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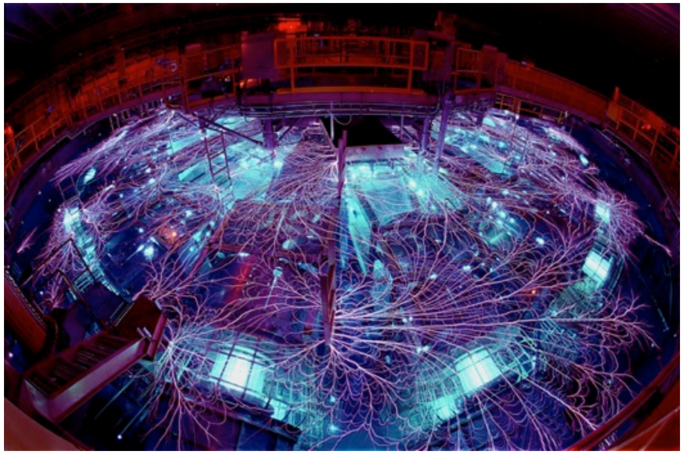


Overview of High Energy Density Research at Sandia National Laboratories

Pulsed Power Sciences

Harnessing Extreme Environments

Kyle J Peterson

Manager, ICF Target Design Dept.
Sandia National Laboratories

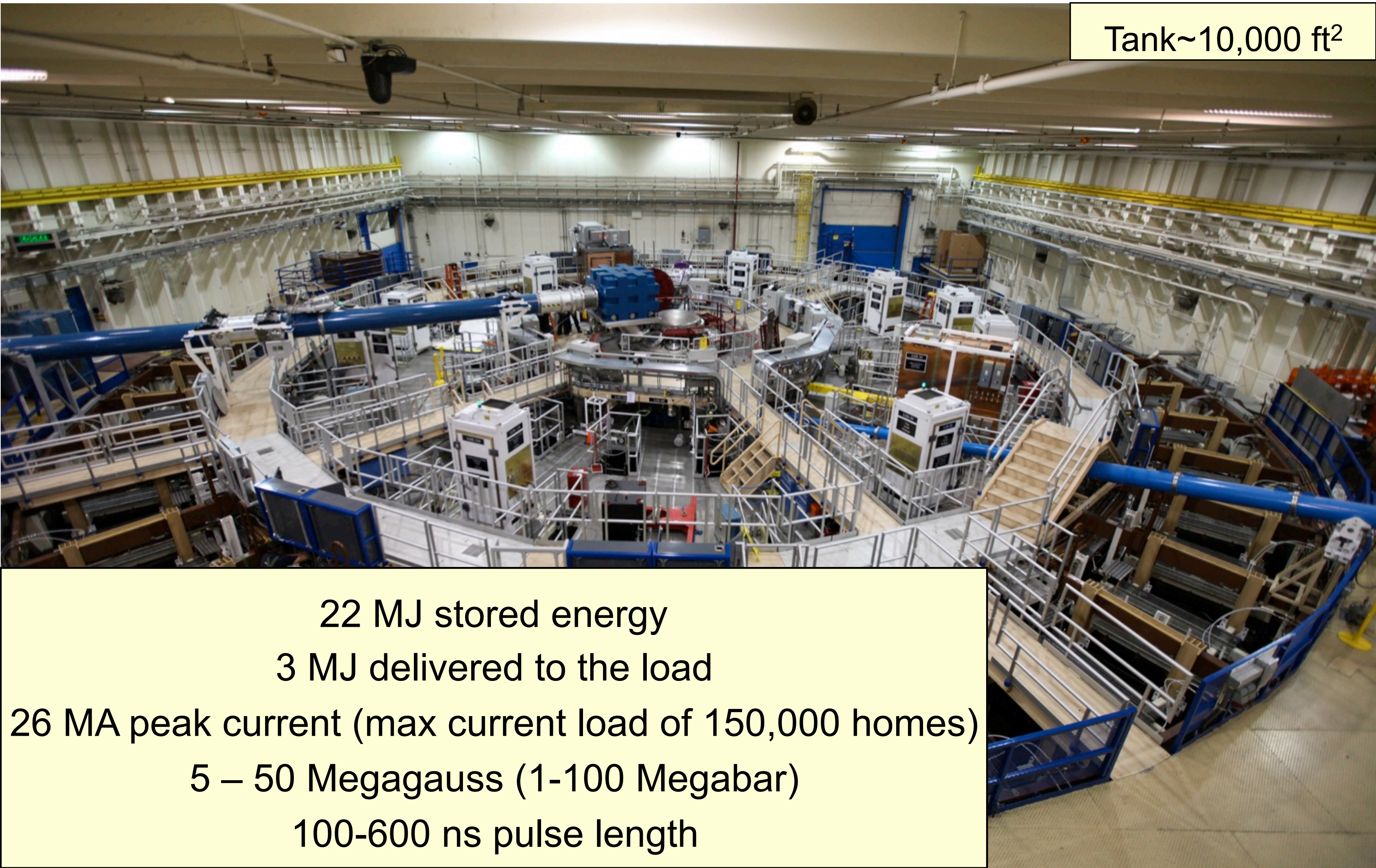
Omega Users Group Workshop,
April 23-25, 2014, Rochester, NY

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

We use the Z pulsed power facility at Sandia to generate large magnetic fields & couple MJs of energy



Tank~10,000 ft^2

22 MJ stored energy

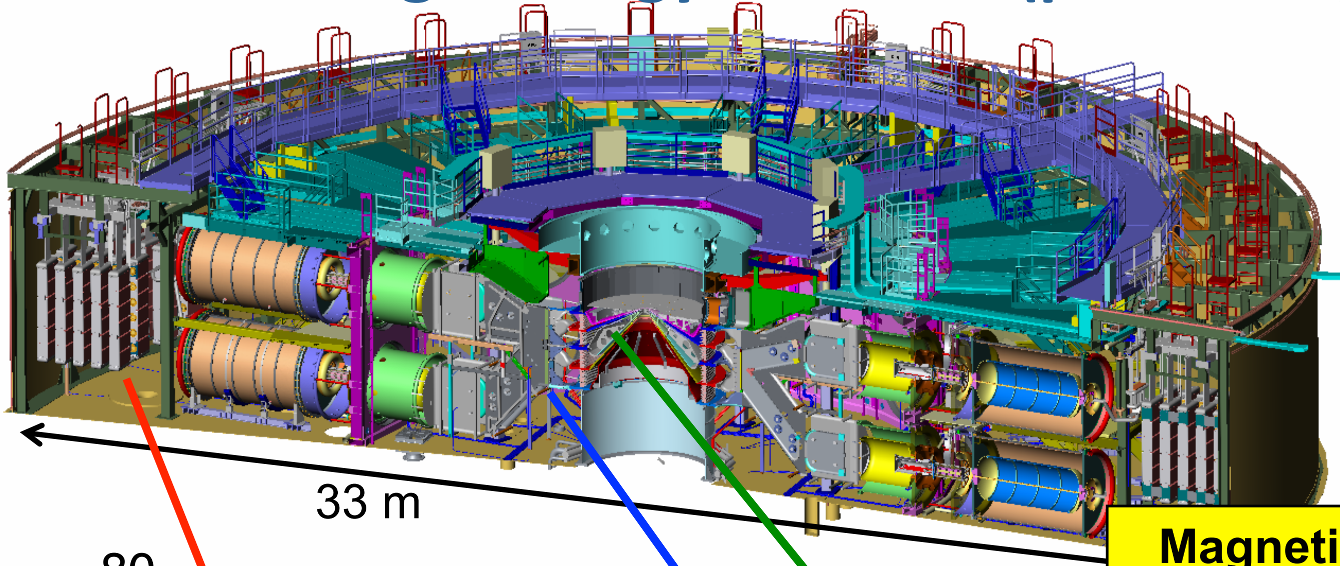
3 MJ delivered to the load

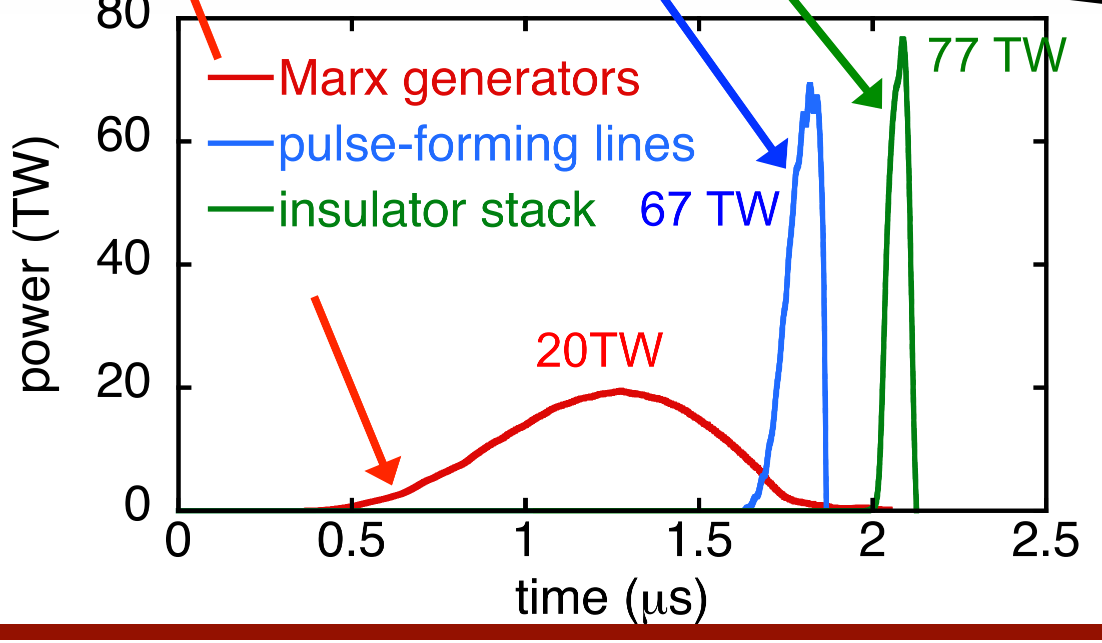
26 MA peak current (max current load of 150,000 homes)

5 – 50 Megagauss (1-100 Megabar)

100-600 ns pulse length

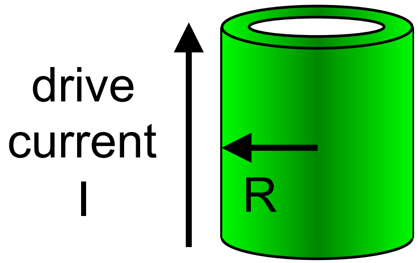
Z works by compressing energy in space and time to reach high energy densities (pressures)





Magnetically-Driven Implosion

$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$



100 MBar at 26 MA and 1 mm

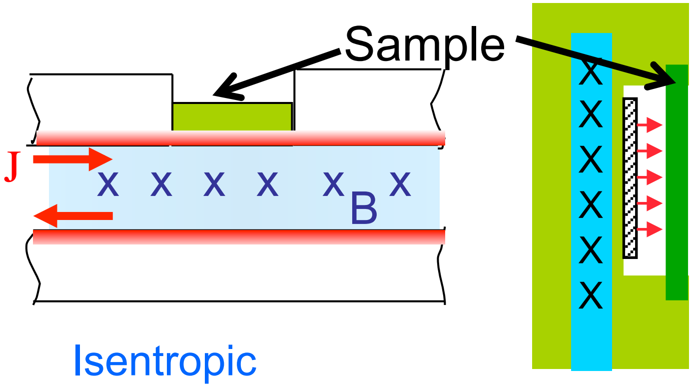
Large currents and the corresponding magnetic fields can be used to create and control high energy density matter

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) = \frac{\mathbf{J}\times\mathbf{B}}{c} - \nabla P \approx \frac{1}{4\pi}\mathbf{B}\bullet\nabla\mathbf{B} - \nabla\left(P + \frac{B^2}{8\pi}\right)$$

- Magnetic pressure can be created efficiently over cm^3 volumes, enabling large samples and energetic sources
- Magnetic pressure increases in a converging geometry
- High pressures can be created *without making material hot*
- Magnetic fields can be generated over long time scales with significant control over the time history (pulse shaping)

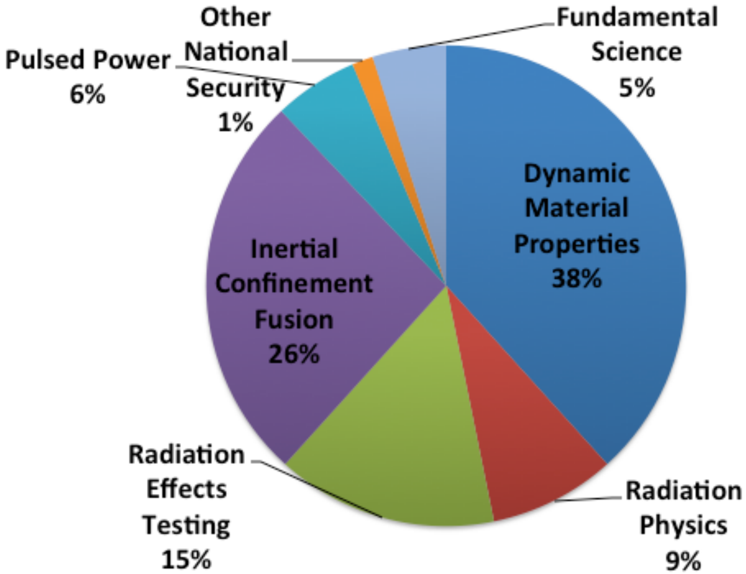
We use magnetic fields on Z in several ways to create High Energy Density matter for stockpile stewardship applications

Dynamic Material Properties

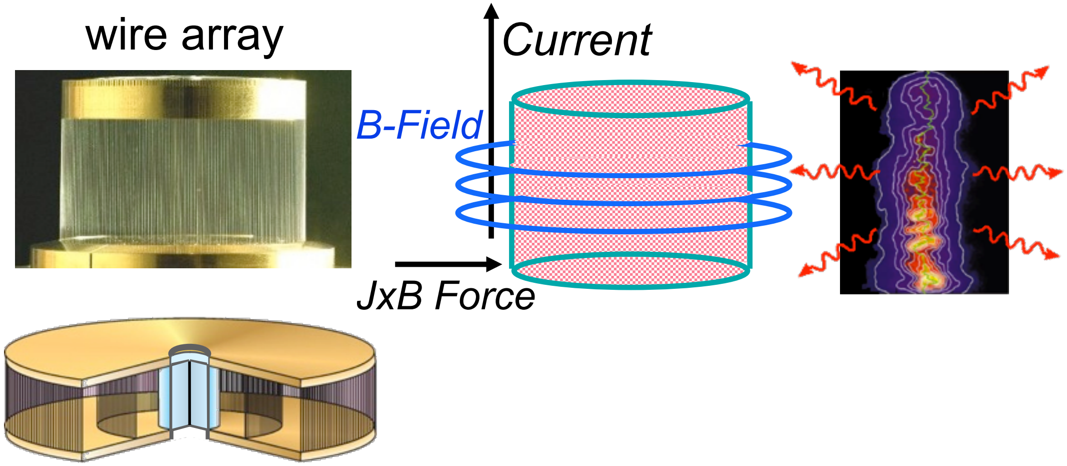


Isentropic Compression

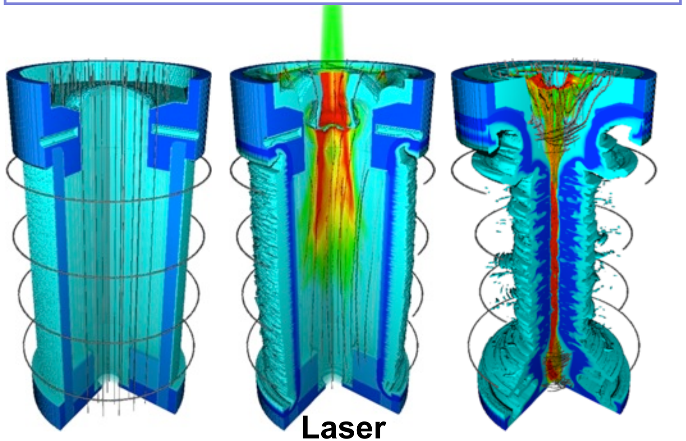
Flyer Plate



Z-Pinch X-ray Sources (RES, Rad. Physics)

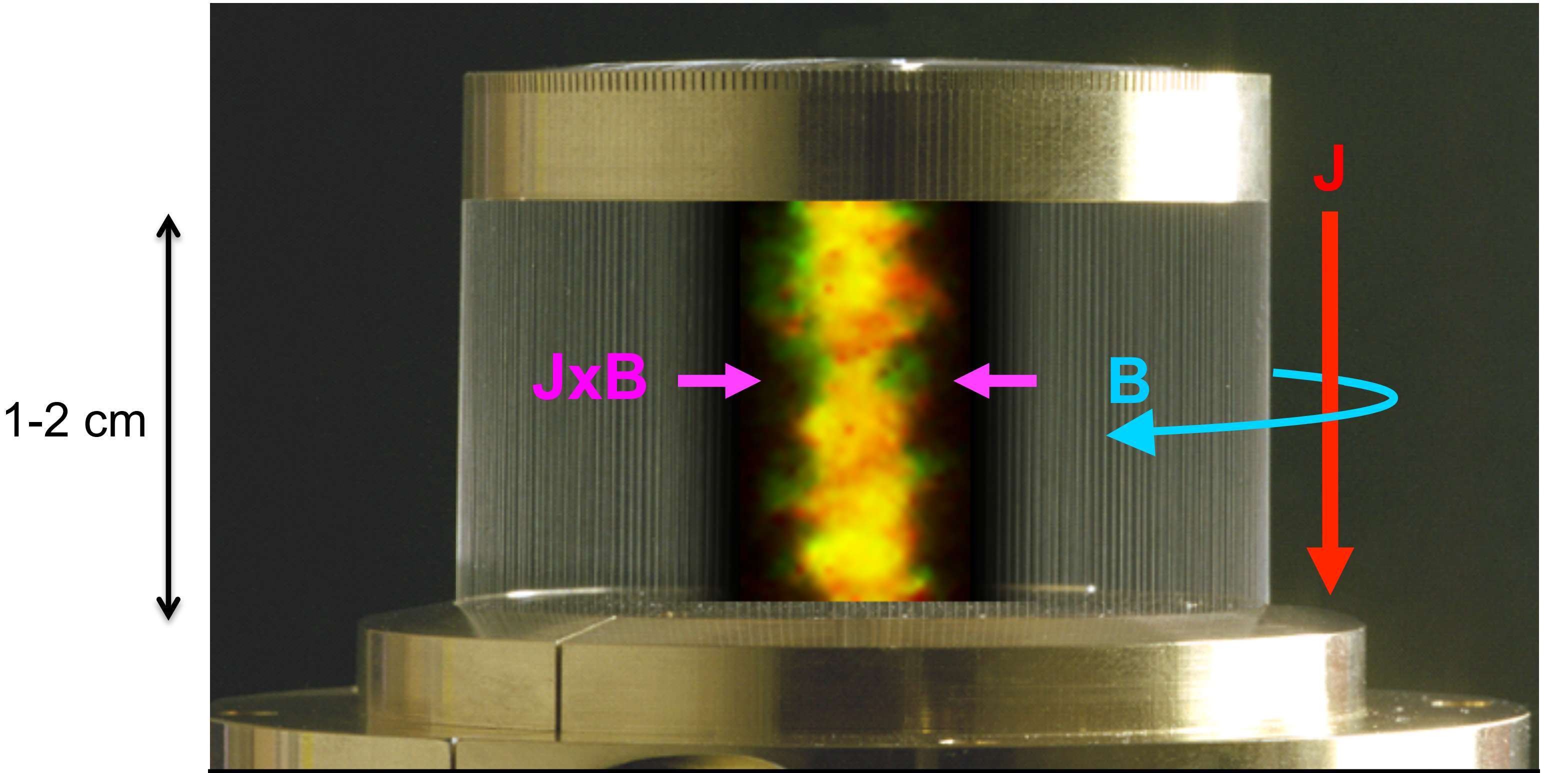


Inertial Confinement Fusion



Magnetization **Laser Heating** **Compression**

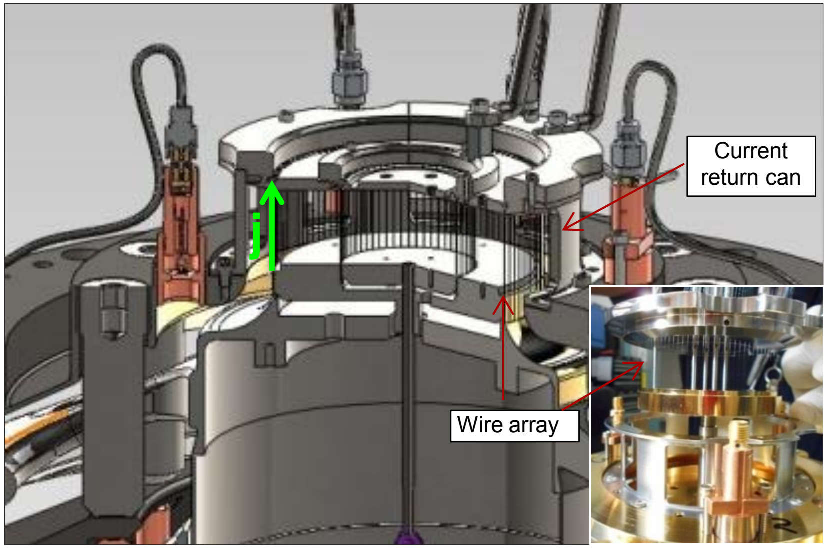
Magnetically driven implosions are efficient, powerful, x-ray sources from 0.1 to 10 keV

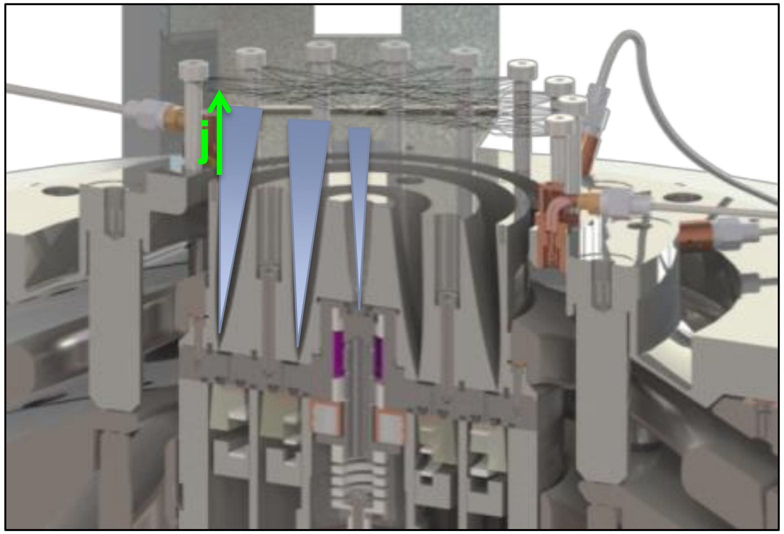


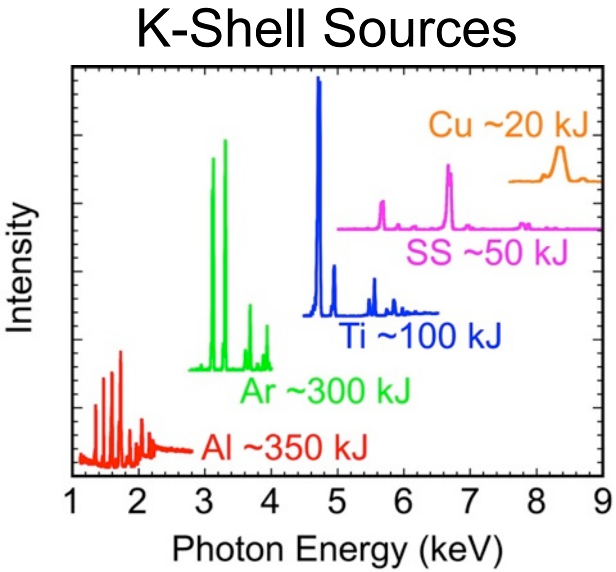
P_{rad} ~ 400 TW, Y_{rad} ~ 2.5 MJ

~ 10-15% wall plug efficiency

Z-pinches are used to generate a wide variety of x-ray sources for radiation effects sciences



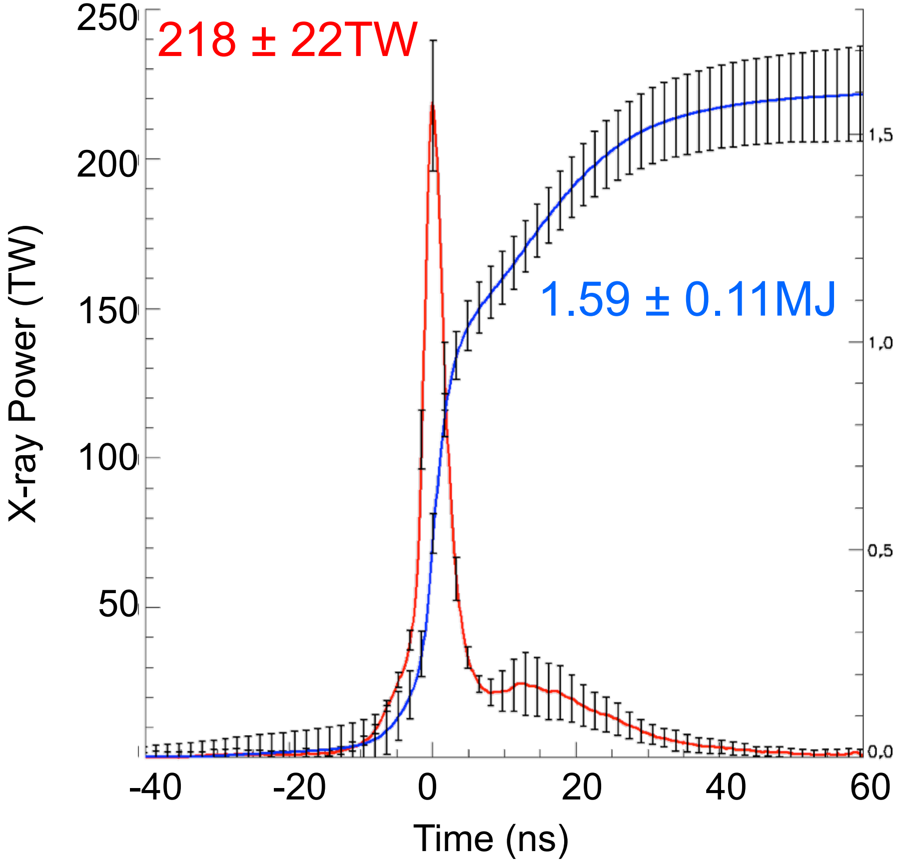




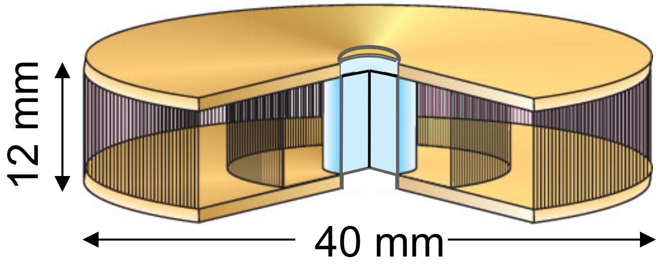
- Wire arrays
  - ~100 nested wires, ~.5 mg/cm
  - Al, Stainless Steel, Cu, Mo, Ag
- Gas puffs
  - Azimuthally symmetric gas shells
  - ~1 mg/cm
  - Shell-like and ramped profiles
  - Ar, Kr
- Initial diameter, mass and mass distribution define stagnation temperature, uniformity

The z-pinch dynamic hohlraum (ZPDH) is highly reproducible x-ray source

Radial X-ray Power and Energy (20 shot average)



Z-pinch Dynamic Hohlraum



	ZR
Ipeak	25.8 MA
Mass	8.5 mg
Peak Power	220 TW (10%)
Radiated Energy	1.6 MJ (7%)

Standard ZPDH Characteristics

360 W wires – 11.4 μm

m = 8.5 mg W total

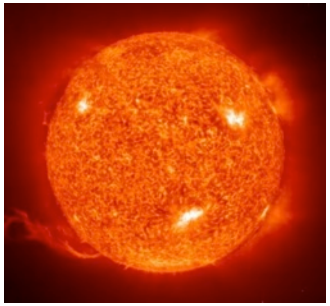
V_{marx} = 85 kV (21 MJ)

I_p = 25.8 ± 0.4 MA [20 shots]

Sanford et al., POP 9 (2002)
Bailey et al., POP 13 (2006)
Lemke et al., POP 12 (2004)
Slutz et al., POP13 (2006)
Rochau et al., PPCF 49 (2007)

ZAPP experiments exploit megaJoules of x-rays to simultaneously address four separate astrophysics topics

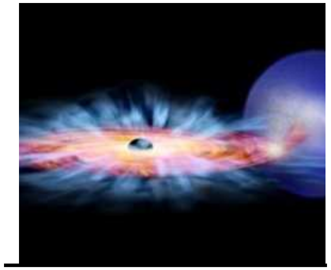
Stellar interior opacity

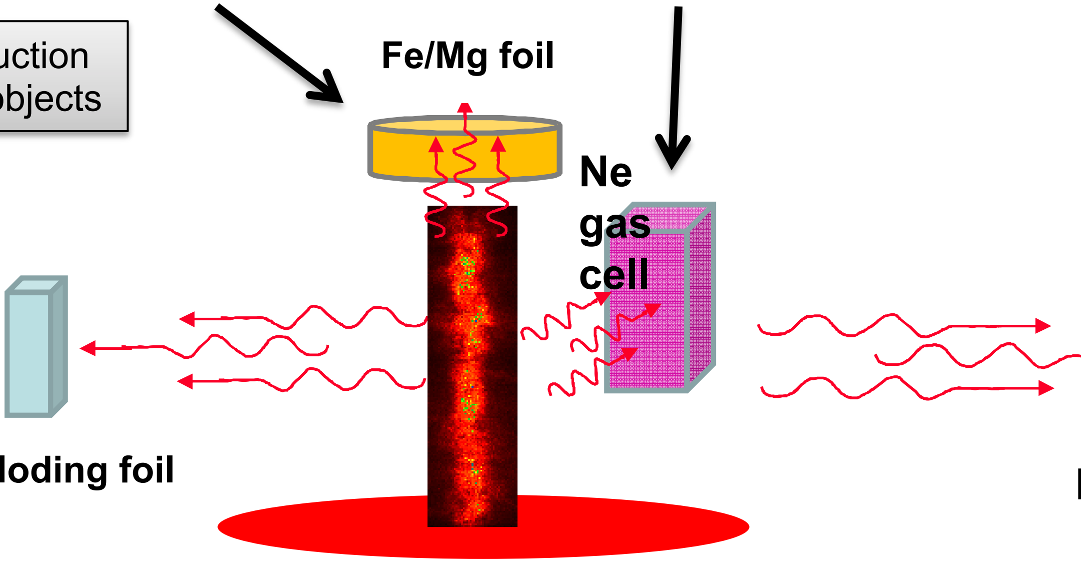


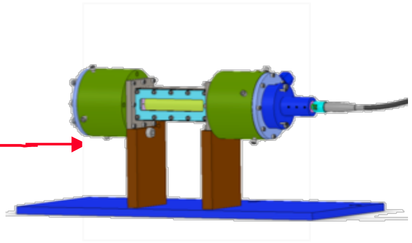
Atomic kinetics in warm absorber photoionized plasmas

Spectral line formation in white dwarf photospheres

Resonant Auger destruction in accretion powered objects

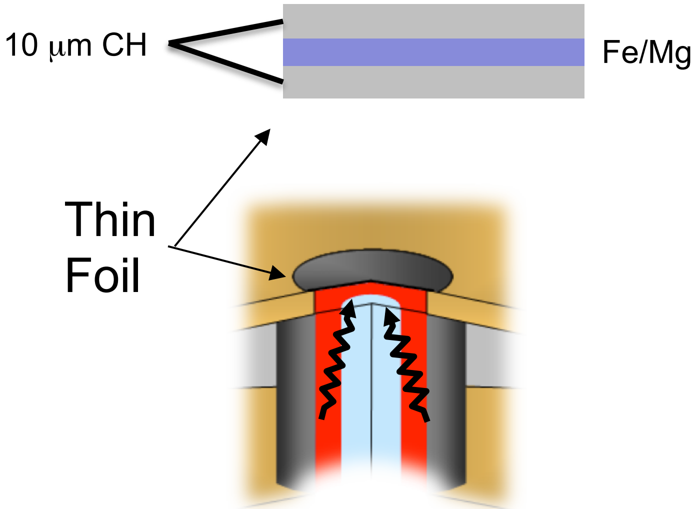




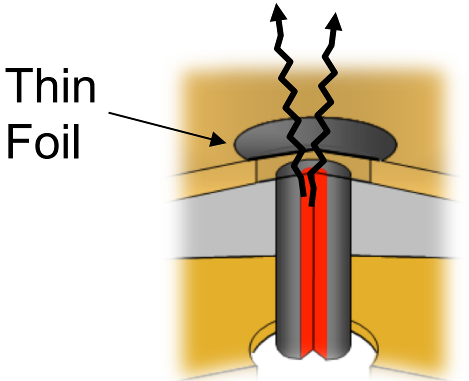


Up to 59 spectra obtained on single shot!

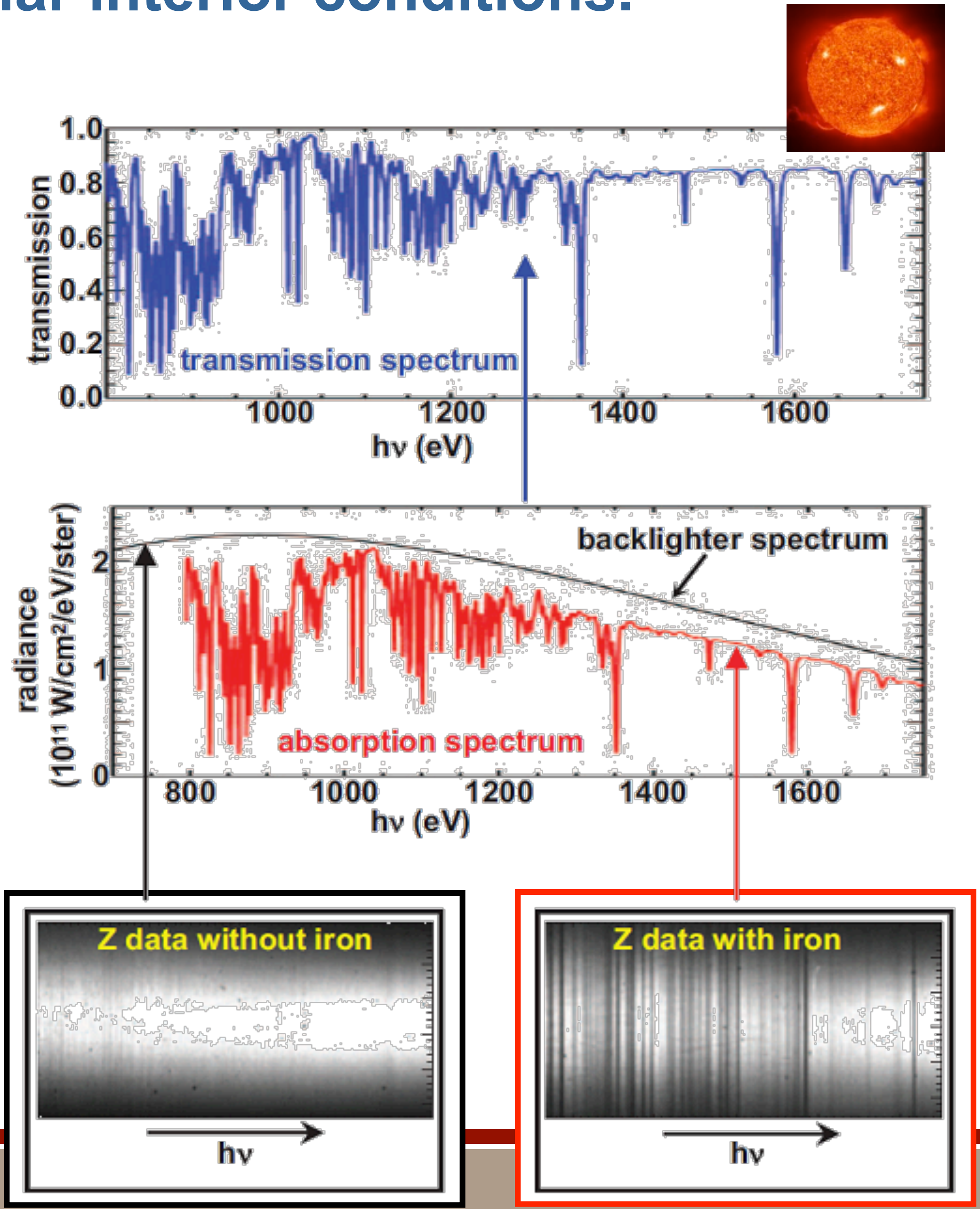
The ZPDH radiating shock is used to both heat and backlight samples to stellar interior conditions.



Foil is heated during the ZPDH implosion

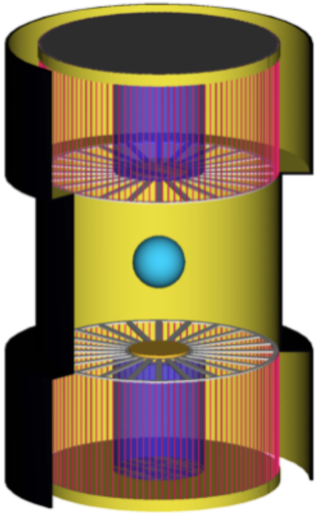


Foil is backlit at shock stagnation

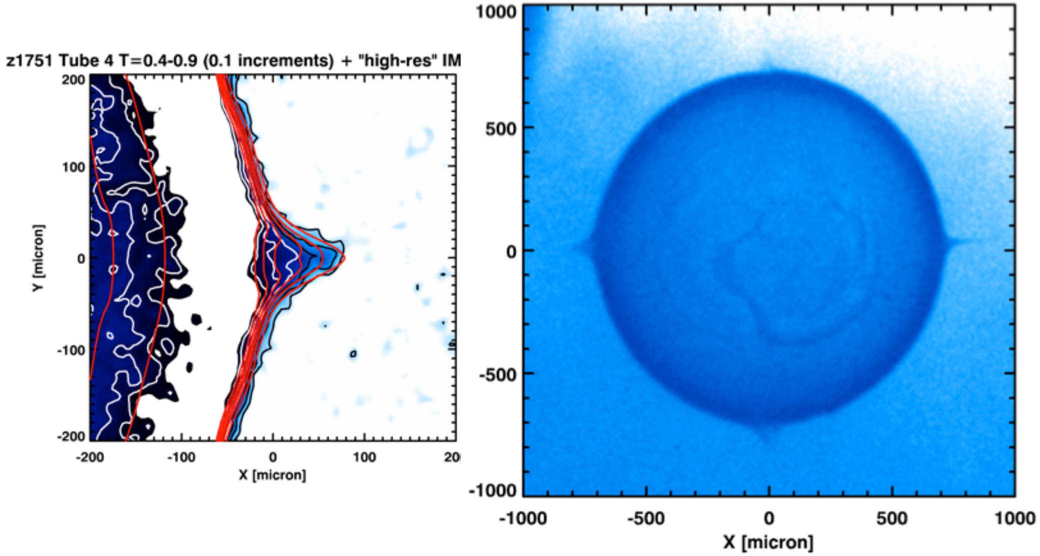


Bailey et al., POP 16 (2009)

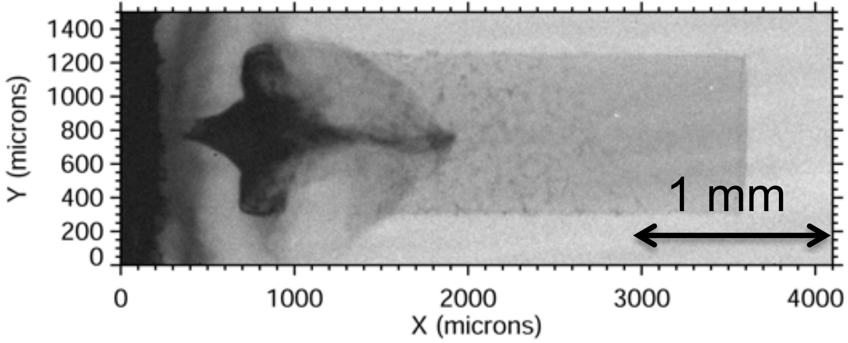
Magnetically-driven x-ray sources have also been used to study radiation hydrodynamic experiments



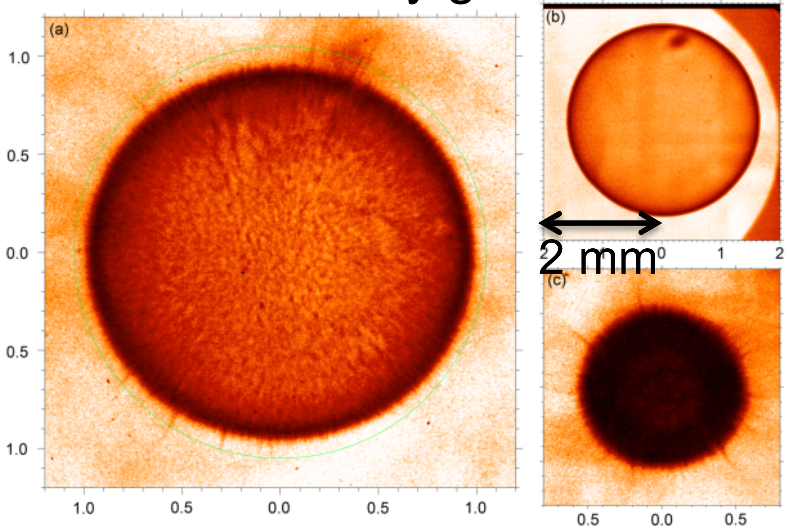
NIF fill tube experiments[1]



Hydrodynamic jet experiments[2]



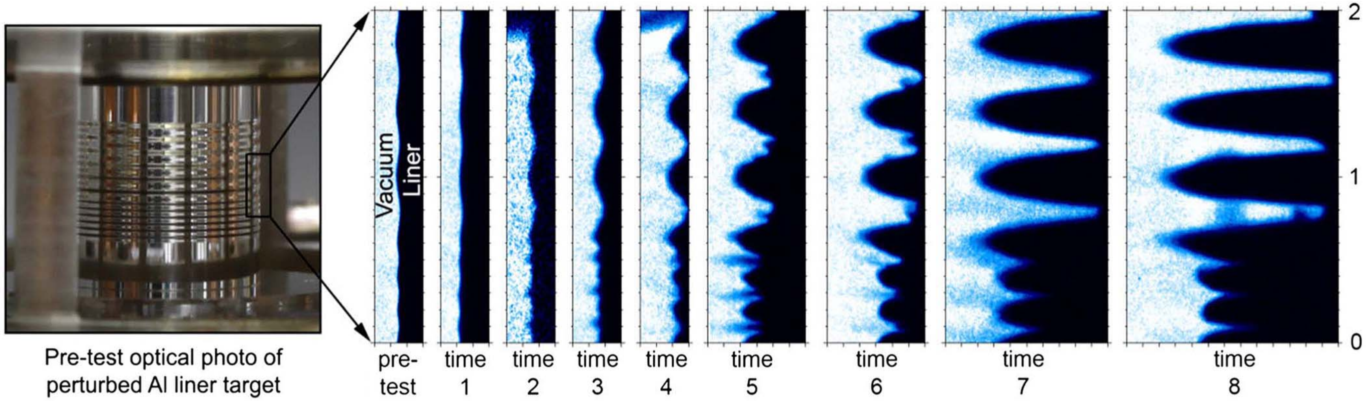
Instability growth[3]

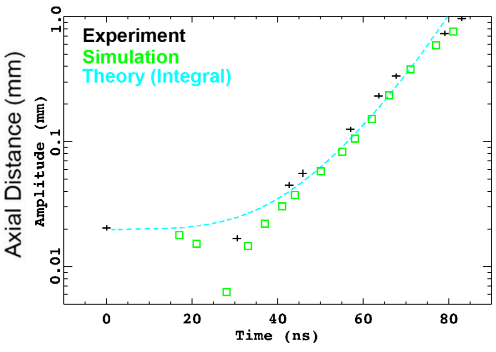


[1] G.R. Bennett, et al., Phys. Rev. Lett. 205003 (2007).
[2] D. B. Sinars, et al., Rev. Sci. Instrum., Vol. 75, No. 10 (2004)
[3] M.E. Cuneo et al., IEEE T. Plas. Sci. 40, 3222 (2012).

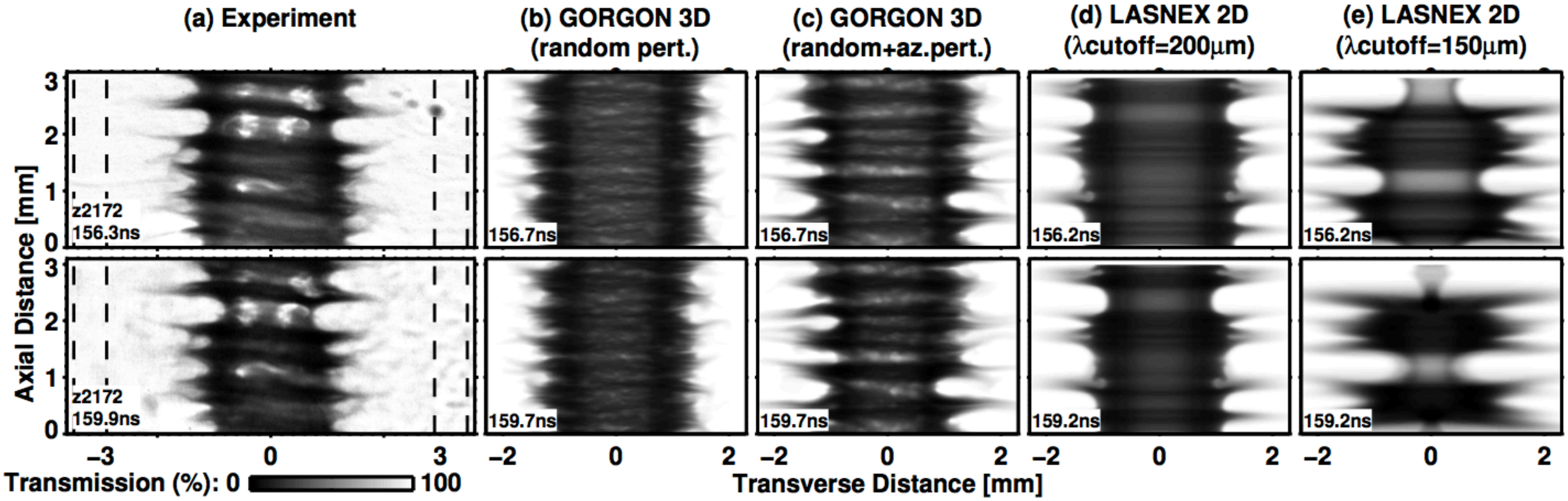
We have been studying the liner instabilities in MagLIF relevant targets during the last several years

- D.B. Sinars *et al.*, Phys. Rev. Lett. 105, 185001 (2010); Phys. Plasmas 18, 056301 (2011).

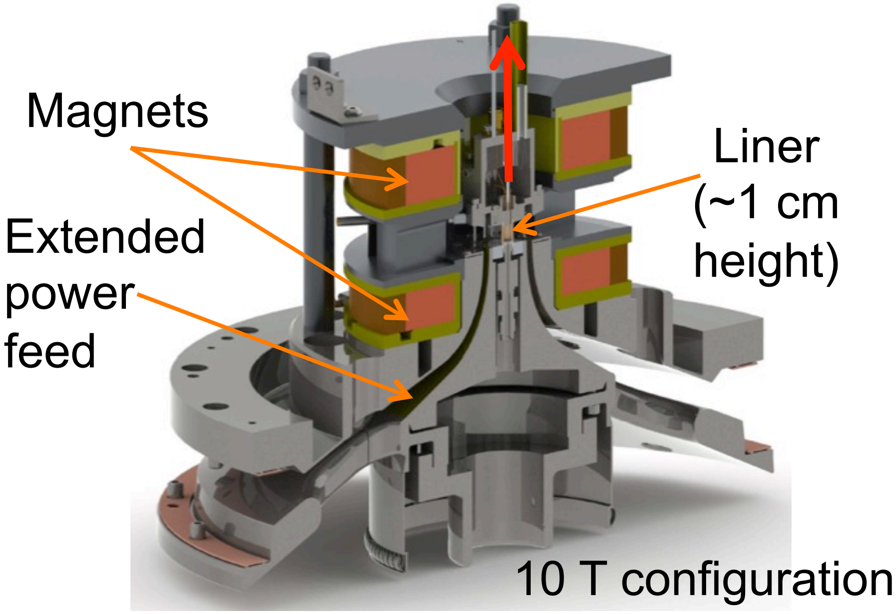

Pre-test optical photo of perturbed Al liner target



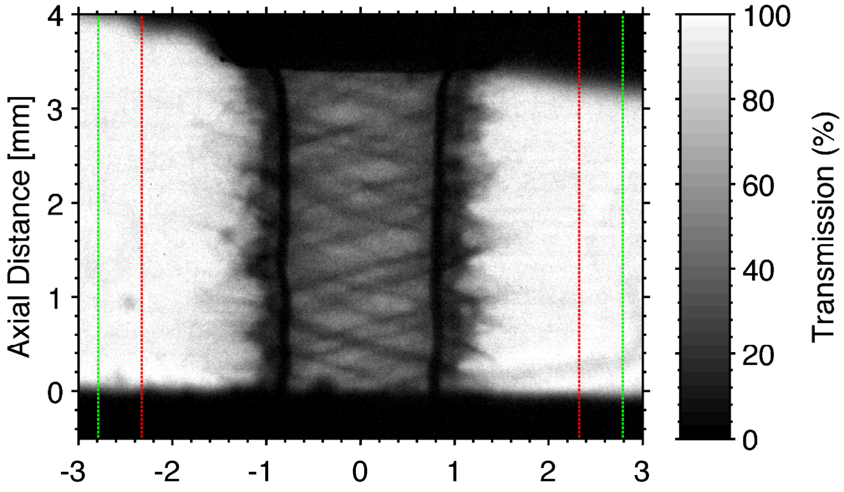
- R.D. McBride *et al.*, Phys. Rev. Lett. 109, 135004 (2012); Phys. Plasmas 20, 056309 (2013).



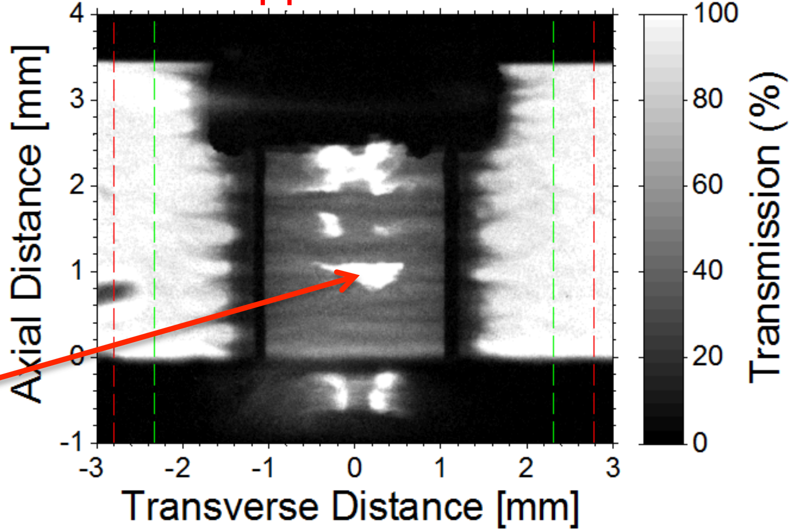
The addition of a 7-10 T axial magnetic field produces a dramatic change in the structure of the liner instabilities



7 Tesla Bz-field



No applied Bz-field

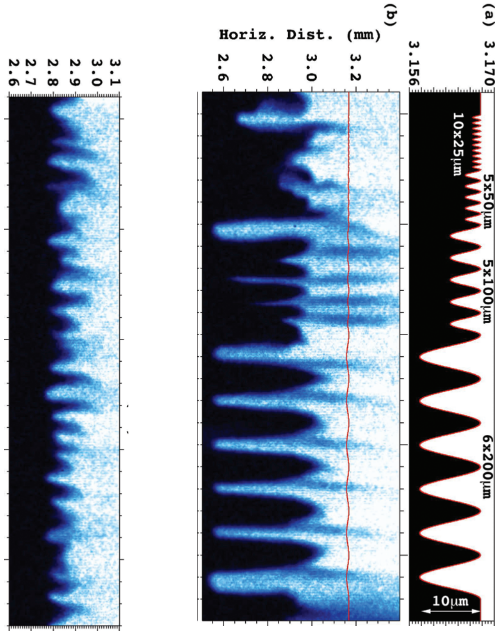


- Rather than cylindrically symmetric structures, we see helical structures
- Use of compressible electrodes mitigates edge instabilities
- Magnetic field reduced multi-keV x rays associated with late-time instabilities

Surface roughness and small defects do not appear to be the seed for MRT instability growth as in radiative driven laser ICF targets

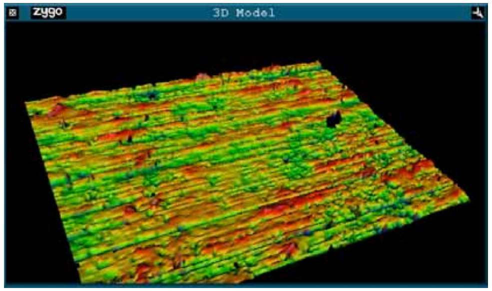
Axially polished liner experiments suggest symmetry is not sensitive to surface characteristics

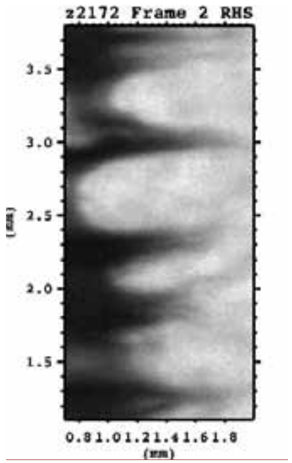
Observed Instability growth is not linearly proportional to the amplitude of the initial perturbations.



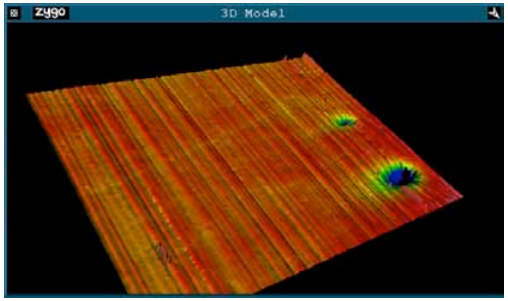
Ao = 60 nm

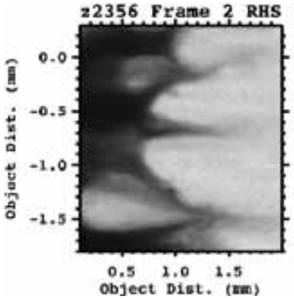
Standard Process
(50 nm RMS)





axial machining and polishing
(50 nm RMS)





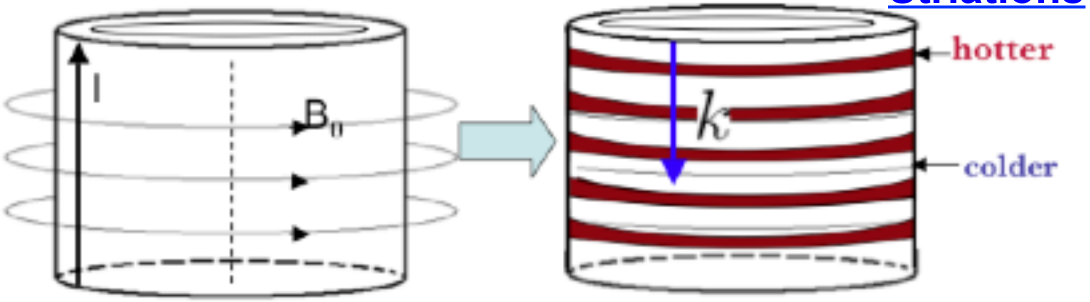
Symmetry may generally be worse for axially-polished liners

The electro-thermal instability is an important mechanism that could seed MRT growth*

Most metals initially have increasing resistivity with increasing temperature

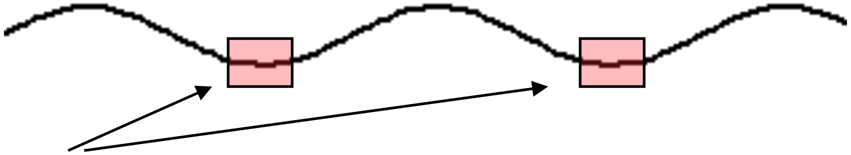
$$\frac{d\eta(T)}{dT} > 0$$

Striations



which couple to Rayleigh-Taylor

Consider

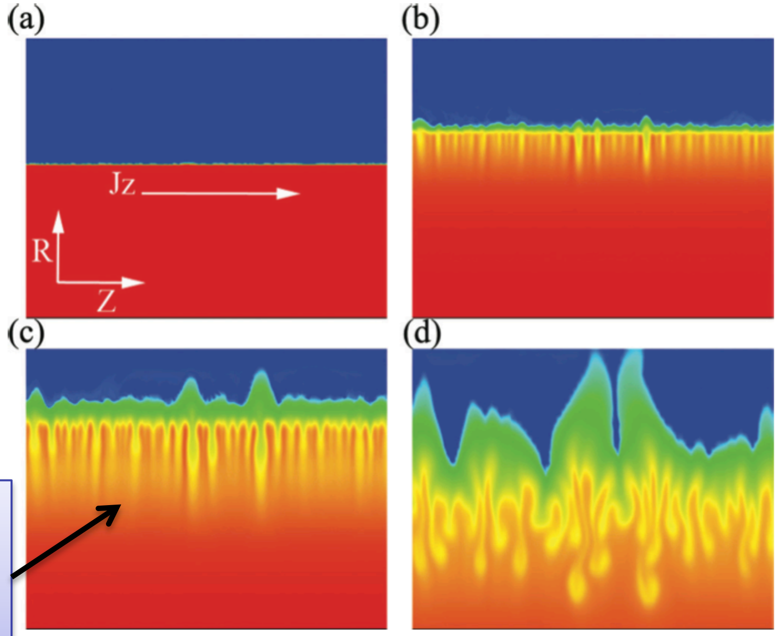


$$\delta T > 0$$

Then, η increases which consequently increases the localized ohmic heating, η j^2

Which leads to increased δT

Temperature perturbations give rise to pressure variations which eventually redistribute mass



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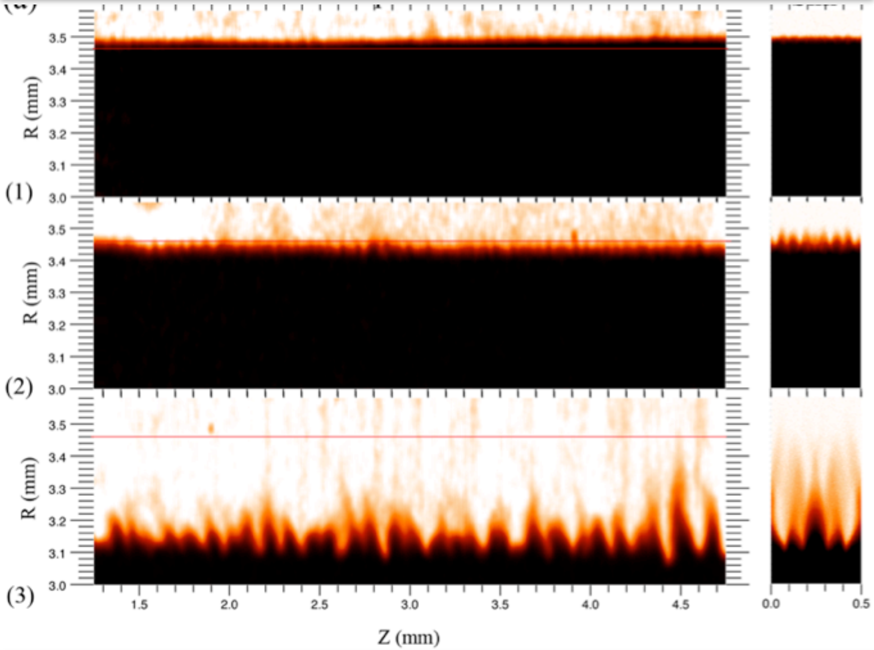
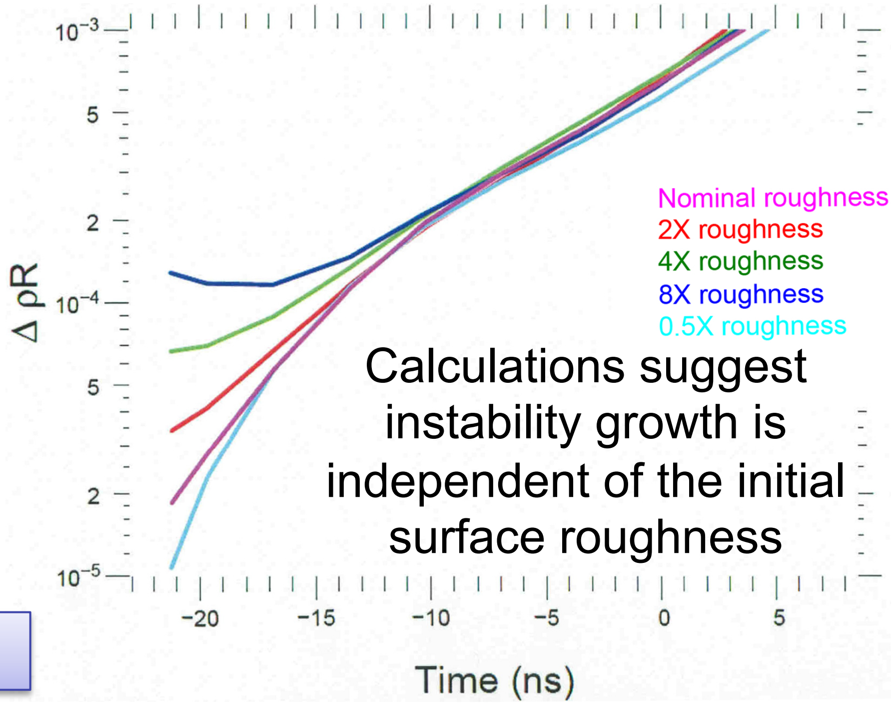
*K.J. Peterson *et al.*, Phys. Plasmas (2012); K.J. Peterson *et al.*, Phys. Plasmas 20, 056305 (2013).

Our modeling agrees well with observed instability growth in solid Al liners—the perturbation growth is larger than expected from MRT alone starting from surface roughness

Experimental (left) & simulated (right) radiographs





Calculations suggest instability growth is independent of the initial surface roughness

Estimated MRT Only Perturbation Growth

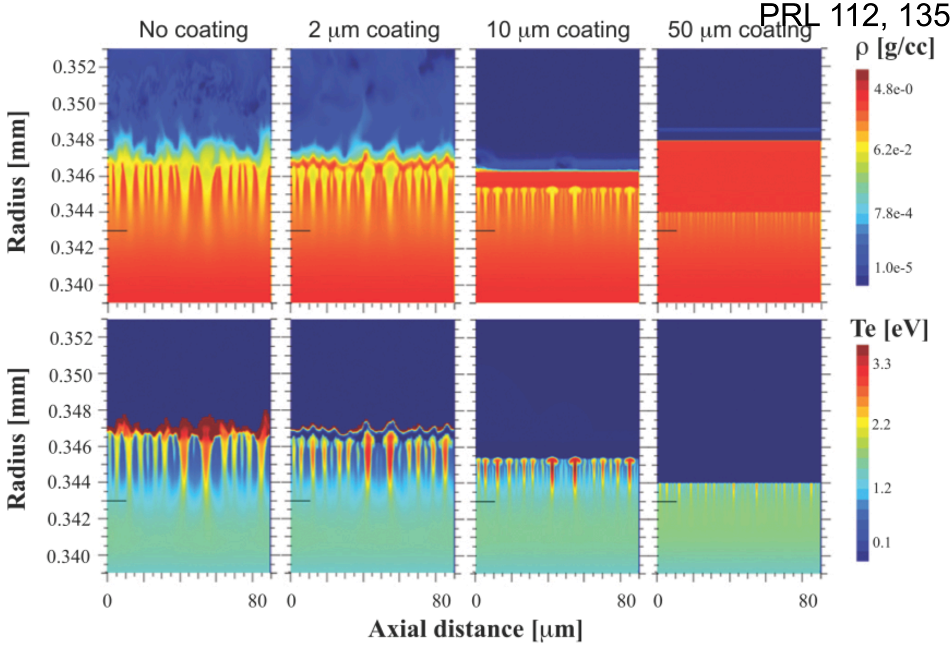
Time	Est. MRT (λ=100 μm)	h=0.06Agt^2	Observed
A	0.36 μm	6.2 μm	13 ± 7 μm
B	24 μm	41 μm	80 ± 7 μm

Note that the change from cylindrical to helical perturbations with the addition of an axial magnetic field may also be consistent with ETI seeding hypothesis

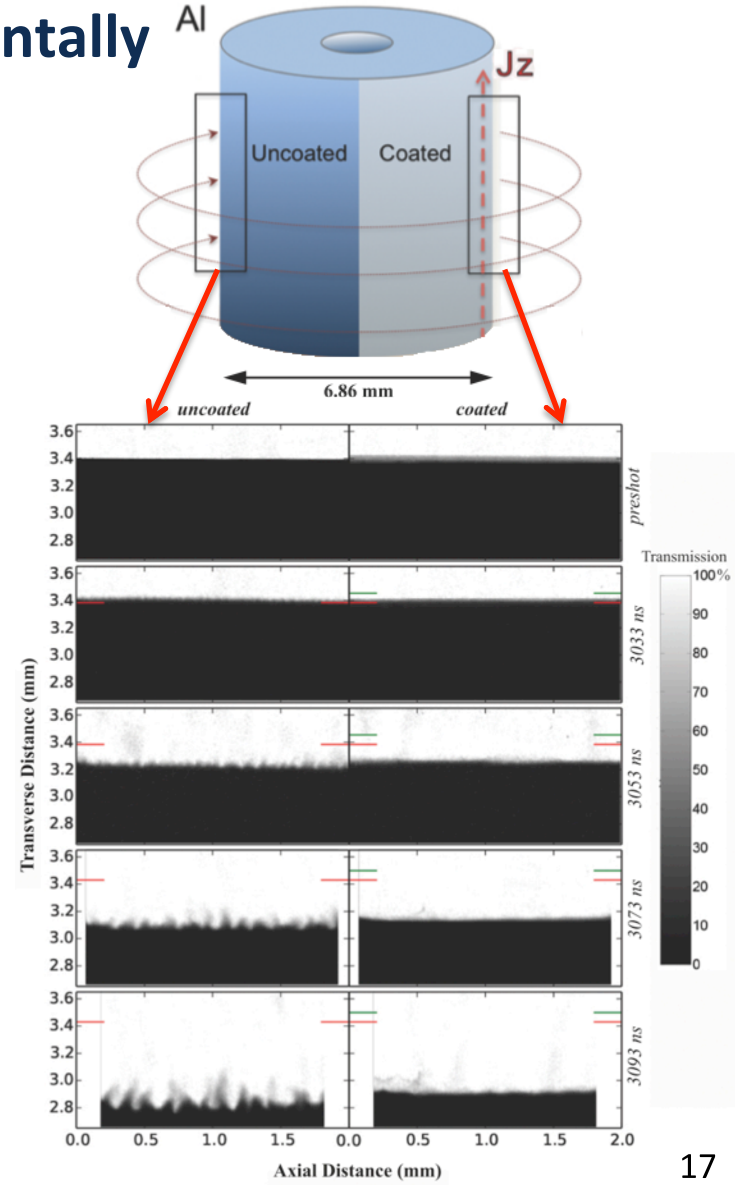
*K.J. Peterson *et al.*, Phys. Plasmas (2012); K.J. Peterson *et al.*, Phys. Plasmas 20, 056305 (2013).

Simulations predicted that we could mitigate the impact of the electrothermal instability by tamping out the density variations—this was confirmed experimentally

- No ETI growth in plastic coating
  - Carries very little current
  - Theoretically ETI stable
- Experimental radiographs of coated and uncoated halves of a solid rod target confirm idea



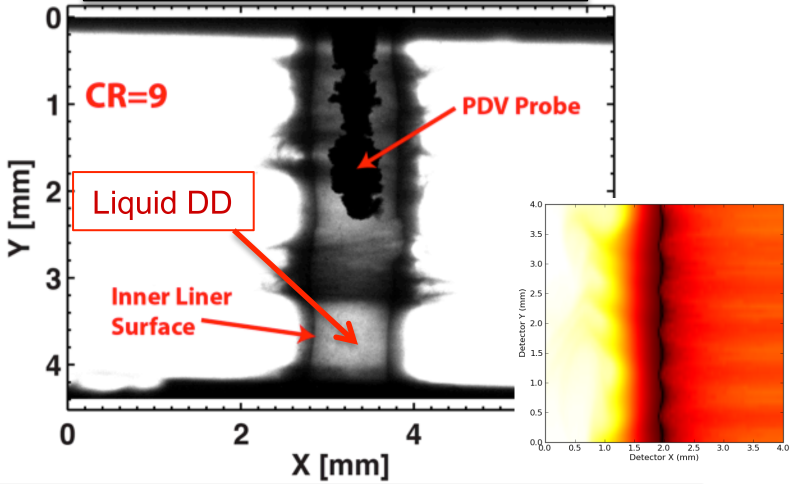
PRL 112, 135002 (2014)



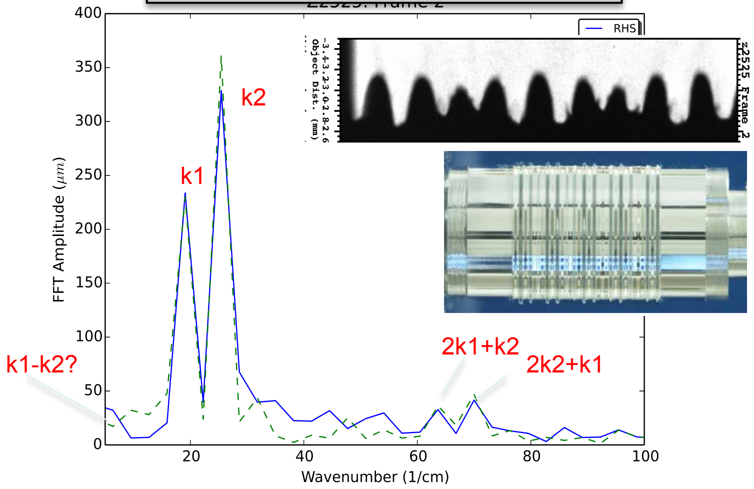
K.J. Peterson *et al.*, Physical Review Letters 112, 135002 (2014)

Recently we have begun studying more advanced instability configurations

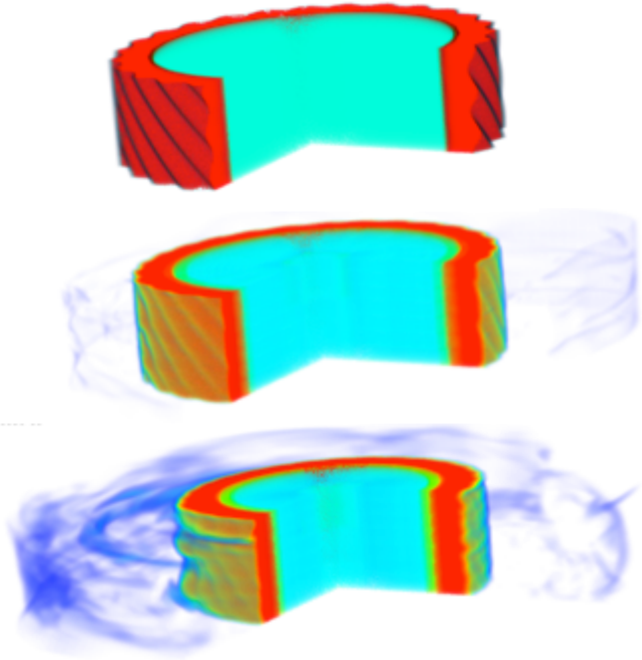
Deceleration instabilities

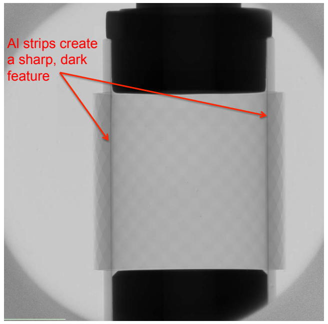


Multimode instabilities

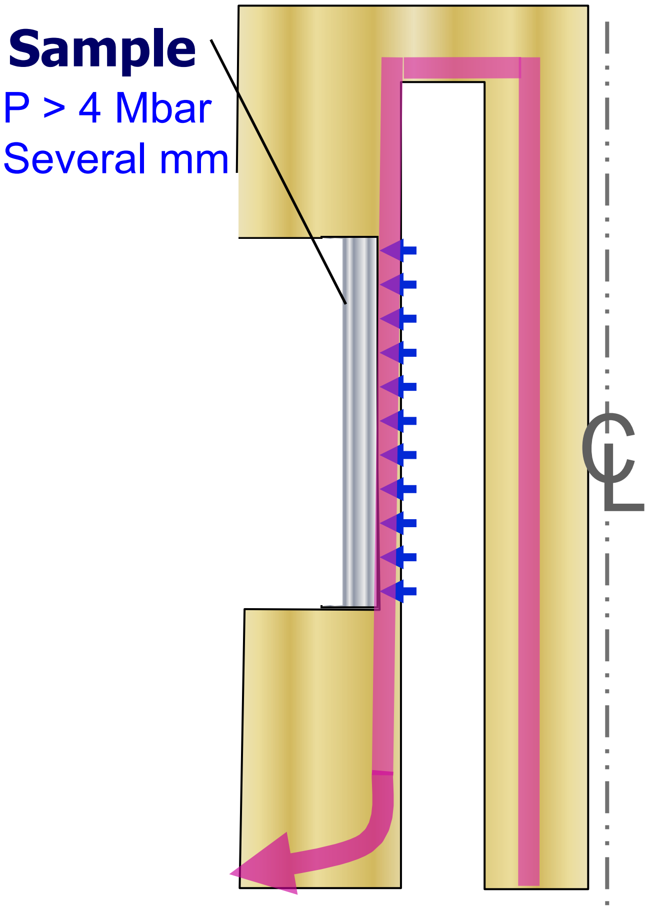


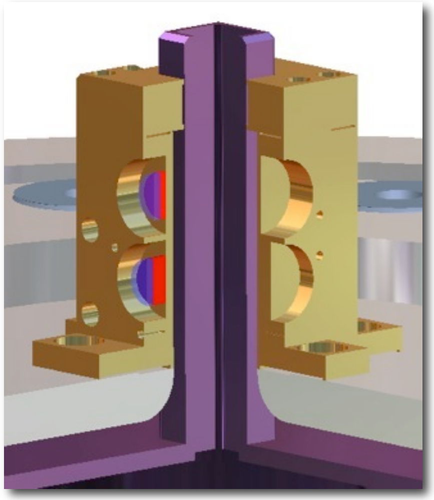
Imposed Helical Perturbations

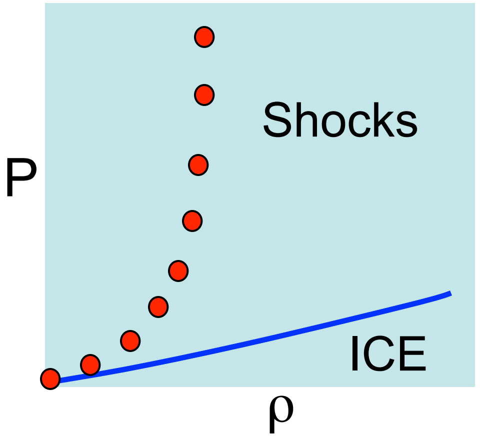


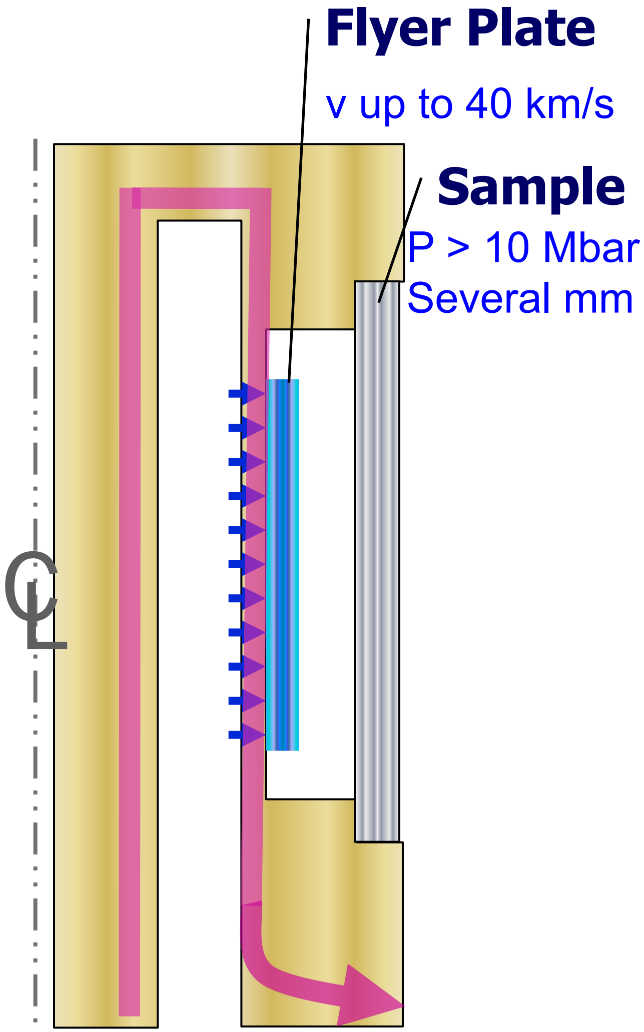


Z can perform both shockless and shock-wave compression experiments





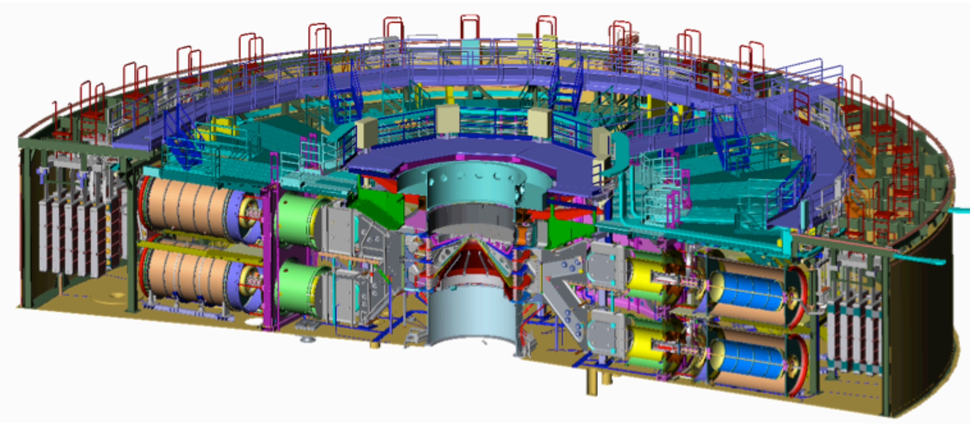


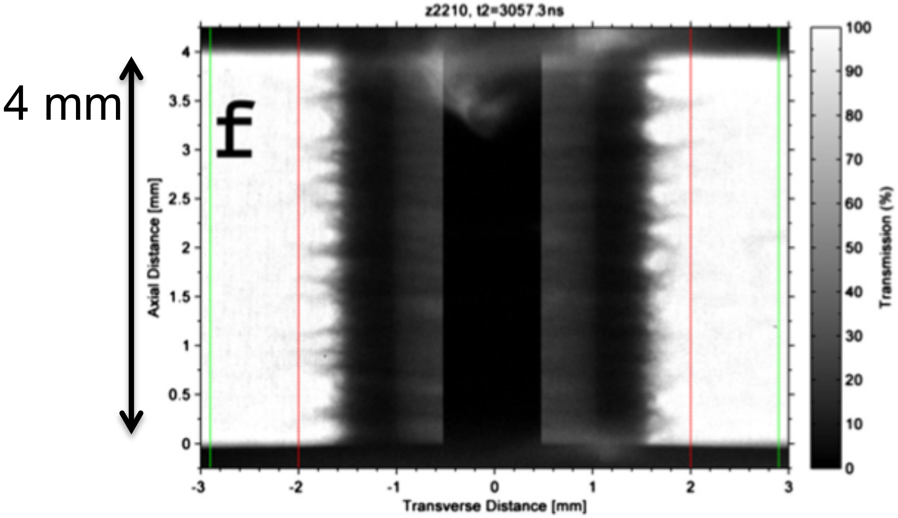


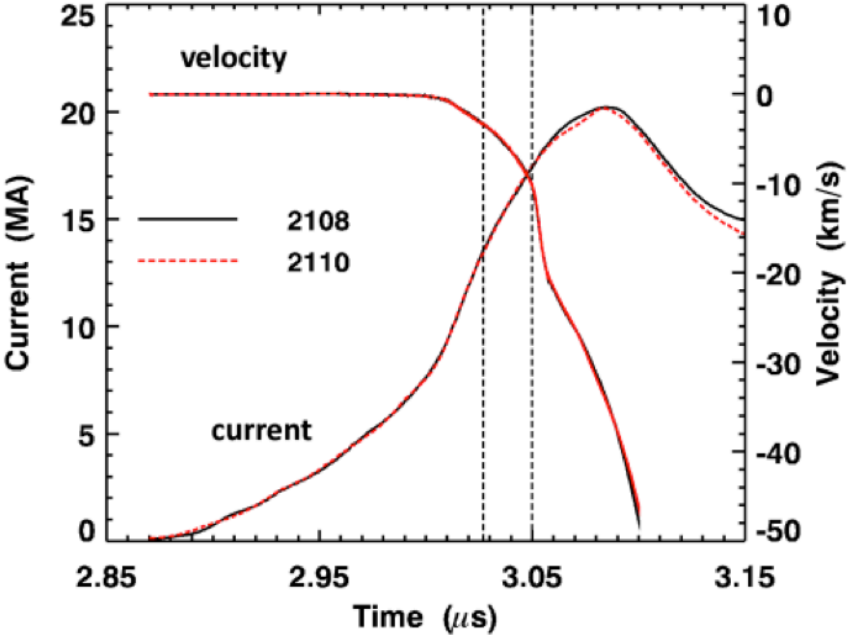
Isentropic Compression Experiments:
gradual pressure rise in sample

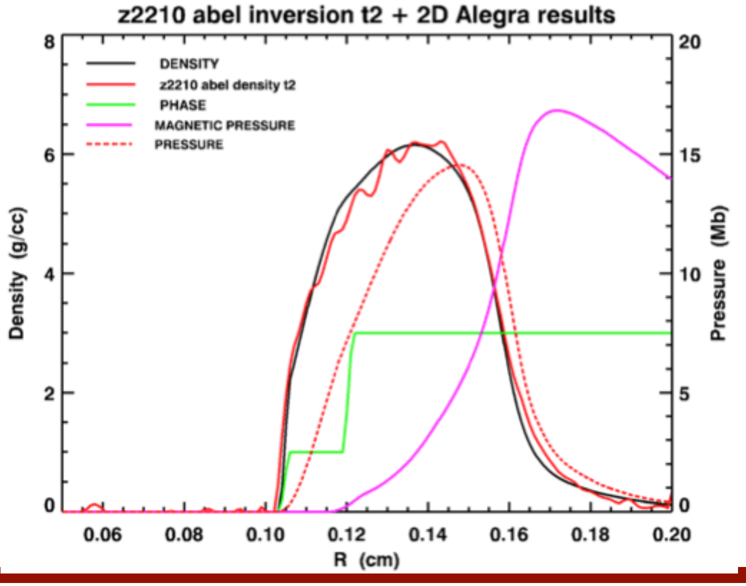
Shock Hugoniot Experiments:
shock wave in sample on impact

By independent triggering of the 36 different lines we can reproducibly create the complex time-dependent drive needed for shockless compression



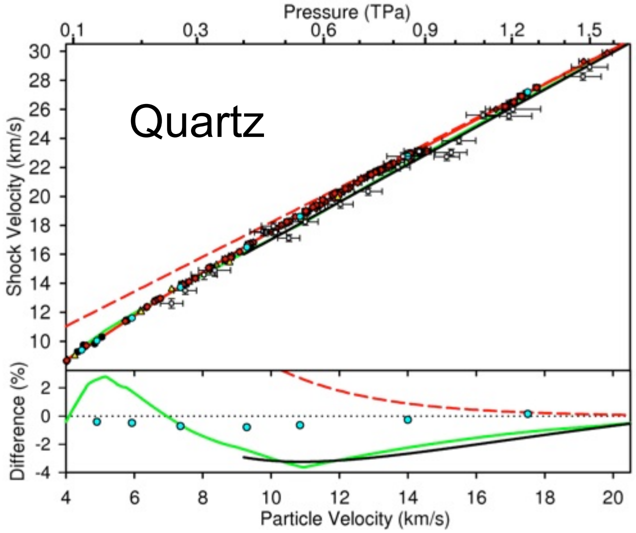


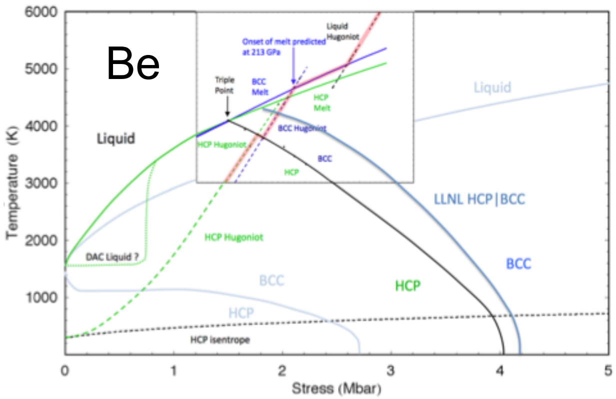


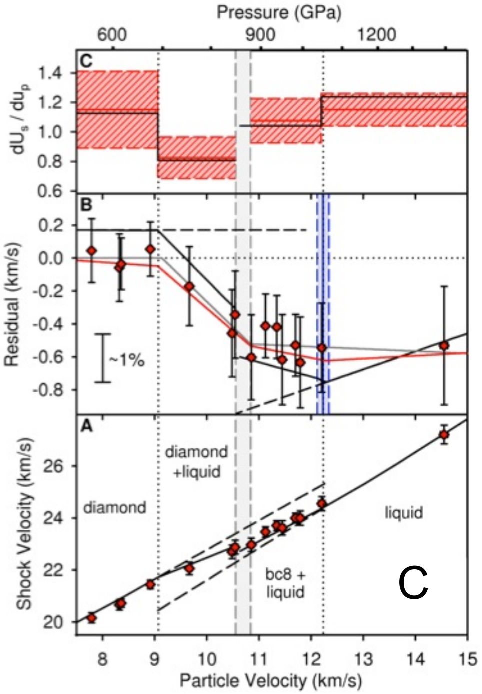


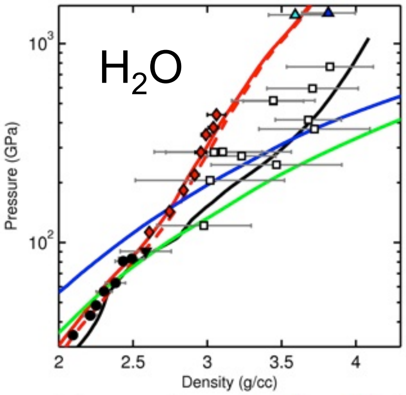
Example cylindrical Be data from M.R. Martin *et al.*, Phys. Plasmas 19, 056310 (2012).

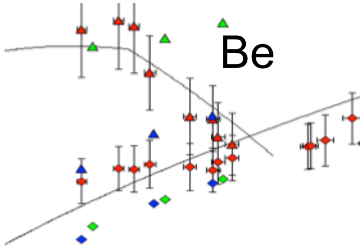
Z has been used to study material properties in the multi-Mbar regime for many materials

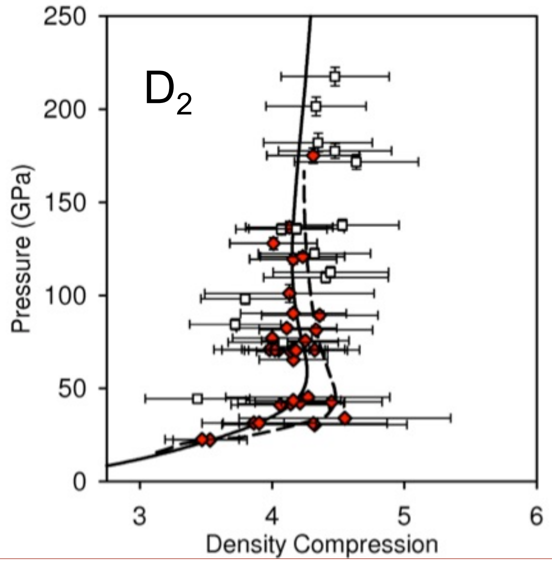


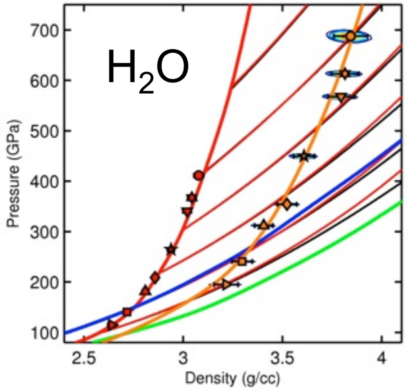


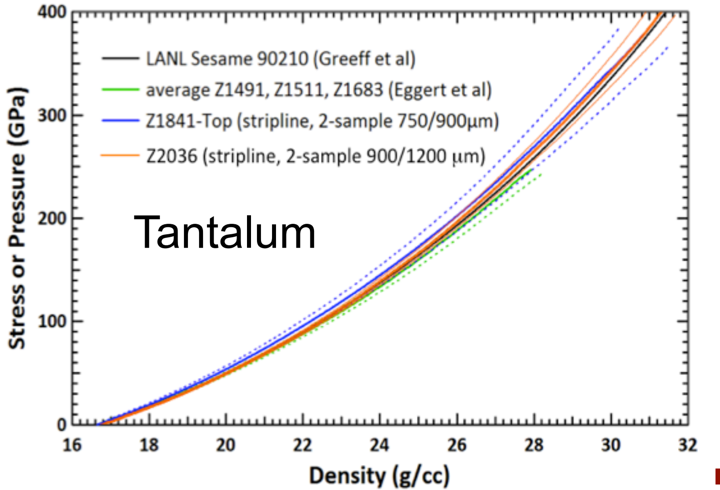






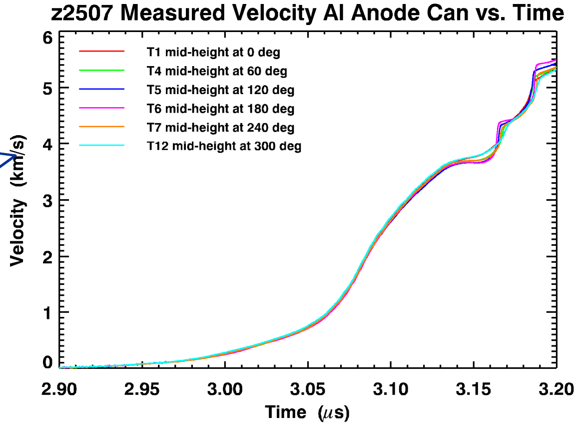


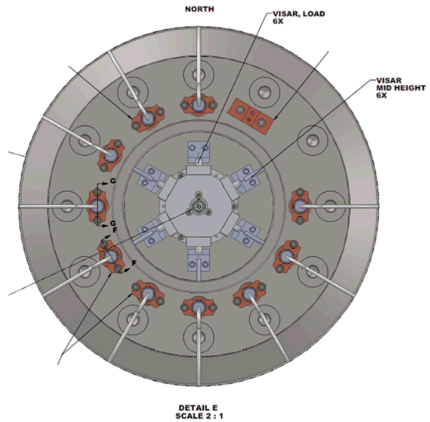




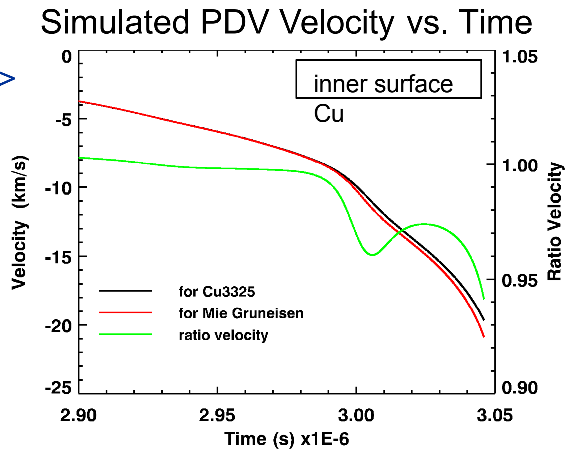
Shockless compression to peak stresses of ~20MB are possible on Z with cylindrical liner implosions

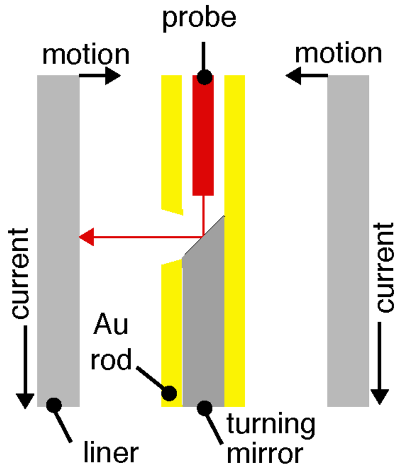
6 **external** radial measurements of the anode velocity show a high degree of symmetry during the implosion

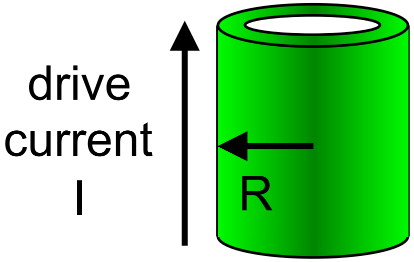




Different sample EOS results in **internal** velocity differences that can be distinguished using PDV







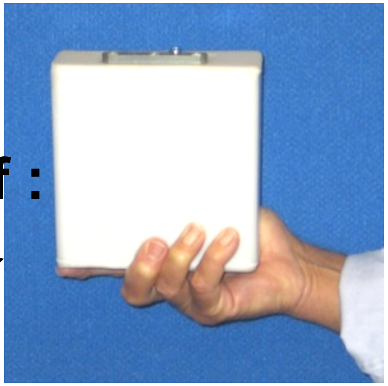
$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$

New technologies: The Linear Transformer Driver (LTD) is the most fundamental advance in pulsed power since the invention of the Marx generator in 1924

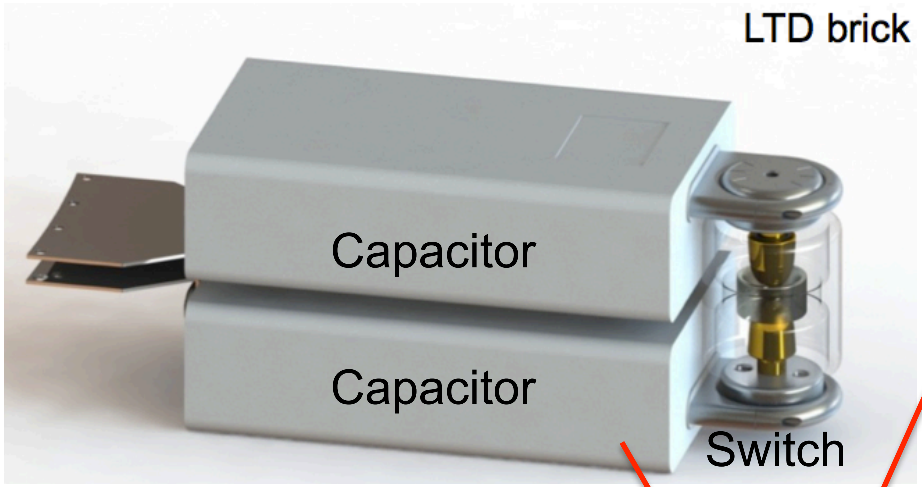
An LTD Cavity is the building block of a future high yield facility

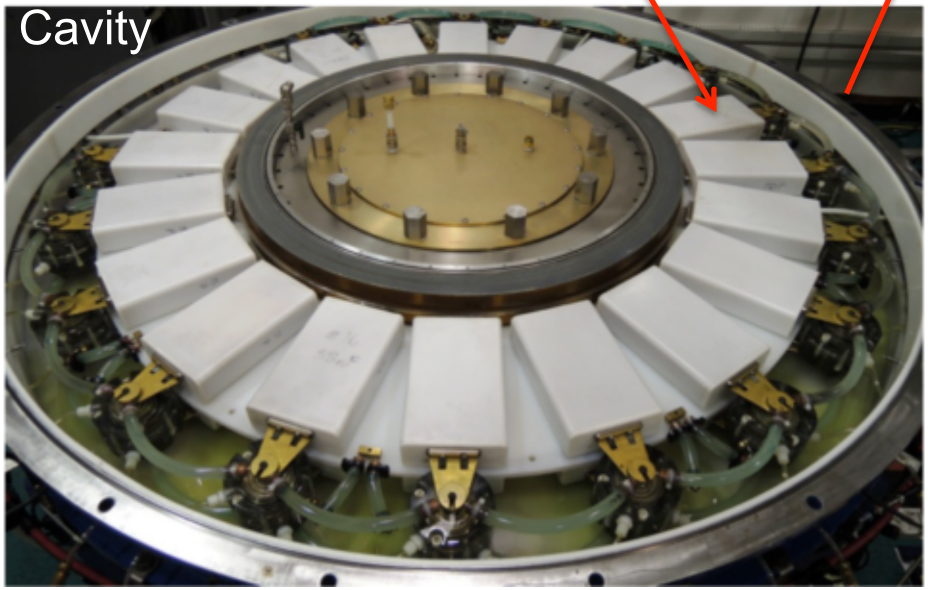
An LTD consists of :

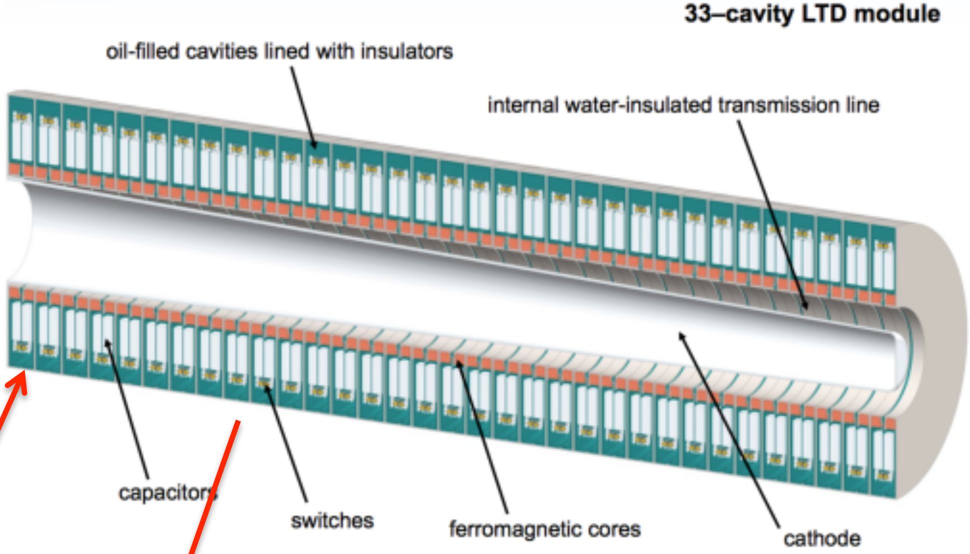
- **Capacitors**
- **Switches**
- **Magnetic cores**

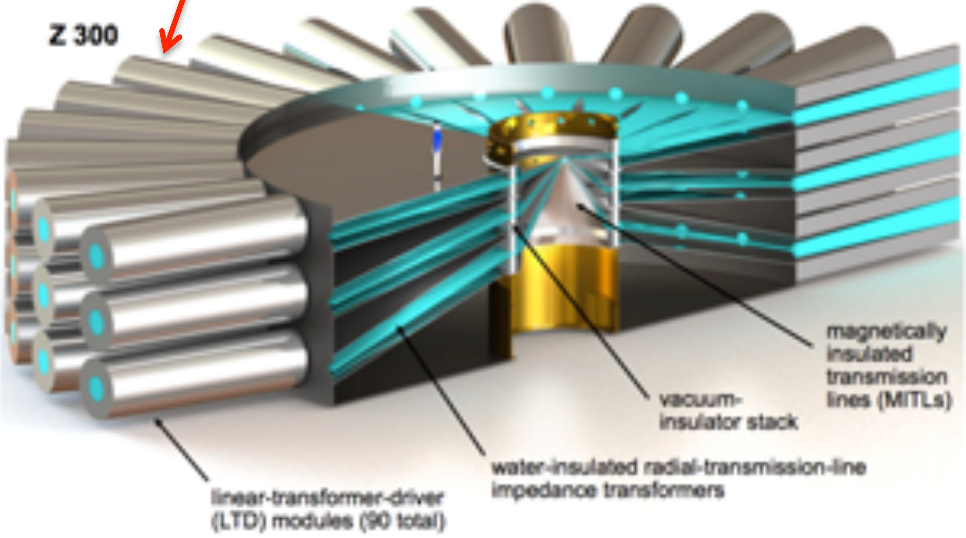


The Linear Transformer Driver (LTD) architecture can scale to very large systems.









Many thanks to the large dedicated team of scientists and engineers that have contributed to this talk

P. D. Ampleford, B.W. Atherton, T.J. Awe, J.E. Bailey, V. Bigman, J.H. Carpenter, K.R. Cochrane, M.E. Cuneo, J.P. Davis, M.P. Desjarlais, A.D. Edens, D.G. Flicker, S.B. Hansen, D.L. Hanson, G.S. Heffelfinger, M.C. Herrmann, C.A. Jennings, B.M. Jones, K. Killebrew, M.D. Knudson, G.T. Leifeste, R.W. Lemke, A.J. Lopez, M.R. Lopez, R.J. Magyar, M.R. Martin, R.D. McBride, R.G. McKee, J.L. Porter, G.A. Rochau, S. Root, D.C. Rovang, M.E. Savage, L. Shulenburger, A. B. Sefkow, D.B. Sinars, S.A. Slutz, J. Shores, I.C. Smith, W.A. Stygar, M.A. Sweeney, R.A. Vesey, E.P. Yu, and M.K. Matzen

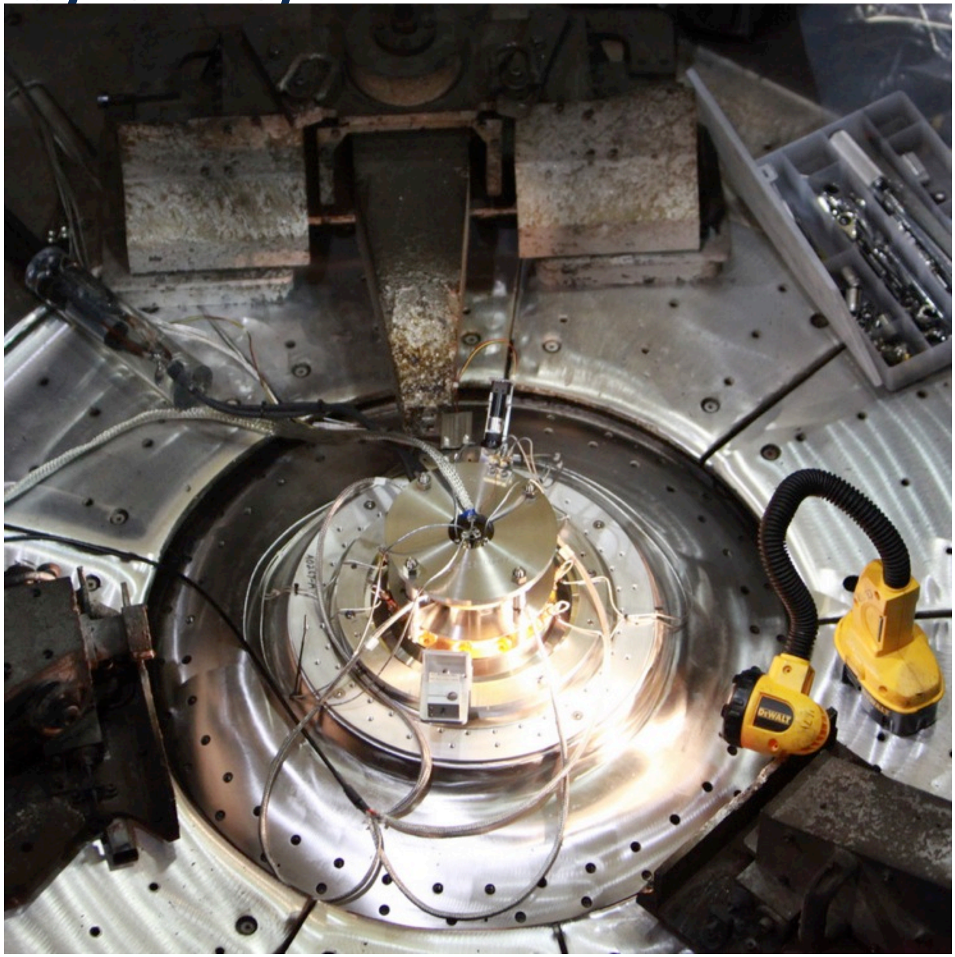
Sandia National Laboratories, Albuquerque, NM, USA

Brent Blue*, Randy Holt*, Korbie Killebrew*, Diana Schroen*, Robert Stamm*, Kurt Tomlinson*

General Atomics, San Diego, CA, USA

BACKUPS

Debris from Z experiments makes diagnostic development challenging (several MJ energy release equivalent to few sticks of dynamite)



Pre-shot photo of coils & target hardware

Post-shot photo

Z' s drive pressures allow it to be used for a variety of High Energy Density Physics (HEDP) applications

- Pressure (Pascals, bars) is equivalent to Energy Density (J/m^3)
  - 1 Mbar = 10^6 atm = 10^{11} Pascals = 10^{11} J/m^3
- HED threshold is pressures >1 Mbar, which exceeds the internal energy density of molecules/atoms (solids become compressible, etc.)

Object	Pressure (Mbar)
Z Storage Capacitor	2e-6
TNT	0.07
Internal energy of H atom	1.00
Estimated pressure of metallic H in Jupiter's core	30.00
Z magnetic drive pressure	~100.00
Center of the sun	250,000.00
Hot spot plasma in ICF target	~800,000.00

Pulsed Power

Can directly compress (dynamic mats.)

Can accelerate & converge fusion fuel (ICF)

ZAPP campaigns simultaneously study multiple issues spanning 200x in temperature and 10^6x in density

Solar Opacity

Question:
Why can't we predict the location of the convection zone boundary in the Sun?

Achieved Conditions:
$T_e \sim 200$ eV, $n_e \sim 10^{23}$ cm^{-3}

Photoionized Plasmas

Question:
How does ionization and line formation occur in accreting objects?

Achieved Conditions:
$T_e \sim 20$ eV, $n_e \sim 10^{18}$ cm^{-3}

White Dwarf Line-Shapes

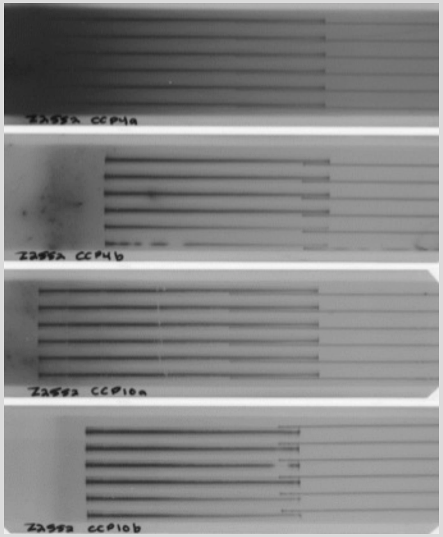
Question:
Why doesn't spectral fitting provide the correct properties for White Dwarfs?

Achieved Conditions:
$T_e \sim 1$ eV, $n_e \sim 10^{17}$ cm^{-3}

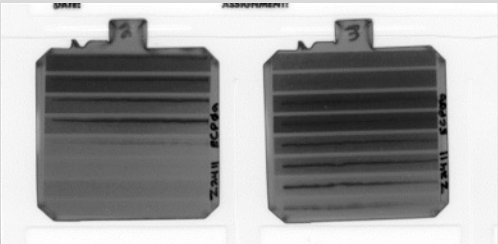
ZAPP campaigns acquire up to 59 spectra on a single shot

Solar Opacity

24 Space-Resolved
Fe Absorption Spectra

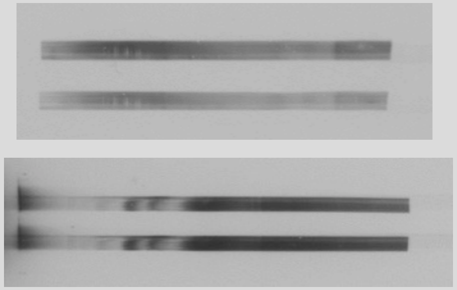


16 Time-Resolved
Fe Absorption Spectra

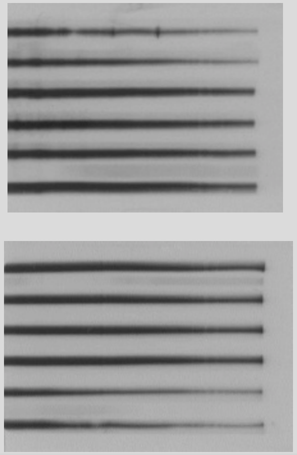


Photoionized Plasmas

4 Space-Resolved
Si Absorption Spectra

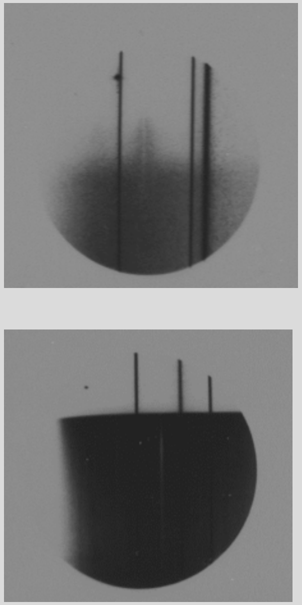


12 Space-Resolved
Ne Absorption Spectra



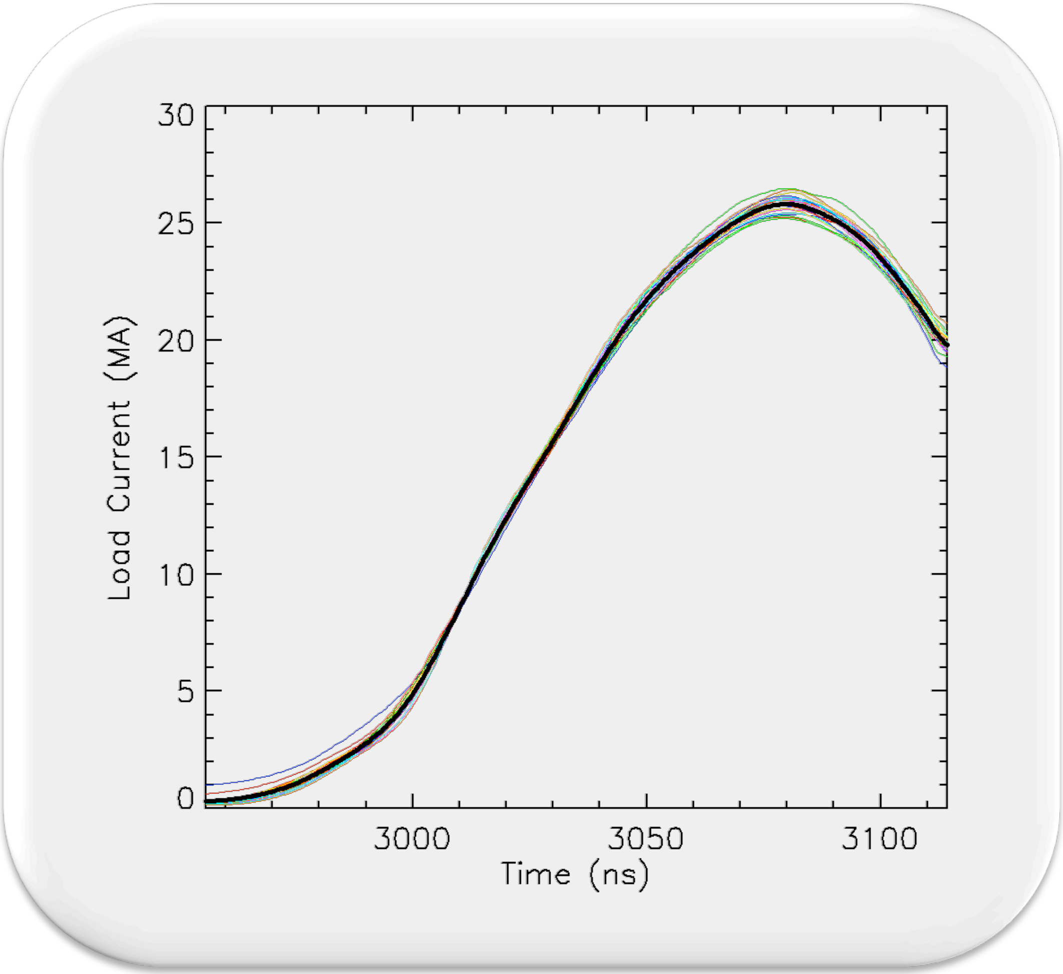
White Dwarf Line-Shapes

3 Streaked
H Absorption Spectra

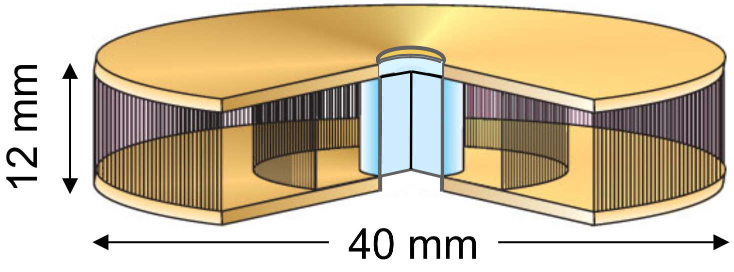


The z-pinch dynamic hohlraum (ZPDH) produces record currents of 25.8 MA with 1.5% reproducibility

Load Currents (20 shot average)



Z-pinch Dynamic Hohlraum



Standard ZPDH Characteristics

360 W wires – 11.4 μm diameter

m = 8.5 mg W total

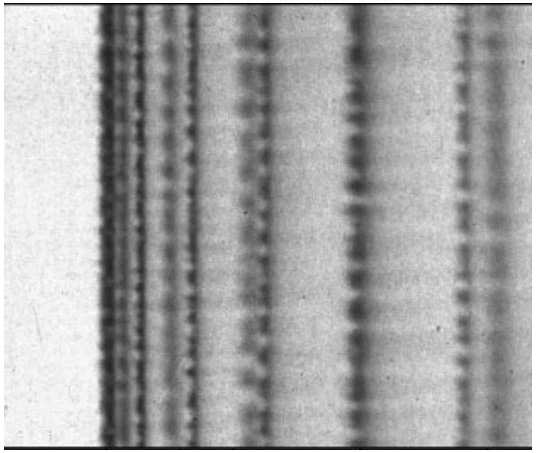
V_{marx} = 85 kV (21 MJ)

I_p = 25.8 ± 0.4 MA [20 shots]

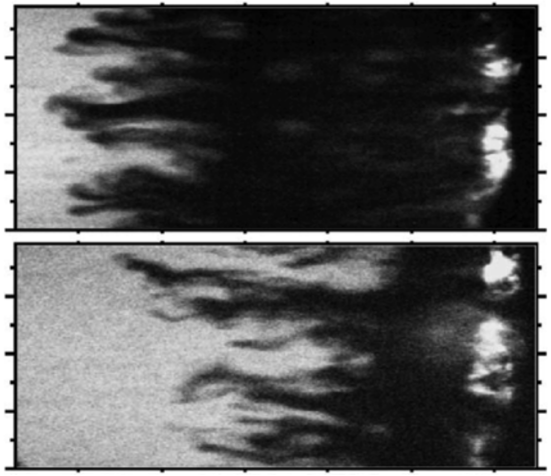
Sanford et al., POP 9 (2002)
Bailey et al., POP 13 (2006)
Lemke et al., POP 12 (2004)
Slutz et al., POP13 (2006)
Rochau et al., PPCF 49 (2007)

Magnetically driven implosions are efficient, powerful, soft and K-Shell x-ray sources

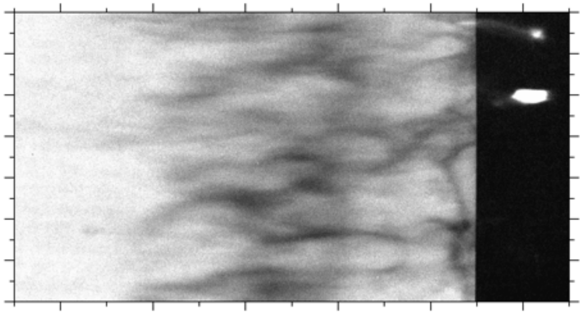
Ablation

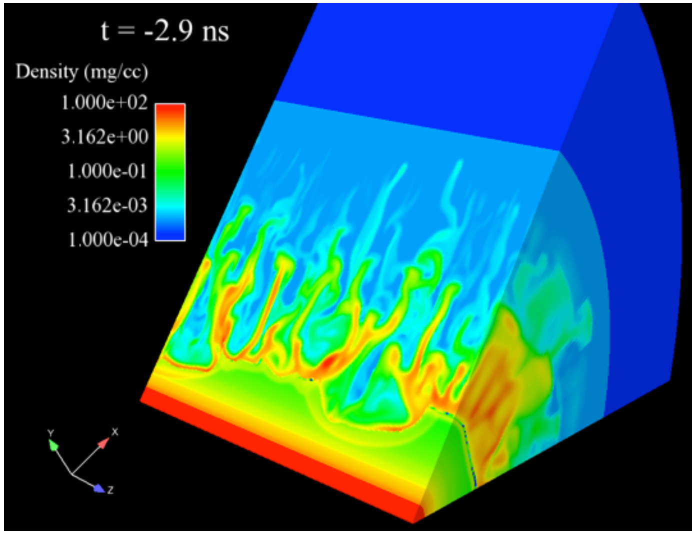


Implosion



Stagnation &
X-ray production





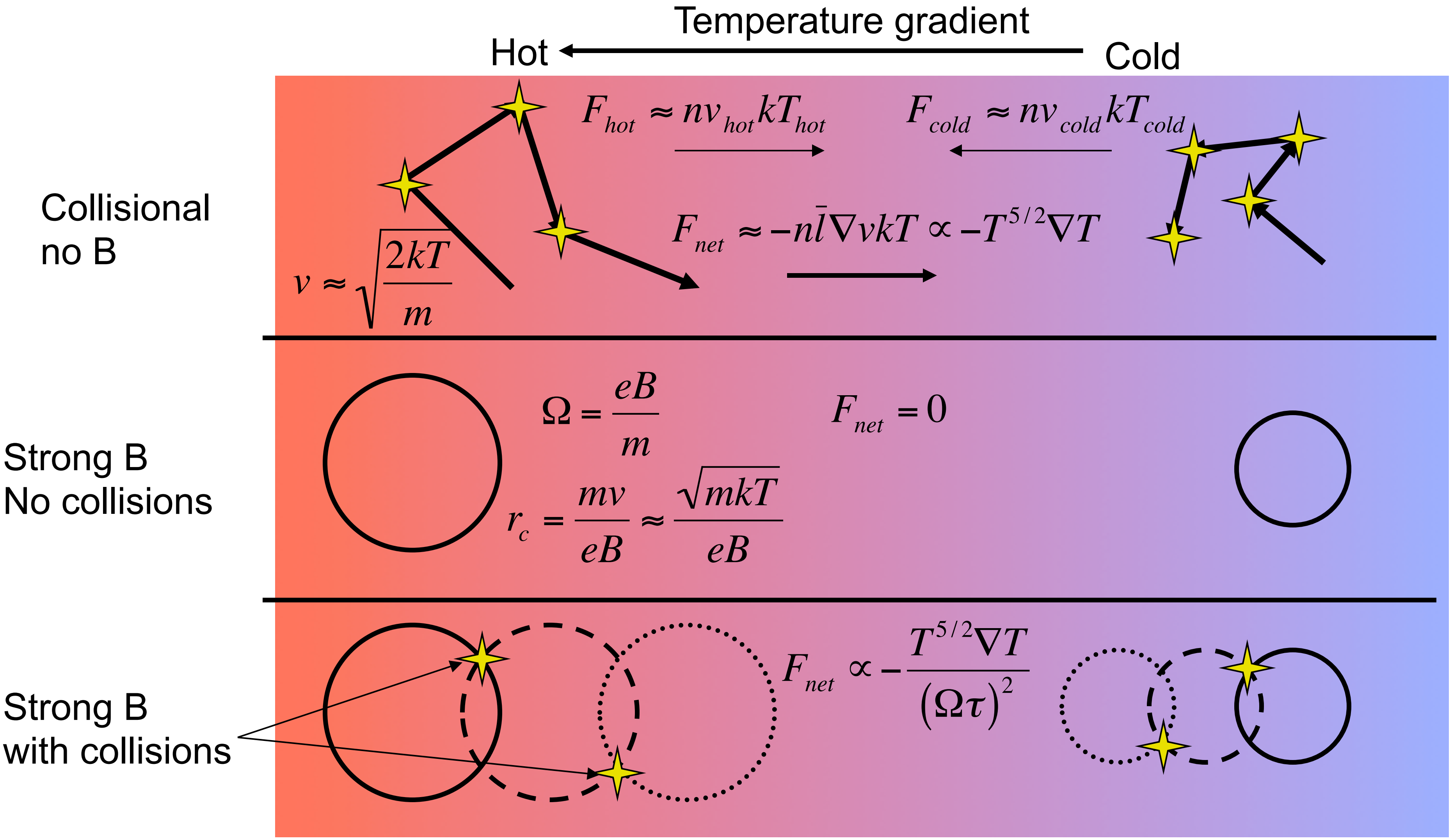
3D Rad/MHD simulations are just beginning to be applied to magnetically-driven implosions

What limits are there are on soft x-ray and K-shell production efficiency and powers?

Can we validate our computational tools for wire array implosions?

References…

The presence of a magnetic field can strongly affect transport properties, e.g. heat conduction



Temperature gradient

Hot ← Cold

Collisional
no B

$F_{hot} \approx n v_{hot} k T_{hot}$ →

$F_{cold} \approx n v_{cold} k T_{cold}$ ←

$F_{net} \approx -n\bar{l}\nabla v k T \propto -T^{5/2}\nabla T$ →

$v \approx \sqrt{\frac{2kT}{m}}$

Strong B
No collisions

$\Omega = \frac{eB}{m}$

$F_{net} = 0$

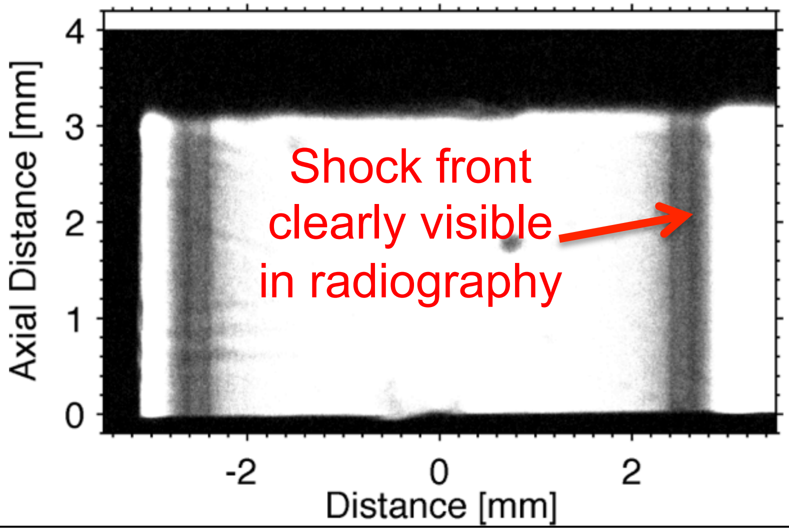
$r_c = \frac{mv}{eB} \approx \frac{\sqrt{mkT}}{eB}$

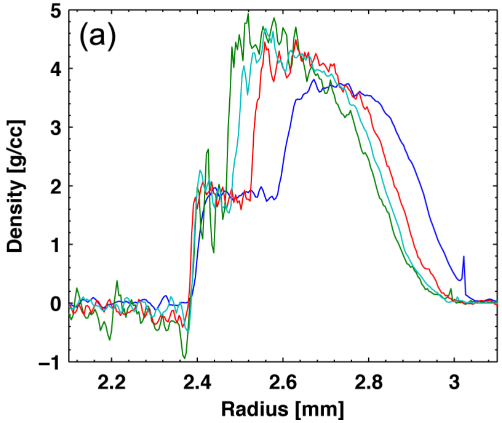
Strong B
with collisions

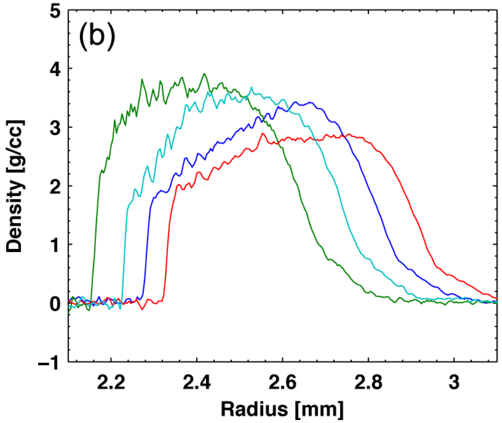
$F_{net} \propto -\frac{T^{5/2}\nabla T}{(\Omega\tau)^2}$

Energetic particles (e.g., alpha particles) can also be strongly affected by magnetic fields

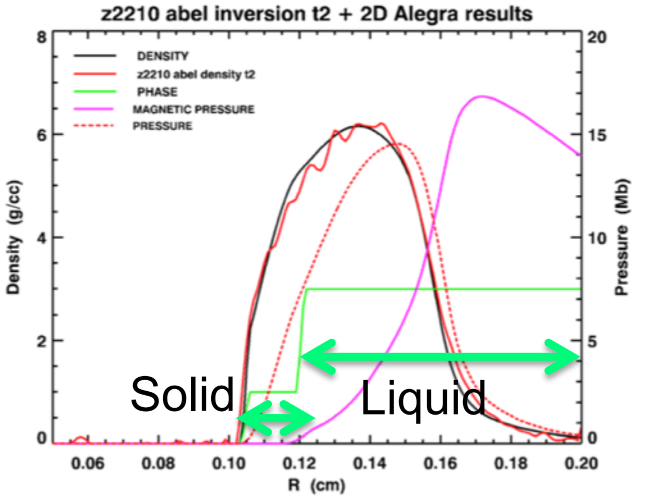
One way to maintain strength and potentially mitigate MRT is to shape the current pulse to avoid shock heating of the liner—a technique ultimately limited by magnetic diffusion


Shock front clearly visible in radiography


Shocked density profile


Pulse-shaped density profile

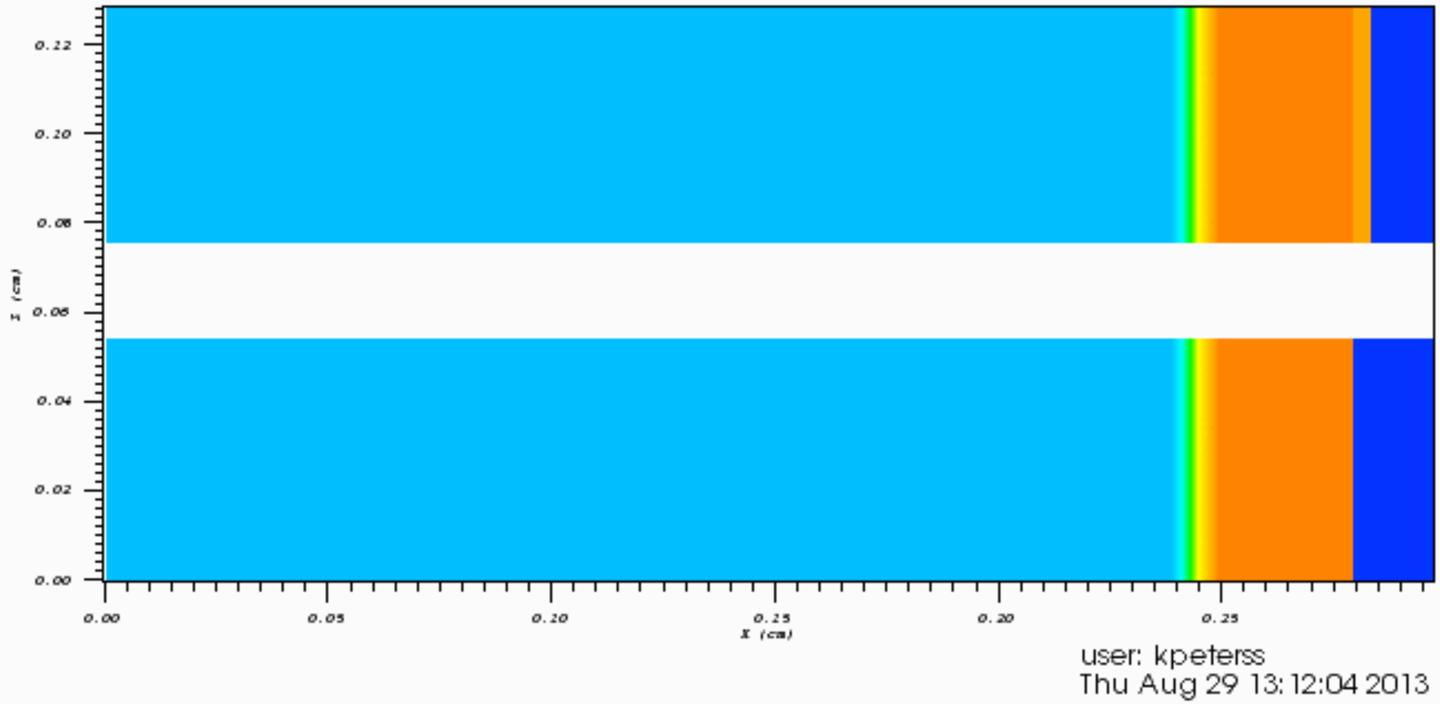
- Maintaining liner in solid/liquid state affects the liner conductivity, which may affect instability growth
- Maintaining a solid inner surface may reduce ablation into the fuel region, and also help with deceleration MRT
- Cylindrical liner implosions were recently used to measure Be EOS to 6 Mbar, and up to 20 Mbar in Al!



M.R. Martin *et al.*, Phys. Plasmas 19, 056310 (2012).
M.R. Martin *et al.*, AIP Conf. Proc. 1426, 357 (2012).
R.W. Lemke *et al.*, AIP Conf. Proc. 1426, 473 (2012).
R.D. McBride *et al.*, invited manuscript submitted to Phys. Plasmas (2012).

Simulations suggest that ETI coatings will improve the stability of MagLIF liners dramatically

HYDRA MHD



user: kpeterss
Thu Aug 29 13:12:04 2013

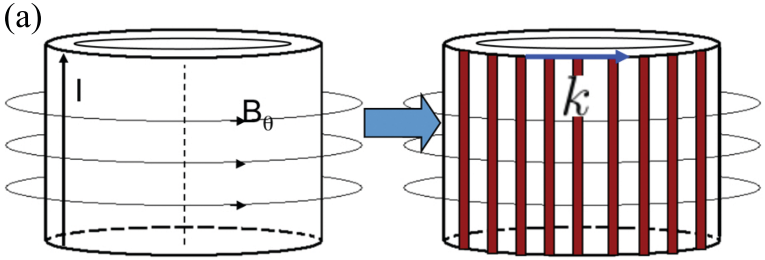
40 µm coating

uncoated

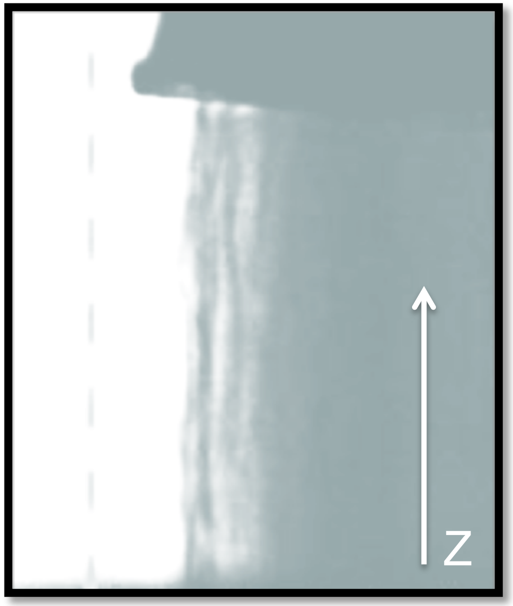
Electrothermal filamentation may be introducing azimuthal asymmetries and limiting correlation

- Postulated in the past based on analytical arguments
- Relevant to Laser driven ICF concepts*
- Simulation of this physics is difficult

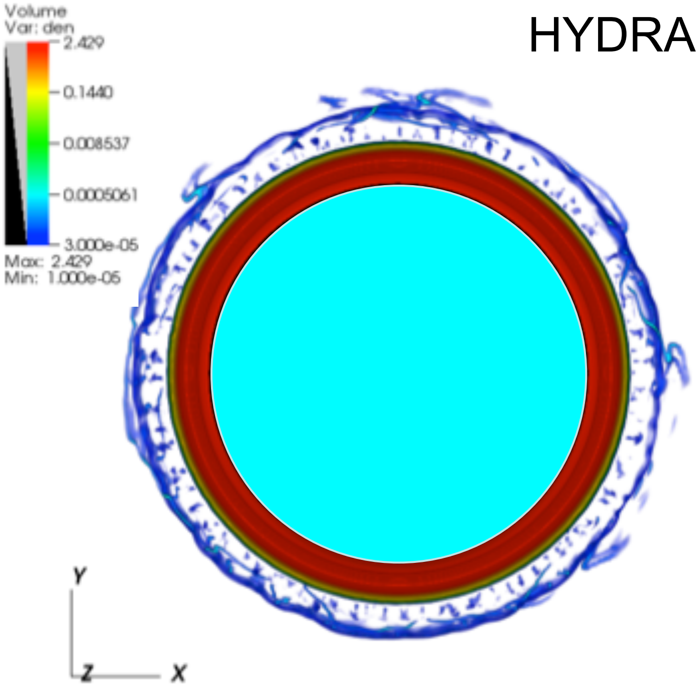
$$\frac{d\eta(T)}{dT} > 0$$

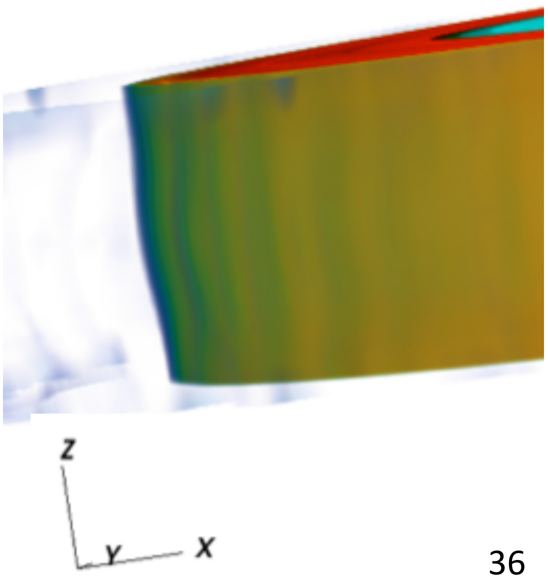


Evident on Z2509?



HYDRA Simulations





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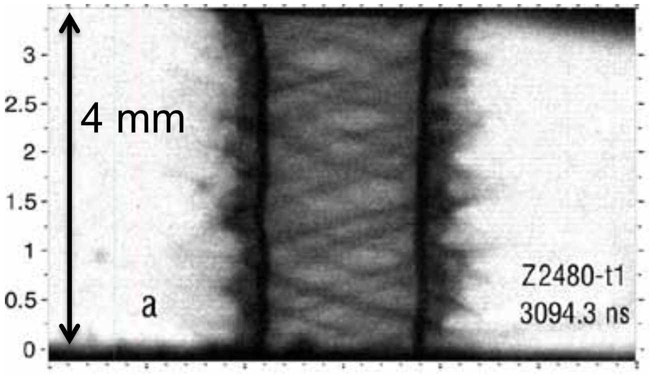
*F. H. Se´guin *et al.*, Phys. Plasmas **19,** 012701 (2012)

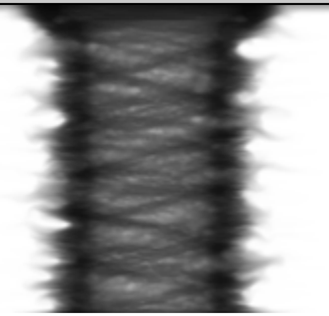
Simulating the results obtained with the first axially-magnetized liner implosions has been difficult

Roosevelt I Experiment with applied Bz field



CR =2.7

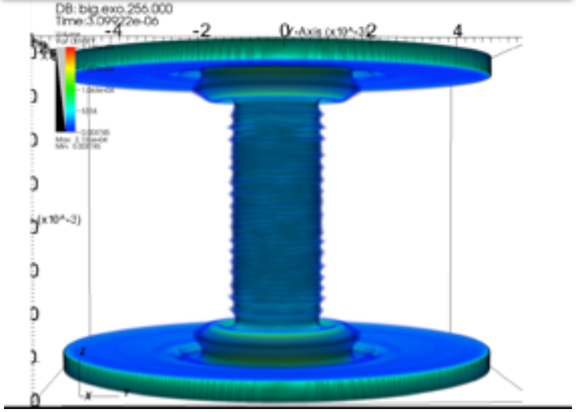
GORGON Simulation[1] with pre-imposed helical perturbations



See O.Tu_C12 for further discussion and theory

- Multiple simulation codes/models
  - HYDRA, GORGON, ALEGRA
- Qualitatively similar results have only been obtained using pre-imposed helical perturbation simulations
  - Unsatisfying (Doesn't constrain physics)
  - Perturbation Seed?
  - Missing physics? **ETI**?

ALEGRA Simulation[2] with nominal surface roughness



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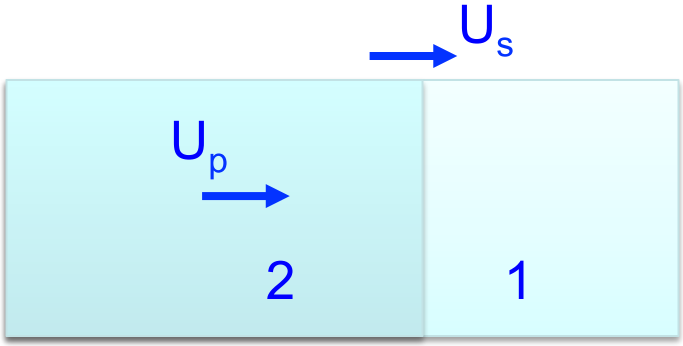
[1] Christopher Jennings Simulation, [2] Matthew Martin Simulation

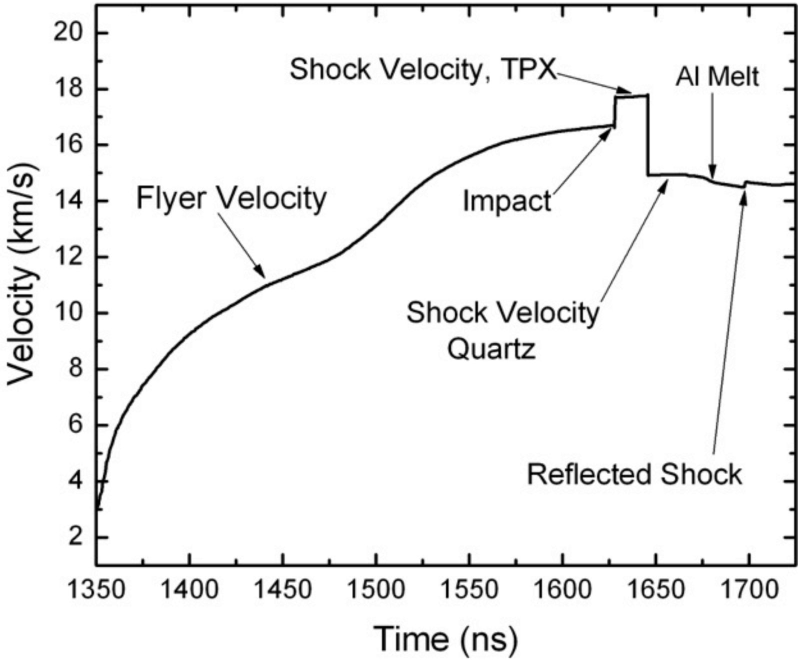
We reach Mbar pressures in materials by executing flyer-plate impact experiments

- Straightforward to analyze plate-impact data
  - Long steady shocks
  - Conservation of mass, momentum, and energy
  - Rankine-Hugoniot relation

$$2(E_2 - E_1) = (P_2 + P_1)(\upsilon_1 - \upsilon_2)$$

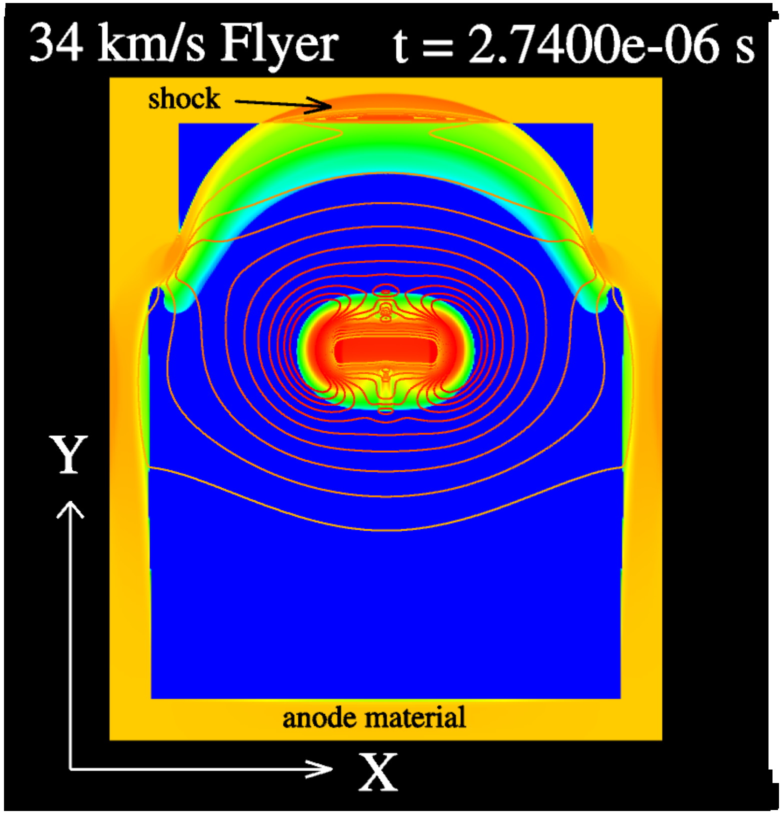


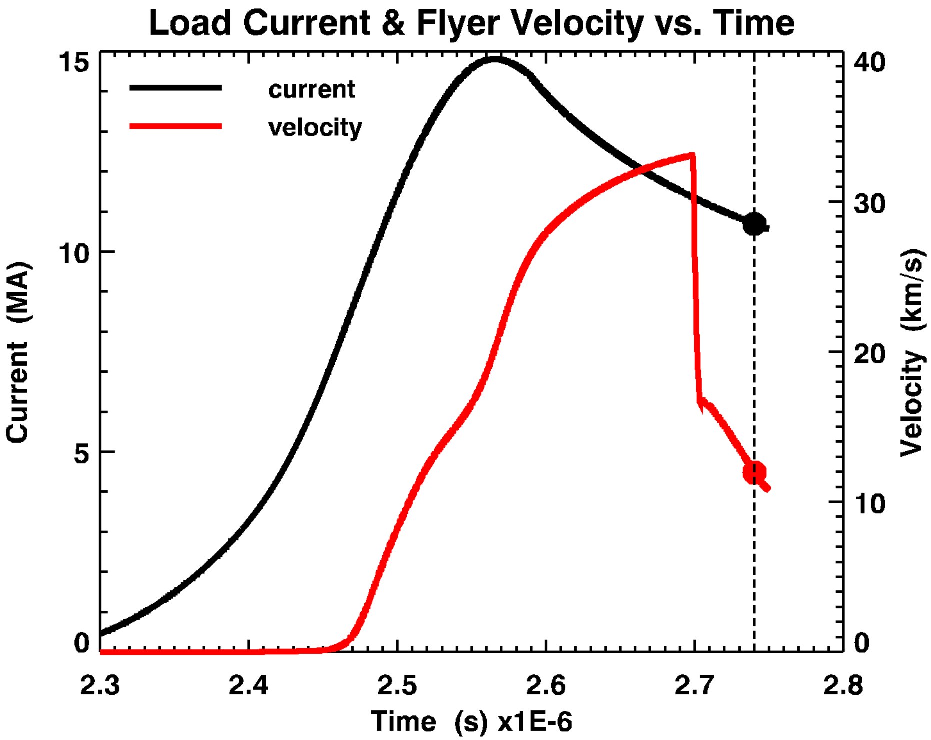
Steady shock wave in plastics



Data from a flyer impact experiment: tracking flyer velocity and shock speeds in quartz and TPX, both having reflective shock fronts.

Snapshots from 2D numerical simulation show dynamics of flyer in high velocity experiment

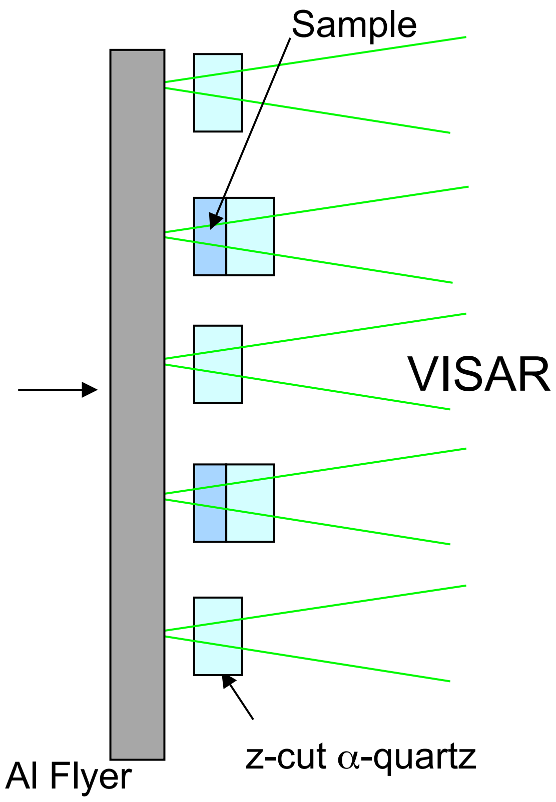




In these experiments conditions are much better defined (less integrated, typically single measurement, but conditions are also much less extreme)

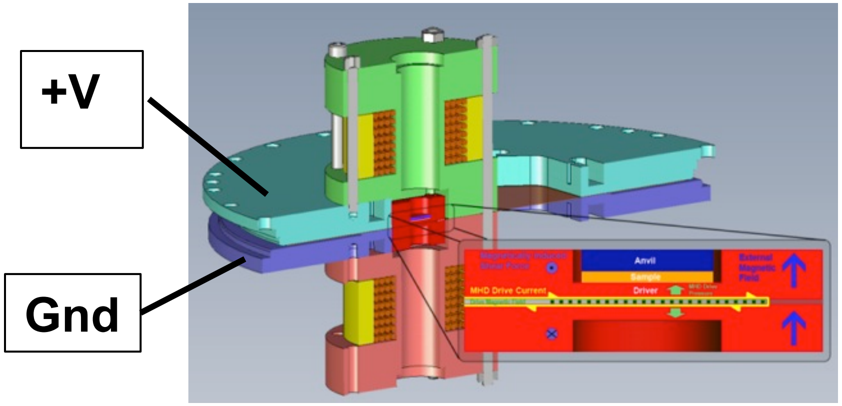
Note velocity predictions have been in good agreement with experiment

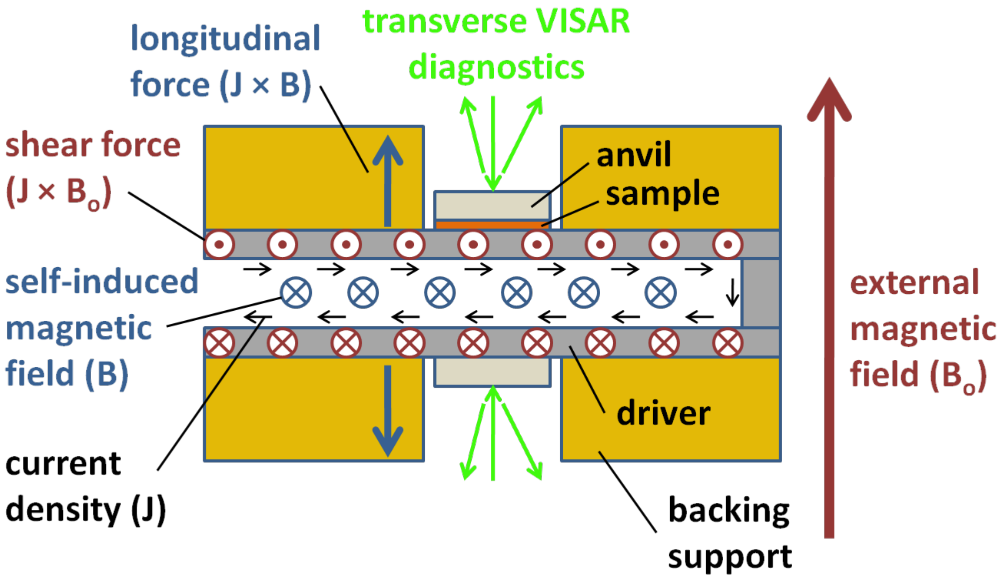
We measure shock velocities in plastic and other transparent materials with sub-percent accuracy



- VISAR measurements as main tool:
  - Up to 4 VPF (velocity per fringe) measurements
  - Flyer velocity
  - Time of impact
  - Shock arrival at sample/quartz interface
  - Shock velocity in sample and breakout time
- Steady shocks, large samples, and long times yield high precision measurements

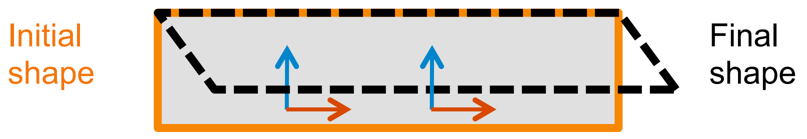
We will also use our applied magnetic field capability to generate shear waves in dynamic material samples





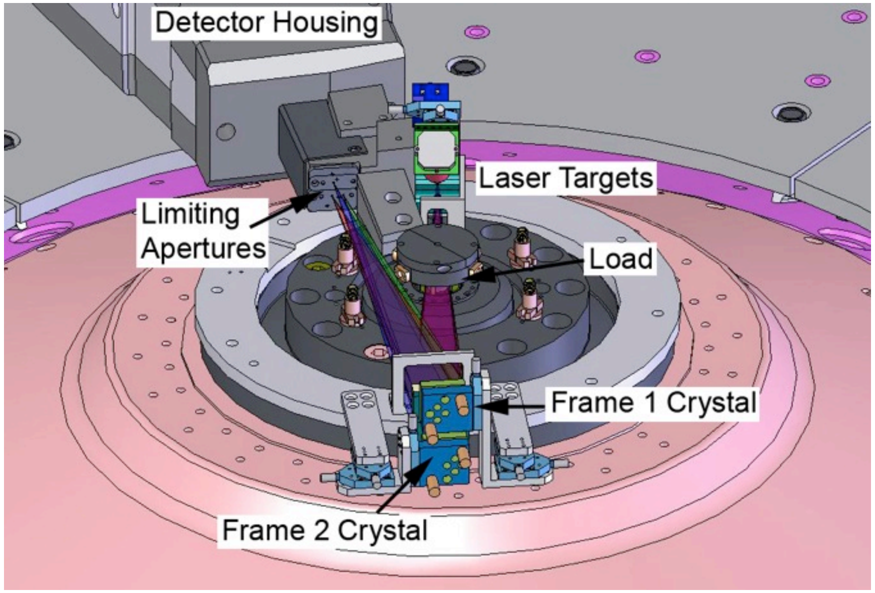
- Longitudinal force results from self-generated magnetic field
- Shear force is generated by application of an external magnetic field
- Initial experiments planned for March 2013 at 3-5 Tesla

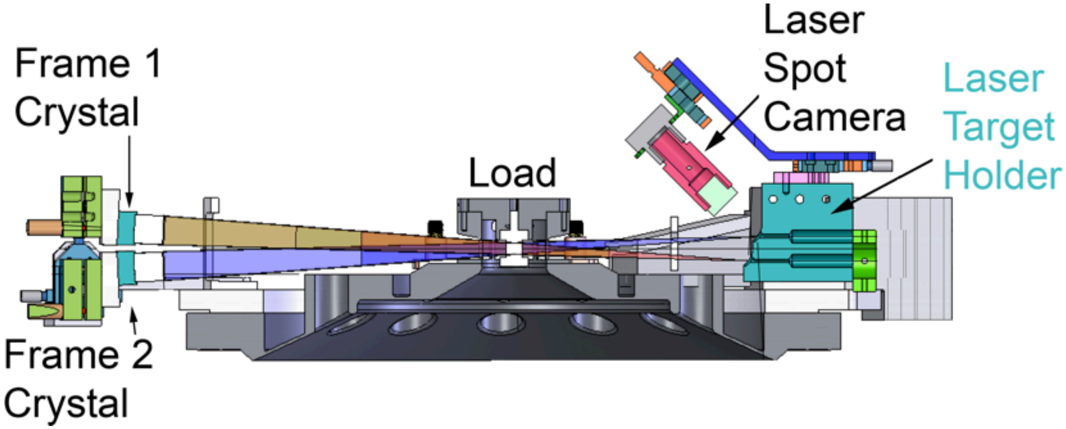
<u>end view of sample</u>



Sample is compressed by the longitudinal force and then sheared by the shear force

We use a 2-frame 6.151 keV monochromatic crystal backlighting diagnostic to study liner dynamics on Z





Radiograph lines of sight ±3° from horizontal

2-frame 6.151 keV Crystal Imaging

- **Monochromatic (~0.5 eV bandpass)**
- **15 micron resolution (edge-spread)**
- **Large field of view (10 mm x 4 mm)**
- **Debris mitigation**

- **Original concept**
  - S.A. Pikuz *et al.,* RSI (1997).
- **1.865 keV backlighter at NRL**
  - Y. Aglitskiy *et al*., RSI (1999).
- **Explored as NIF diagnostic option**
  - J.A. Koch *et al*., RSI (1999).
- **Single-frame 1.865 keV and 6.151 keV implemented on Z facility**
  - D.B. Sinars *et al*., RSI (2004).
- **Two-frame 6.151 keV on Z facility**
  - G.R. Bennett *et al*., RSI (2008).