Producing HED material states via magnetically driven planar and cylindrical configurations on Z

Ray Lemke

Sandia National Laboratories

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- Marcus Knudson, Jean-Paul Davis, Dan Dolan (experiments, design & analysis, data).
- Mike Desjarlais (theory & QMD simulation).
- Experimental support technicians & entire Z crew.

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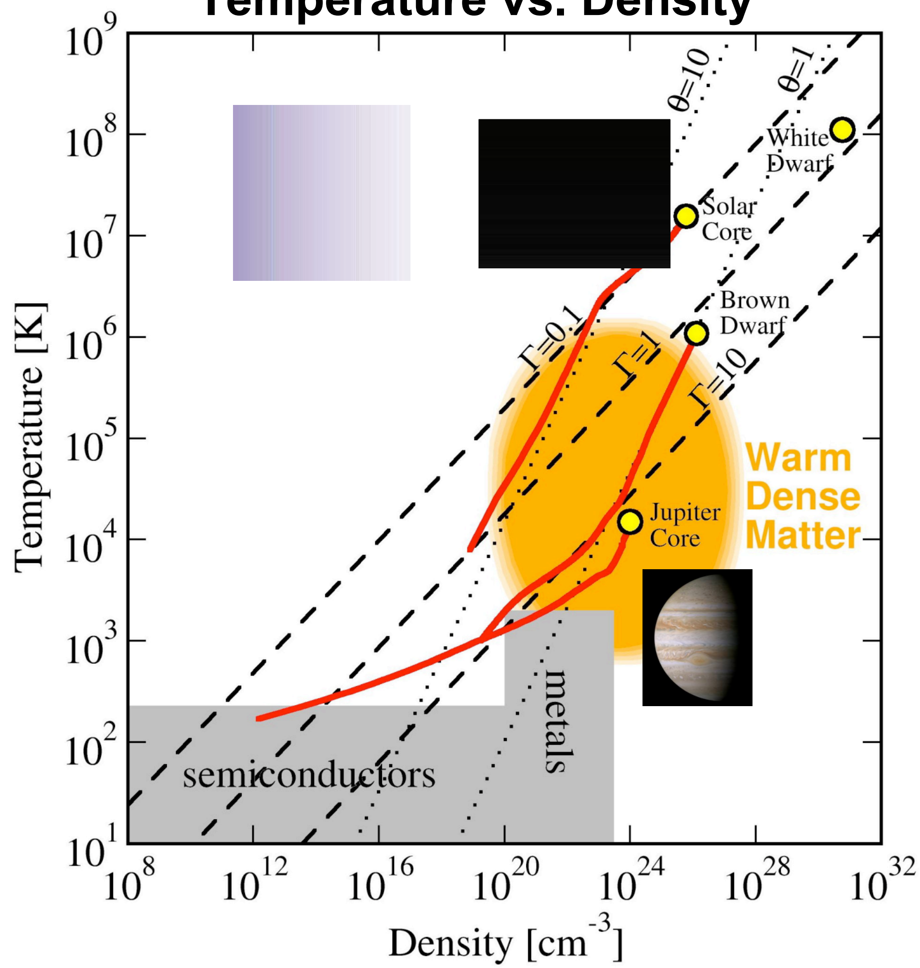
Warm dense matter: strongly coupled, quantum effects, coulomb potential ~ thermal energy

Plasma parameters:
coupling
Γ=L/D
degeneracy
$\Theta = k_B T / E_F$

Temperature vs. Density



Shock waves probe WDM up to several Mbar (gas gun, Z pinch, explosions, laser).

States **deep in interiors** of GPs and BDs will be accessible (e.g. Z machine).

Flyer plate impact & isentropic compression experiments on Z yield highly accurate EOS data

- Uncertainty ~1-2% typical due to accurate VISAR, uniformity of pressure drive, sample size & time scale.
- Current pulse shaping and large magnetic field (>1200 T) enable multi-megabar pressure drive (>6 Mbar).
  - Flyer plate velocities > 40 km/s.
  - 20.7 Mbar sapphire; 15.7 Mbar quartz (shock)
  - 5.5-14.0 Mbar diamond; 1.8 Mbar cryogenic D_2 (shock)
  - 3.8 Mbar Ta; 3.5 Mbar Be (ICE)
- Relevant to ICF, planetary physics, basic science (validation).

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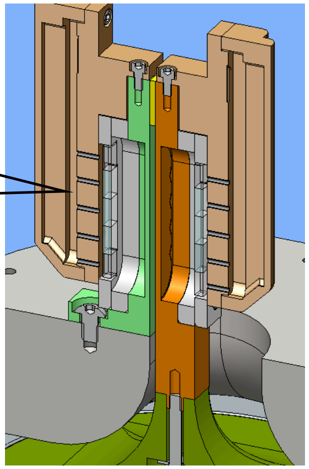
Computational & theoretical tools provide predictive capability for EOS experiments

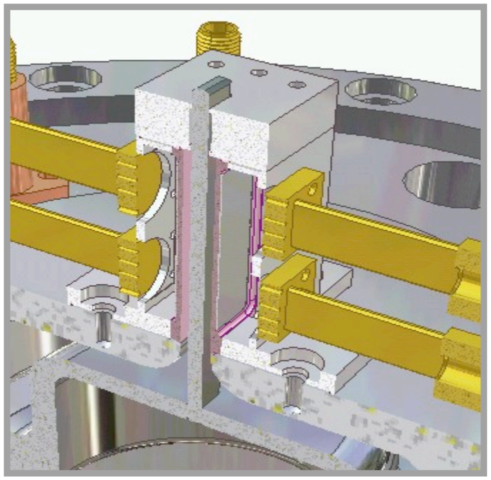
- VASP (Vienna ab initio simulation program; Technical U Vienna).
  - DFT (density functional theory) Kohn-Sham approximation to Schroedinger equation [A. E. Mattsson et al., Modelling Simul. Mater. Sci. Eng. 13 (2005) R1].
  - Calculations of equation of state / electrical conductivities (Desjarlais QMD/LMD).
- ALEGRA 2D & 3D resistive magneto hydrodynamics & radiation (SNL).
  - $\mathbf{J} = \sigma (\mathbf{E} + \mathbf{v} \times \mathbf{B})$.
- DAKOTA ---- SNL optimization code.
- BERTHA ---- NRL transmission line and circuit code.
- LASNEX ---- 2D, RZ, resistive MHD & radiation (LLNL).

Two platforms have been developed for accurate equation of state experiments on Z

planar stripline



rectangular, coaxial



Isentropic Compression Experiments (ICE)*

Magnetically driven Isentropic Compression Experiments (ICE) to provide measurement of continuous compression curves to ~4 Mbar
- previously unavailable at Mbar pressures

* Developed with LLNL

Magnetically launched flyer plates

Magnetically driven flyer plates for shock Hugoniot experiments at velocities to > 40 km/s
- exceeds gas gun velocities by > 5X and pressures by > 8X with comparable accuracy

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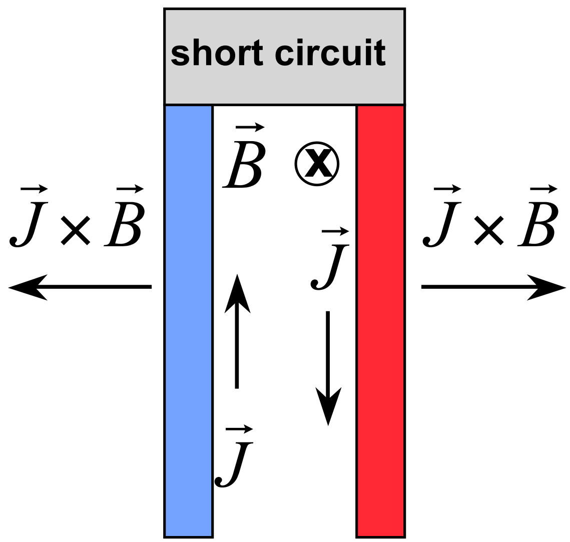
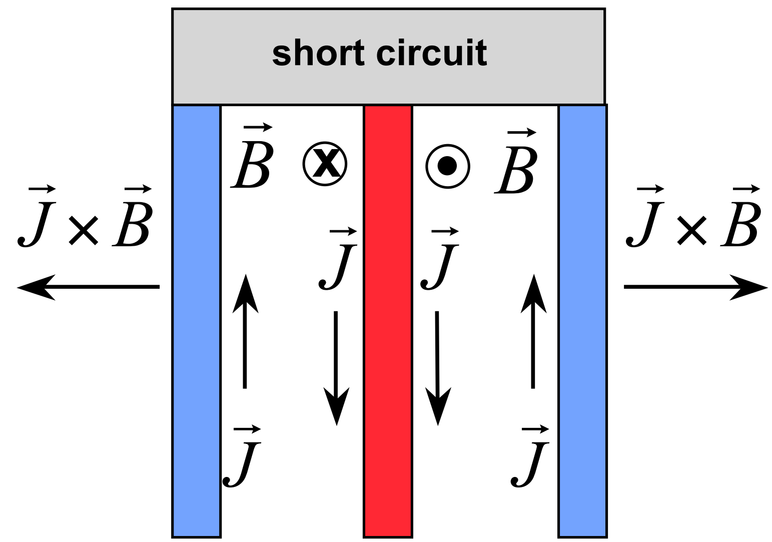
Planar strip-line flyer / ICE load guarantees symmetric pressure drive: produces larger pressure for same current

New planar strip-line: material samples or flyers both electrodes



Identical pressure on both electrodes in horizontal plane.

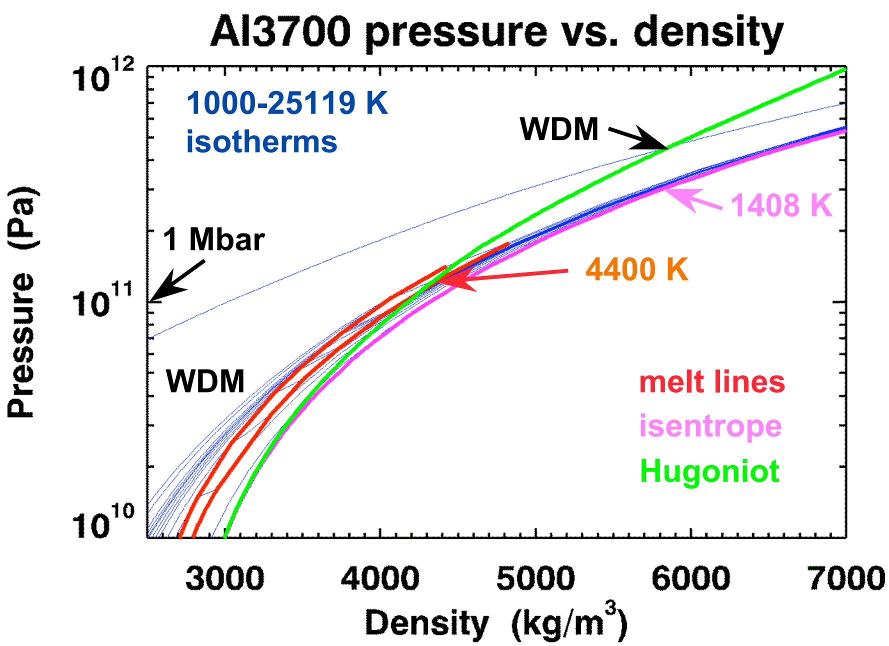
Rectangular coax load: material samples or flyers anodes only



Misaligned cathode causes unequal pressures on anodes in horizontal plane.

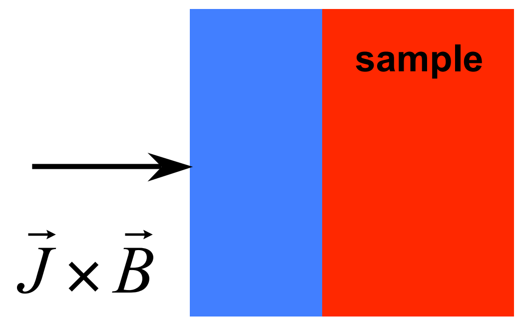
= anode **= cathode**

ICE yields an isentrope to a peak pressure; plate impact yields a point on a shock adiabat (Hugoniot)



Shock and release trajectory will go through WDM phase.

<u>*Isentropic Compression Experiment (ICE)*</u>



<u>*Plate Impact Experiment (Hugoniot)*</u>

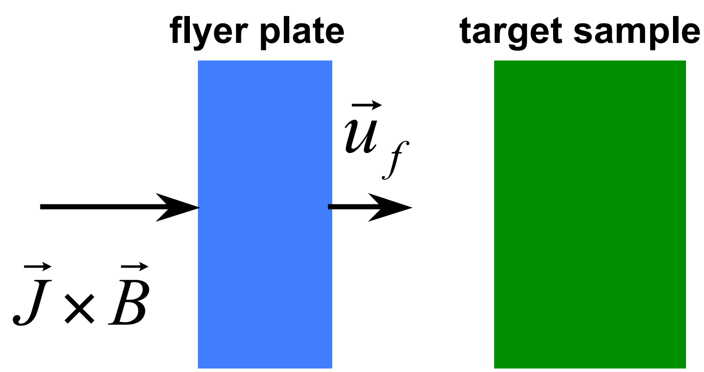


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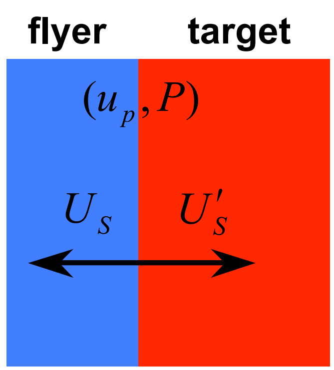
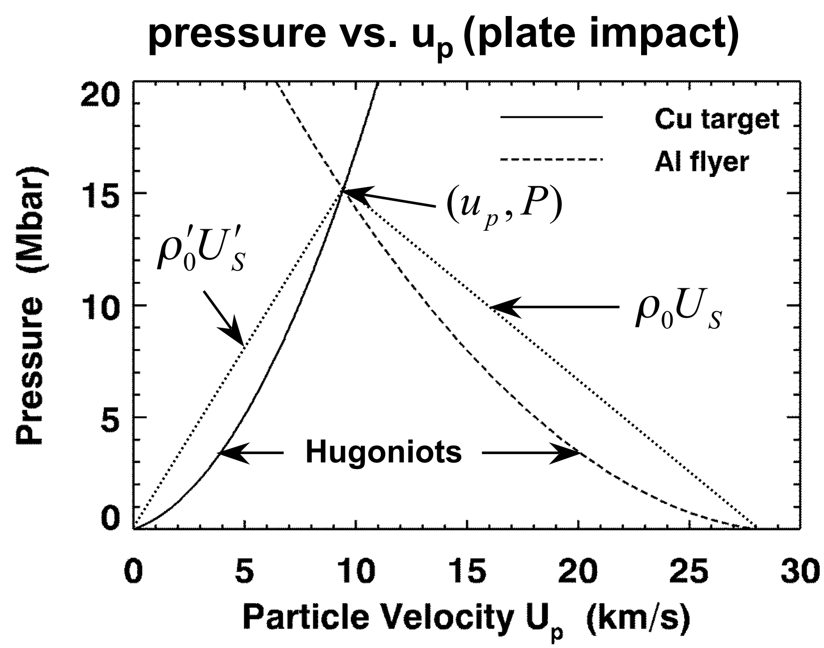
Plate impact experiments: state of flyer at impact is assumed to be known

Flyer plate & target sample after impact



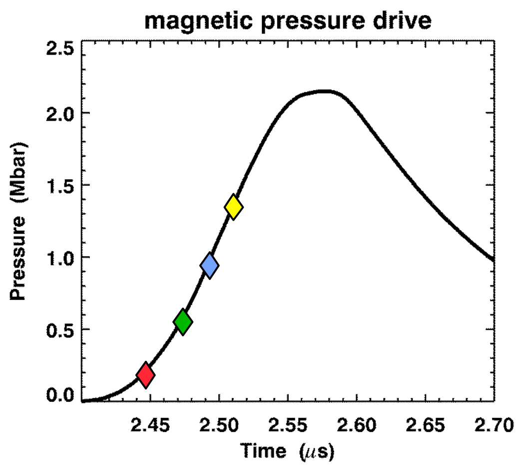
$$\rho_0 U_S (u_f - u_p) = \rho'_0 U'_S u_p$$

measured



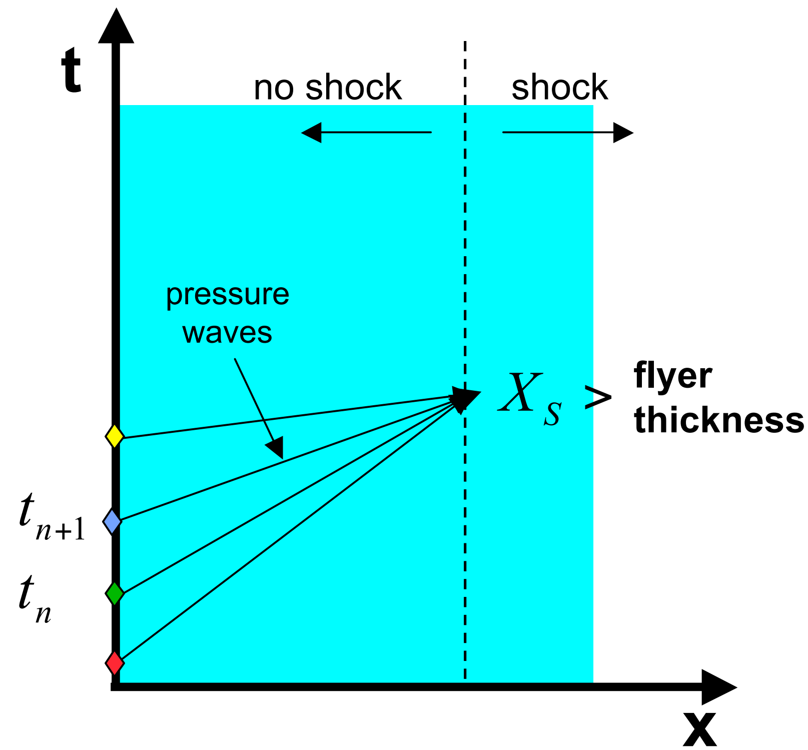
Shock-less acceleration of flyer plate achieved if applied magnetic pressure follows isentrope

Dynamic loading: speed of sound increases with increasing pressure; shock forms if rise time too fast.



dynamic loading

Lagrangian frame of material



Rise time of pressure drive:

$$t_{n+1} - t_n = \left[\frac{1}{C_L(P_n)} - \frac{1}{C_L(P_{n+1})}\right] X_S$$

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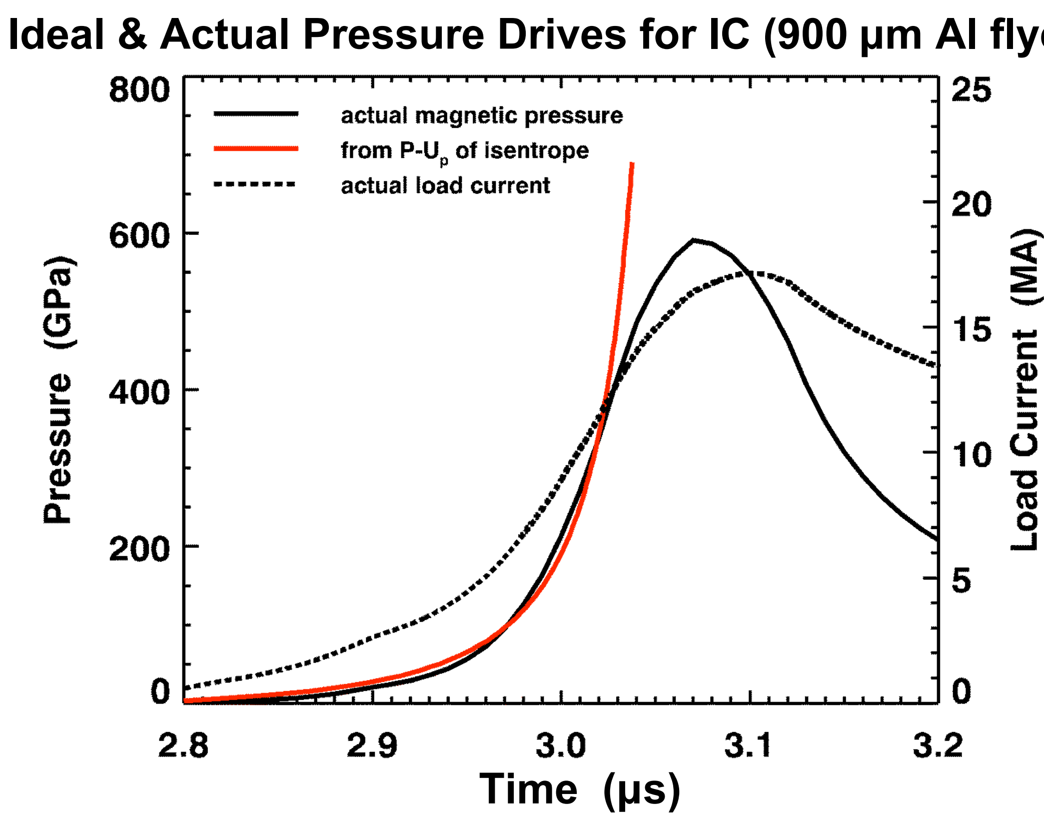
Ideal pressure drive must be mapped to a current that Z can produce



Feasibility of current shape determined using ALEGRA 2D MHD and detailed circuit model of Z in BERTHA.

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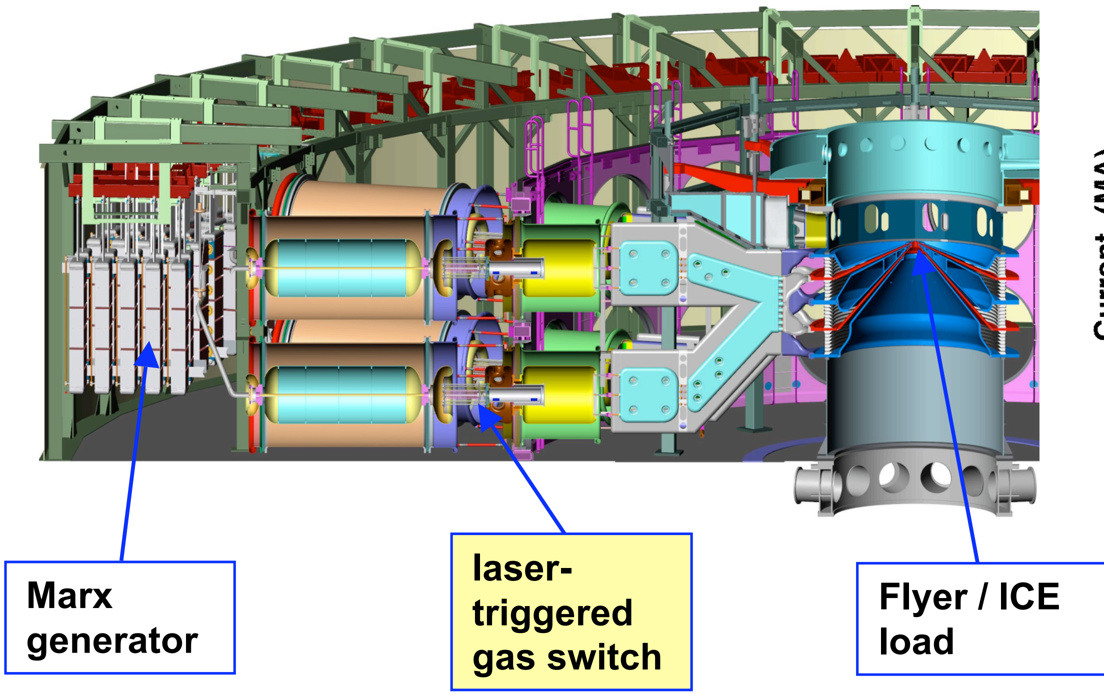
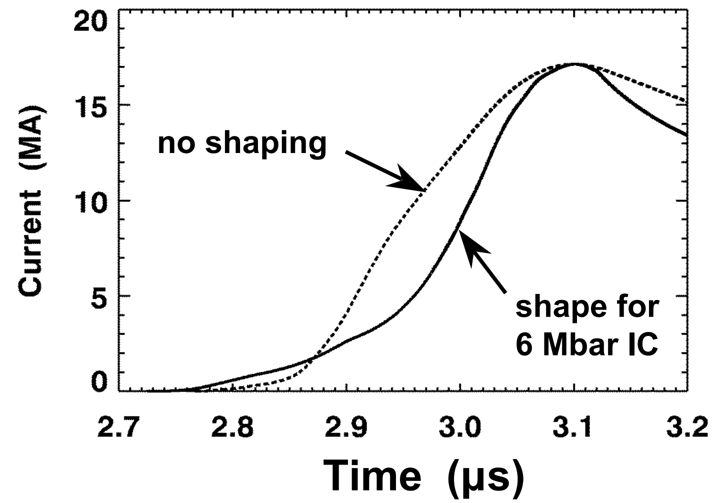
18 pairs, independently timed laser triggered switches enable current shaping for ICE & Flyers

Z accelerator



Shaped & Unshaped Load Current



Timing of laser triggered switches determined by detailed circuit model of Z in BERTHA with 2D MHD results.

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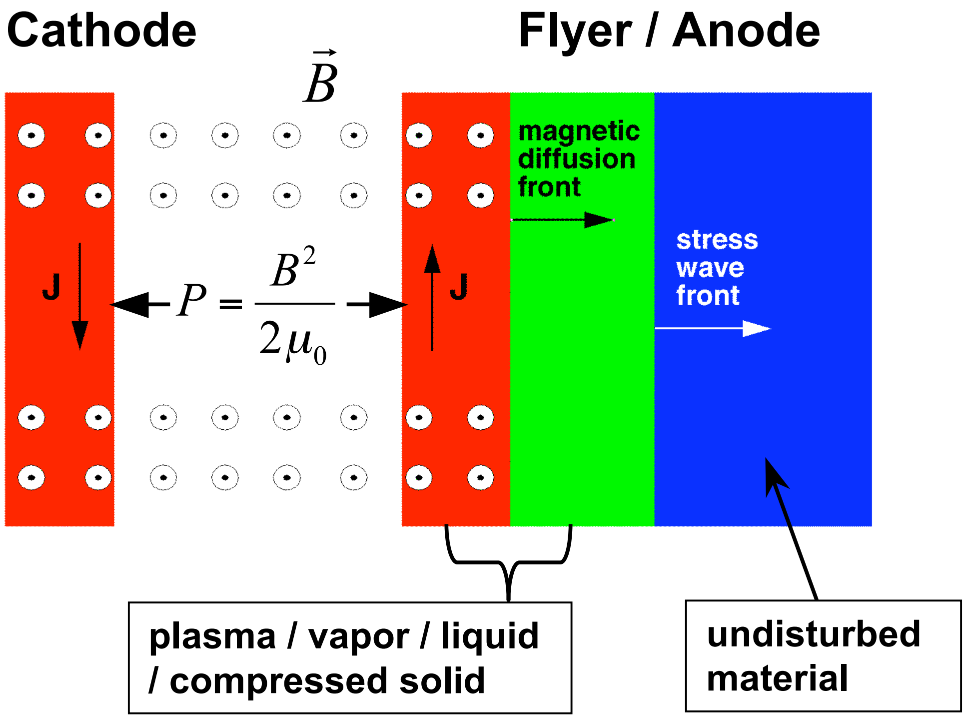
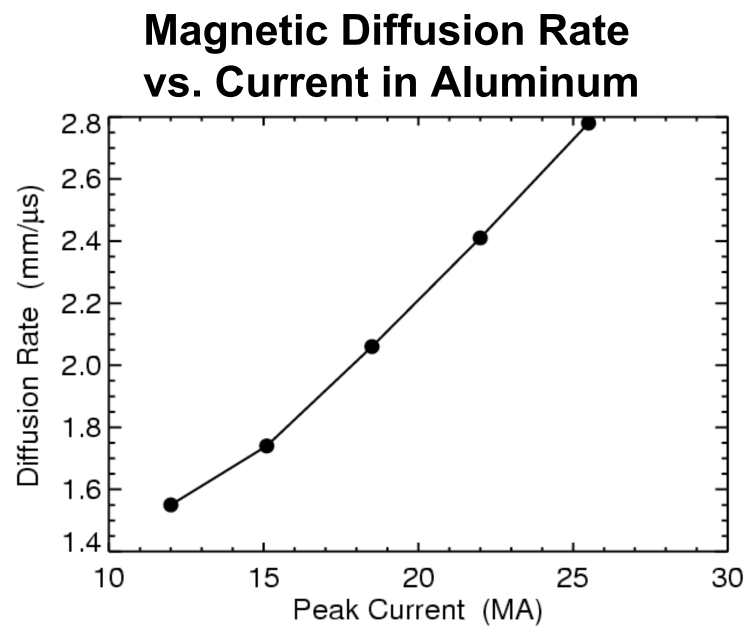
Magnetic acceleration of flyer plates: Joule heating destroys flyer if flight time too long





Flyer survival: flight time < flyer thickness / magnetic diffusion rate.

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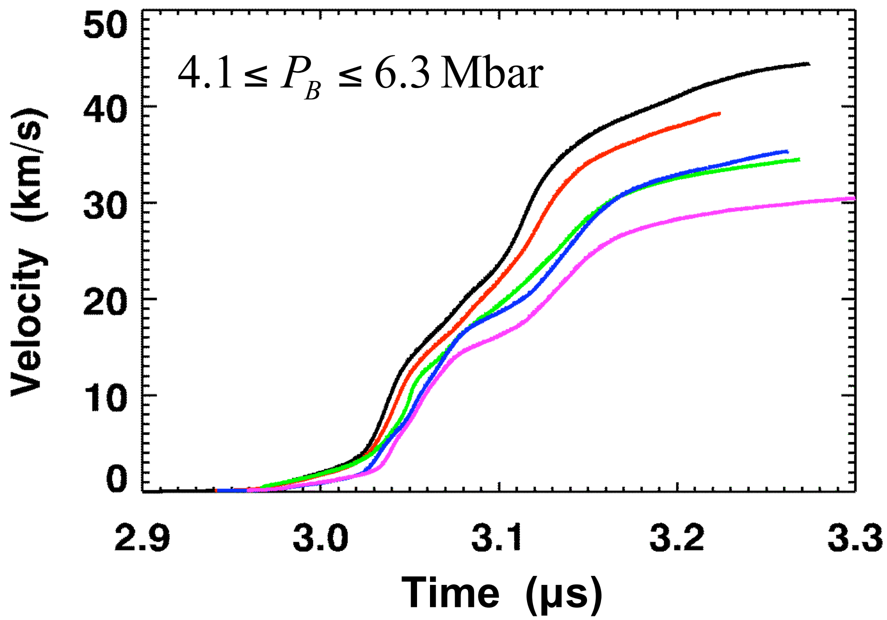
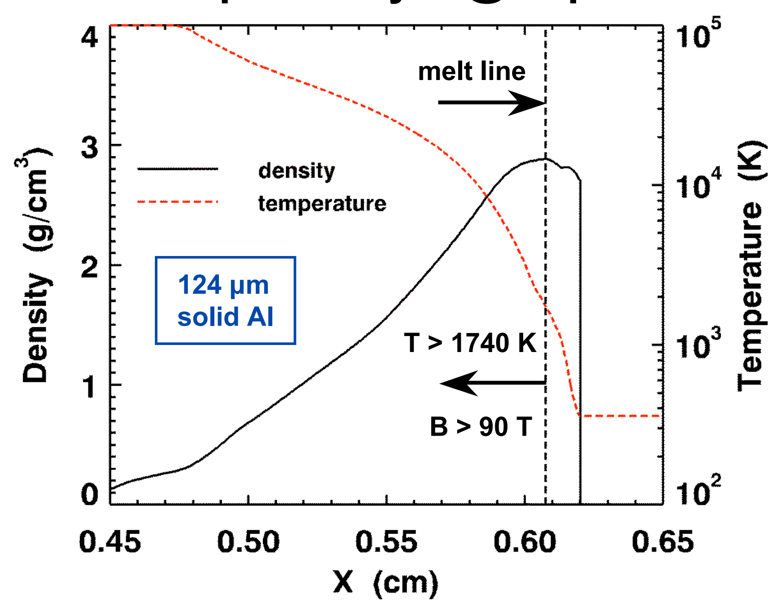
Strip-line flyer plate impact experiments on Z produced velocities > 40 km/s exceeding old record by ~30%

Velocity 900 µm Al Flyer Plate; all Strip-line Geometries



Density & Temperature of 900 µm Al Flyer @ Impact



40 km/s Al flyer shocked quartz to 15.7 Mbar, sapphire to 20.7 Mbar (would shock Cu target to ~29 Mbar).

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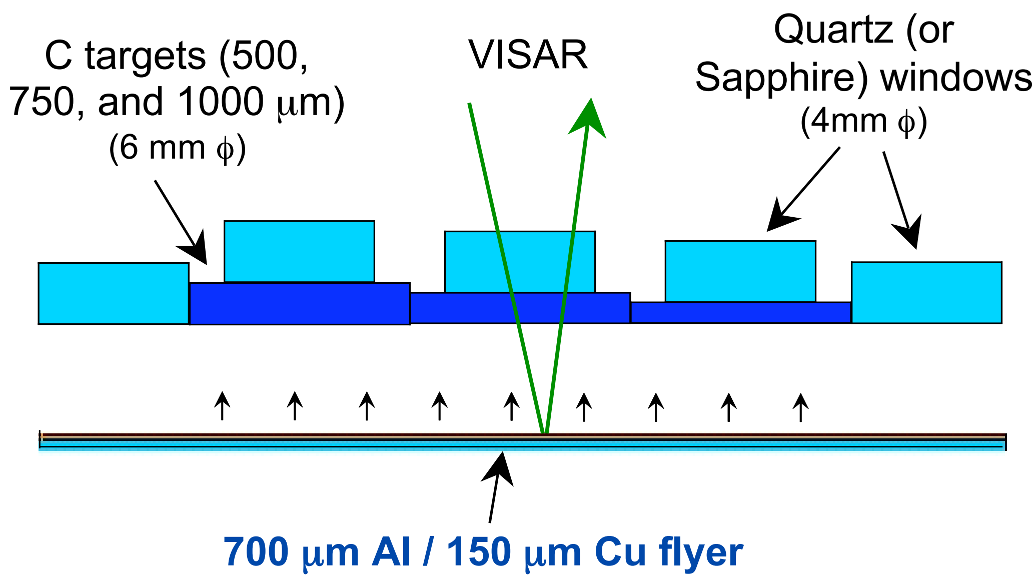
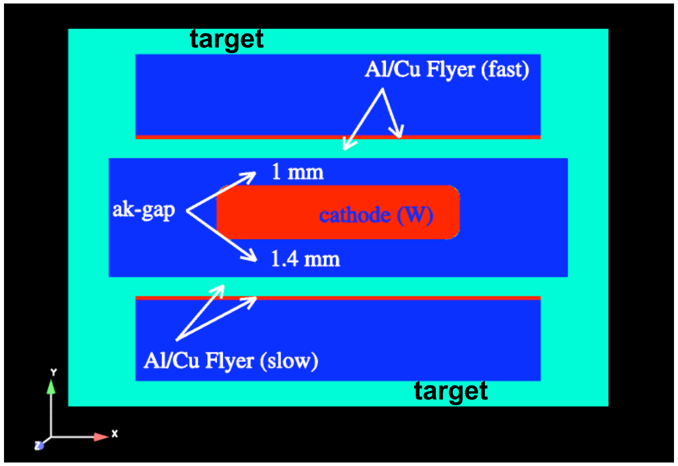
See R. W. Lemke et al., J. Appl. Phys. 98, 073530 (2005) for related work.

Diamond EOS experiments: 2D MHD simulations critical for defining load, flyer velocities & Z charge voltage



- Load designed to produce 2 flyers / shot with 10% difference in peak velocity.
- $7 \leq \textit{flyer velocity} \leq 24\ \text{km/s}$ (all shots)

Simulated asymmetric load



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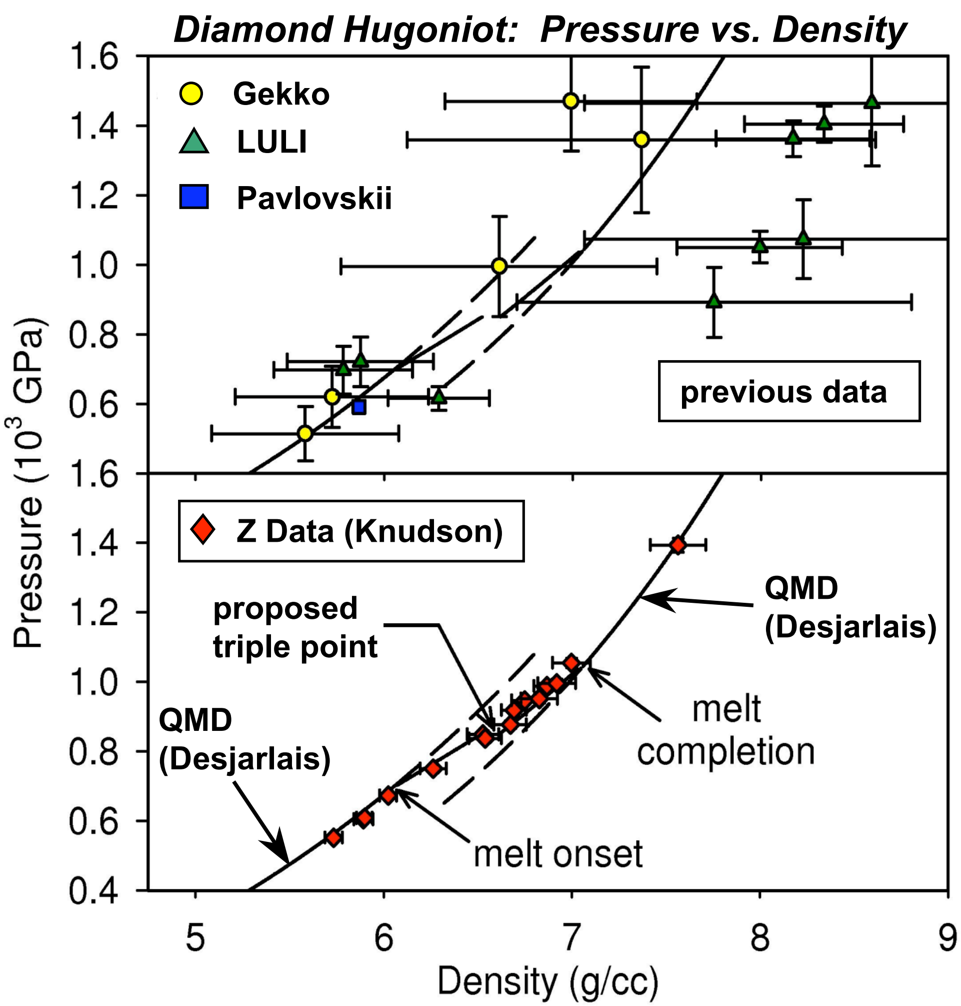
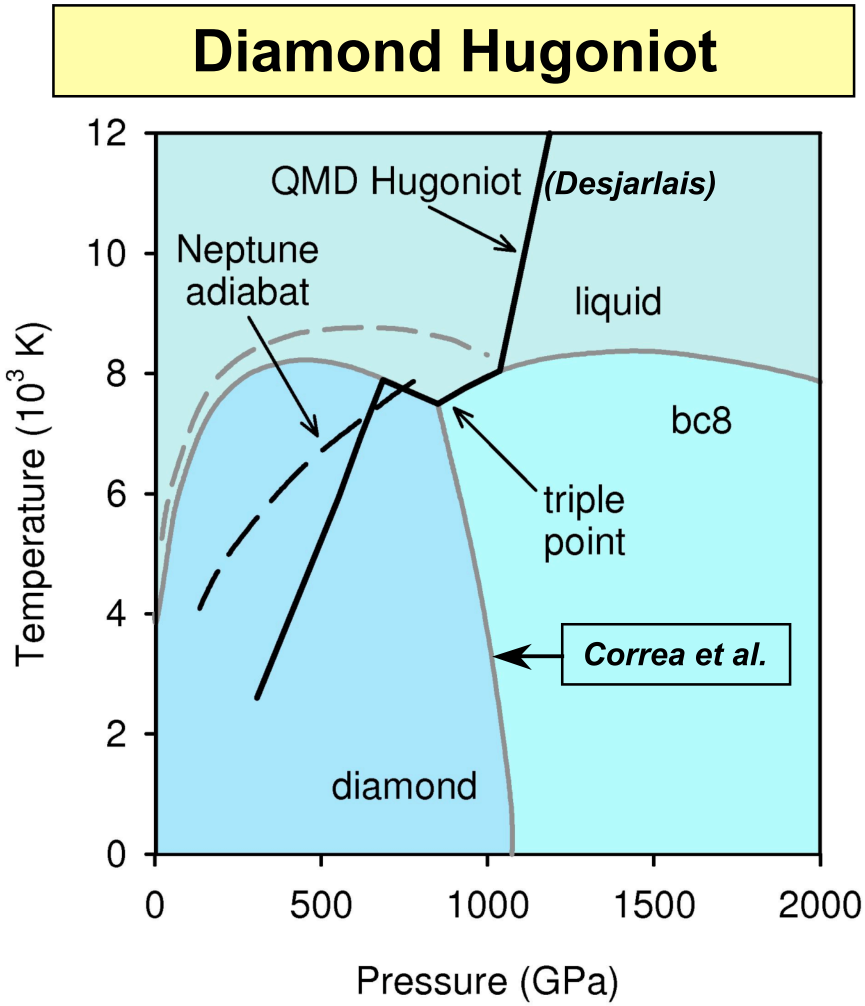
Accuracy of plate impact experiments on Z allowed for quantitative comparison with QMD predictions





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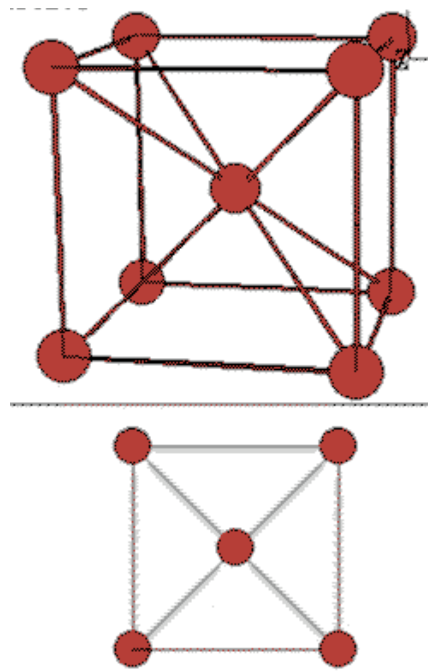
M.D. Knudson, M.P. Desjarlais & D.H. Dolan, Science 322, 1822 (2008)

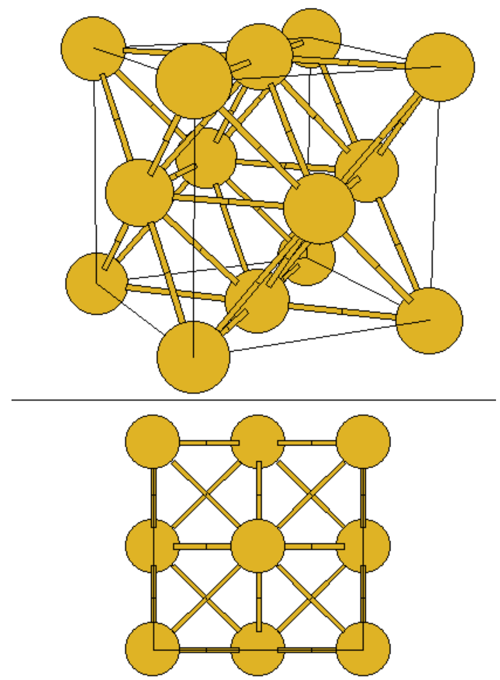
X-ray diffraction could be used on Z to determine lattice structure of compressed solids

- Lattice structure affects melt transition and strength.
- Lindeman melt law different for different lattices [S. Cho, J. Phys F: Met. Phys. 12, 1069 (1982)].
- For example, LiF lattice @ WSU [P. A. Rigg & Y. M. Gupta, Phys. Rev. B 63, 094112 (2001)].

BCC (body centered cubic)



FCC (face centered cubic)



http://cst-www.nrl.navy.mil/lattice

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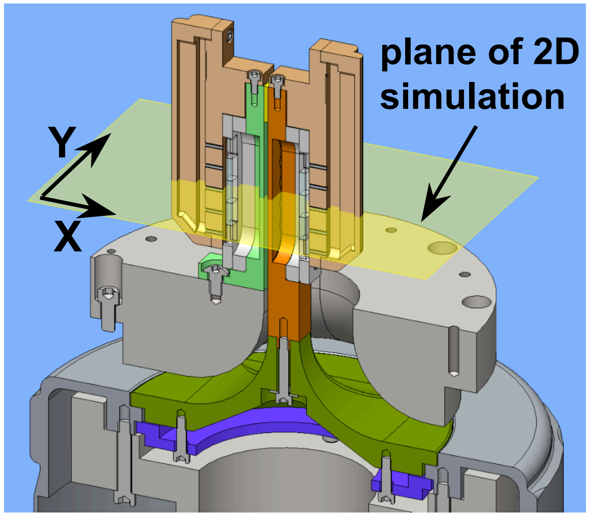
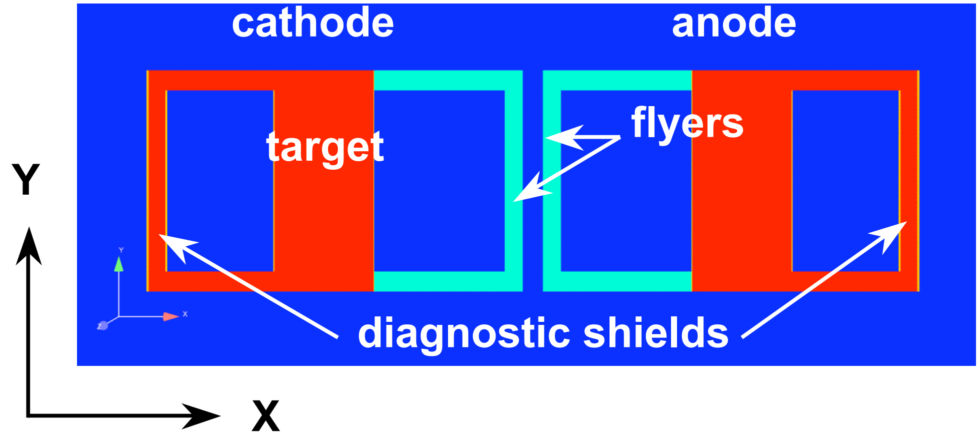
ALEGRA 2D MHD circuit driven simulations model power flow coupled to dynamic geometry

Two-sided Strip-line Flyer Plate Experiment



2D Simulation Plane of Two-sided Strip-line



Electrode motion limits peak magnetic pressure that can be achieved.

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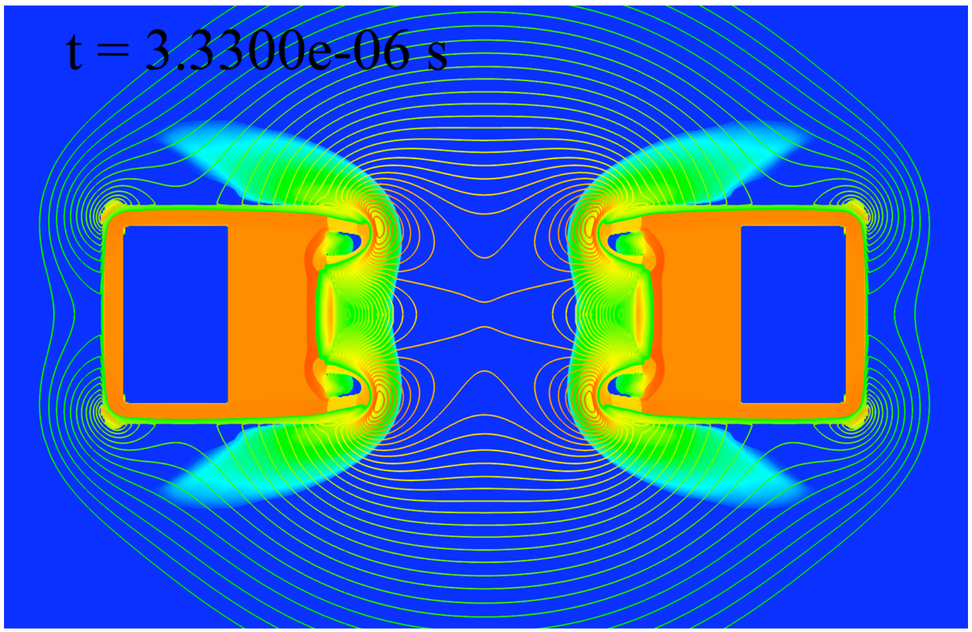
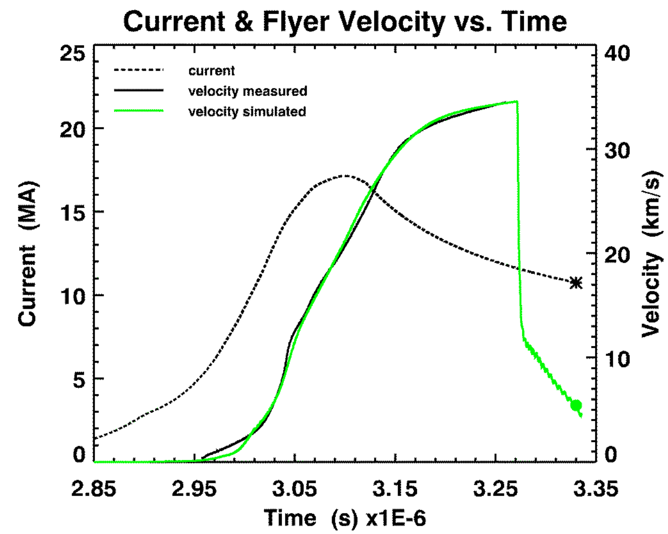
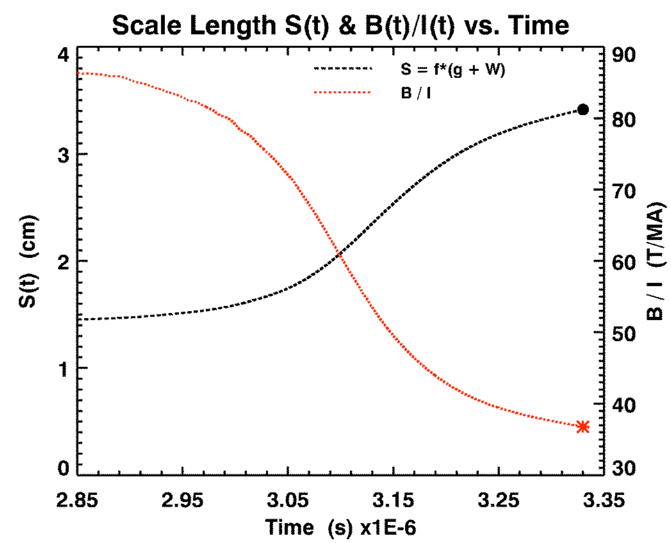
Strip-line magnetic field not confined to flyer region: plasma jets & electrode motion reduce B/I in ak-gap

Simulation 2-sided, 11 mm strip-line, 900 µm Al flyers, density & magnetic field





$$V_{flyer}(t) \cong \frac{1}{\rho_0 D} \int_0^t \frac{B^2(t')}{2\mu_0} dt'$$



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Electrodrode motion reduces magnetic pressure for a given current & ultimately limits flyer velocity

- Magnetic field and inductance in ak-gap / flyer region (strip-line):

$$B_{gap}(t) / I(t) = \mu_0 / S(t) \text{ where } S(t) = f[g(t) + W(t)]$$

$$L_{gap}(t) = l\mu_0 g(t) / S(t) \quad \text{limits current}$$

$$V_{flyer}(t) \cong \frac{\mu_0}{2\rho_0 D} \int_0^t \left[I(t') / S(t') \right]^2 dt'$$

- Flyer velocity increases slower than $I^2(t)$ as pressure increases.

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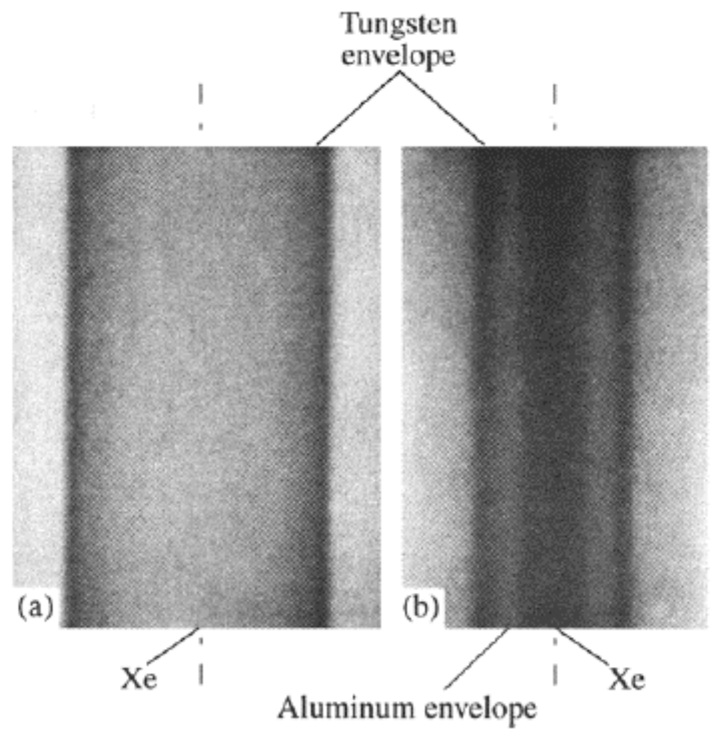
Cylindrical liners are an attractive load for EOS studies on Z: magnetic pressures > 10 Mbar possible

- Liner radius 0.2 cm, I=19 MA, B=1900 T, P=14.4 Mbar.
- Magnetic pressure α *1/R²*.
- EOS data unfolded from x-ray backlighting measurements.
- We are investigating possible loads for EOS liner implosion experiments on Z.
- Possible experiments include cylindrical plate impact, direct drive, reflected shock followed by quasi isentropic compression.

X-ray imaging used to measure pressure on Xe isentrope to 7.2 Mbar, T=14300 K, 5% accuracy*.



***O. L. Mikhailova et al., High Temperature, Vol. 38, No. 2, 210-214 (2000).**

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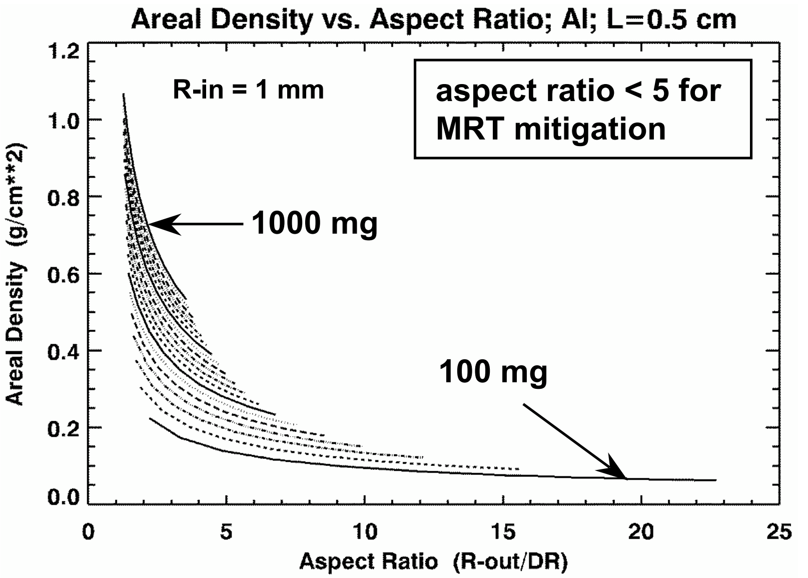
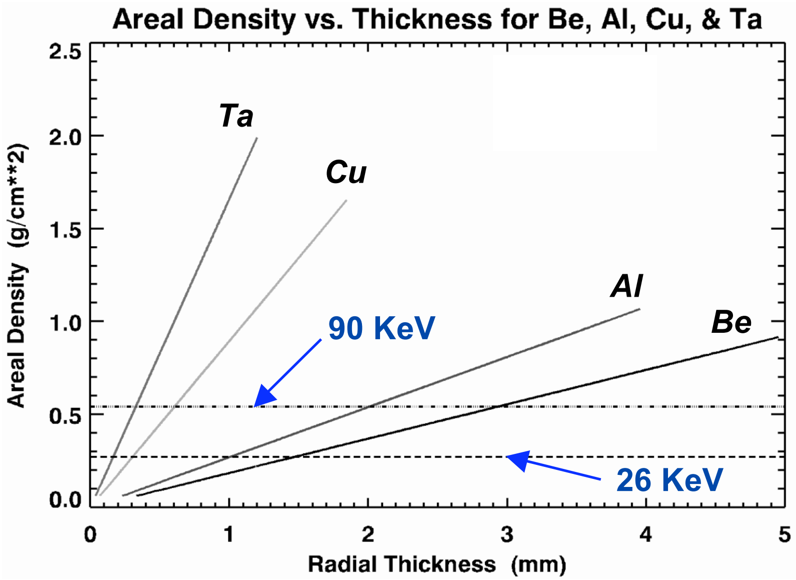
Need higher energy backlight capability at Z to image liners with relevant areal densities





- Present capability: Z-beamlet laser K-shell backlighter 6.151 KeV.
- Future capability: Z-petawatt (ZPW) laser K-shell backlighter ~8-30 KeV.
- Research: ZPW bremsstrahlung x-ray backlighter with > 100 KeV x-ray energy.

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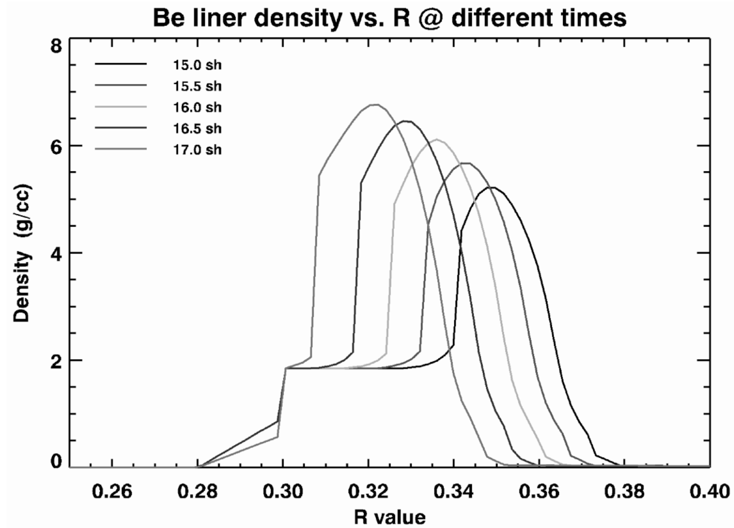
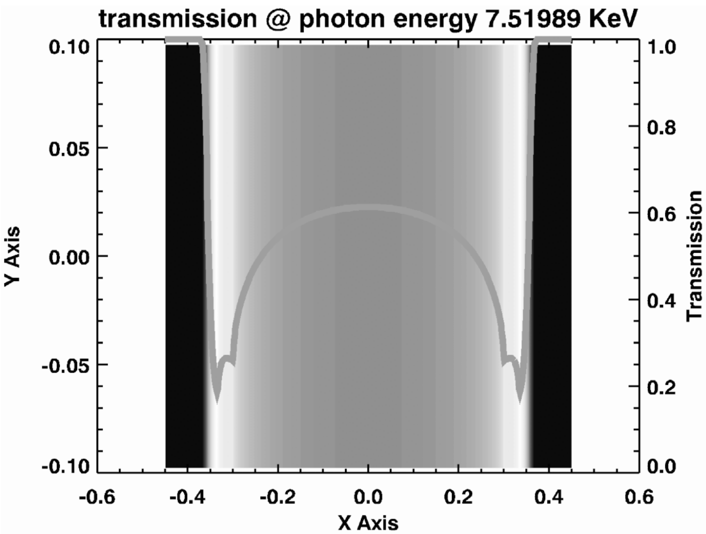
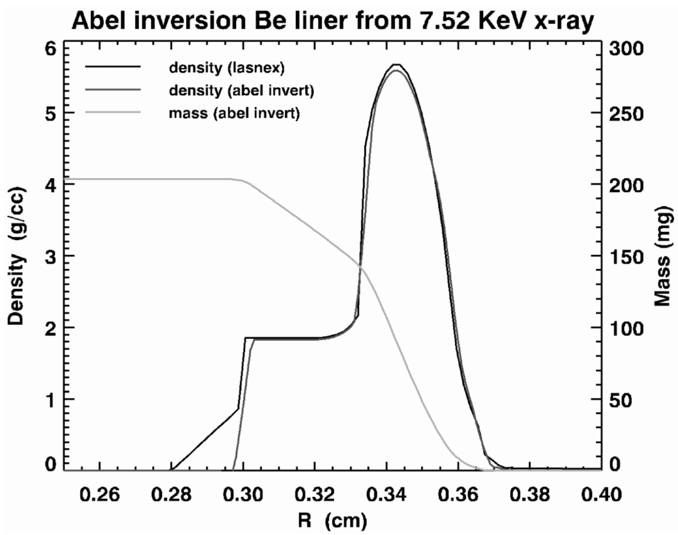
Concept can be tested using Be liners and present Z-beamlet backlight capability

- X-ray imaging & Abel inversion yield shock speed U_S and density (d).
- $U_p = U_S*(1 – d_0 / d)$
- $P_H = d_0*U_S*U_p$







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Additional possible diagnostics and experiments for HED research at Z

- ***X-ray Thomson scattering diagnostic for density & temperature measurements (Jim Bailey; SNL)***
- ***Ultra high velocity flyer plate impact shock & release experiments (planar geometry).***
- ***Cylindrical liner implosions for quasi-isentropic compression of shock pre-heated material.***

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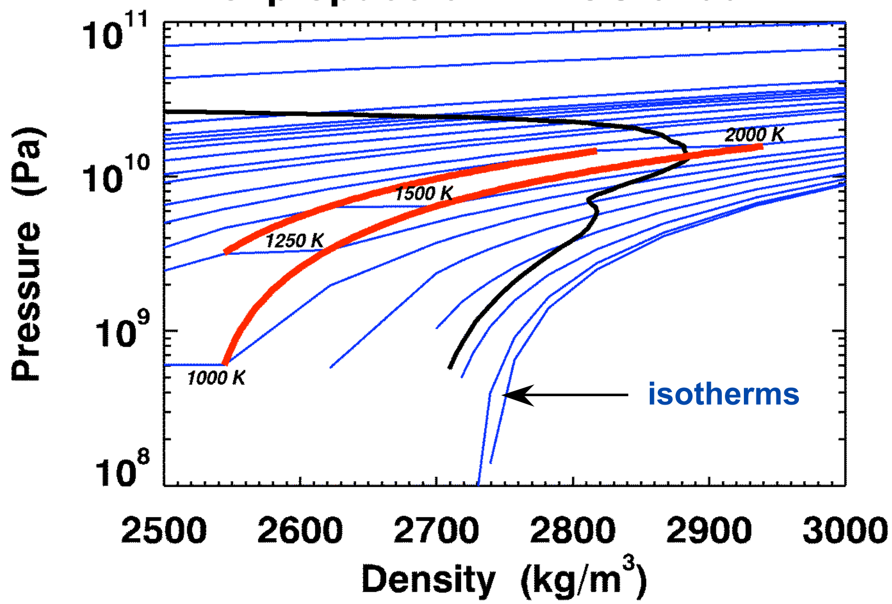
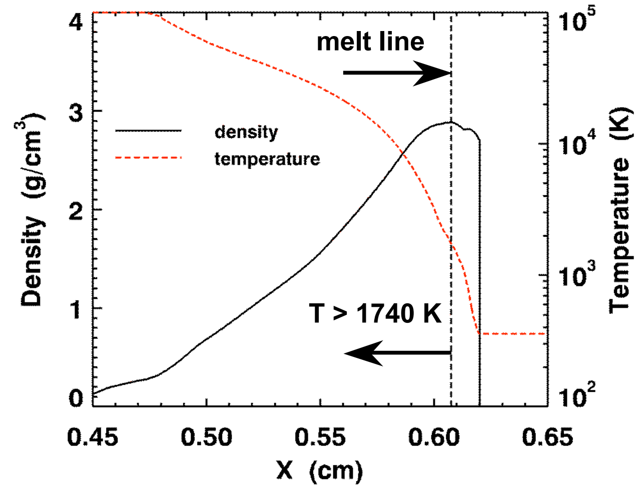
High resolution, 1D MHD Lagrangian simulation of 40.8 km/s flyer shows 124 µm solid aluminum at impact

40.8 km/s flyer trajectory in P vs. ρ space of Al EOS 3700

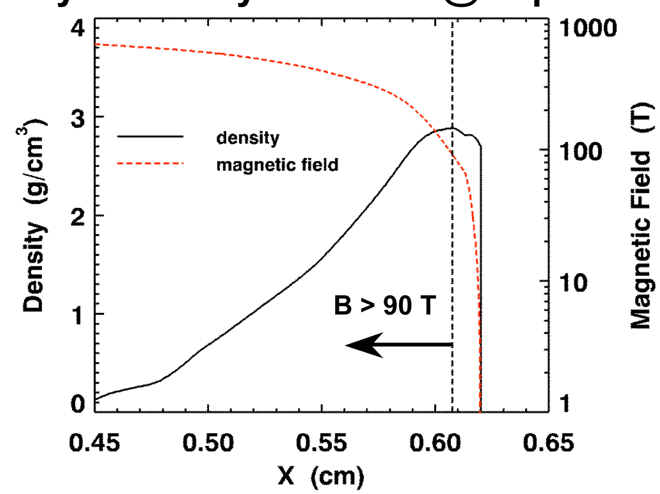


Results are consistent with previously published work; R. W. Lemke, et al., J. Appl. Phys. 98, 073530 (2005).

Flyer Density & Temperature @ Impact



Flyer Density & B-Field @ Impact



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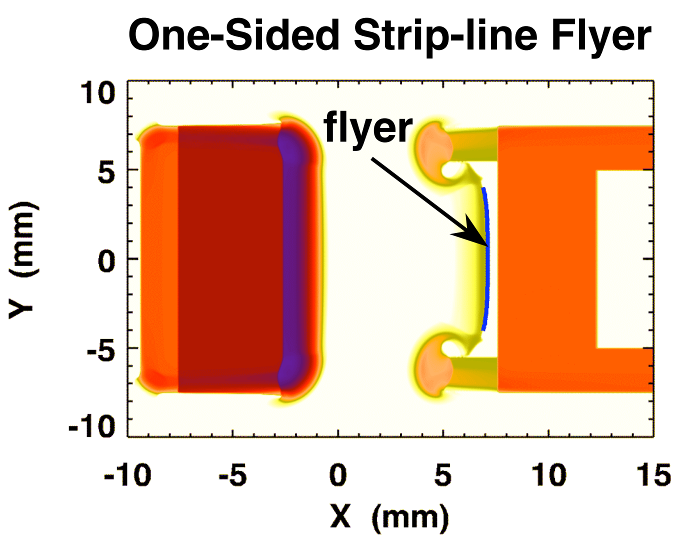
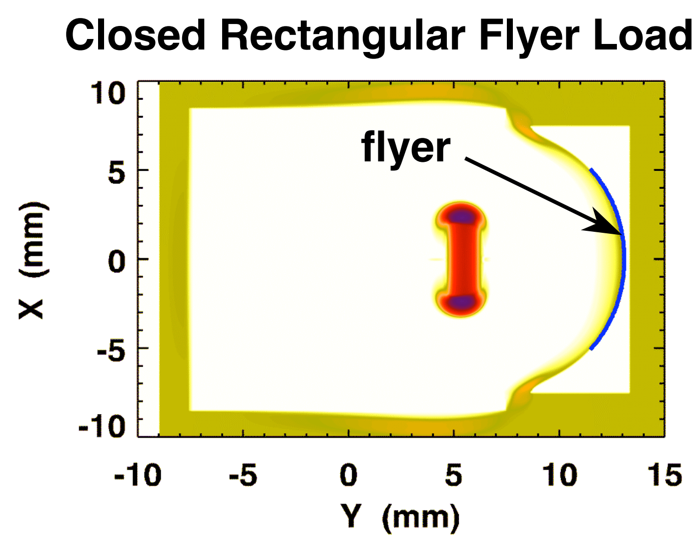
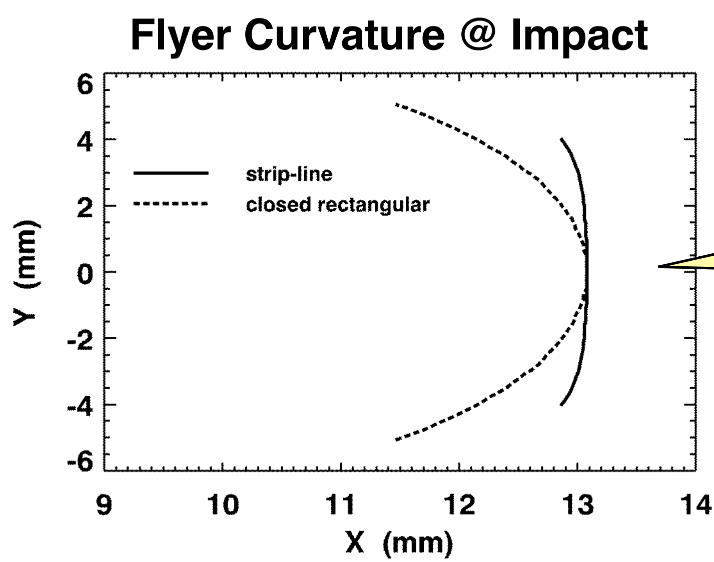
Strip-line reduces curvature of Al flyer at impact







Width of ± 0.5% variation from planar increases from 2.1 to 4.8 mm.

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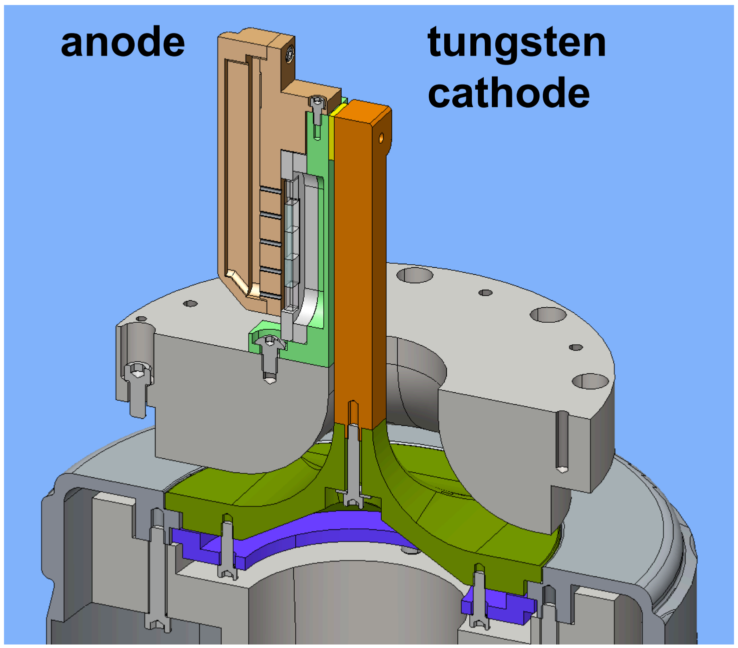
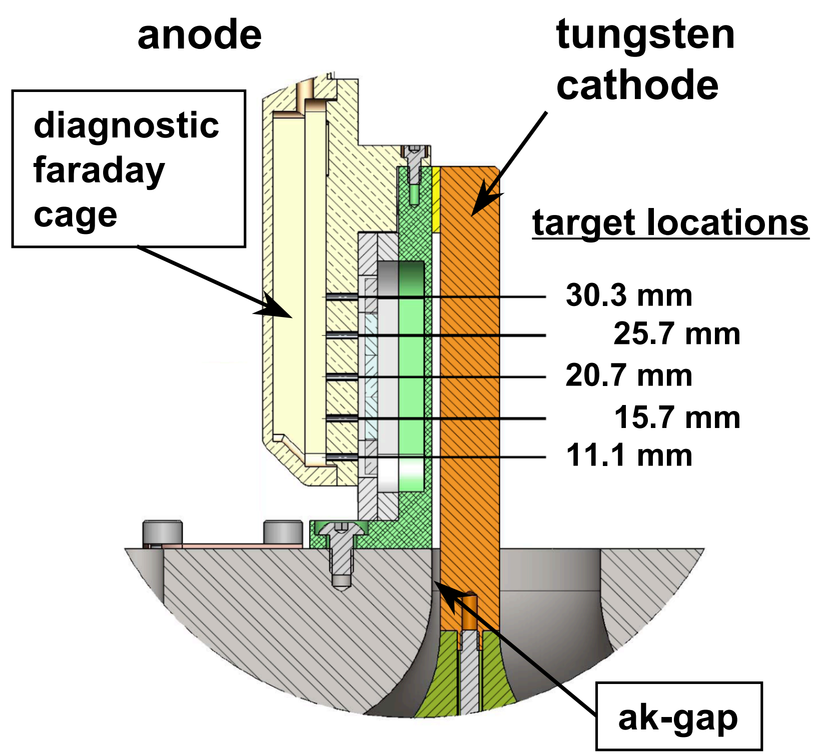
Single-sided strip-line with tungsten cathode produces higher pressure than two-sided

Flyers & targets on anode side only.

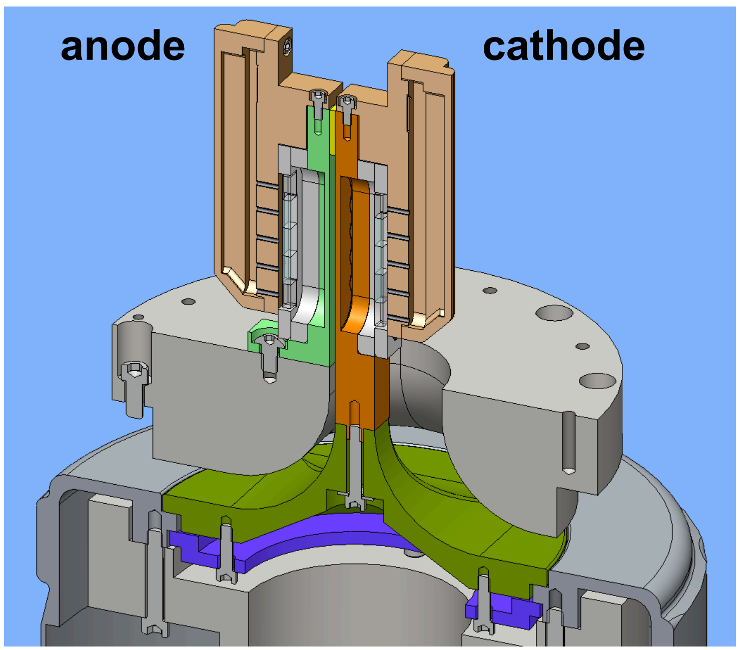


Schematic courtesy of Dustin Heinz-Romero (SNL).

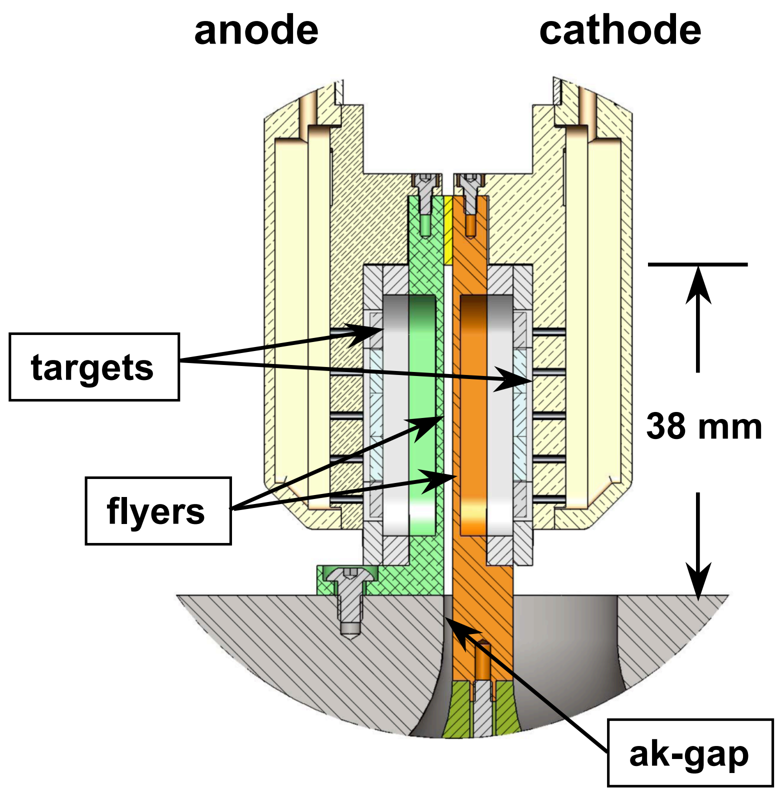


Two-sided strip-line flyer geometry provides measurements for 10 plate-impact experiments

Five flyers (900 μm Al) & targets (α-quartz or sapphire) on each electrode.



Schematic courtesy of Dustin Heinz-Romero (SNL).



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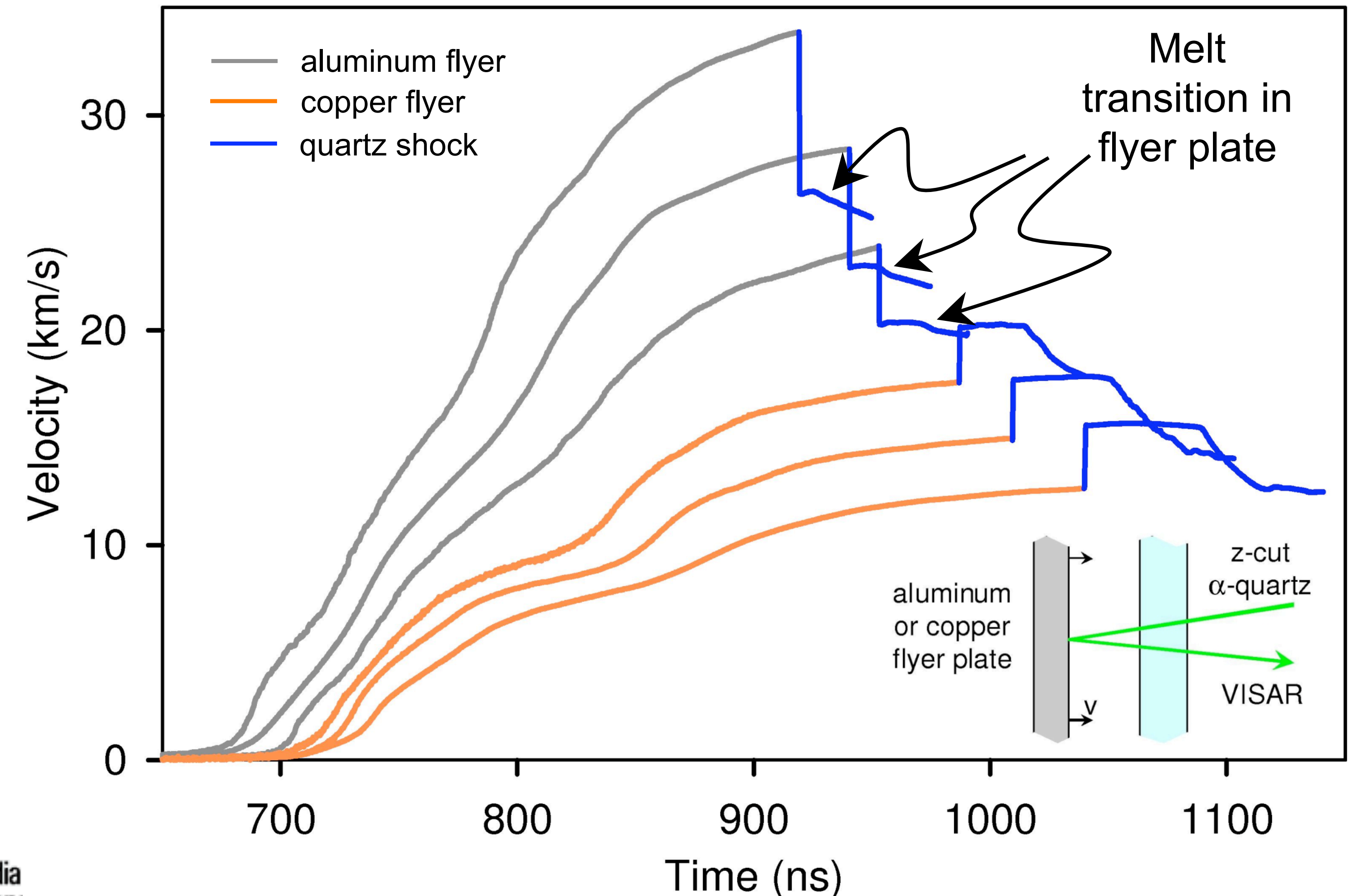
VISAR provides highly accurate in line flyer plate and quartz shock velocity measurements



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