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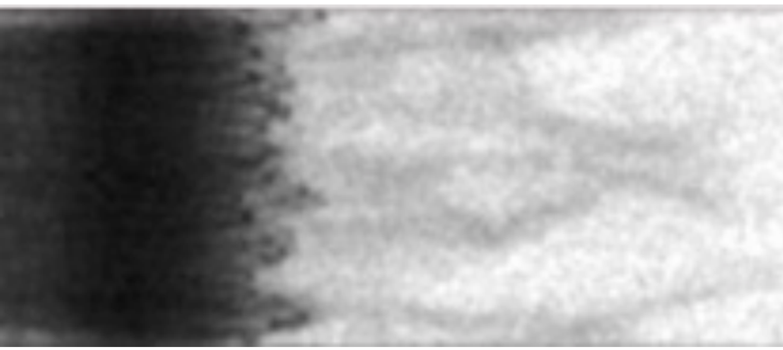

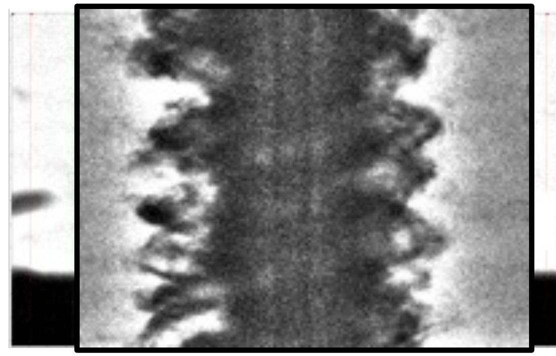

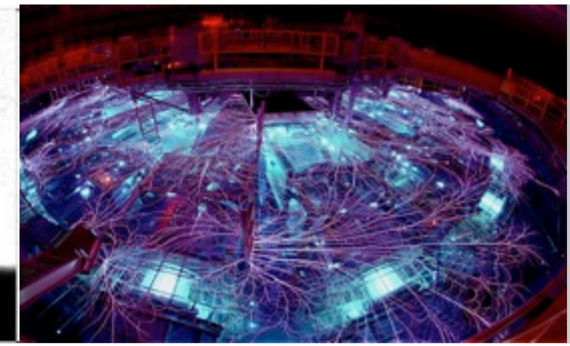

Modeling, measuring, and mitigating instability growth in liner implosions on Z

Kyle Peterson, Thomas Awe[1], Ryan McBride[1], Dan Sinars[1], Adam Sefkow[1], Edmund Yu[1], Matthew Martin[1], Christopher Jennings[1], Steve Rosenthal[1],Steve Slutz [1], Roger Vesey[1], Kurt Tomlinson[2], Joseph Koning[3]

1) Sandia National Laboratories, USA

2) General Atomics, USA

3) Lawrence Livermore National Laboratory, USA

57th Annual Meeting of the APS Division of Plasma Physics
November 16-20, 2015 • Savannah, Georgia

Pulsed Power Sciences – Harnessing Extreme Environments

U.S. DEPARTMENT OF ENERGY

NNSA – National Nuclear Security Administration

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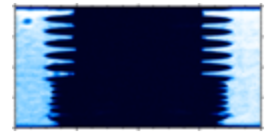
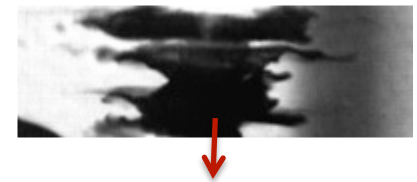
We have made significant progress in advancing our understanding of magnetically driven implosions for fusion

- Based on modeling and simulation, we believe that we can create controlled fuel compression with relatively slow, thick liners.

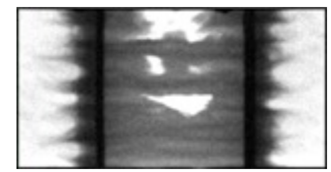
MRT studies



Fast, high AR implosions



Slow, low AR Implosions



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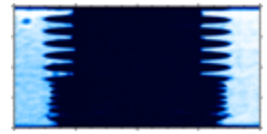
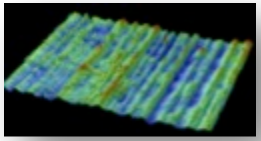
MRT studies



Improved Surfaces



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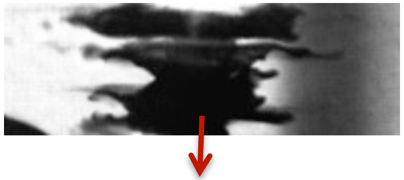

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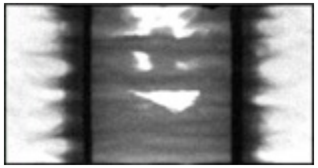

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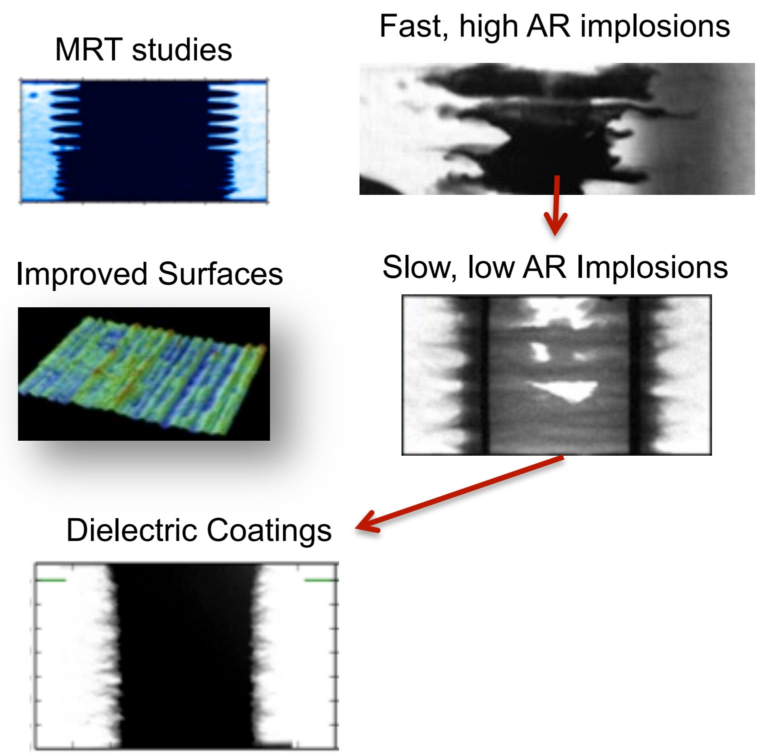

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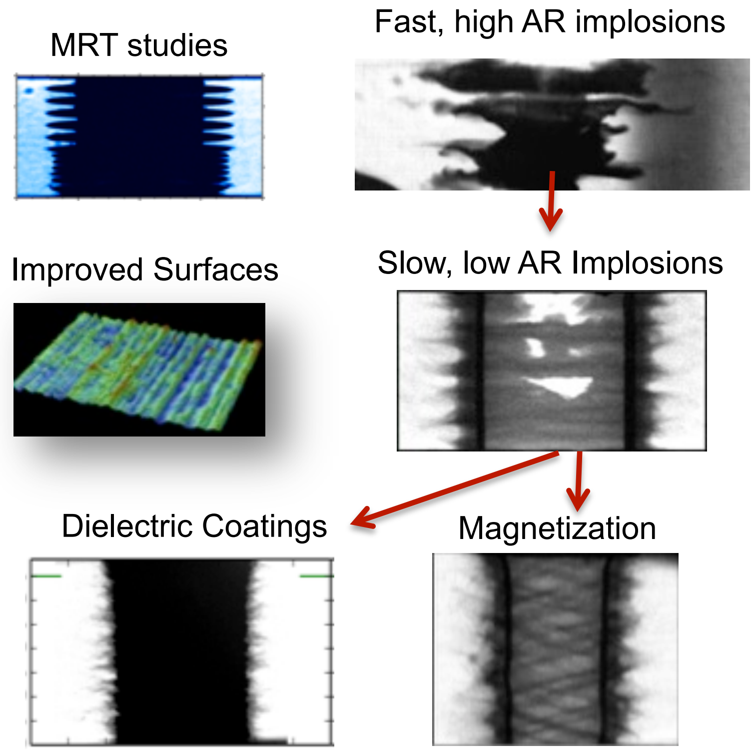

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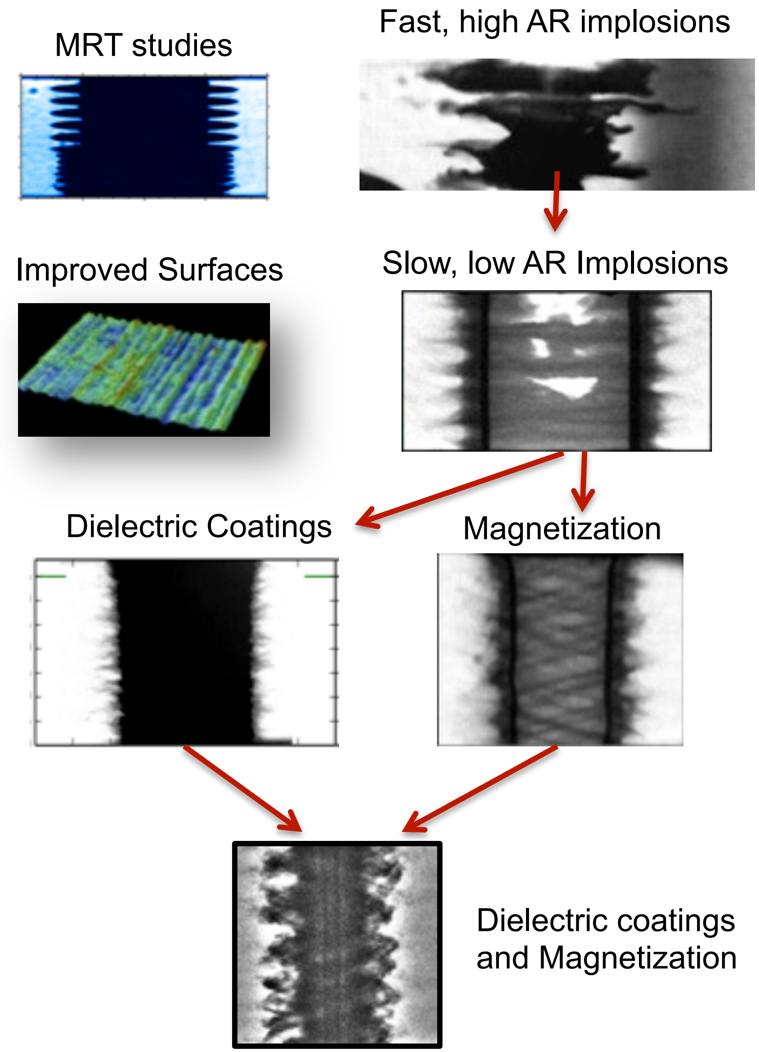
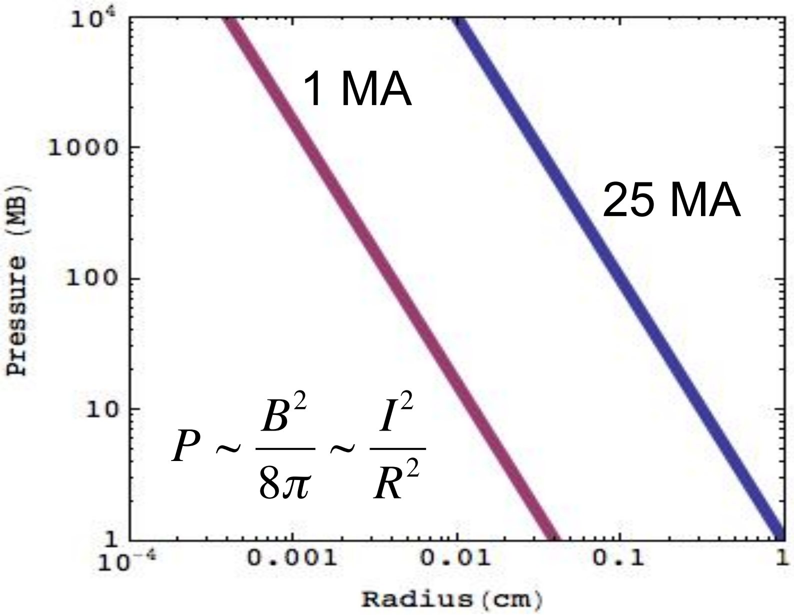
- Thick insulating coatings can be effectively employed to mitigate ETI and significantly reduce instability growth.
- A strong axial magnetic field can affect 3D structure and reduce acceleration instabilities
- Combining dielectric coatings and magnetization has produced remarkably stable implosions
- We believe that these developments may open up the design space for magnetically driven implosions



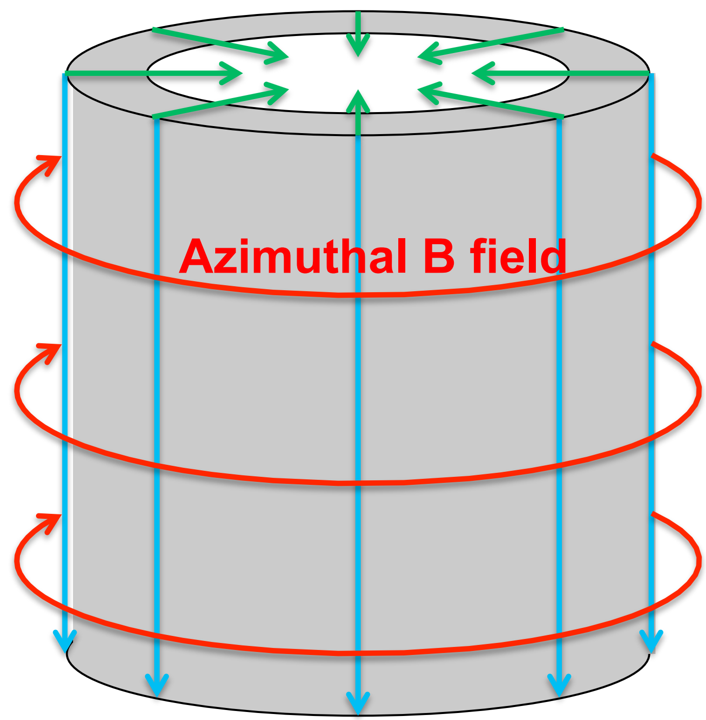
Can magnetic fields be used to directly drive metallic liners for inertial confinement fusion?

A current carrying cylinder is driven more strongly the farther it converges



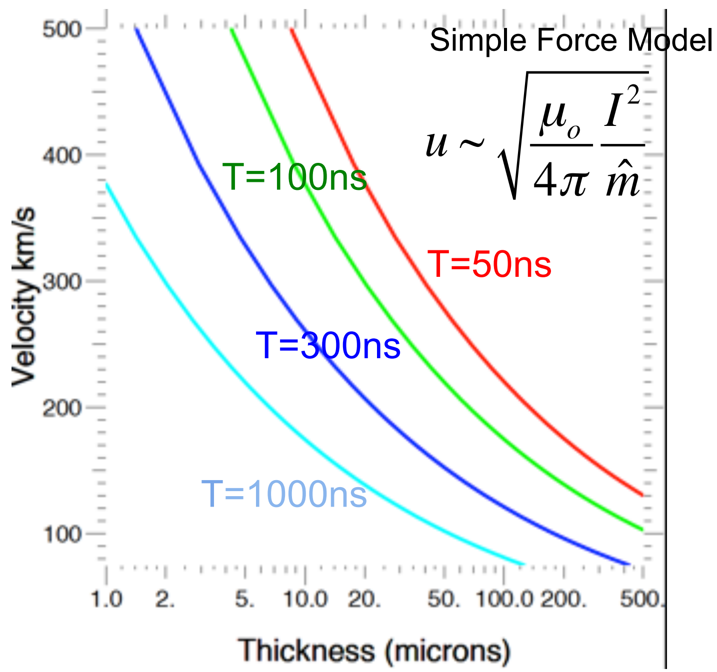
Magnetic-Drive – 140 Mbar at 30 MA and 1 mm radius
Radiation-Drive (Sphere) – 140 Mbar at 300eV

What limits the minimum radius of current delivery?

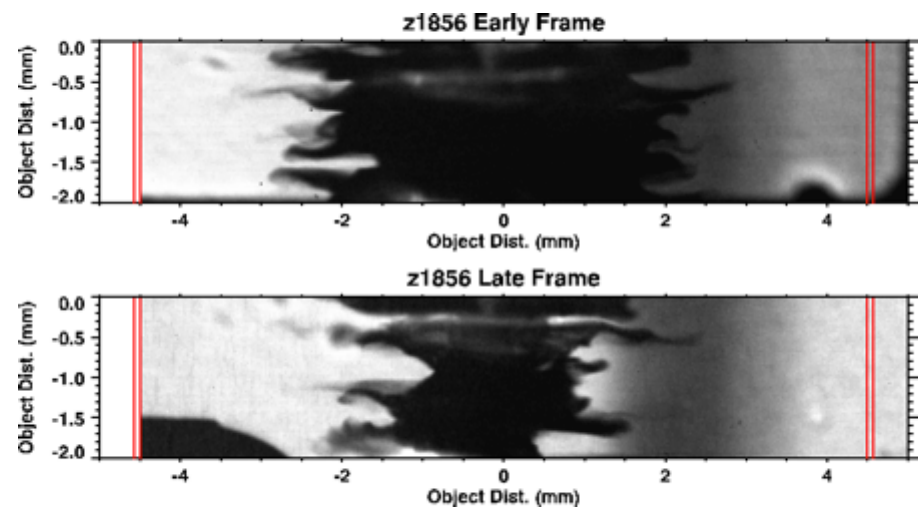


High velocities require relatively high aspect ratio liners (radius/thickness)

Be Liner velocity with constant 25MA



Aluminum liner AR 60,
R=0.45 cm, Δ=75 μm



Black = absorption

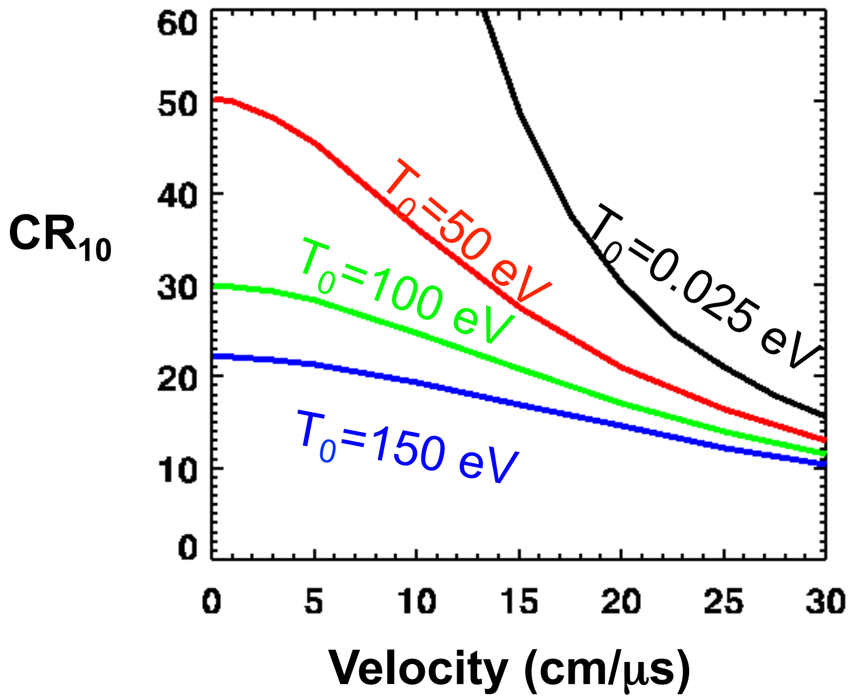
White = transmission

A thickness of ~7 microns is needed for implosion velocity of 400 km/s (I=25 MA, 100 ns)

Instabilities >> thickness, strong instability feedthrough, complete loss of confinement

Heating the fuel prior to compression can lower traditional ICF requirements on velocity and fuel convergence

Simulation with:
- Constant velocity
- No radiation loss
- No conductivity loss

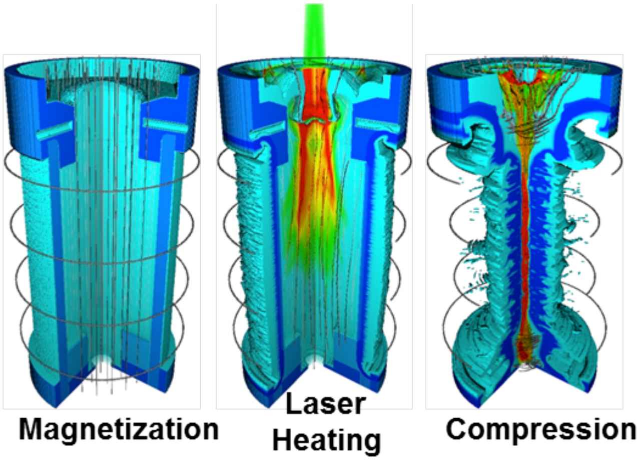


CR_{10} = Fuel Convergence Ratio (R_0/R_f) needed to obtain 10 keV

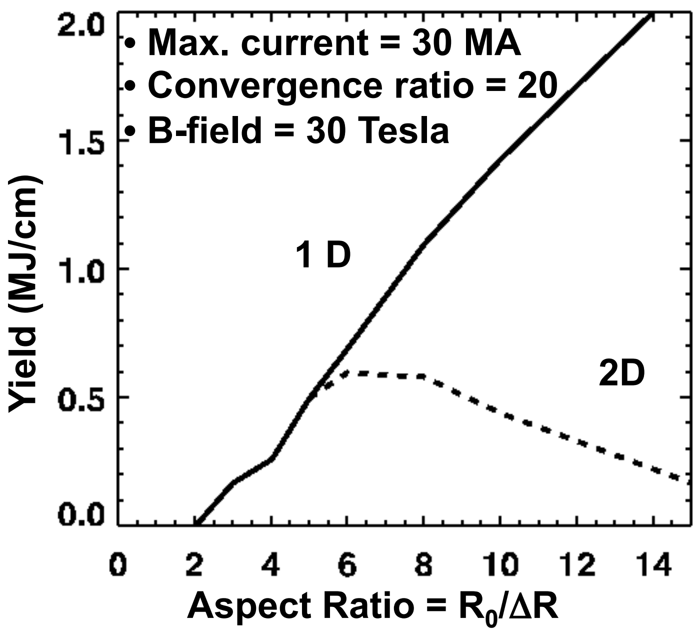
Fusion relevant temperatures can be obtained with slow implosions *if* fuel is preheated and losses can be controlled

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

MagLIF reduces implosion velocity requirements through fuel heating and magnetization which allows the use of thicker, more massive liners to compress the fuel



Hahn CP12.00131
Gomez JO6.00001
Geissel JO6.00002
Jennings JO6.00003
Slutz JO6.00007
McBride GP12.00042
Woodbury GP12.00041



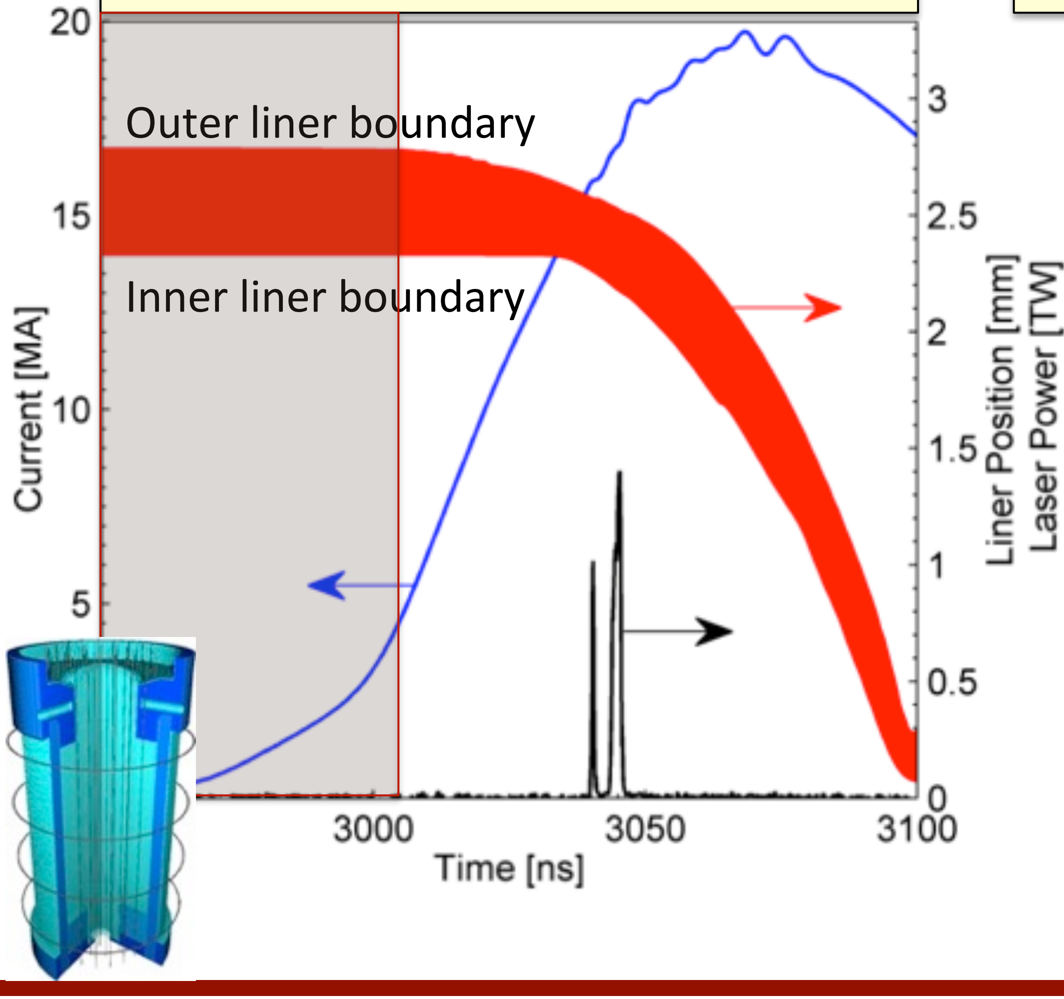
- Axial magnetization of fuel/liner (B_{z0} = 10-30 T)
  - Inhibits thermal conduction losses
- Laser heating of fuel (2-10 kJ)
  - Reduces amount of radial fuel compression needed to reach fusion temperatures (R_0/R_f = 23-35)
- Liner compression of fuel (70-100 km/s, ~100 ns)
  - Thick liners ($R/\Delta R$~6) that are more robust to instabilities

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

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

Instabilities in MagLIF targets can be affected by wide range of physics during the different phases of an implosion

MagLIF target implosion history

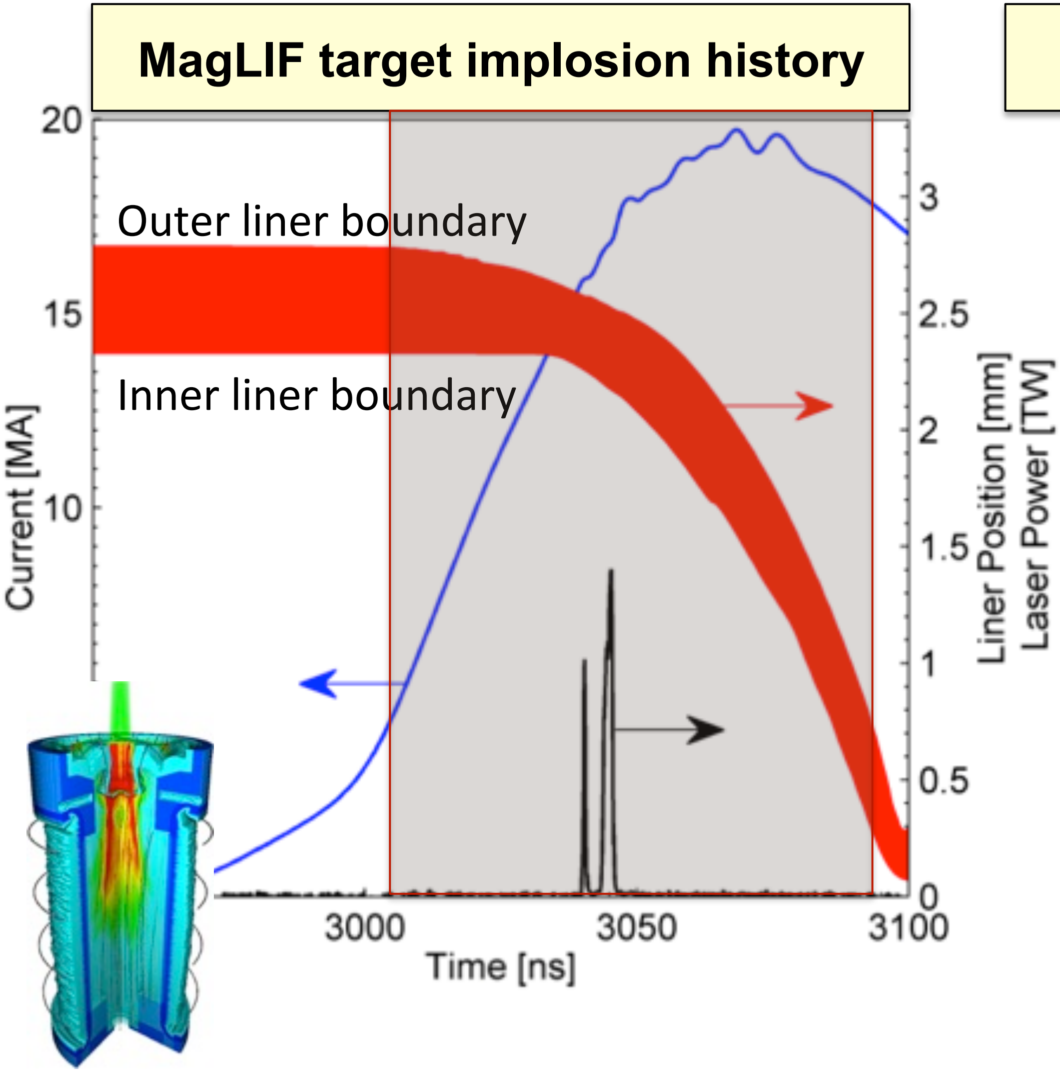


Initiation Phase

- Surface defects /roughness
- Electrode contacts, electrical breakdown
- Material strength, melt
- Magnetization
- Electrothermal instabilities
- Kinetic effects?
- **Skin depth << thickness**

Initial Conditions
- **Be liner**
- **ρ_{DT}~1-4 mg/cc**
- **B_{z0}~10-30 T (~0.1 MG)**

Instabilities in MagLIF targets can be affected by wide range of physics during the different phases of an implosion

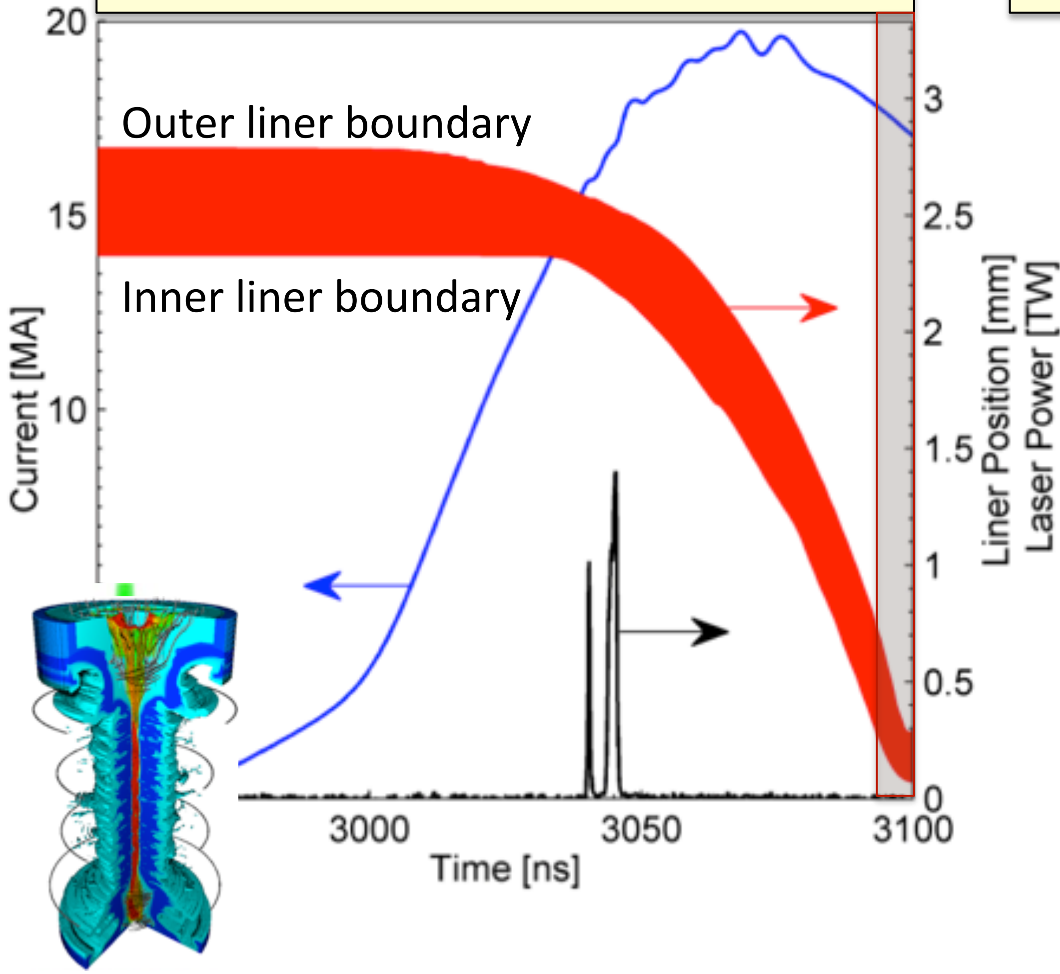


Acceleration Phase

- Magneto Rayleigh-Taylor instabilities
- Electrothermal instabilities
- Laser heating
- **Outer surface begins to implode tens of ns before inner surface moves**
- **Substantial instabilities can exist on outer surface while inner surface is unperturbed**

Instabilities in MagLIF targets can be affected by wide range of physics during the different phases of an implosion

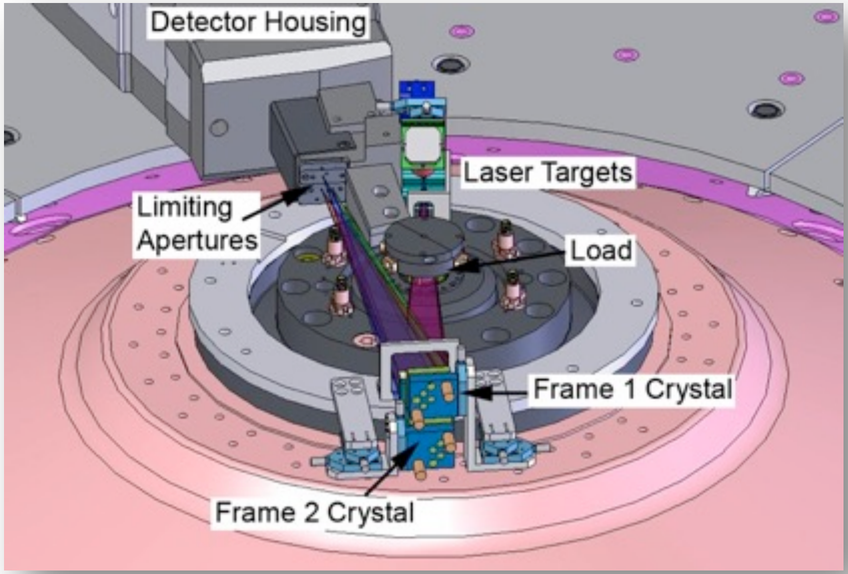
MagLIF target implosion history

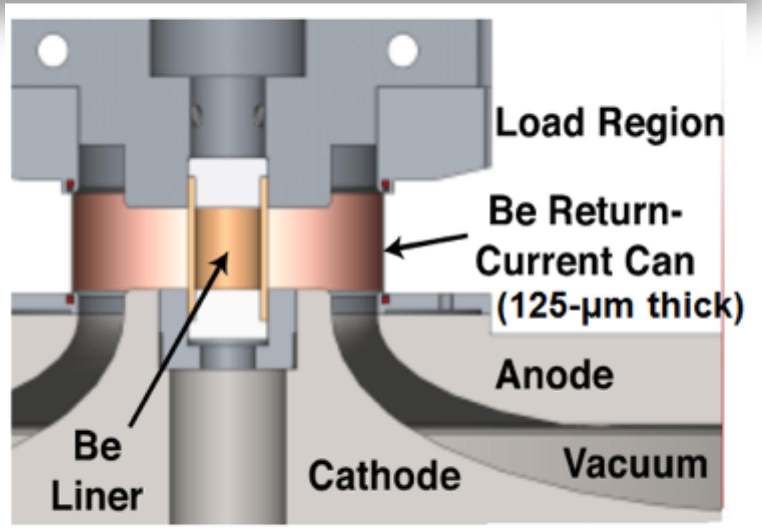


Deceleration Phase

- Rayleigh-Taylor instabilities
- High beta stagnation
- Current delivery
- **Need sufficient areal density at stagnation (absence of feedthrough insufficient)**

Our primary diagnostic for measuring instability growth is a 2-frame monochromatic crystal backlighter





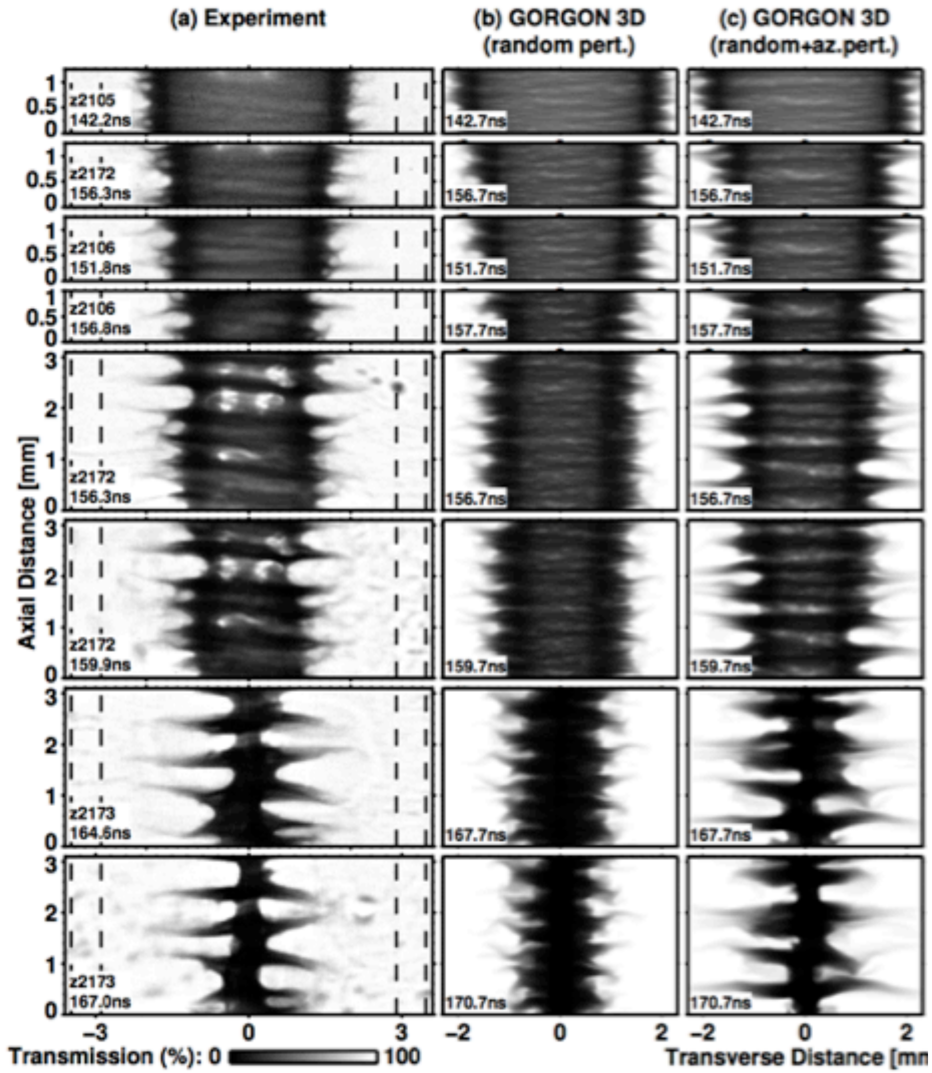
2-frame keV Crystal Imaging

- **Monochromatic (~0.5 eV bandpass)**
- **6.151 keV (Mn)**
- **15 micron resolution**
- **Large Field of View (4 mm x 10 mm)**
- **Debris mitigation**

- **Original concept**
  - S. A. Pikuz *et al.*, RSI (1997)
- **1.865 keV backlighter at NRL**
  - Y. Aglitskiy *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)
- **Inner surface enhanced with thin high-z tracer layer**

Instability growth in relatively slow AR6 implosions can be reasonably modeled in 3D, but questions remain

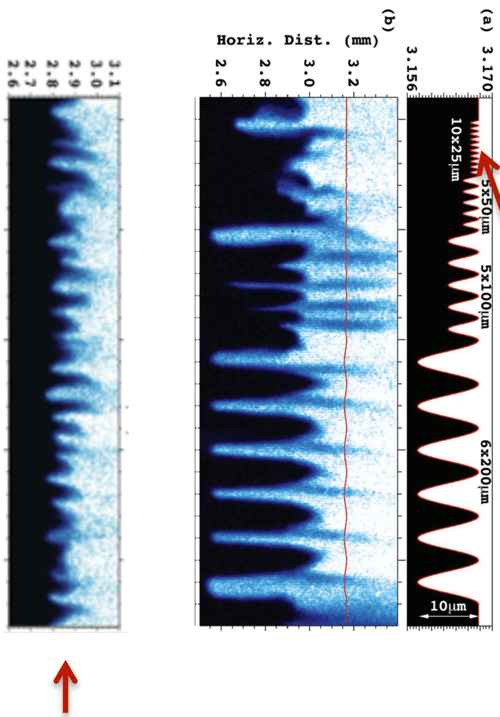
- Why are relatively large initial density perturbations required?
- What is the initial seed for MRT growth?
- Why is a small bias of initial azimuthal correlation required?
- What is the nature of the helical instability structure observed in magnetized targets (MagLIF)?



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.

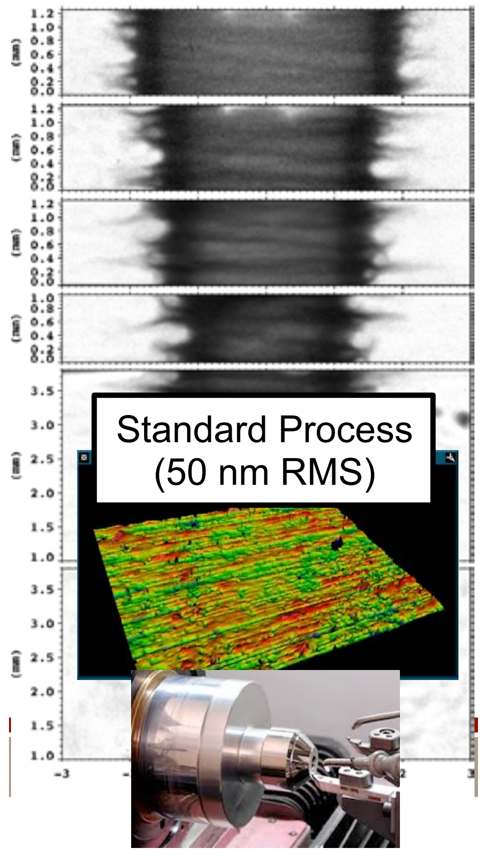
Axially polished liner experiments suggest symmetry is not sensitive to surface characteristics



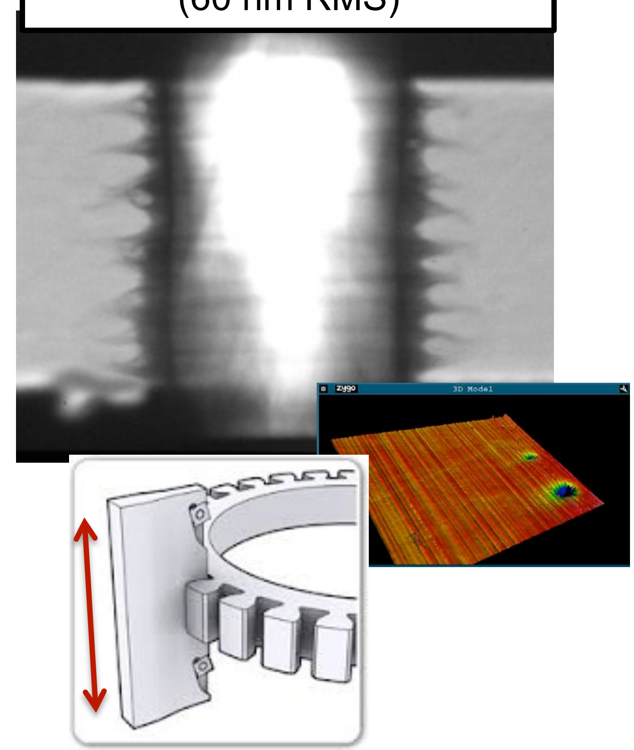
A_o = 60 nm

A_o = 10 μm

McBride PRL data

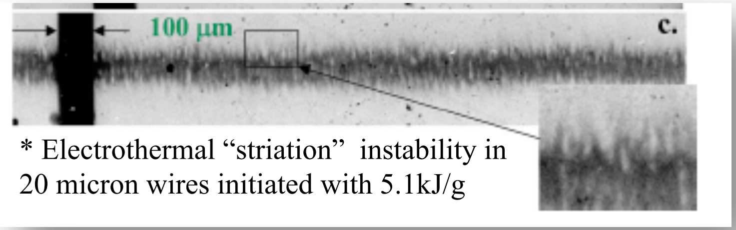


axial machining and polishing
(60 nm RMS)

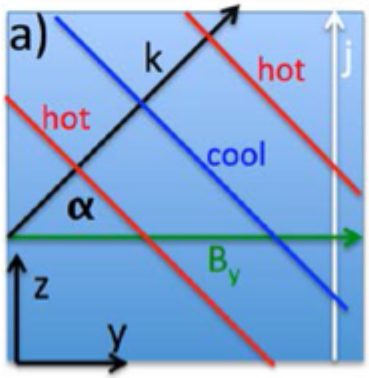


We hypothesize that MRT is seeded by an electro-thermal instability

Evidence in single wire explosions



* A.G. Rousskikh et al., Physics of Plasmas (2008)



thermal conduction, radiation, ohmic heating, pdV

$$\rho c_v \frac{\partial T}{\partial t} = \nabla \cdot (\kappa \nabla T) - q_r - \eta j^2 - p\nabla \cdot \mathrm{v}$$

$$\delta(\eta J^2) = \delta\eta J^2 + 2\eta J \delta J$$

Perturbing the ohmic heating produces the growth rate:

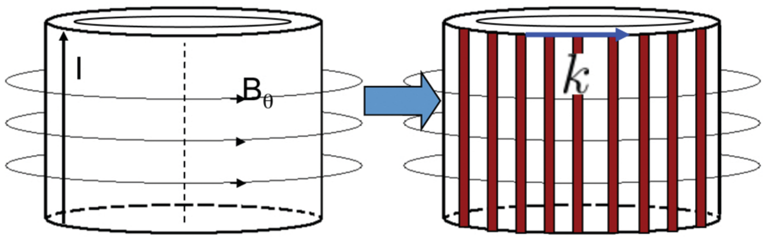
$$\gamma = \frac{j^2 \frac{\partial \eta}{\partial T} - k_z^2 \kappa}{\rho c_v} \left[1 - \frac{2\cos^2\alpha}{1 + \gamma / \gamma_o} \right]$$

What about skin depth << liner thickness and non-uniform current density?

*D. Ryutov *et al.*, Rev. Mod. Phys. **72** (2000), V.I. Oreshkin, Phys. Plasmas **15** (2008)

Electrothermal instabilities occur when material conductivity is dependent on temperature

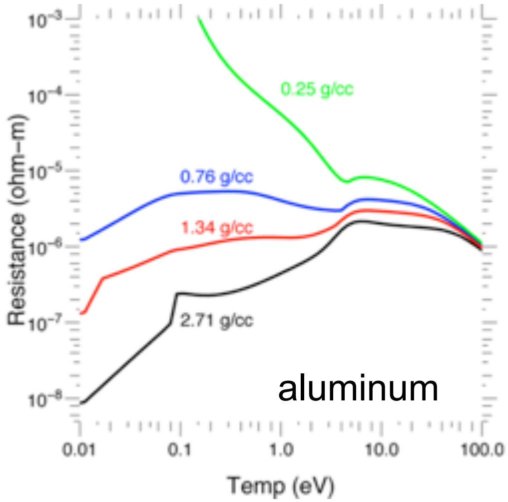
Theory



Filamentations

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

- High temperature (>10 eV) plasmas



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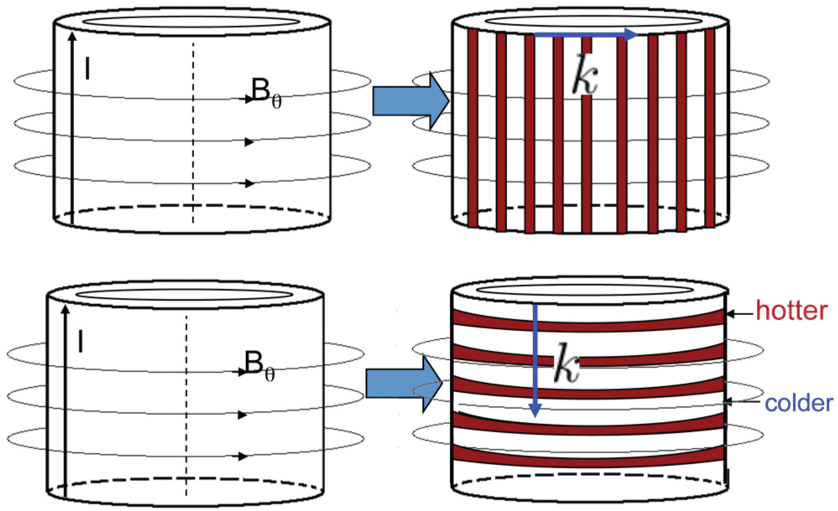
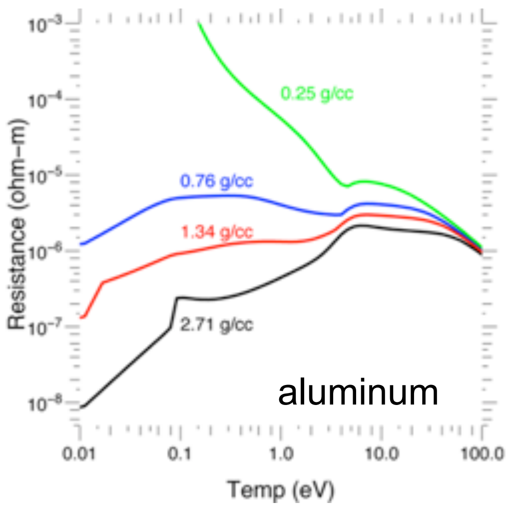


Striations

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

- Also sometimes referred to as thermal *"overheat"* instabilities
- Occurs in condensed states of metals
- ***Focus of remainder of talk***



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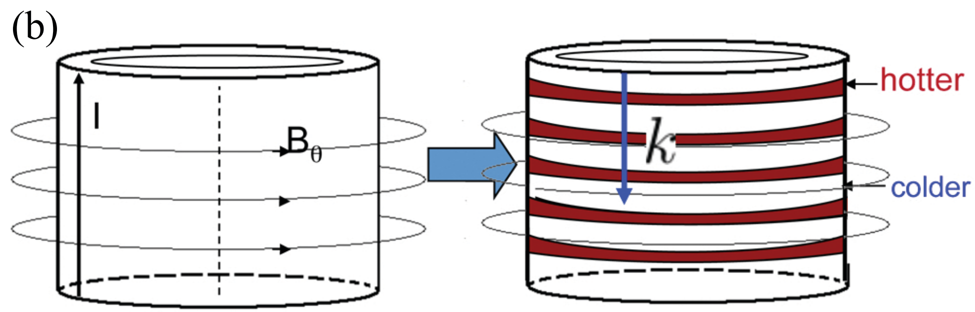
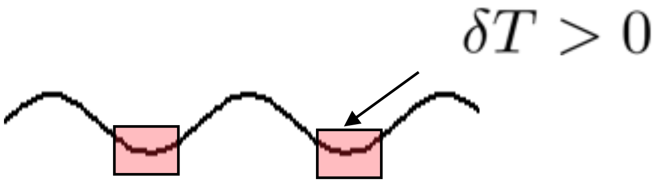
$$\frac{d\eta(T)}{dT} > 0$$





Consider a small temperature perturbation due to localized variations in ohmic heating

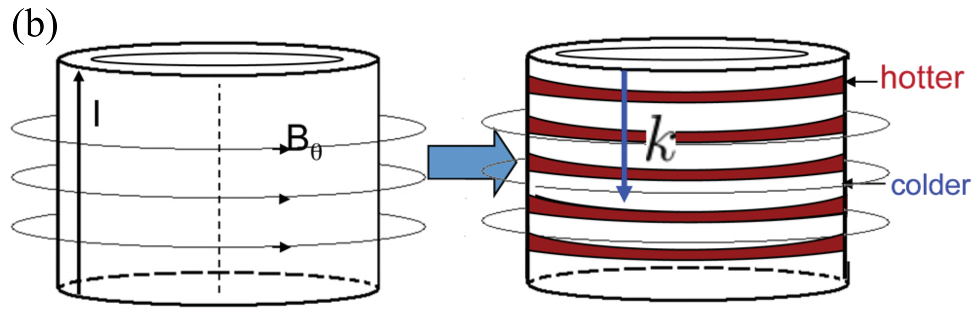
- surface contaminants (variations in η)
- surface roughness (B_θ ~ I/r, in cylinders)
- grain boundaries or inclusions

Electrothermal instabilities occur when material conductivity is dependent on temperature

Theory

Striations

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



$\delta T > 0$

Consider a small temperature perturbation due to localized variations in ohmic heating

- surface contaminants (variations in η)
- surface roughness (B_θ ~ I/r, in cylinders)
- grain boundaries or inclusions

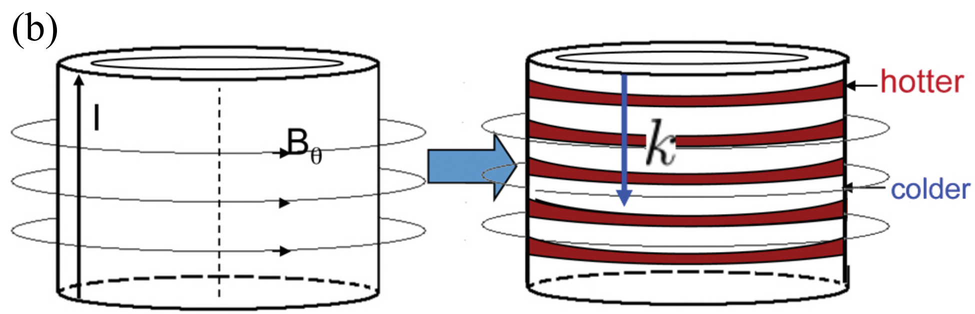
Then, η increases which consequently further enhances the localized ohmic heating (ηj^2),

Electrothermal instabilities occur when material conductivity is dependent on temperature

Theory

Striations

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



$$\delta T > 0$$

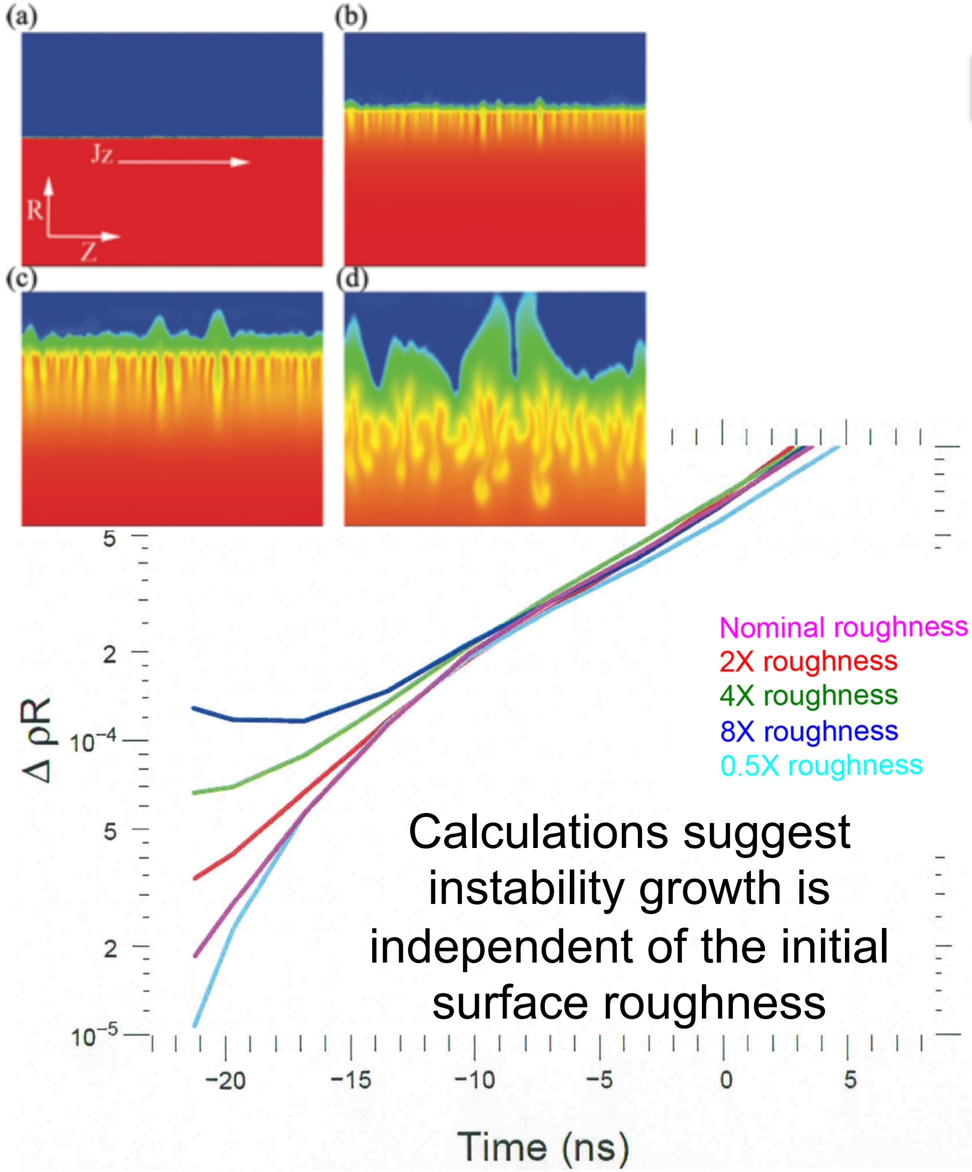
Temperature perturbations give rise to pressure variations which eventually redistribute mass

Consider a small temperature perturbation due to localized variations in ohmic heating

- surface contaminants (variations in η)
- surface roughness (B_θ ~ I/r, in cylinders)
- grain boundaries or inclusions

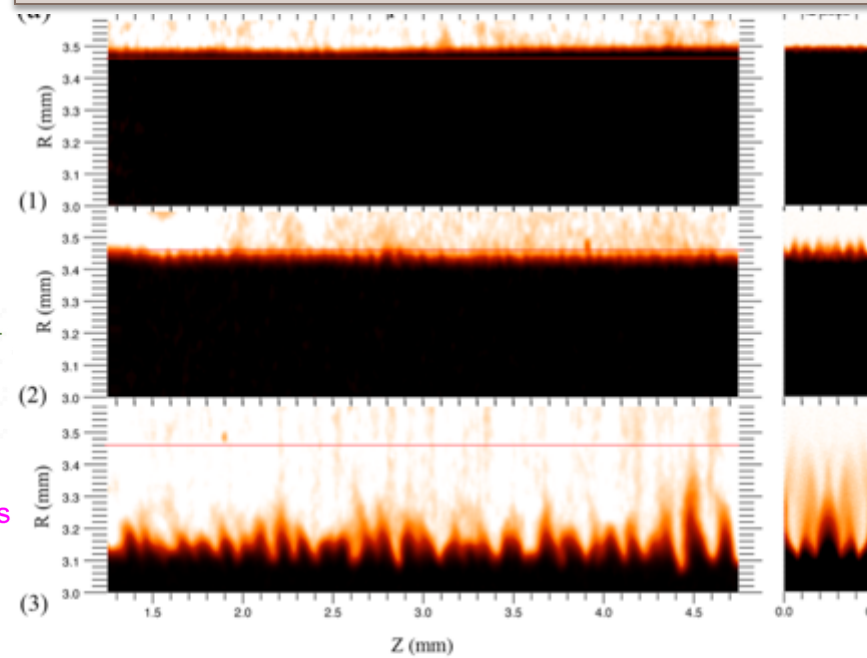
Then, η increases which consequently further enhances the localized ohmic heating (ηj^2), which leads to increased δT

High resolution 2D simulations of electrothermal instabilities are consistent with experimental observations



Calculations suggest instability growth is independent of the initial surface roughness

Experimental (left) & simulated (right) radiographs



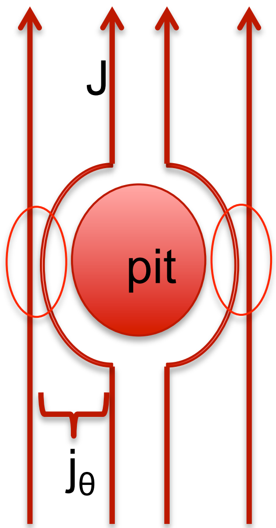
Perturbation Growth Comparison

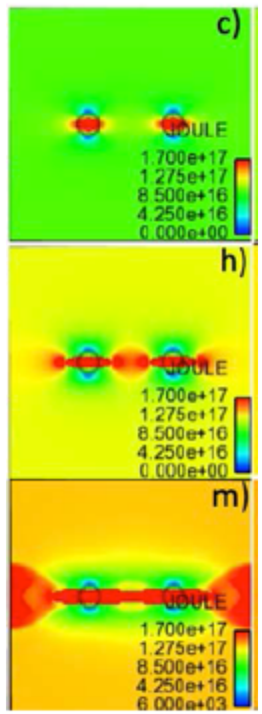
Time	Est. MRT (λ=100 μm)	$h=0.06Agt^2$	Observed
A	0.36 μm	6.2 μm	13 ± 7 μm
B	24 μm	41 μm	80 ± 7 μm

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

We are continuing to study surface initiation, ETI, and correlation

Correlation of two pits[1]





Current "bunches up"

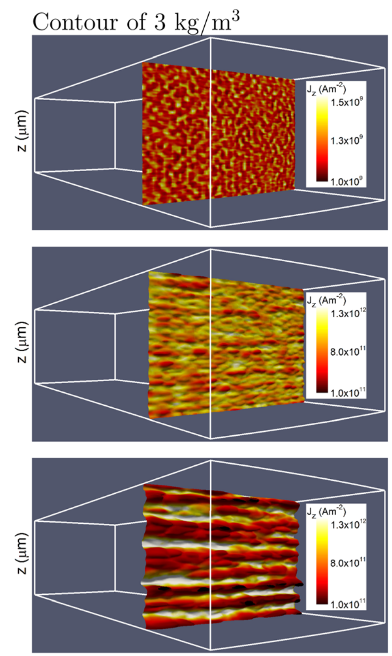
➔$\delta(\eta j^2)>0$

➔$\delta T>0$

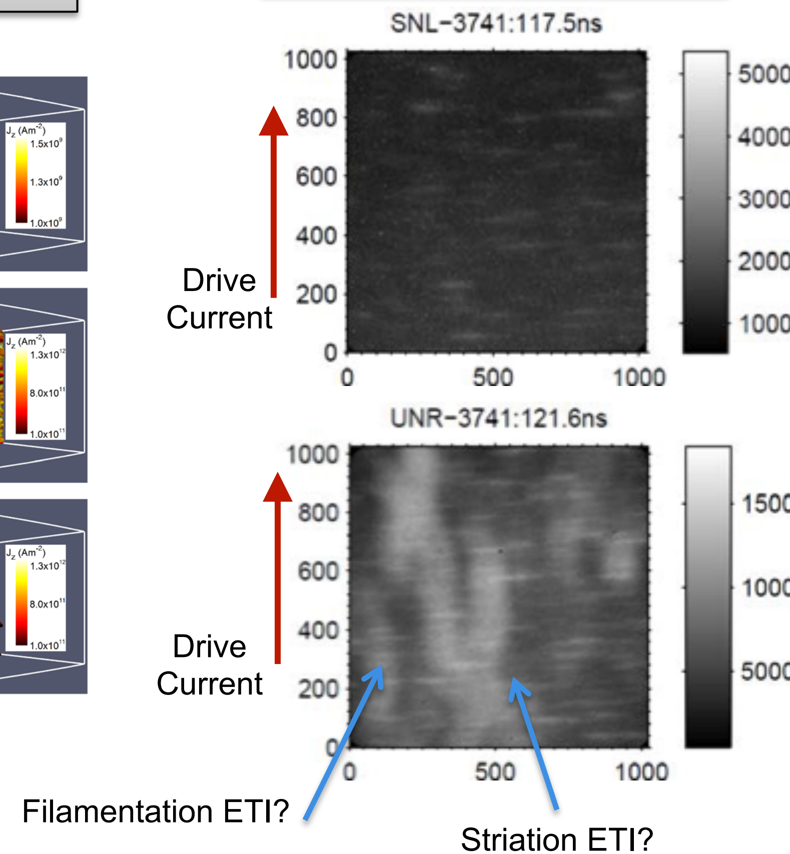
➔$\delta\eta>0$ (η rises with T)

region is ETI unstable, and is seeded by current redistribution

3D GORGON Sims of ETI correlation[2]



High resolution (3 μm) visible self emission imaging on Zebra (UNR)[3]

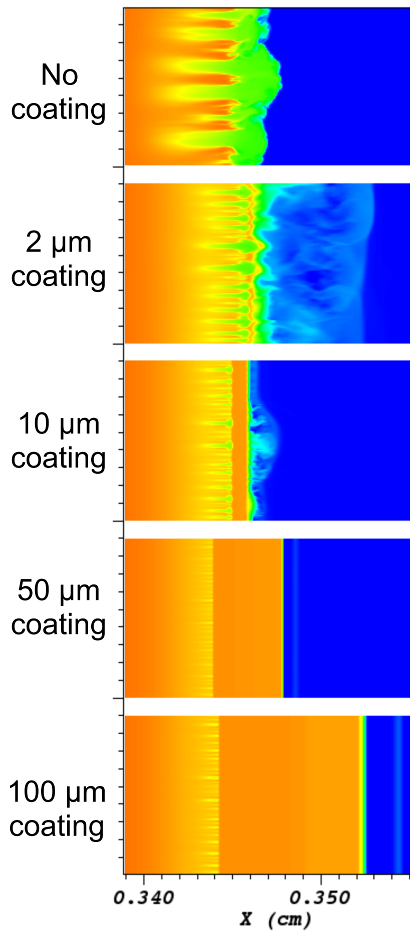


Preliminary

Pecover JO6.00004

[1] E. P. Yu, *et. al.*, in preparation, J. Pecover , Phys. Plasmas 22, 102701 (2015)[2], T. J. Awe, *et. al.*, *in preparation*

Relatively thick insulating coatings mitigate effects of ETI and reduce seed for MRT growth



No ETI (striation) growth in dielectric coating

- Carries very little current
- Theoretically ETI Stable

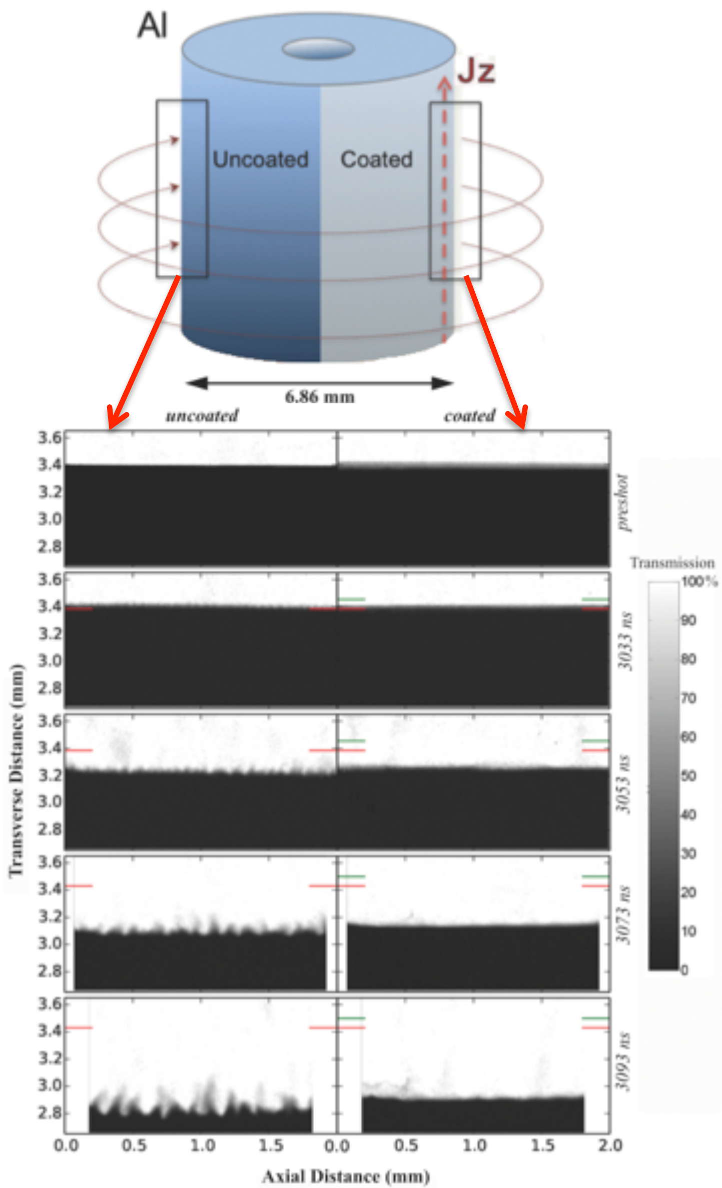
$$\frac{d\eta(T)}{dT} > 0$$

Linear ETI growth of temperature perturbations still present in metal

- Reduced by density dependence of growth rate

Mass redistribution from ETI is tamped by the coating

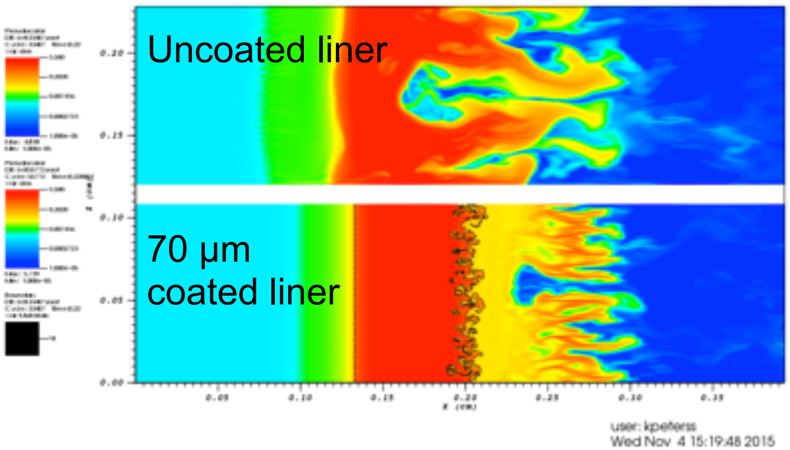
- Reduces seed for MRT growth
- Reduces integral instability growth



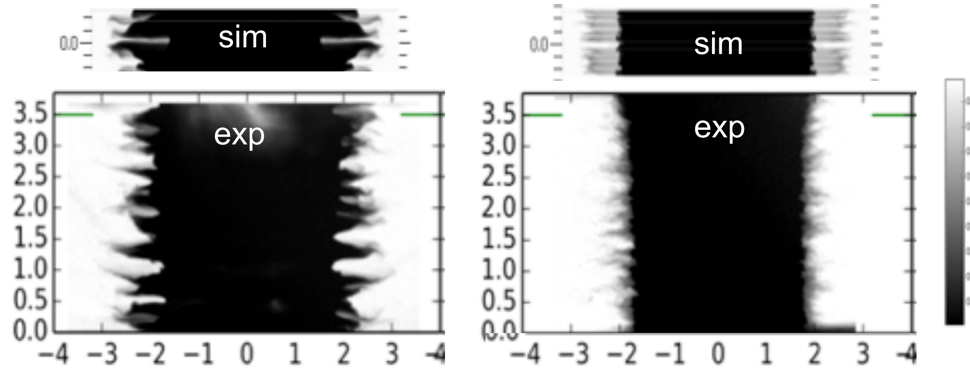
K.J. Peterson *et al.*, Phys. Rev. Lett. 112, 135002 (2014)

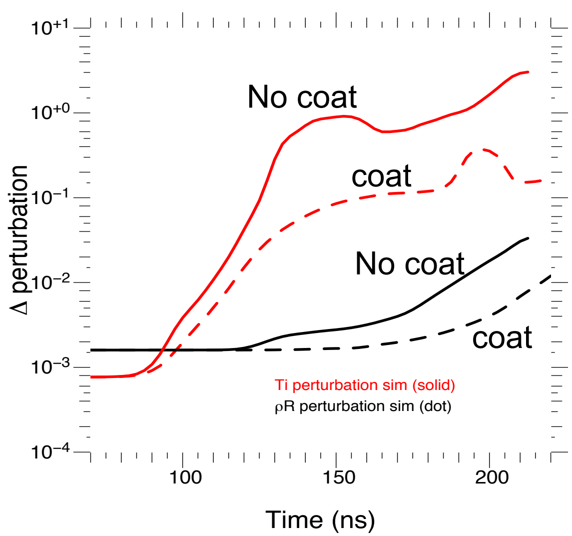
Recent experiments confirmed that coated aluminum imploding liners exhibit a dramatic reduction in instability growth

(Al) Log Density Contours, CR ~2



Excellent agreement with 2D simulations



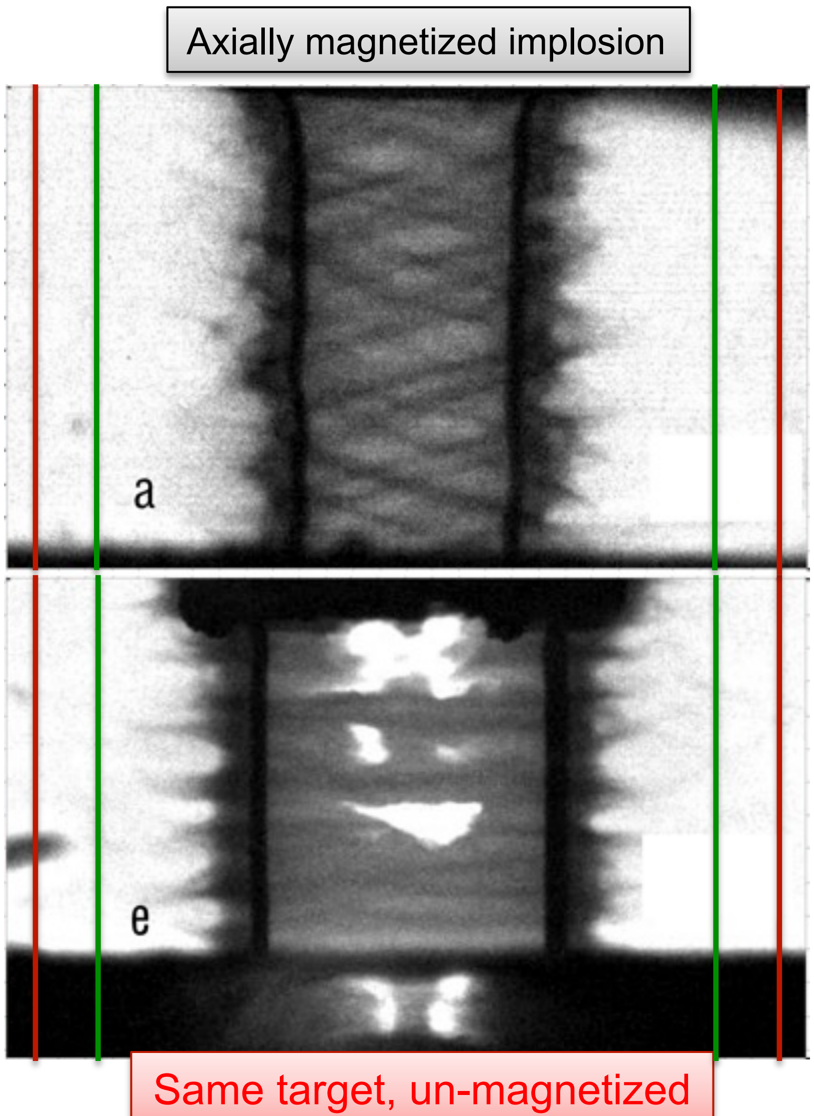


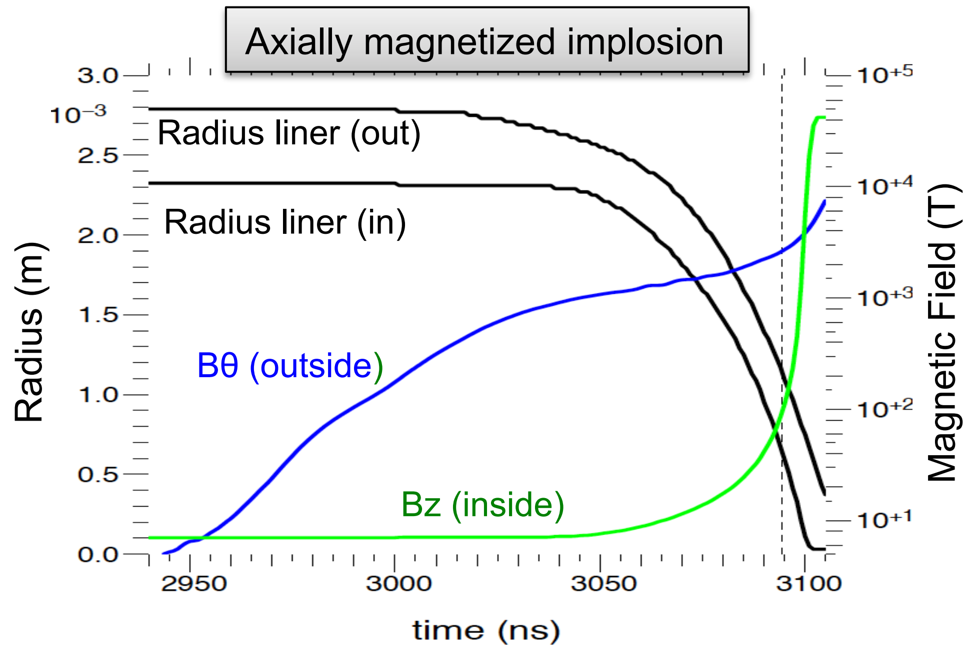
Coated Liners

- Less correlation
- Smaller amplitude MRT
- Smaller wavelength MRT
- More stable inner surface (observed with Be liners)

T. J. Awe & K. J. Peterson, et. al., *submitted PRL* (2015).

Magnetized liner implosions produce helical MRT structures that helps mitigate liner instability growth





- **Evidence for a more stable implosion**
  - Lack of time integrated self emission in magnetized case
  - Significantly less stagnation x-ray emission in magnetized case

T. J. Awe et al., Phys. Rev. Lett. 111, 235005 (2013). T. J. Awe et al., Phys. Plasmas 21, 056303 (2014).

We have not yet self consistently generated helical structure in our simulations, but we are making progress

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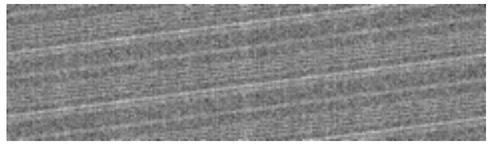
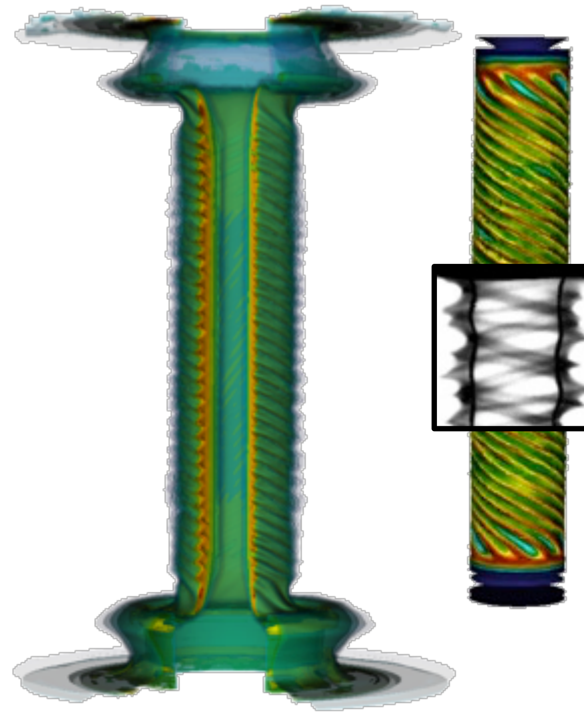
Initial Conditions

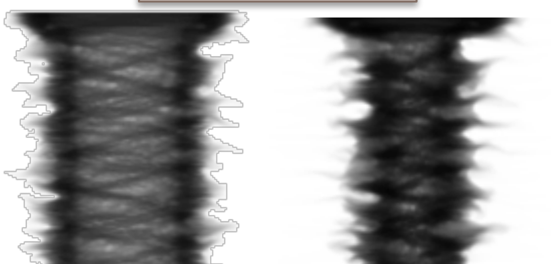


7.2 degree helix etched onto liner surface at 20 micron grid resolution

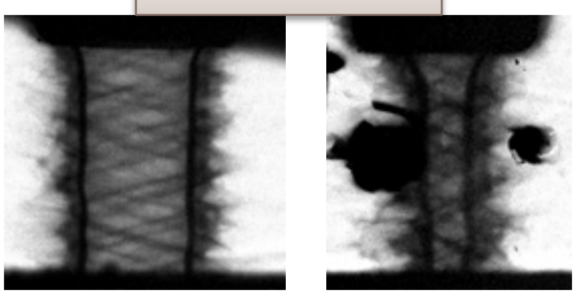
HYDRA[2]



GORGON[1]



Z 2480 Data



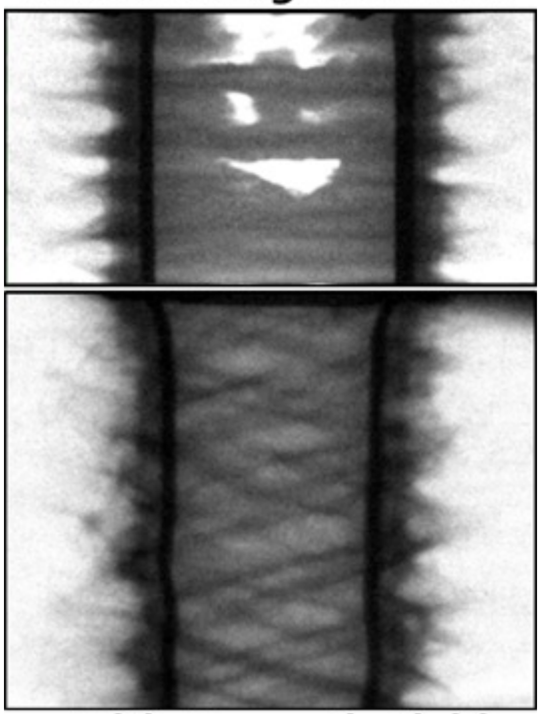
CR 6.4

- **Helical structure persists throughout implosion (grows w/ constant pitch)**
- **These calculations did not include initial 10T Bz field. It is <u>not</u> required for initial perturbation to persist**

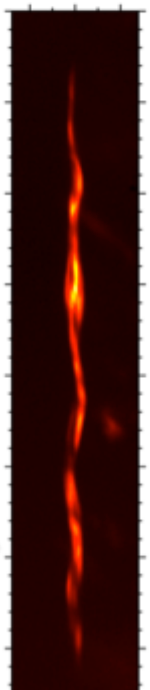
Experiments are planned to test whether pre-imposed helical perturbations of sufficient size grow and persist

Combining magnetization with thick dielectric coatings appears to produce remarkably uniform compression of the fusion fuel in our highest convergence radiographs to date

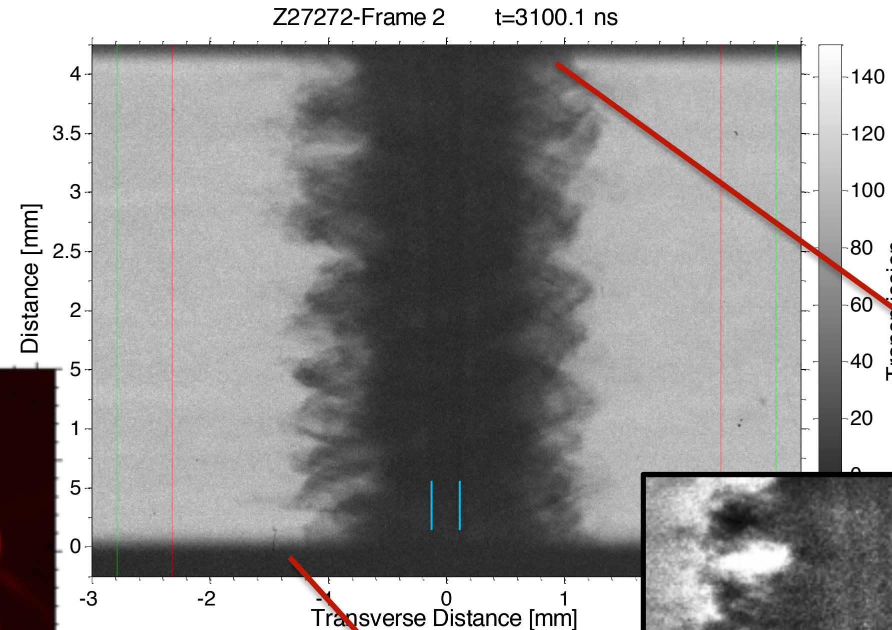
Without Magnetic Field



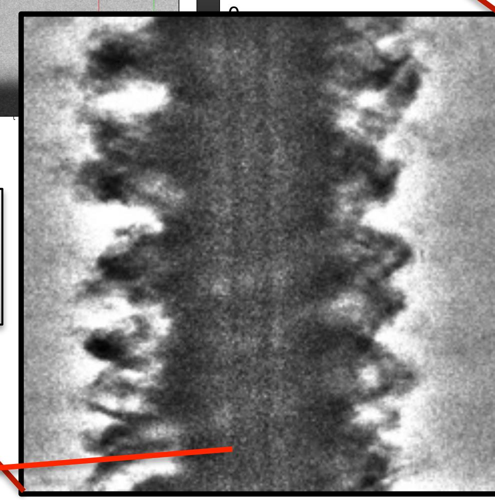
With Magnetic Field



Weakly helical structure at stagnation believed to be related to liner instability



Magnetized & CH-coated Be implosion **(CR ~21)**



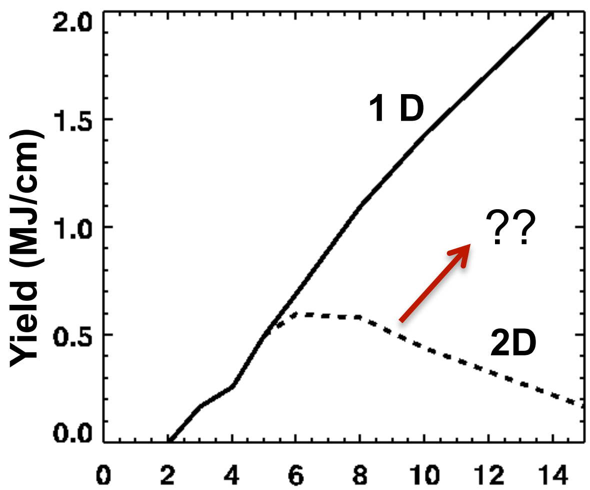
Inner liner radius ~ 120 microns!

?

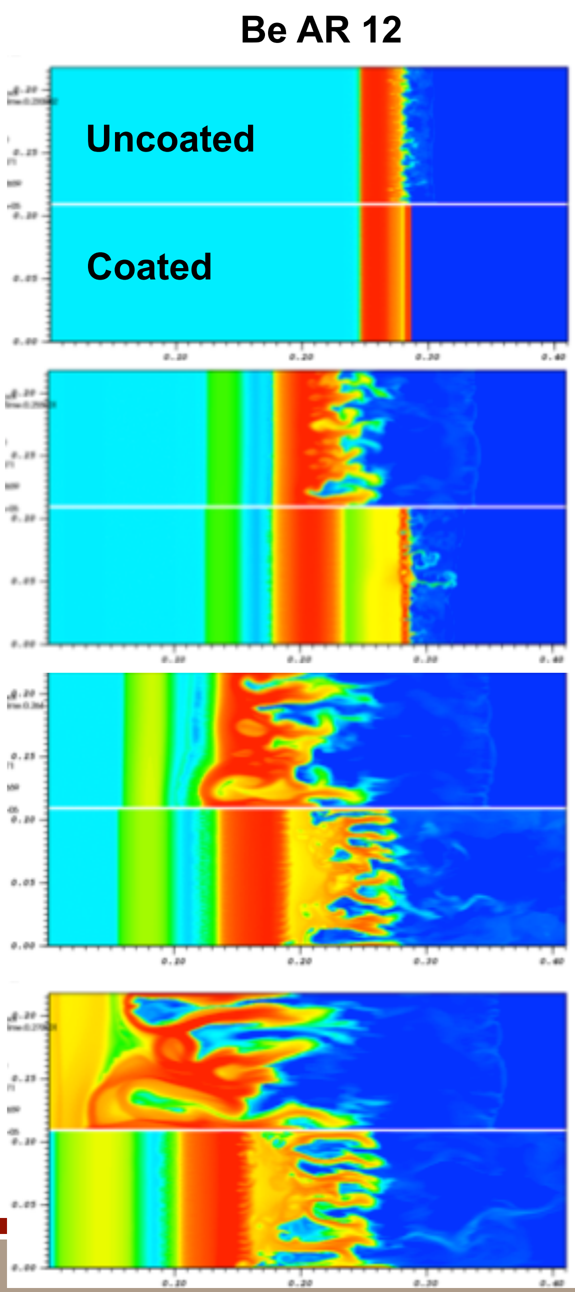
Can this technique produce more uniform fusing plasmas?

Dielectric coatings open up design space for MagLIF implosions

- Could improve current AR6 MagLIF targets if perturbations are limiting areal density
  - Experiments are planned for next year
  - Does helical stagnation emission remain?
- 2D simulations predict quasi-1D performance with AR 12
  - Reduce preheat requirement
  - Enhance yield performance



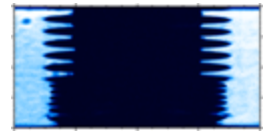
- Max. current = 30 MA
- Convergence ratio = 20
- B-field = 30 Tesla



We have made significant progress in advancing our understanding of magnetically driven implosions for fusion

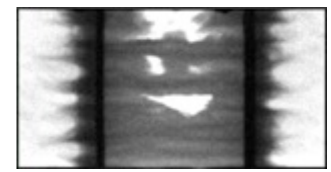
- Based on modeling and simulation, we believe that we can create controlled fuel compression with relatively slow, thick liners.

MRT studies



Fast, high AR implosions

Slow, low AR Implosions



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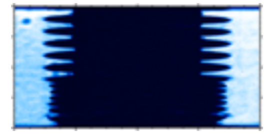
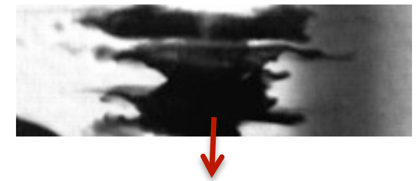
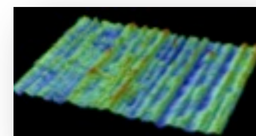
MRT studies



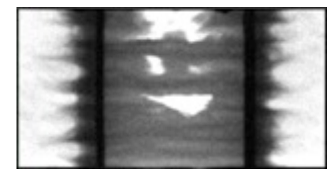
Fast, high AR implosions



Improved Surfaces



Slow, low AR Implosions



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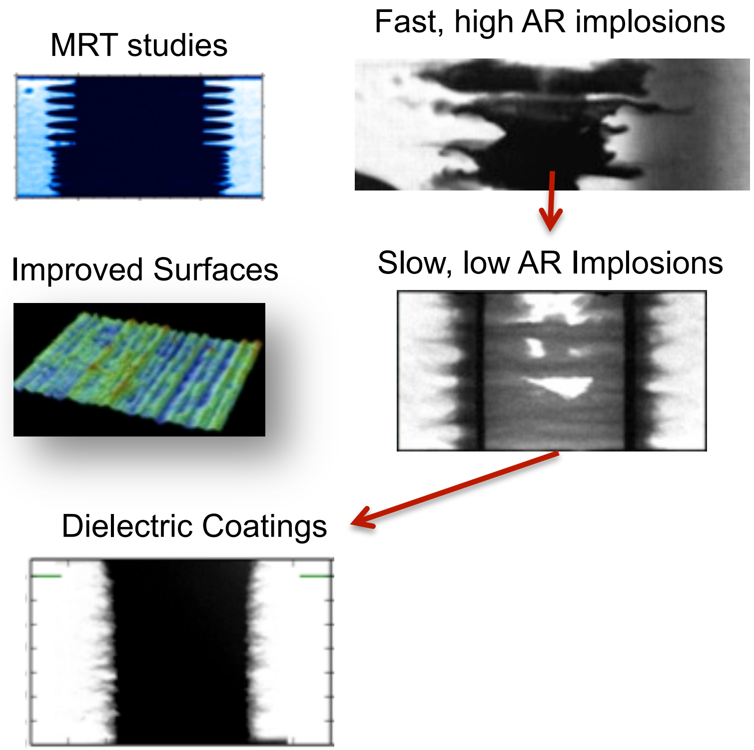

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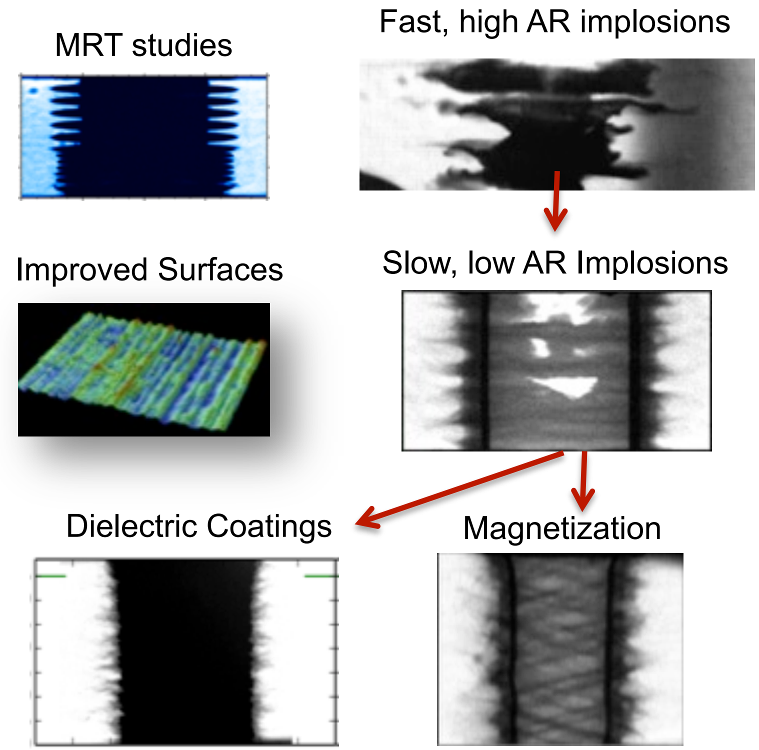

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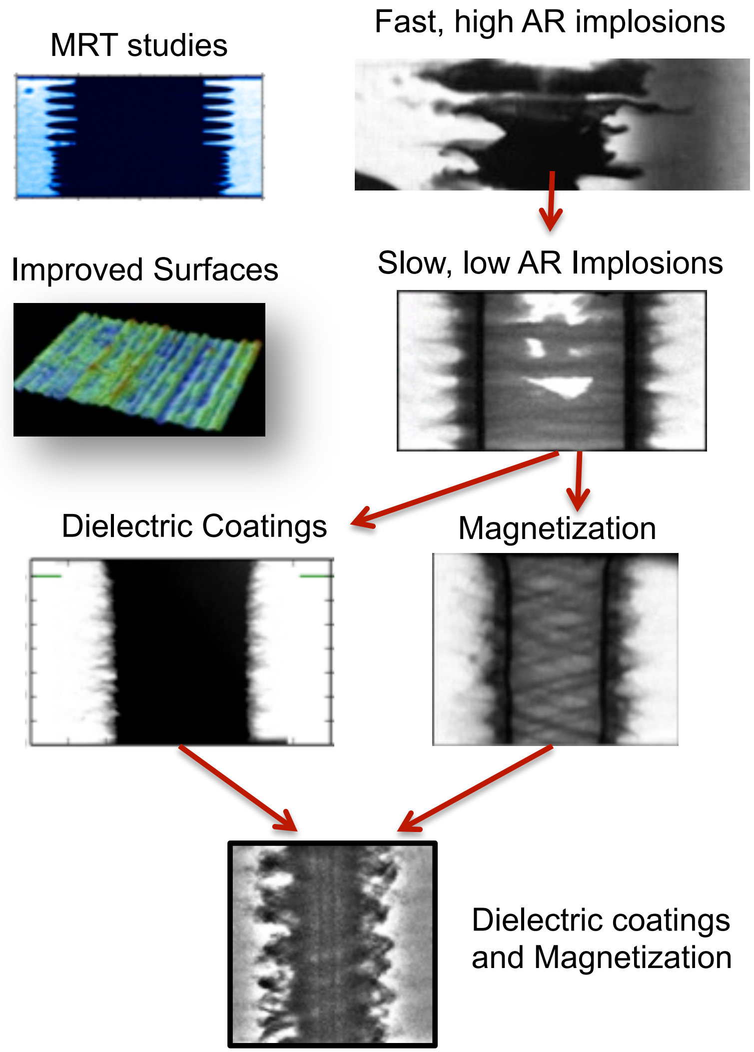
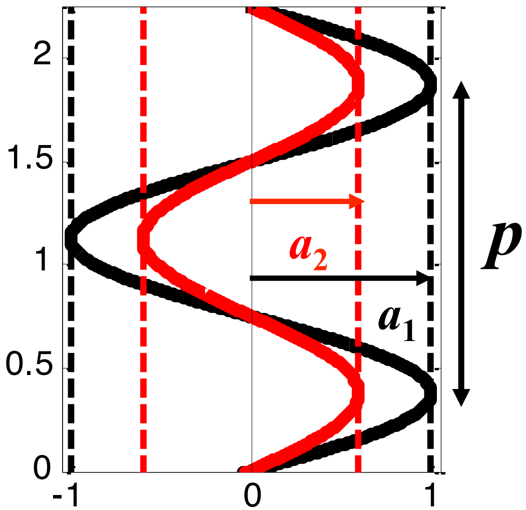
- Thick insulating coatings can be effectively employed to mitigate ETI and significantly reduce instability growth.
- A strong axial magnetic field can affect 3D structure and reduce acceleration instabilities
- Combining dielectric coatings and magnetization has produced remarkably stable implosions
- We believe that these developments may open up the design space for magnetically driven implosions



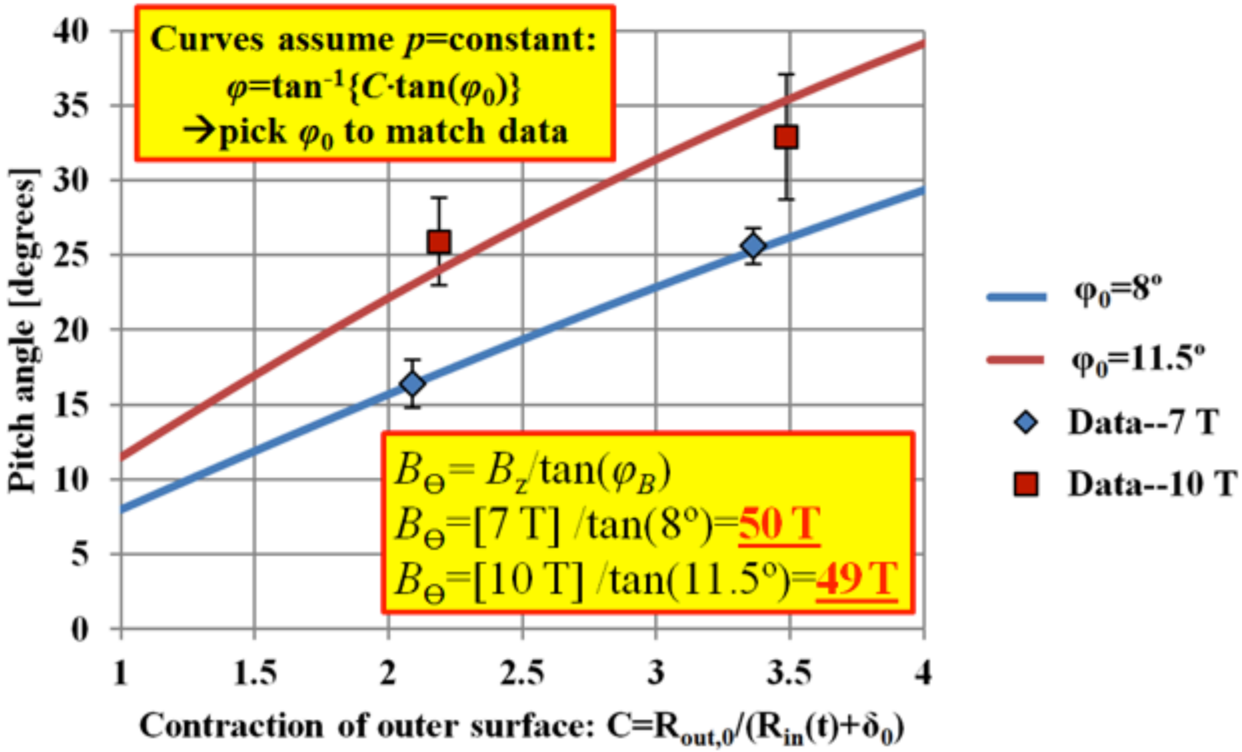
Backups

Data indicates pitch of instability potentially increases with increasing Bz

Data supports constant pitch (p) assumption: Relatively small initial pitch angle (φ) increases as the liner implodes



p≈constant



Analysis: T. Awe

Under constant pitch (p) assumption, the helical perturbation is locked in *later* with dielectric coatings

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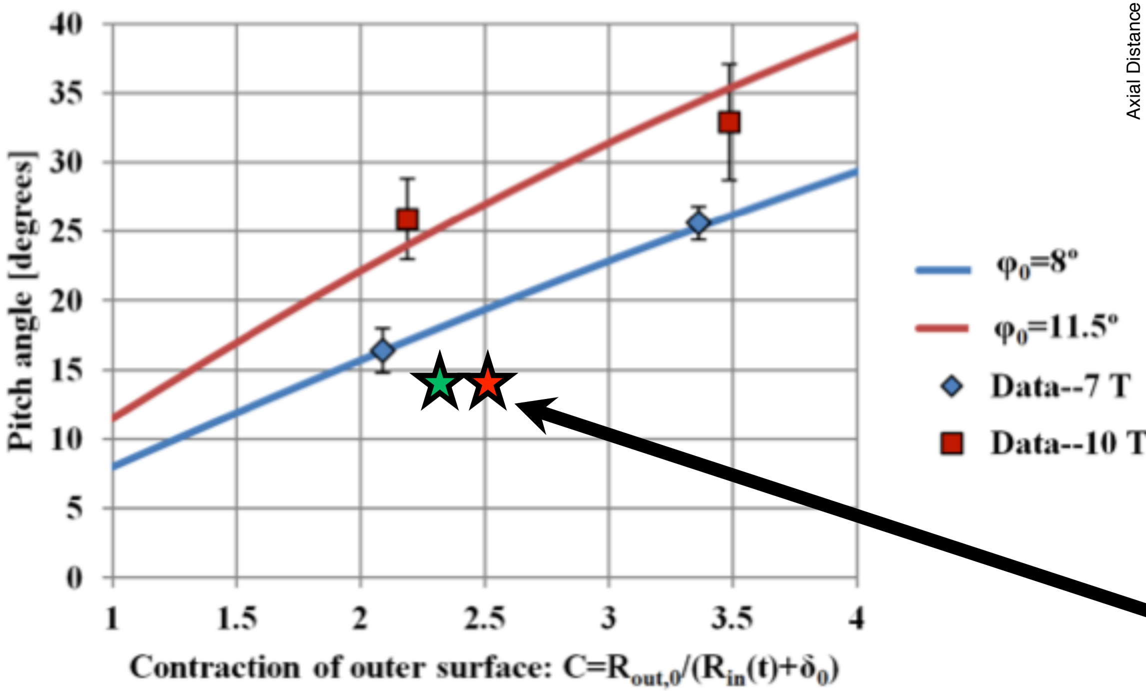
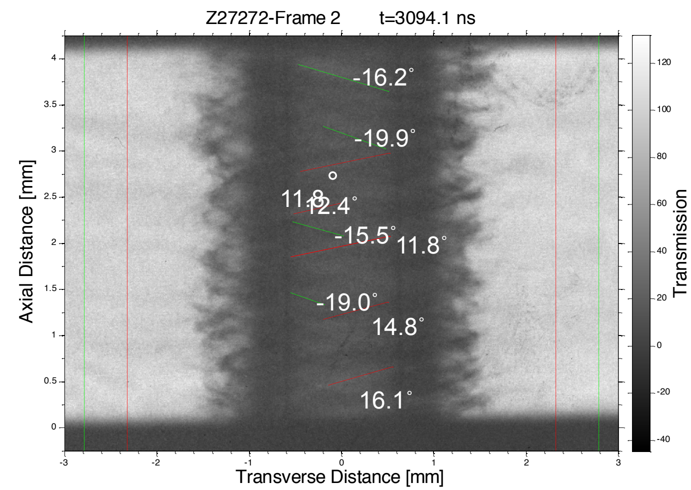
Curves assume p=constant:
$\varphi=\tan^{-1}\{C\cdot\tan(\varphi_0)\}$
→pick φ_0 to match data





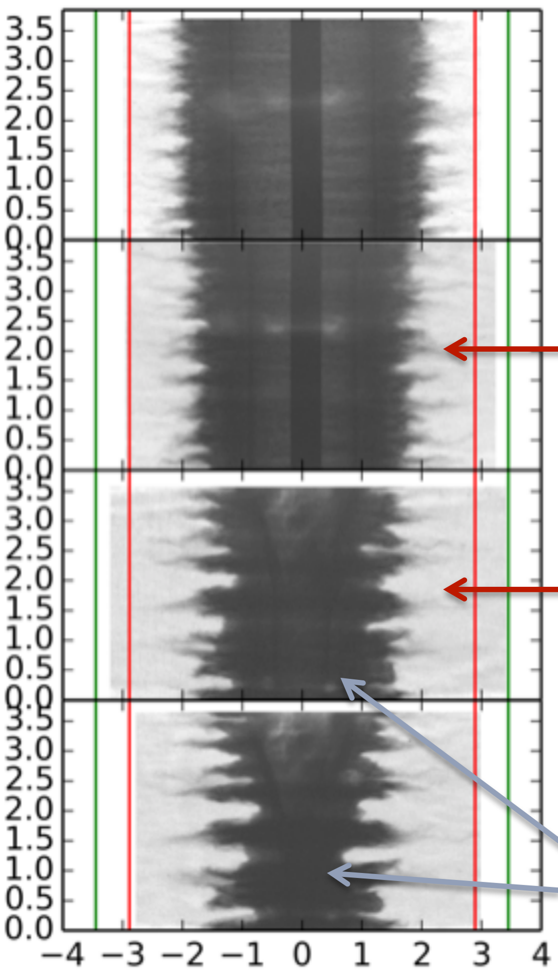
Z2772-t1
$R_{in}(t)$=651 μm
Φ~15°
$R_{out,0}$=2.79 mm; δ_0=465 μm; C=2.50
$R_{out,0}$=2.86 mm; δ_0=535 μm; C=2.41

$B_\Theta= B_z/\tan(\varphi_B)$
B_Θ=[7 T] /tan(8°)=**50 T**
B_Θ=[10 T] /tan(11.5°)=**49 T**
B_Θ=[7 T] /tan(<8°) > **50 T coated ????**

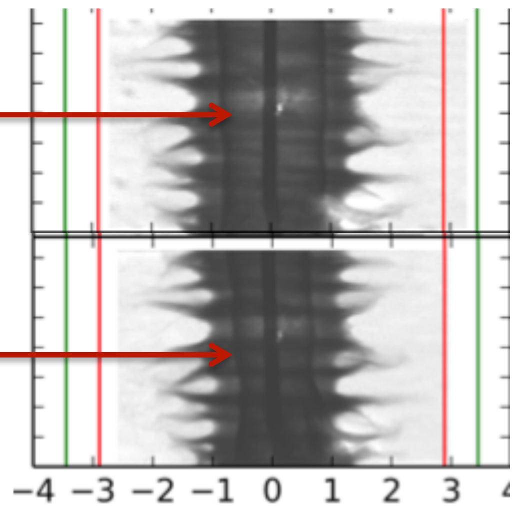
Perturbation growth is consistent with hypothesis of electrothermal instabilities seeding subsequent MRT instabilities

- Simulations
  - Most perturbation growth occurs in regions shown to be stable to MRT and unstable to electrothermal instabilities
  - Tests of constant electrical conductivity and enhanced thermal conduction are consistent with electrothermal instabilities
  - Perturbation growth rates were shown to be consistent with growth rates predicted by electrothermal instability theory
- Experiments
  - Excellent agreement between experimental and simulated radiographs, especially for Aluminum
  - Observed perturbation growth is larger than can be explained my MRT alone

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)

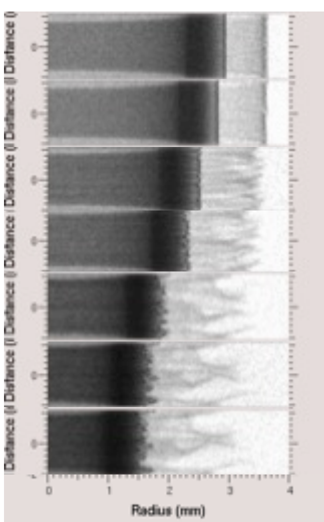


Compromised implosion from unmitigated wall instability?

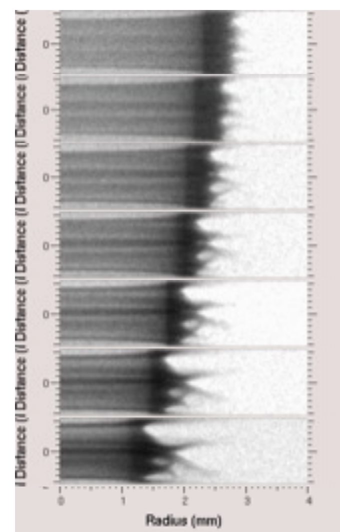
Coated Liners

- Less correlation
- Smaller amplitude MRT
- Smaller wavelength MRT
- More stable inner surface

2D HYDRA SIM
(70 µm coat)



2D HYDRA SIM
(No coat)



Almost all of the observed perturbation growth is localized to regions that are stable to MRT instabilities

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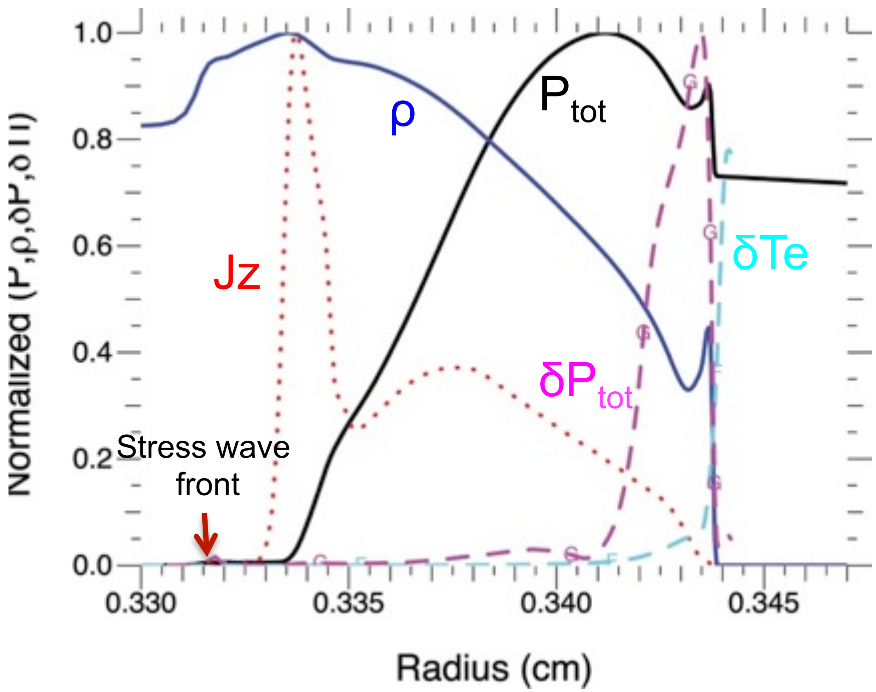
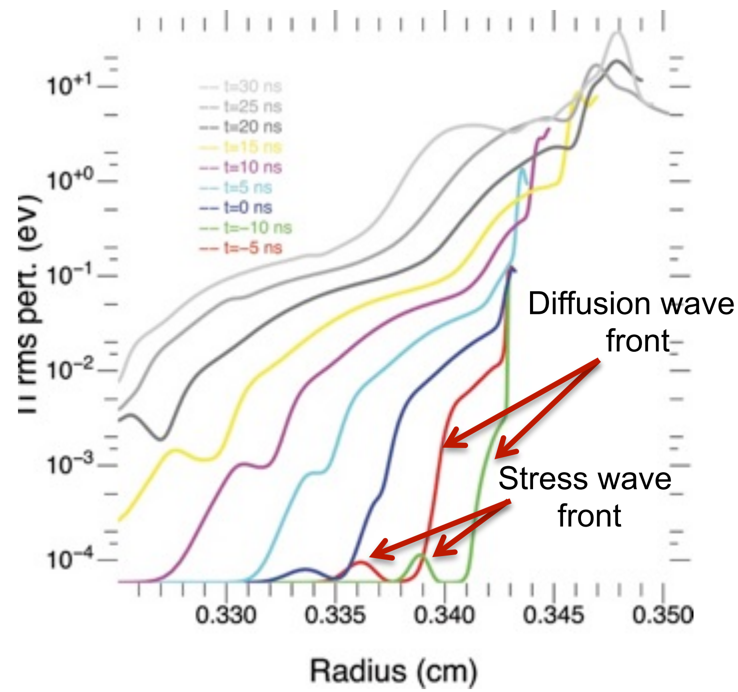
Simulation

Stability profile @ t=13 ns



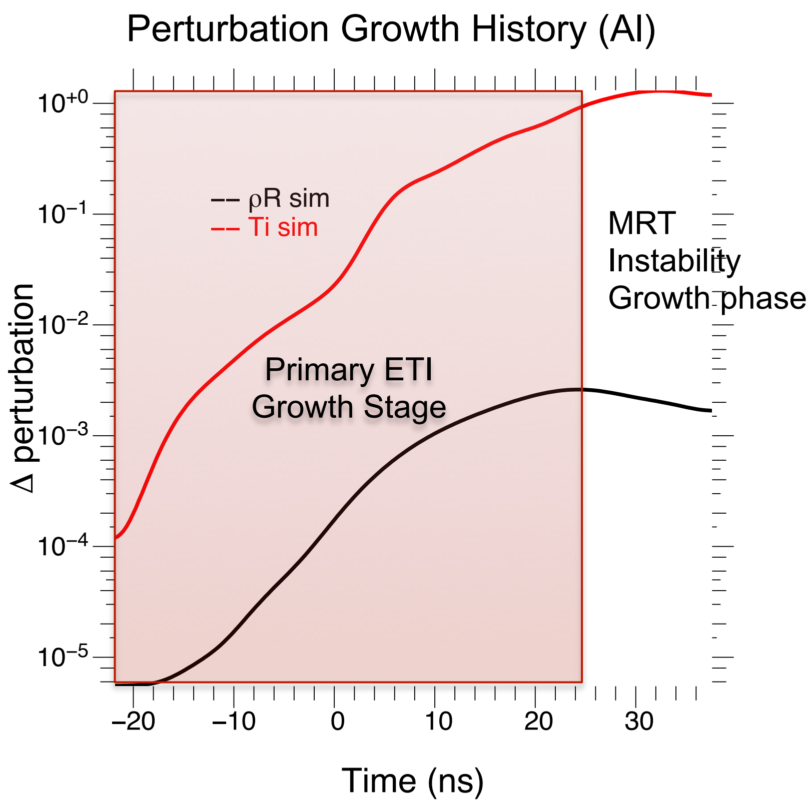
Temperature perturbation vs depth

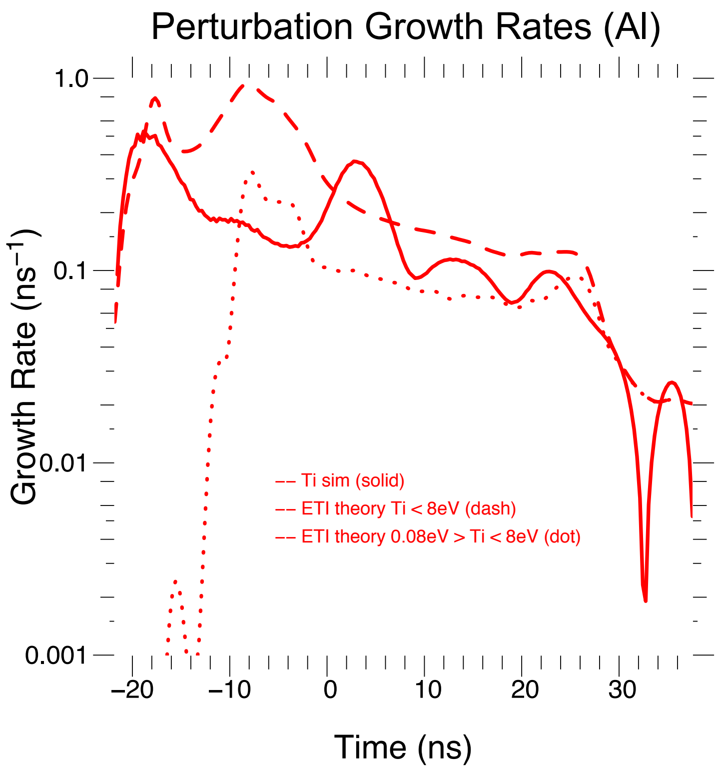


- Initial stress wave front provides small perturbation in solid material. However, the magnetic diffusion wave front is primarily responsible for propagating small temperature perturbations (rod temperature initially isotropic) from surface which seeds electrothermal instability growth
- Electrothermal instability growth extends from diffusion front to the outermost surface layers where most of the perturbation growth is localized

Simulated perturbation growth rates are consistent with theoretical growth rates

Simulation





- Electrothermal theoretical growth rates determined using average values of (Jz, ρ, c_v, Ti)
- Assumed no thermal conduction

Several tests were performed to ensure results of 2D simulation are consistent with electrothermal instabilities

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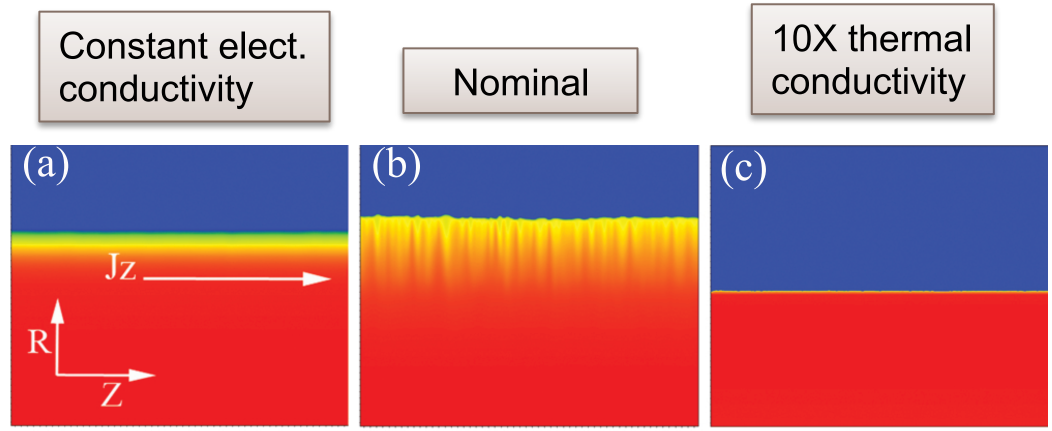
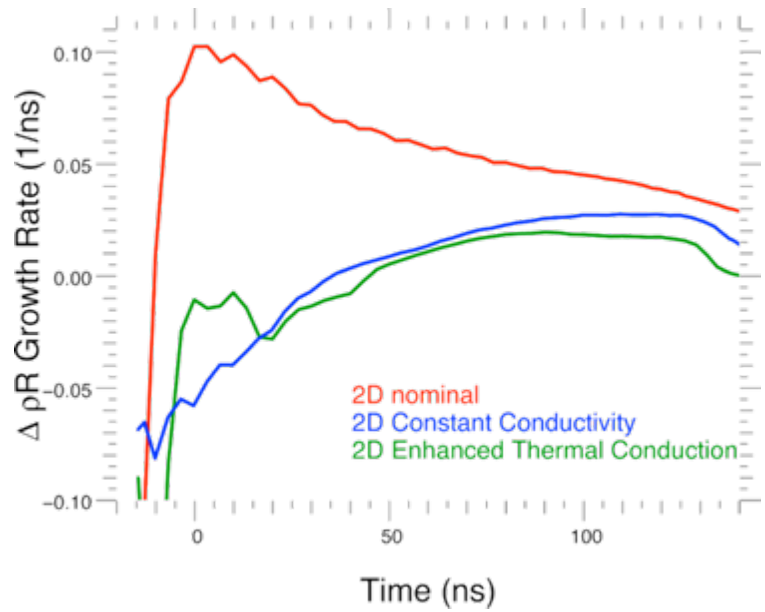
Simulation

- Constant electrical conductivity
  - Completely stable to electrothermal instabilities
  - Perfect conductors approach “classical” Rayleigh-Taylor
- Enhanced thermal conduction
  - Increases stabilization
  - Delays onset of melt

$$\gamma = \frac{j^2 \frac{\partial \eta}{\partial T} - k_z^2 \kappa}{\rho c_v}$$



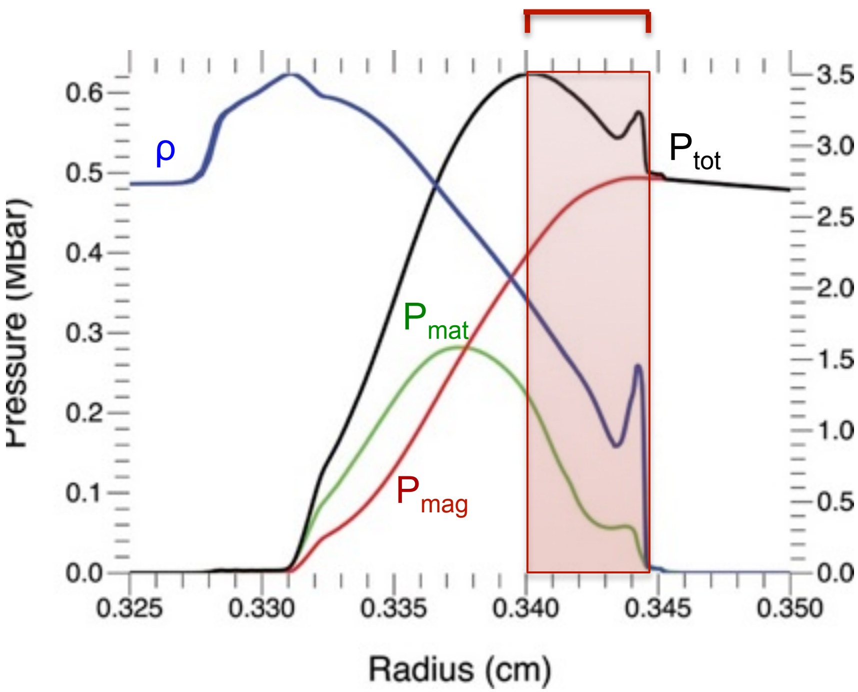


High resolution simulations with high fidelity material models capture ETI physics

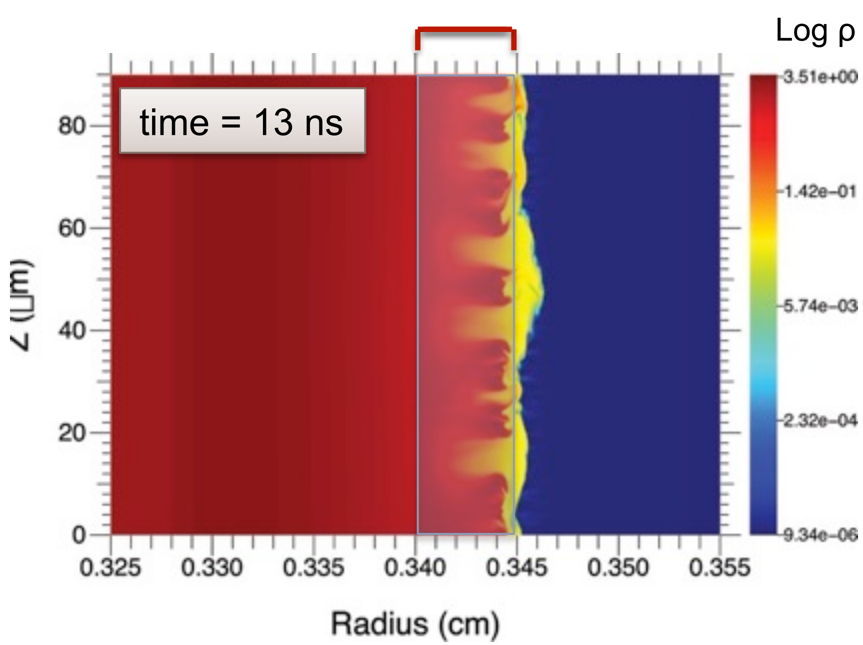
Simulation

Strong instability growth in regions stable to MRT

Radial Lineouts of Pressure & Density



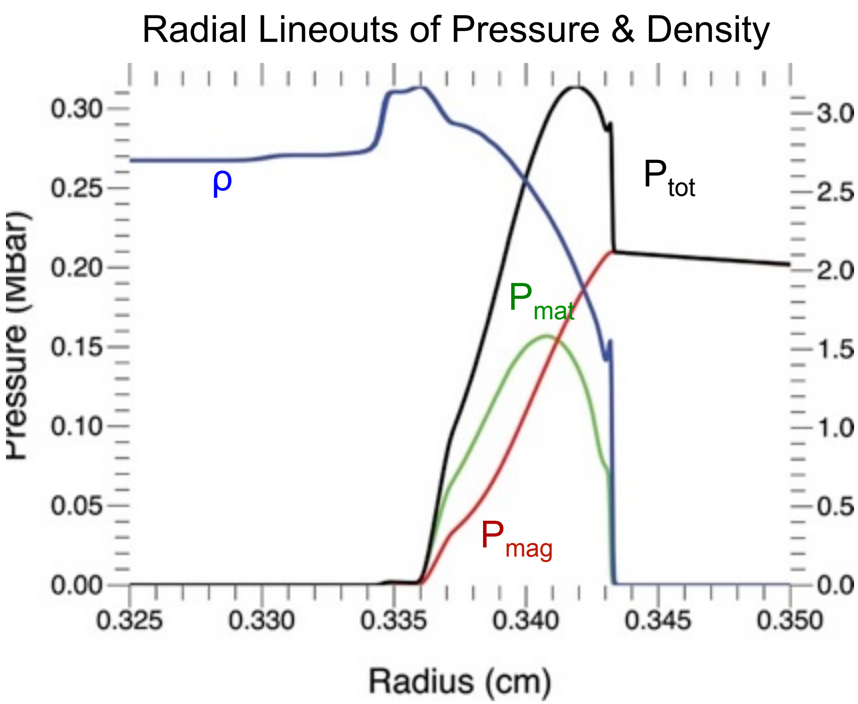
2D Hydra simulation (Al)

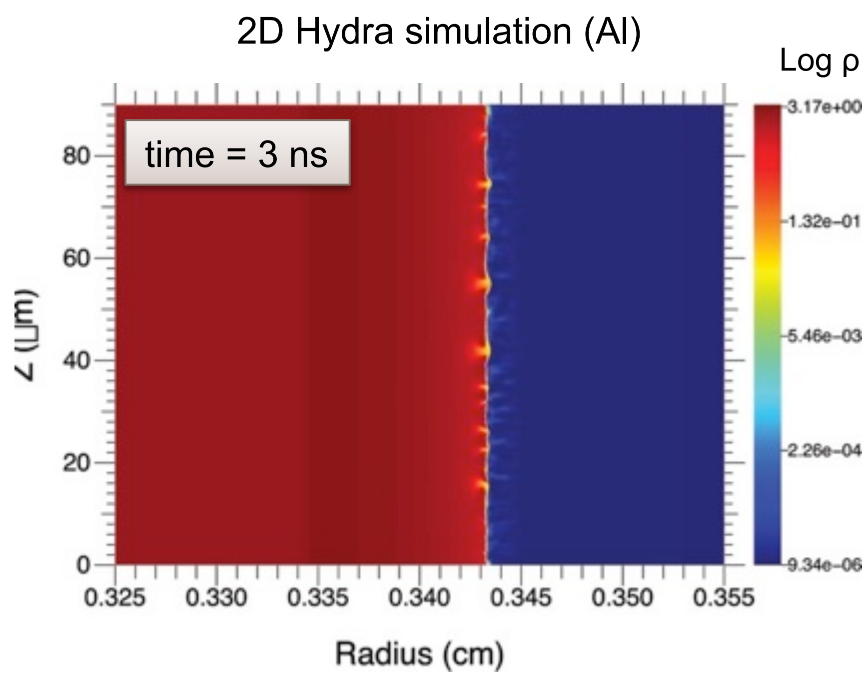


It can be shown that the general condition for MRT instability is, $\nabla P_{tot} \cdot \nabla \rho < 0$, where $P_{tot}=P_{mag}+P_{mat}$

As soon as current begins to flow a nonlinear magnetic diffusion wave propagates into the rod

Simulation





Significant instability growth is observed in regions *stable* to MRT as the surface of the rod expands

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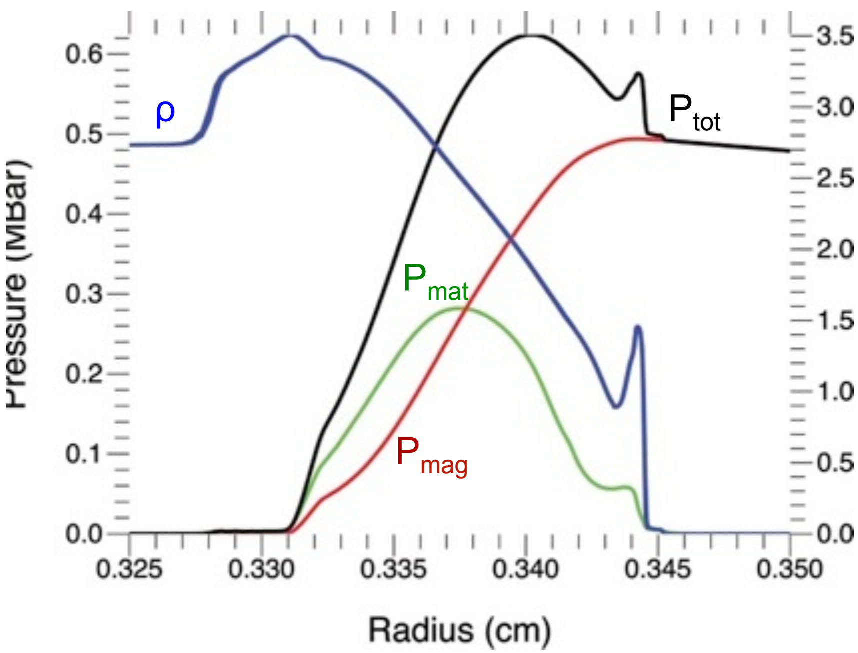
Simulation

Radial Lineouts of Pressure & Density



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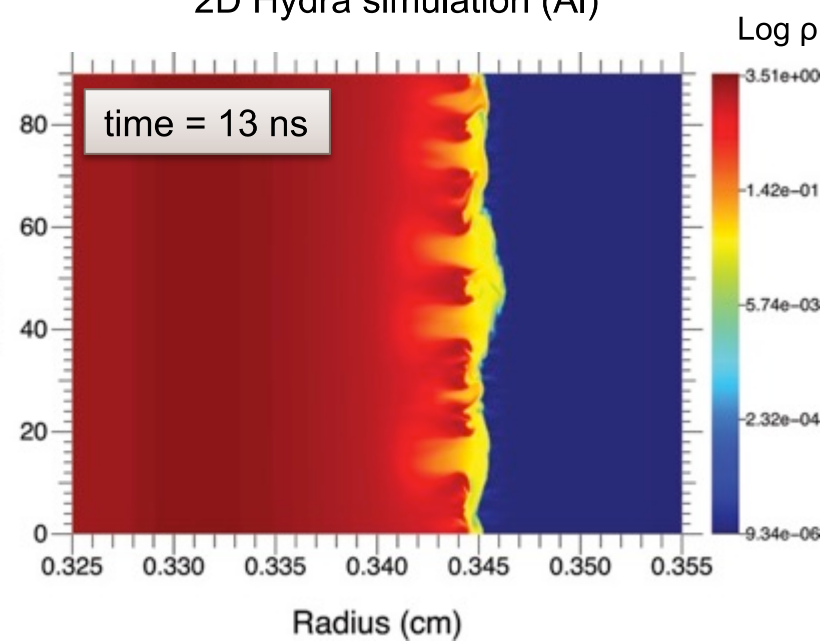
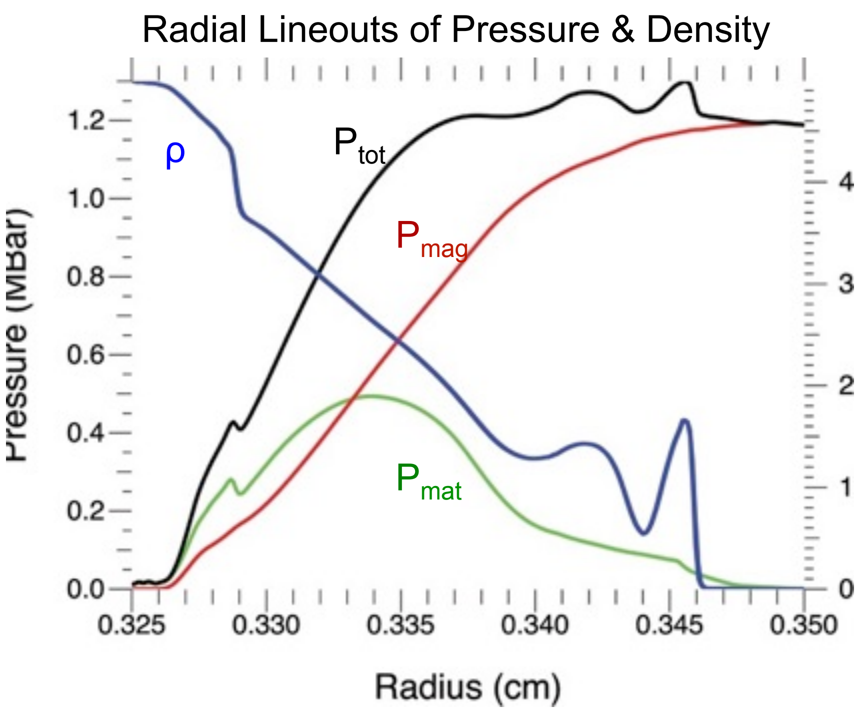
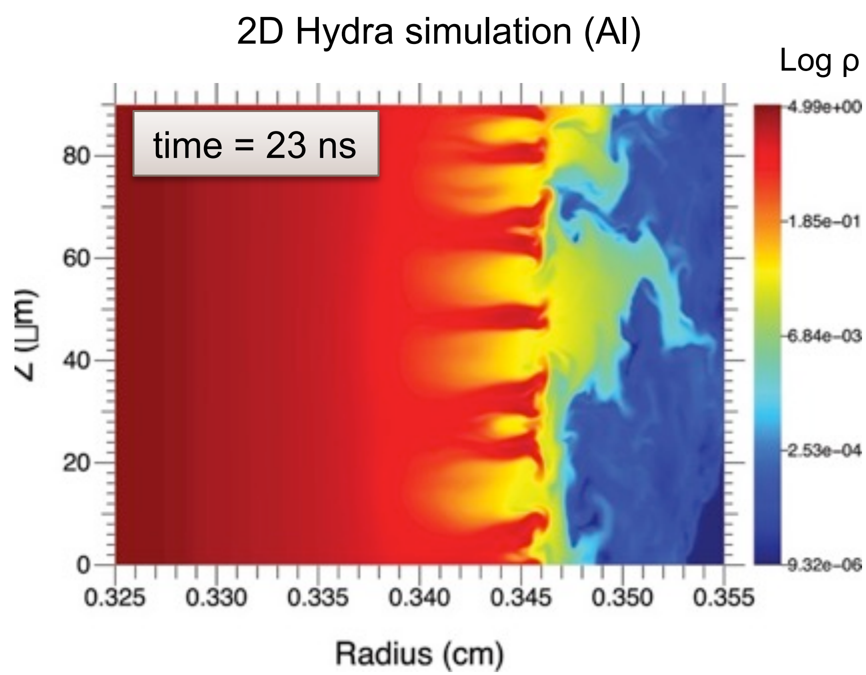


It can be shown that the general condition for MRT instability is, $\nabla P_{tot} \cdot \nabla \rho < 0$, where $P_{tot}=P_{mag}+P_{mat}$

At later times, the rod becomes *unstable* to MRT growth as it begins to compress under the magnetic pressure

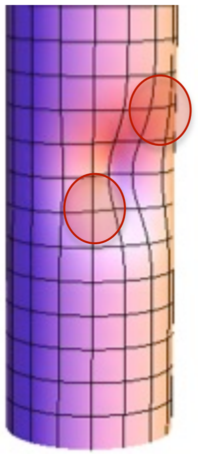
Simulation





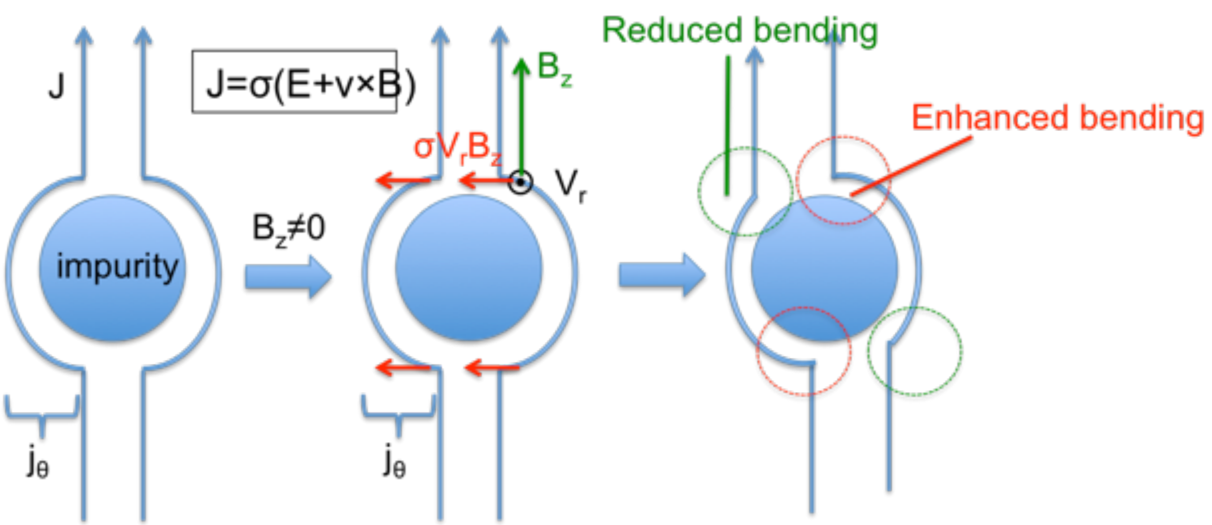
Melted portions of the rod become <u>MRT unstable</u> during deceleration of outer expansion and remain so throughout the rest the current pulse. $\nabla P_{tot} \cdot \nabla \rho > 0$

Adjacent unstable ETI regions can correlate and tilt with Bz



Pit, $B_z = B_\theta$

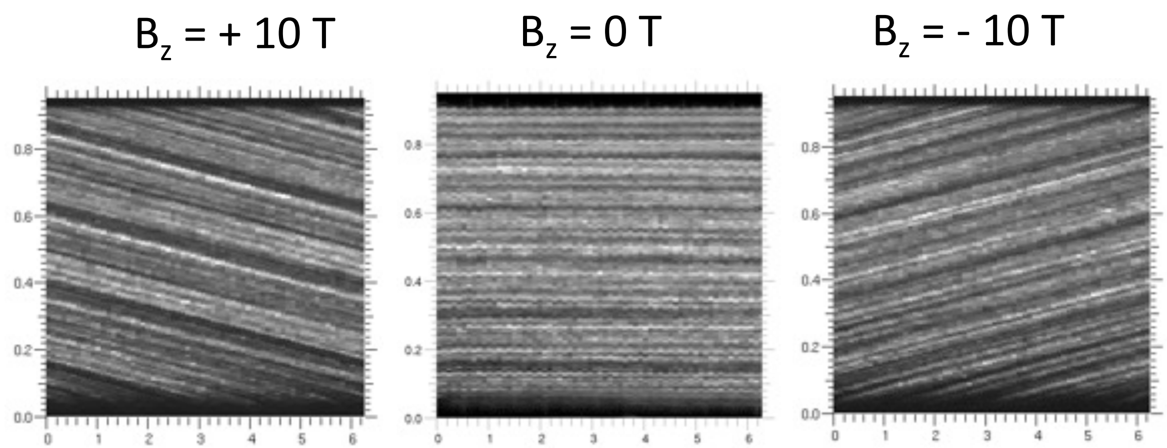
adjacent pits can
"correlate" and tilt with Bz



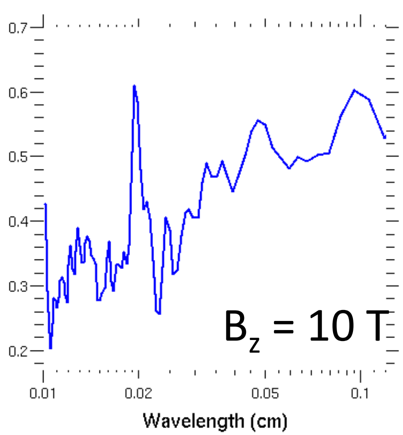
E. P. Yu, et. al., *in preparation* (2015).

Non-MHD mechanisms may be key to fully explaining level of azimuthal correlation and initial helical formation

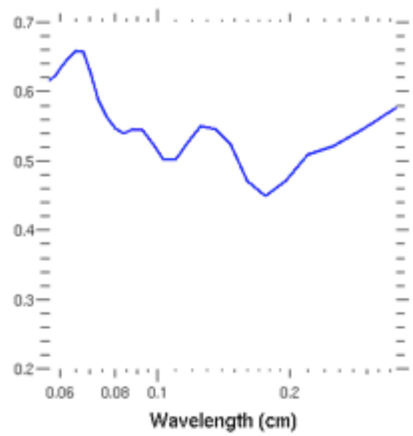
- Recent first principles LSP simulations are showing promise
- Captures necessary mode structure for coupling to 3D MHD simulations



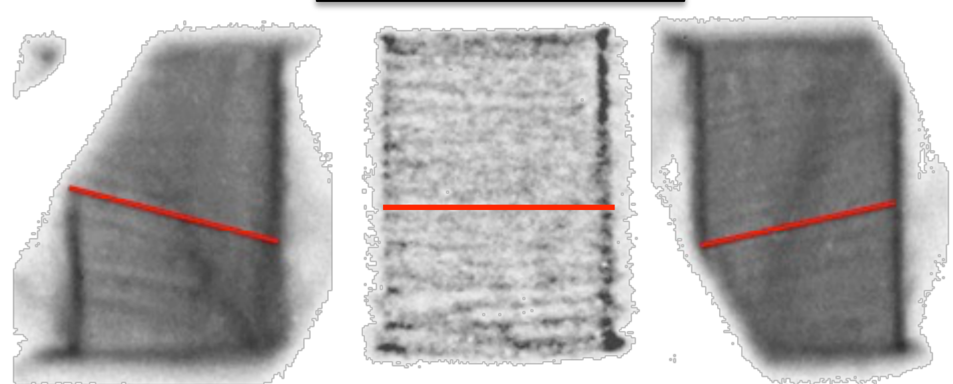
FFT of axial modes



FFT of azimuthal modes



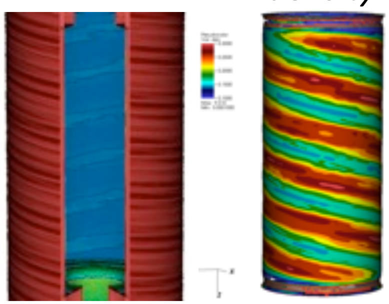
XUV emission on COBRA, L. Atoyan et. al. (Cornell) APS-DPP 2014 Poster



A. B. Sefkow, et. al., *in preparation* (2015).

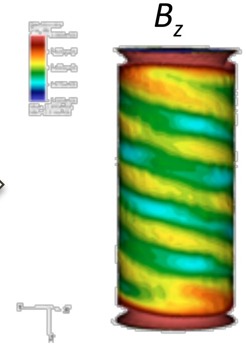
3D simulations suggest average stagnation quantities in current MagLIF implosions may be described by 1D

Early-time inner boundary
density



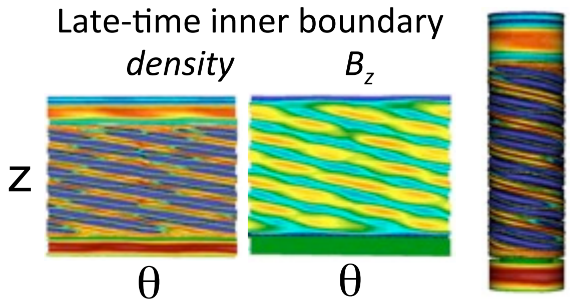
Long axial λ_z ~1 mm is from early-time feedthrough and imprints at the liner/gas interface

Inner boundary
B_z



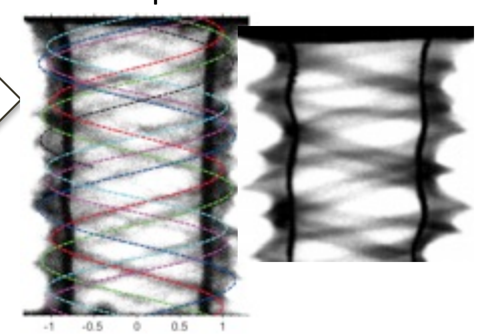
Since the interface is magneto-Rayleigh-Taylor stable, the gas is high β, and flux pile-up occurs there, λ_z also imprints on B_z

Late-time inner boundary
density B_z

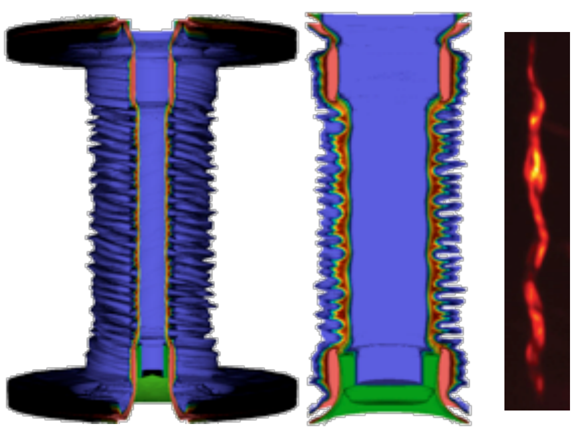


As in helical perturbation on rear side of liner, inner surface helix persists and grows as well

Exp Sim



Resulting structure does not strongly modify 2D physics

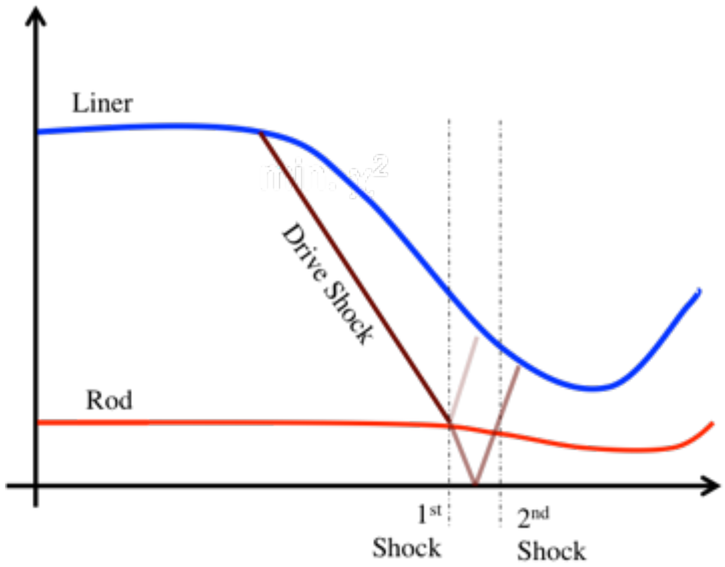


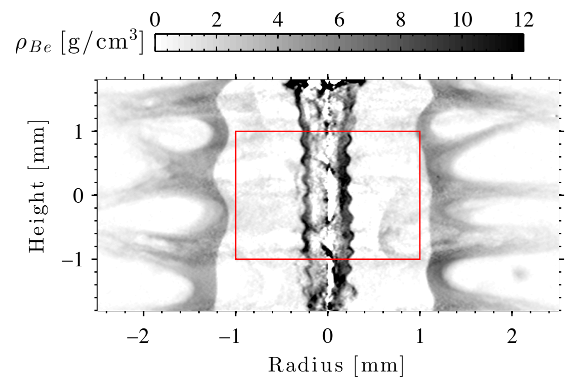
Resulting weakly helical (dr << dz) emitting stagnation column remains quasi-2D such that $P_{stag}^{exp} \sim P_{stag}^{3D} \sim P_{stag}^{2D} \sim 1$ Gbar

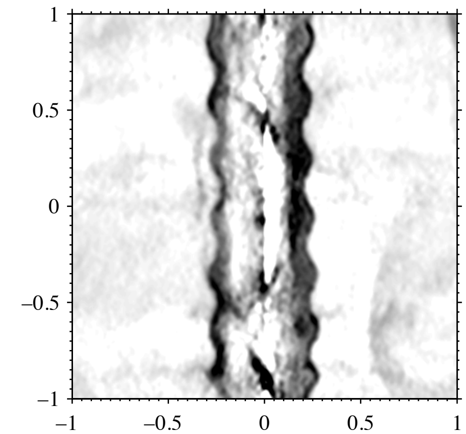
When not accounting for variations due to convergence as *f*(z), the averaged quantities may be approximately described even in 1D

A. B. Sefkow, et. al., *in preparation* (2015).

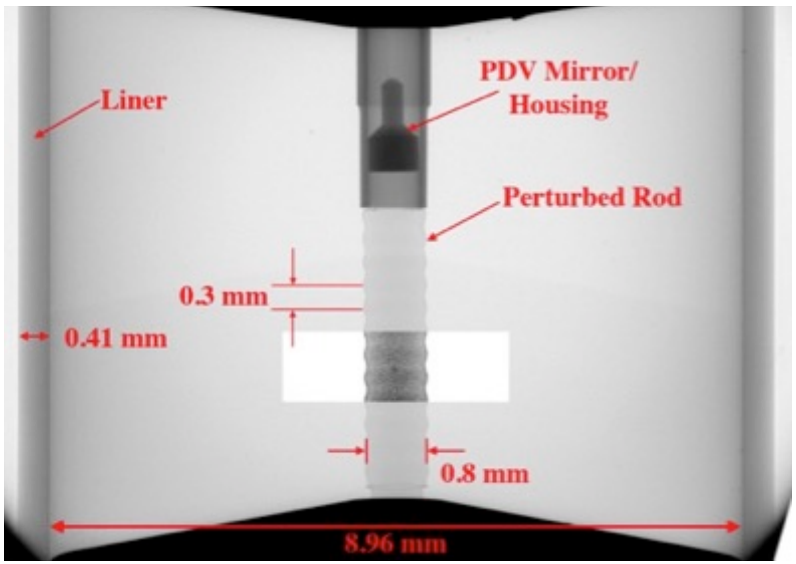
We have also started to study instability growth during the deceleration phase of liner implosions



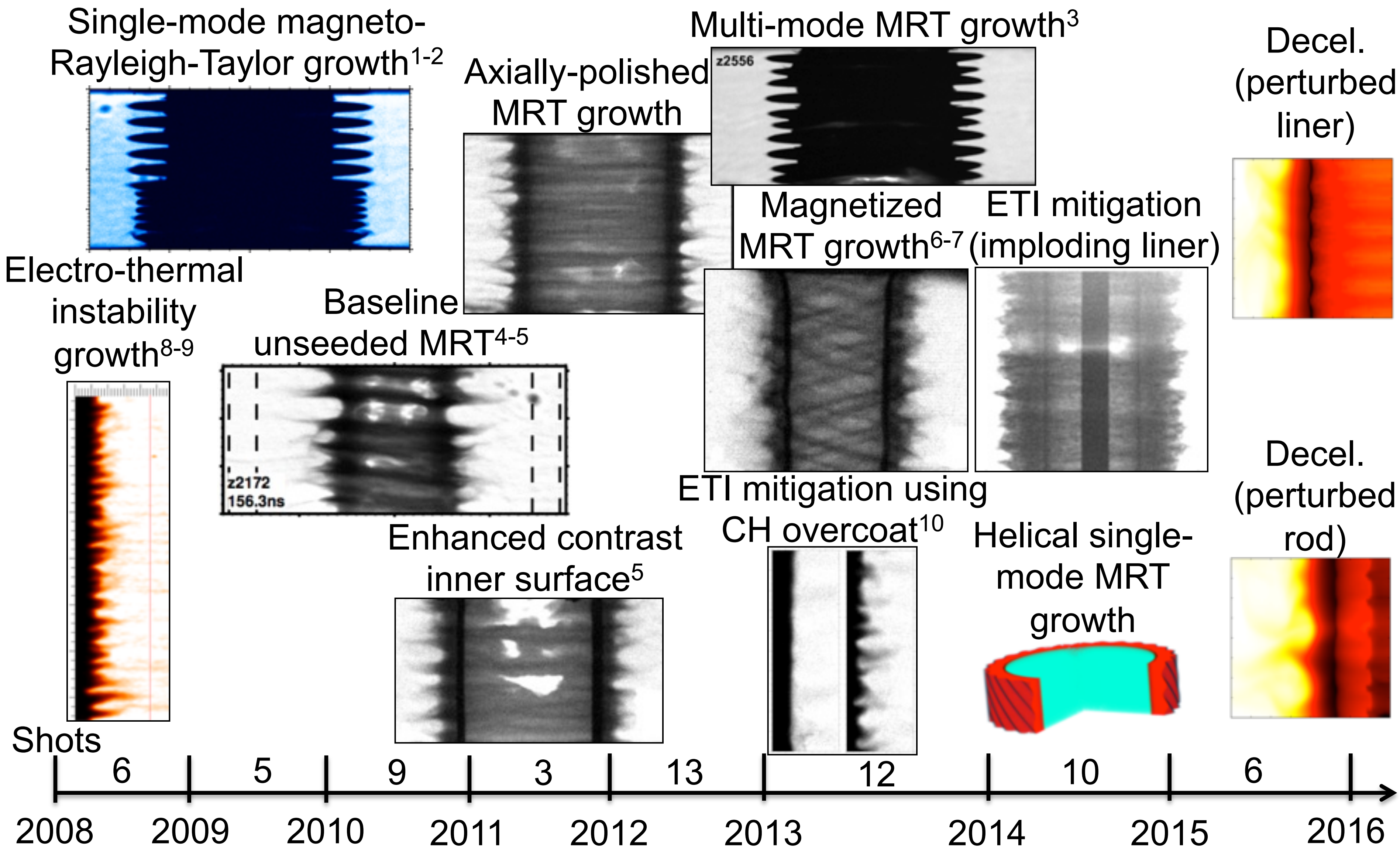




- The RM/RT unstable Be/liquid D2 interface is radiographed at shock impact
- The shock reflects off the axis and re-shock of the Be/liquid D2 interface is radiographed



Over the past several years, we performed several liner instability designed to test our modeling of magnetically driven implosions



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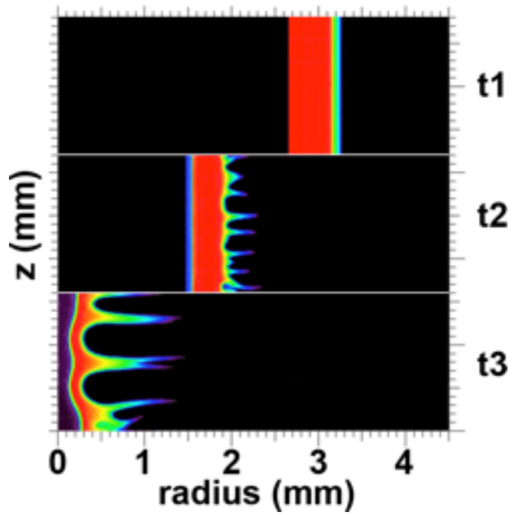
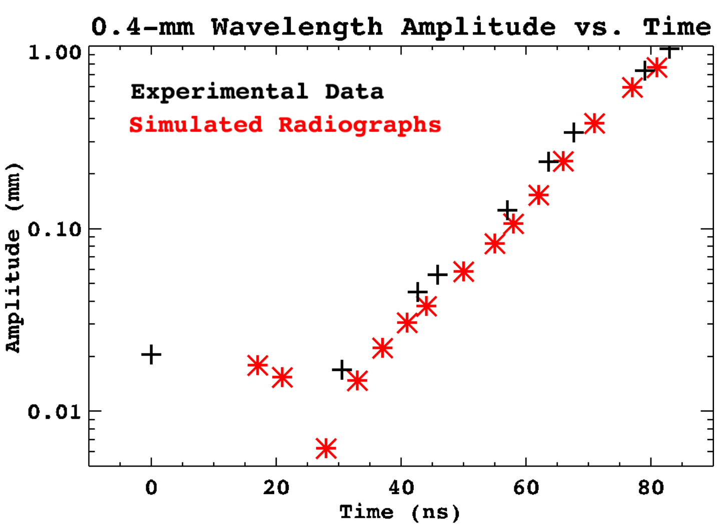
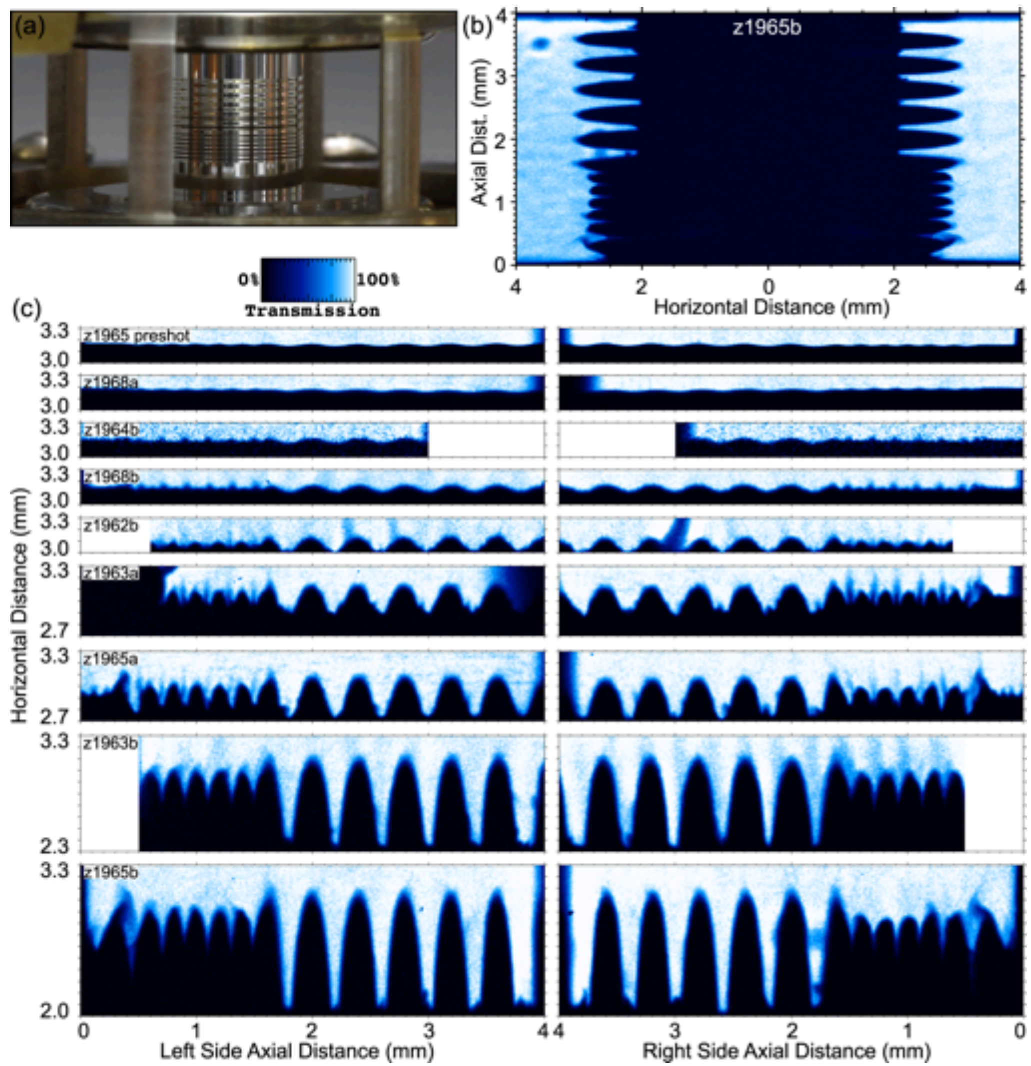
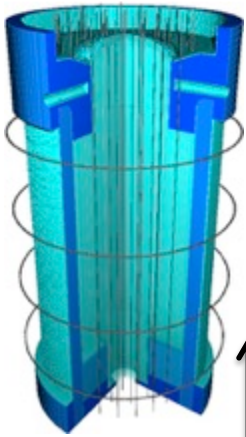
We observe excellent agreement between theory and experiment for single-mode MRT growth experiments





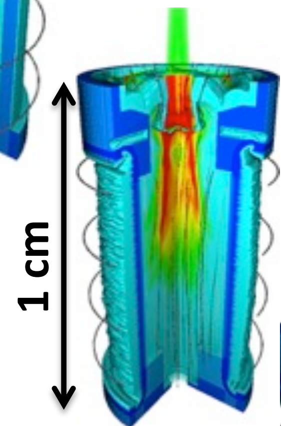


The Magnetized Liner Inertial Fusion (MagLIF) target design for Z leverages expertise from traditional ICF



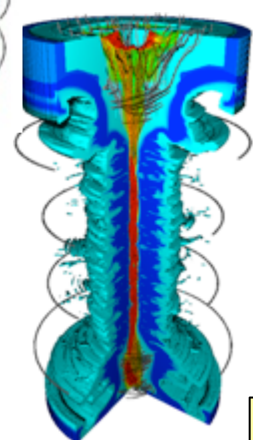
Axial Magnetic Field (10 T initially; 30 T available)

- Inhibits thermal losses from fuel to liner
- May help stabilize liner during compression
- Fusion products magnetized



Laser heated fuel (2 kJ initially; 6-10 kJ planned)

- Initial average fuel temperature 150-200 eV
- Reduces compression requirements (R_0/R_f ~ 25)
- Coupling of laser to plasma in an important science issue



Magnetic compression of fuel (~100 kJ into fuel)

- ~70-100 km/s, quasi-adiabatic fuel compression
- Low Aspect liners ($R/\Delta R$~6) are robust to hydrodynamic (MRT) instabilities
- Significantly lower pressure/density than ICF

Hahn CP12.00131
Gomez JO6.00001
Geissel JO6.00002
Jennings JO6.00003
Slutz JO6.00007
McBride GP12.00042
Woodbury GP12.00041

Goal is to demonstrate scaling: $Y\ (B_{z0}, E_{laser}, I)$
DD equivalent of 100 kJ DT yield possible on Z

S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz & R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

2D Hydra predictions of Lincoln ETI experiments show dramatic differences in instability growth