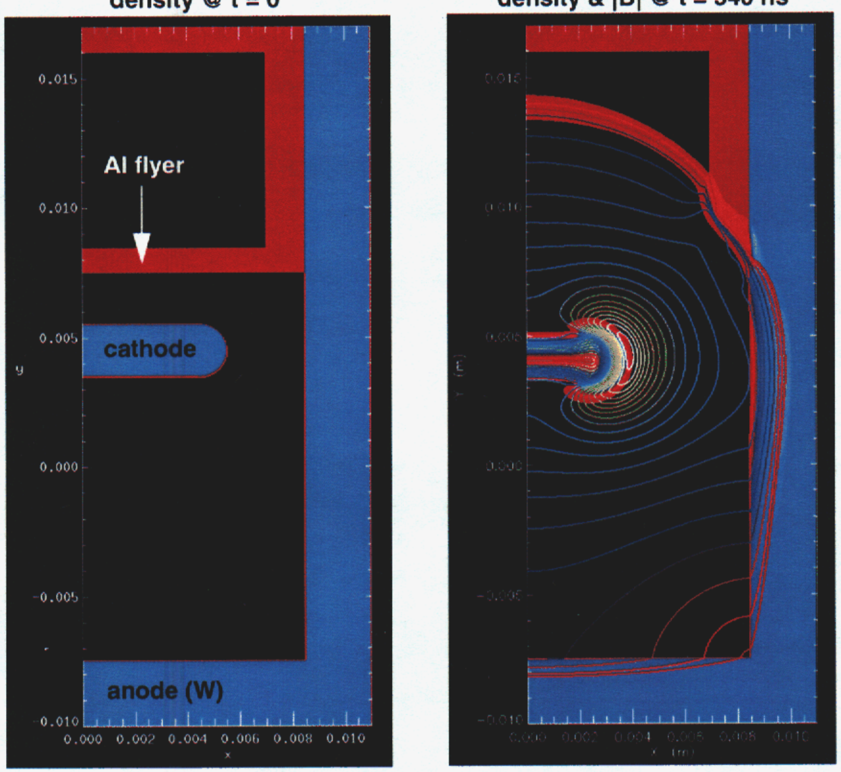
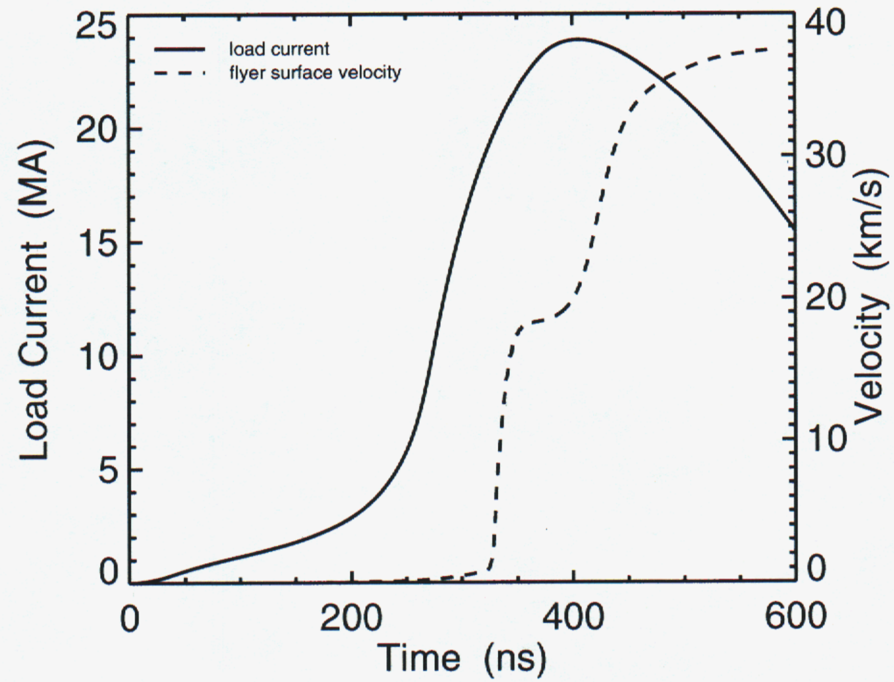
ZR applications: ultra high velocity flyers for EOS studies

- 37 km/s flyer velocity predicted by 2D MHD simulation: 0.1 cm thick Al flyer; ZR circuit; shaped voltage waveform; 6 Mbar drive; tungsten electrodes.
- Would extend D_2 EOS data up to 2 Mbar.

High Velocity Flyer Configuration



Load Current & Flyer Surface Velocity



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Conclusions

- *2D MHD simulation shows that loads used in EOS studies on the refurbished Z-machine (ZR) will undergo a substantial increase in inductance during the rise of the current pulse due to a combination of magnetic diffusion and deformation of the electrodes. Electrode deformation is the predominant cause of increasing inductance (L-dot), which has the affect of reducing the peak magnetic pressure that can be achieved relative to a static geometry.*
- *Using 2D MHD simulation that self-consistently accounts for the L-dot effect, we have shown that pressures exceeding 10 Mbar are possible on ZR when: (1) the load geometry is designed to concentrate magnetic flux on one area of the anode, (2) the waveform of the driving voltage is shaped to delay significant electrode deformation until peak current, and (3) at a minimum the cathode material is as stiff as is possible.*
- *Simulations using a semi-optimized configuration predict pressures of 6.2 Mbar, 9.2 Mbar and 10.2 Mbar can be achieved on ZR in Al, Cu, and W, respectively. In the case of Al, a flyer velocity of ~37 km/s is predicted, which would be used to generate up to 2 Mbar pressure in D_2. In the case of Cu, a pressure of ~13 Mbar could be generated in some nuclear materials of interest.*