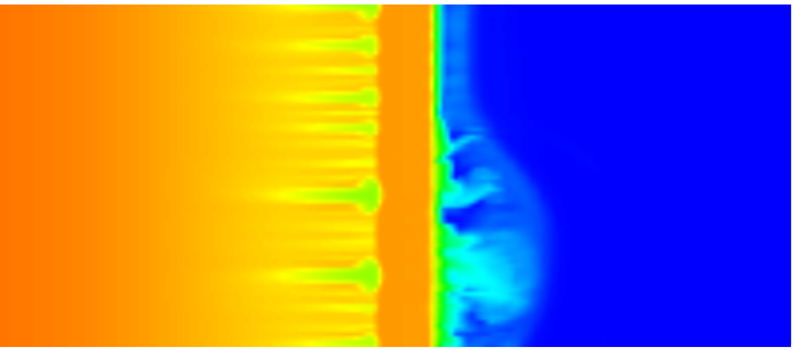
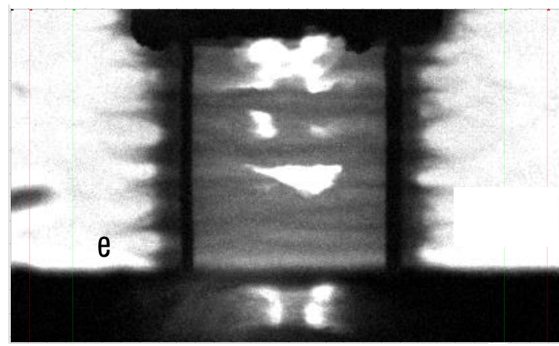
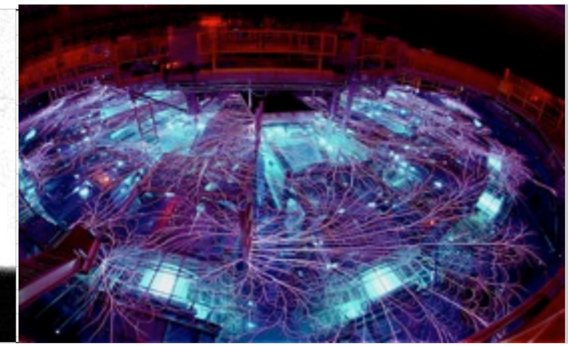
Exceptional service in the national interest

SAND2015-2649C

Sandia National Laboratories







Instability growth, mitigation, and stabilization techniques of magnetically driven liner targets

Kyle Peterson, on behalf of the Sandia MagLIF Team

International Workshop on Electromagnetically Driven High Energy Density Physics

國際研討會上的電磁驅動的高能量密度物理

April 12-15, 2015

4月12-15日，2015年

Chengdu, China

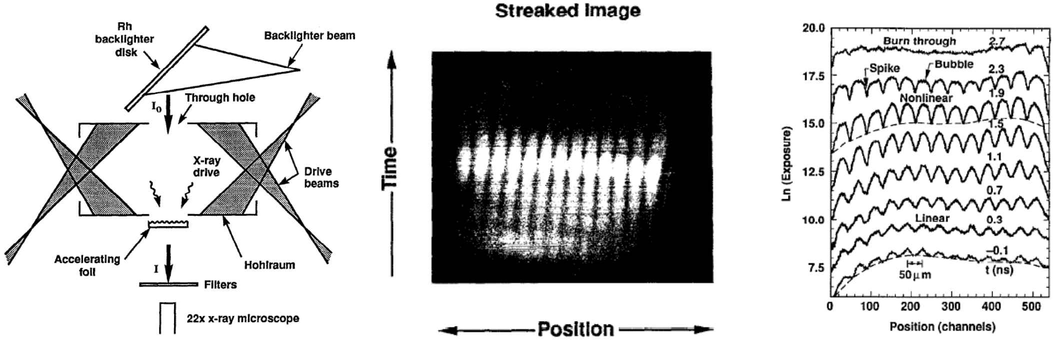
成都，中國

Pulsed Power Sciences — Harnessing Extreme Environments

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

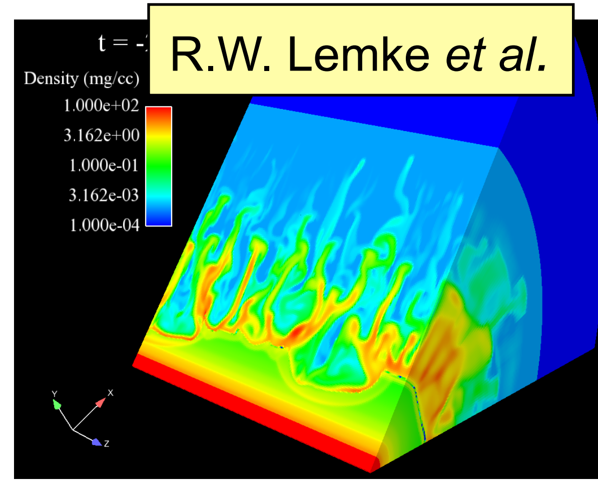
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Numerous studies have been performed to study instabilities in the context of ICF and magnetically driven implosions



B.A. Remington *et al.*, Phys. Rev. Lett. (1991); + many others (single-mode, multi-mode, 3D, etc.).

R.W. Lemke *et al.*



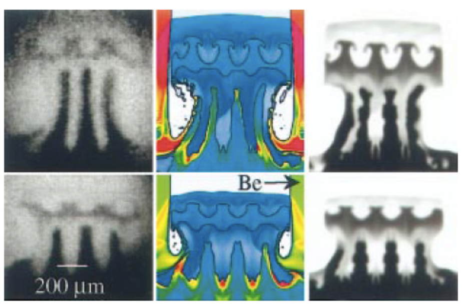
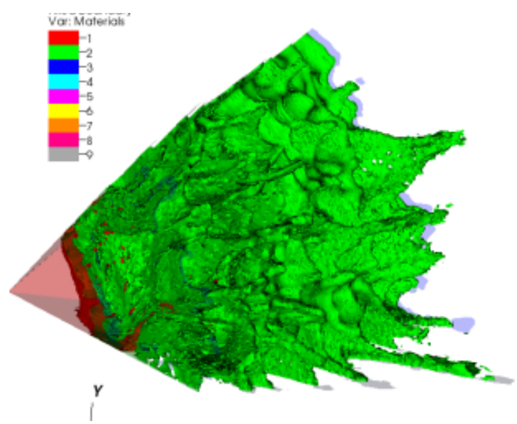
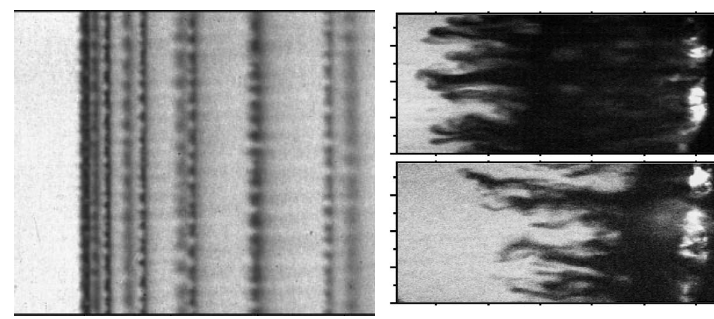


FIG. 4. (Color). Data and simulations. Bottom: $t = 39$ ns. Top: $t = 65$ ns. Left: data. Middle: CALE density. Right: simulated radiograph of PROMETHEUS results.



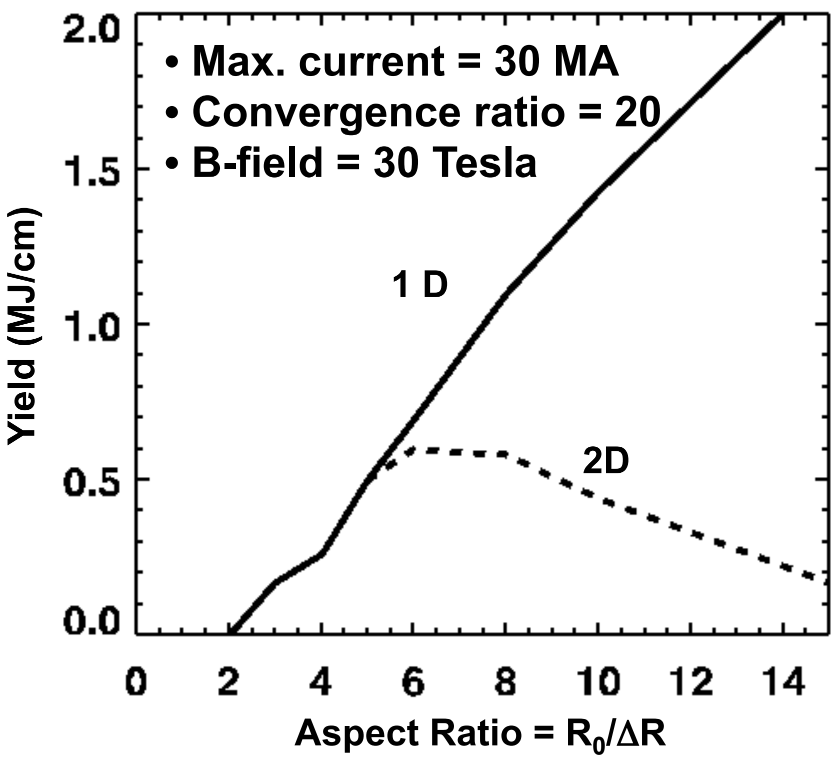
Wire array Z-pinch

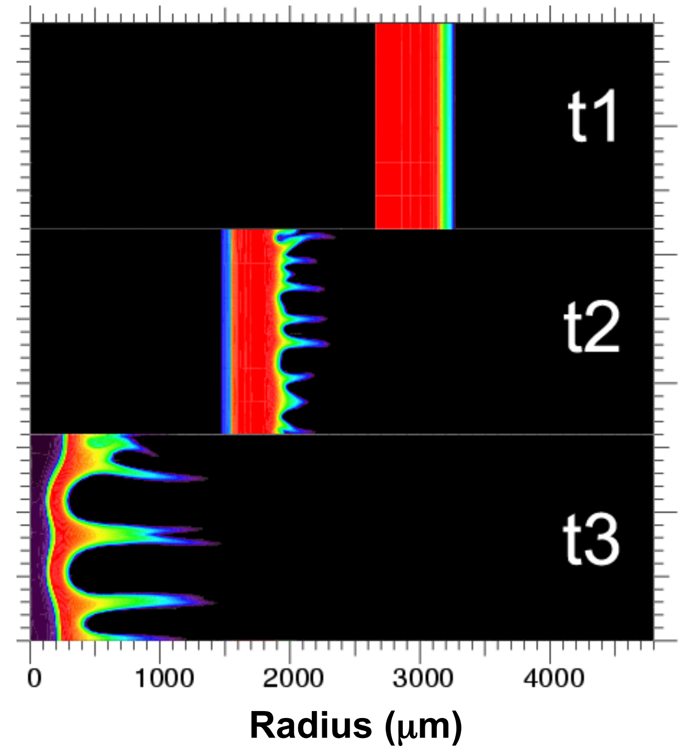


In all fusion concepts, It is critical to understand and mitigate the growth of instabilities

MAGNETO-RAYLEIGH TAYLOR INSTABILITIES AND SURFACE INITATION

Reducing the implosion velocity requirements through fuel heating and magnetization allows us to use thicker, more massive liners to compress the fuel that are more stable



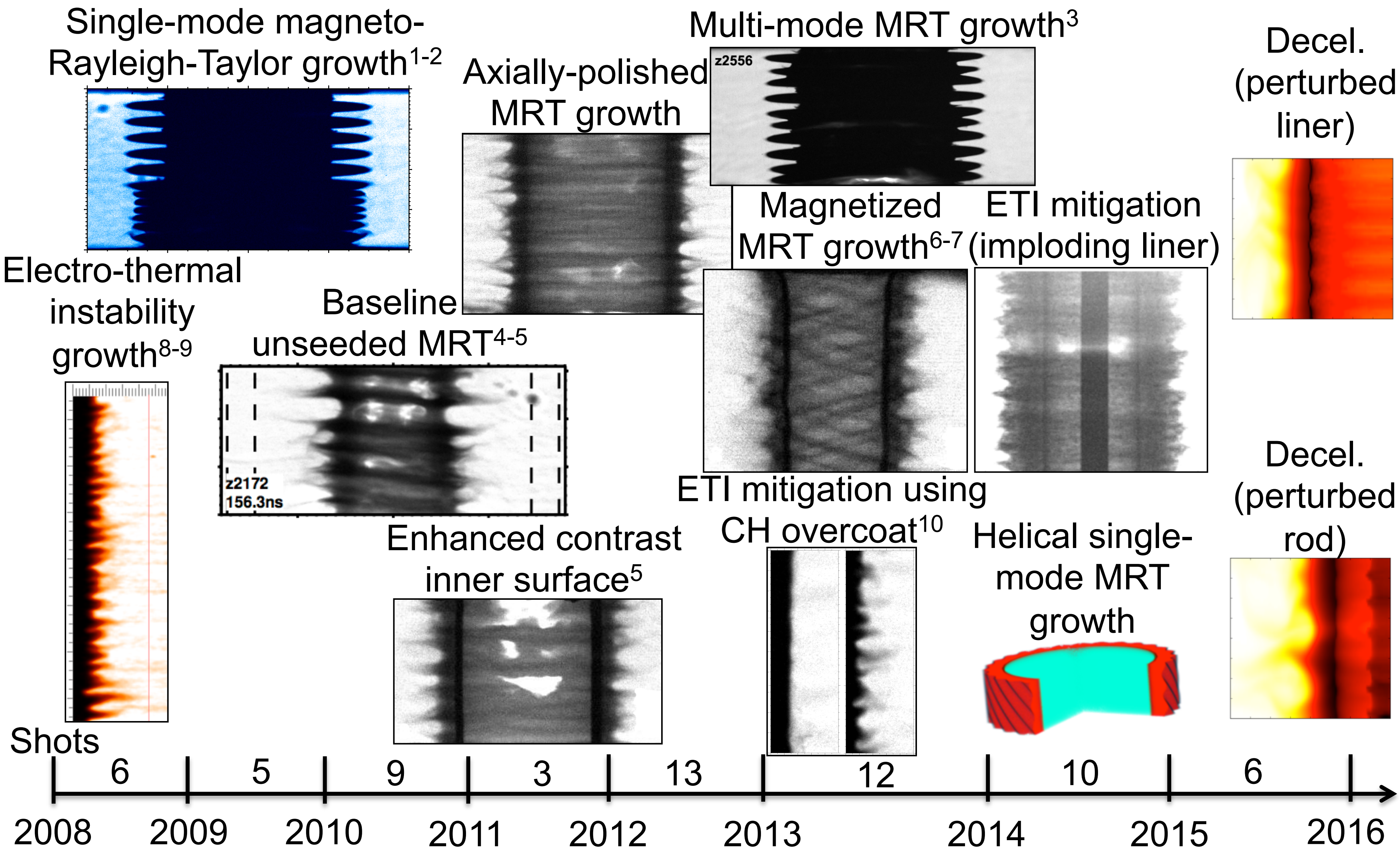


- The Magneto-Rayleigh-Taylor instability degrades the yield as the aspect ratio is increased (due to decreased liner ρR)

- Simulations of AR=6 Be liner show reasonably uniform fuel compression and sufficient liner ρR at stagnation to inertially confine the fuel—important because fuel density is low!

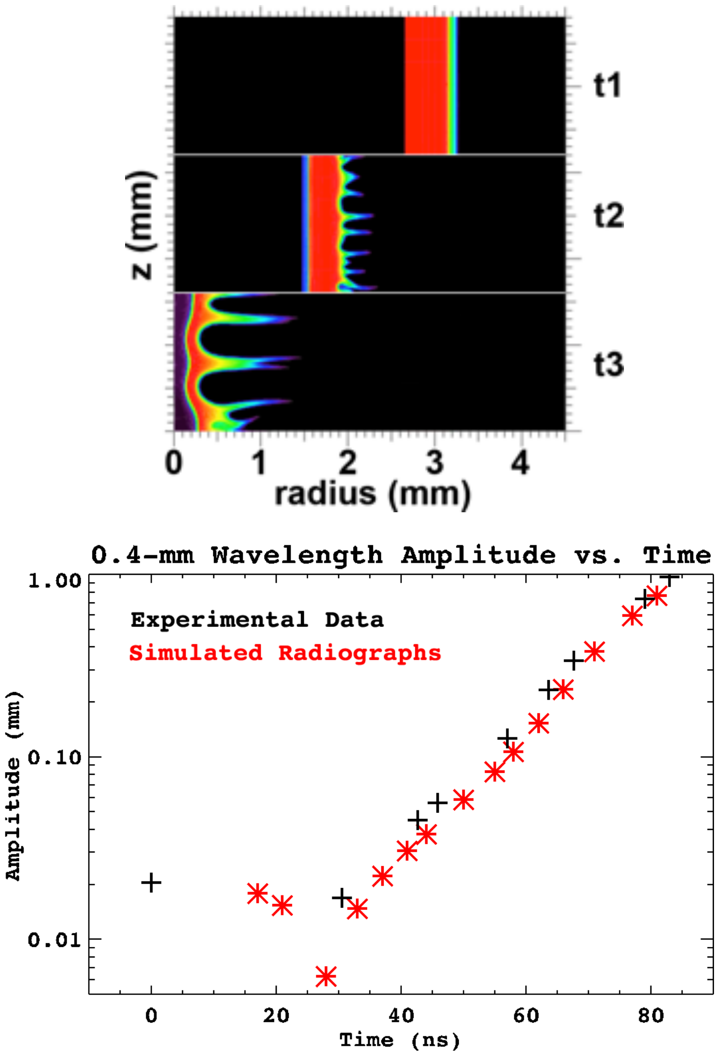
S.A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).

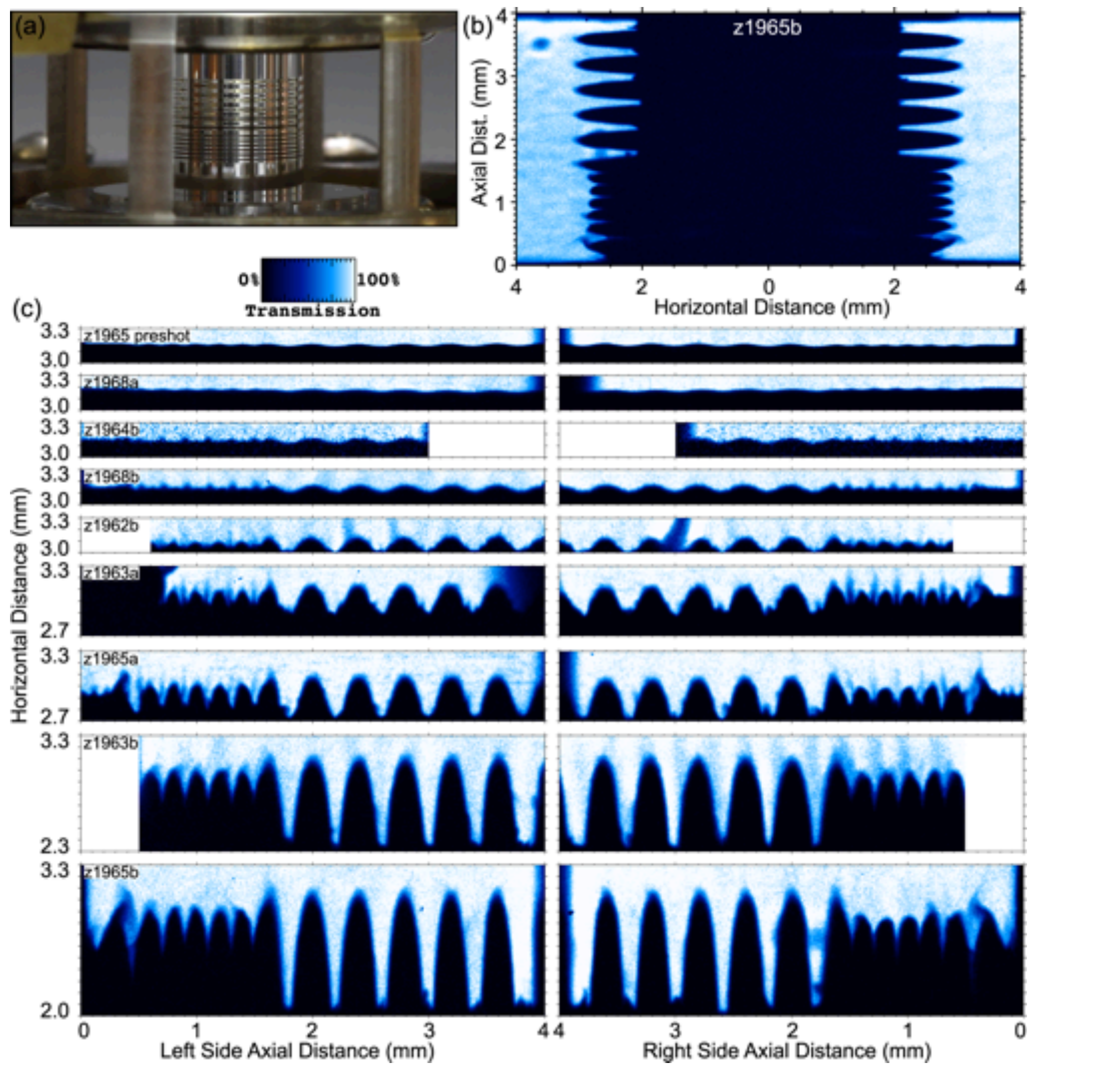
Fundamental liner instability experiments represent an important example of a sustained focused science effort—we are transitioning from experiments on initiation/acceleration stages to deceleration stage



Study the underlying science Publications to date include 4 PRLs, 5 PoPs, more in prep.

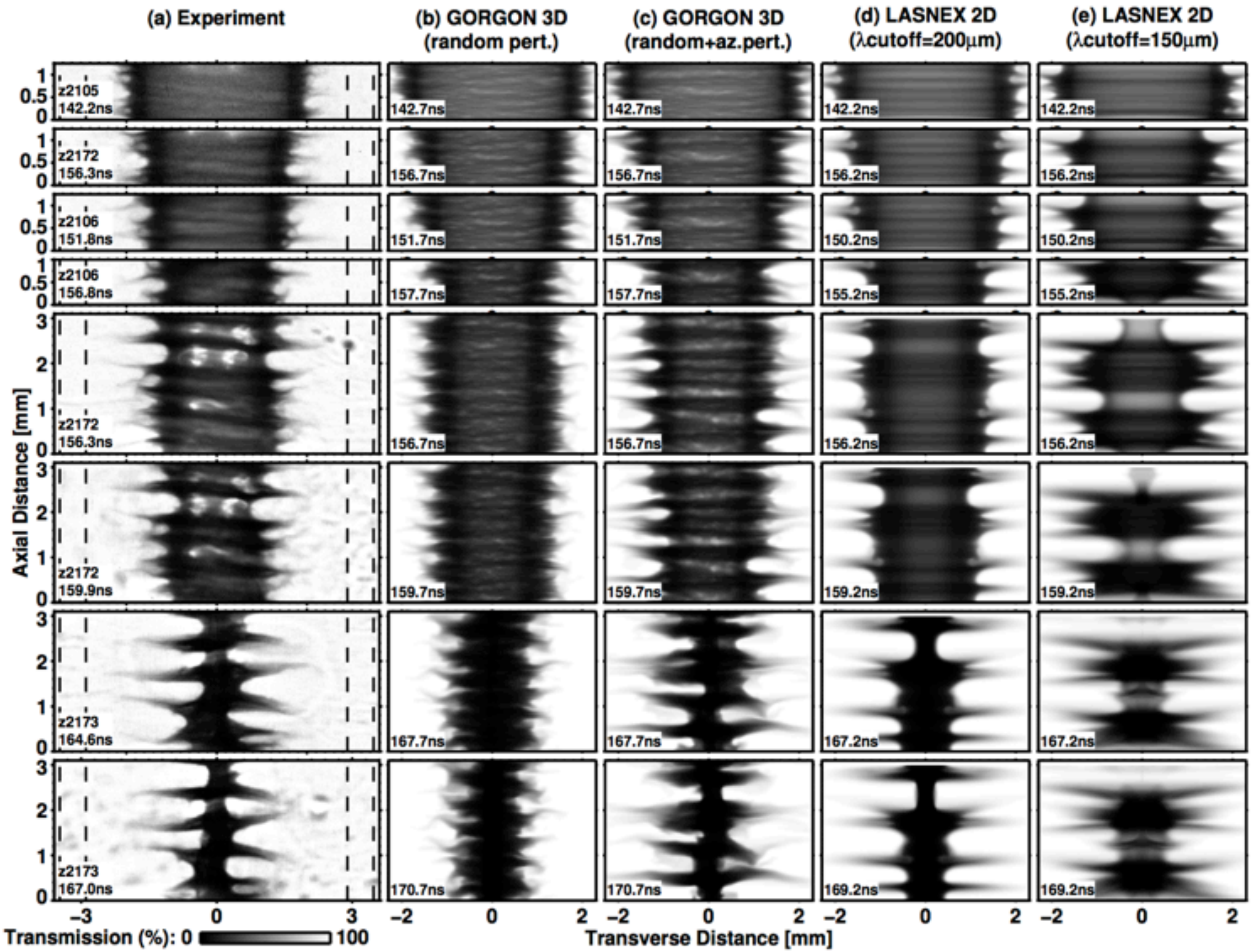
We observe excellent agreement between theory and experiment for single-mode MRT growth experiments





D.B. Sinars et al., Phys. Rev. Lett. (2010); D.B. Sinars et al., Phys. Plasmas (2011).

Previous experiments have also studied multi-mode MRT growth in Beryllium liners with initially flat contours

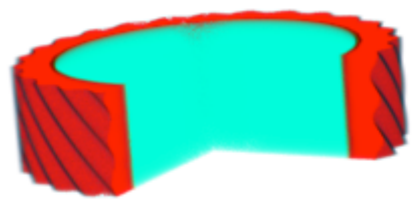


R.D. McBride et al., Phys. Rev. Lett. 109, 135004 (2012).

Helical perturbations are also being investigated as a means to mitigate instabilities

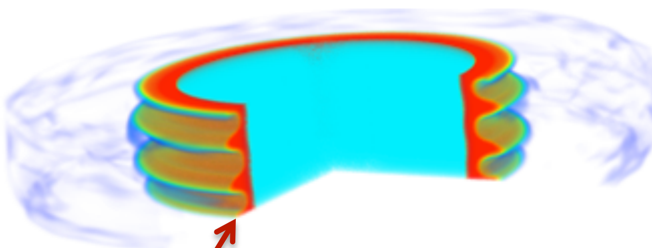
Lincoln single-mode MRT
λ=400 μm test target

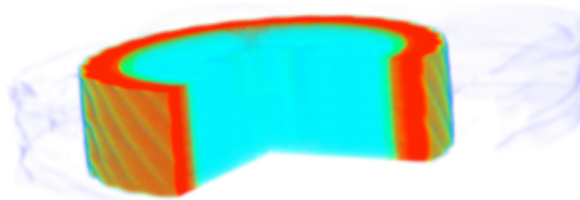
Single-mode MRT
λ=400 μm, 45° pitch target



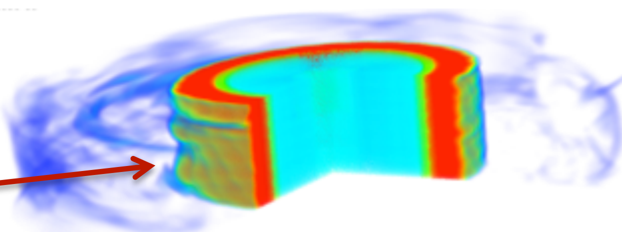
$\lambda_{kp} = 4\pi\Delta\cos^2\theta$

$$\lambda_{kp} = 4\pi\Delta\cos^2\theta$$

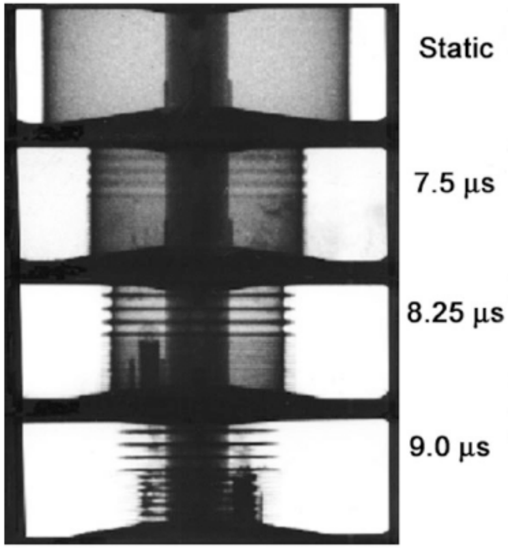




Fundamental mode grows like $\Gamma^2 = kg$



~Zero growth in Fundamental mode



Radiographic Data

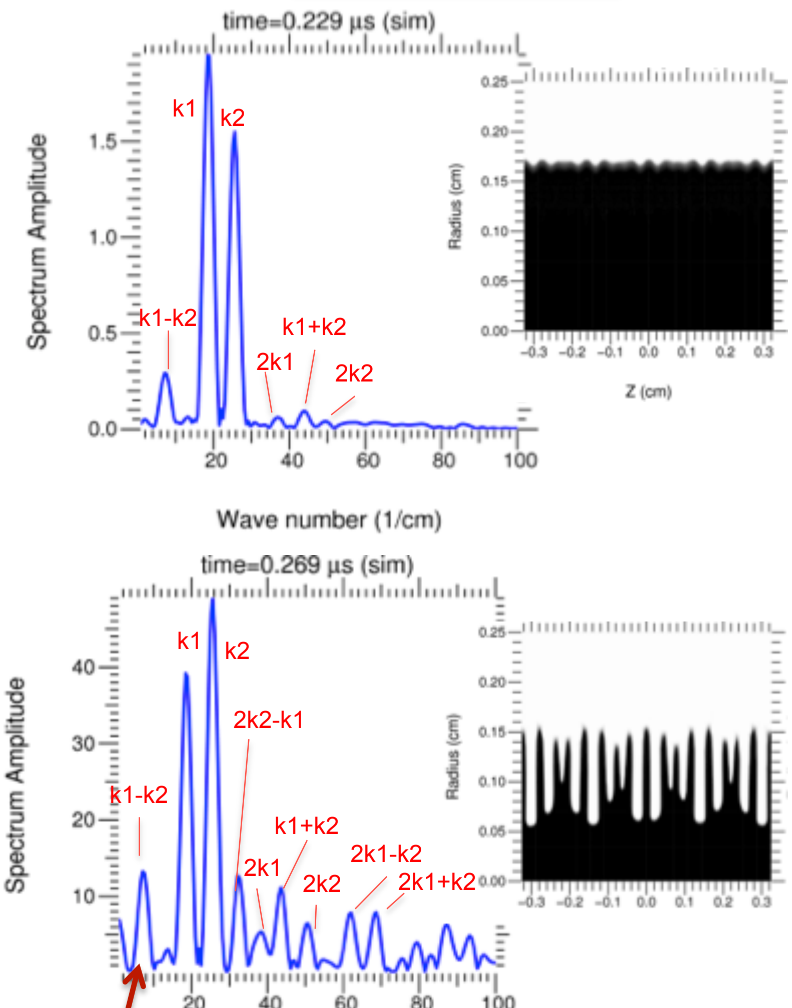
Joint LANL/VNIIEF helical liner Experiment on PEGASUS*

*B. G. Anderson *et al.*, Pulsed Power Plasma Science (2001).

We have begun to study nonlinear MRT instabilities and mode coupling in carefully seeded multi-mode experiments

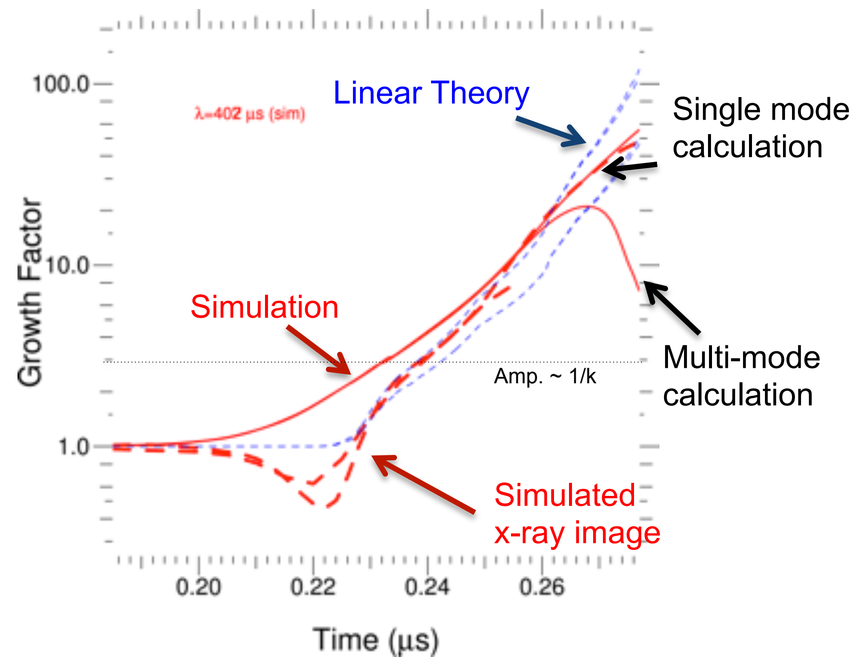
Sandia National Laboratories

HYDRA Simulations



Inverse cascade process

$$\Gamma^2 = k\frac{\mu_0}{8\pi^2}\frac{I^2}{R^2}\frac{1}{\rho(\Delta r)}$$

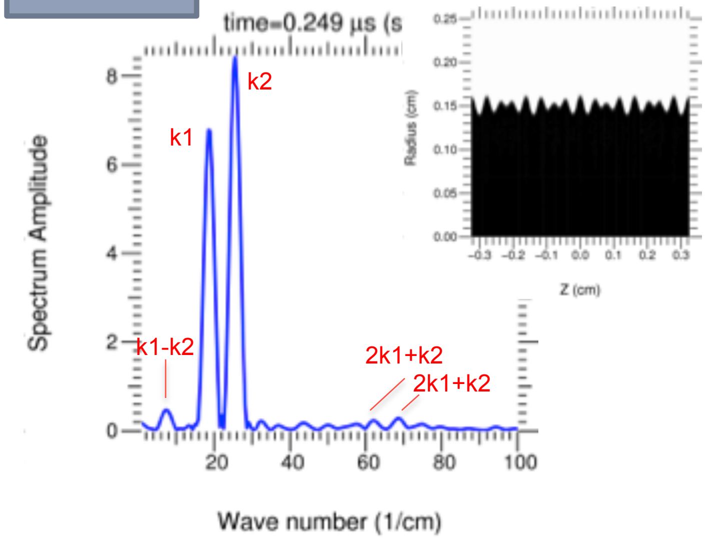


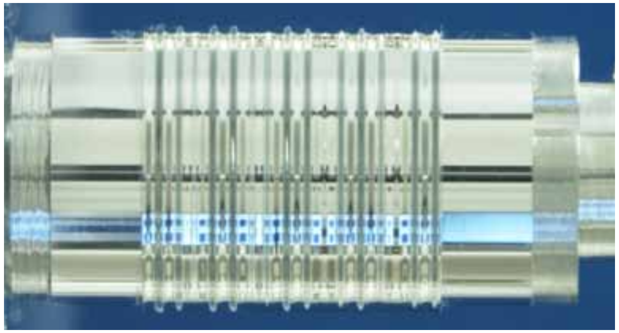
For k<(1/h), linear theory increasingly poor approximation as amplitude goes to ~1/k ,.

*Ryutov, Derzon, & Matzen, Rev. Mod. Phys. 72, 167 (2000)

Initial results indicate that we are doing a reasonable job of modeling multimode MRT instability growth

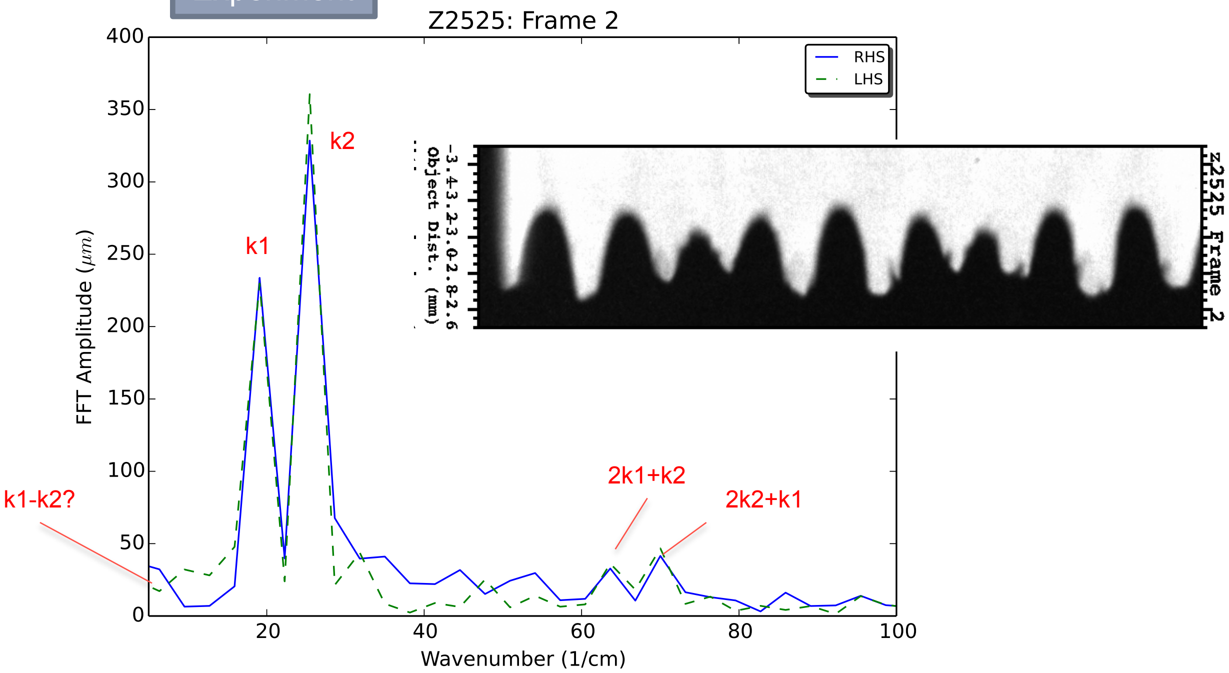
Simulation



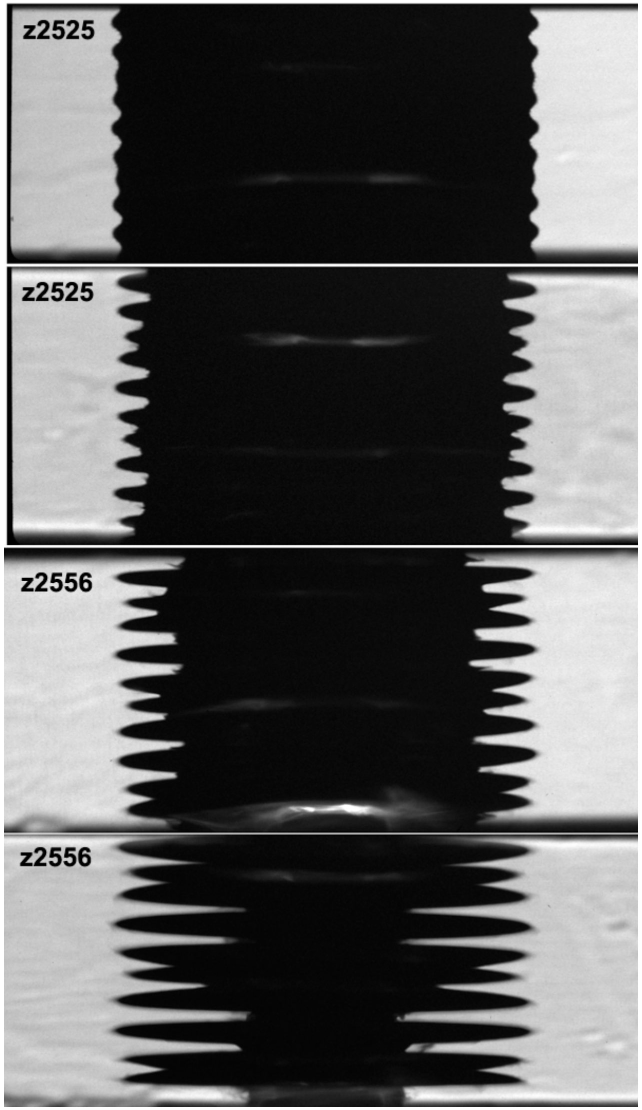


Experimental data does show additional short wavelength features not present in simulations

Experiment



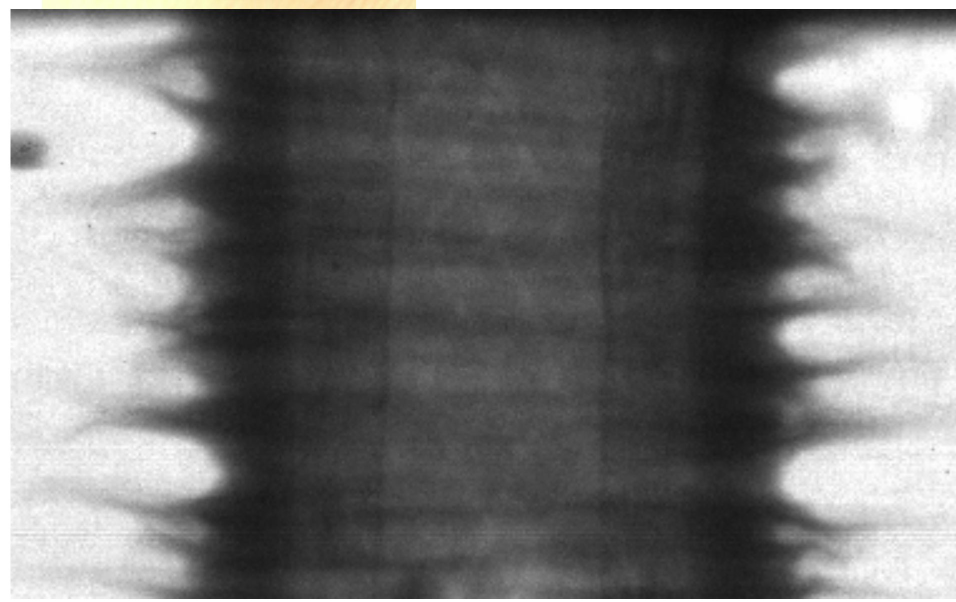
How do different modes of the MRT instability interact with each other?



Overlapping λ = 400,550 μm seeds

Similar idea to work by Douglas *et al.* (PoP 1998)

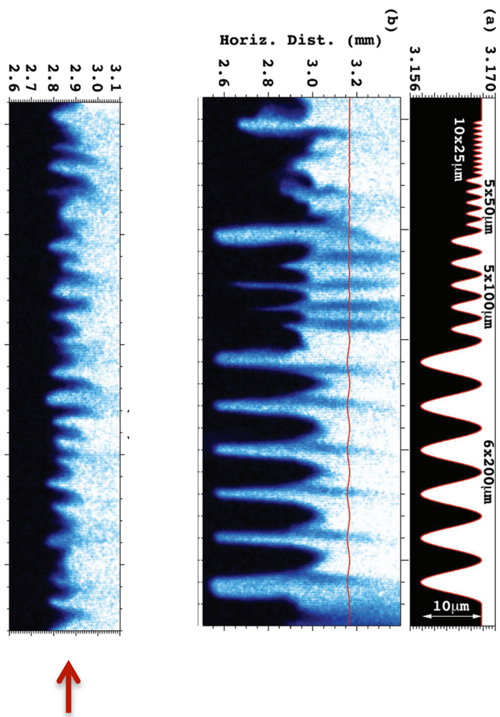
Helically-perturbed target shows both helical structure and the usual cylindrically symmetric structure superimposed at late times!



D.B. Sinars, K.J. Peterson, unpublished.

Experiments have shown that surface roughness and small defects are not the dominant source of MRT instabilities

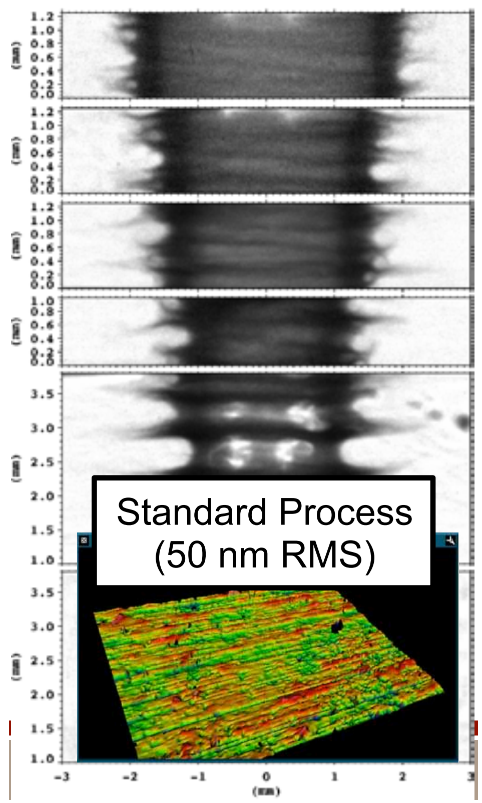
Observed Instability growth is not linearly proportional to the amplitude of the initial perturbations.



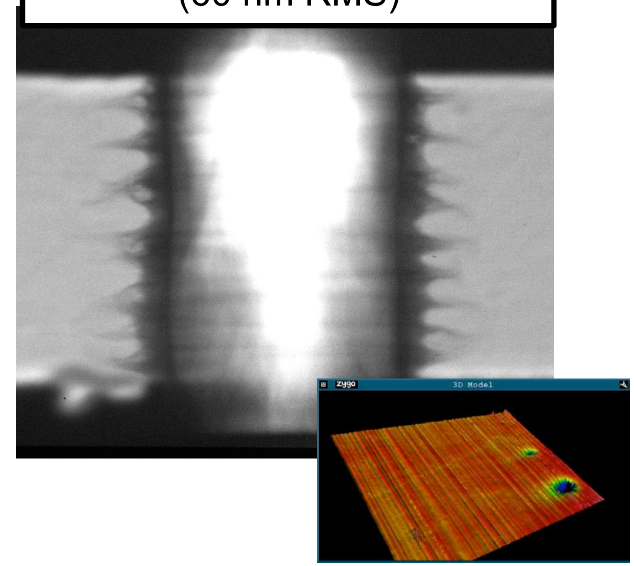
A_0 = 60 nm

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

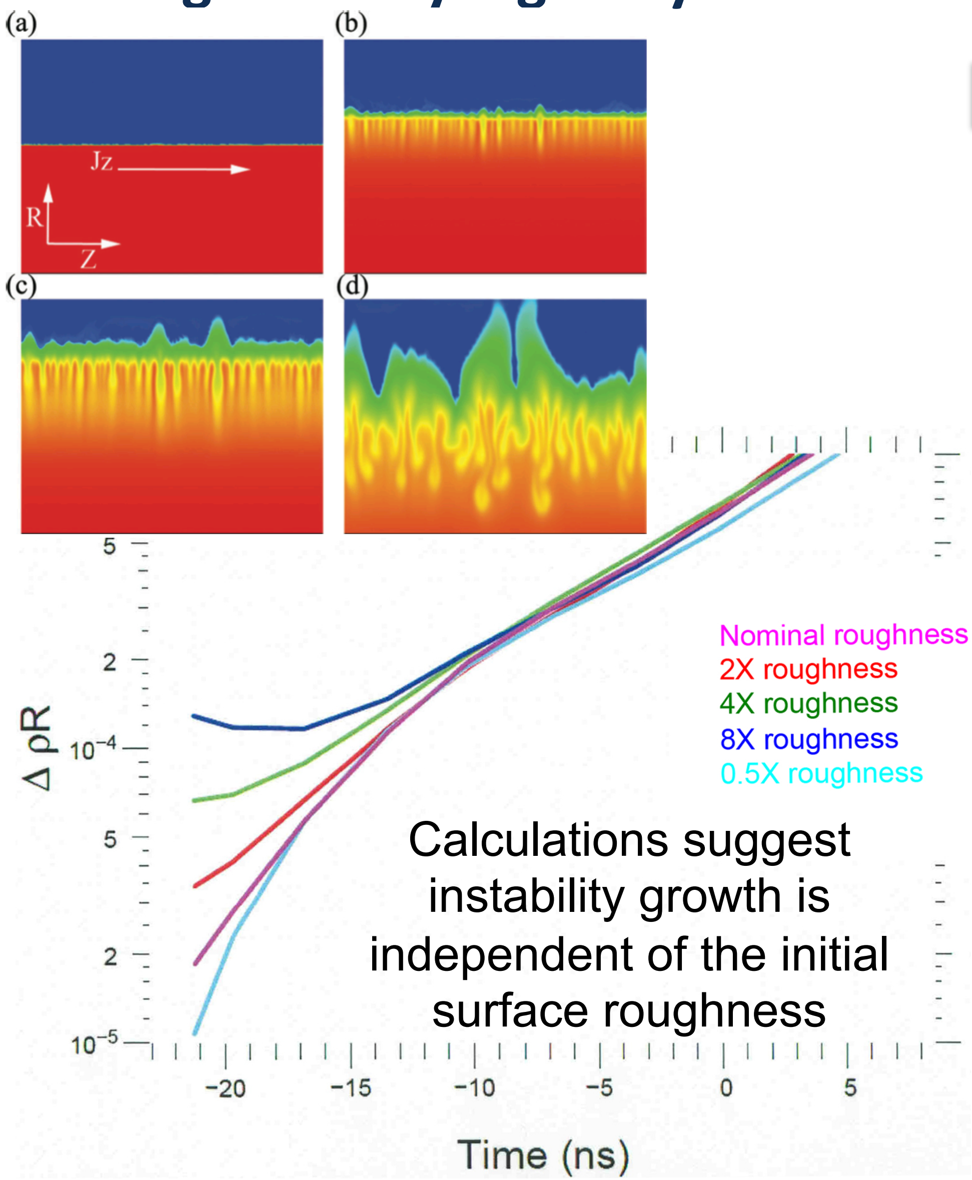
McBride PRL data



axial machining and polishing
(60 nm RMS)

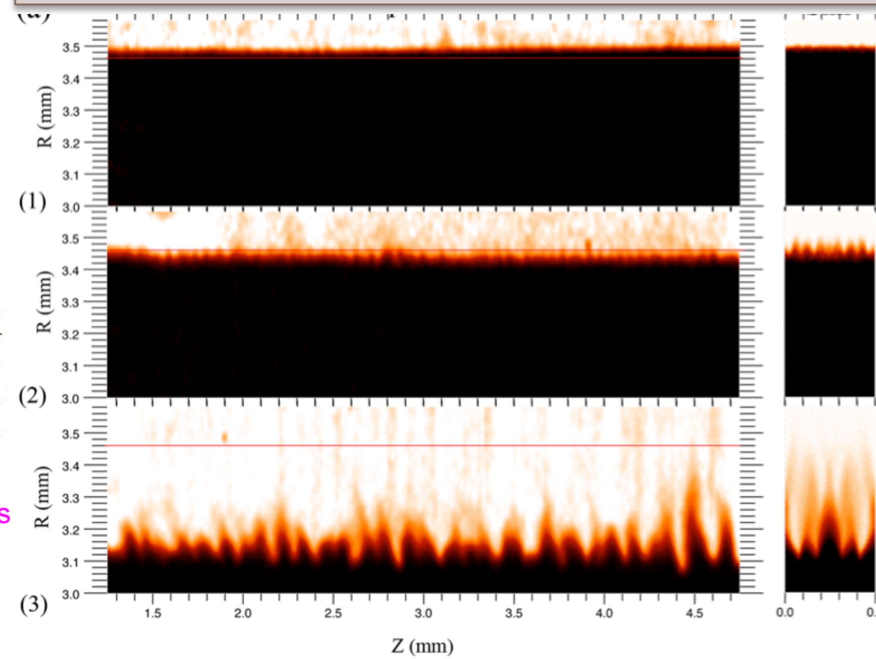


Is the electro-thermal instability the main seed for the magneto-Rayleigh-Taylor instability?



Calculations suggest instability growth is independent of the initial surface roughness

Experimental (left) & simulated (right) radiographs



Perturbation Growth Comparison

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

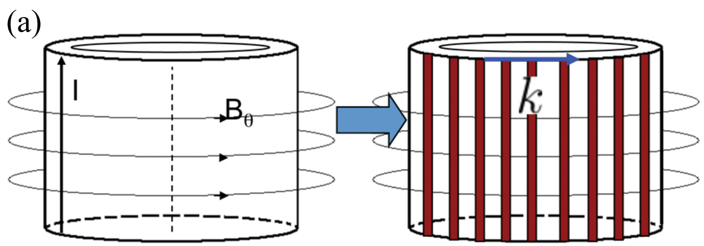
K.J. Peterson *et al.*, Phys. Plasmas (2012); K.J. Peterson *et al.*, Phys. Plasmas 20, 056305 (2013).

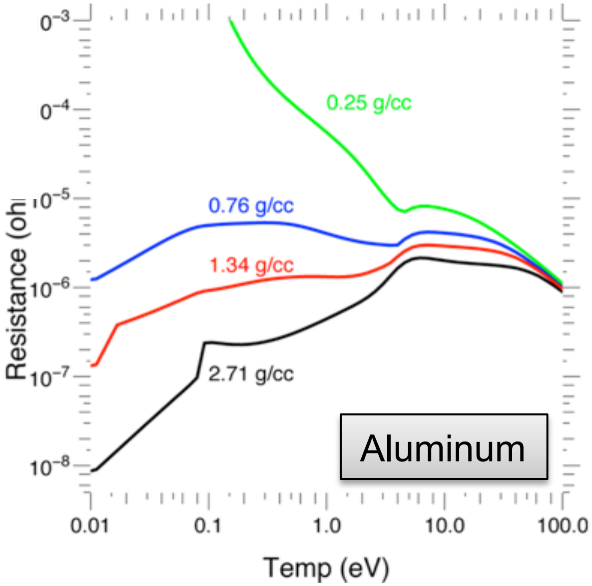
Electrothermal instabilities occur when material conductivity is dependent on temperature

Theory

Filamentations

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



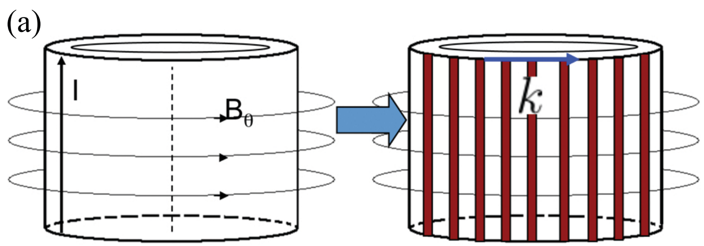


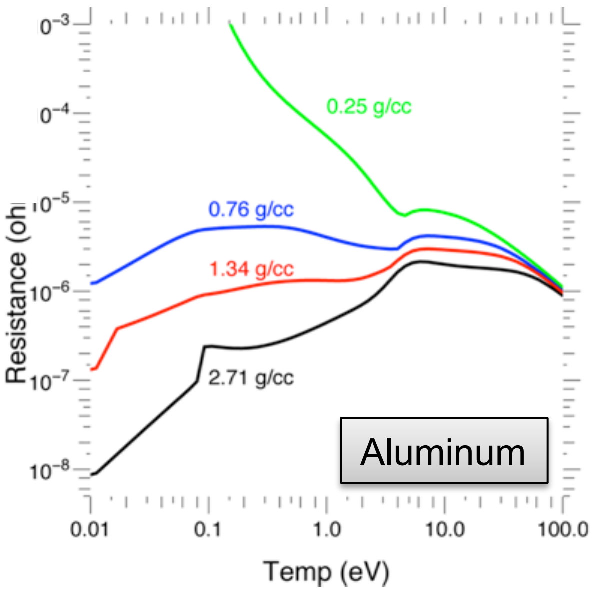
Electrothermal instabilities occur when material conductivity is dependent on temperature

Theory

Filamentations

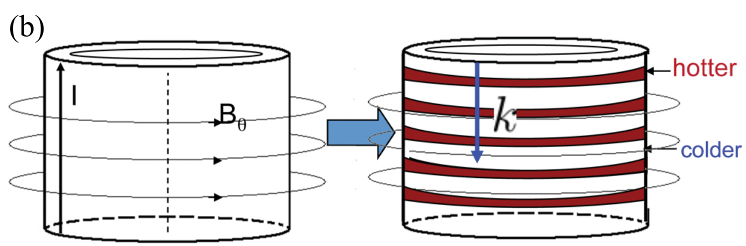
$$\frac{d\eta(T)}{dT} < 0$$





Striations

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

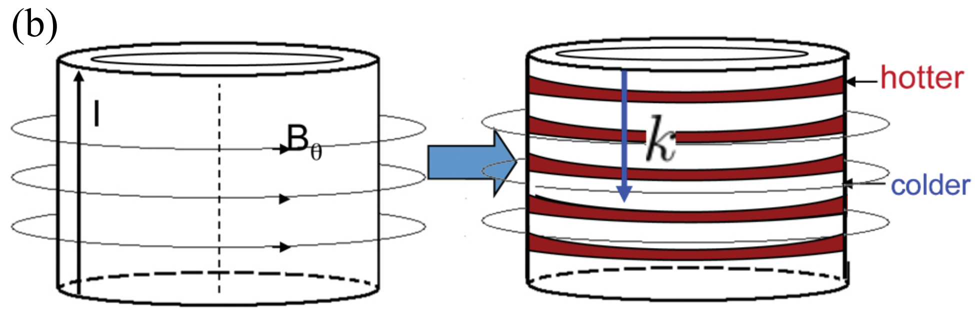


Electrothermal instabilities occur when material conductivity is dependent on temperature

Theory

Striations

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



$$\delta T > 0$$

Temperature perturbations give rise to pressure variations which eventually redistribute mass

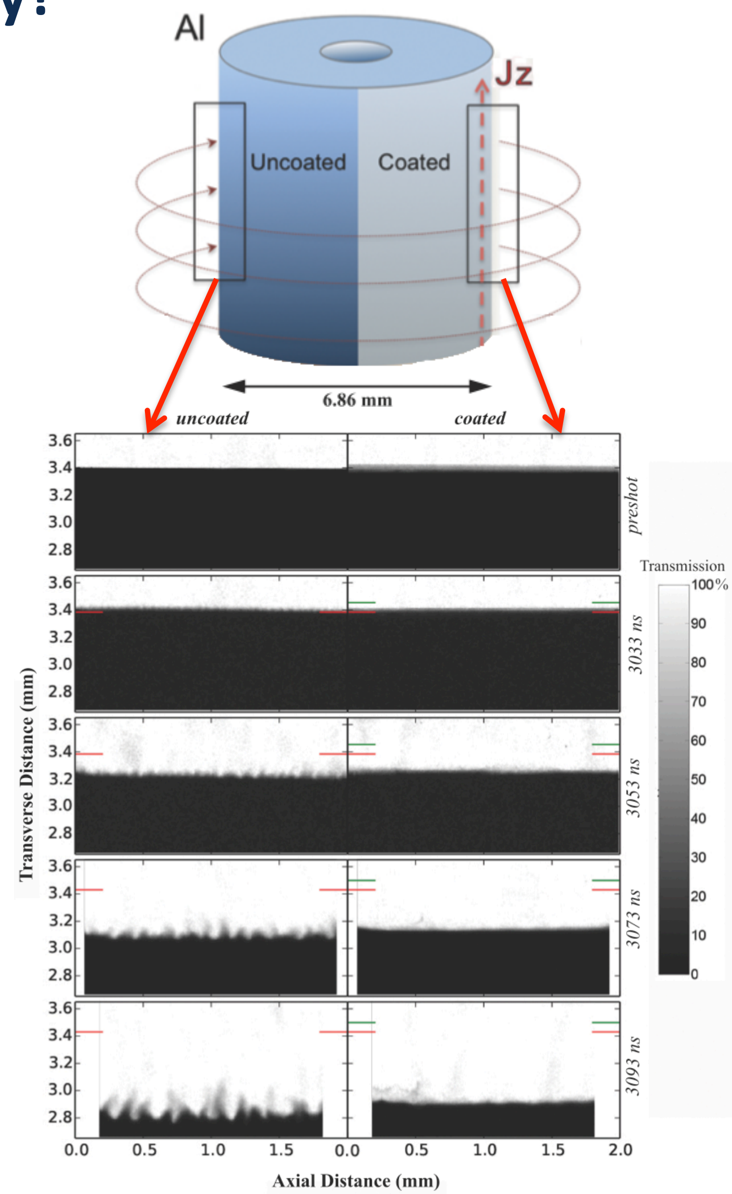
Consider a small temperature perturbation due to localized variations in ohmic heating
- surface contaminants (variations in η)
- surface roughness ($B_\theta \sim I/r$, in cylinders)

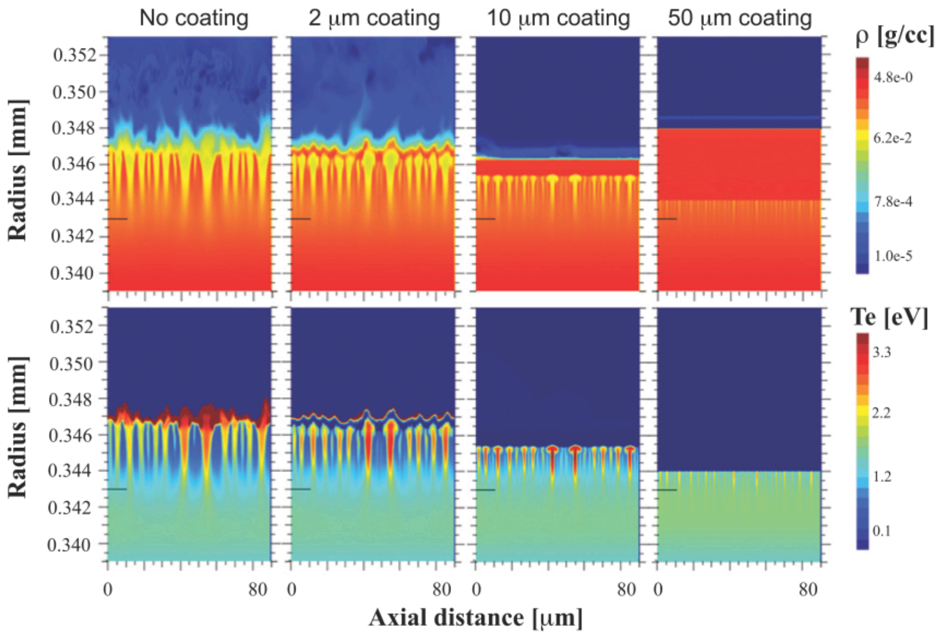
Then, η increases which consequently further enhances the localized ohmic heating (ηj^2),

which leads to increased δT

Liner Compression: Is it possible to suppress the growth of the magneto-Rayleigh-Taylor instability?

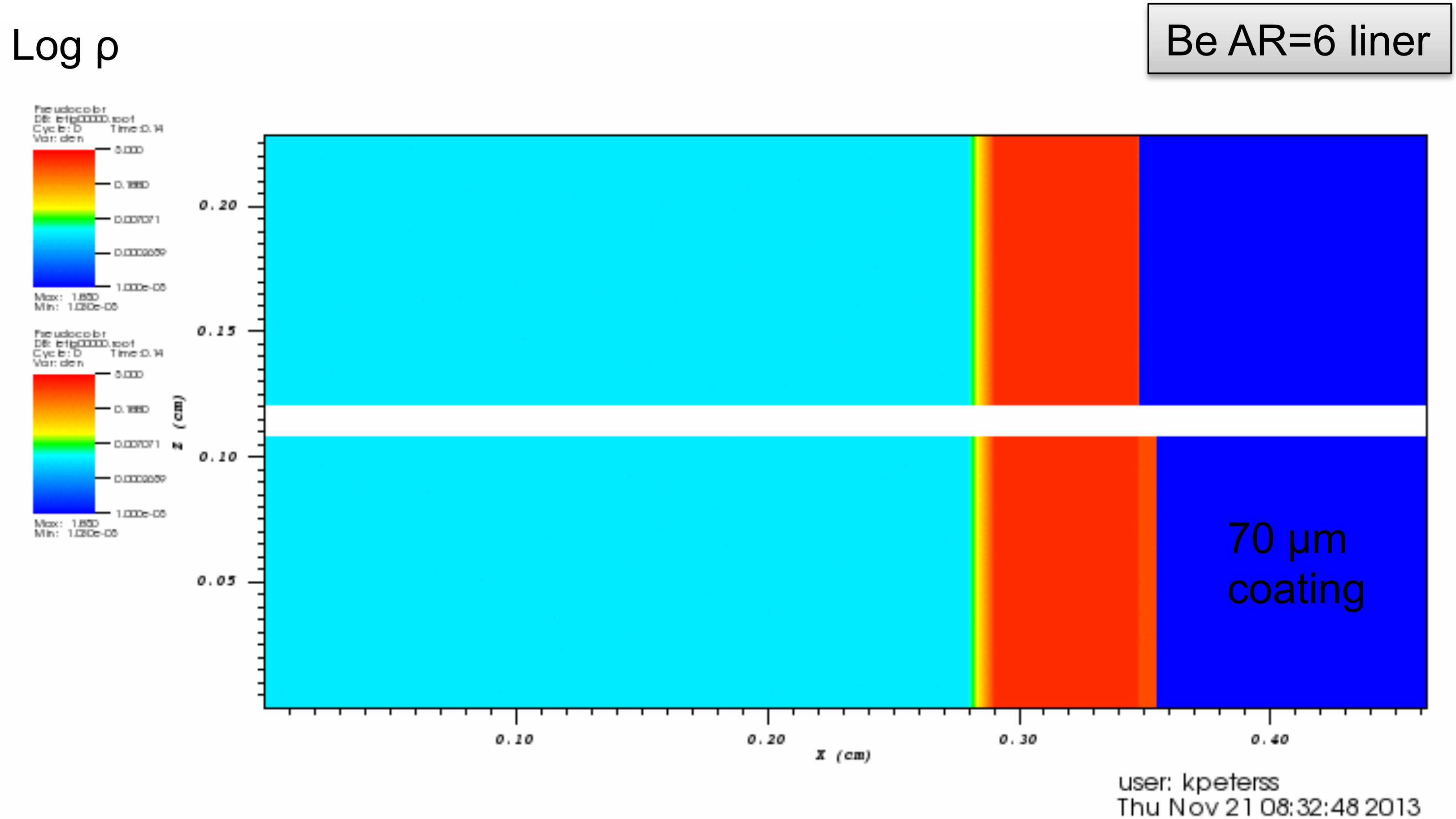
- No ETI growth in plastic coating
  - Carries very little current
  - Theoretically ETI stable
- Demonstrated to help suppress early-time growth, but will it help with full implosion? (more Z shots in 2015 on this topic)



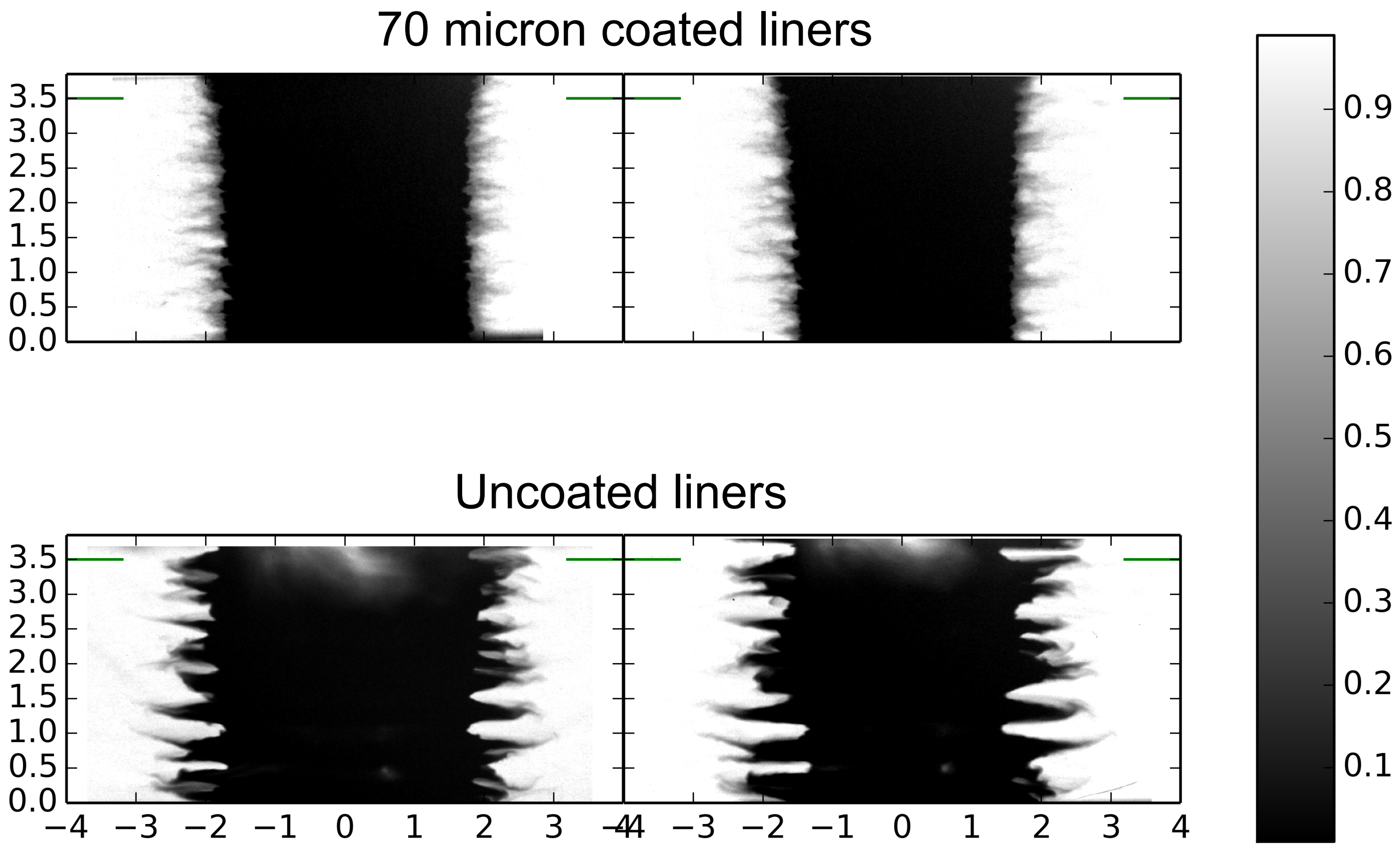


K.J. Peterson *et al.*, Phys. Rev. Lett. 112, 135002 (2014). See also GO5.00012 on Tues.

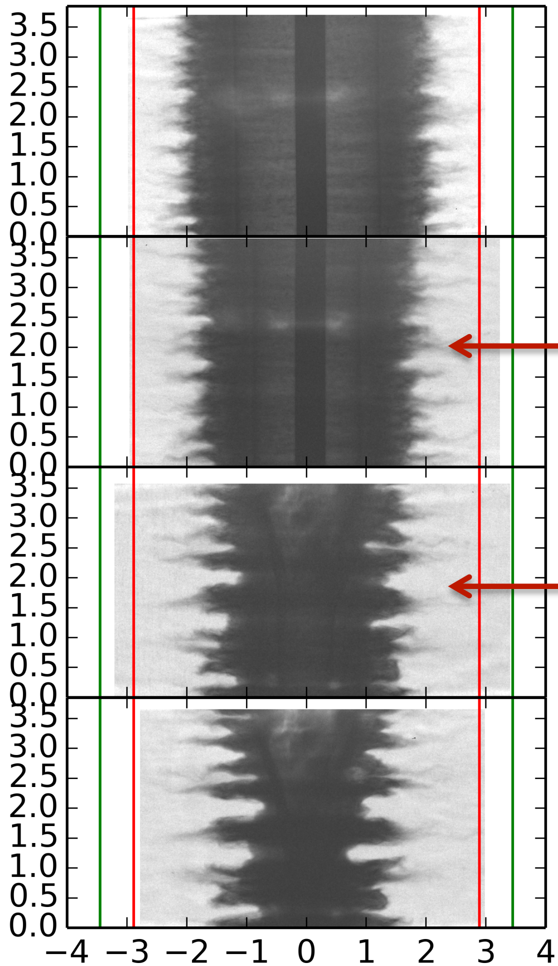
2D Hydra simulations also predicted dramatic differences in instability growth in imploding liners



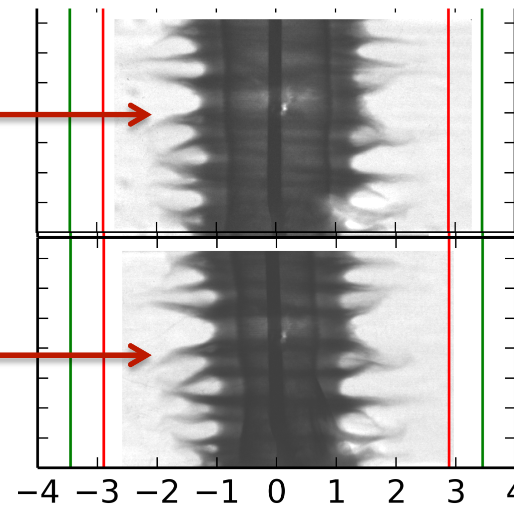
Recent experiments confirmed that coated aluminum imploding liners exhibit a dramatic reduction in instability growth



Coated Be liners also show instability improvement at similar times compared to uncoated Be liners, but not as dramatic as the Aluminum data



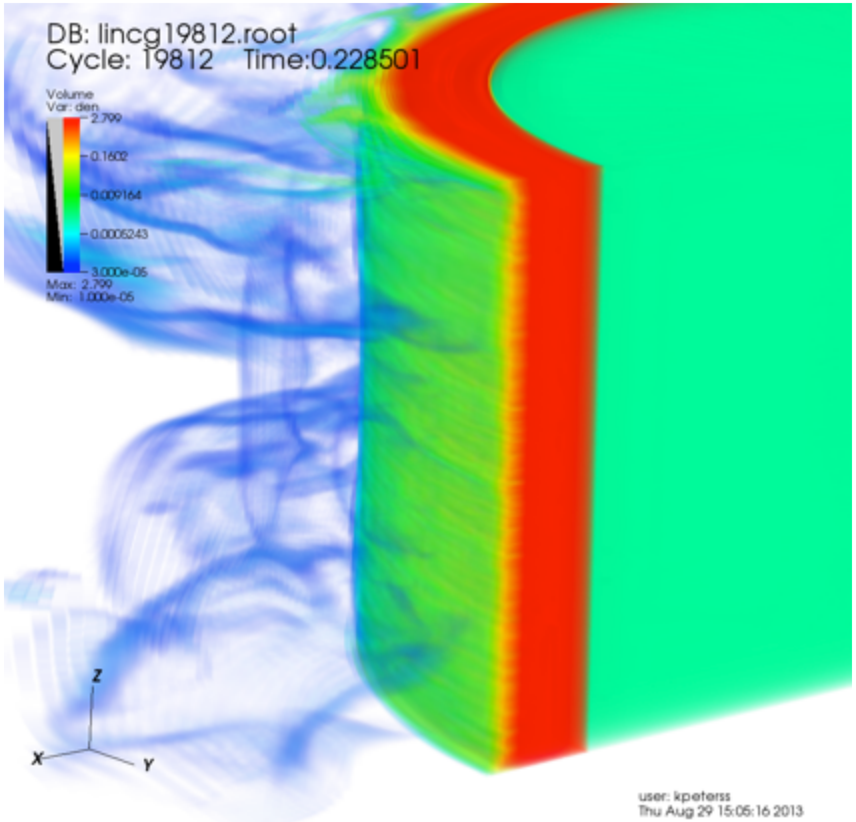
R.D. McBride et al.,
POP **20**, 056309 (2013)



Be coated liner

- Less correlation
- Smaller amplitude MRT
- Smaller wavelength MRT
- More stable inner surface
- A more quantitative analysis is underway

We are beginning to simulate ETI effects on MagLIF liners in 3D



Do electrothermal instabilities explain why large initial density perturbations have been historically been required to simulate Z-pinch liners and wire arrays?

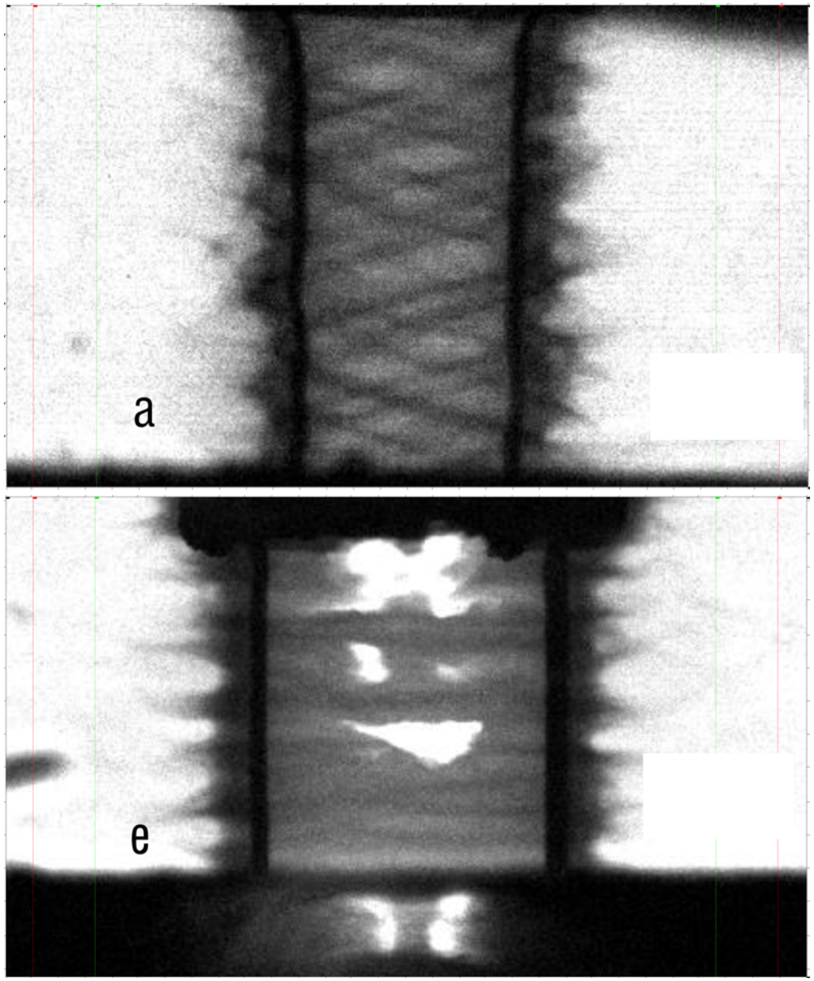
- Challenging zoning requirements
  - Large Eulerian cells (>1 μm) are not sufficient to resolve ETI
- Bz field introduces boundary condition complexities
- Link different spatial scales
  - High resolution surface ETI simulations
  - Lower resolution liner dynamics simulations

HELICAL INSTABILITIES

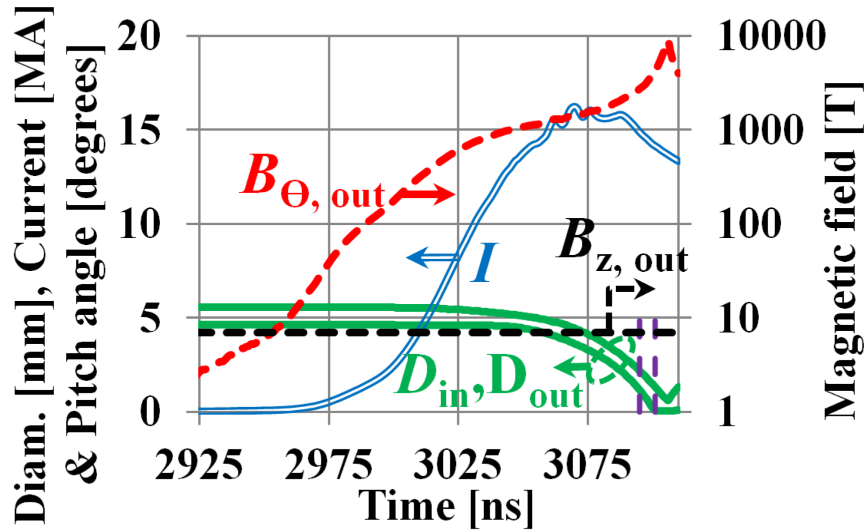
What is the physical mechanism behind the helical instability seen in magnetized liner implosions? Does it help mitigate liner instability growth?

Sandia National Laboratories

Axially magnetized implosion



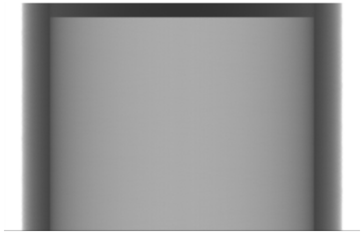
Same target, un-magnetized

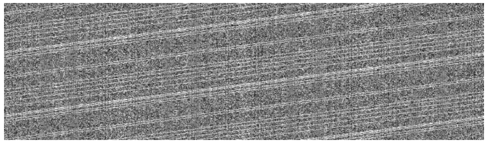


- Observed pitch angle inconsistent with expected Bθ vs. Bz at radiograph time
- Idea 1: Angle is "frozen in" at early time when two are comparable—simulations suggest a helical perturbation early on persists (Awe)
- Idea 2: Bz permeates entire load region, could be swept up and compressed making Bz large at this time (Ryutov)

Qualitative agreement in 3D simulations can be achieved by seeded an initial helical structure

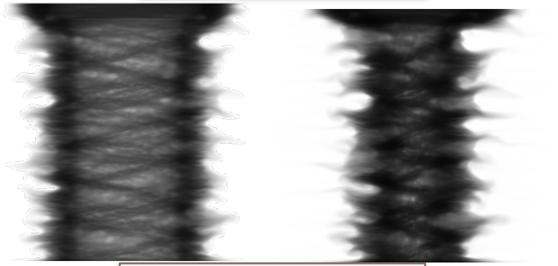
Initial Conditions



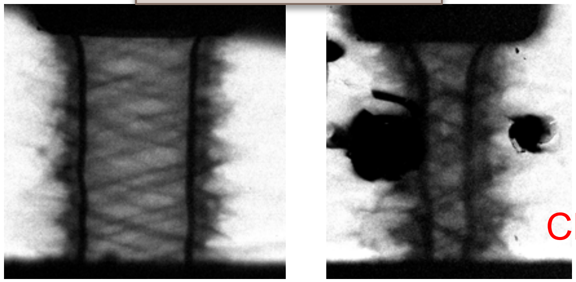


7.2 degree helix etched onto liner surface at 20 micron grid resolution

GORGON[1]



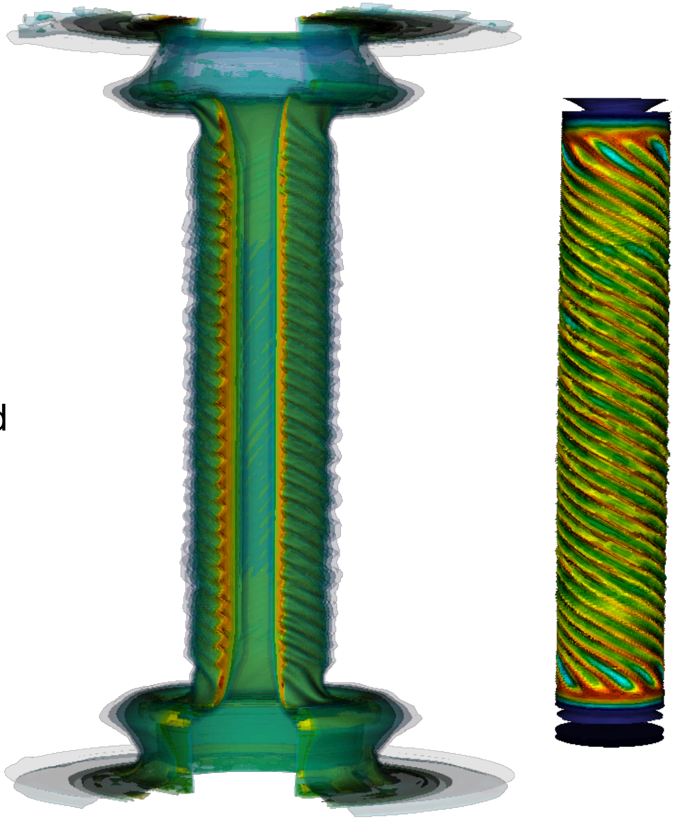
Z 2480 Data



CR 6.4

- Helical structure persists throughout implosion and grows enough to be retained in radiographs during implosion

HYDRA[2]



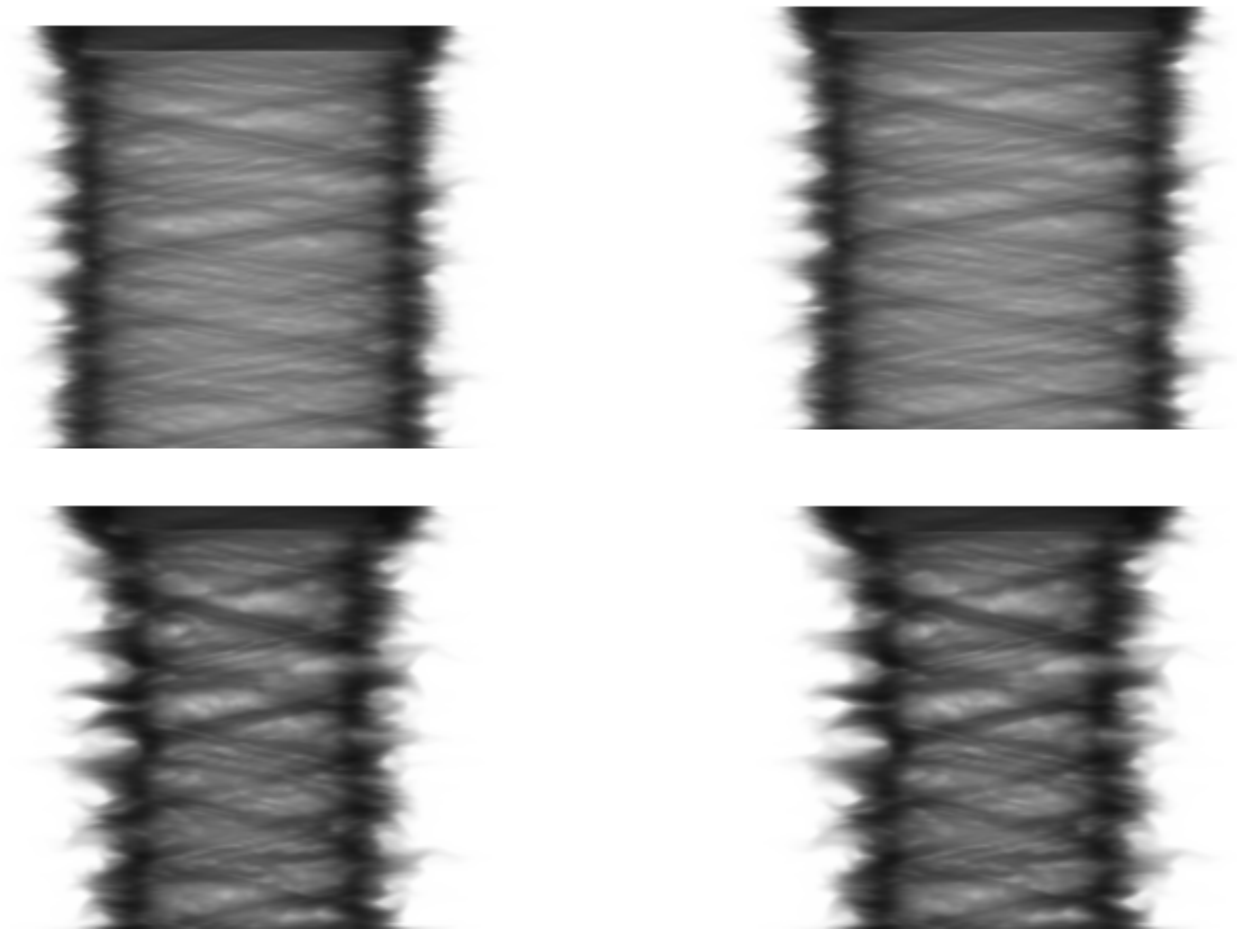
[1] Christopher Jennings Simulation, [2] Adam Sefkow Simulation

If initially seeded by a helical structure, an applied B_z is not required for the perturbation to persist

No B_z field | $B_{z,0}$ =10 T

3082 ns

3090 ns

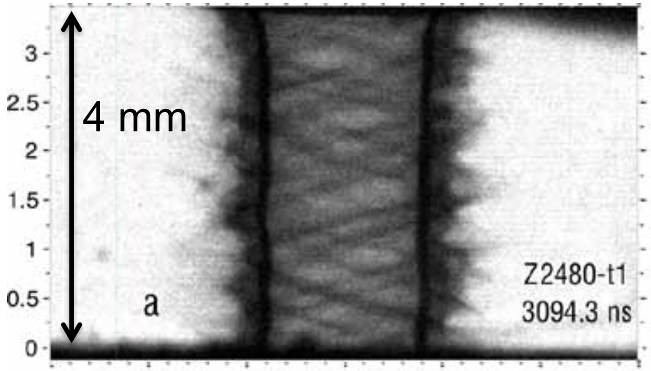


This hypothesis will soon be tested on Z

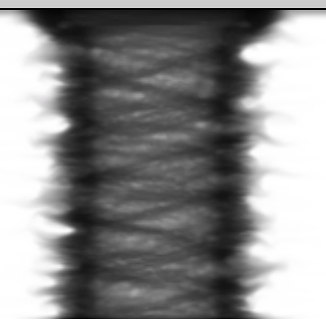
Without a pre-imposed helical structure, modeling helical instability development in magnetized liner implosions has been difficult

Roosevelt I Experiment with applied Bz field

CR =2.7

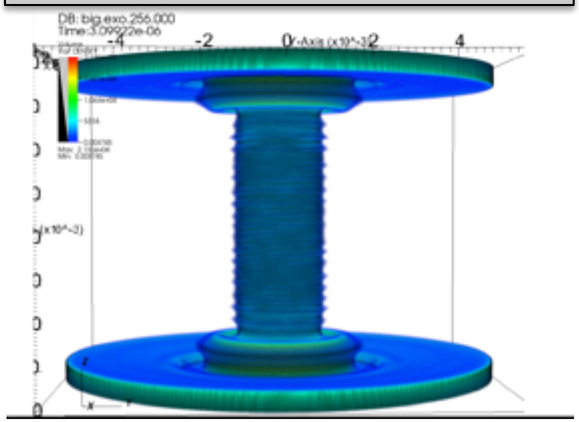


GORGON Simulation[1] with pre-imposed helical perturbations



- Multiple simulation codes/models
  - HYDRA, GORGON, ALEGRA
- Perturbation Seed?
- Missing physics? ETI?

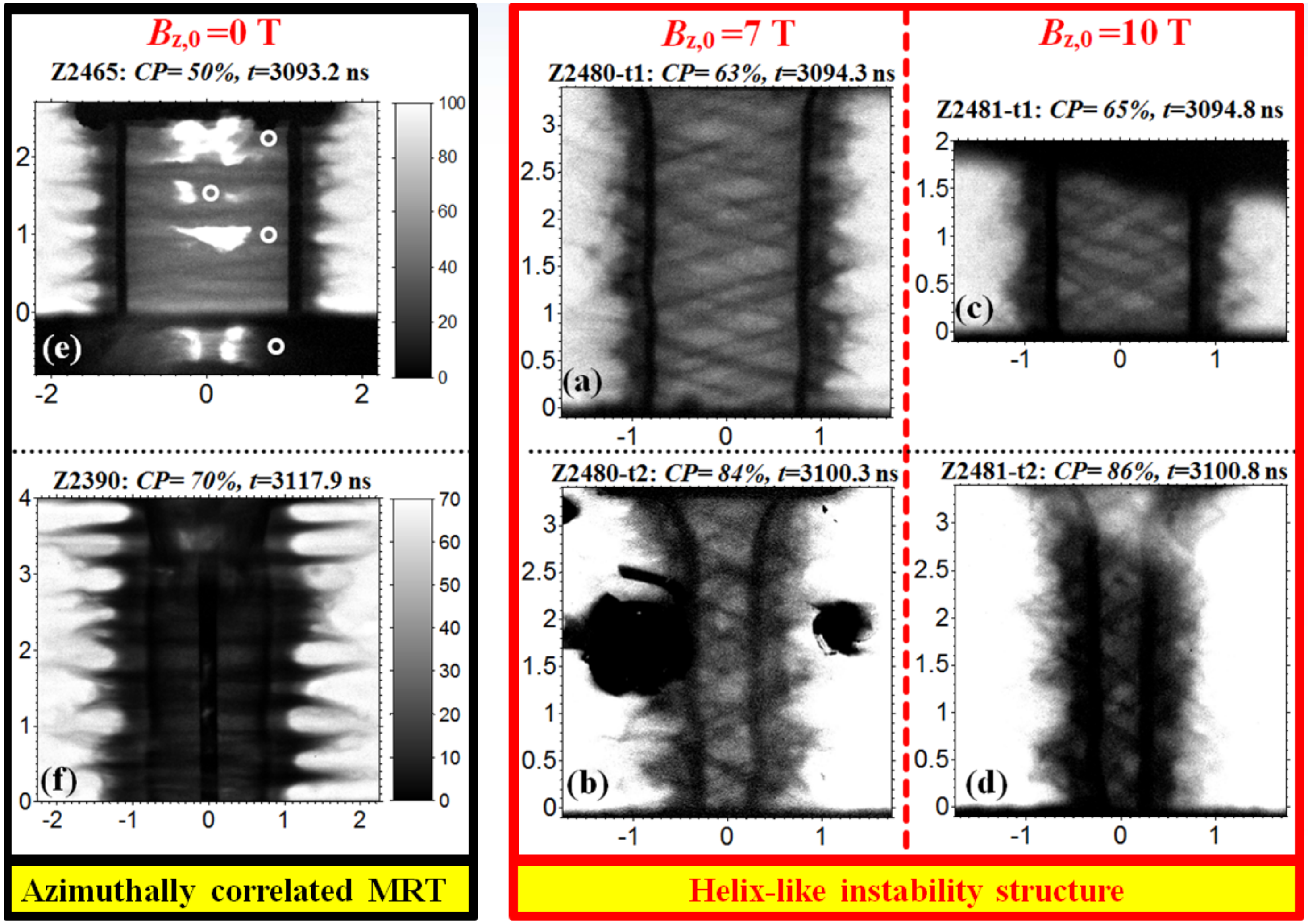
ALEGRA Simulation[2] with nominal surface roughness



See **O.Tu_C12** for further discussion and theory

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

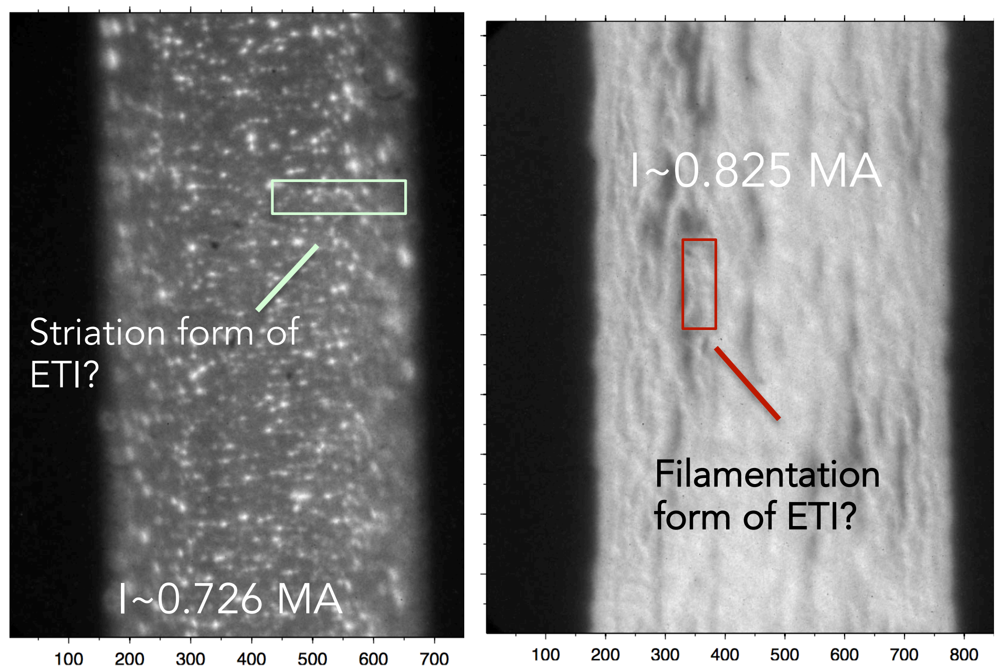
The connection (if any) between ETI and observed helical instabilities on pre-magnetized liners is not yet understood



We are working on understanding the role of surface roughness and volume-distributed impurities in seeding ETI, through current redistribution, in 3D

- Experiments at UNR are providing new insights on early time surface initiation and early stages of 3D ETI development
- Data provides enormous constraints on simulations
- Theoretical work is underway to explain the observed structures

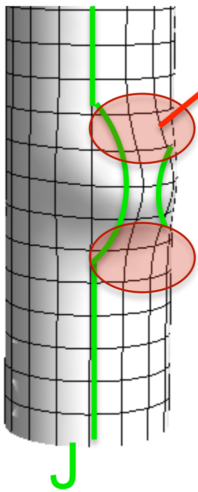
Visible emission of R~0.5 mm Al rod, $B_z=0$



Data taken at Zebra generator, UNR
Courtesy T.J. Awe

We are currently studying how a collection of bumps/ pits, as well as volume-distributed impurities, redistribute current and generate ETI

Bump, $B_z=0$



Current “bunches up” here

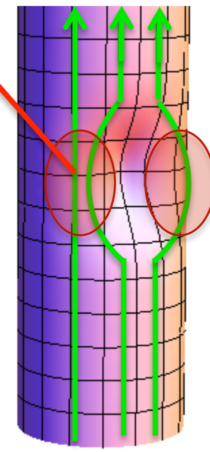
➔ $\delta(\eta j^2)>0$

➔ $\delta T>0$

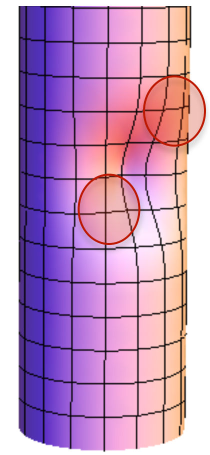
➔ $\delta\eta>0$ (η rises with T)

➔ $\delta(\eta j^2)>0$

i.e. this region is ETI unstable, and is seeded by current redistribution



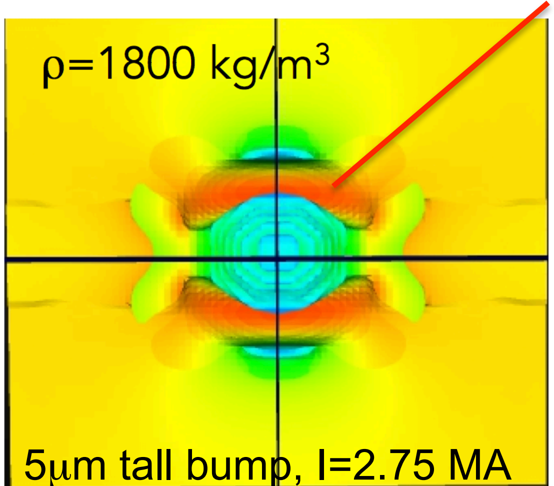
Pit, $B_z=0$

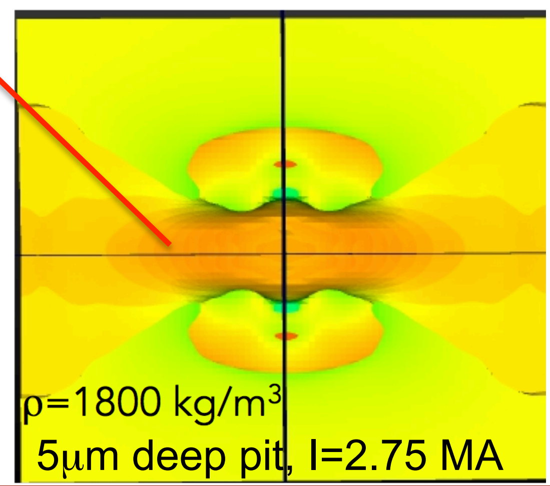


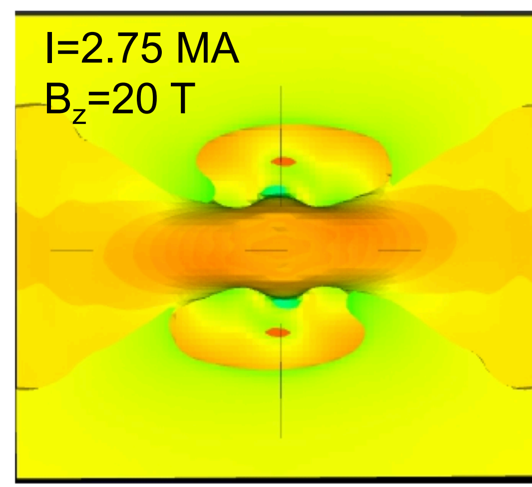
Pit, $B_z=B_\theta$

ETI-unstable regions have exploded
(2 adjacent pits can “correlate”)

3D MHD simulation (ALEGRA) confirms this intuition.

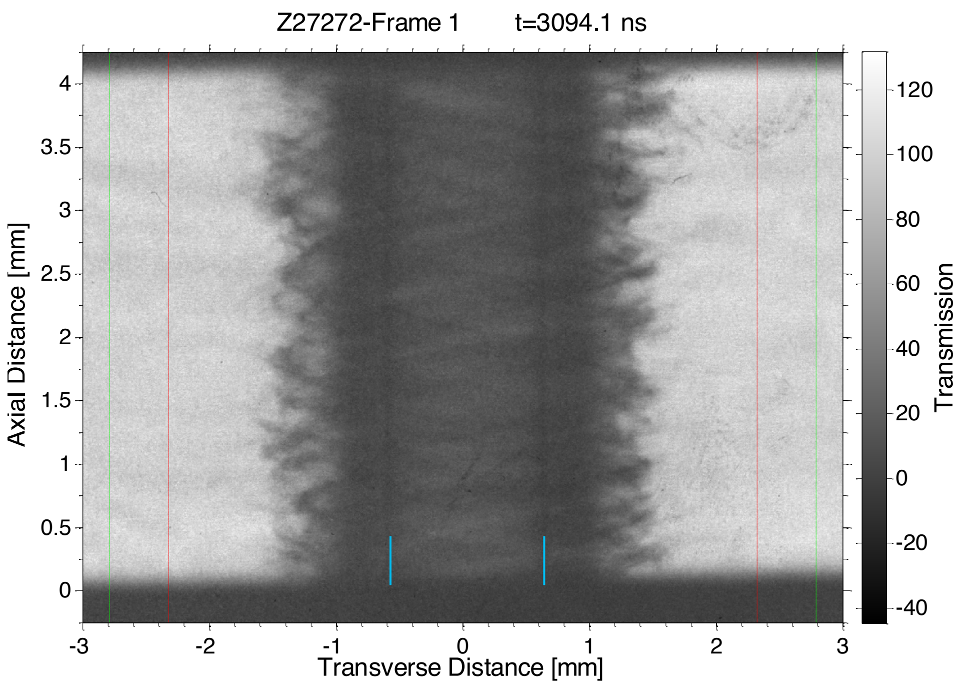


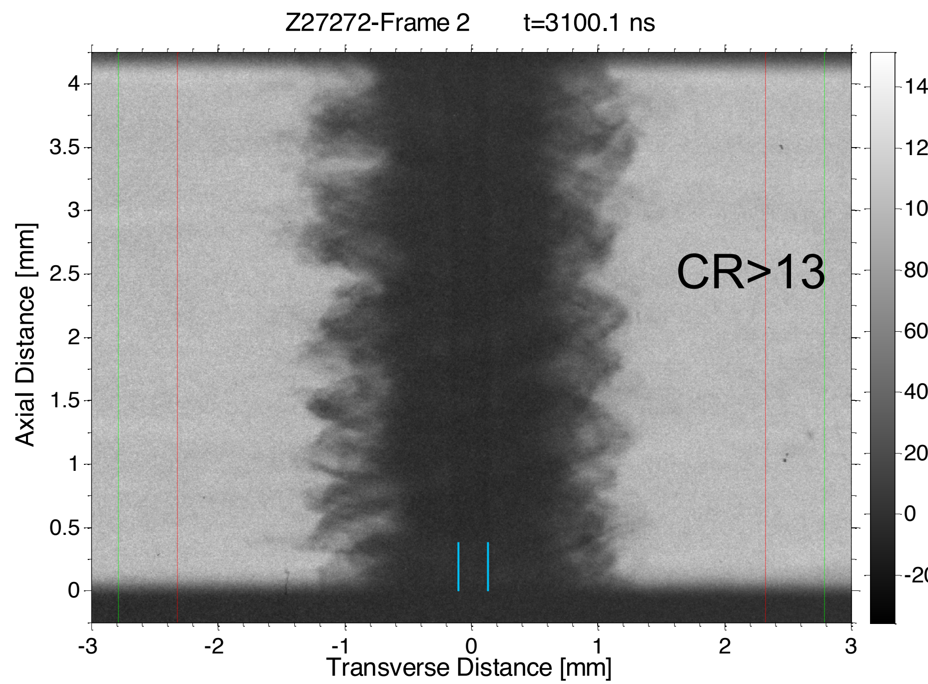




We have recently examined ETI mitigation with thick dielectric coatings on magnetized liners

- Helical structure still present with dielectric coating added
- Radiographs demonstrate remarkable implosion uniformity





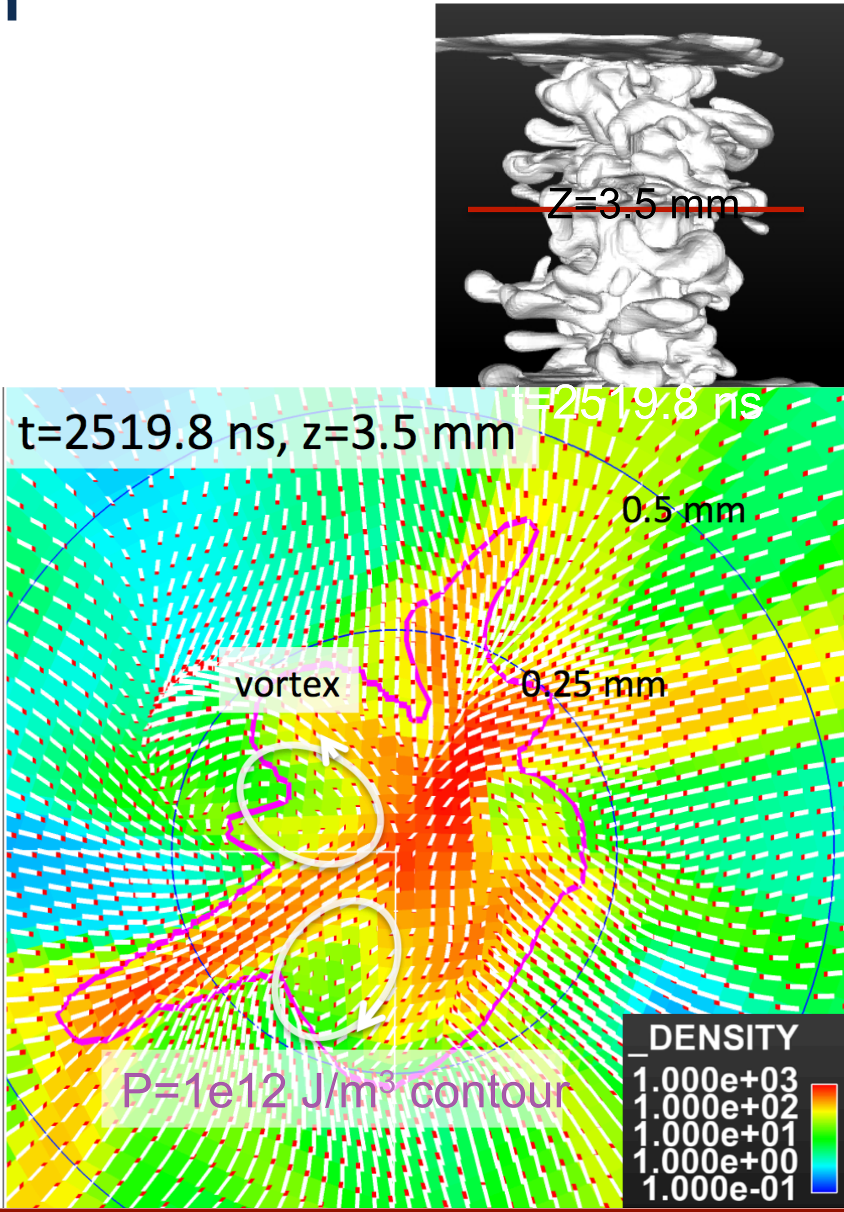
Alternative Explainations

STAGNATION AND FUEL ASSEMBLY

We are exploring fundamental processes that limit compression and thermalization

Sandia National Laboratories

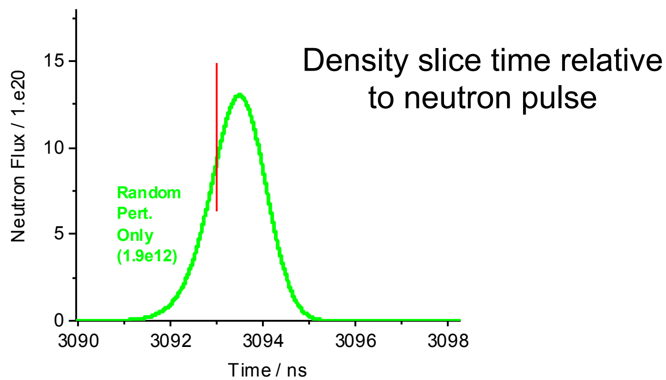
- Non-uniform compression or fuel heating could excite a fully 3D velocity field
- Spatial non-uniformities can lead to partially stagnated plasma with significant residual kinetic energy
- Significant v_θ (see vortices), which can generate centrifugal force



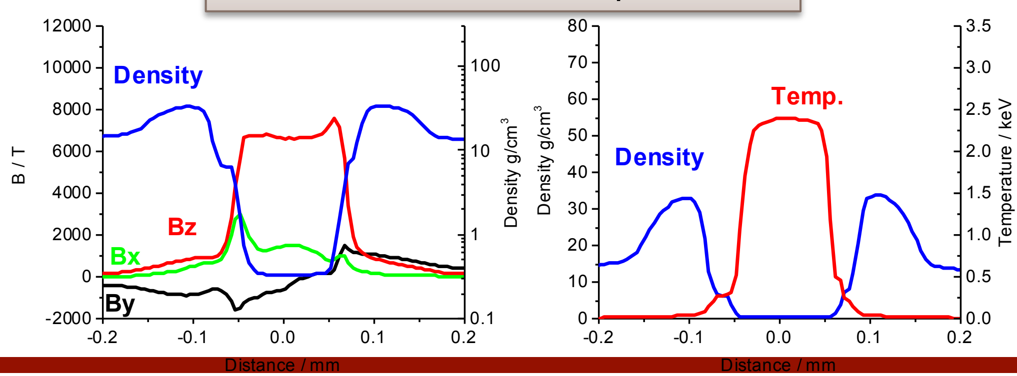
E.P. Yu, A.L. Velikovich, and Y. Maron, Physics of Plasmas **21**, 082703 (2014).

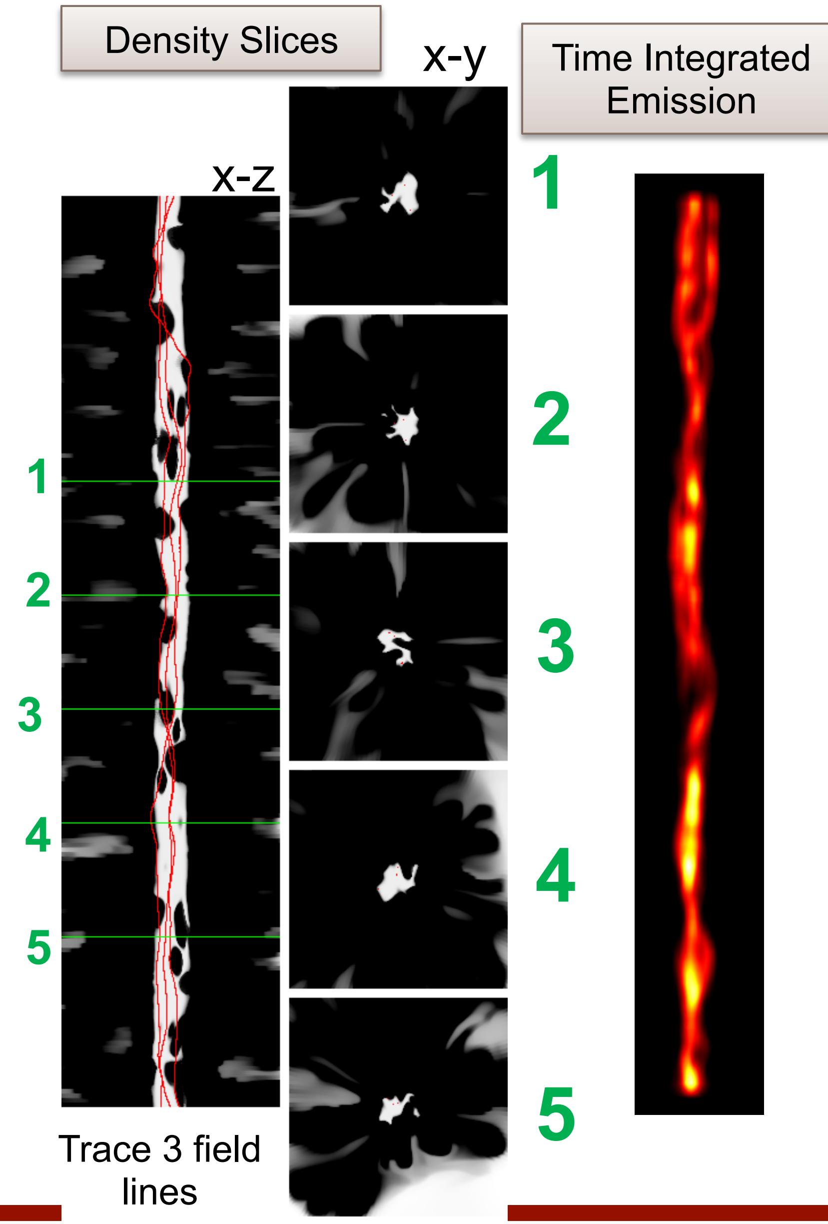
Uncorrelated perturbations can feed through to fuel at stagnation

- Finite azimuthal structure very detrimental to final compression
- Variations in emission data is a result of both opacity and emission variations



Field structure and Temperatures

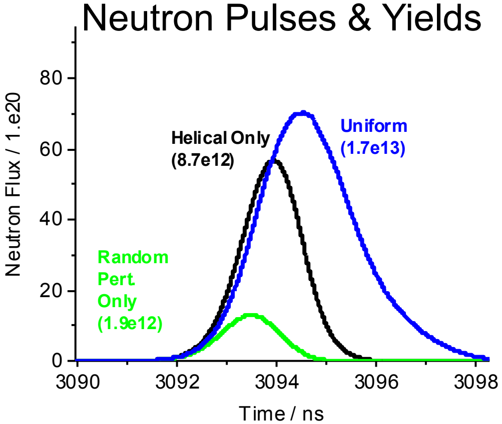




Can we measure and model deceleration instability growth in liner implosions?

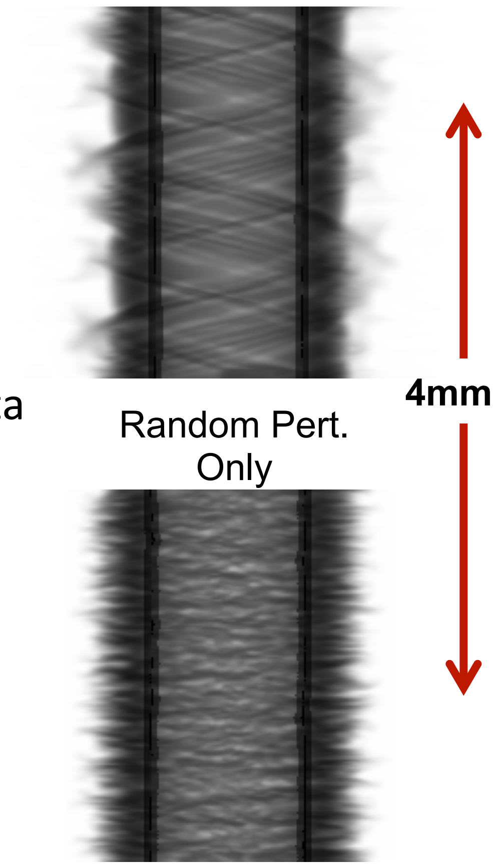
- Difficult to image instability growth with sufficient time and spatial resolution and photon energy during stagnation phase
- We are currently looking at designing validation experiments to image deceleration instability growth at larger radii as well as draw inferences from related data

Neutron Pulses & Yields



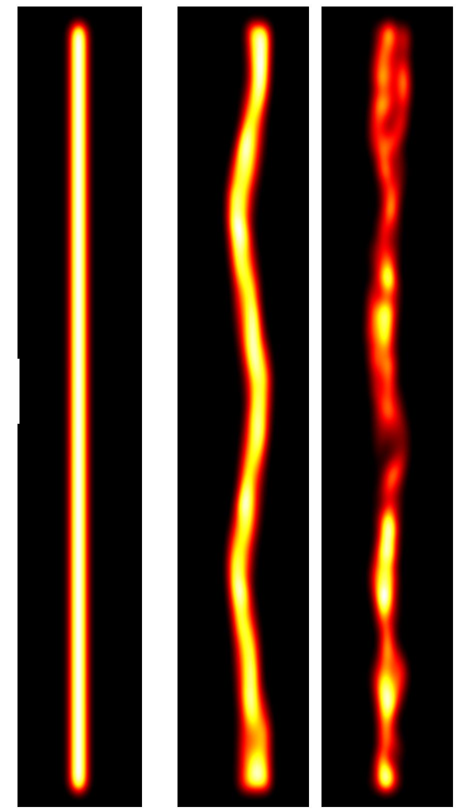
Helical Only

Random Pert. Only



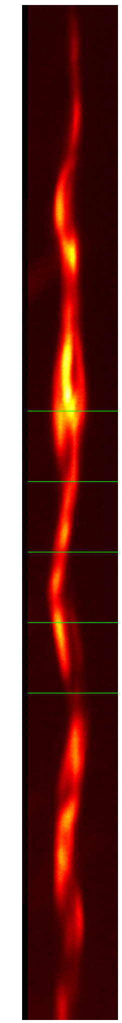
Disruptions in azimuthal correlation limits compression and confinement

Uniform | Helical Only | Random Pert. Only



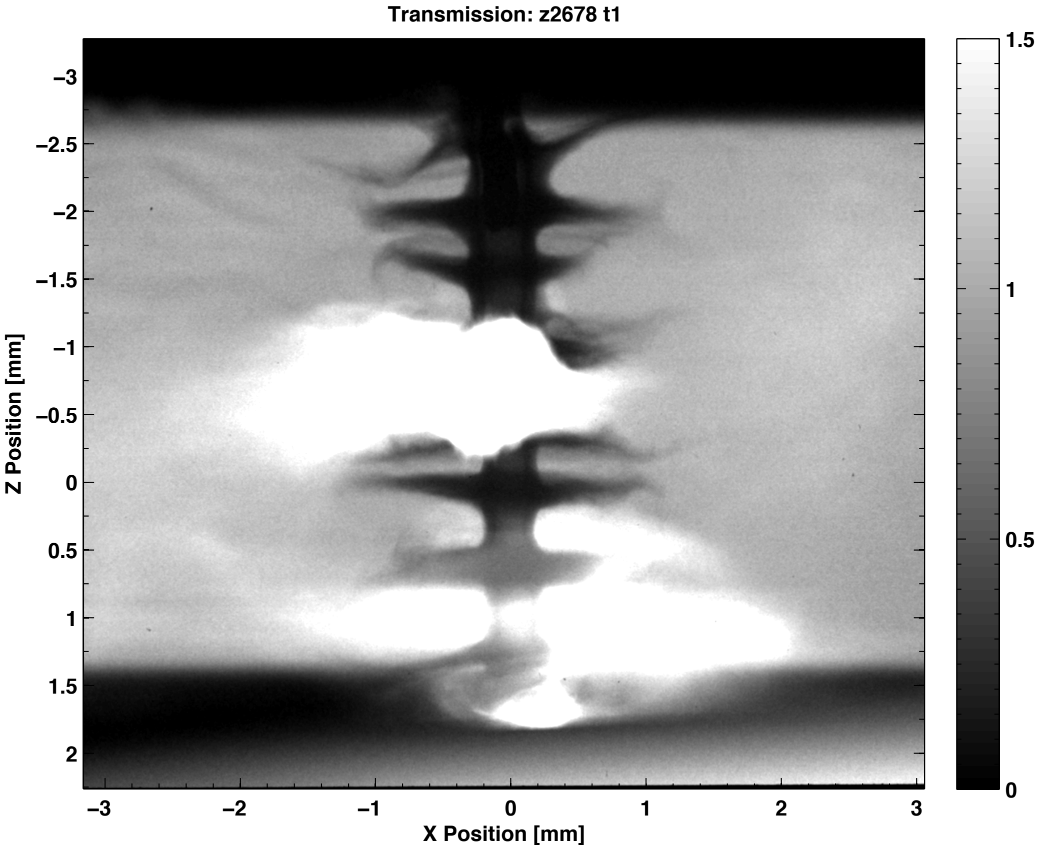
Time integrated synthetic crystal imaging

Data

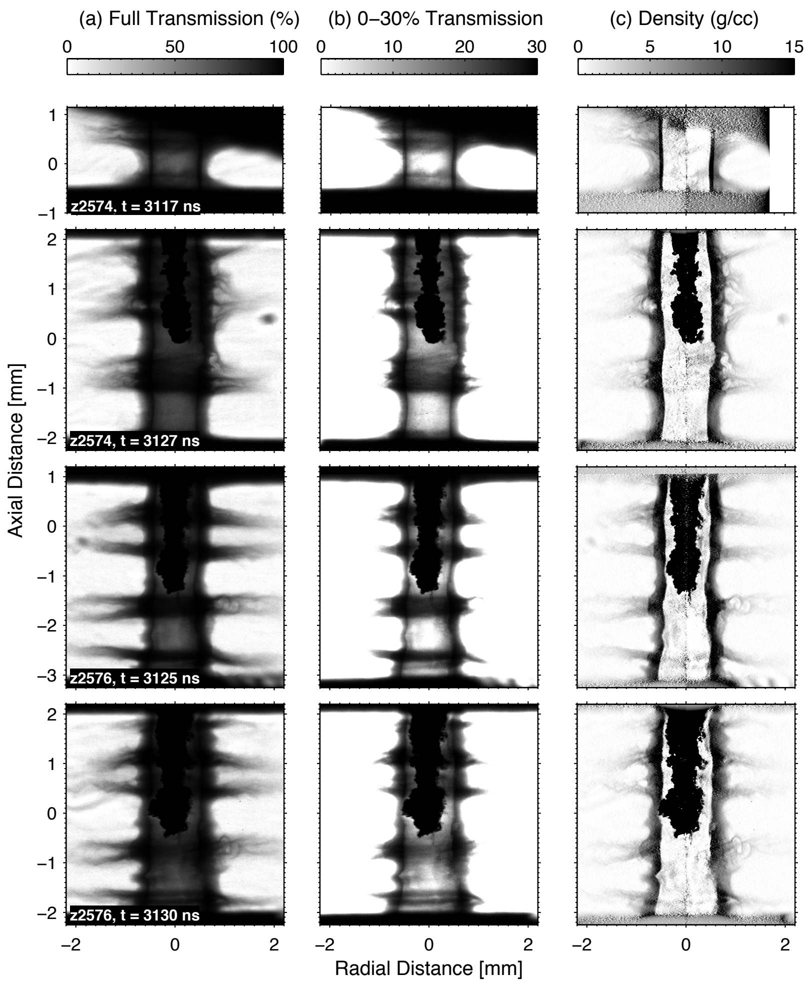


We are also studying our predictive capability to symmetrically compress fuel in high convergence implosions

Sandia National Laboratories



Cylindrical DD EOS Experiment

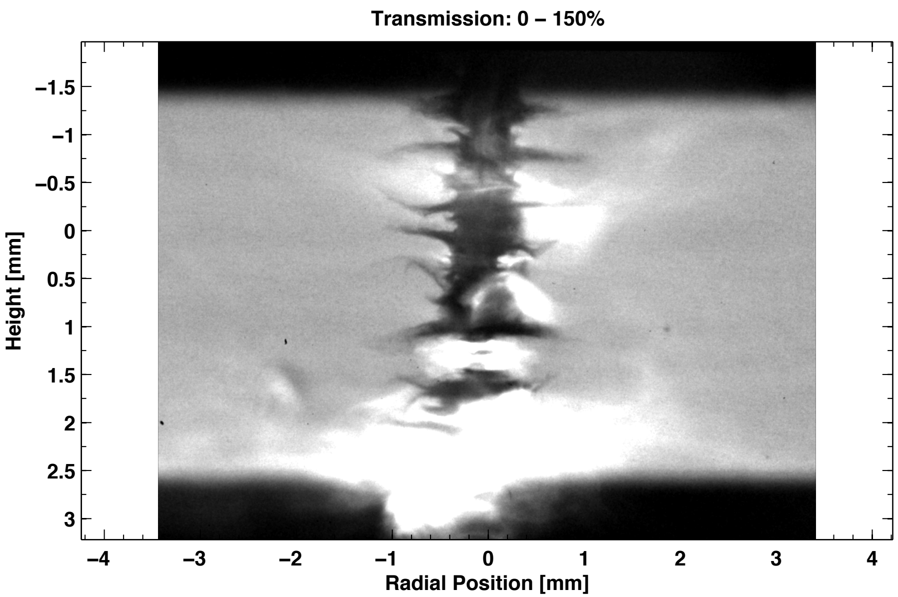


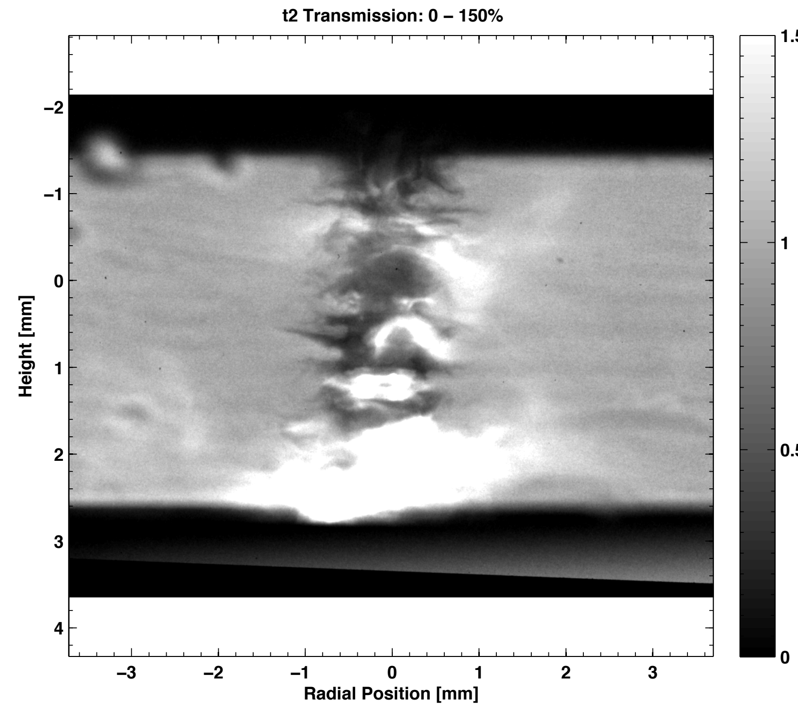
$$\langle \rho \rangle = 60\ \mathrm{g/cm^3} \qquad CR \approx 19$$

$$r_{stag} = 110 - 170\ \mu\mathrm{m} \qquad \langle \rho R \rangle = 0.5\ \mathrm{g/cm^2}$$

Courtesy Patrick Knapp & Matthew Martin

Despite a rather azimuthally symmetric assembly of fuel at stagnation, images captured post-bounce, reveal a 3D disassembly





- Post stagnation radiography does NOT show a cylindrical shell bouncing off of stagnated fuel
- Disassembly shows a high degree of 3D structure

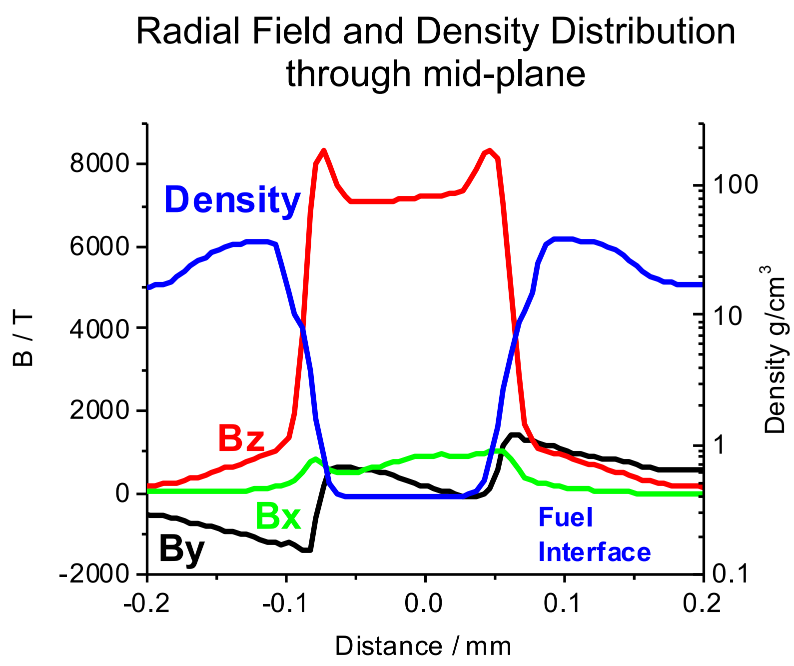
Conclusions

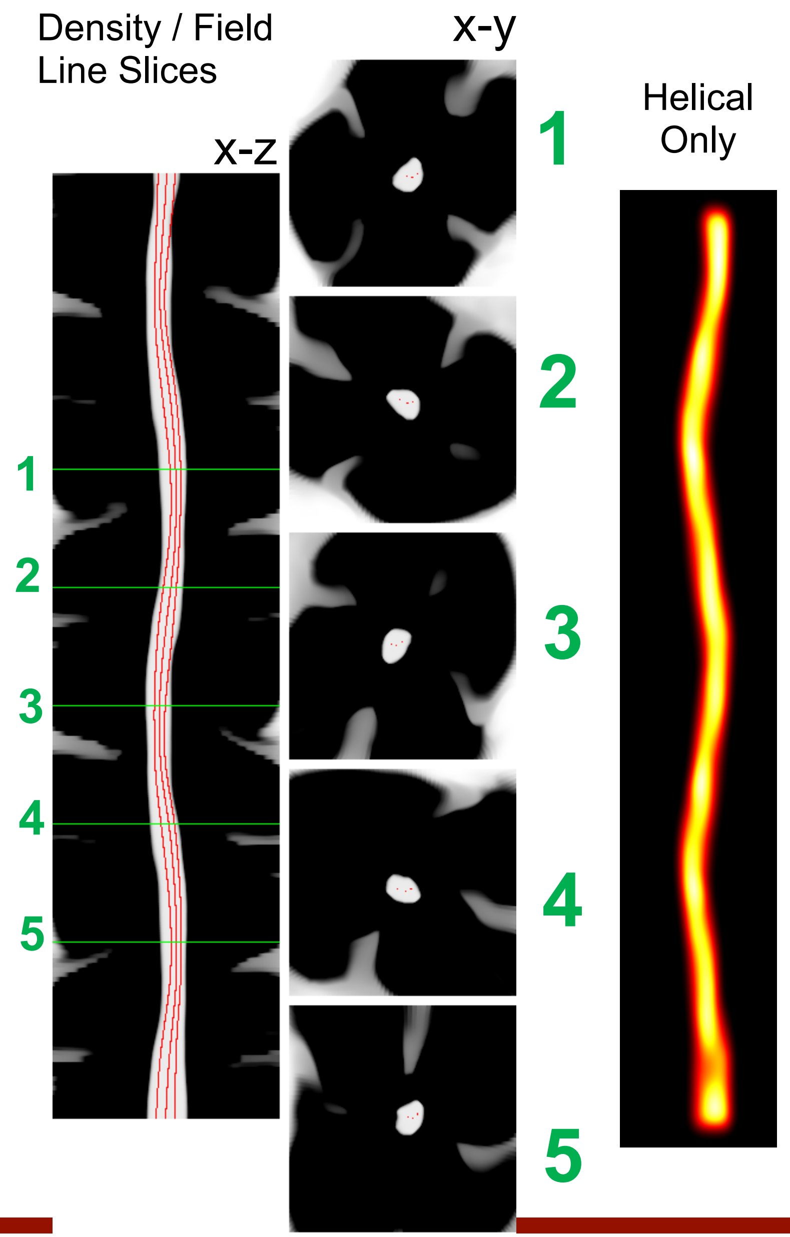
- Our ultimate goal is to be able to develop and validate a predictive capability for the growth and scaling of the most important instabilities for MDI approaches
- We are making significant progress in our understanding and control of instabilities in magnetized liner implosions
  - Controlled single and multimode MRT validation experiments
  - Influence of surface roughness and correlation on instability growth
  - Electrothermal instabilities
  - Helical structures
- Understanding and mitigation of electrothermal instabilities appears promising, many open up design space for MDI targets
- We have demonstrated the capability to predict and control instability growth in high convergence implosions
- We are continuing to develop 3D simulation capabilities to better understand fuel compression, thermalization, and effect of magnetization on instability development

Backups

Field Deformed to Follow Helical Contour of Imploding Surface

10 T initial applied Bz
3093ns (half way up neutron pulse rise)





Additional field components are being introduced by shape of imploding surface

2D Hydra simulations also predicted dramatic differences in instability growth in imploding liners

Log ρ

Be AR=12 liner