Using Magnetic Fields to Create and Control High Energy Density Matter

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in collaboration with my colleagues at Sandia National Laboratories

Presentation to the
IPAM Workshop on Computational Challenges in Hot Dense Plasmas
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National Nuclear Security Administration

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It's an exciting time to be working in Magnetized HED science

- Our understanding of Magnetized HED science is being applied to important applications
- Ever more extreme conditions are being reached using magnetized HED science
- Magnetic fields appear spontaneously and now are observed in many HED plasmas
- We are poised for exciting advances in inertial confinement fusion using magnetized concepts
- Many computational challenges remain in this subfield of HED

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What are Magnetized High Energy Density Plasmas and what is interesting about them?

Our working definition of Magnetized High Energy Density Plasmas :

HED Plasmas with fields magnetic fields > 5 Megagauss (Magnetic Pressure > 1 MB)

and/or

HED Plasmas whose transport processes are significantly affected by the presence of a magnetic field

If strong enough Magnetic Fields fundamentally alter the behavior of HED plasmas:

- **Magnetic fields and currents can push on plasmas in unique ways**
- **Magnetic fields can be spontaneously generated and amplified**
- **Magnetic fields change the way particles and energy are transported in a plasma**

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Large currents and the corresponding magnetic fields can be used to create 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 fields have some unique advantages when creating HED plasmas:

- **Magnetic fields are very efficient at creating HED matter enabling large samples and energetic sources**

- **Magnetic fields have very interesting properties in converging geometry**

Magnetic fields have interesting contrasts with other ways of generating HED:

- **Magnetic fields can create high pressures without making material hot**

- **Magnetic fields can be generated over long time scales with significant control over the time history**

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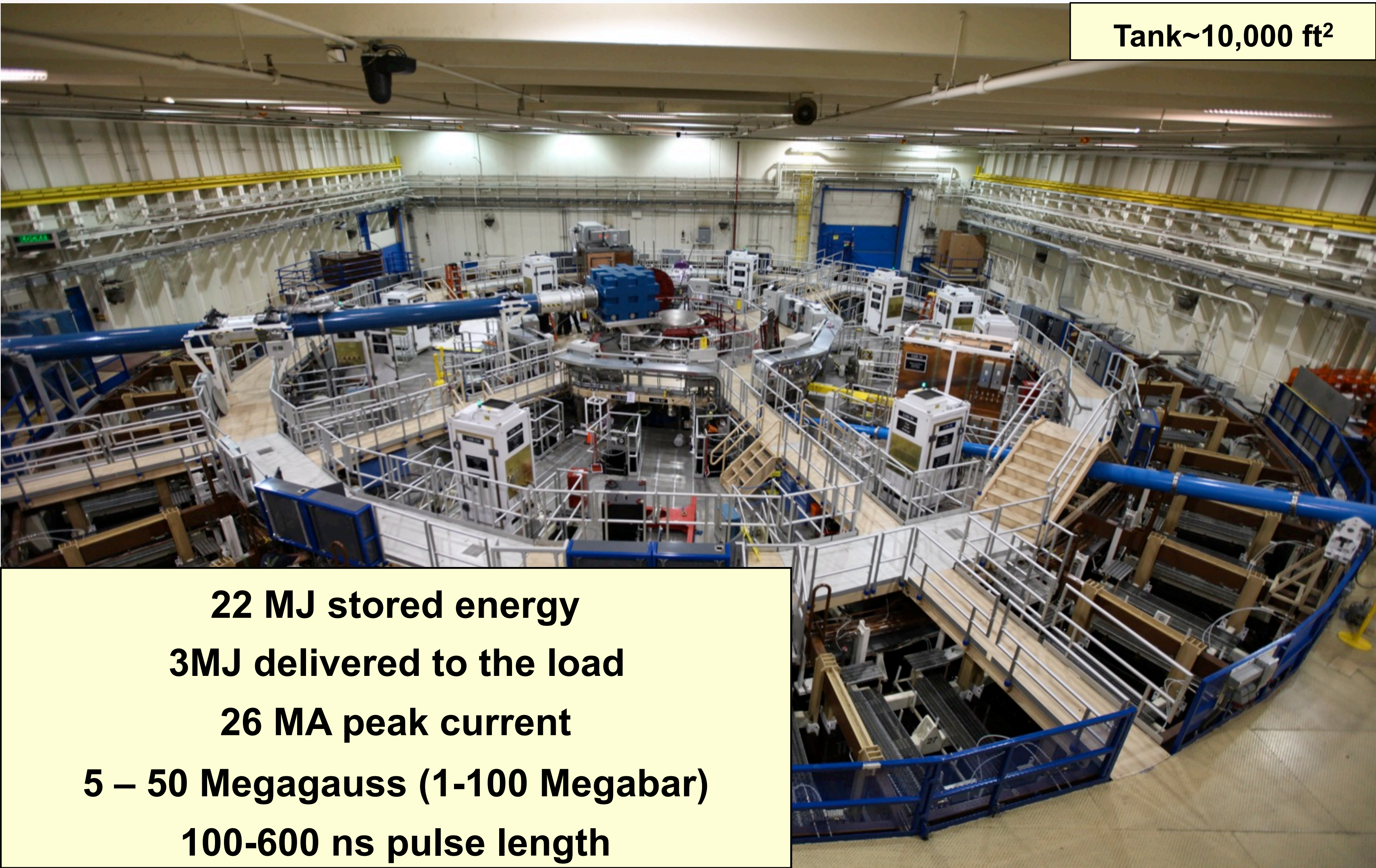
We use the Z pulsed power facility to generate large magnetic fields



Tank~10,000 ft^2

22 MJ stored energy

3MJ delivered to the load

26 MA peak current

5 – 50 Megagauss (1-100 Megabar)

100-600 ns pulse length

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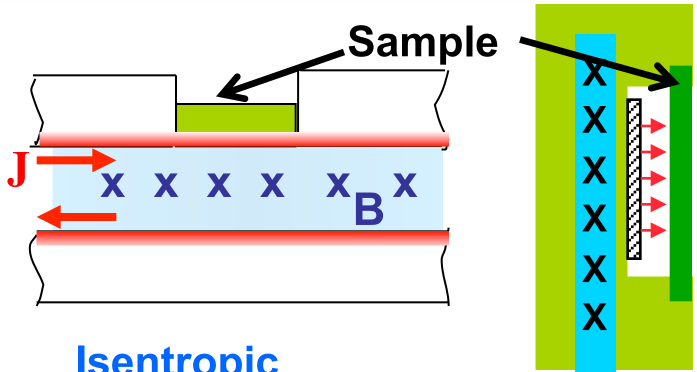
We use magnetic fields to create HED matter in different ways for different applications

Materials Properties

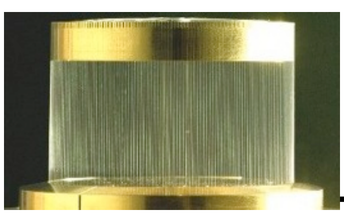


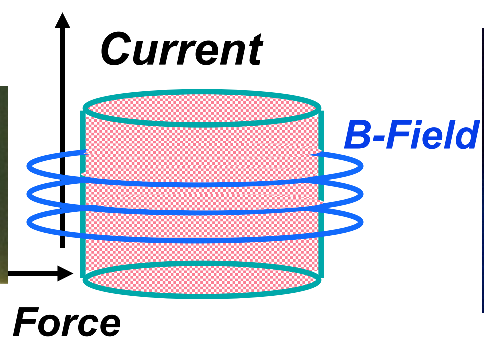
Isentropic Compression

Flyer Plate

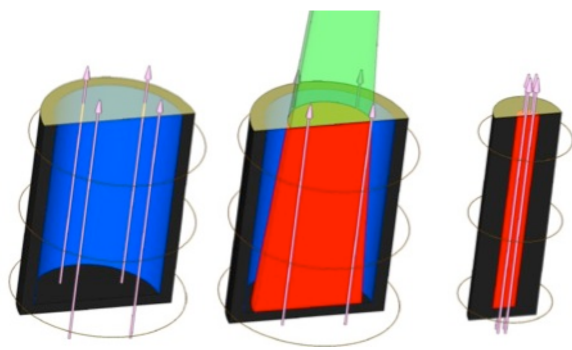
Z-Pinch X-ray Sources

wire array

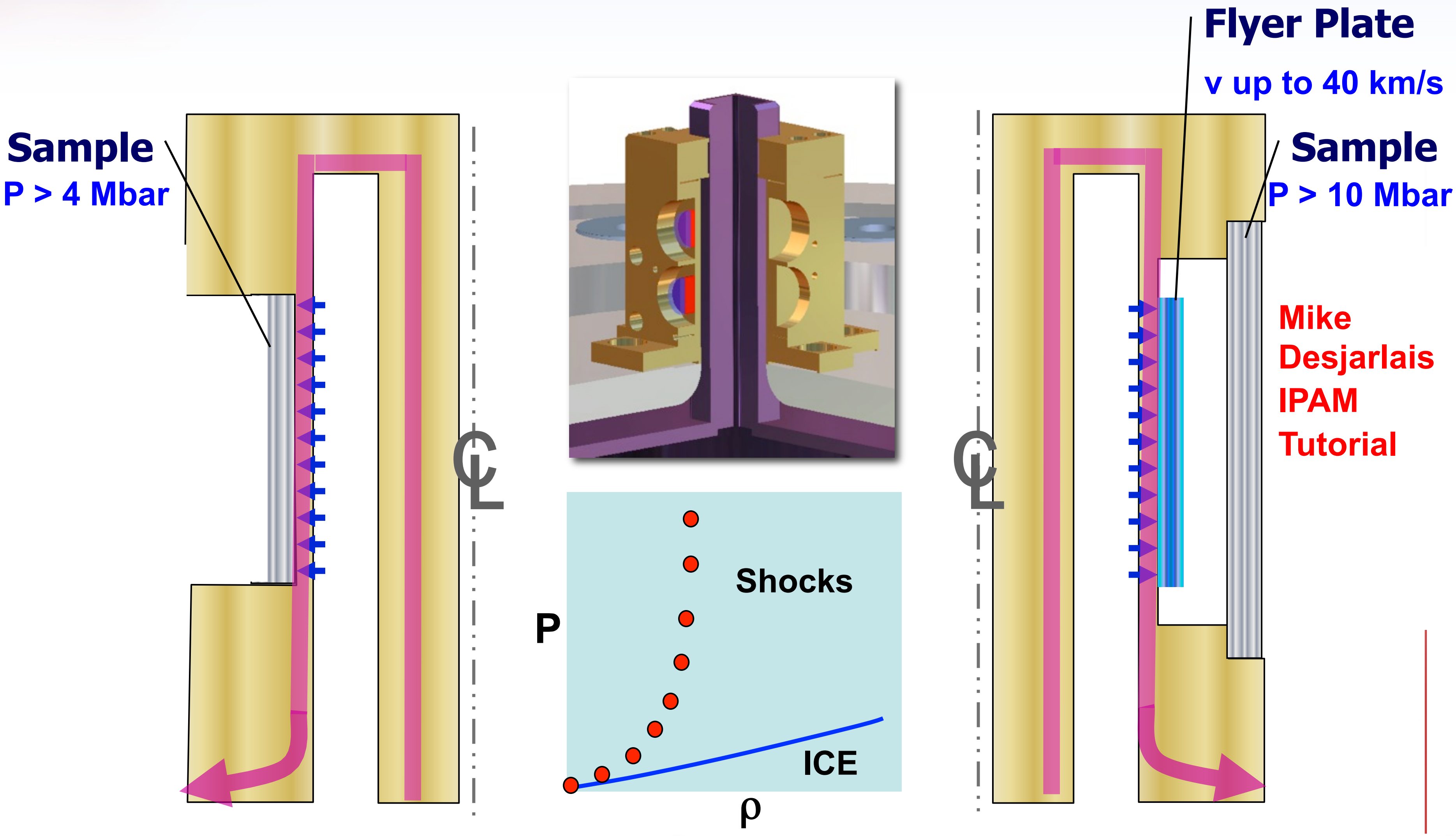




Inertial Confinement Fusion



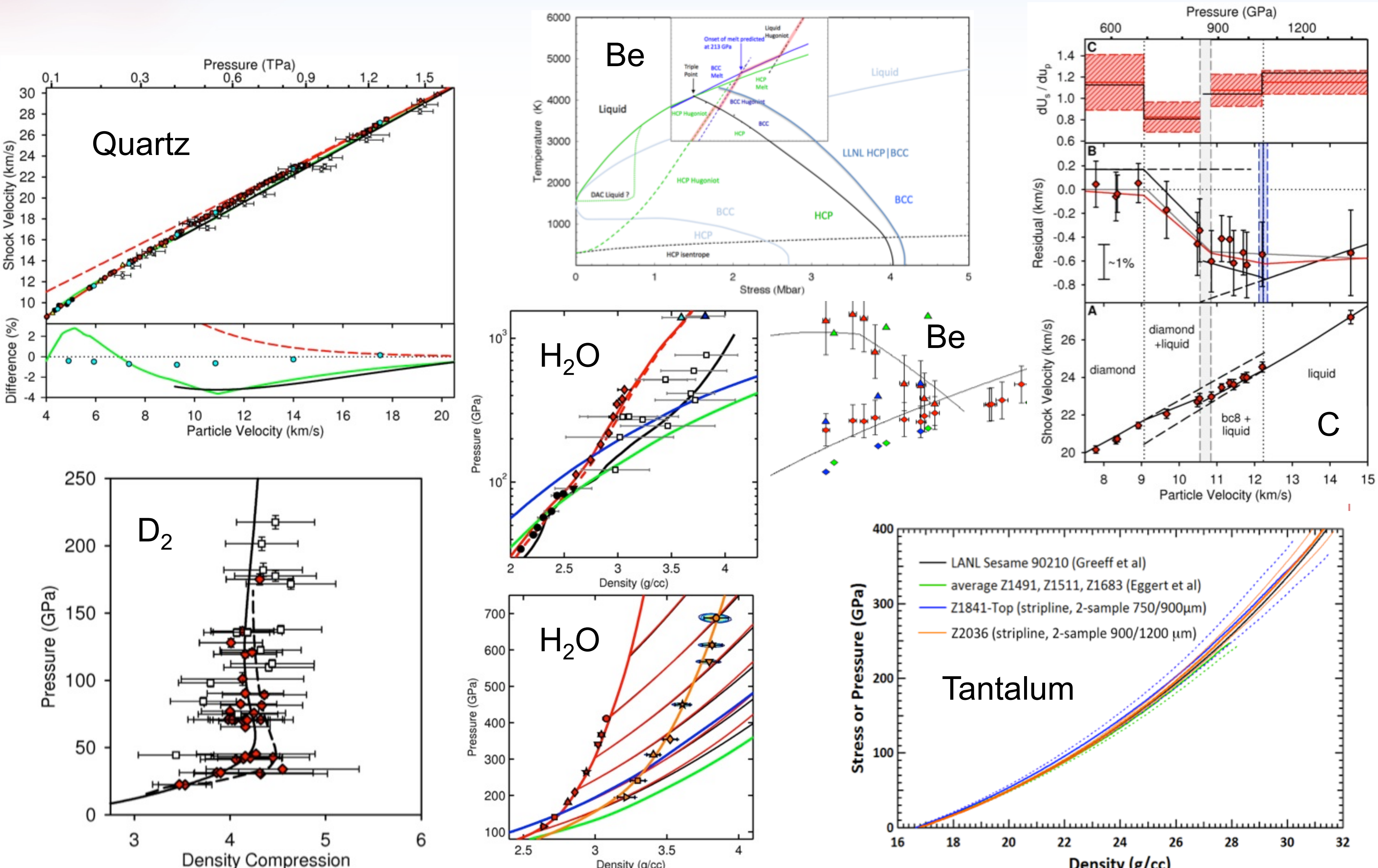
Understanding of Magnetized HED science enables the design of experiments to isentropically compress or shock impact materials and obtain high accuracy data on material properties



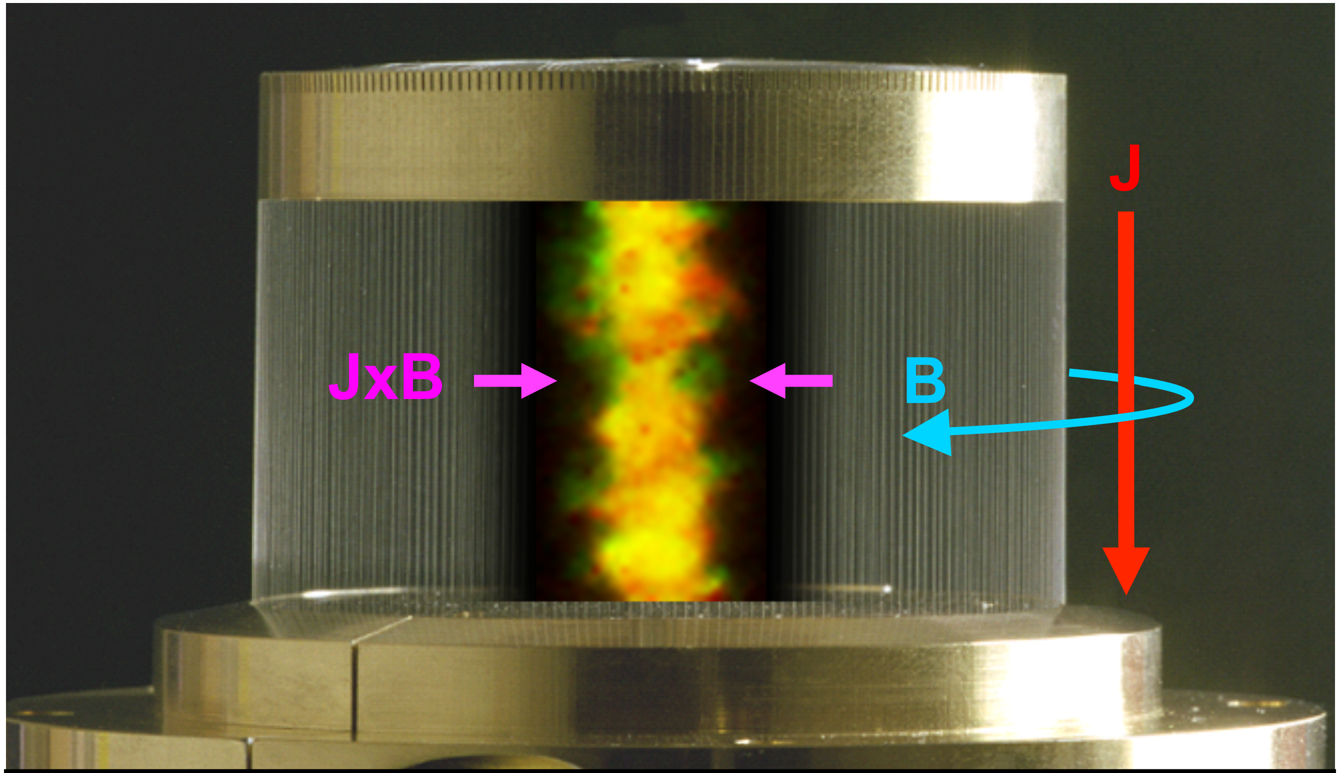
<u>Isentropic Compression Experiments:</u>
gradual pressure rise in sample

<u>Shock Hugoniot Experiments:</u>
shock wave in sample on impact

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



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

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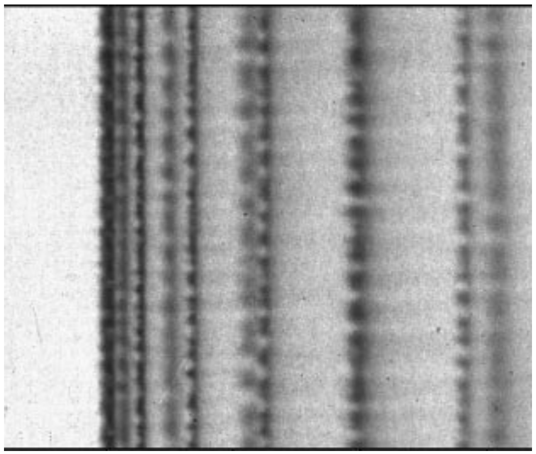
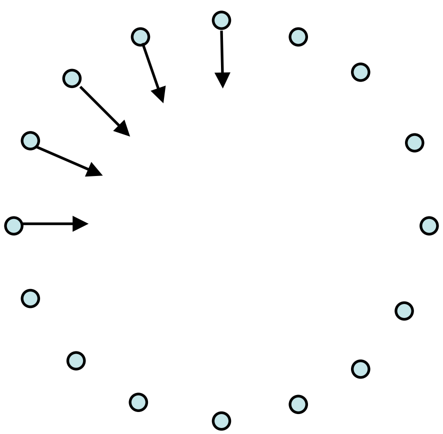
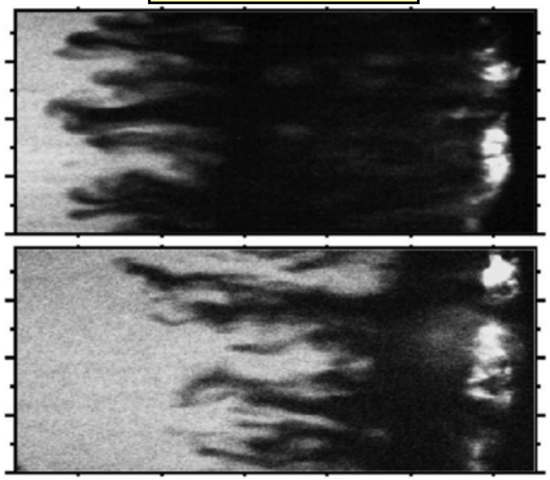
Significant progress has been made in understanding and improving wire array performance based on diagnostic advances and work on smaller scale drivers

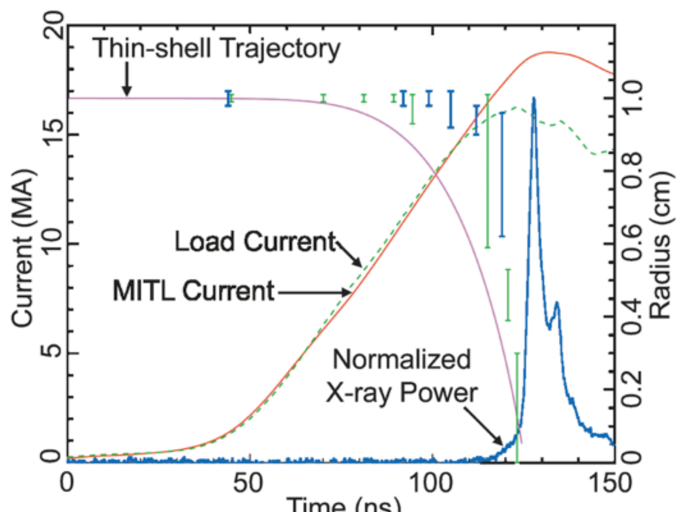
Ablation



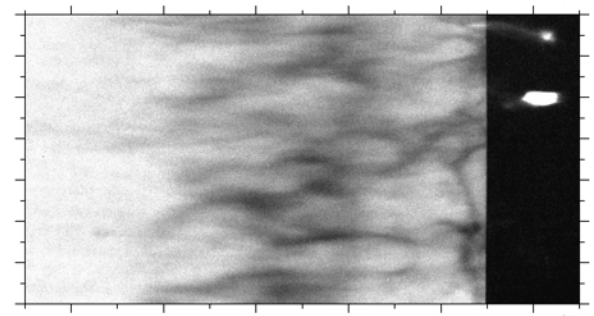


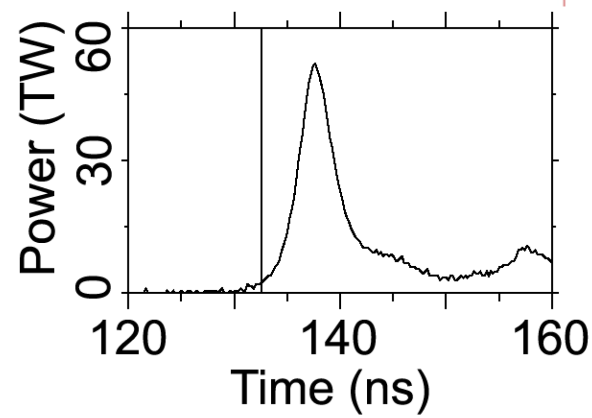
Implosion





Stagnation & X-ray production





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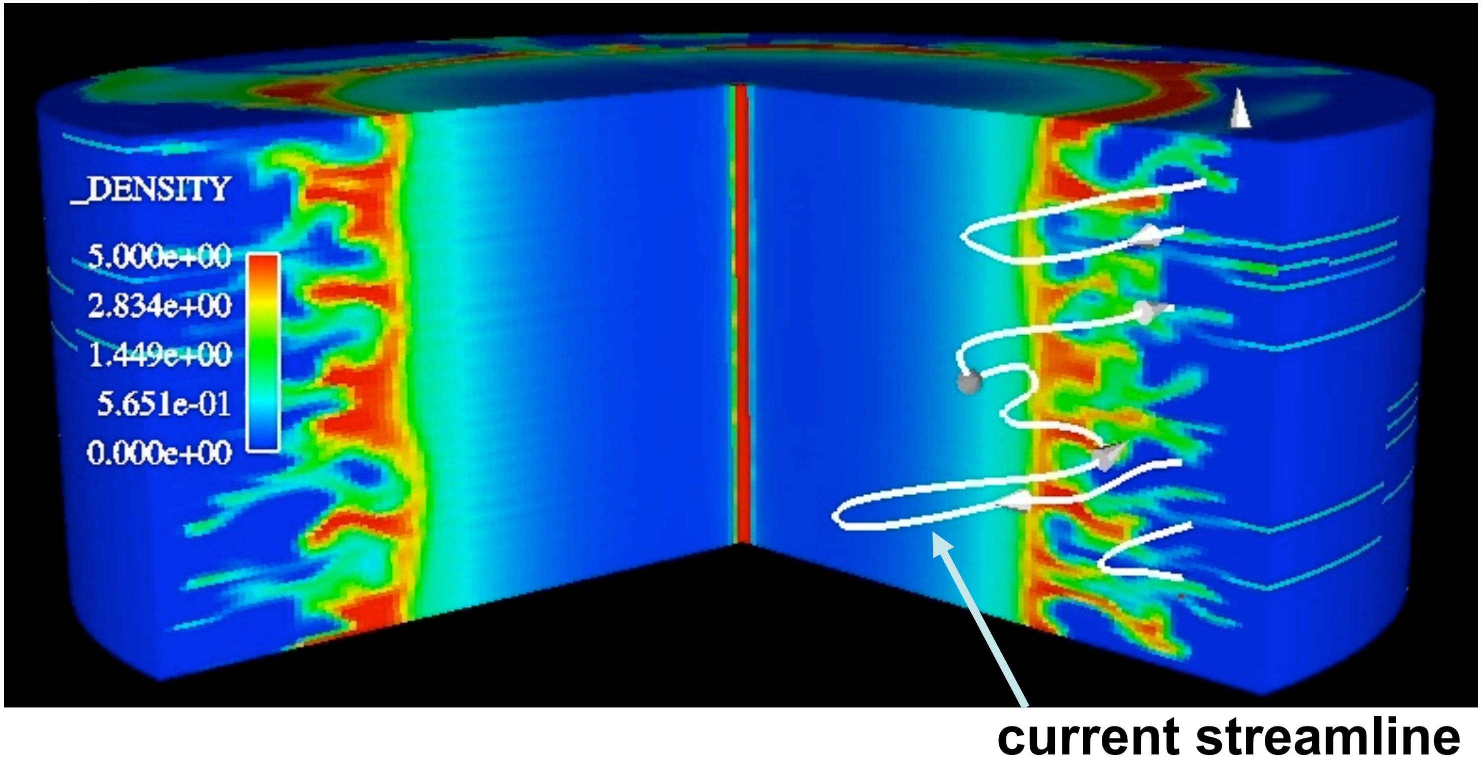
3D Rad/MHD simulations are beginning to be applied to magnetically-driven implosions



3D (and even 2D!) Rad/MHD codes are just now becoming usable tools. Many issues remain to be worked through and benchmarked with experimental data.

The physics of shorting/current delivery is important to study and understand

Yu, et al., Phys. Plasmas (2008)

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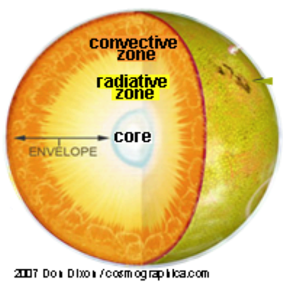
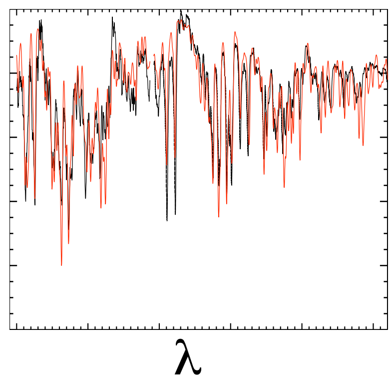
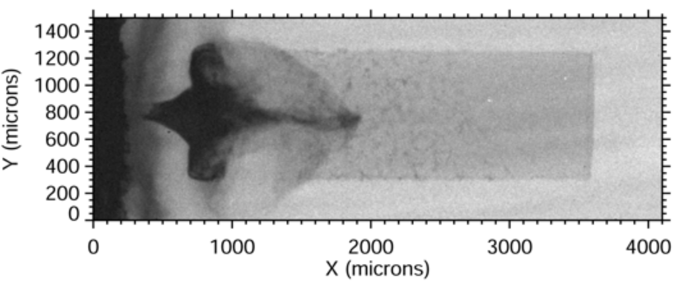
Magnetically driven X-ray sources can be used for a variety of applications

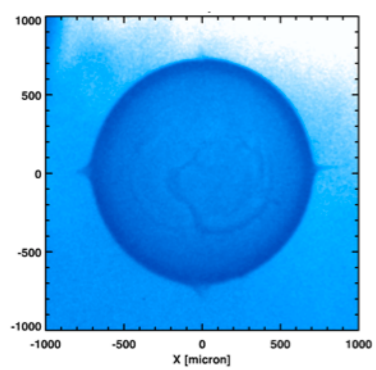
Opacity Measurements and Photo Ionized plasmas[1]



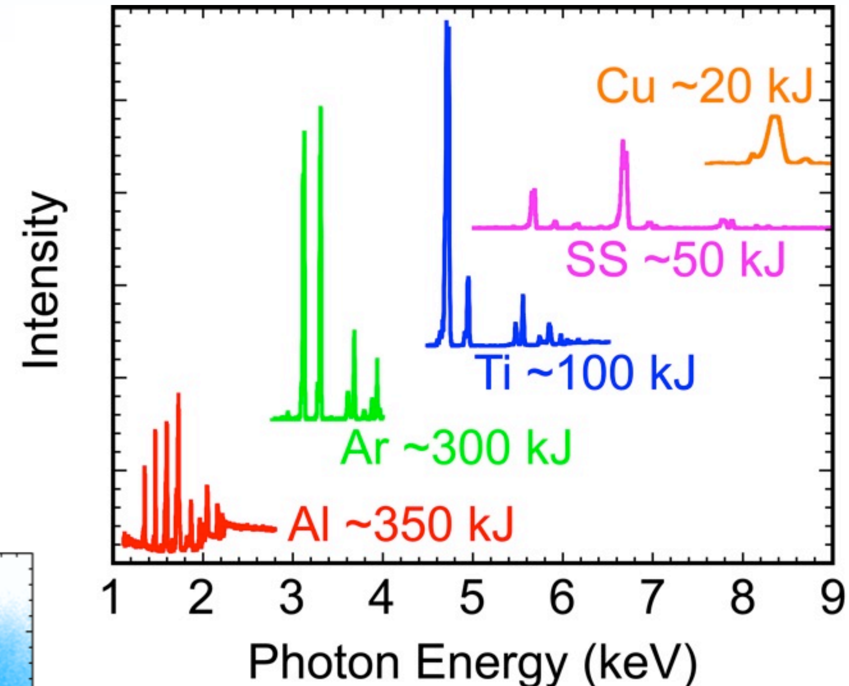


Radiation Hydrodynamics[2]





K-Shell Sources[3]



Tom Mehlhorn will discuss the modeling of these interesting sources

[1] J.E. Bailey, et al, Phys. Rev. Lett. 99, 265002 (2007)

[2] G.R. Bennett, et al., Phys. Rev. Lett. 205003 (2007)

[3] C. A. Coverdale et al., IEEE T. Plasma Sci. 35, 582 (2007).

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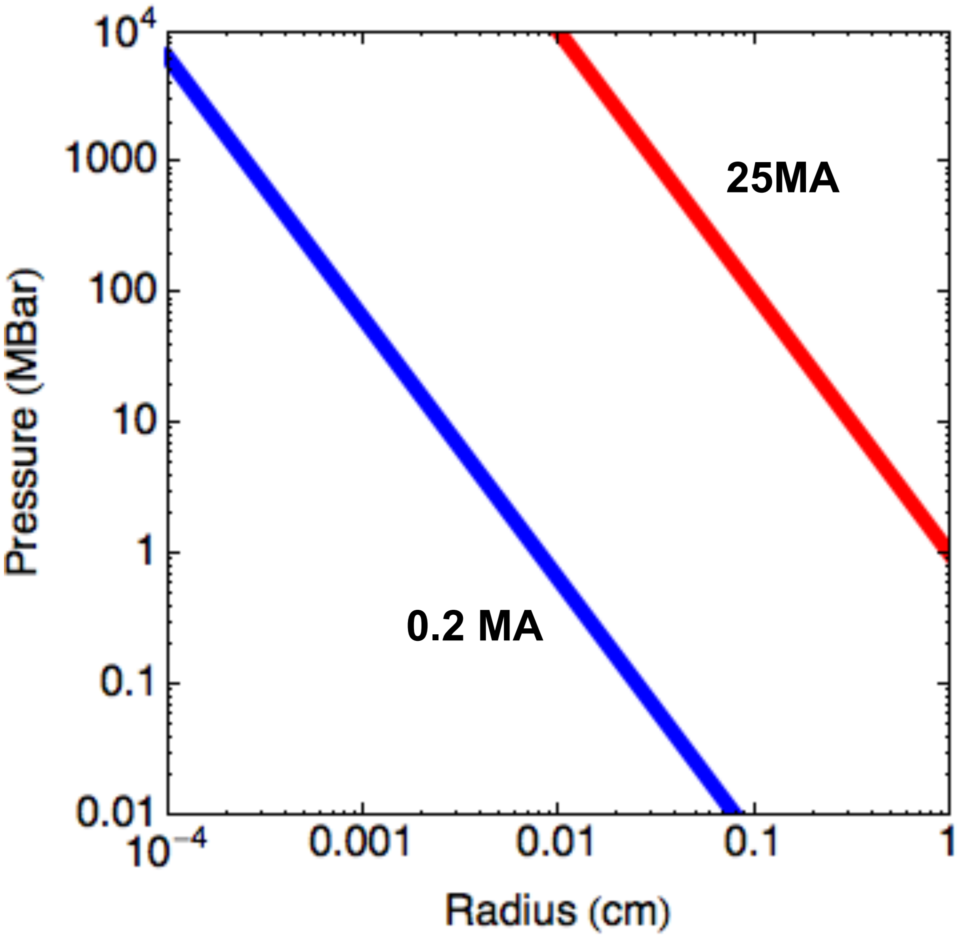
Magnetic implosions can reach very high pressures, if the current can reach small radius

Magnetic Pressure versus radius for a cylinder carrying current



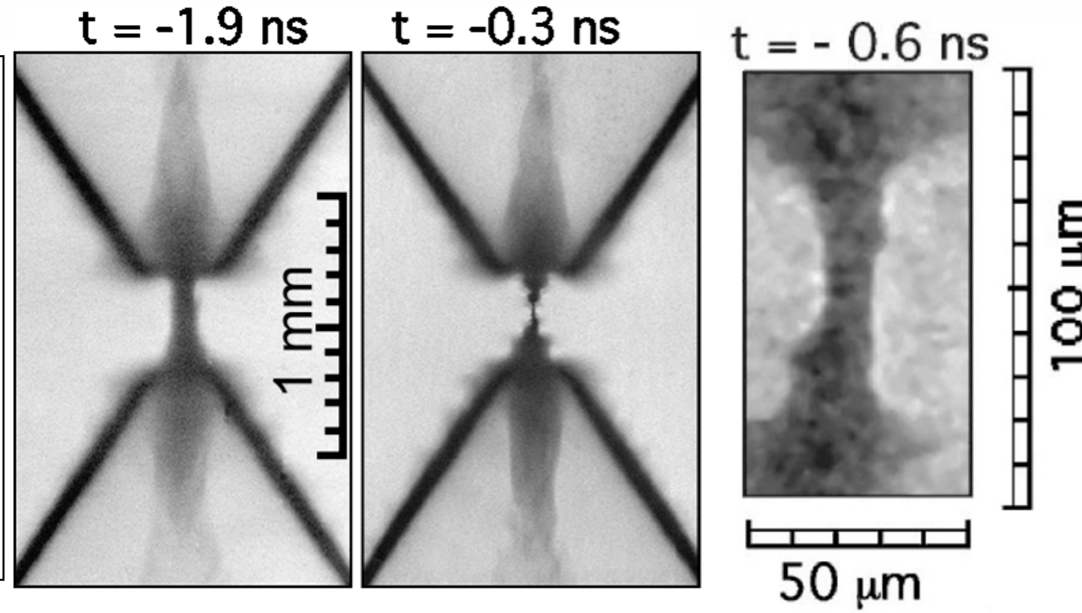
$$B_\theta(G) \sim \frac{I(\mathrm{A})}{5R(\mathrm{cm})}$$

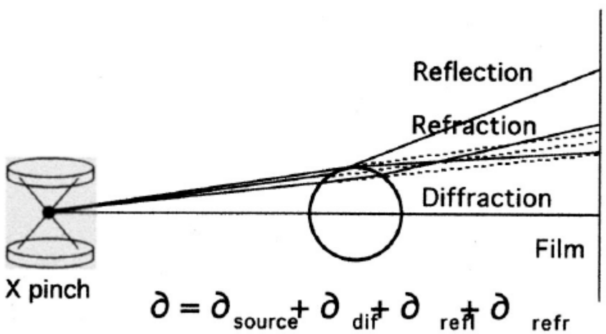
$$P \sim \frac{B^2}{8\pi} \sim \frac{I^2}{R^2}$$

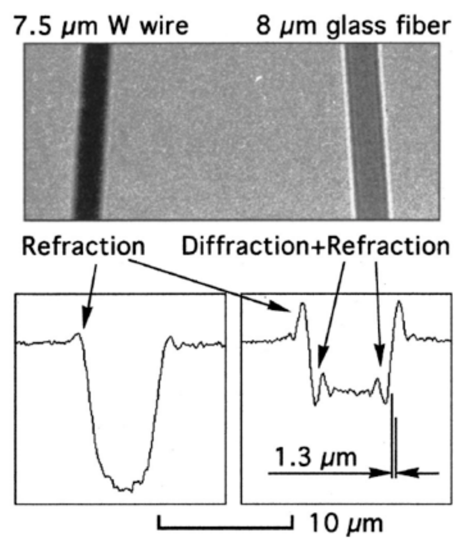
25 MA at R= 1cm 5 10^6 G= 1 Mbar
25 MA at R=0.1cm 5 10^7 G= 100 Mbar

X pinches driven by 200 kA currents are an extreme example of current reaching small radius

- **Diameter:** **1.2±0.5 μm**
- **Duration:** **10-100 ps**
- **T_e: ~1 keV (Ti, Mo)**
- **n_i: ≥0.1 * Solid density**
- **Matter pressure at ~1 g/cc and 1 keV is ~1 Gbar**
- **200 kA at 1 micron radius has magnetic pressure ~ few Gbar!**





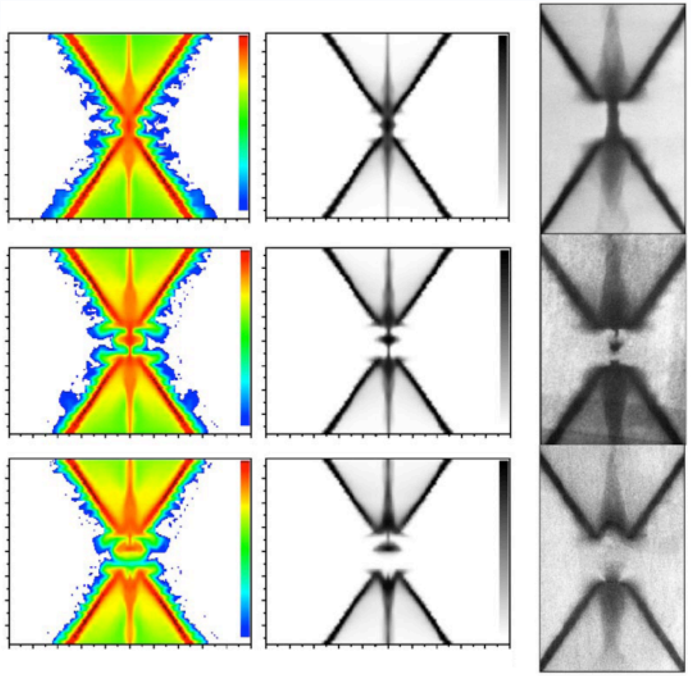


How much current gets to 1 μm?
Why does it stop at 1 μm?

T.A. Shelkovenko *et al.*, RSI 72, 667 (2001).

What happens as the current in X-pinches is increased?

- 0.2 MA Mo X-pinch modeling reproduces data†
  - Model based on approximate Bennett equilibrium conditions and a balance between blackbody radiation and thermal heating
  - Axial mass flow leads to a collapse that is halted when the electron drift velocity exceeds the ion sound speed (critical line density)
- At 1 MA the model breaks down
  - Predicts ~30 nm, 1290x solid density!
- Assume all current collapses to 1 μm radius
  - 1 MA: 10x solid density
  - 10 MA: 250x solid density



What limits the collapse of current to small radius?
What states of matter can be created using large currents at small radii?

† Chittenden *et al.*, Phys. Rev. Lett. 98, 025003 (2007).

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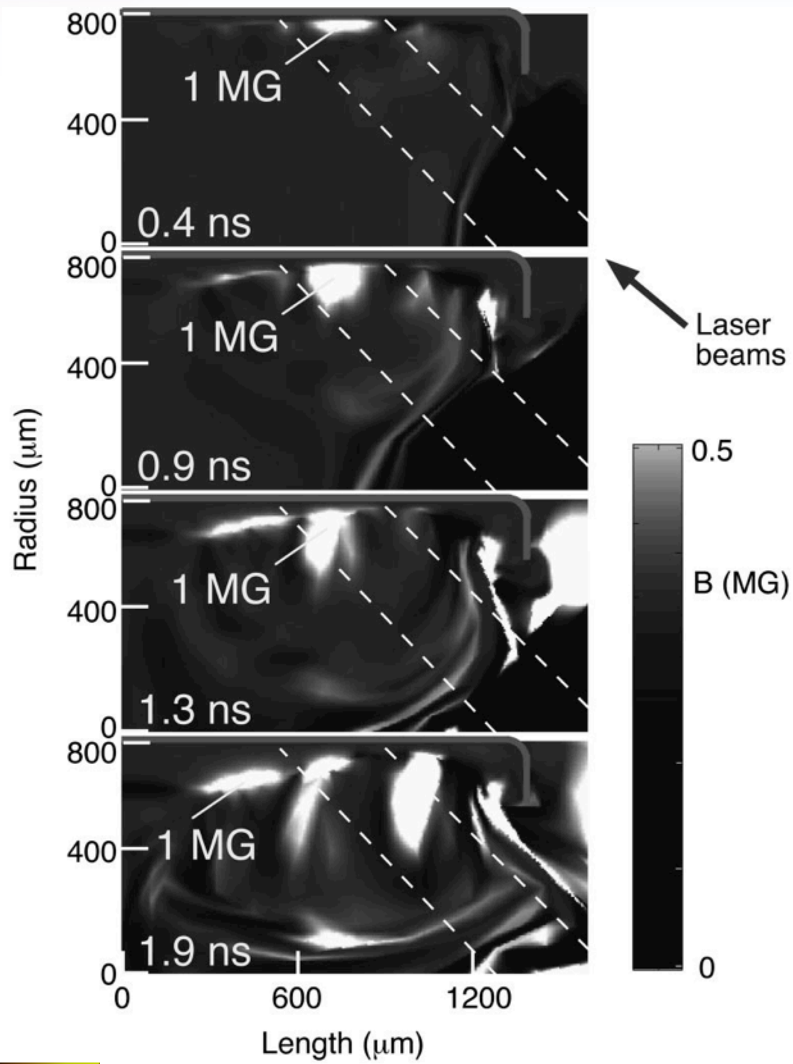
Magnetic Fields can be spontaneously generated from plasma gradients in HED plasmas



Magnetic field generation is ubiquitous in HED plasmas:

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{\nabla T_e \times \nabla n_e}{e\, n_e}$$

These fields do not affect the plasma motion ($\beta \sim P/B^2 >> 1$)

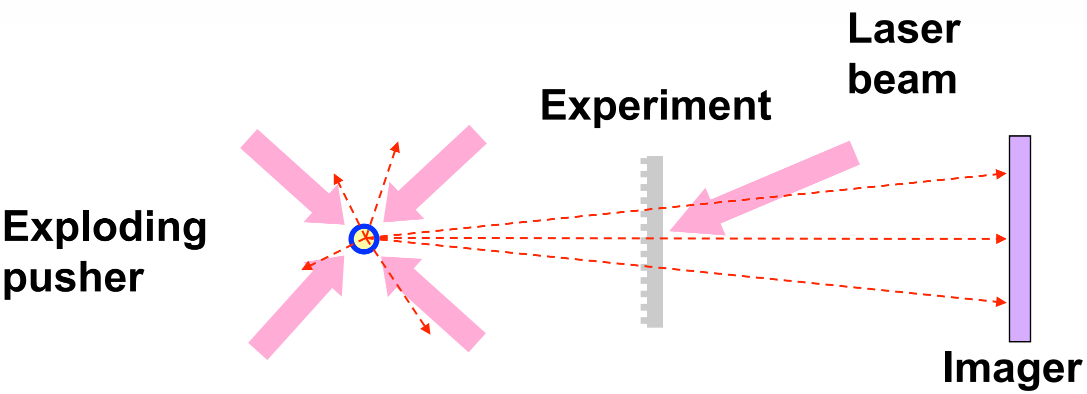
The fields can significantly change electron heat transport since $\Omega\tau > 1$. This in turn can lead to changes in deposition.

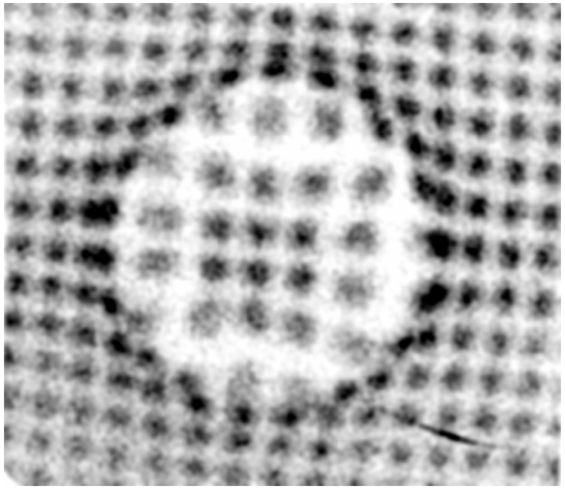
Simulations suggest this field can have 10-20% effects on the electron temperature in laser hot spots

This will need to be validated to have a complete understanding of hohlraums

R. P. J. Town, UCRL PRES-216240

A powerful diagnostic technique for detecting electric and magnetic fields in HED plasmas is proton radiography





$D + {}^3He \rightarrow \alpha\ (3.6\ MeV) + p\ (14.7\ MeV)$

$D + D \rightarrow T + p\ (3.0\ MeV)$

Proton image of an expanding plasma bubble

FSC UR LLE NLUF MIT

C. K. Li et al., Phys. Rev. Lett. 97, 135003 (2006)

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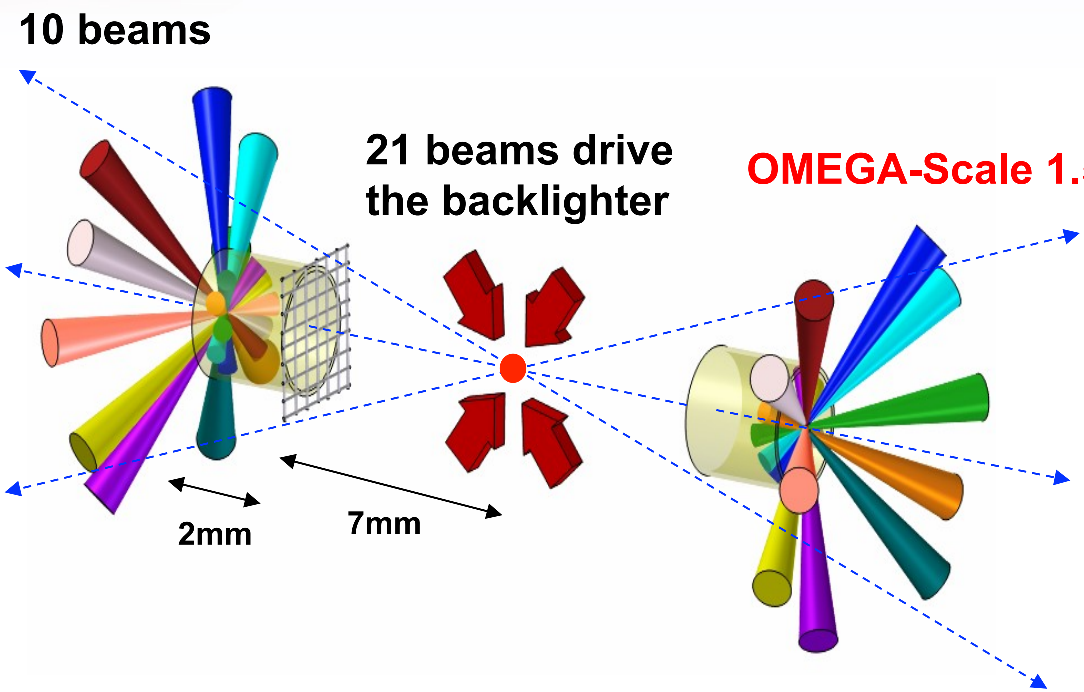
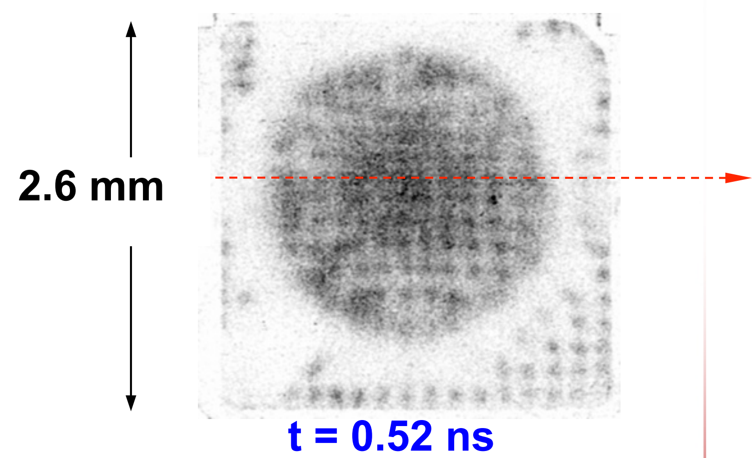
Spontaneous fields of ~10^6 gauss B field have been observed in hohlraums





Field is inferred from deflection of beamlets.
By using 2 different proton energies can distinguish between an electric field and a magnetic field.

C. K. Li et al., Phys. Rev. Lett. 102, 205001 (2009)

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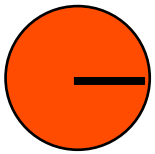
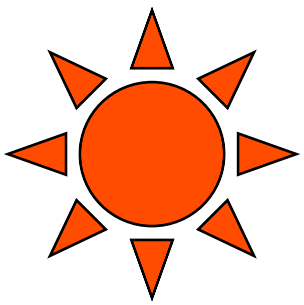
Under extreme conditions a mass of DT can undergo significant thermonuclear fusion before falling apart



ρ, R, T



- Consider a mass of DT with radius R, density ρ, and temperature T
- How does the disassembly time compare with the time for thermonuclear burn?

$$\tau_{disassembly} \sim \frac{R}{c_s} \sim \frac{R}{\sqrt{T}} \qquad \tau_{burn} \sim \frac{1}{n_i\langle\sigma v\rangle} \sim \frac{1}{\rho\langle\sigma v\rangle}$$

- The fractional burn up of the DT (for small burn up) is:

$$f_{burn} \approx \frac{\tau_{disassembly}}{\tau_{burn}} \sim \rho R \frac{\langle\sigma v\rangle}{\sqrt{T}}$$

- At sufficiently high ρR and T the fractional burn up becomes significant and the energy deposited by alpha particles greatly exceeds the initial energy in the fusion fuel (“ignition”)

- Typical conditions are:

$$\rho R \approx 0.4\,\mathrm{g/cm^2}$$
$$T \approx 5\,\mathrm{keV}$$

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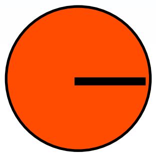
For hot spot ignition fusion fuel must be brought to a pressure of a few hundred billion atmospheres



ρ, R, T

For ignition conditions: $\left\{ \begin{array}{l} \rho R \approx 0.4\,\mathrm{g/cm^2} \\ T \approx 5\,\mathrm{keV} \end{array} \right\}$

$$E_{HS} \propto m_{HS} T_{HS} \propto \rho_{HS} R_{HS}^3 T_{HS} \propto \frac{(\rho_{HS} R_{HS})^3 T_{HS}^3}{P_{HS}^2}$$

$E_{NIF} \sim 15\,\mathrm{kJ} \Rightarrow P \sim 400\,\mathrm{GBar}$ $\quad R \sim 30\,\mu\mathrm{m} \Rightarrow$ and $\rho \sim 130\, g/cm^3$

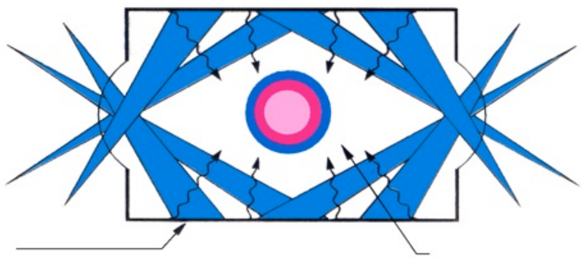
Max Tabak will discuss ways of relaxing this via fast ignition

Note for magnetic confinement fusion ignition

$P \sim \text{few Bars} \quad \rho \sim \text{few } 10^{-10}\, g/cm^3$

High velocity, low adiabat thin shells are the most common approach to reach these conditions

Indirect Drive (X-ray)



Direct Drive (Laser)

In either direct or indirect drive, peak drive pressures are of order ~ 50-150 MBars

We need to get pressures to > 1000X that for ignition!

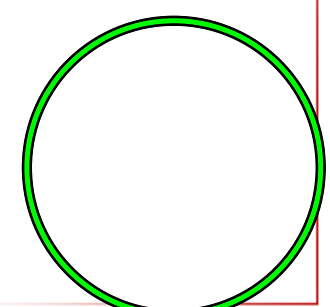
Spherical implosions enable us to store energy in the fusion fuel in the form of kinetic energy, which is converted to pressure at stagnation

$$P_{stag} \sim \alpha\,\rho_{stag}^{5/3} \qquad \alpha\,\rho_{stag}^{2/3} \sim \mathrm{v}^2 \Rightarrow P_{stag} \sim \mathrm{v}^5 / \alpha^{3/2}$$

$$\alpha \equiv P/P_{Fermi}$$

Thin shell implosions can reach the 200-400 km/sec needed for ICF

$$\int P_{drive}\,\mathrm{dV} = \frac{1}{2} m\mathrm{v}^2 \qquad m \sim 4\pi R^2 \rho\,\delta R$$



$$P_{drive} R^3 \sim R^2 \rho\,\delta R\,\mathrm{v}^2 \Rightarrow \mathrm{v}^2 \sim \frac{P_{drive}}{\rho}\frac{R}{\delta R}$$

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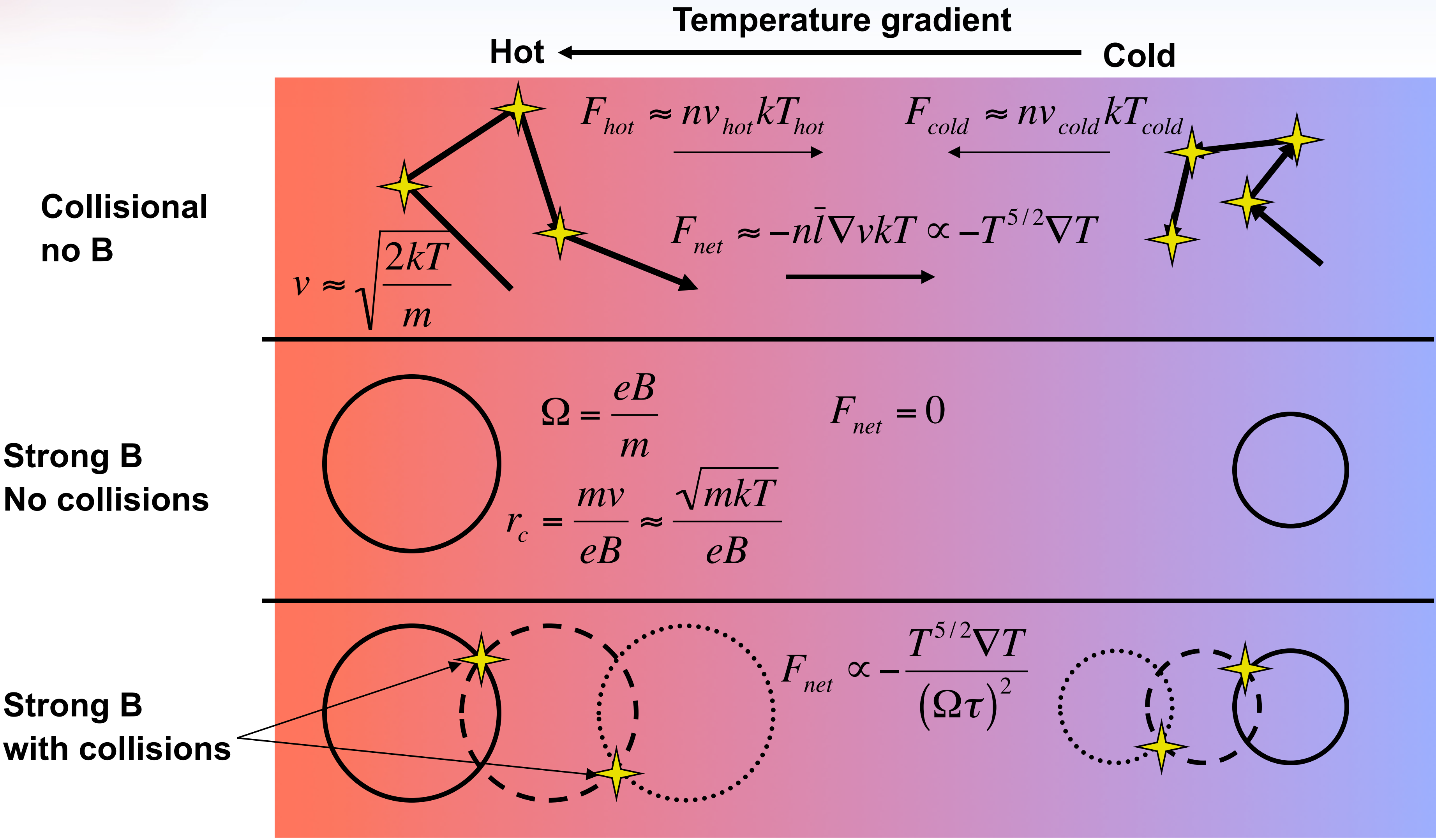
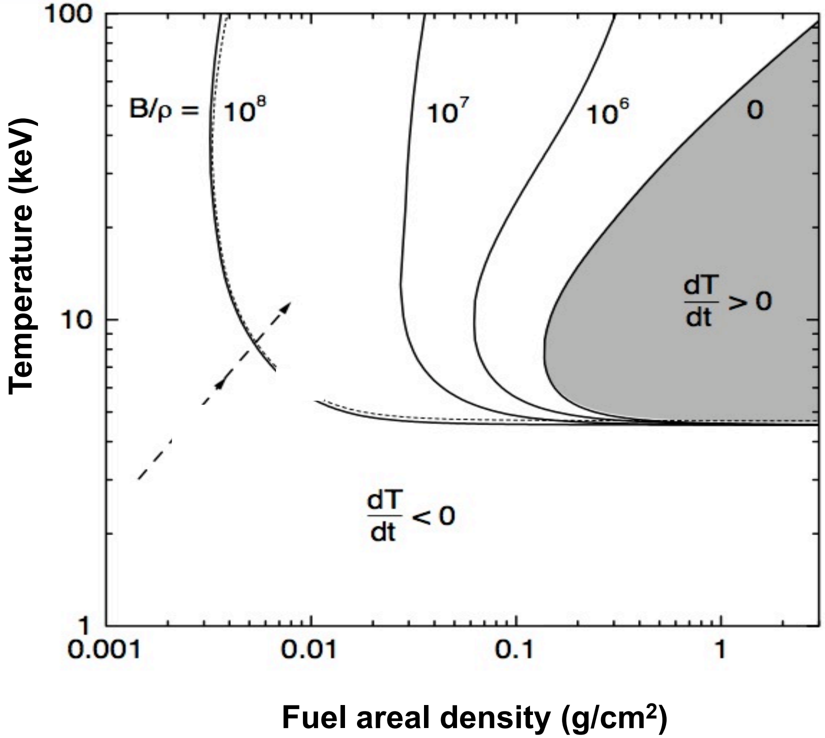
The presence of a magnetic field can strongly affect transport properties, e.g. heat conduction



Energetic particles can also be strongly affected by magnetic fields

Magnetization significantly reduces the self heating (ignition) requirements for inertial confinement fusion

**Basko et al. Nuc. Fusion (2000)*



The ρr needed for ignition can be significantly reduced by the presence of a strong magnetic field inhibit electron conduction and confinement of alpha particles

Lower ρr means lower densities are needed (10^{-3}-1 g/cc << 100g/cc)

Pressure required for ignition can be significantly reduced to ~5 Gbar (<< 500 Gbar for hotspot ignition)

Large values of B/ρ are needed and therefore large values of B are needed.

B~ 50-150 Megagauss >> B_0 -> flux compression is needed

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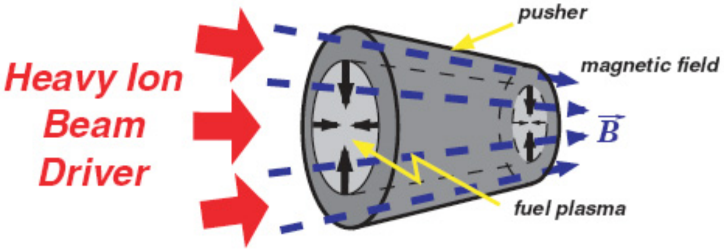
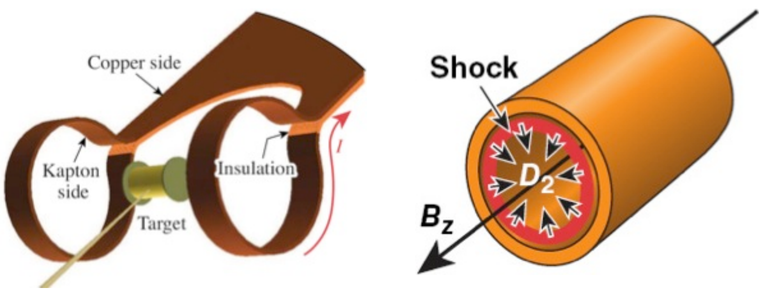
The parameter space for magnetized ICF is large allowing a diverse set of approaches

Max Planck / ITEP



Basko, Kemp, Meyer-ter-Vehn, *Nucl. Fusion* **40**, 59 (2000)
Kemp, Basko, Meyer-ter-Vehn, *Nucl. Fusion* **43**, 16 (2003)

U. Rochester LLE

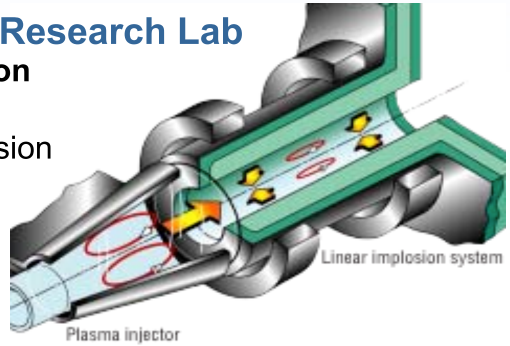


Direct drive laser implosion of cylinders
-- shock pre-heating, high implosion velocity

Gotchev *et al.*, *Bull. Am. Phys. Soc.* **52**, 250 (2007)
Gotchev *et al.*, *Rev. Sci. Instr.* **80**, 043504 (2009)
Gotchev *et al.*, Phys. Rev. Lett. **103**, 215004 (2009)
Knauer *et al.*, *Phys. Plasmas* **17**, 056318 (2010)

Los Alamos / Air Force Research Lab

Field Reversed Configuration
Shiva Star generator
~20 μs, 0.5 cm/μs liner implosion



Taccetti, Intrator, Wurden *et al.*, *Rev. Sci, Instr.* **74**, 4314 (2003)
Degnan *et al.*, *IEEE Trans. Plas. Sci.* **36**, 80 (2008)

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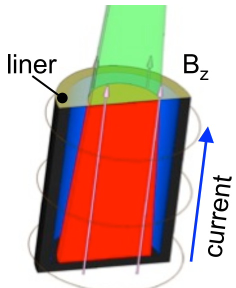
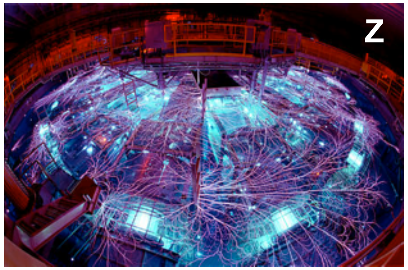


Magnetized Liner Inertial Fusion

Laser preheated magnetized fuel

LASNEX simulations indicate interesting yields



S. A. Slutz *et al.*, *Phys. Plasmas*, **17**, 056303 (2010).
D.B. Sinars *et al.*, Phys. Rev. Lett. **105**, 185001 (2010)

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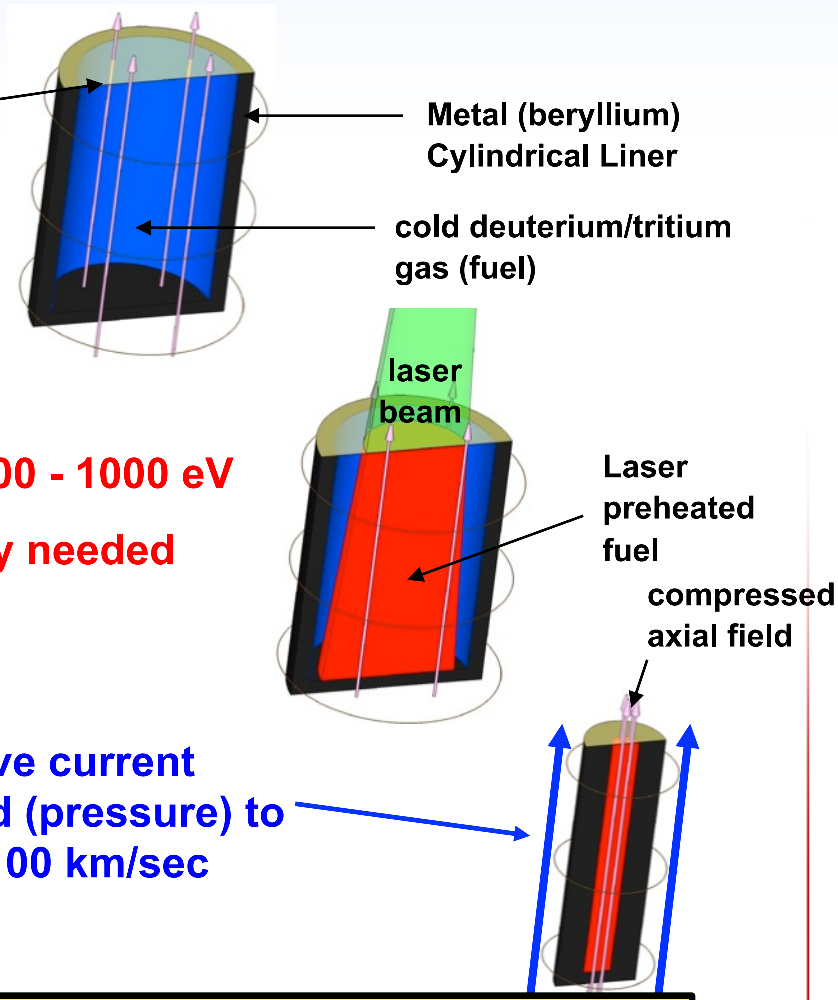
The Z facility provides an opportunity to test the benefits of fuel magnetization and preheat

1. A 100-500 kG axial magnetic field is applied before the implosion

2. Z Beamlet can preheat the fuel to ~100 - 1000 eV to reduce the compression and velocity needed

3. The Z accelerator can provide the drive current which generates an azimuthal drive field (pressure) to efficiently implode the thick liner at 50-100 km/sec and compress the axial field to 100 MG



Simulations indicate scientific breakeven (fusion energy out = energy deposited in fusion fuel) may be possible on Z

* S. A. Slutz *et al*., Physics of Plasmas 17, 056303 (2010).

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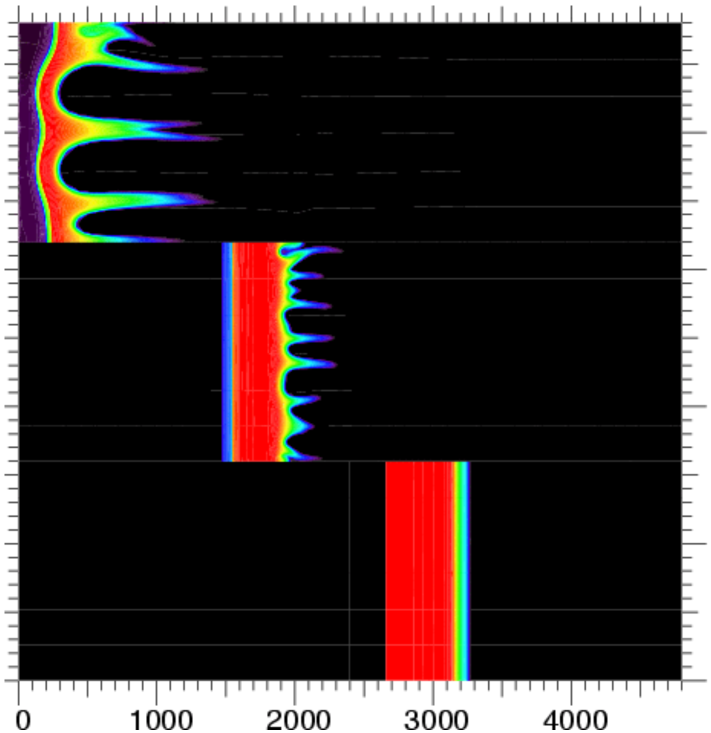
Simulations indicate scientific breakeven (fusion energy out = energy deposited in fusion fuel) may be possible on Z with DT fuel

INITIAL CONDITIONS	
Peak Current:	27 MA
Be Liner R0:	2.7 mm
Liner height:	5 mm
Aspect ratio (R0/ΔR):	6
Initial gas fuel density:	3 mg/cc
Initial B-field:	30 T

FINAL CONDITIONS	
Energy in Fusion Fuel	~200 kJ
Target Yield:	500 kJ
Convergence ratio (R0/Rf):	23
Final on-axis fuel density:	0.5 g/cc
Peak avg. ion temperature:	8 keV
Final peak B-field:	13500 T
Peak pressure:	3 Gbar

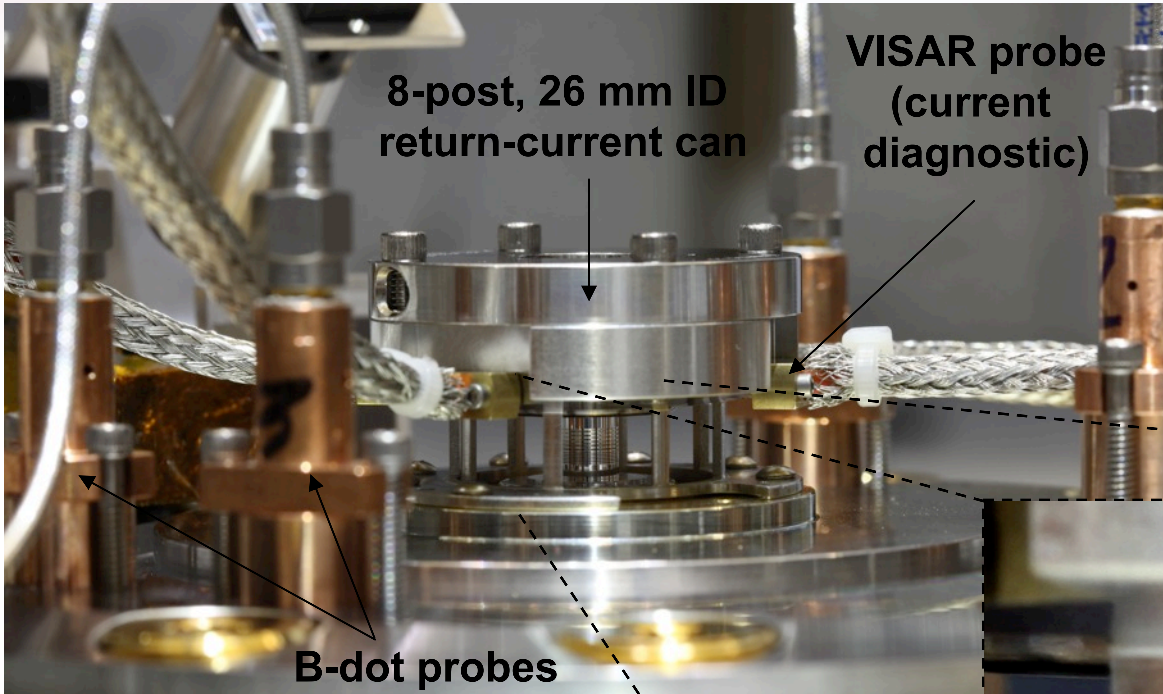
60 nm surface roughness,
80 (μm) waves are resolved

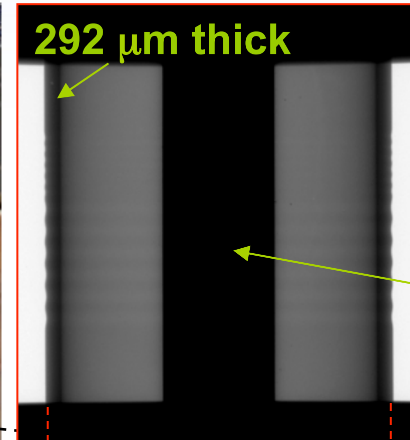


2D yield for a DT target ~ 350 kJ (70% of 1D)

The magneto-Rayleigh Taylor instability is the biggest concern for this concept

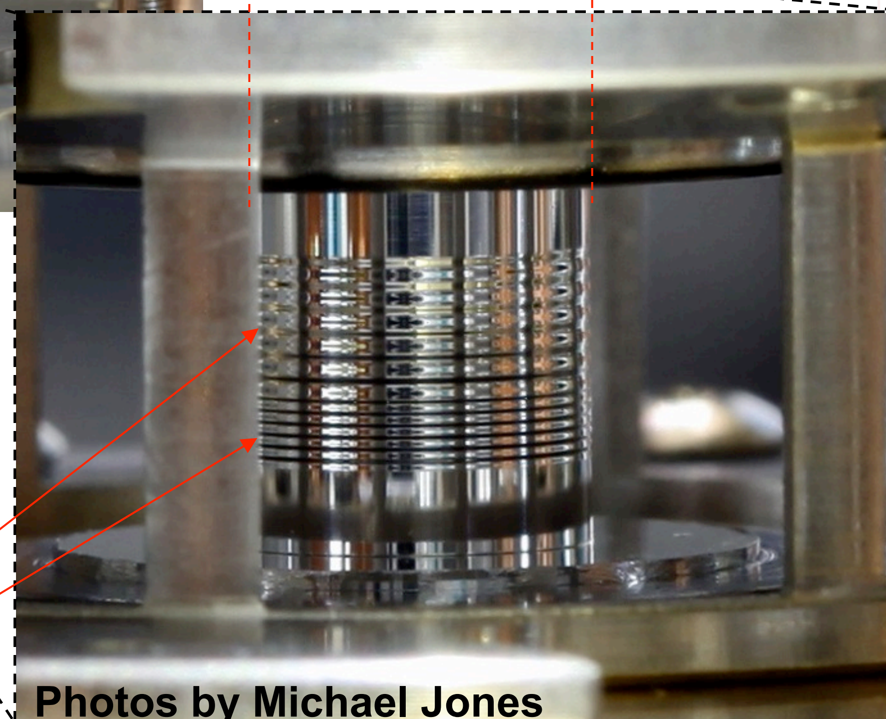
A series of experiments were carried out on Z to test the code's predictions of MRT growth





55-60 keV pre-shot radiograph (W Kα source)

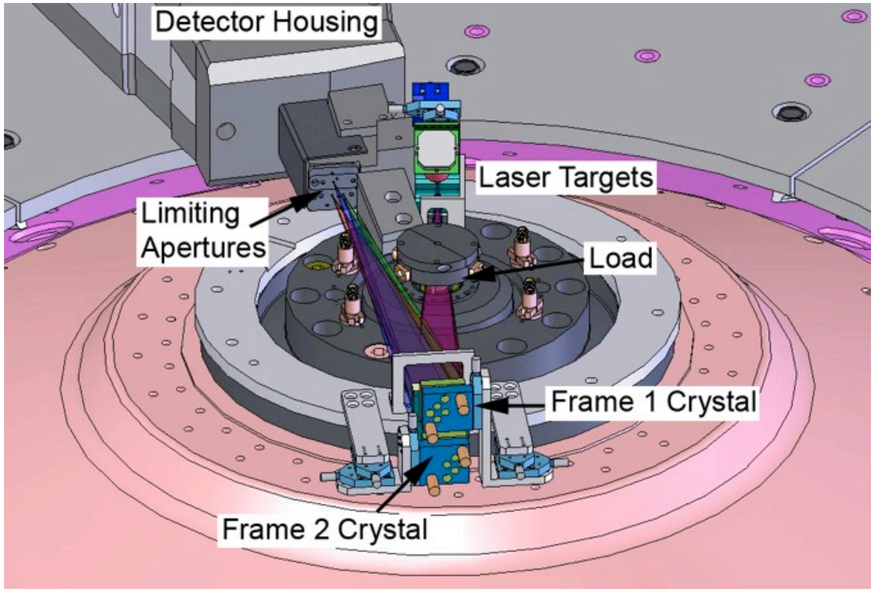
2 mm diam. W rod on axis (suppress x rays)



- Solid cylindrical liner (Al 1100 alloy)
- 6.5 mm tall, 6.34 mm diameter, AR=10
- 10 nm surface finish (diamond-turned)
- 12 sinusoidal perturbations:
  six 400-μm wavelength, 20-μm amplitude
  six 200-μm wavelength, 10-μm amplitude

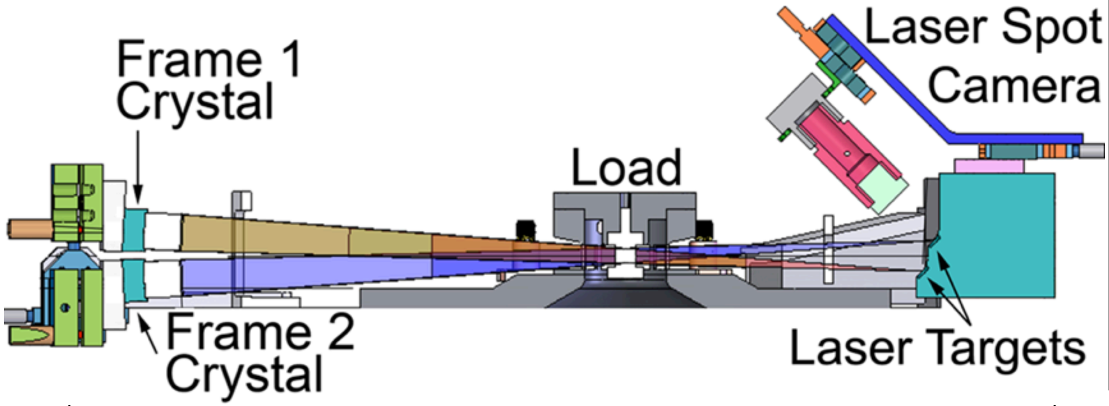
Targets made by General Atomics

The key diagnostic was 2-frame 6.151 keV monochromatic radiography



<u>2-frame 6.151 keV Crystal Imaging</u>

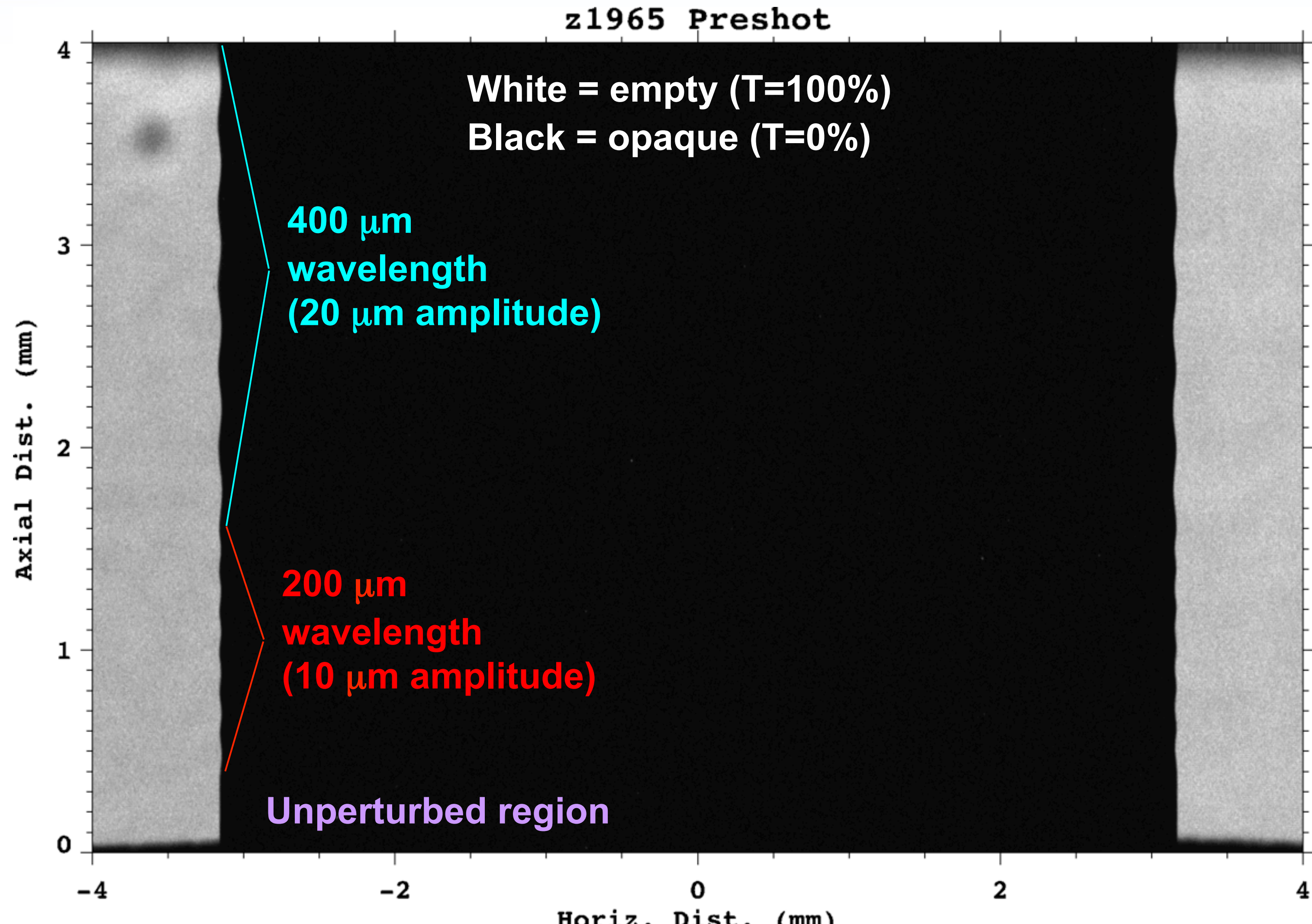
- Monochromatic (~0.5 eV bandpass)
- 15 micron resolution (edge-spread)
- Large field of view (10 mm x 4 mm); a >2 Megapixel camera
- Debris mitigation



Radiograph lines of sight ±3° from horizontal

- **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).**

A preshot radiograph shows the resolution that can be attained by the bent crystal imaging system



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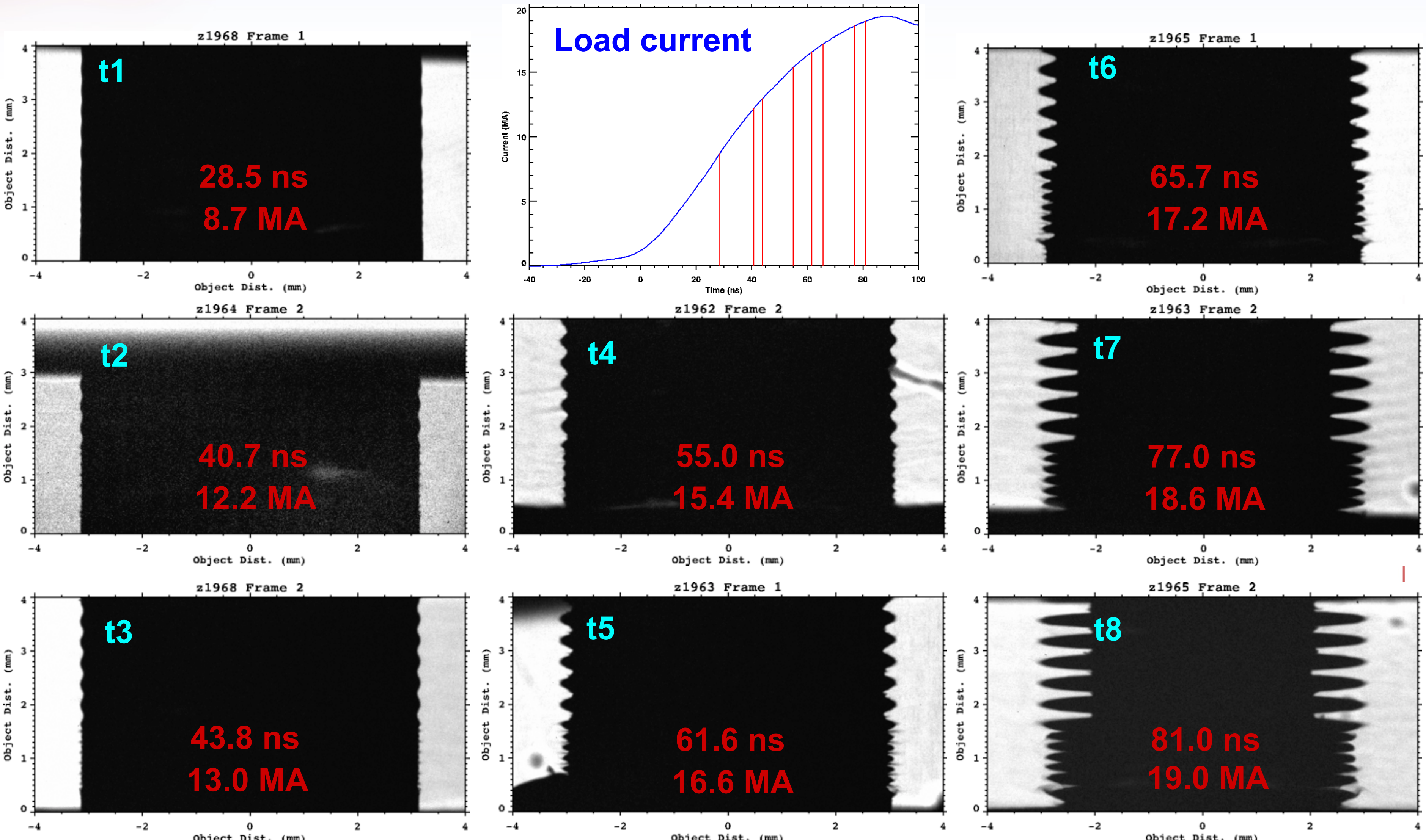
Reproducible machine and liner performance enabled an 8 frame movie over 5 shots



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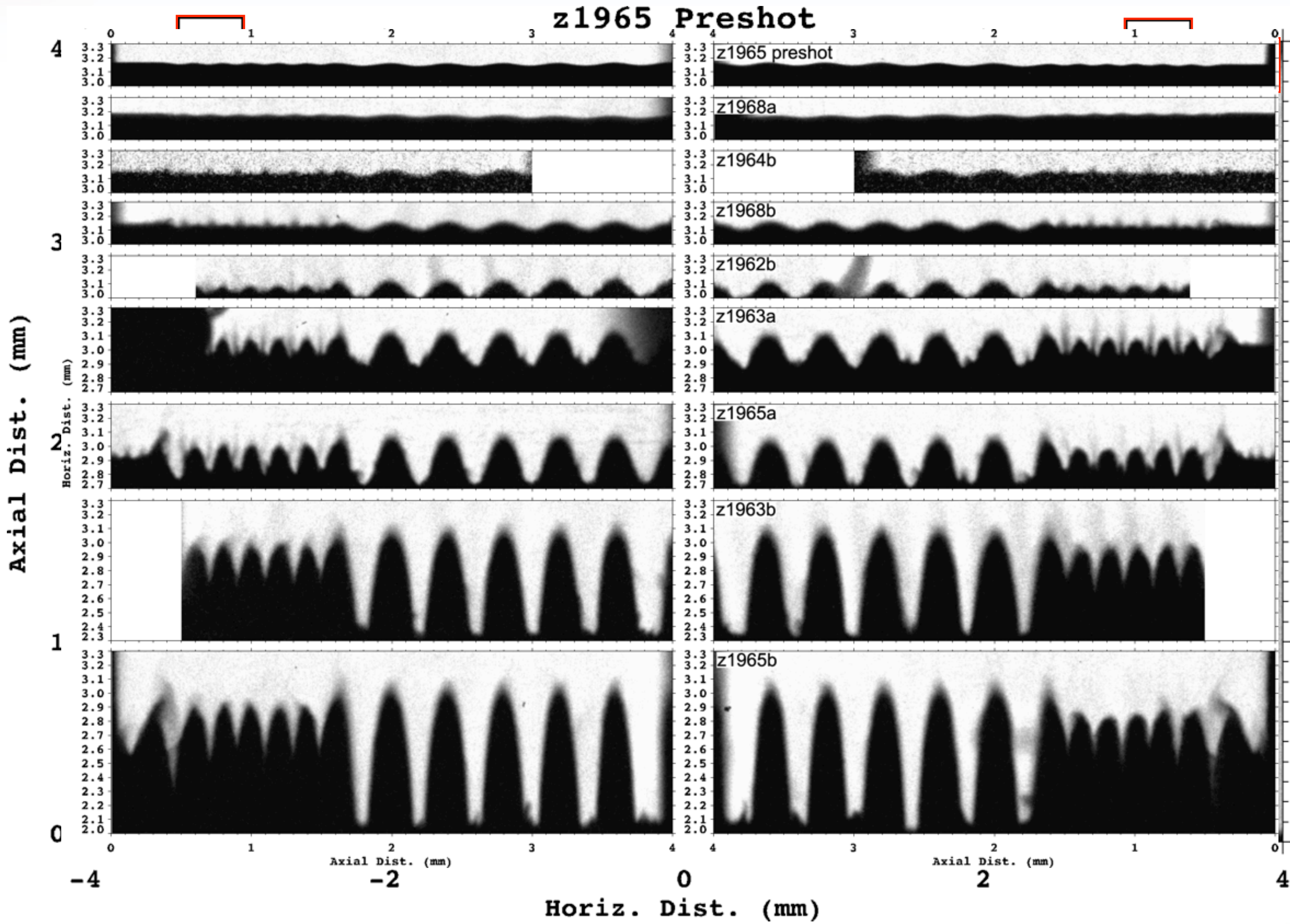
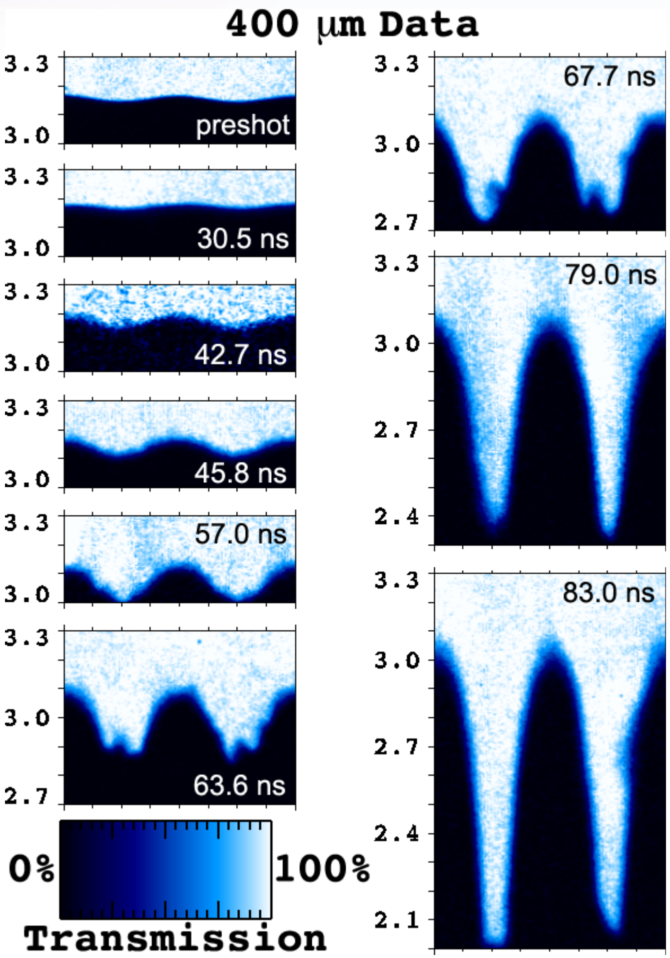
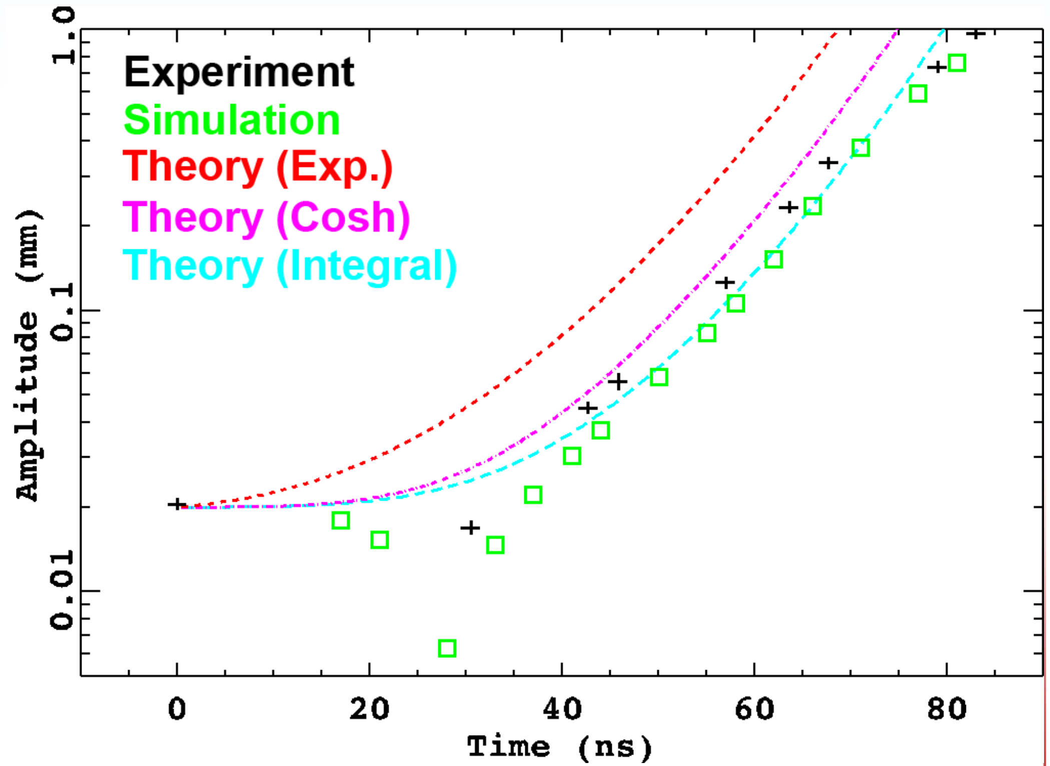
The radiographs show ablation, jetting, and small-scale instability growth, in addition to the seeded instability

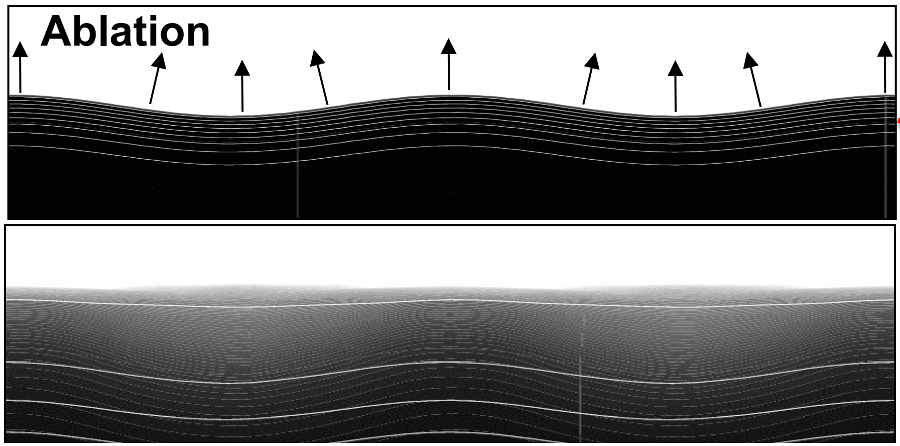


Calculations are in good agreement with experiment for 400 μm wavelength

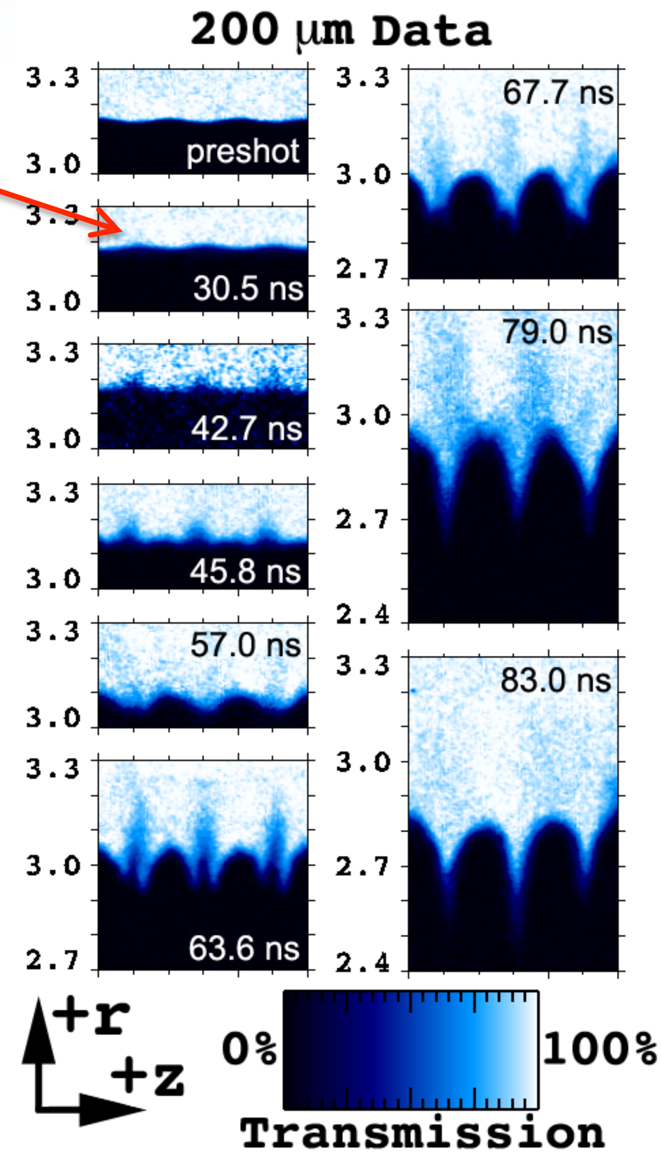




The radiographs show ablation, jetting, and small-scale instability growth, in addition to the seeded instability



Simulated density map with rB_θ contours



The current concentrated near the liner surface at early times heats the outer layer and causes it to ablate.

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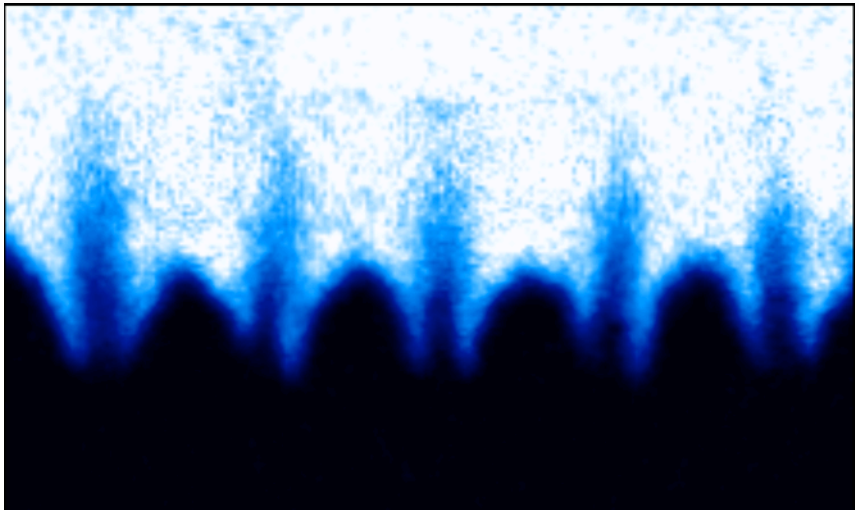
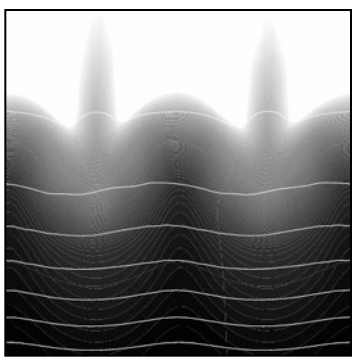
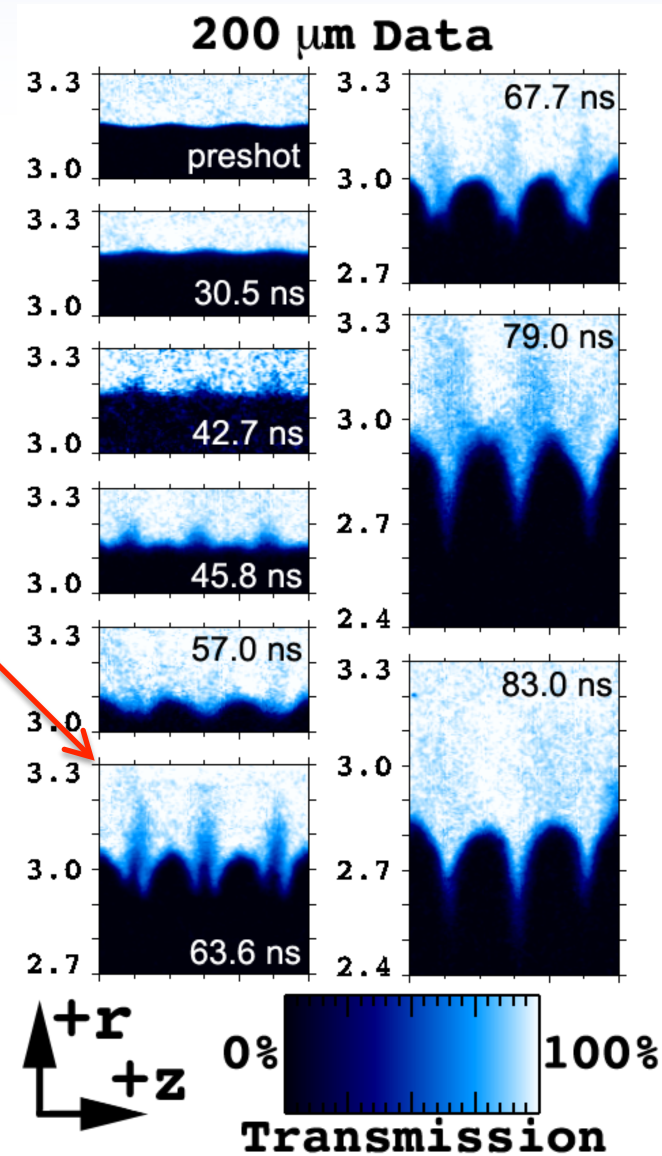
The radiographs show ablation, jetting, and small-scale instability growth, in addition to the seeded instability





Simulated density map with rB_θ contours

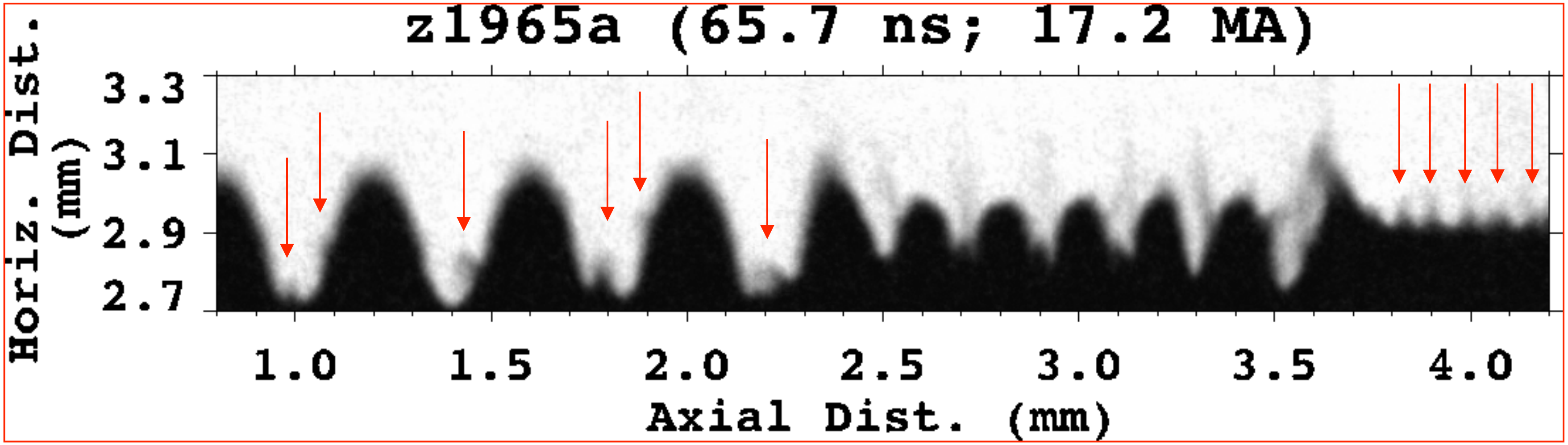
Ablated material coalesces in valleys to form jets visible in the radiographs



Simulation: T_{jets} ~30 eV; T_{valley} ~100 eV

The radiographs show ablation, jetting, and small-scale instability growth, in addition to the seeded instability

Small-scale instabilities appear to have similar character to instabilities growing on initially unperturbed regions



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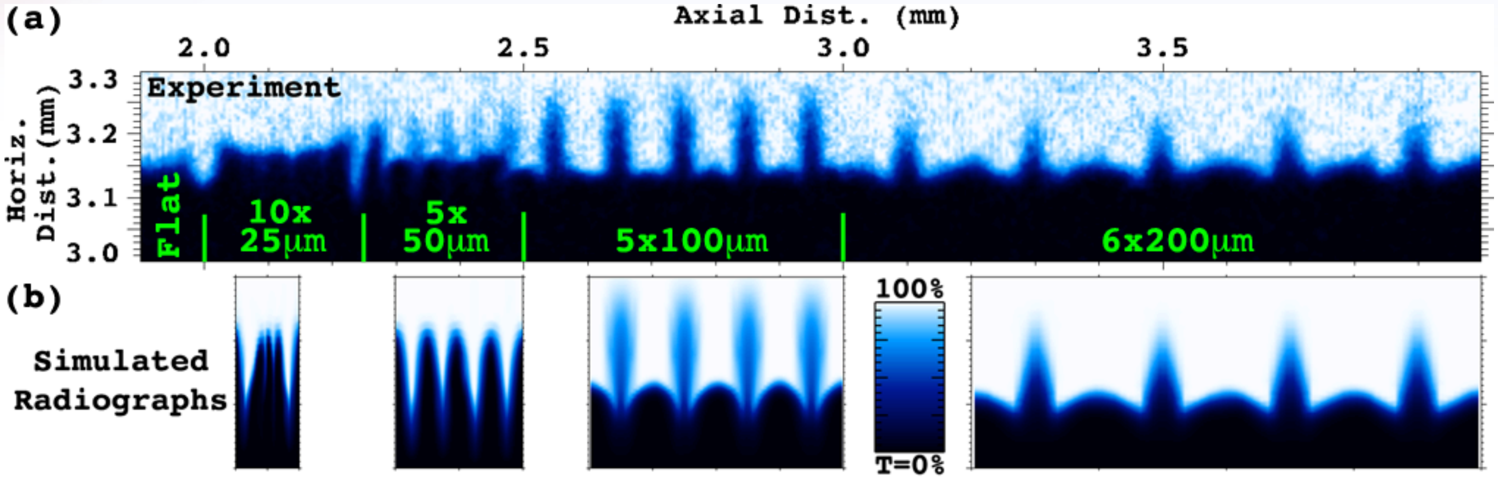
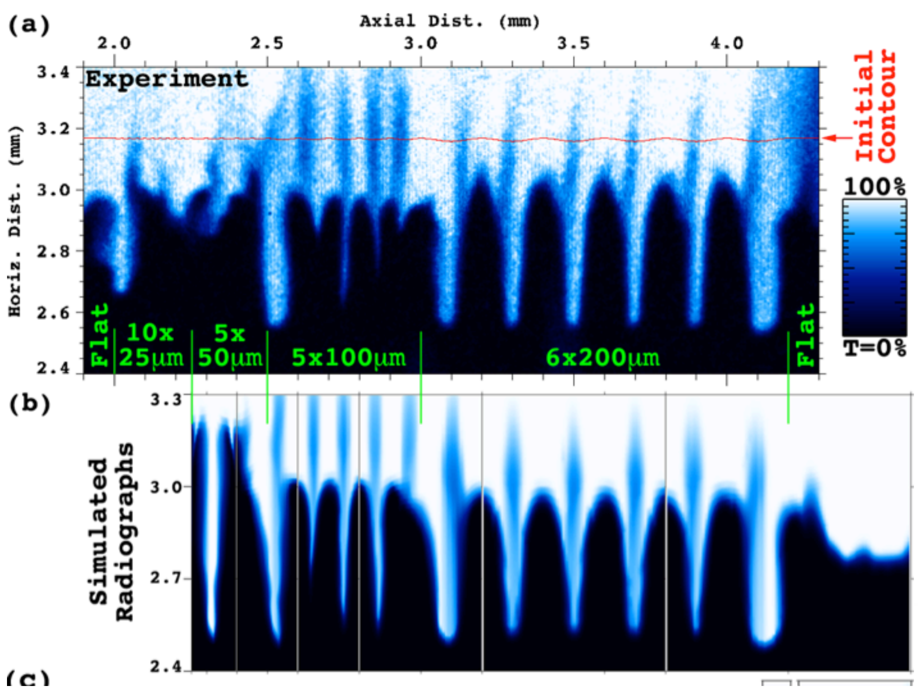
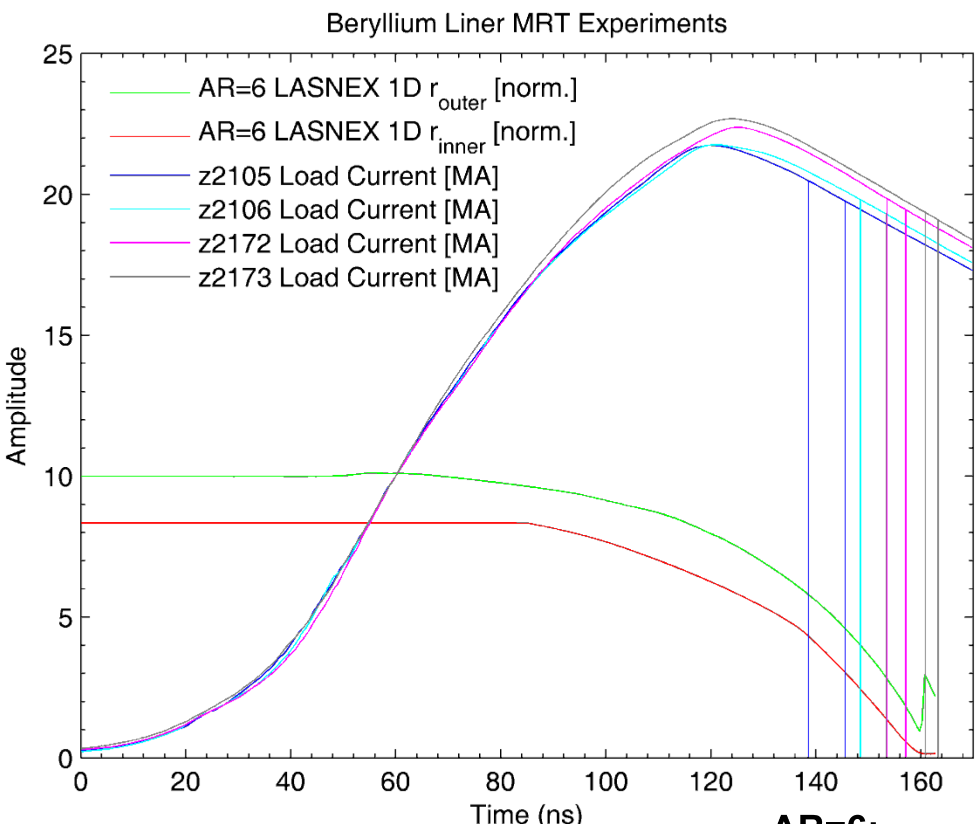
Our LASNEX simulations capture the ablation and jetting well down to ~50 μm wavelength scales





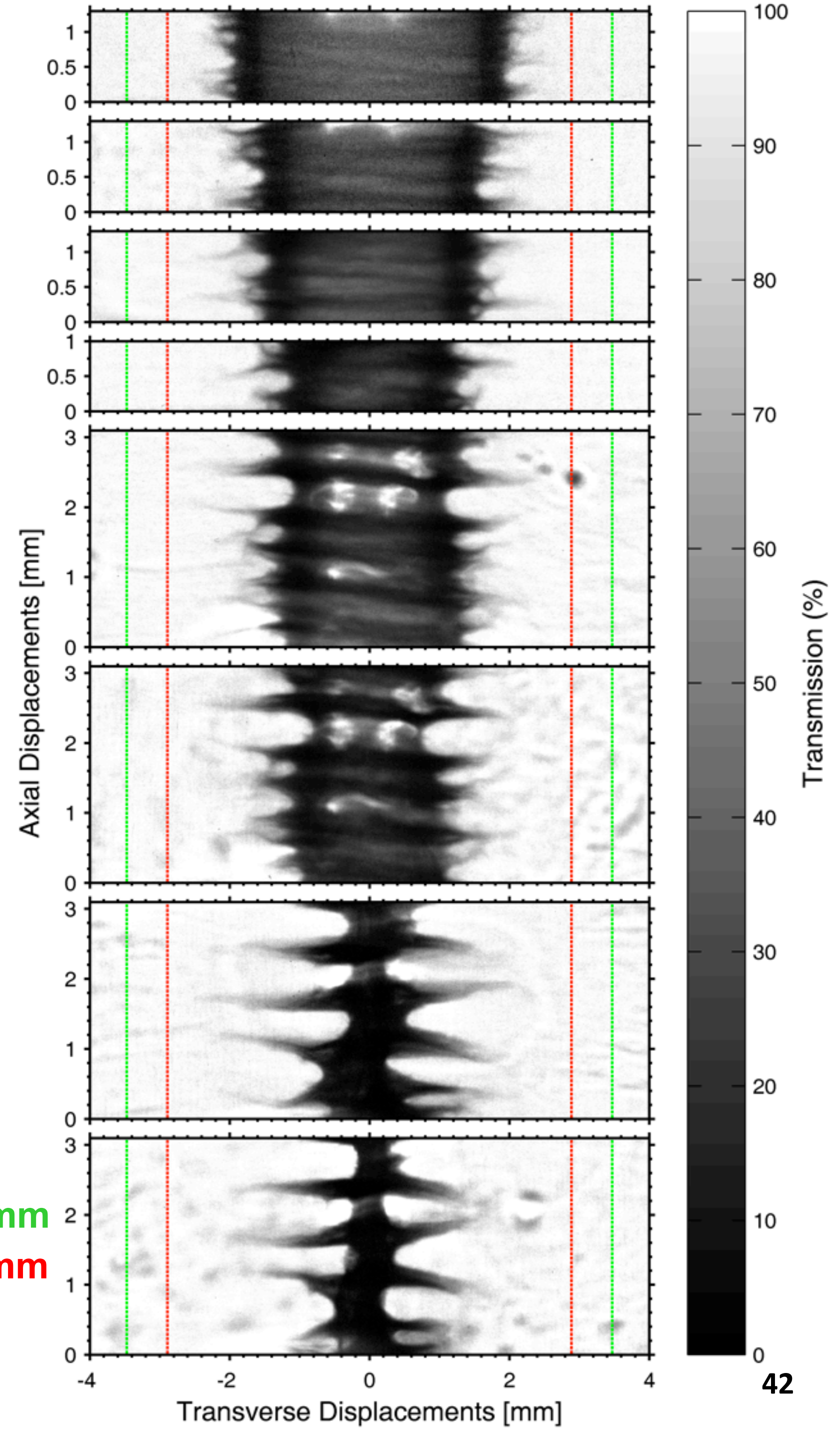
We've done multimode MRT experiments on Be liners at higher radial convergence



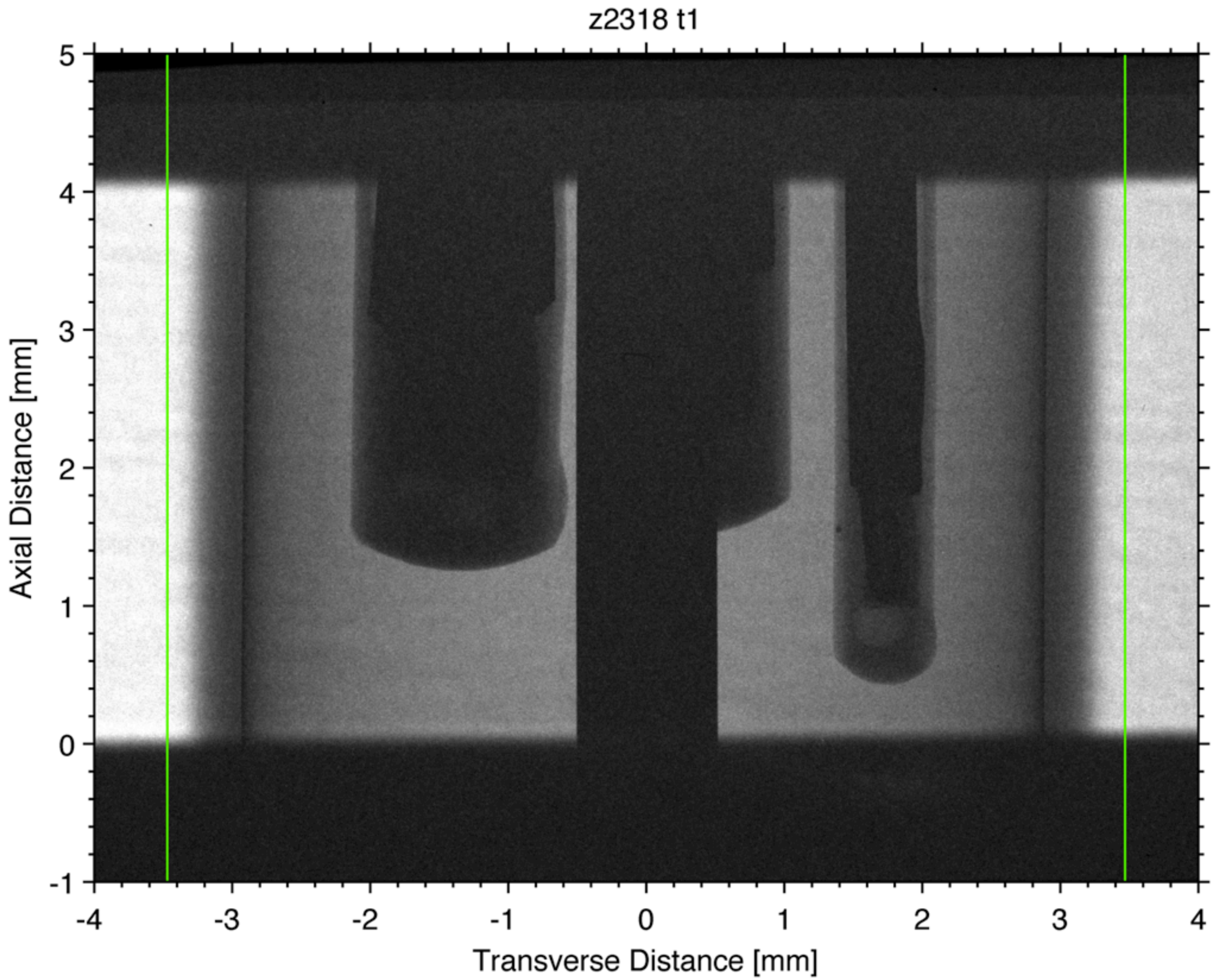
AR=6:

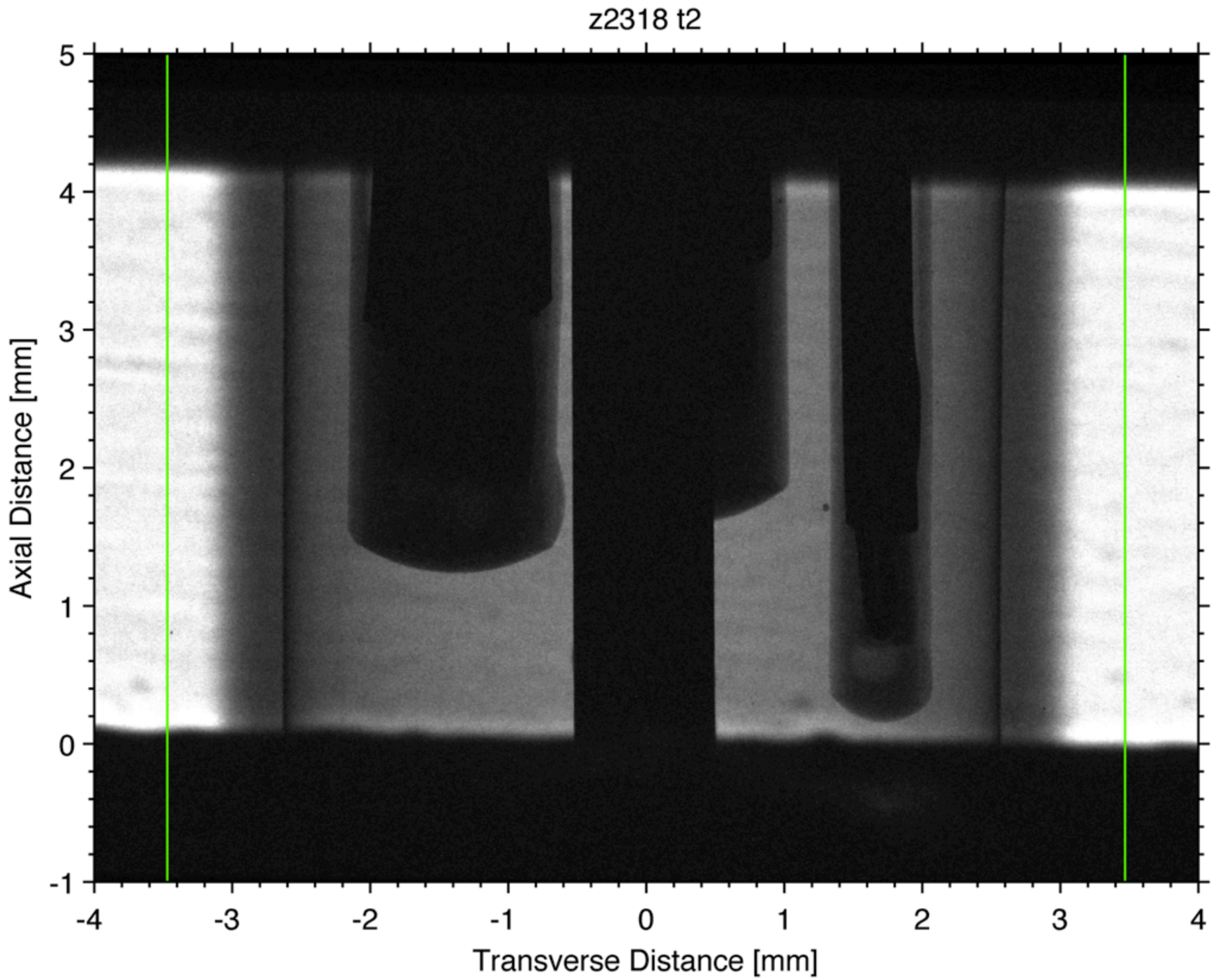
$r_{outer,0}$ **= 3.47 mm**

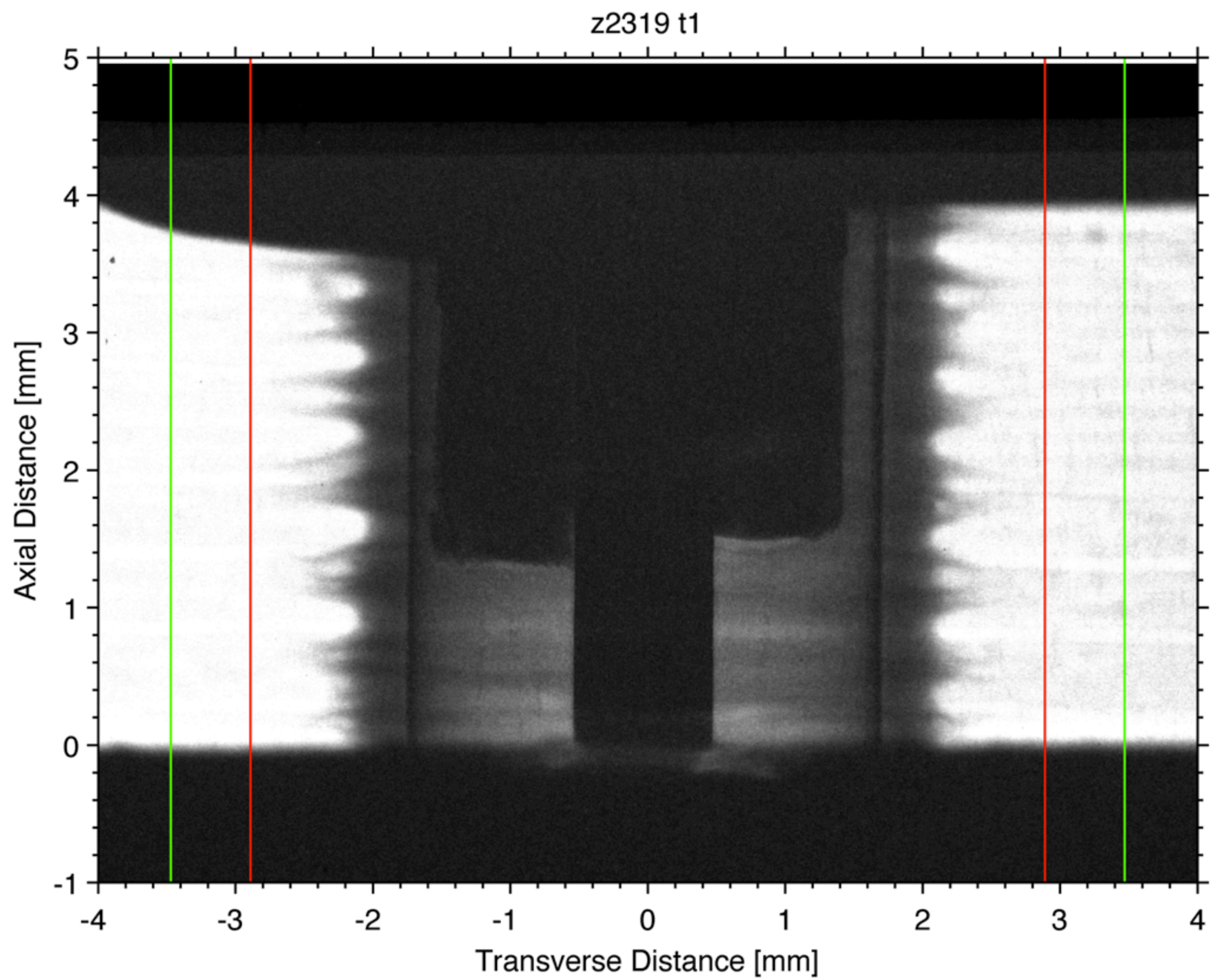
$r_{inner,0}$ **= 2.89 mm**



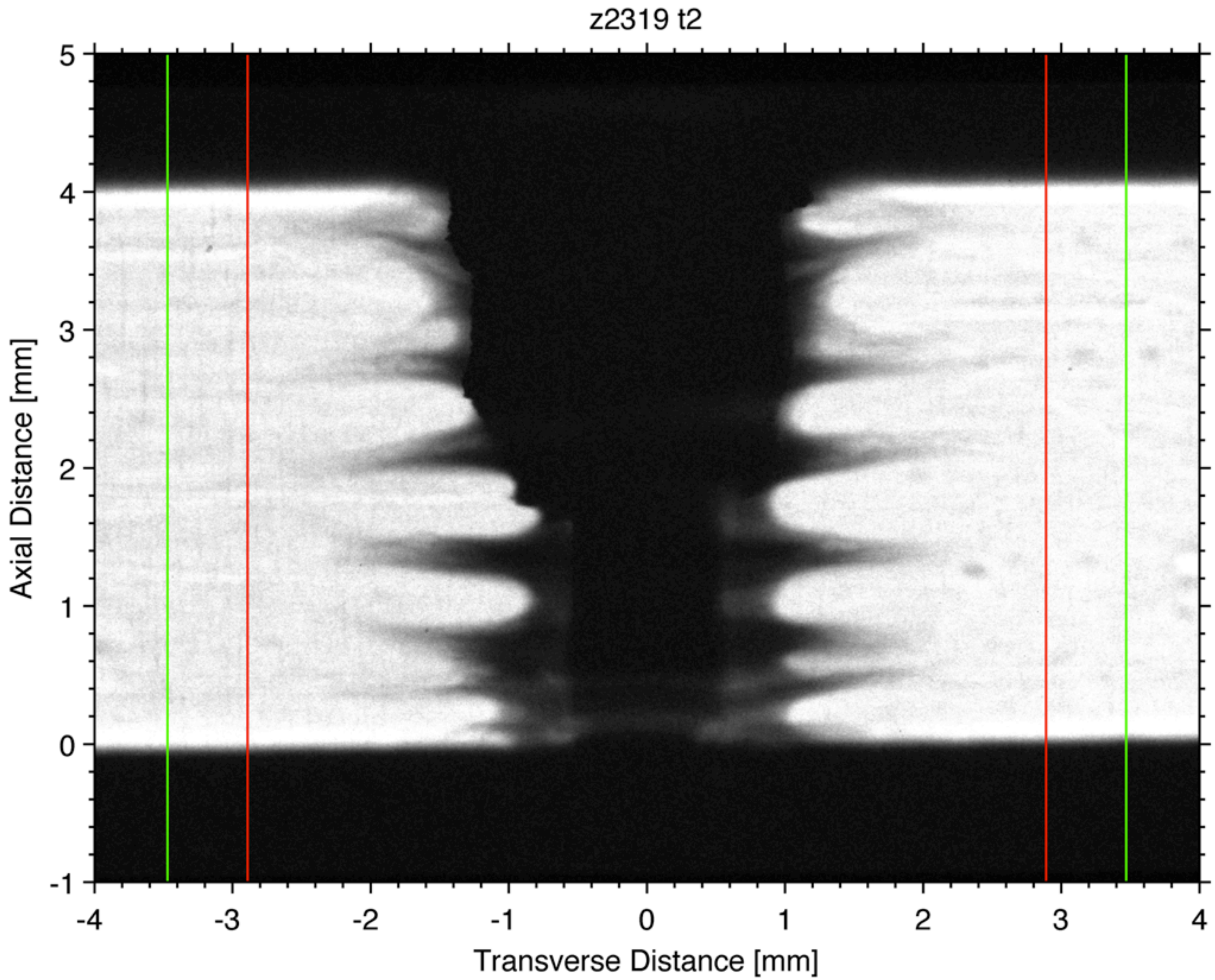
How does the 2D correlation emerge?


z2318 t1
Axial Distance [mm]
Transverse Distance [mm]
5
4
3
2
1
0
-1
-4
-3
-2
-1
0
1
2
3
4


z2318 t2
Axial Distance [mm]
5
4
3
2
1
0
-1
-4
-3
-2
-1
0
1
2
3
4
Transverse Distance [mm]



z2319 t1
Axial Distance [mm]
Transverse Distance [mm]
5
4
3
2
1
0
-1
-4
-3
-2
-1
0
1
2
3
4


z2319 t2
Axial Distance [mm]
Transverse Distance [mm]
5
4
3
2
1
0
-1
-4
-3
-2
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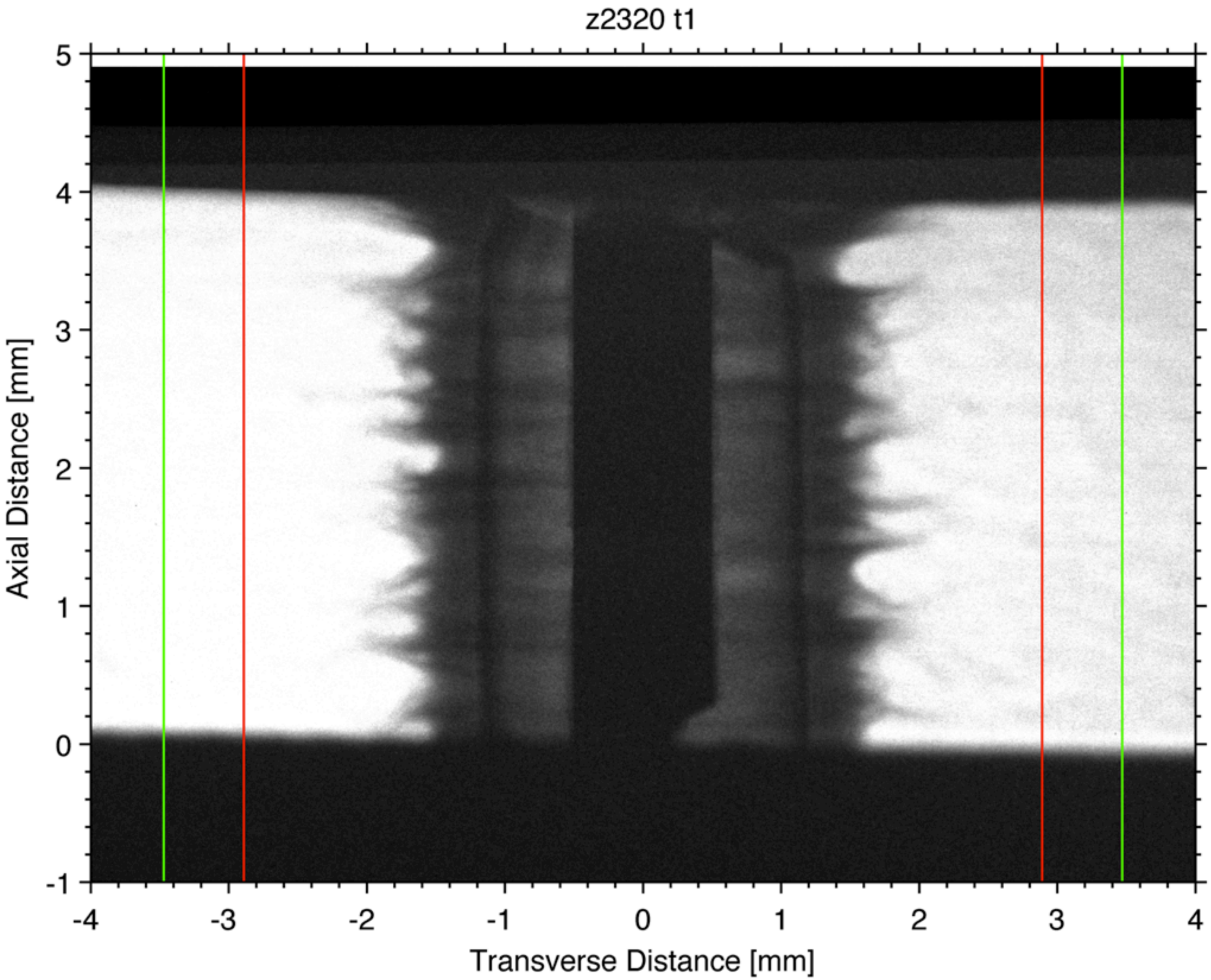
0
1
2
3
4



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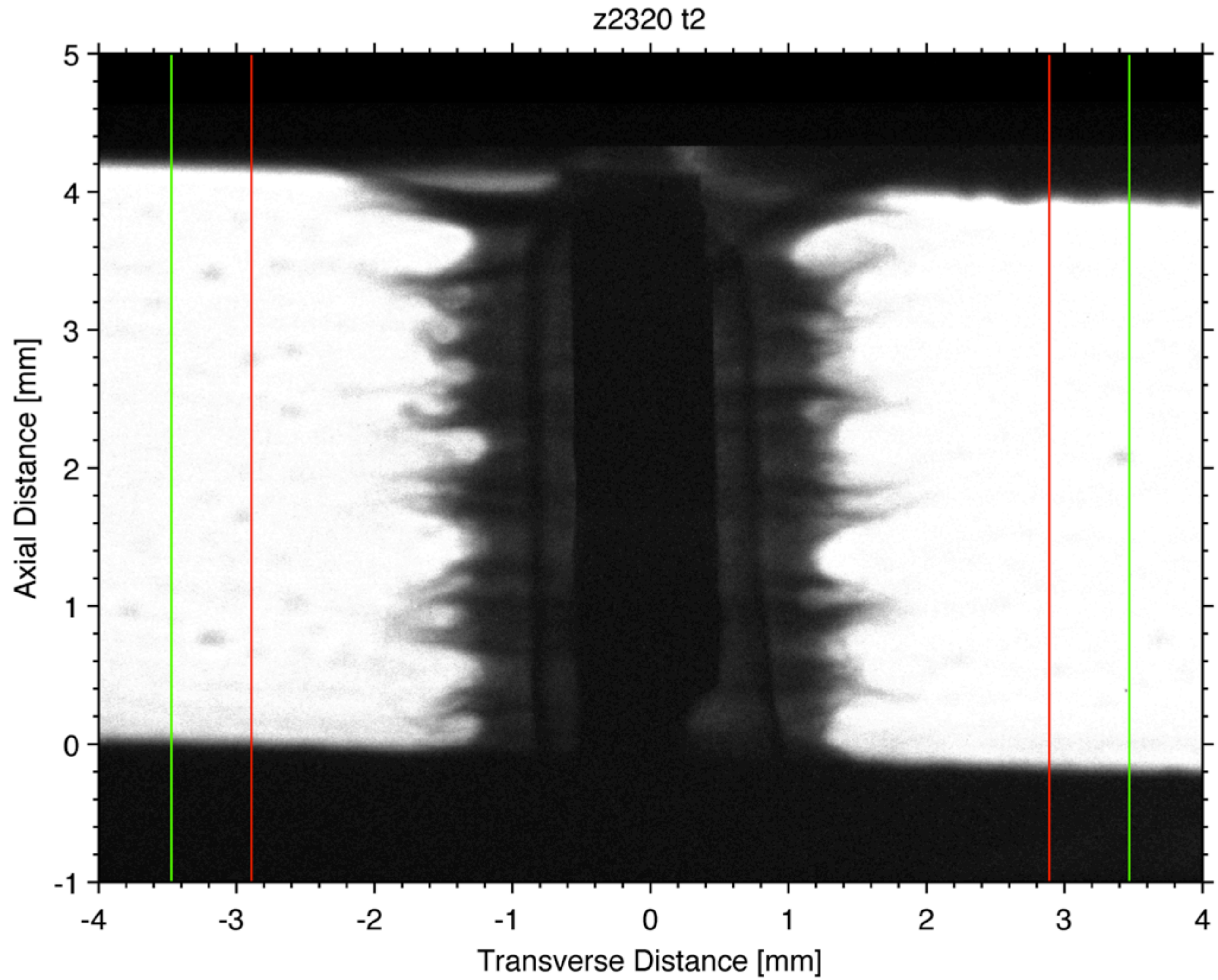

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It's an exciting time to be working in Magnetized HED science

- Our understanding of Magnetized HED science is being applied to important applications
- Ever more extreme conditions are being reached using magnetized HED science
- Magnetic fields appear spontaneously and now are observed in many HED plasmas
- We are poised for exciting advances in inertial confinement fusion using magnetized concepts
- Many computational challenges remain in this subfield of HED

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Many computational challenges remain in Magnetized High Energy Density Science

- **MHED has all the challenges of Rad-Hydro, with the additional challenge of determining the currents and the magnetic fields**
- **Even in the simplest case of resistive MHD highly resolved 2D and 3D simulations are computationally challenging**
- **Current distribution is sensitive to very low density material (shorting) which, given the dependence of pressure on radius can significantly alter the dynamics.**
- **Magnetic fields strongly affect transport properties**
- **Resistive MHD is not adequate for many of our problems (next slide)**

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XMHD Modeling of HED Sources

- **Magnetized HED plasma sources demonstrate regimes of anode-cathode asymmetry* and contain regions subject to magnetic reconnection**

- **Resistive MHD codes are symmetric under anode-cathode inversion and cannot properly model the transition to collisionless plasma**

- **Ongoing effort to develop the PERSEUS XMHD code, a semi-implicit generalized Ohm's law code with the Hall effect, self-generated magnetic fields, and finite electron inertia**

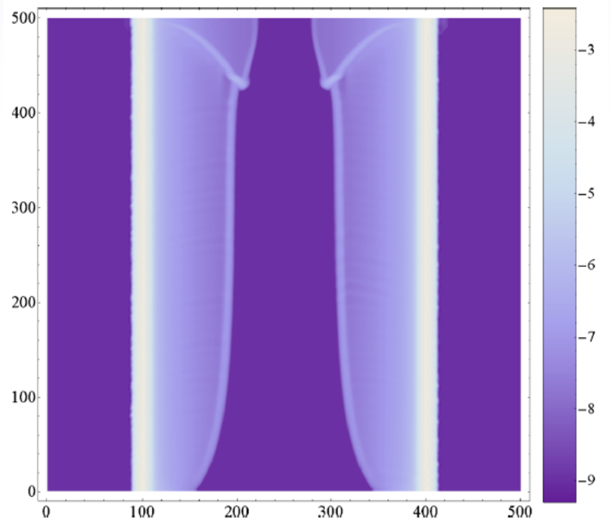

FIG. 11. (Color online) Log density at 25 ns for XMHD foil implosion simulation.

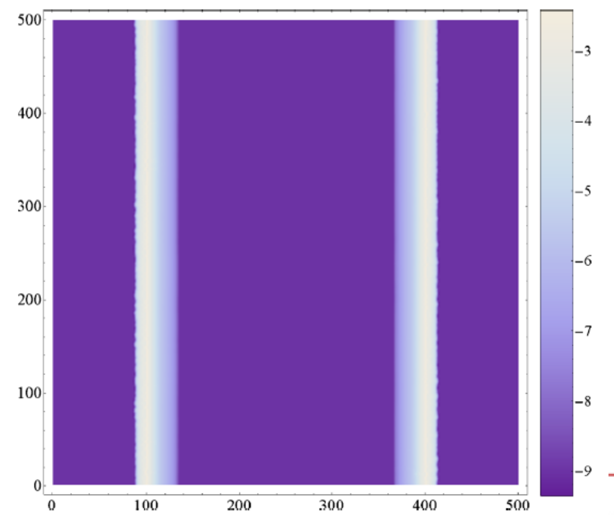

FIG. 12. (Color online) Log density at 25 ns for MHD foil implosion simulation.

*R.D. Mcbride et al, IEEE Trans. Plasma Sci. 2011

Backups