Modified 3D-helix-like instability structure for imploding Z-pinch liners that are premagnetized with a uniform axial field

SAND2014-16754PE

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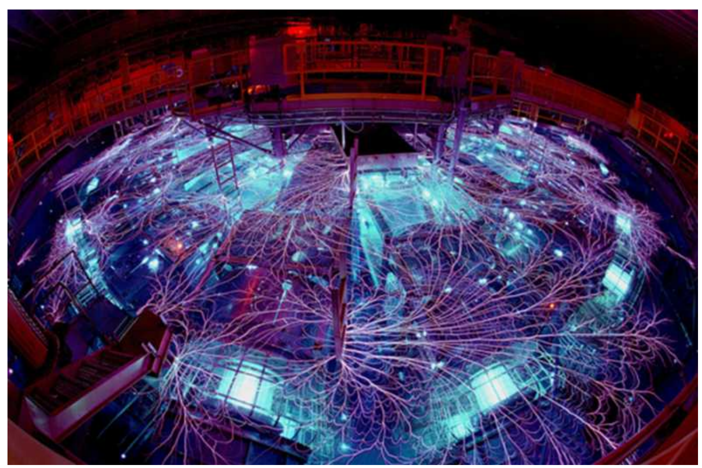

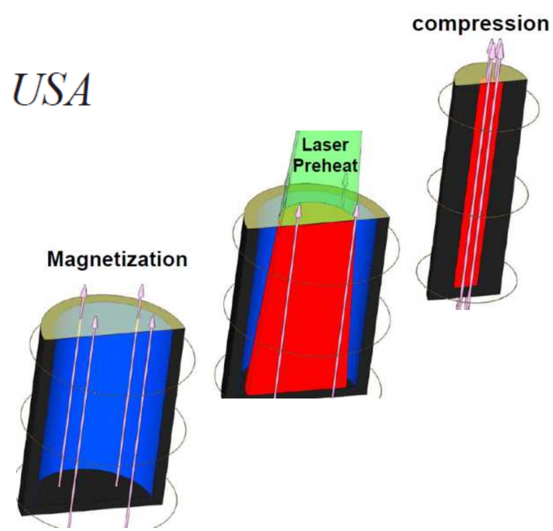

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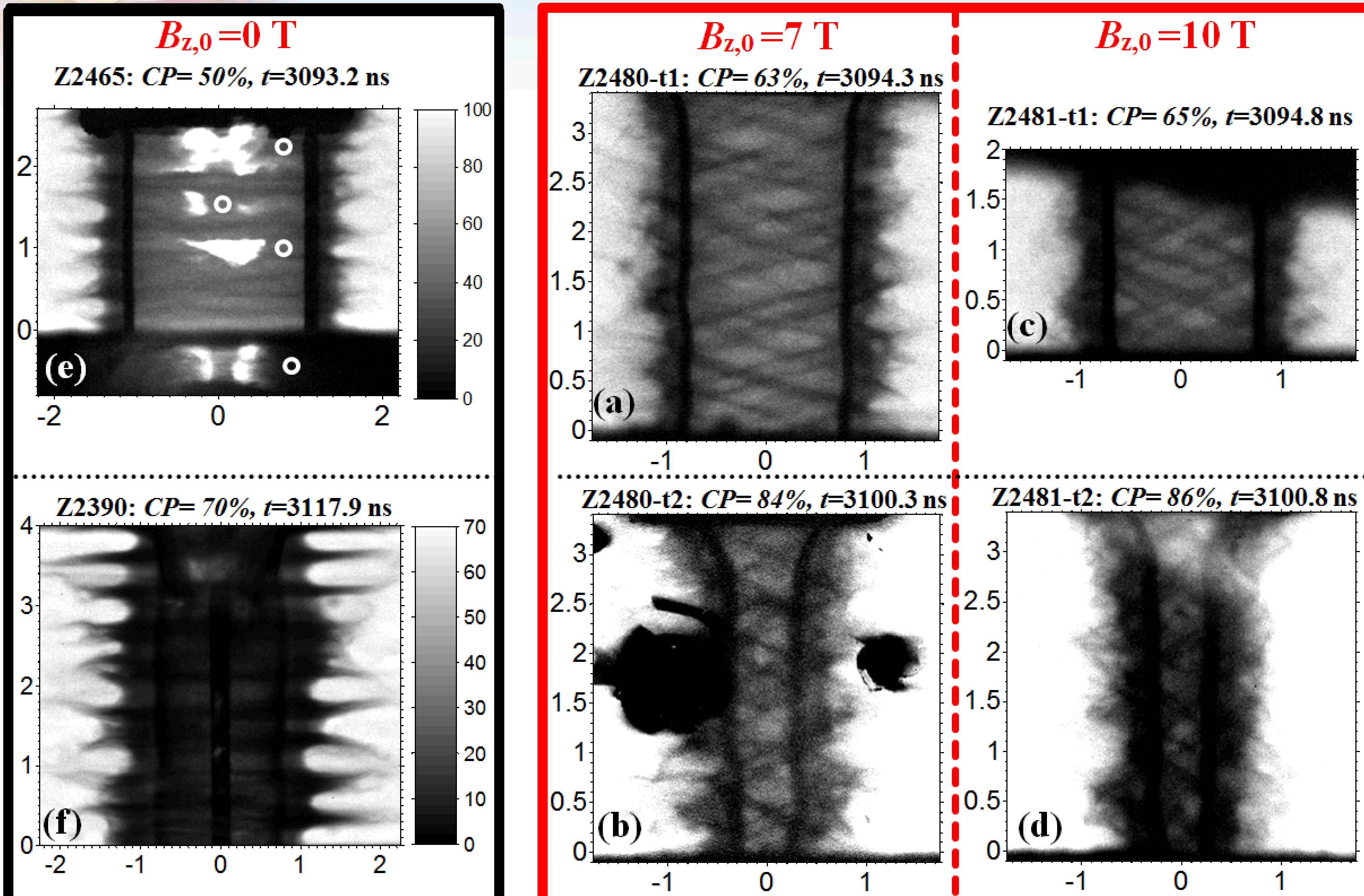
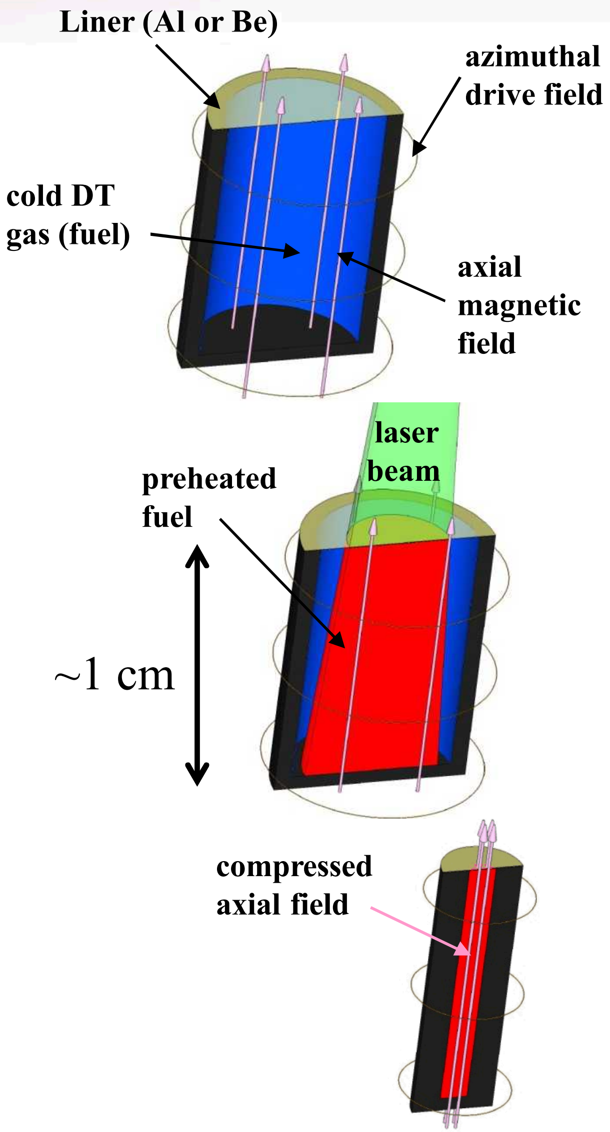
—Presentation Topic—



Azimuthally correlated MRT

Helix-like instability structure

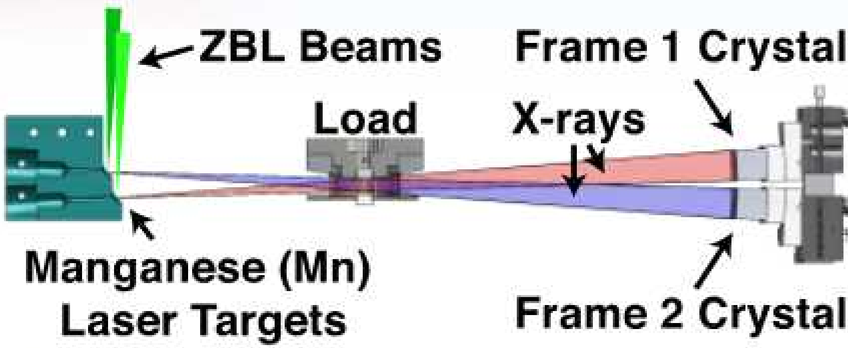
MagLIF: Fuel pre-heat & magnetization allow relatively slow implosions to achieve significant fusion yield



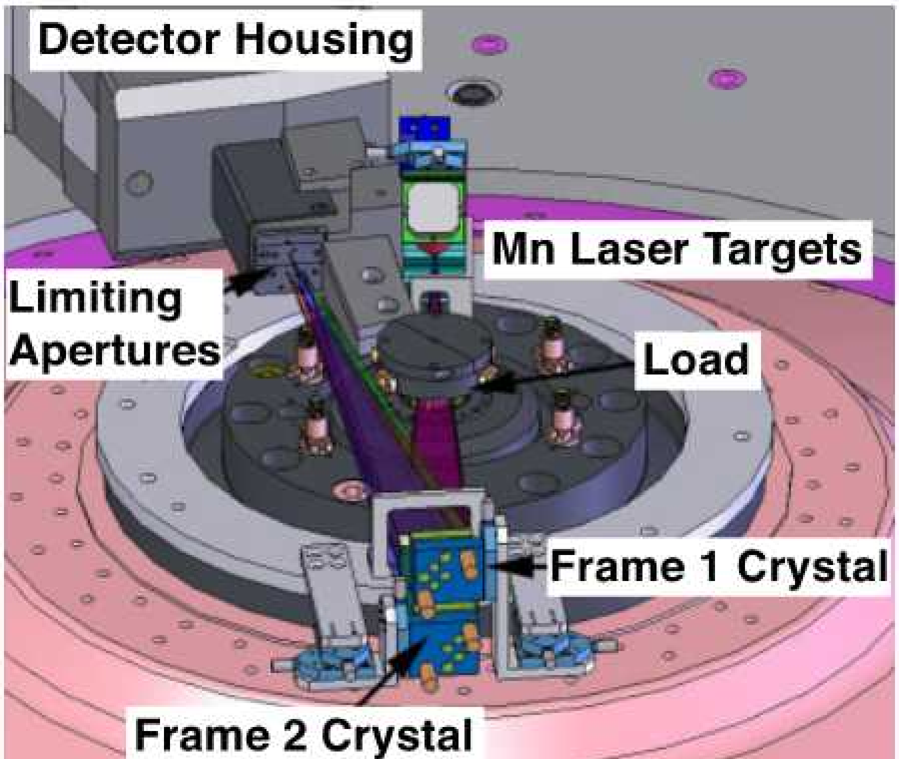
- **An initial 30 T axial magnetic field is applied**
  - **Compressed field inhibits thermal conduction losses**
  - **May help stabilize implosion at late times**
- **During the ~100 ns implosion, the fuel is heated using the Z-Beamlet laser (about 6 kJ in designs)**
  - **Preheating to ~300 eV reduces the compression needed to obtain fusion temperatures to 23 on Z**
  - **Preheating reduces the implosion velocity needed to ~100 km/s, allowing us to use thick liners that are more robust against instabilities**
- **~50-250 kJ energy in fuel; 0.2-1.4% of capacitor bank**
- **Stagnation pressure required is ~5 Gbar**
- **Gain = 1 may be possible on Z using DT (fusion yield = energy into fusion fuel, also called "scientific breakeven")**
  Early experiments would use DD fuel

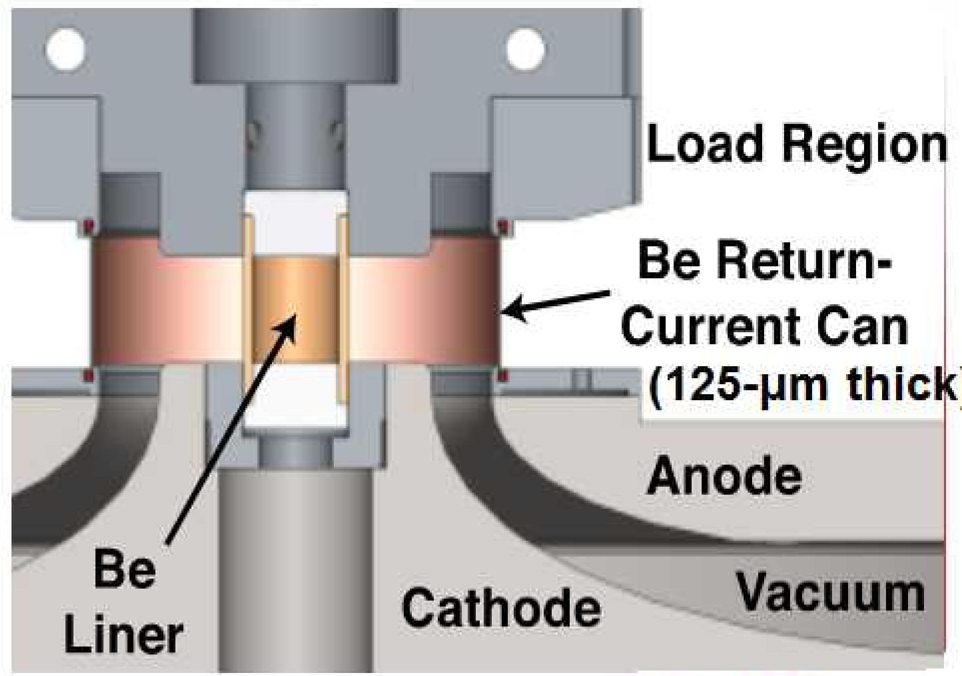
*S.A. Slutz *et al.*, Phys. Plasmas **17**, 056303 (2010); Slutz and Vesey, Phys. Rev. Lett. **108**, 025003 (2012)

Presentation focuses on liner dynamics; primary diagnostic is two-frame monochromatic (6151±0.5 eV) radiography*



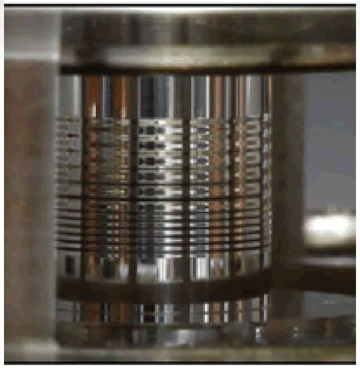
- Spherically-bent quartz crystals (22$\underline{4}$3)
- 15 micron resolution (edge-spread)
- We can see through imploding beryllium (not so for aluminum and other higher-opacity materials).

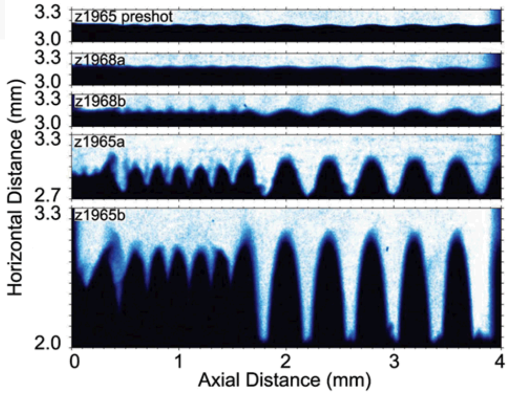




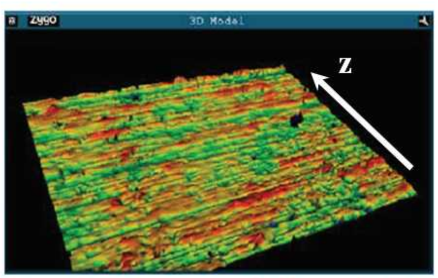
* G. R. Bennett *et al.*, RSI (2008).

Experiments have focused on developing predictive capability of instability growth of imploding liners

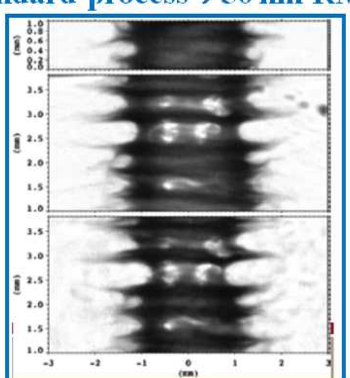


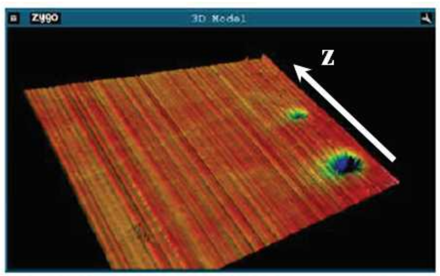


D.B. Sinars *et al.*, Phys. Rev. Lett. 105, 185001 (2010)
D.B. Sinars, Invited Presentation, 2010 APS-DPP

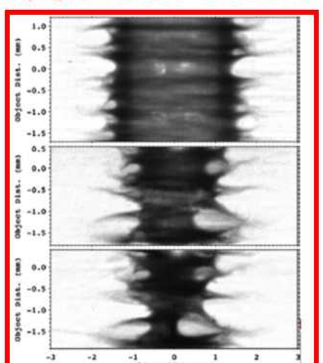


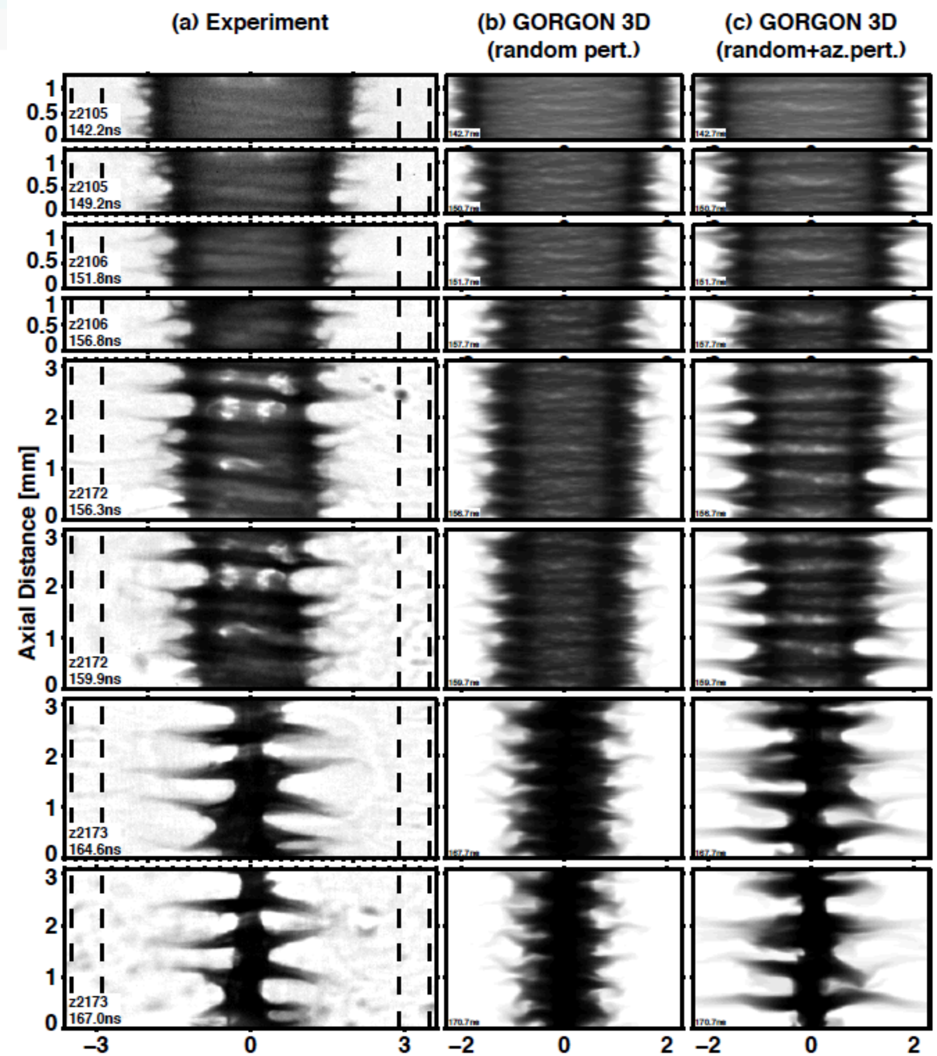
Standard process→50 nm RMS





Axially polished→50 nm RMS





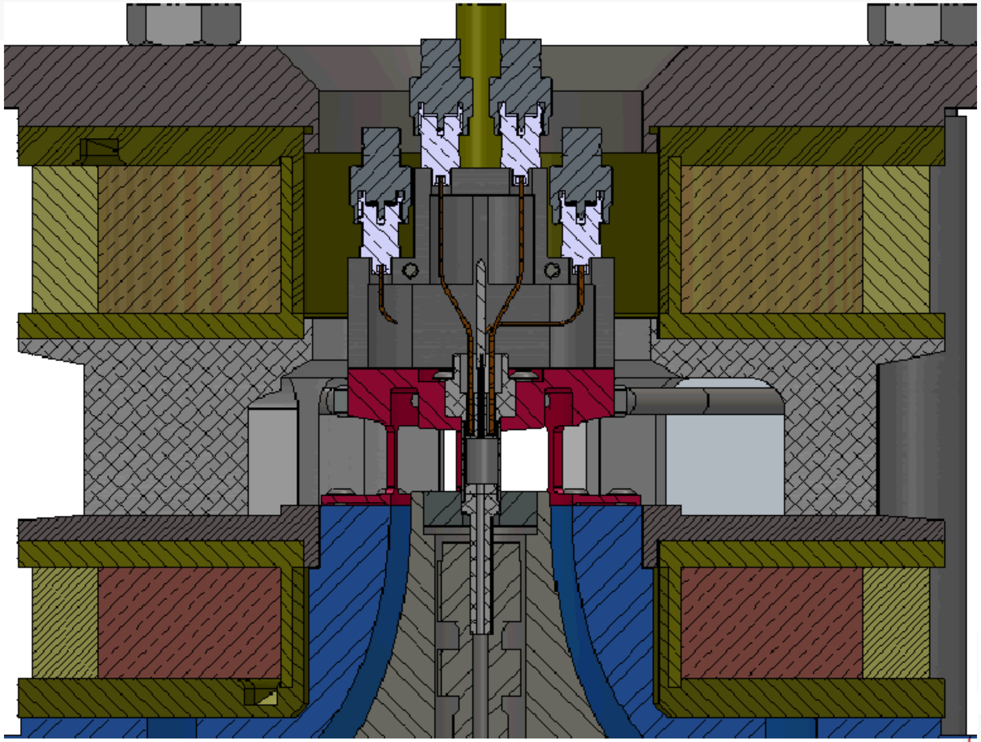
R.D. McBride *et al.*, PRL 109, 135004 (2012)
R.D. McBride, Invited Presentation, 2012 APS-DPP

MagLIF Helmholtz-like coil pair first fielded on Z imploding-liner experiments in February of 2013

Field strength requirements:

−10 T seed field with full diagnostic access

−30 T coils will have limited diagnostic access



Capacitor bank

2x4 mF, V_{max} = 15 kV

Use: 4 mF, 7 kV, 8.6 kA, 10 T

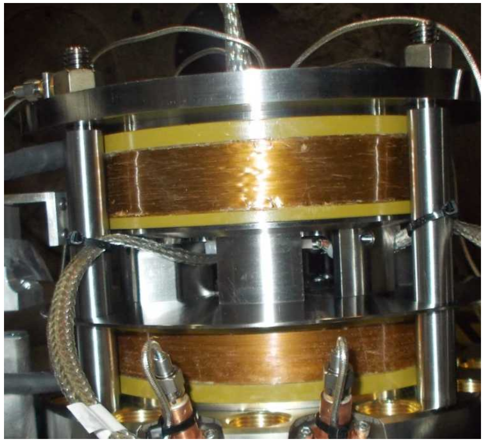
Pulse length requirement:

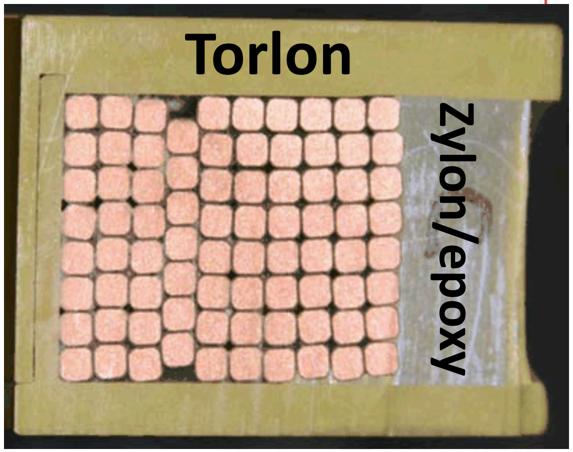
−Coil: ~1 mH

− Must not crush or buckle target or hardware

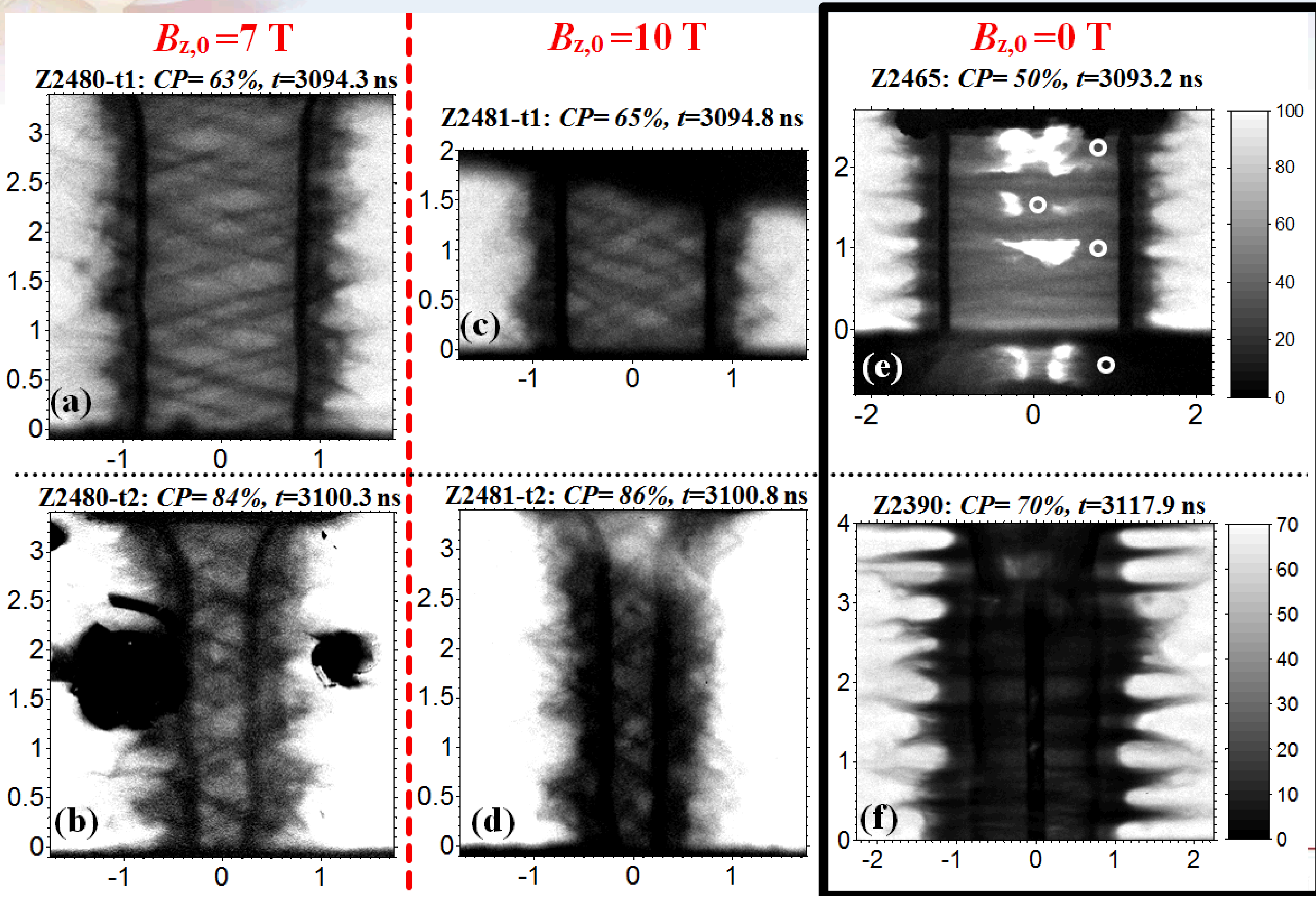
− Fully magnetize liner/fuel with uniform field

− 3.5 ms risetime used





Helix-like instabilities develop on premagnetized liners

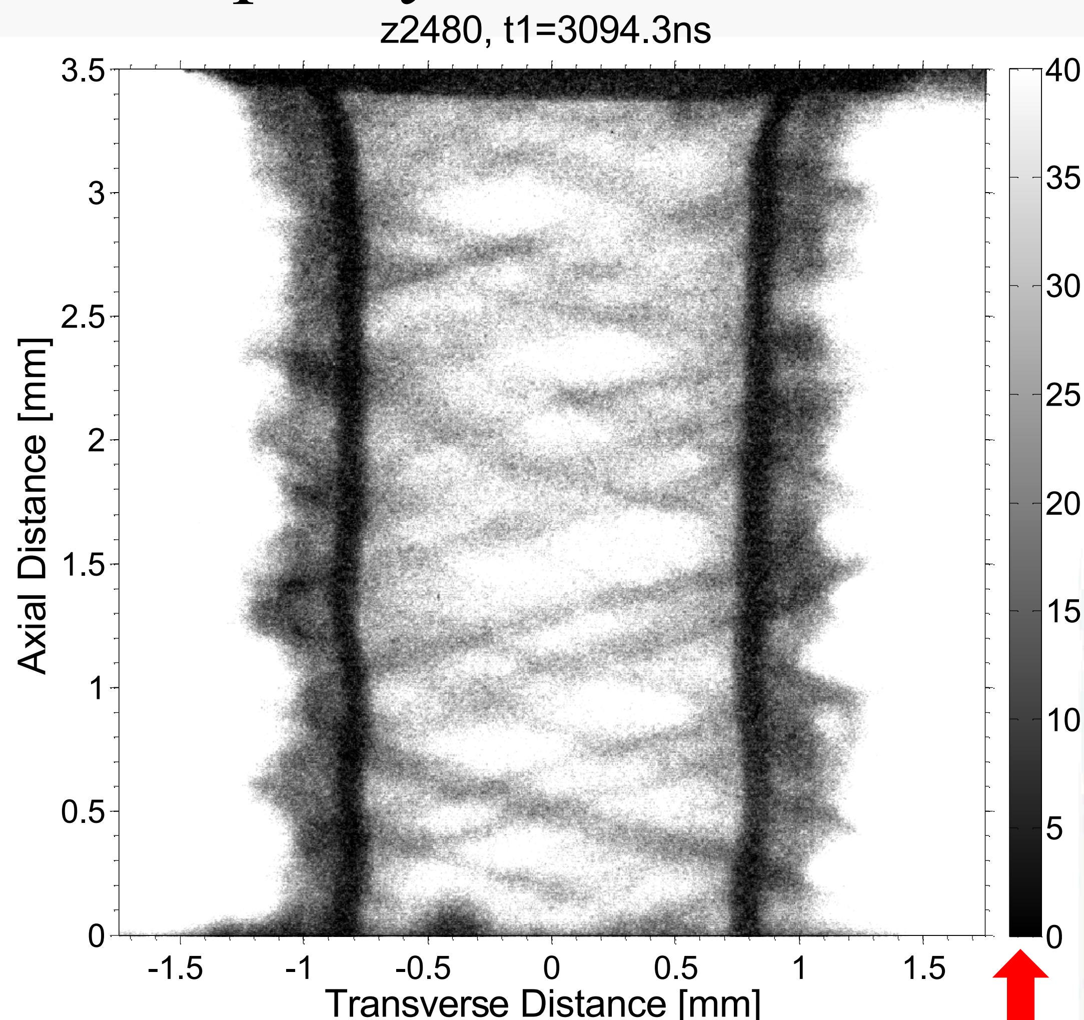


T.J. Awe *et al.*, accepted for publication in *Physical Review Letters*

Well-connected helical structures are easily traced through multiple cycles

High-density structures are at large angle to the z axis

Penetrating radiography "sees" structures at "front" and "back" of liner, so structures with positive and negative slope are observe. This results in the observed cross-hatched pattern



Black=0 % Transmission
White=40% Transmission

Well-connected helical structures are easily traced through multiple cycles

High-density structures are at large angle to the z axis

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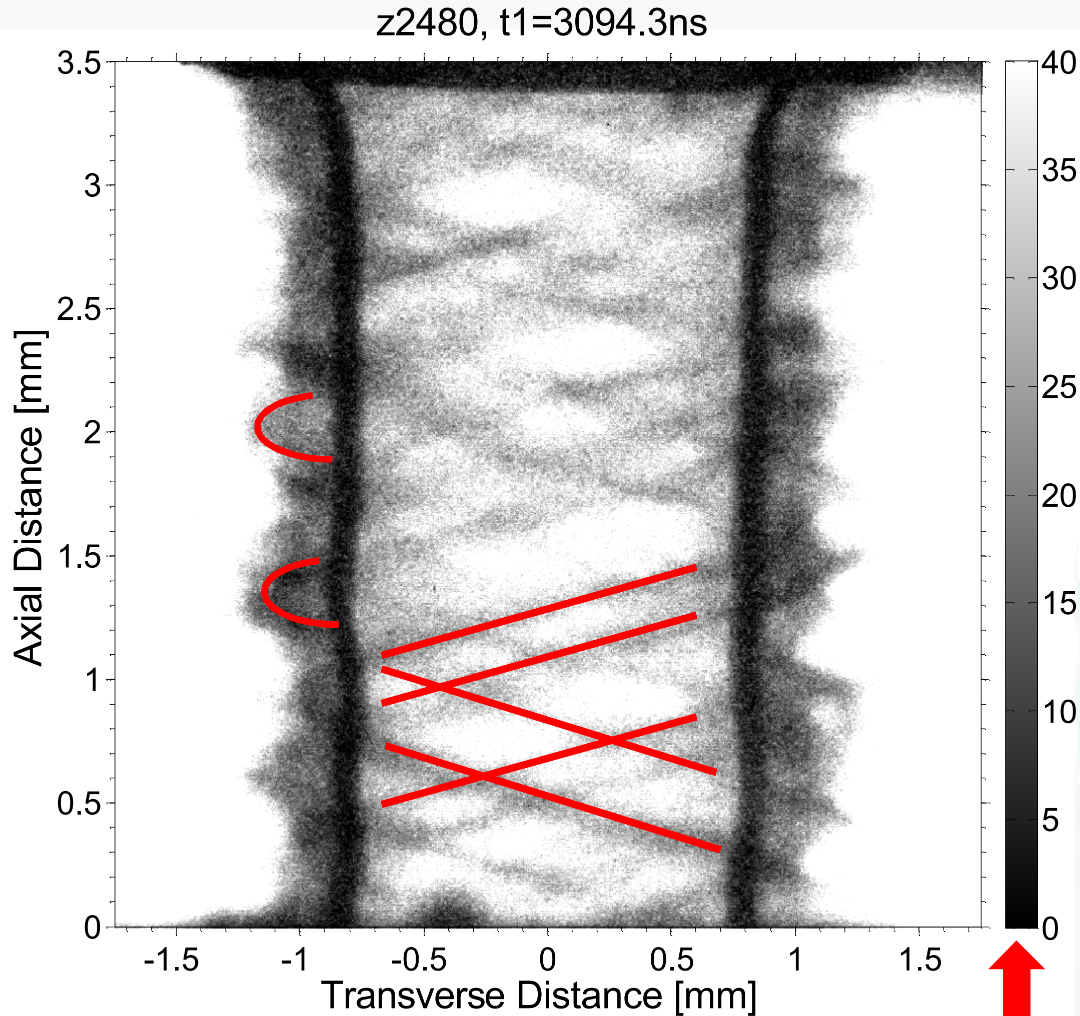
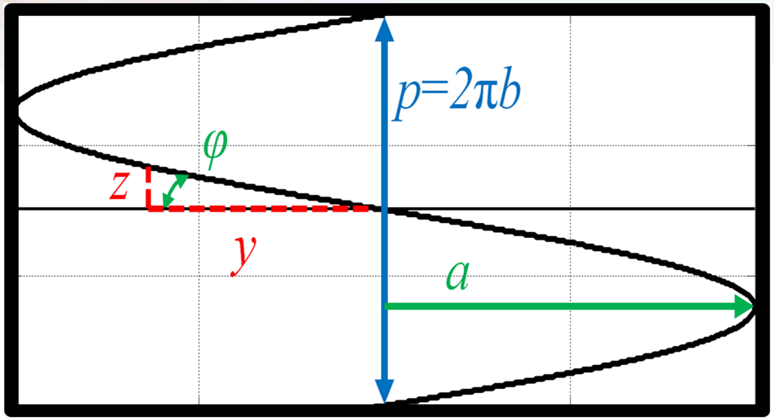


Black=0 % Transmission
White=40% Transmission

A simple cylindrical helix model fits the data well



Cylindrical helix model

$y(\theta)=a\cdot\sin(\theta)$

$z(\theta)=p\cdot\theta/2\pi$

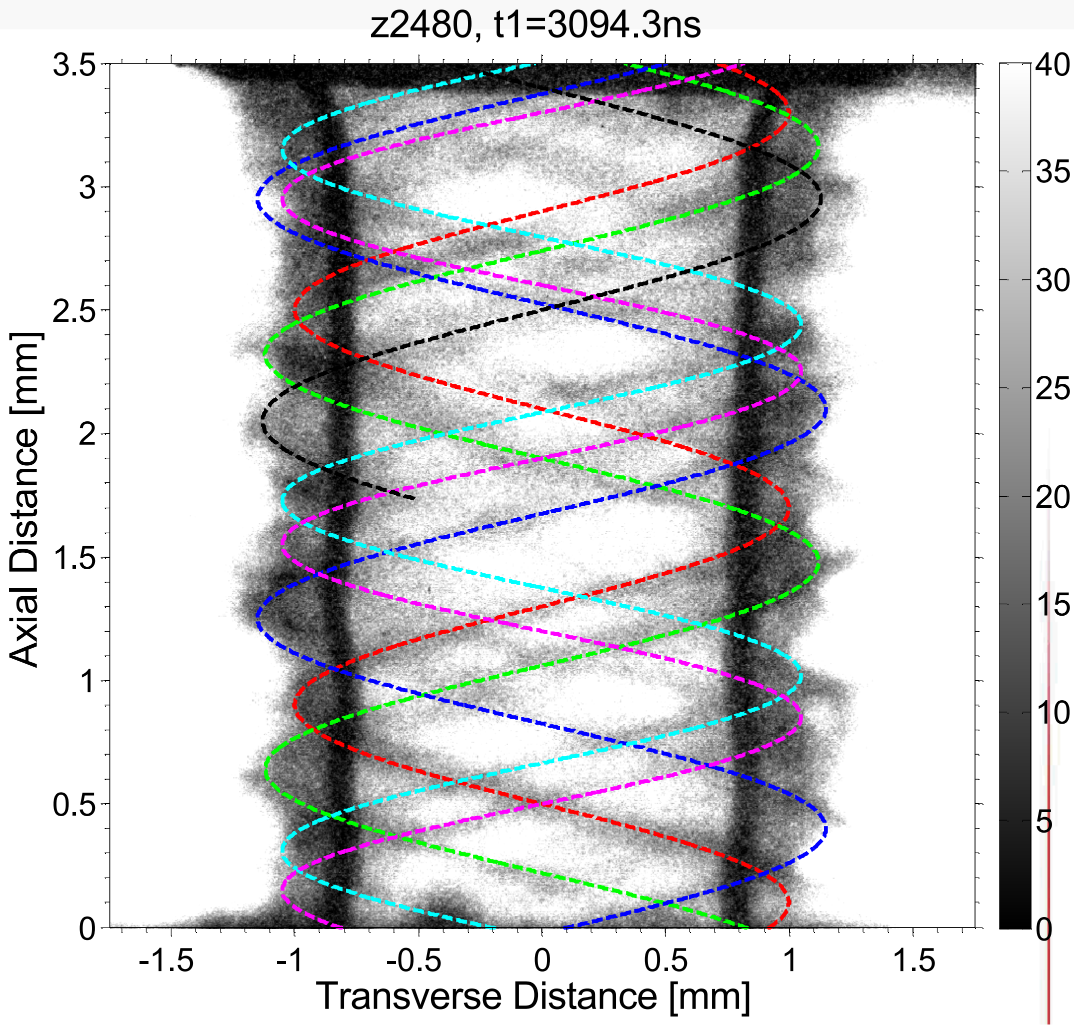
a =radius

p=pitch

"pitch angle"

$\varphi=\tan^{-1}(z/y)$

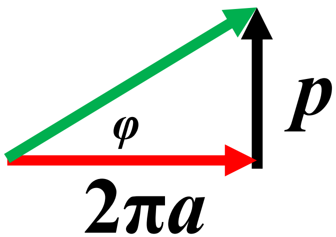
$\varphi\approx\tan^{-1}(p/2\pi a)$



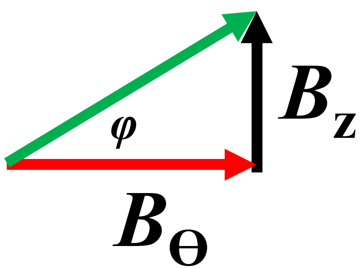
$\mathbf{a_{avg}=1.07\ mm}$

$\mathbf{p_{avg}=1.56\ mm}$

$B_Z + B_\Theta$ magnetic field streamlines follow a helical path along a cylindrical surface



$$p = 2\pi a \tan(\varphi)$$
-or-
$$\varphi = \tan^{-1}(p/2\pi a)$$

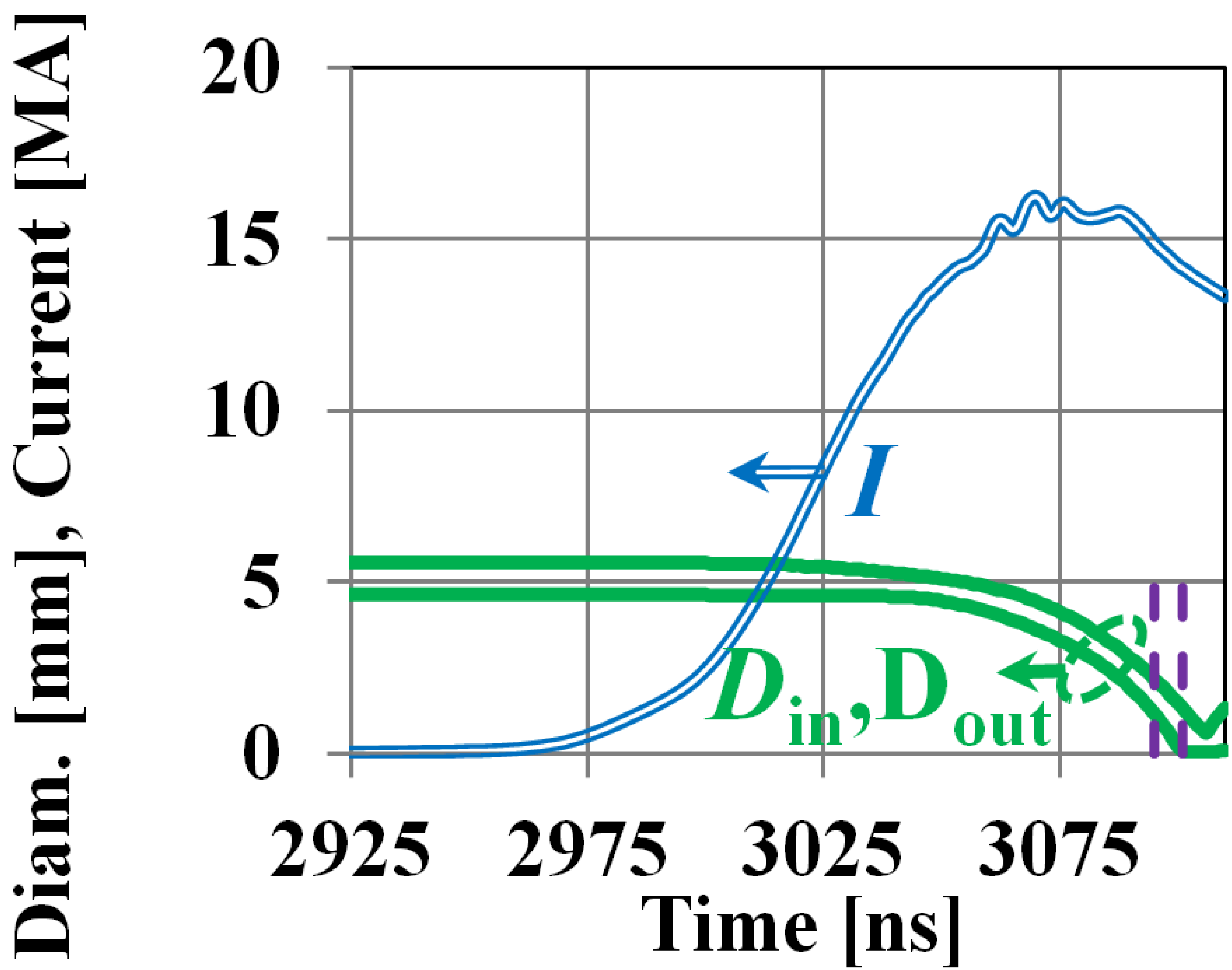


$$B_z/B_\Theta = \tan(\varphi_B)$$
-or-
$$\varphi_B = \tan^{-1}(B_z/B_\Theta)$$

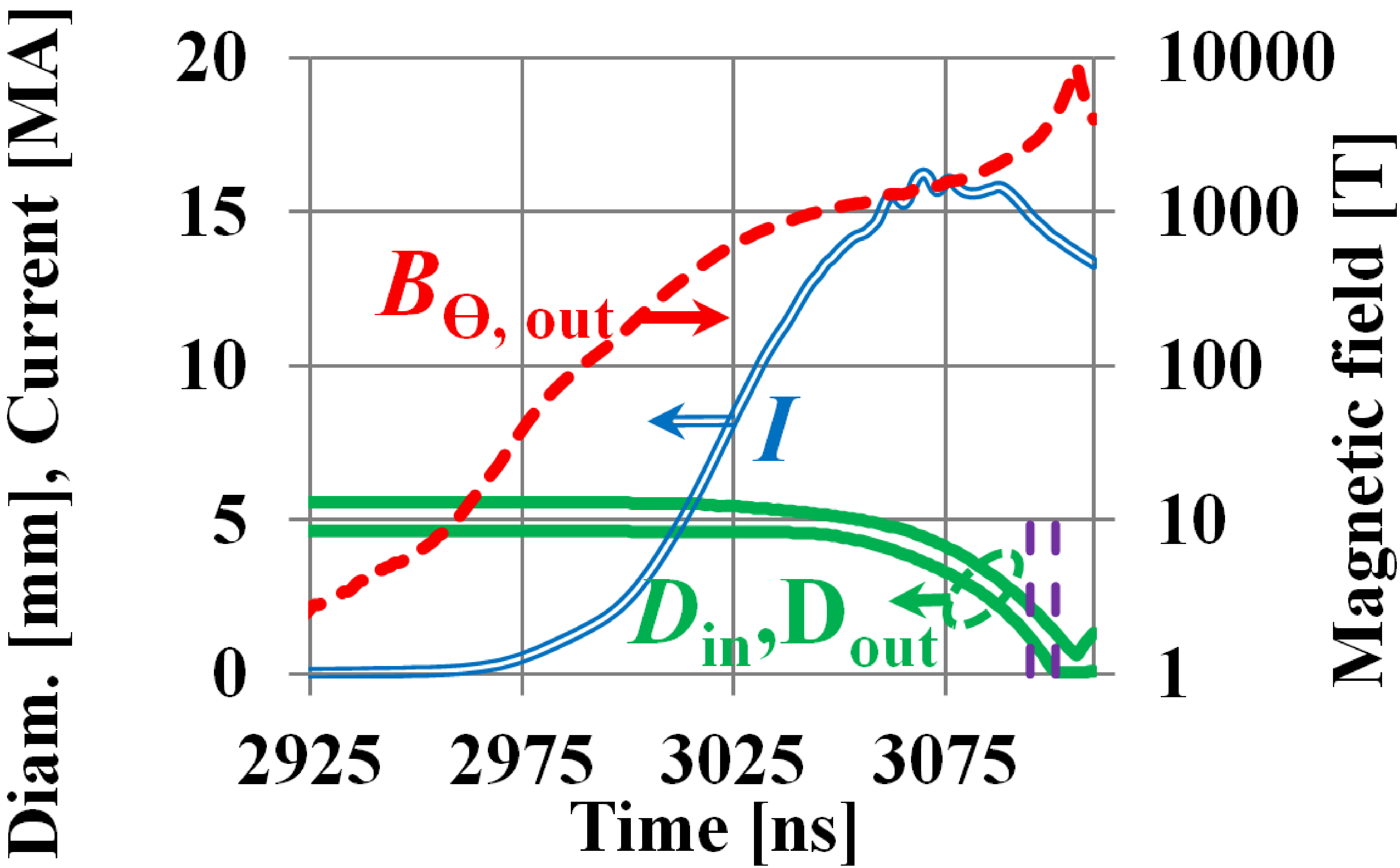
$$p_B = 2\pi a(B_z/B_\Theta)$$

- MRT theory shows that instabilities will have the highest growth rate for $\mathbf{k} \cdot \boldsymbol{B} = 0$
  - If a helical magnetic field topology can be maintained, helical instability structure is to be expected

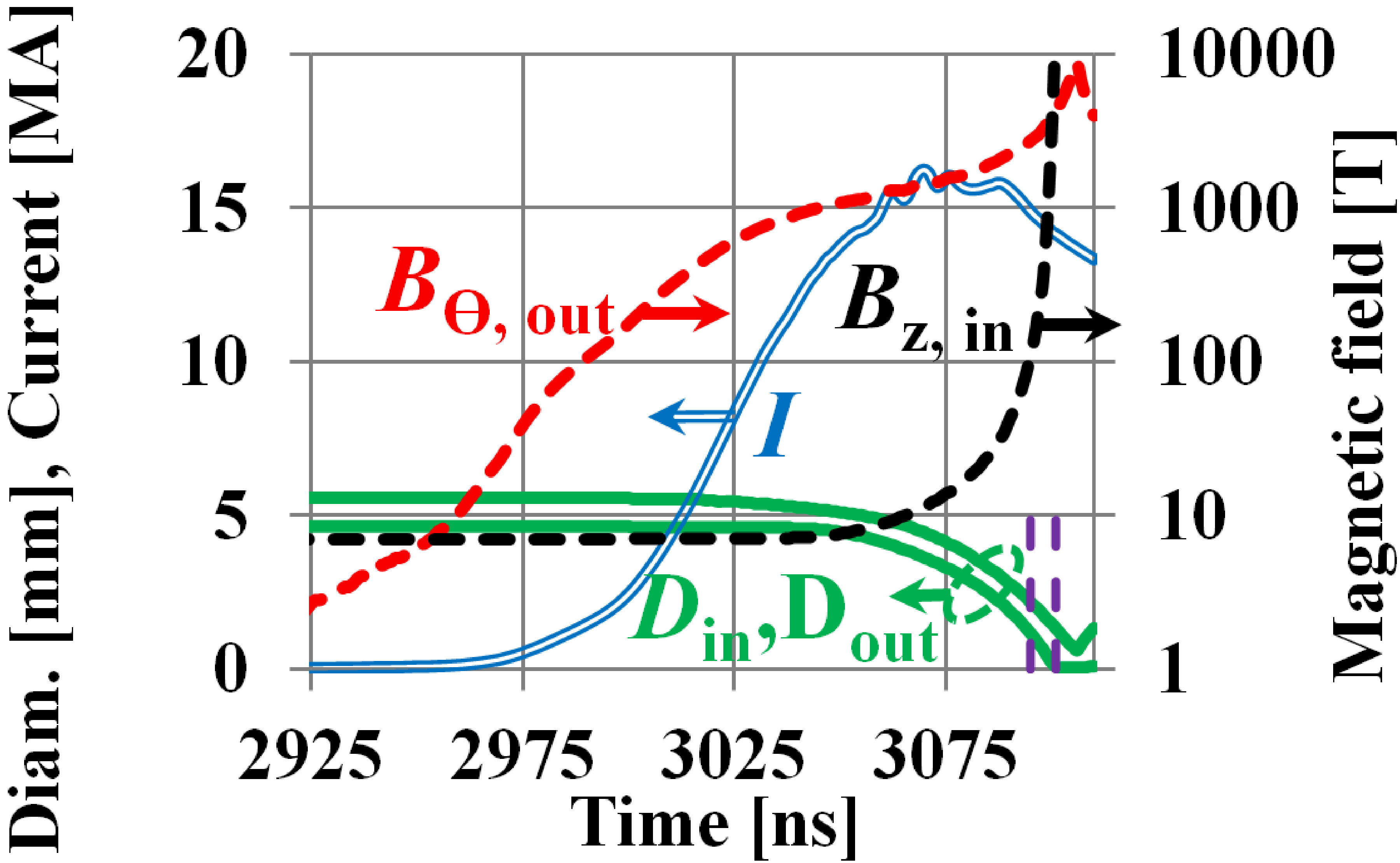
The time-dependent pitch angle of the magnetic field streamline on the liner surface can be estimated



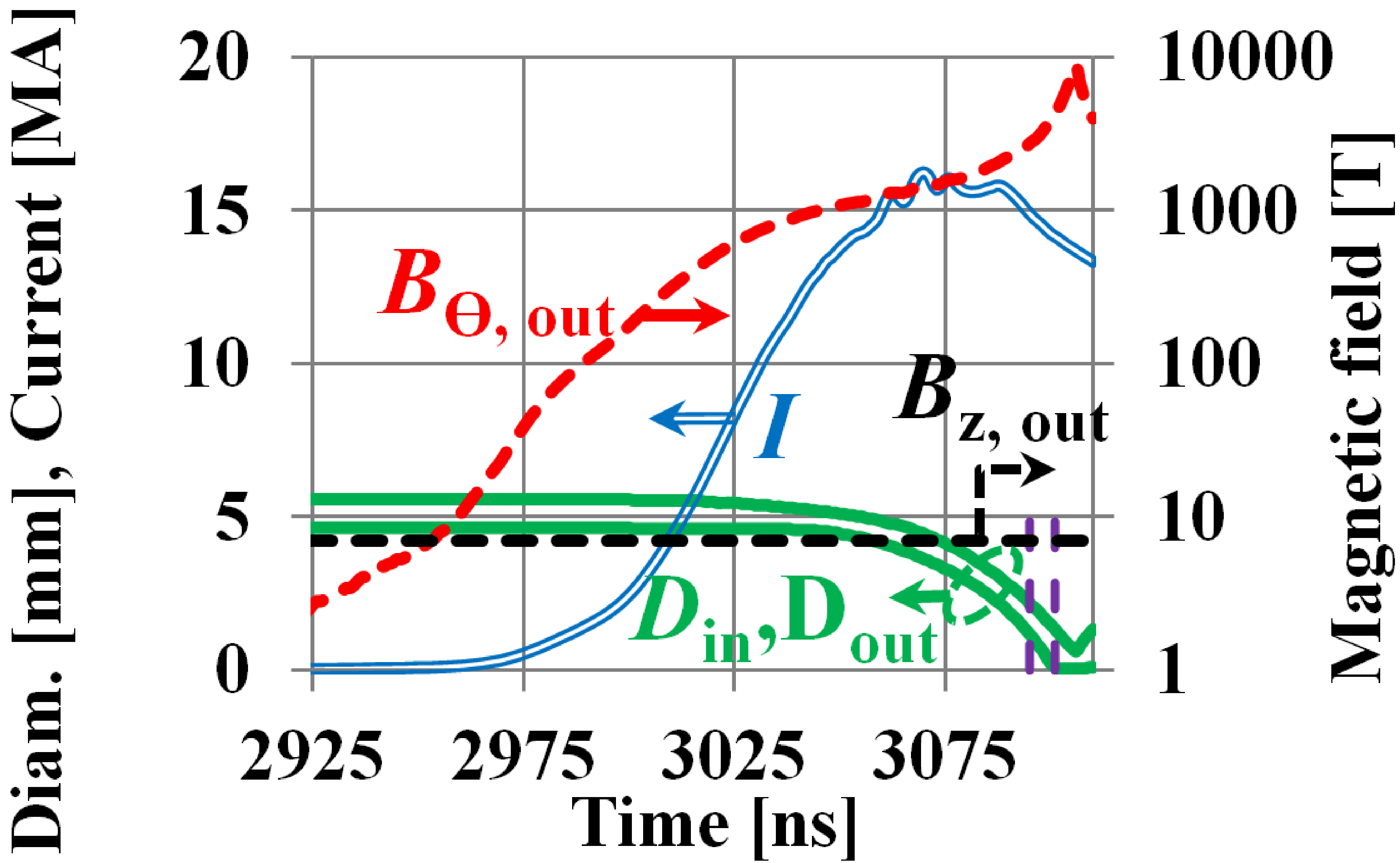
B_Θ is calculated using the experiment current and GORGON liner trajectory



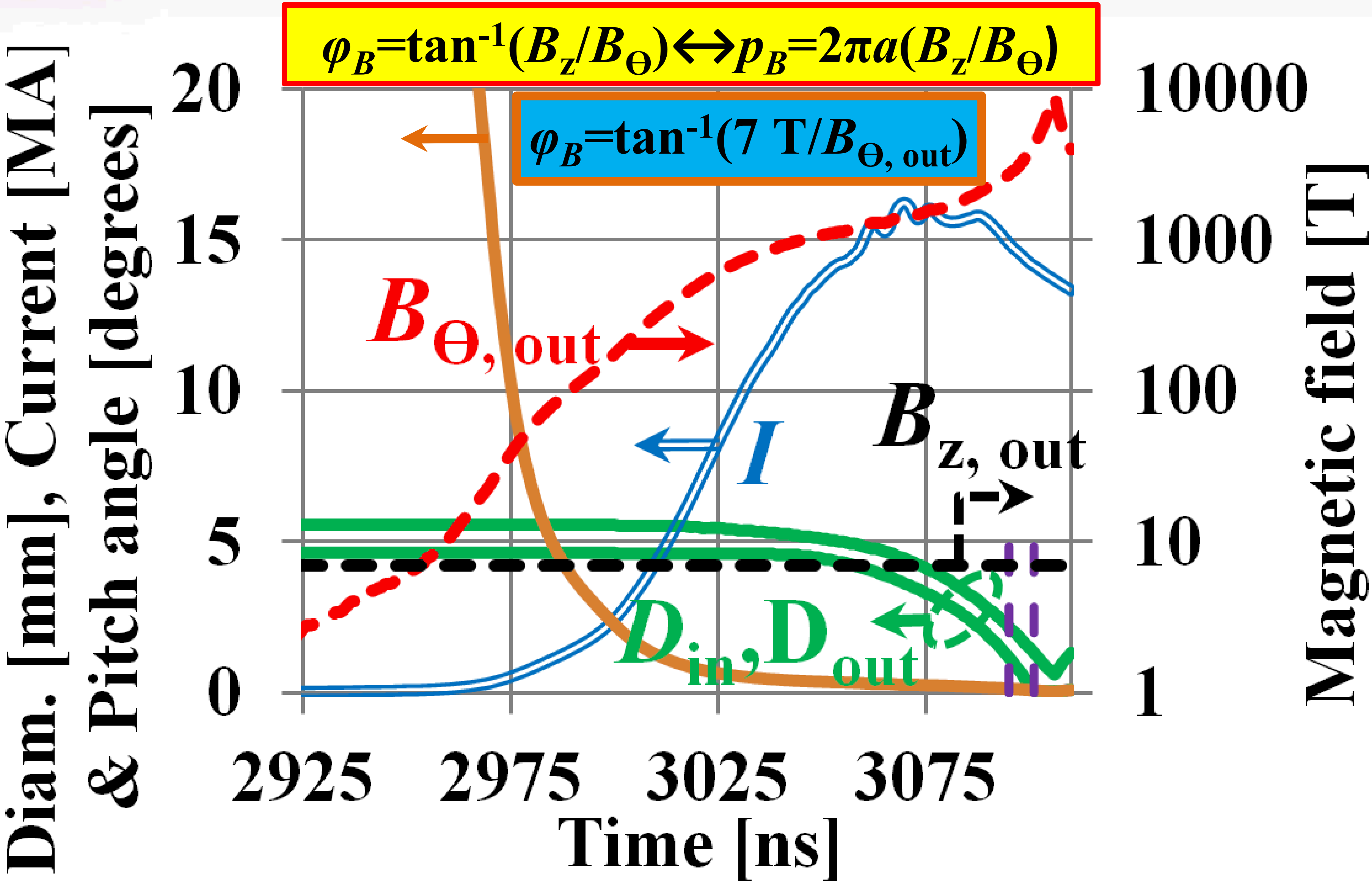
$B_{z,\,in}$ is calculated using $B_{z,0}$=7 T, GORGON liner trajectory, and by assuming perfect flux conservation



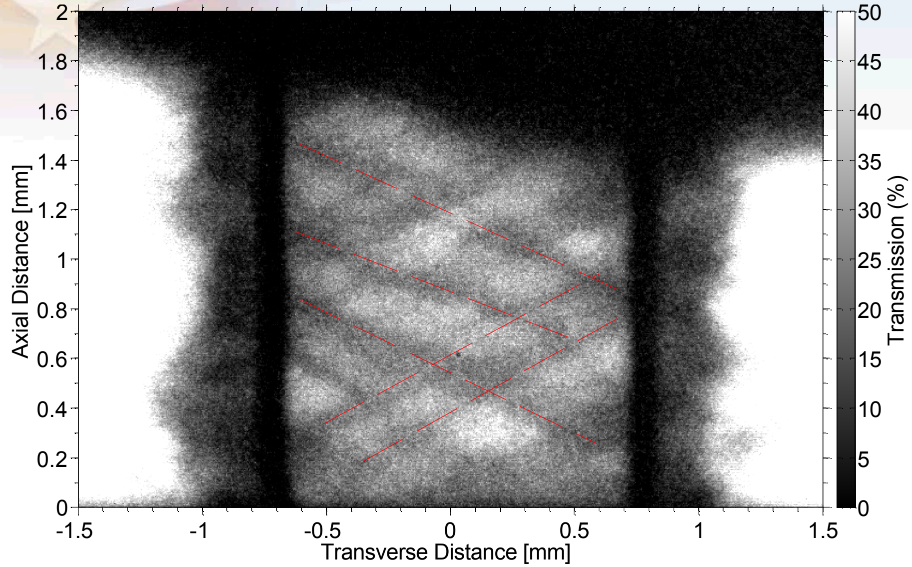
Helical perturbations presumably grow from the liner's surface, so the nearly constant $B_{z,out}$ is most pertinent



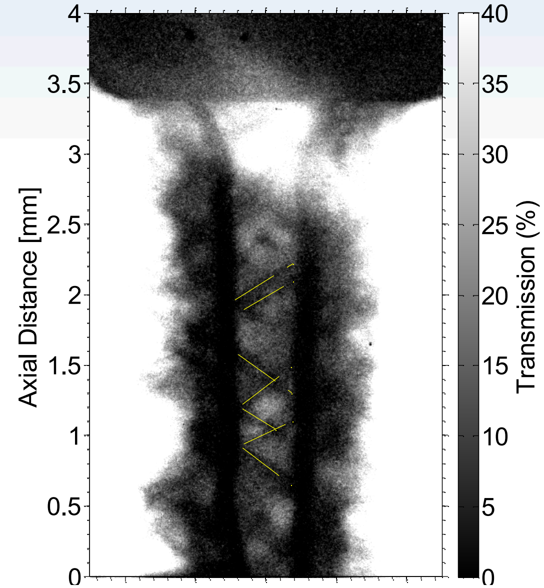
Briefly, $B_\Theta \approx B_z$ early in the experiment, but presumably $B_\Theta >> B_z$ throughout the entire implosion



The pitch angle, φ, can be obtained for all radiographs



φ_{avg}=26°



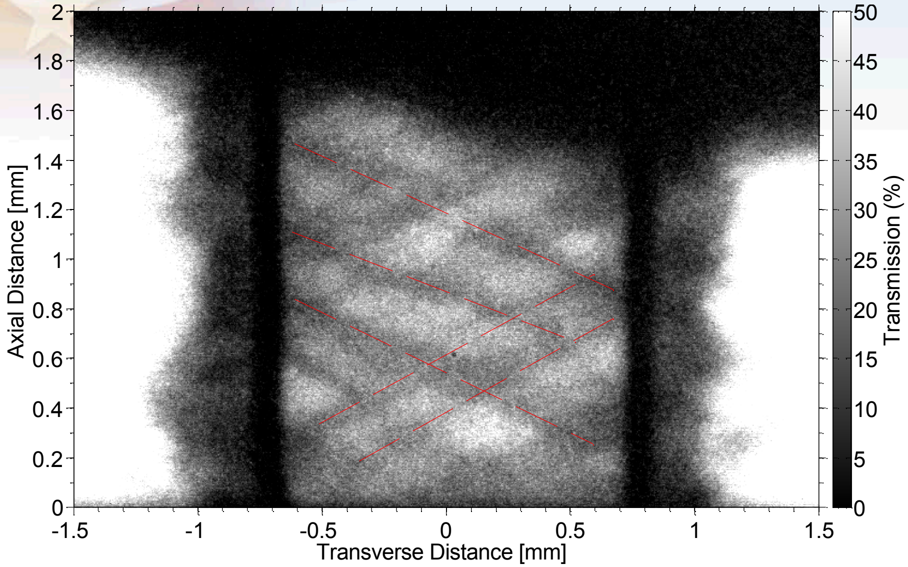
φ_{avg}=33°

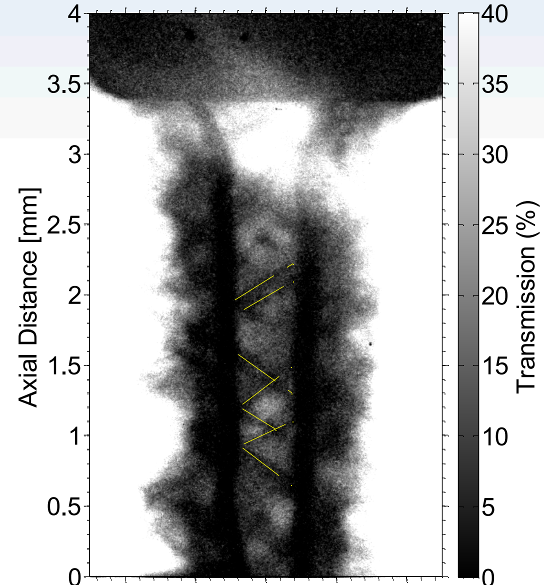
Radiograph	2480-t1	2480-t2	2481-t1	2481-t2
$B_{z,0}$ [T]	7		10	
Radiograph time [ns]	3094.3	3100.3	3094.8	3100.8
$R_{in,avg.}(t)$ [μm]	870±25	365±30	810±30	335±30
$CR=R_{in,0}/ R_{in}(t)$	2.7±0.1	6.4±0.5	2.9±0.1	6.9±0.6
# of lines fit	8	8	5	7
φ_{Avg} [deg]	**16.4**	**25.6**	**25.9**	**32.9**
Std. Dev. [deg]	1.6	1.2	2.9	4.2

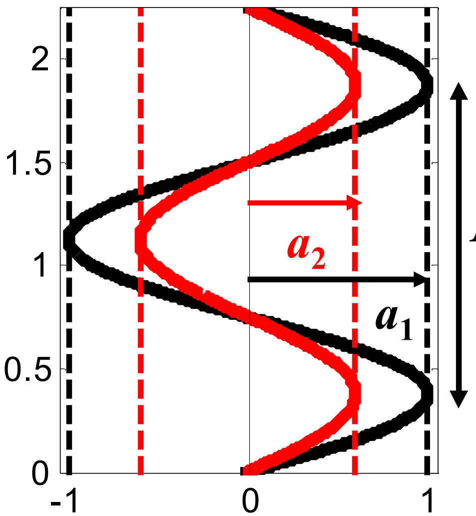
φ_{avg} increases with both $B_{z,0}$ and liner convergence

Increasing $\varphi_{avg} \approx \tan^{-1}(p/2\pi a)$ → pitch changes slowly relative to implosion; helices are entrained in liner wall

For constant pitch, the pitch angle will grow large







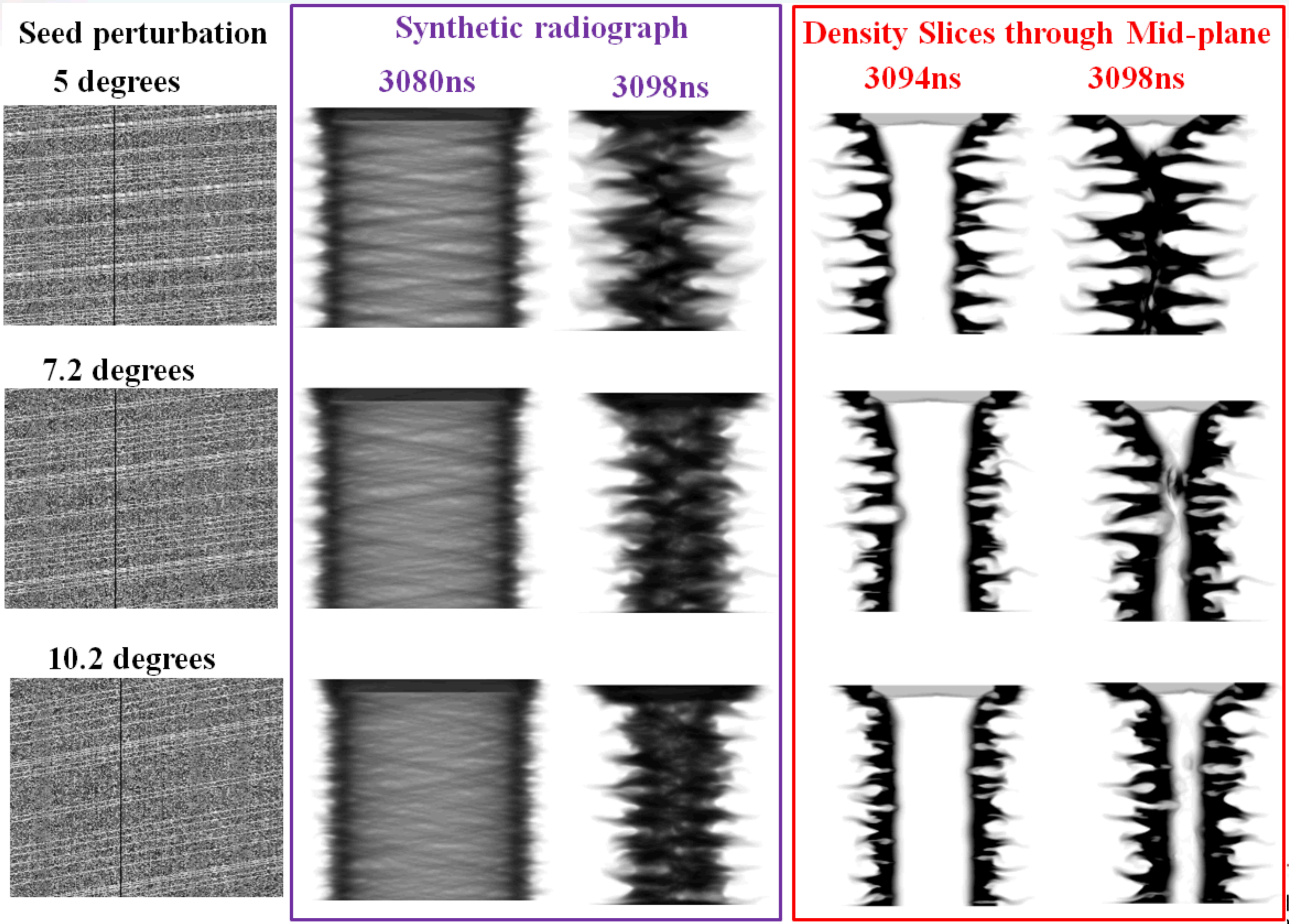
p≈constant

$C \equiv a_1/a_2$

$\varphi_{t2} = \tan^{-1}(C \cdot \tan(\varphi_{t1}))$

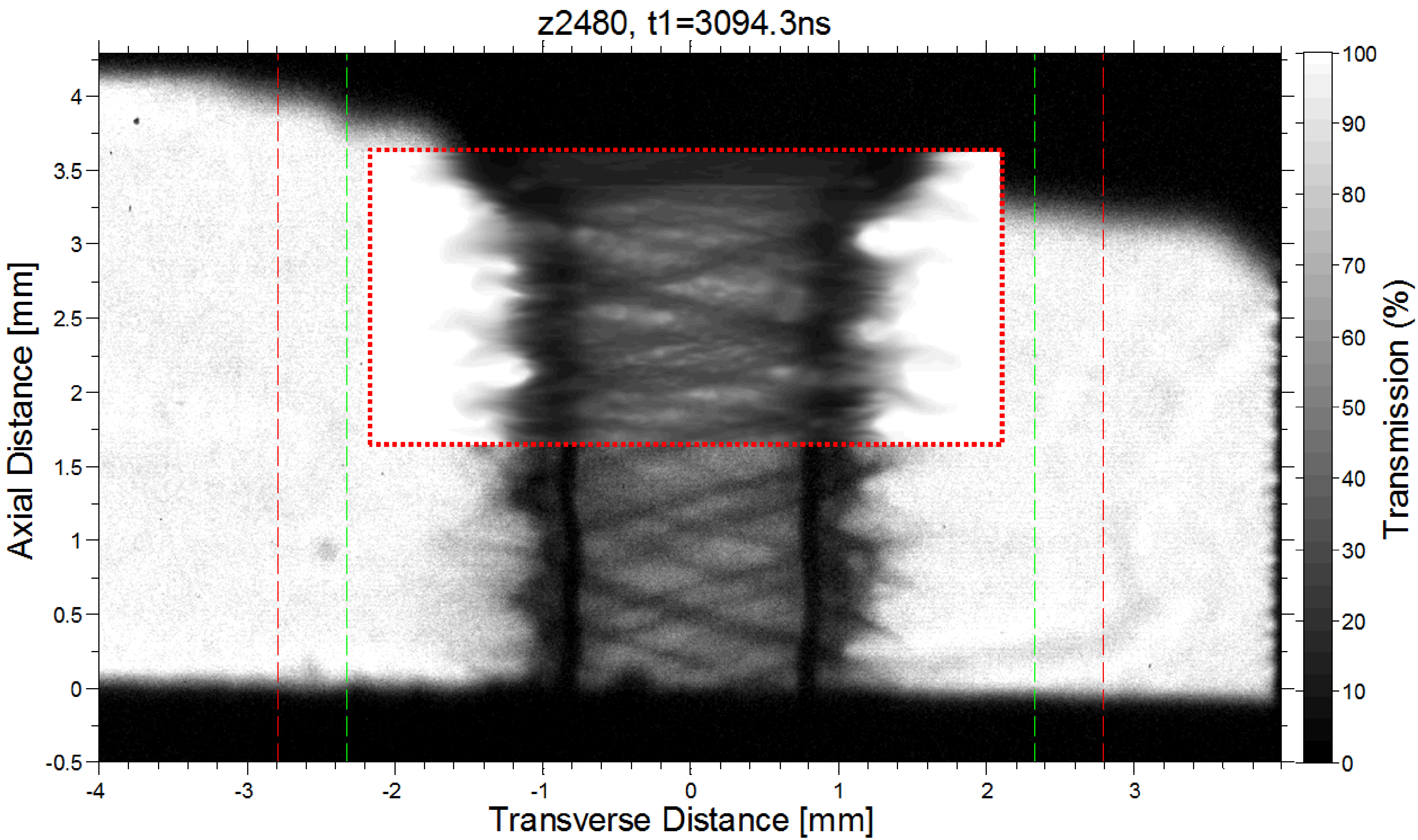
Increasing $\varphi_{avg} \approx \tan^{-1}(p/2\pi a)$ → pitch changes slowly relative to implosion; helices are entrained in liner wall

3D MHD simulations show that an initial helical perturbation will grow in amplitude and pitch angle as the liner converges

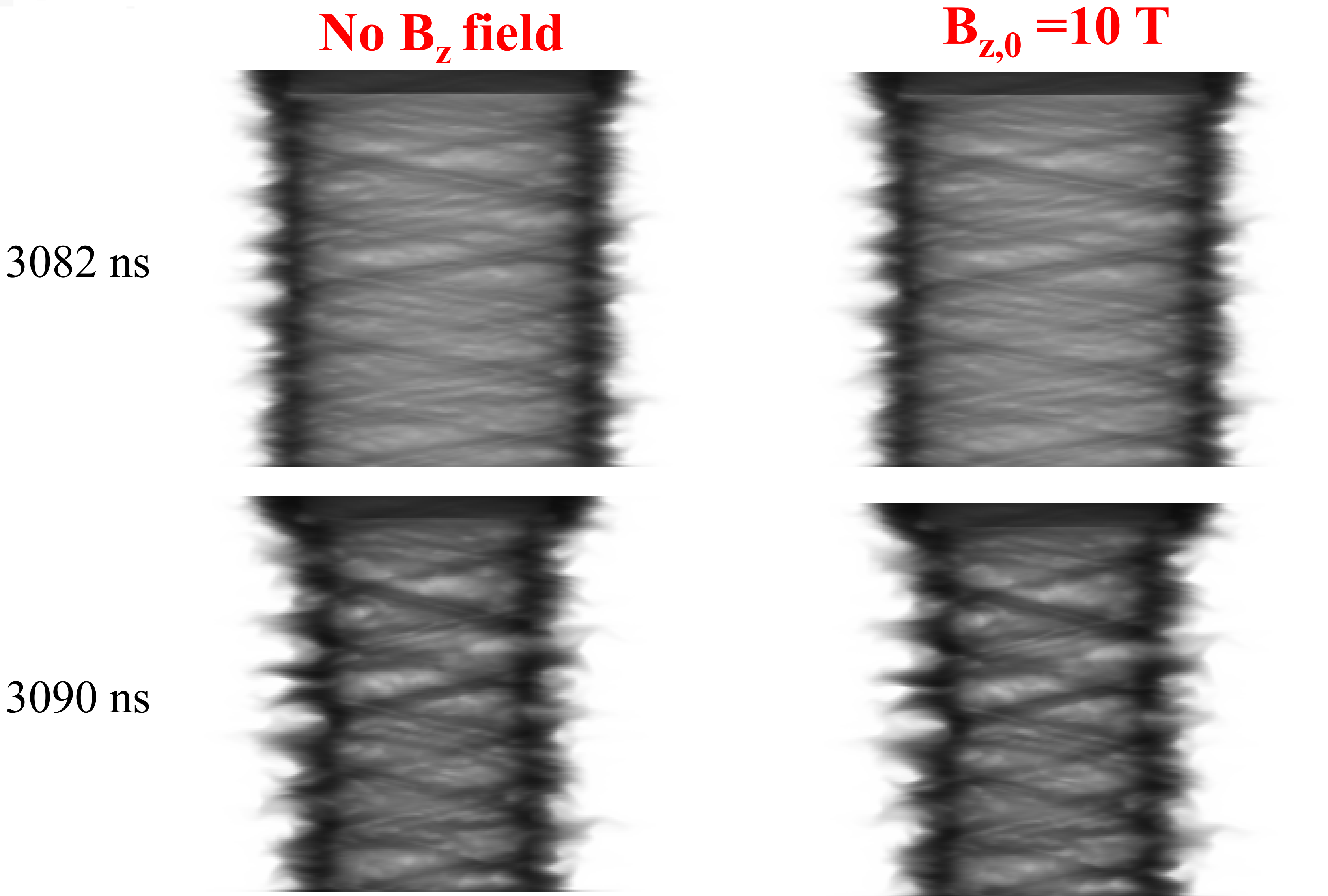


GORGON simulations by Chris Jennings

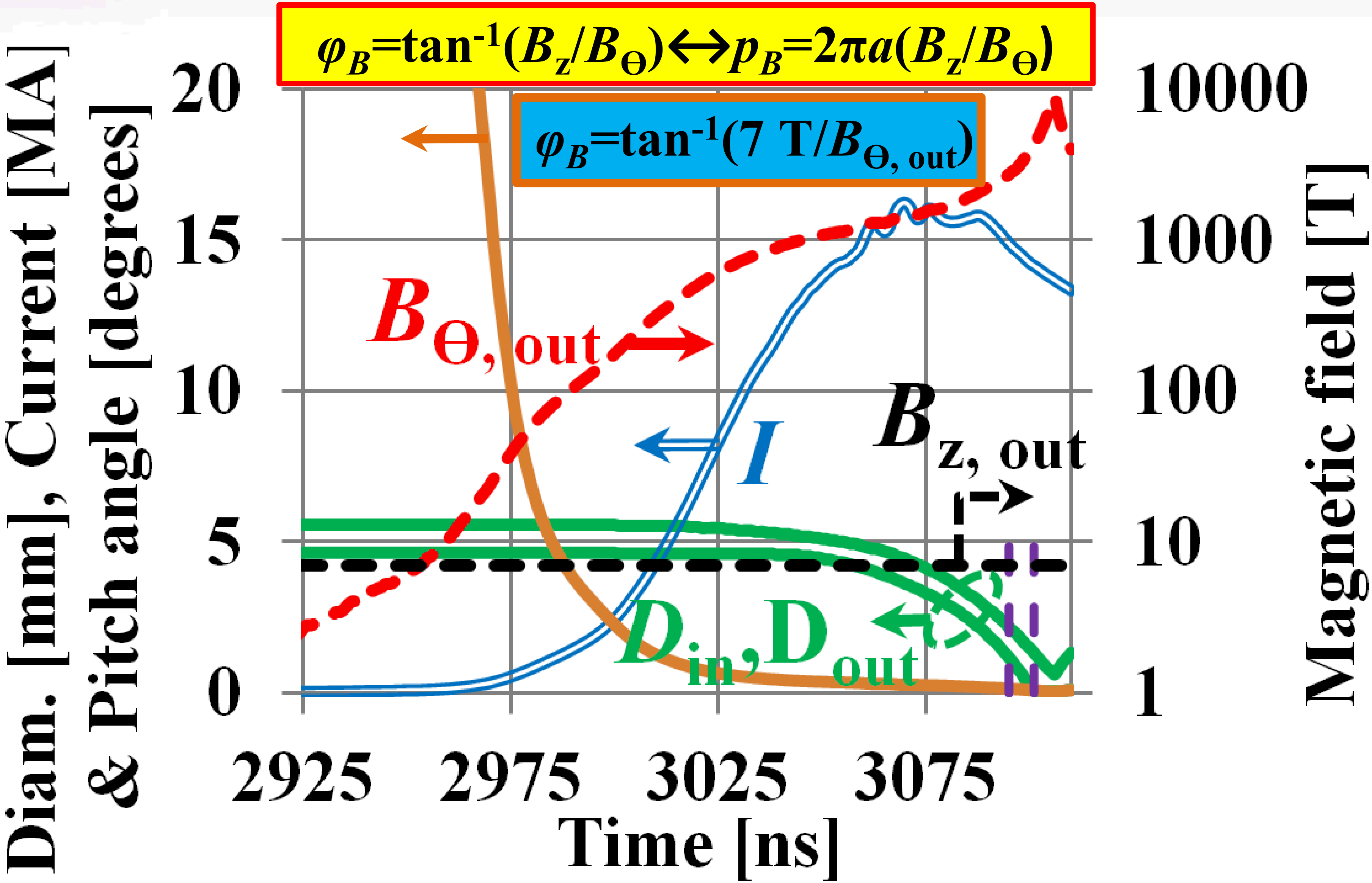
GORGON simulations initialized with a 7.2º perturbation match the late-time instability structure of the $B_{z,0}$=7 T experiment



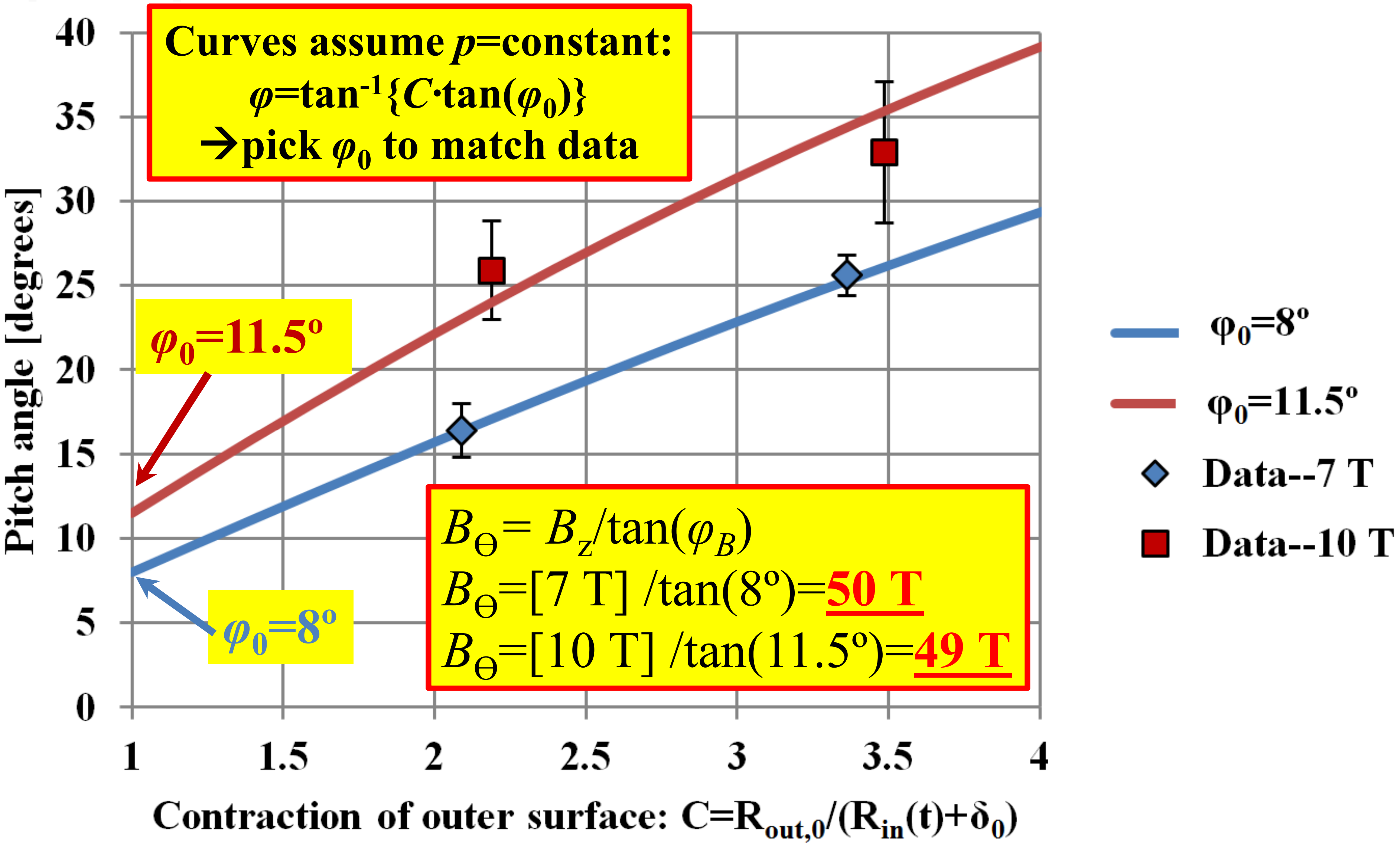
Once set by initial conditions the perturbation does not require further action of the applied B_z to persist



GORGON: If the perturbation is set when $B_\Theta \approx B_z$, it will persist and grow, even for $B_\Theta >> B_z$ throughout the implosion



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



Several physical processes occur at B_Θ~50 T which could allow a seed to be imprinted in the liner surface

- For $B \geq 23$ T, the magnetic pressure $P_B = B_\theta^2/2\mu_0$ exceeds the 207 MPa yield strength of the S-65 structural grade Be used to fabricate the liners
- Be melts at ~1550 K
  - →Temperature scaling with magnetic field for a thick conductor is given by $T \sim B^2/2c_v\mu_0$
  - →Using $c_v = 3.55\times10^6$ J/K·m^3, we find $B_{melt} = 118$ T
- Electrothermal instabilities (ETI) can be seeded at temperatures well below melt when non-uniform joule heating leads to density perturbations

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Hypothesis: Premagnetization provides higher fuel uniformity at stagnation

(1) Feedthrough rate is slower for helical instabilities (vs. "standard" azimuthally correlated instabilities)

(2) Compressed axial field stabilizes m=0 instabilities near stagnation

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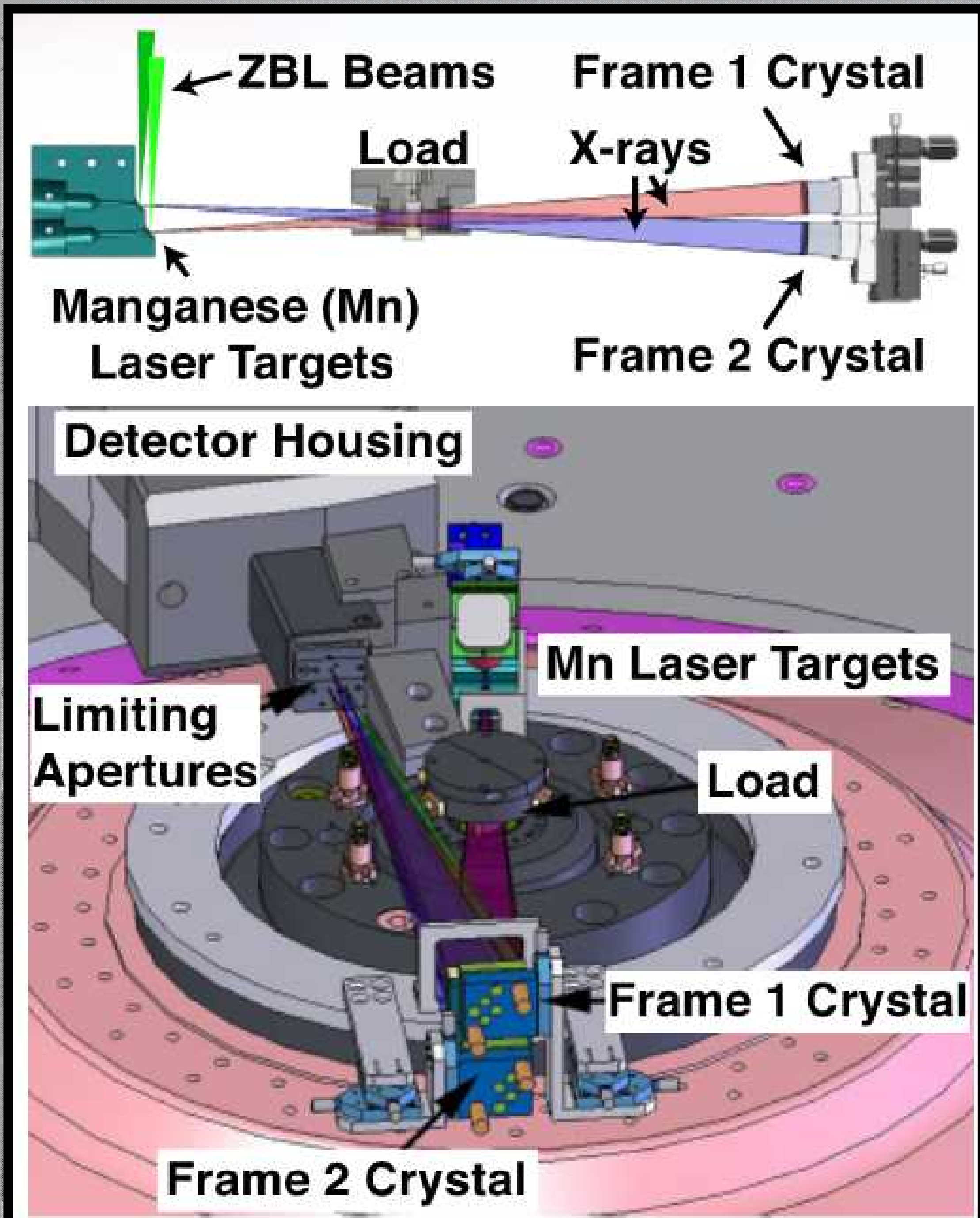
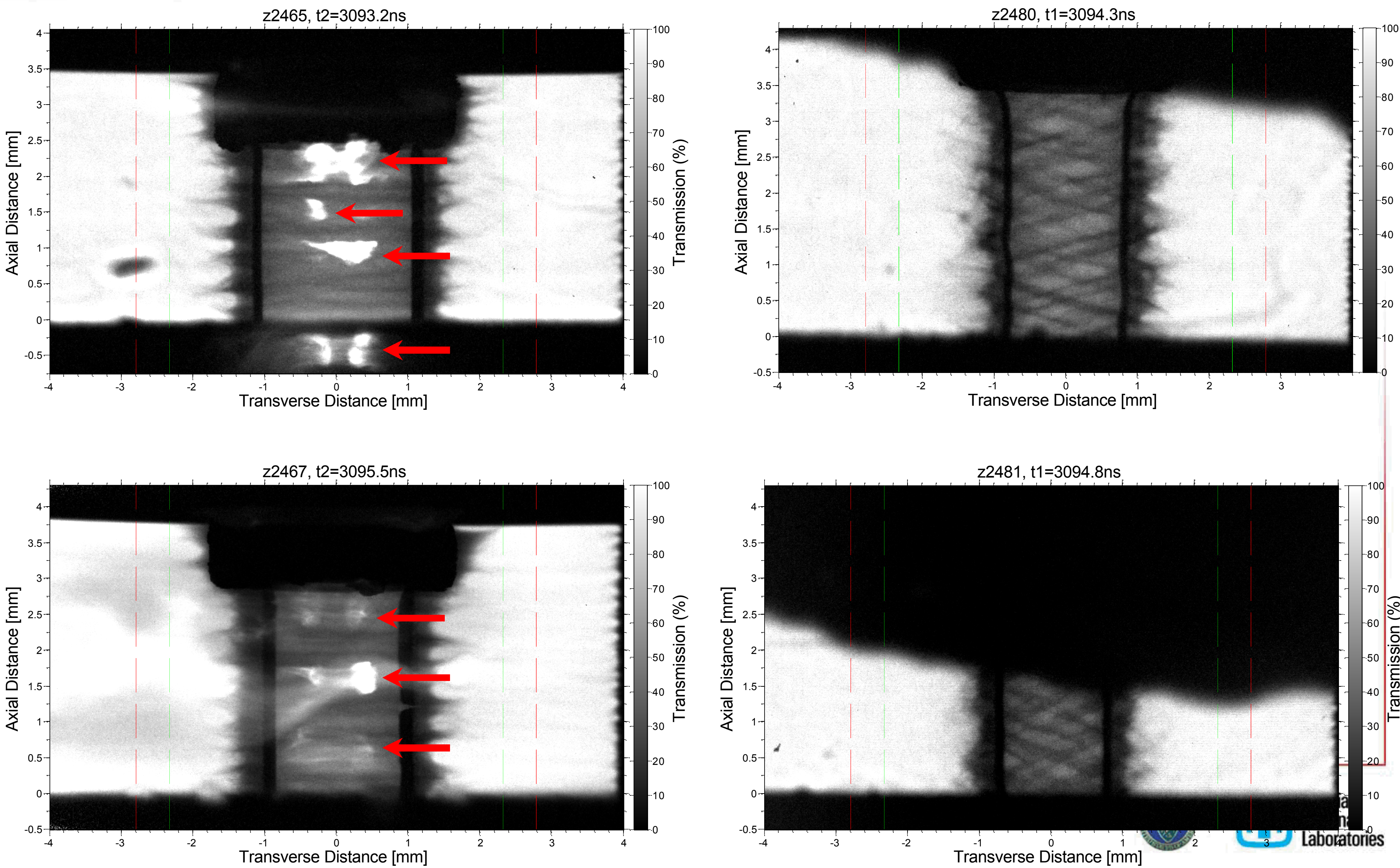
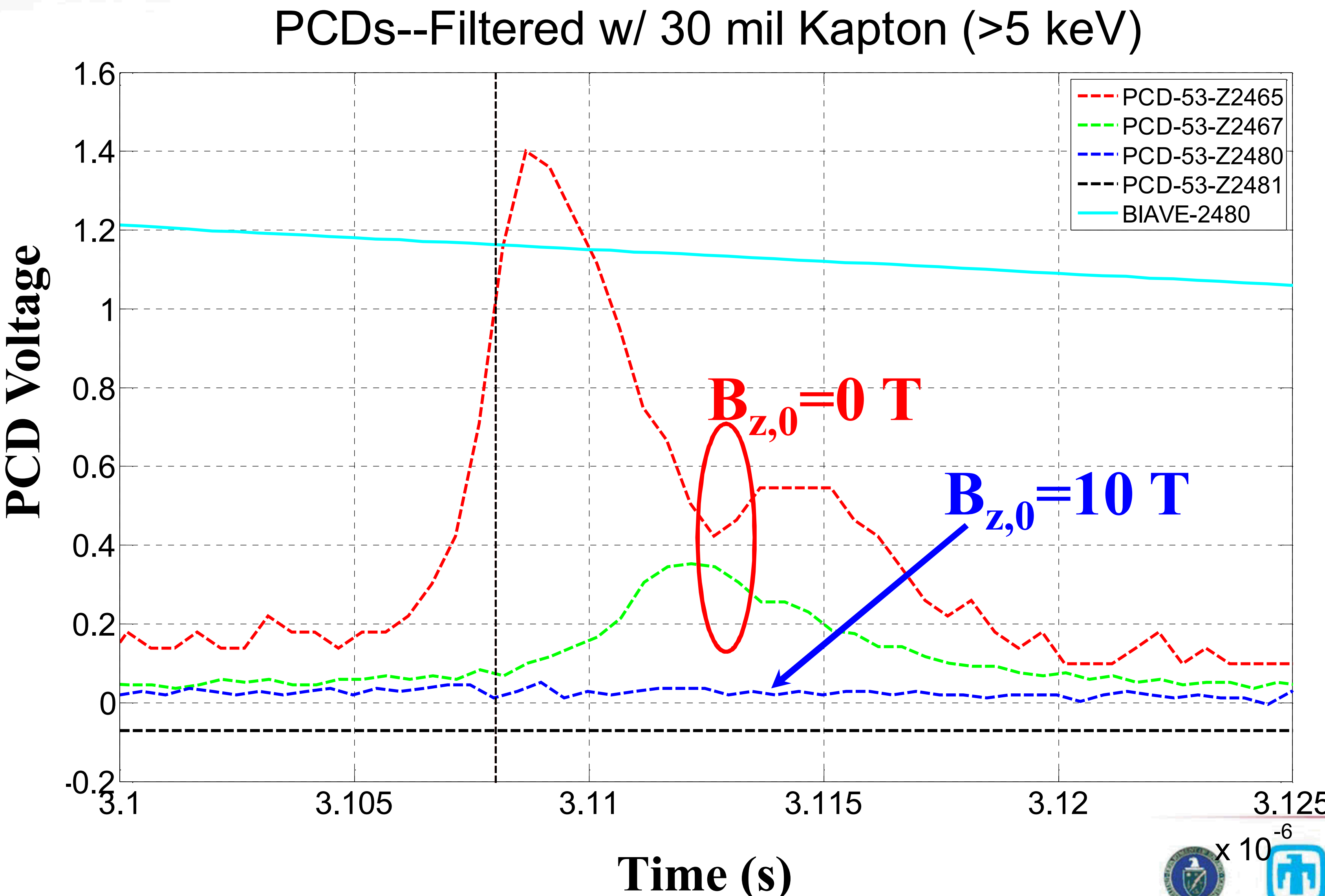


ZBL Beams
Frame 1 Crystal
Load
X-rays
Manganese (Mn) Laser Targets
Frame 2 Crystal
Detector Housing
Mn Laser Targets
Limiting Apertures
Load
Frame 1 Crystal
Frame 2 Crystal

Reduced *time integrated* self emission (TISE) supports that the axial magnetic field enhances stability



Harder X-ray emissions are reduced when the liner/fuel are pre-magnetized with an axial field



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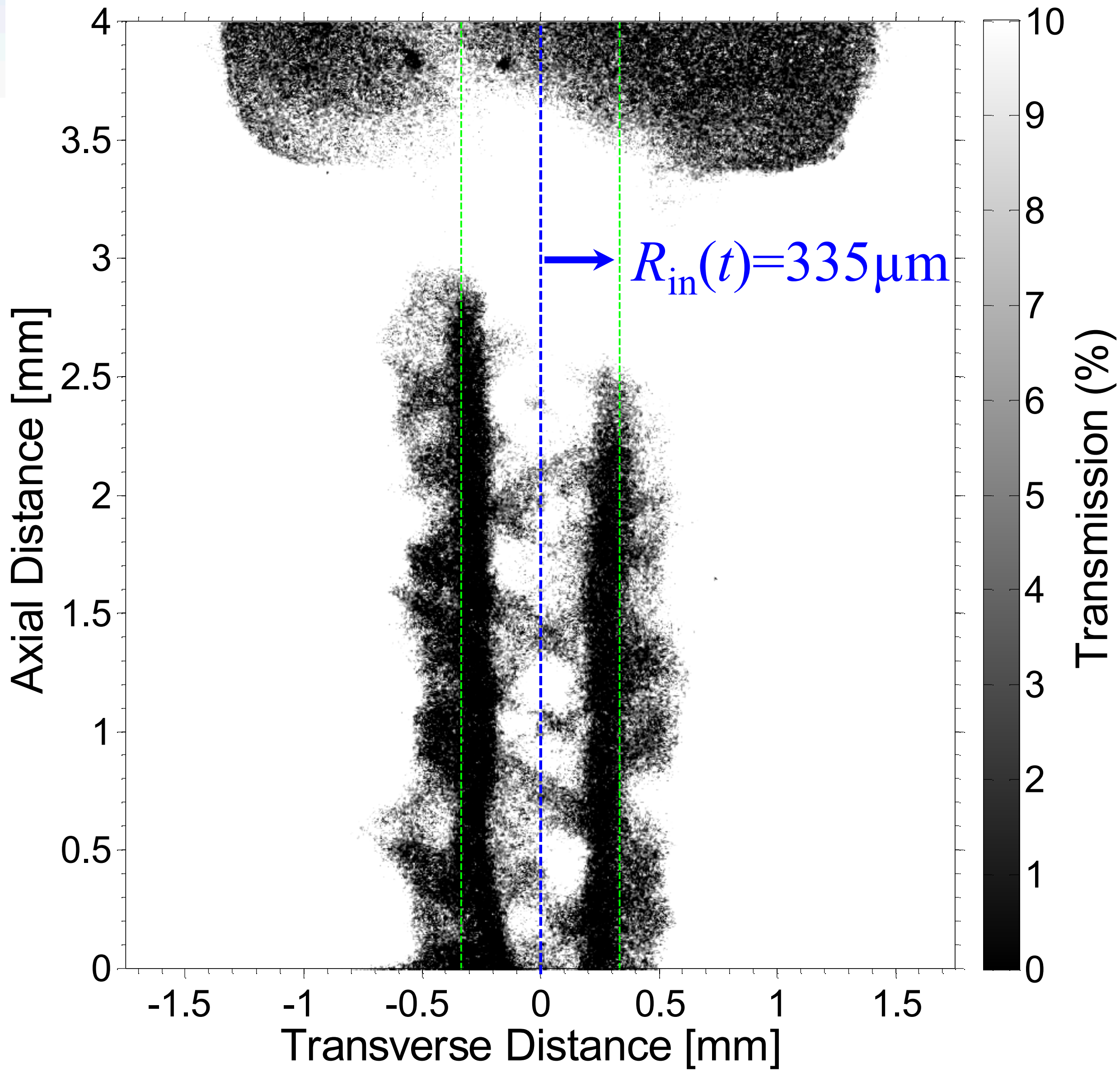
Implosion remains highly uniform at CR=7

$CR \equiv R_{in,0}/R_{in}(t)$

Highest CR radiograph in the MagLIF program to date

CR~10 is maximum possible for Be opacity (areal density increases with CR)



Summary & Conclusions

- Liner implosion & MRT studies using penetrating radiography provide valuable data for benchmarking codes & characterizing a MagLIF-relevant liner implosion through to stagnation
- In stark contrast to liners with no seed B_z field, pre-magnetized liners develop 3D helix-like surface instabilities
- If a small helical perturbation can be set when $B_\Theta \approx B_z$, simulations show it will persist and grow, even when $B_\Theta >> B_z$ during the entire implosion
- A radiograph of a liner at a convergence ratio of 7 shows that the liner's inner wall remains highly uniform
- **Evidence suggests that liner/fuel axial premagnetization may have a stabilizing effect**
  - **Reduced feedthrough rate of helical perturbation**
  - **Compressed axial field stabilizes m=0 instabilities at stagnation**