Sandia National Laboratories

SAND2019-2692C

Improved Stability and Reproducibility of Magnetized Liner Inertial Fusion Implosions

PRESENTED BY

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APS-DPP, Portland, OR 2018

November 6, 2018

U.S. DEPARTMENT OF ENERGY NNSA

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MagLIF is a major effort at Sandia, involving a large group of researchers

This work performed in collaboration with:

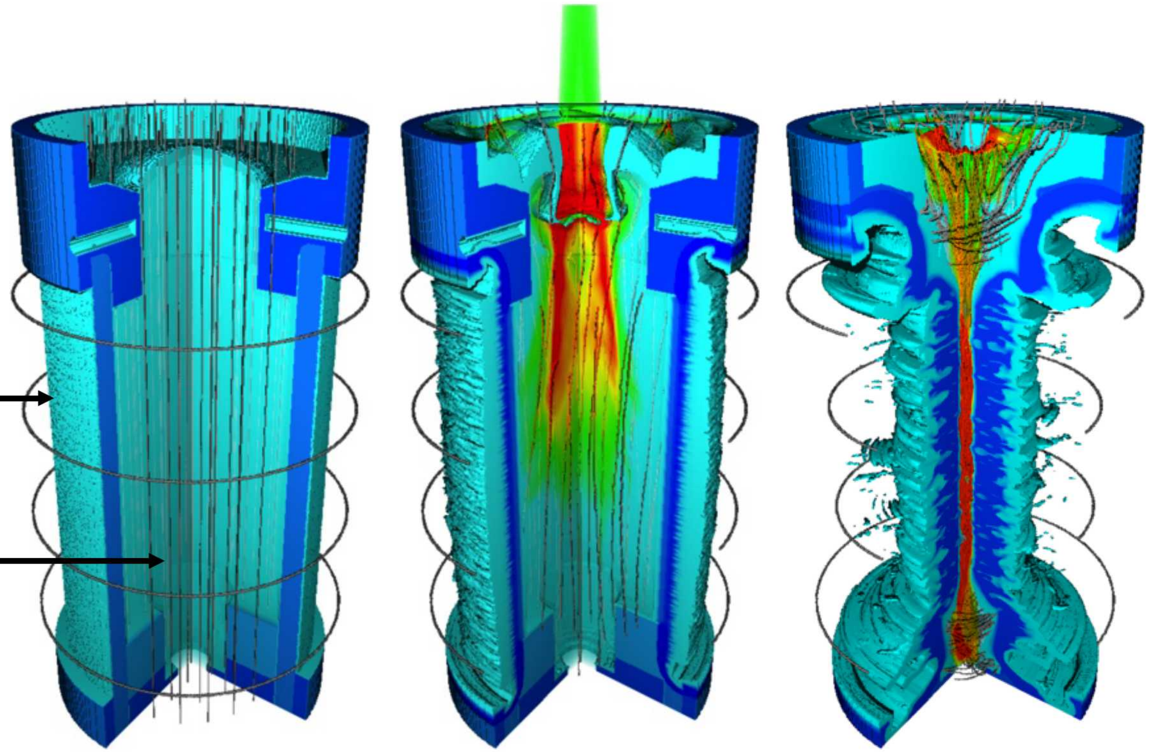
- M. R. Gomez, P. F. Knapp, A.J. Harvey-Thompson, E. C. Harding, M. R. Weis, C. A. Jennings, S. A. Slutz, M. Geissel, J. R. Fein, M. Glinsky, T. Moore, J. L. Porter, P. Rambo, D. E. Ruiz, J. Schwarz, J. E. Shores, I. C. Smith, C. S. Speas, G. A. Chandler, K. D. Hahn, C.R. Ruiz, M. Mangan, S. B. Hansen, D.C. Lamppa, L. Lucero, R. Paguio, L. Perea, G. Robertson, G. E. Smith, K. Whittemore, G. A. Rochau, K. J. Peterson, D. B. Sinars

- A large group of scientists, engineers and technologists that support every shot on Z!

Background: Magnetized Liner Inertial Fusion uses a pulsed power driver to implode a low Z liner (tube) of pre-heated pre-magnetized fusion fuel

Imploding Be tube or “liner”

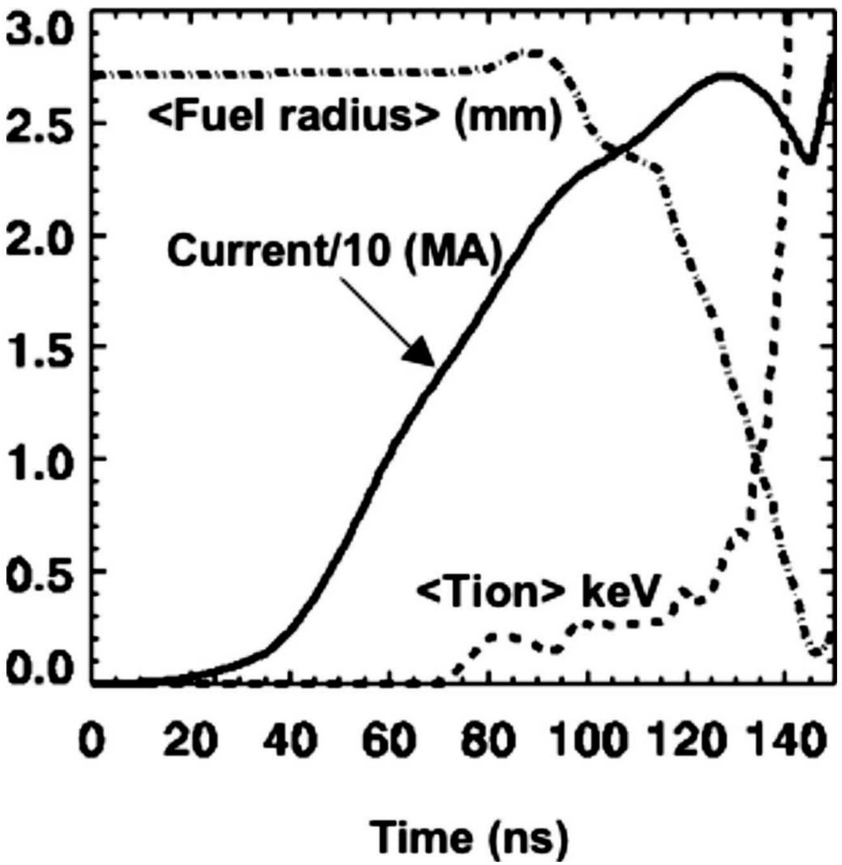
Gaseous D_2 fuel 0.7 mg/cc



Magnetization
B = 10 T

Laser Heating

Compression



S.A. Slutz *et al.*, Physics of Plasmas **17**, 056303 (2010)
M.R. Gomez *et al.*, Phys. Rev. Lett. **113** 155004 (2014)

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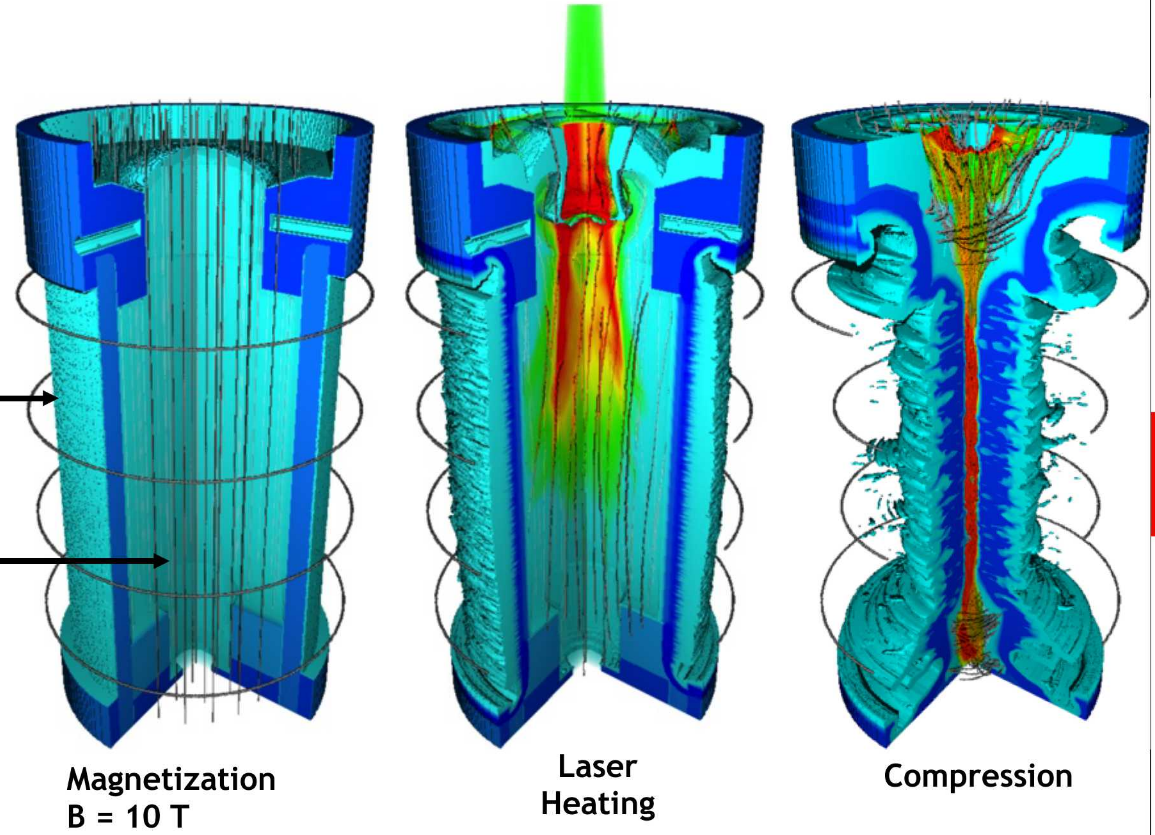
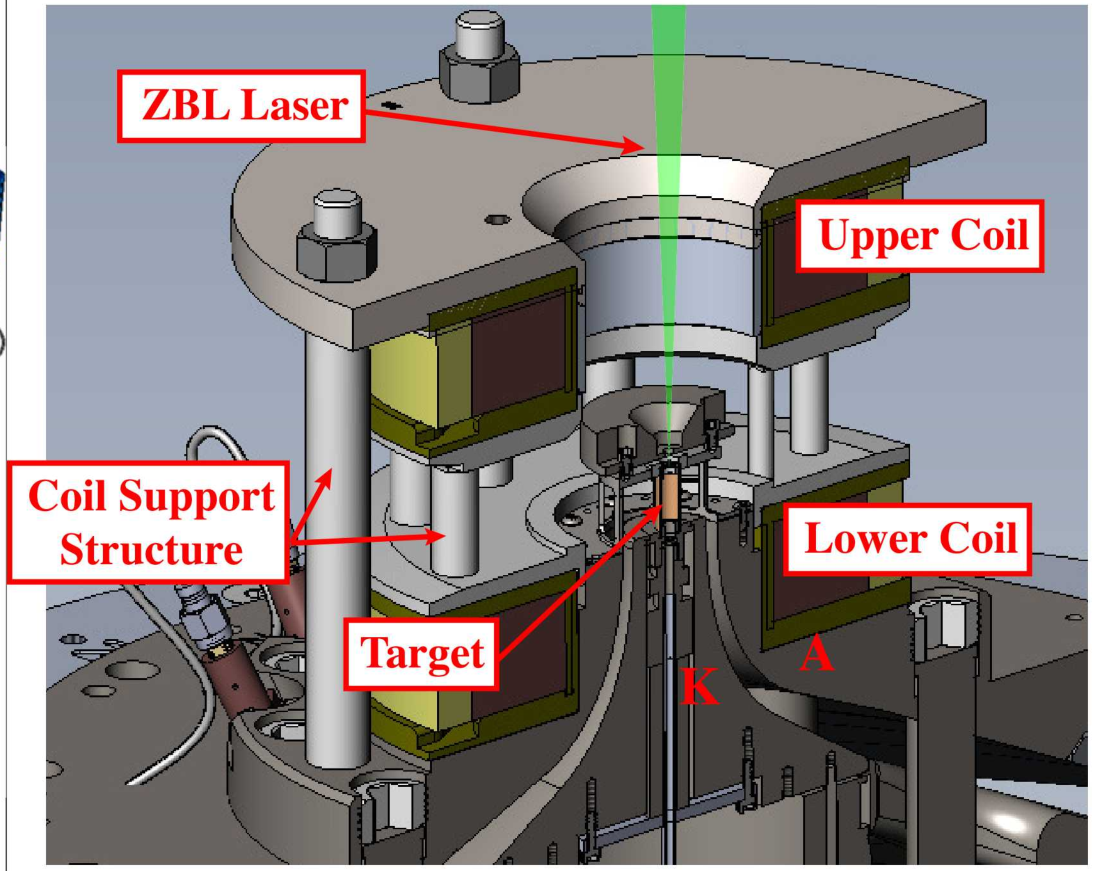


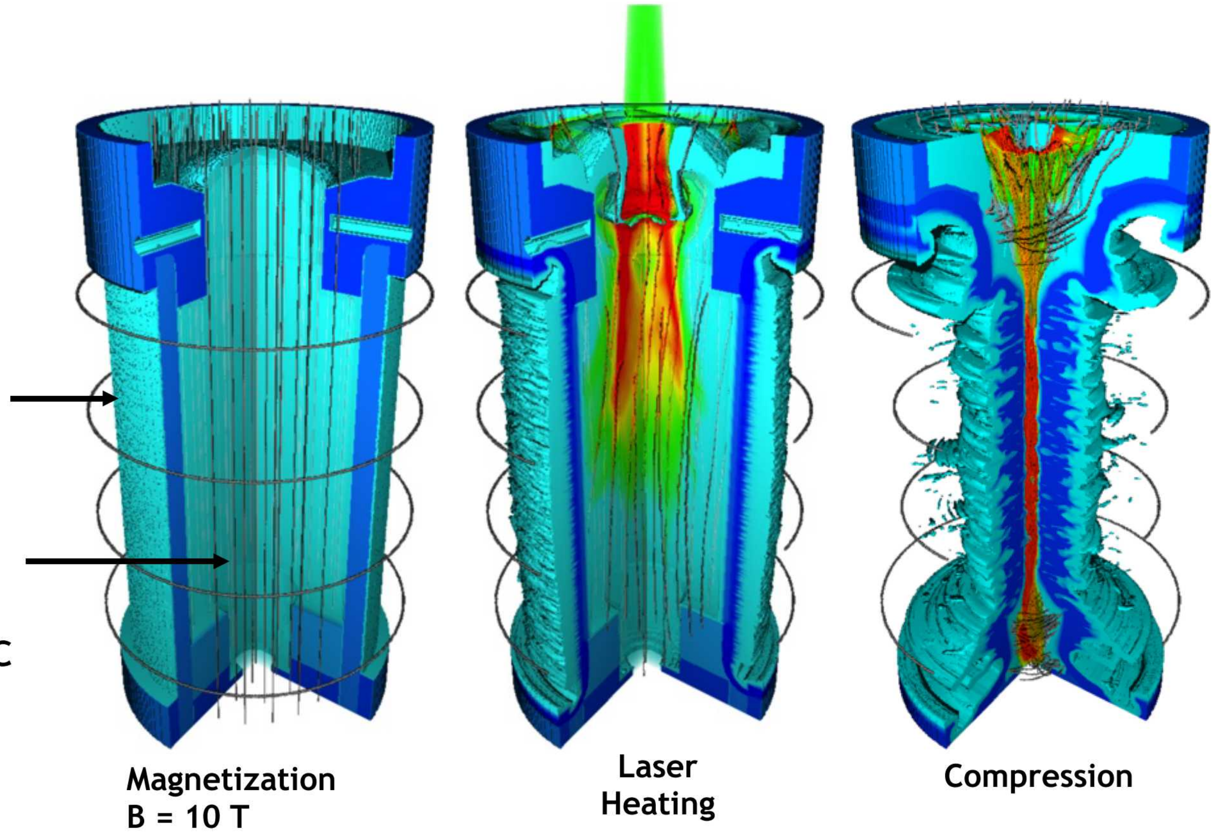


Background: Magnetized Liner Inertial Fusion uses a pulsed power driver to implode a low Z liner (tube) of pre-heated pre-magnetized fusion fuel

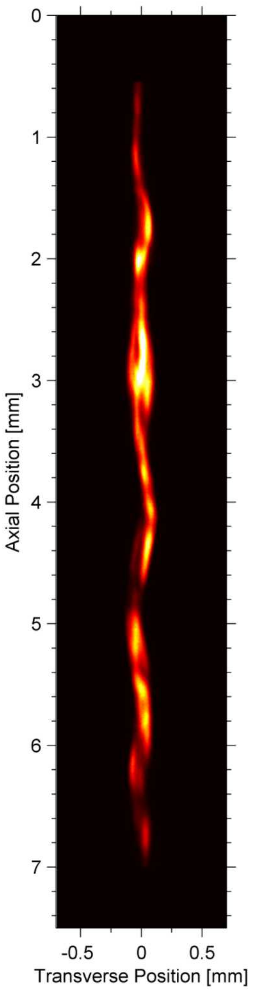
MagLIF experiments have demonstrated the necessary components of magneto-inertial fusion, and achieved primary n_{DD} yields ~10^{12} – 10^{13}

Imploding Be tube or "liner"

Gaseous D_2 fuel 0.7 mg/cc



	No B-field	B-field
No Laser	3e9	1e10
Laser	4e10	2e12



Overview: By reducing the seed of instabilities, we have developed a uniform, reproducible MagLIF platform

MagLIF stagnations exhibit complex helical structures

- These can impact performance, reproducibility and comparisons to simulations
- By varying the liner geometry we can conclude that these are initiated on the outer surface of the liner

We can significantly reduce the seed of these instabilities

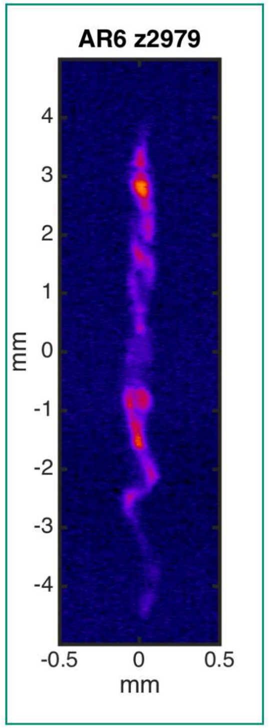
- Previous work has shown seed is early-time electro-thermal instability – we have techniques to reduce

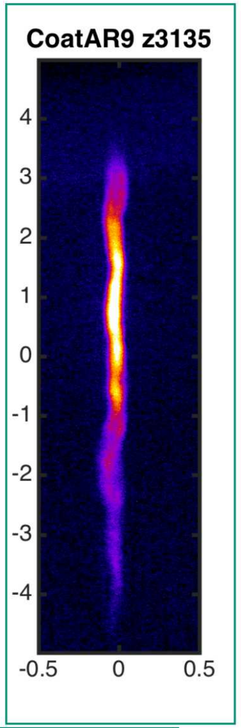
We have demonstrated a uniform stagnation column by reducing this ETI seed

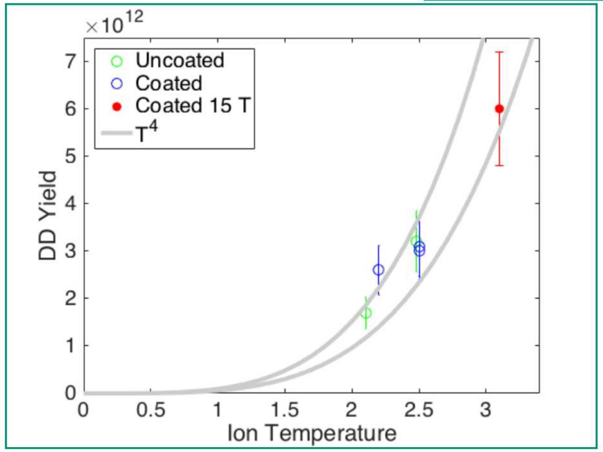
- Helical mode significantly reduced, more uniform brightness axially (in x-rays and neutrons)
- Reproducibility is improved when structure is improved
- Stagnation column is uniform across burn time

This platform enables detailed scaling studies

- Scaling with initial applied axial field





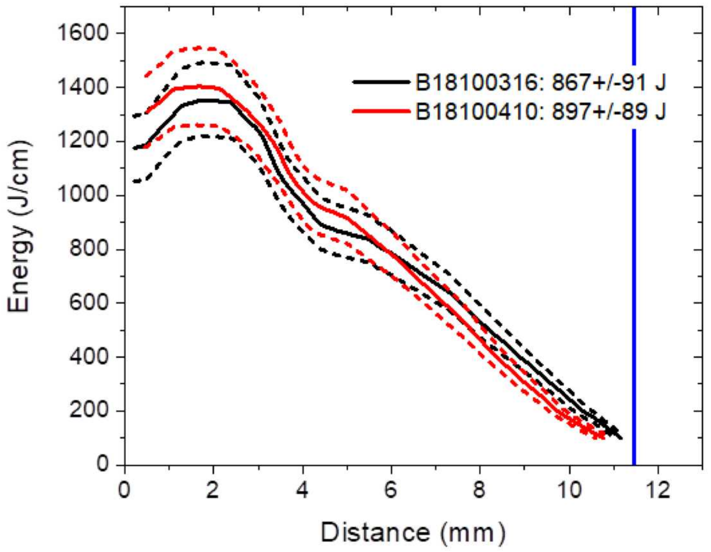


MagLIF stagnations exhibit complex helical structures

For the experiments described here are aimed to have minimal changes between experiments

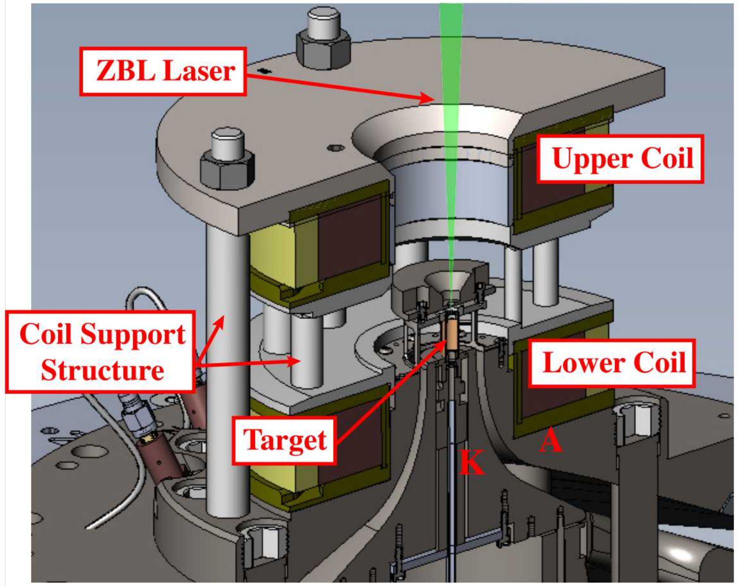
To date, MagLIF has used a variety of laser configurations
- For the purposes of this talk we use an unconditioned laser pulse
- For 2.3 kJ incident on target we estimate 1.28 kJ $\pm$ .14 kJ reproducibly coupled into fuel

For much more detail, see Adam Harvey-Thompson, next talk



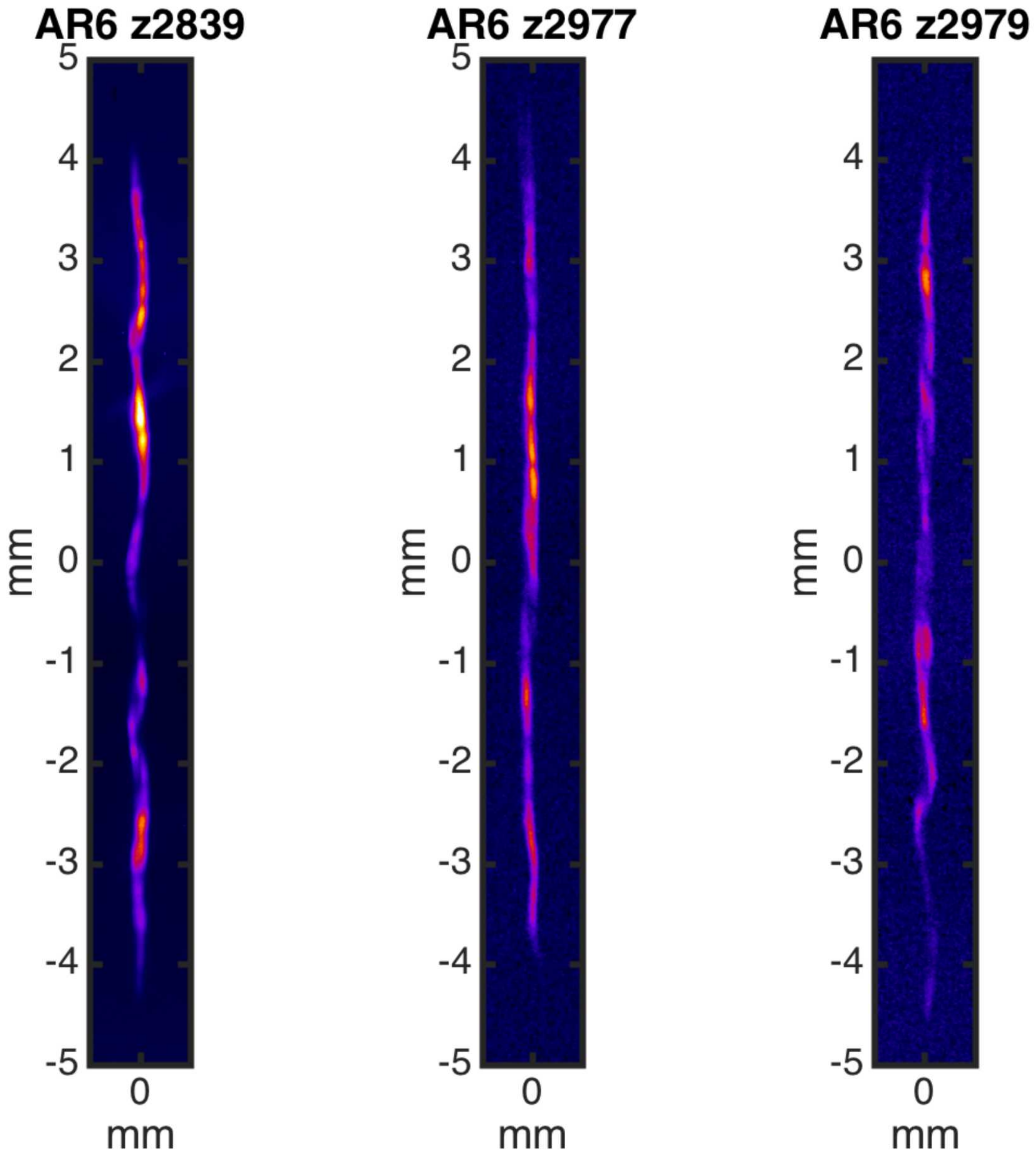
All experiments described here use:
- 10 mm tall target
- 4.65 mm inner target diameter
- 0.7 mg/cm^3 pure DD gas fill

Experiments here use long electrical feed to the target (shown)
- Design allows for uniform field across target height
- High feed inductance (6.8nH)
- Other experiments have reduced this inductance



For other feed geometries see Kyle Peterson CM9.01

Quasi-helical structures exist in MagLIF stagnations



Since the first MagLIF experiments we have observed a helical structure in the stagnation column

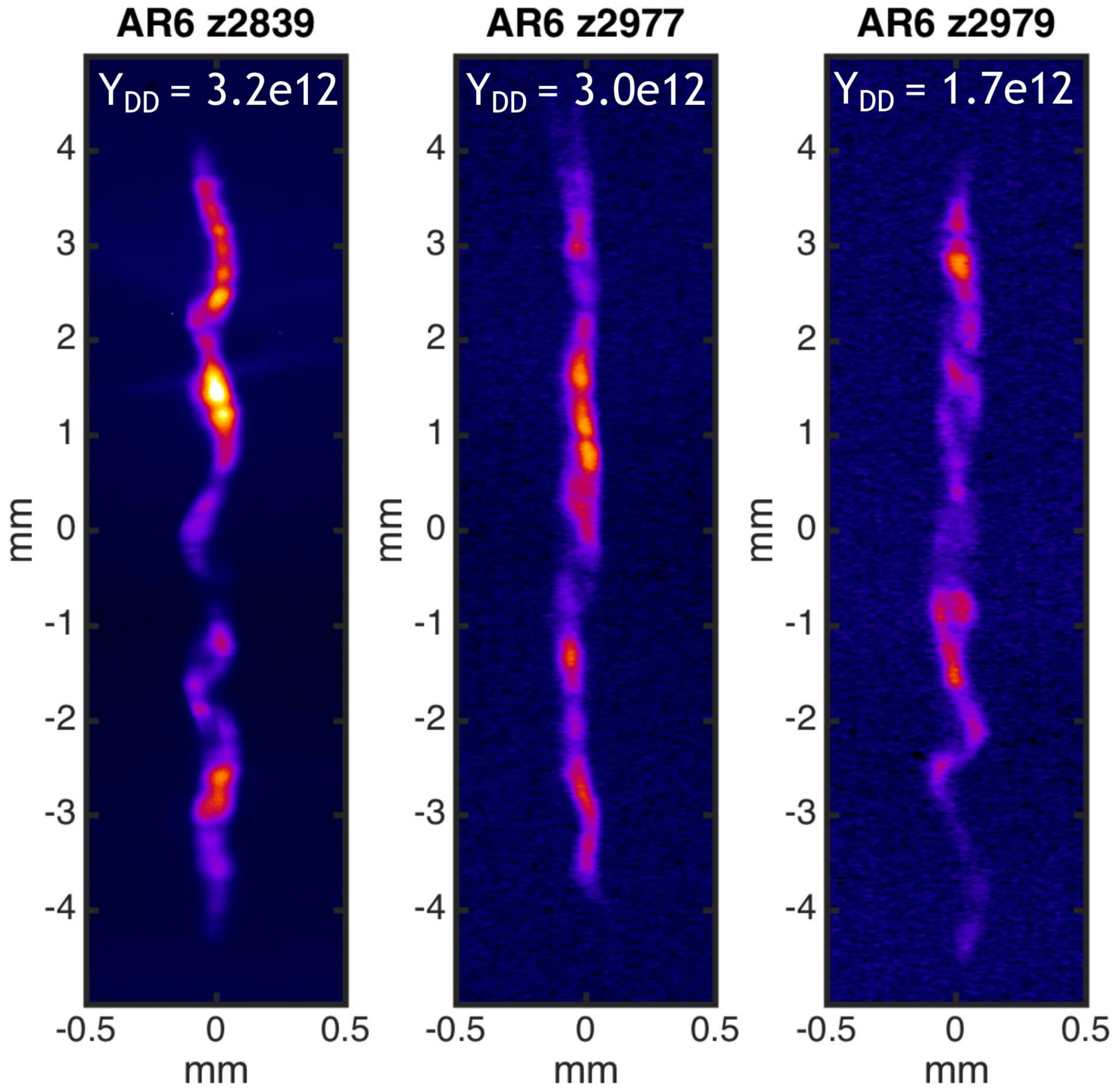
- Images shown use a spherical crystal imager

The three experiments shown are nominally identical

- 10 T field
- 1 cm tall, aspect ratio 6 liners
  - $\mathrm{AR} = \frac{Outer\ Radius}{Wall\ Thickness}$

Crystal imager developed by Eric Harding *et al*.

Quasi-helical structures exist in MagLIF stagnations



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To highlight structure images are stretched radially

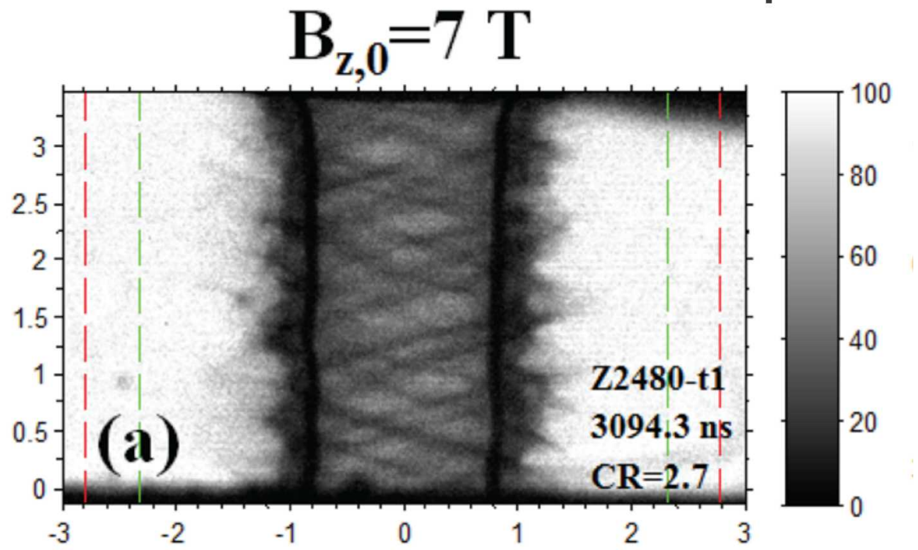
The pitch angles and radii of the helix varies between nominally identical experiments

In some cases we see multiple distinct columns

Brightness varies axially

Crystal imager developed by Eric Harding *et al*.

We have observed helical structures early in time in pre-magnetized liners Various theories exist to explain these structures



In radiography experiments of premagnetized liners we see a helical structure

- We can't presently radiograph experiments with preheat

T.J. Awe *et al.*, Physics of Plamsas 21, 056303 (2014)

There are a number of proposed explanations for these helical structures

- Electrons streaming onto liner surface (Sefkow *et al.*)
- Force free current paths on the liner surface (Velikovich)
- Compression of field by low density feed plasma (Seyler, Martin, Hamlin, Physics of Plasmas 25, 062711 (2018)

3D simulations indicate that these instabilities degrade yield

- Estimated to be 40% effect at present, deteriorates with increasing field, current
- Increase fuel density an preheat energy helps slightly by reducing convergence, but present capabilities won't outweigh field/current impacts

We can design experiments to test if this instability feeds through to the stagnation column

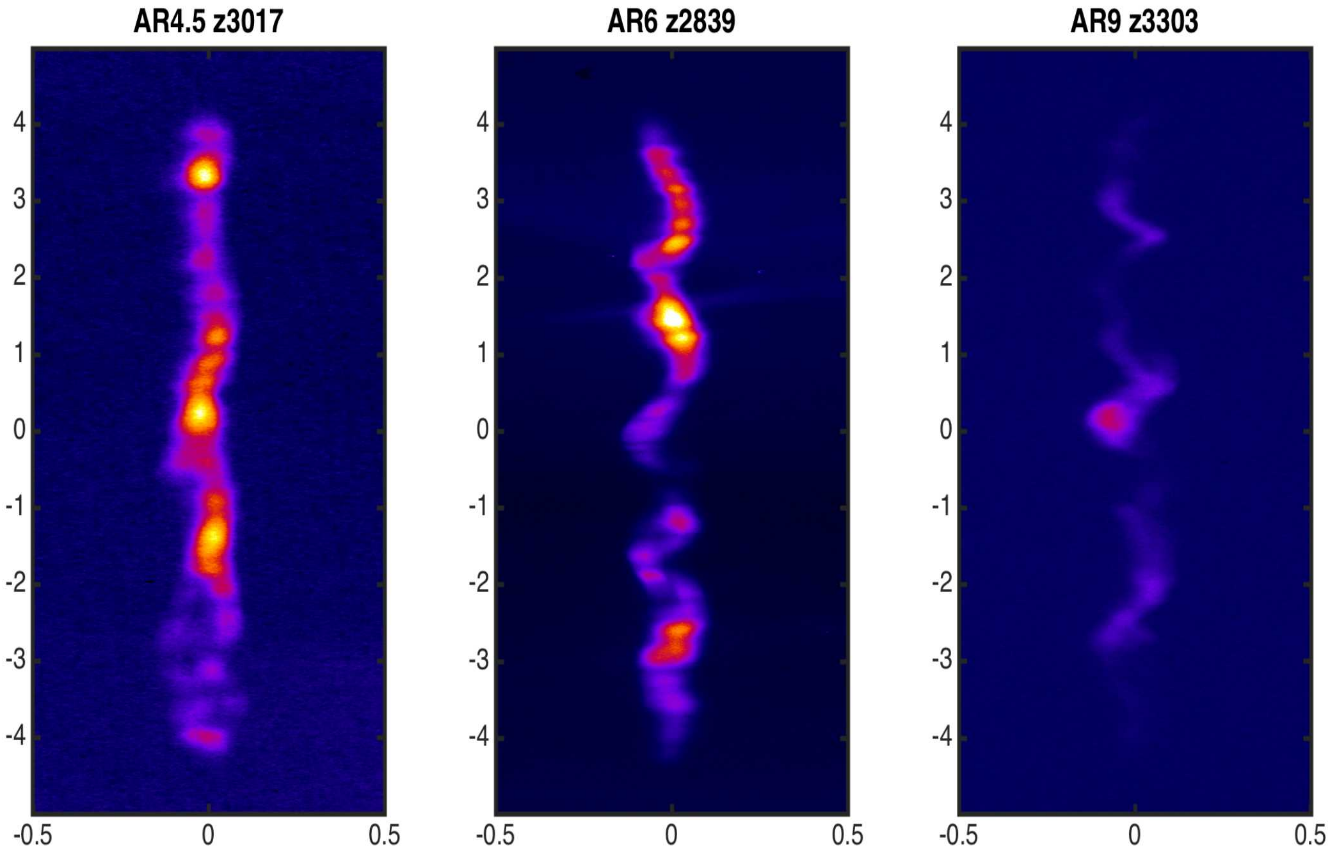
Data indicate that these helical structures at stagnation are the result of early-time helical mode imprinted on the outer surface of the liner

We can control feedthrough of instabilities from the outer surface of the liner

- Aspect ratio will dictate the feedthrough
  - $\mathrm{AR} = \frac{Outer\ Radius}{Wall\ Thickness}$
  - Lower aspect ratios will be more robust to feedthrough
    (e.g. AR4.5)
  - High aspect ratios will have more feedthrough
    (e.g. AR9)

By testing this on Z we have demonstrated that stagnation structures are, in fact, dictated by the liner aspect ratio

- Consistent with feedthrough from the outer surface of the liner



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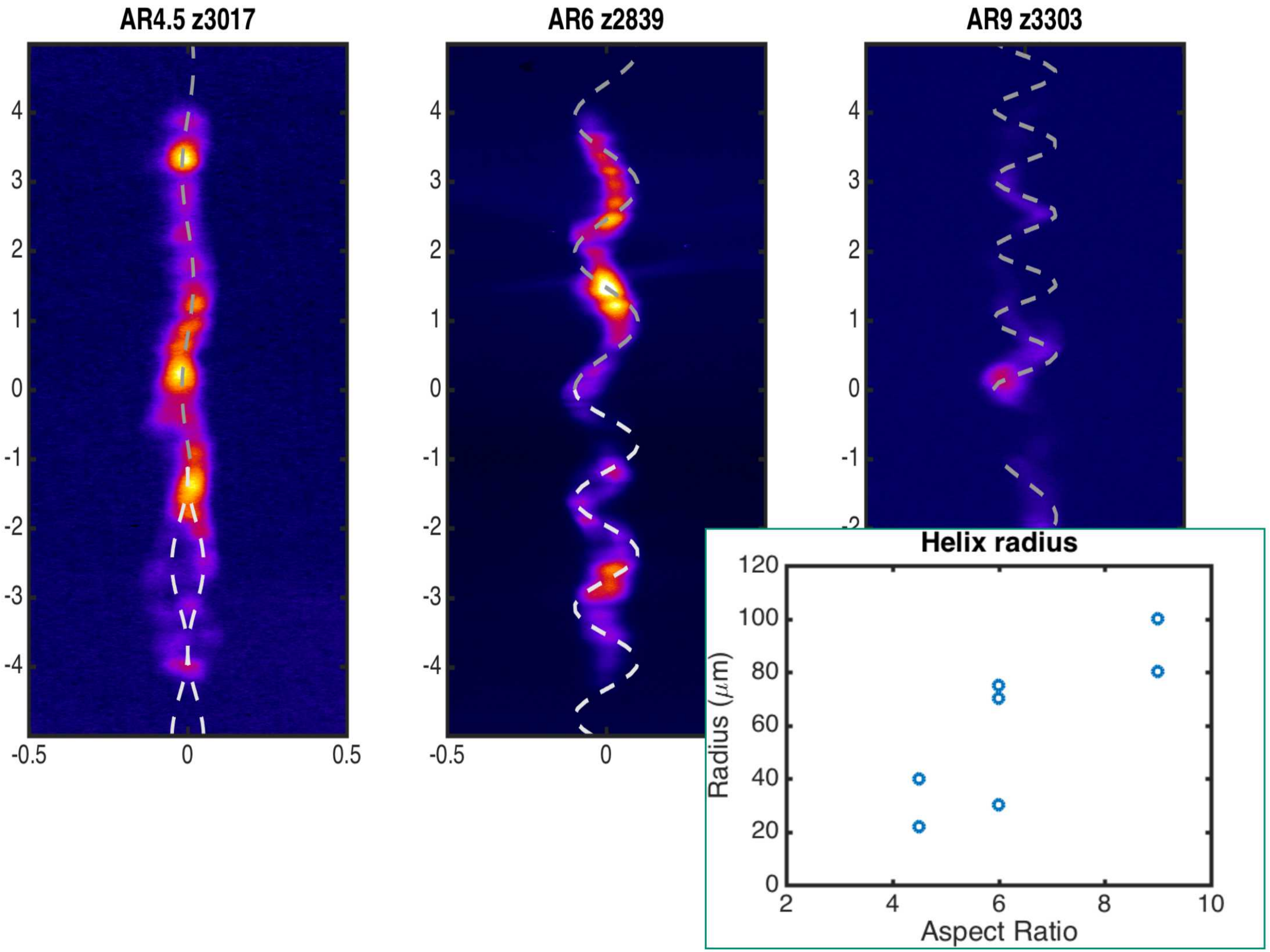
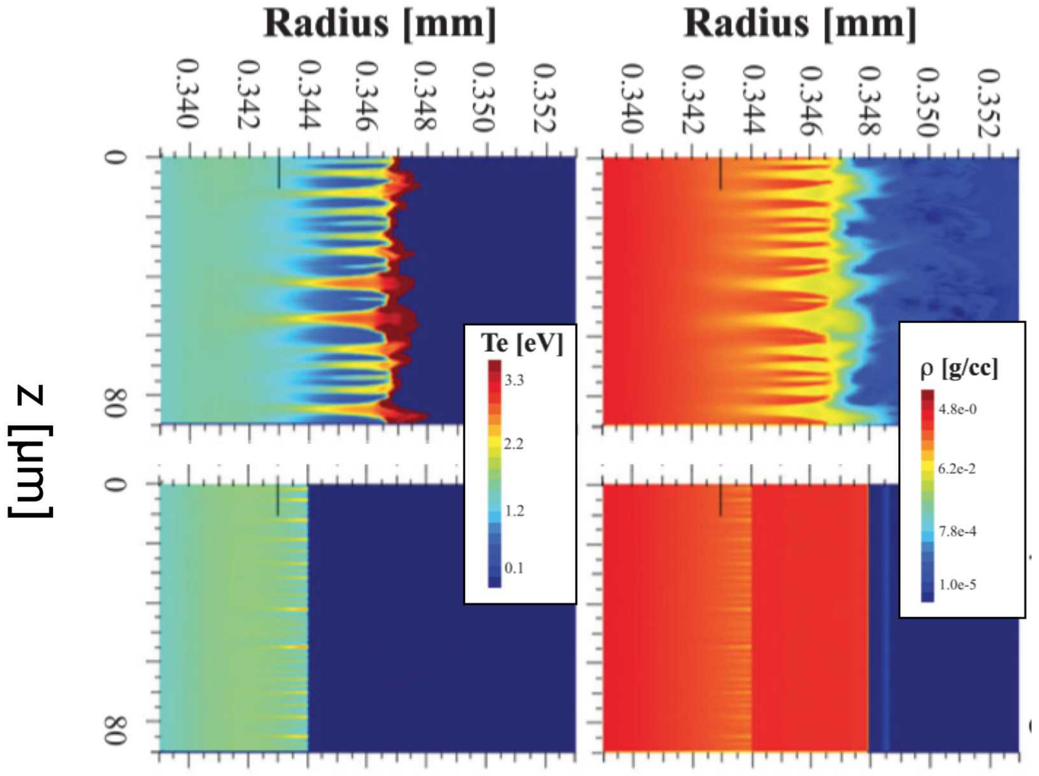


For more detailed classification of images with Mallat Transforms see **YO6.04** (Thomas Moore)

We can significantly reduce the seed of these instabilities

We believe the seed for the helical instability is electro-thermal instability – if it is then theory shows we can fix it

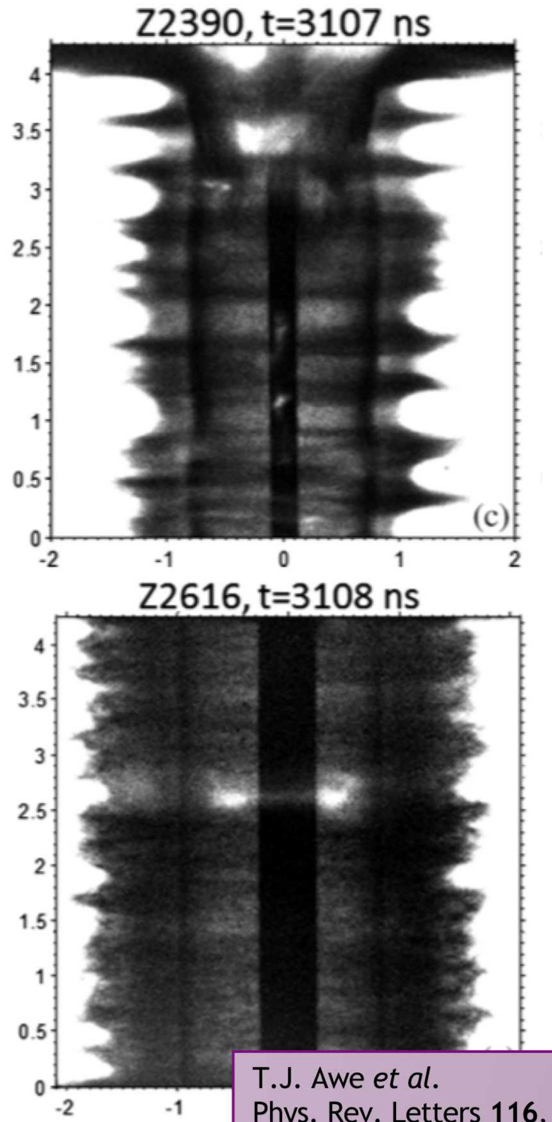
Modeling



Uncoated

Coated

Experiments (AR6)

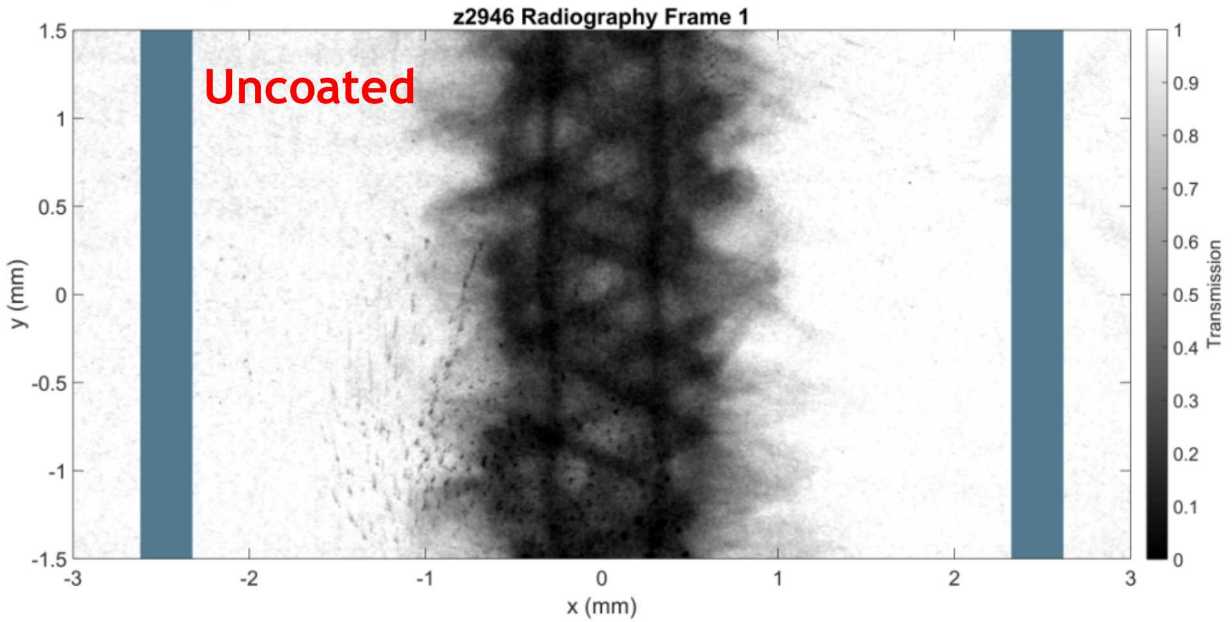


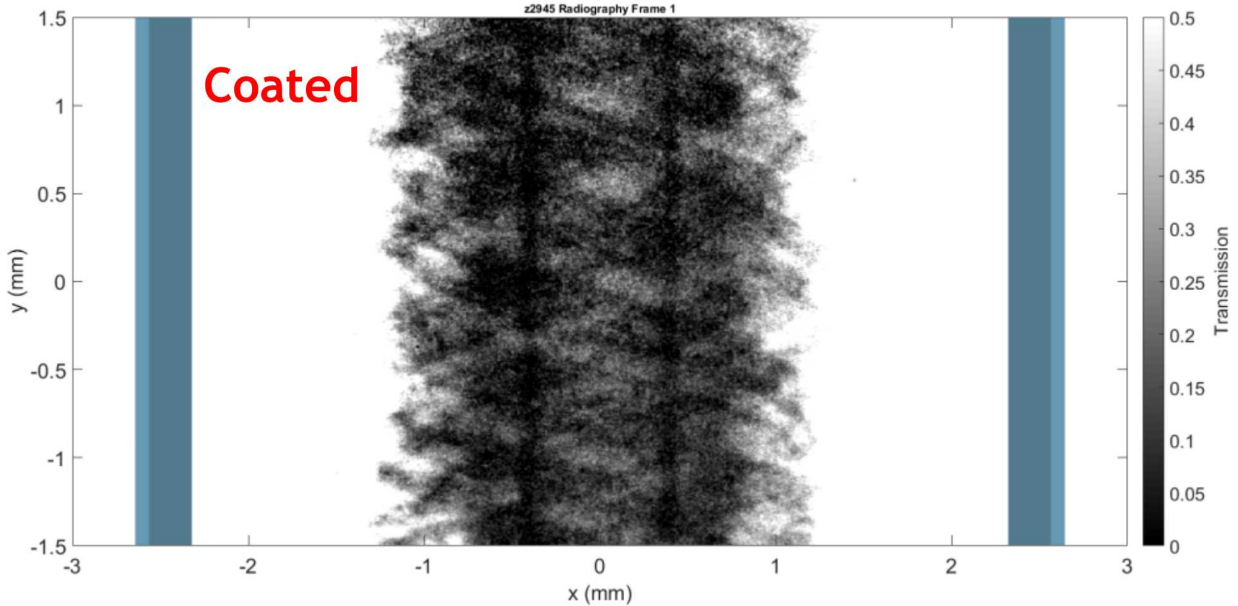
K.J. Peterson *et al.*,
Phys. Rev. Letters **112**, 135002 (2014)

T.J. Awe *et al.*
Phys. Rev. Letters **116**, 065001 (2016)

Applying these coatings to high aspect ratio liners, we can obtain good implosion stability

AR9 data



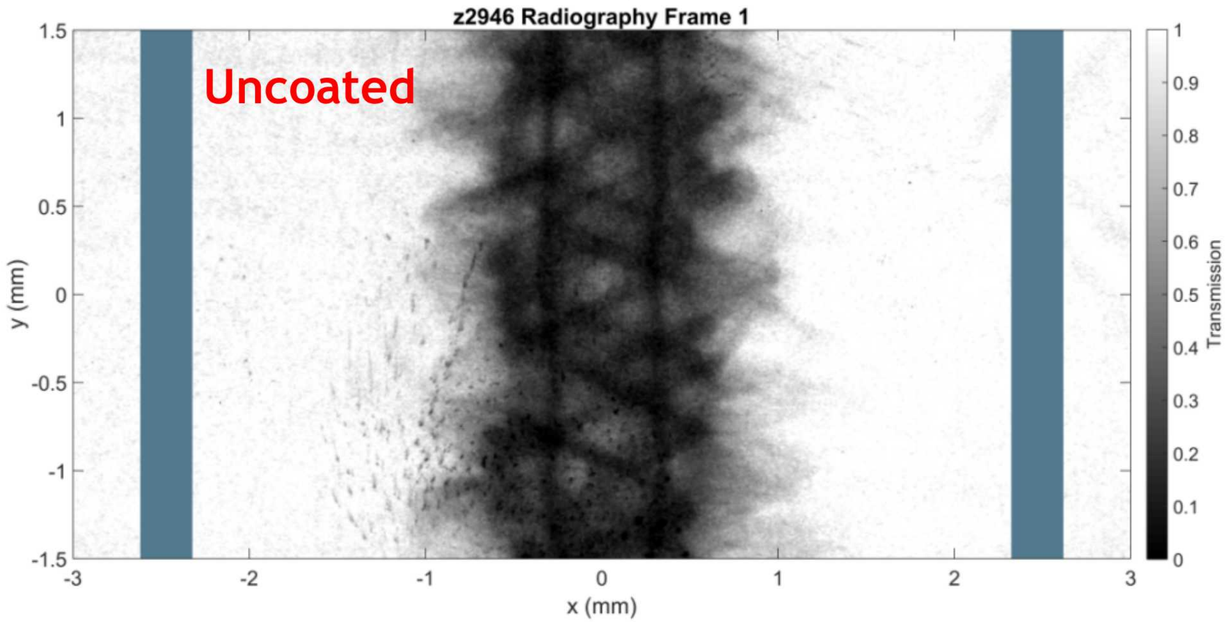


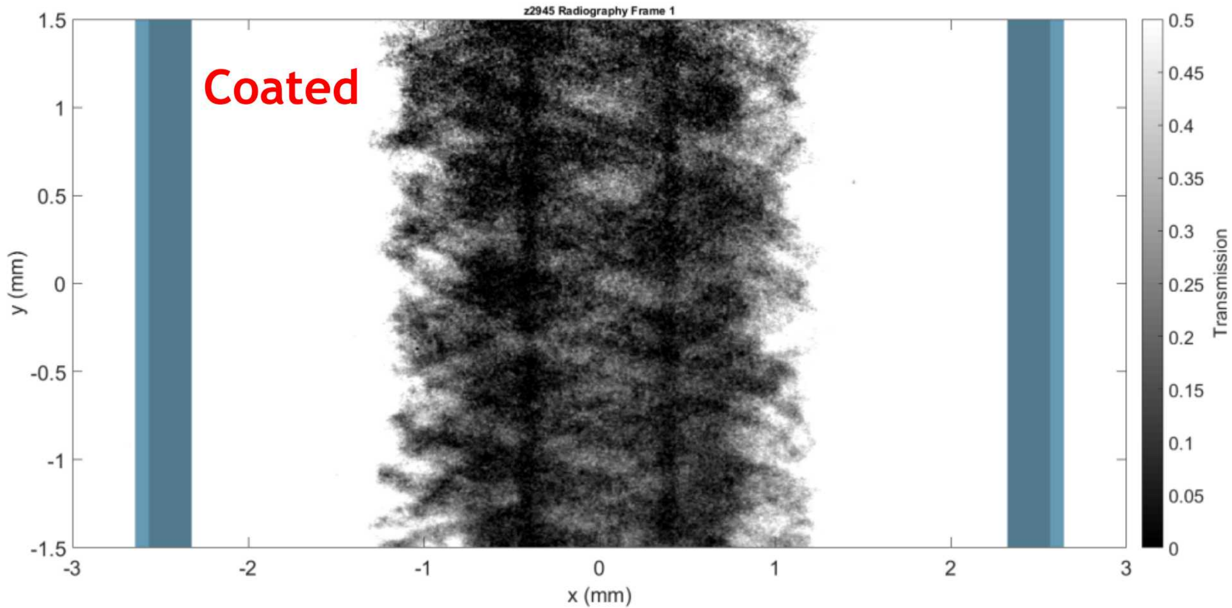
Taking our most unstable (AR9) platform, we explored how coatings would aid stability

- AR9 was most unstable, but can achieve highest implosion velocities
- 10T axial magnetic field
- For remainder of talk, coated AR9 refers to mass-matched AR9
  - Combined liner-coating mass is equal to that of an uncoated AR9 liner

At convergences > 10 we find see that the coated liners maintain good implosion uniformity

Applying these coatings to high aspect ratio liners, we can obtain good implosion stability





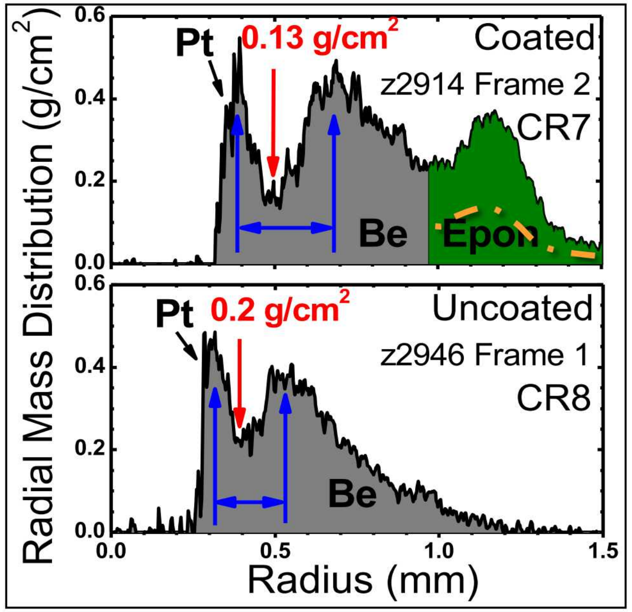
AR9 data

Data indicates that the coated liners have a broader radial distribution of mass

- Effectively reducing the in-flight aspect ratio

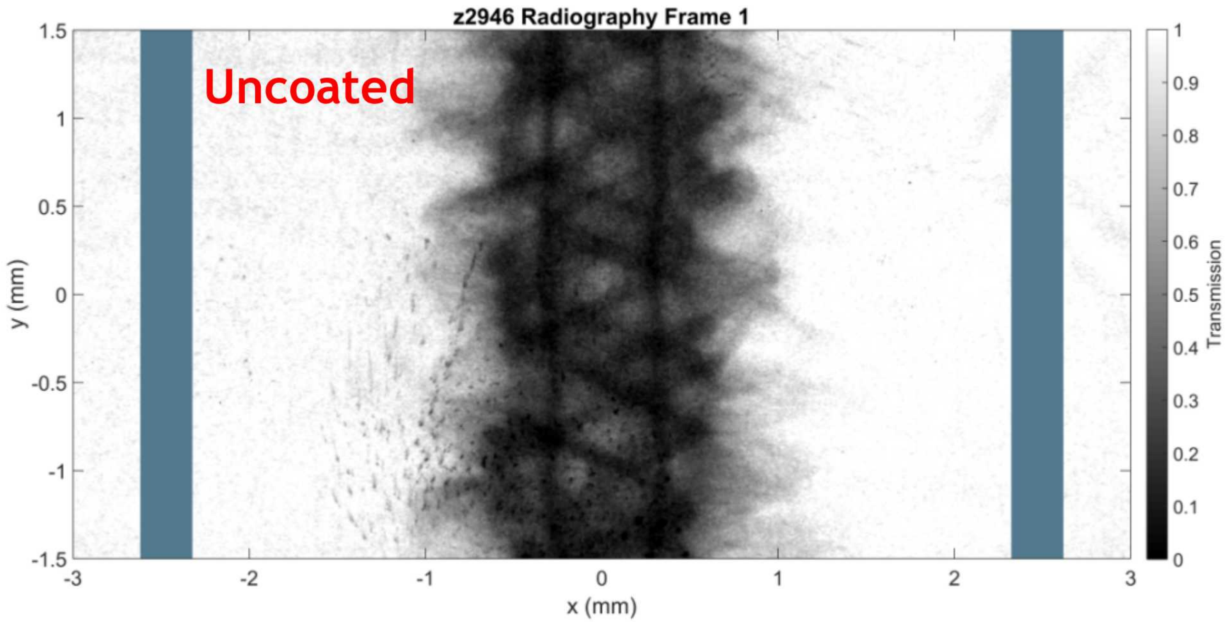
Broader mass distribution will

- Further aid implosion stability
- Reduce confinement at stagnation



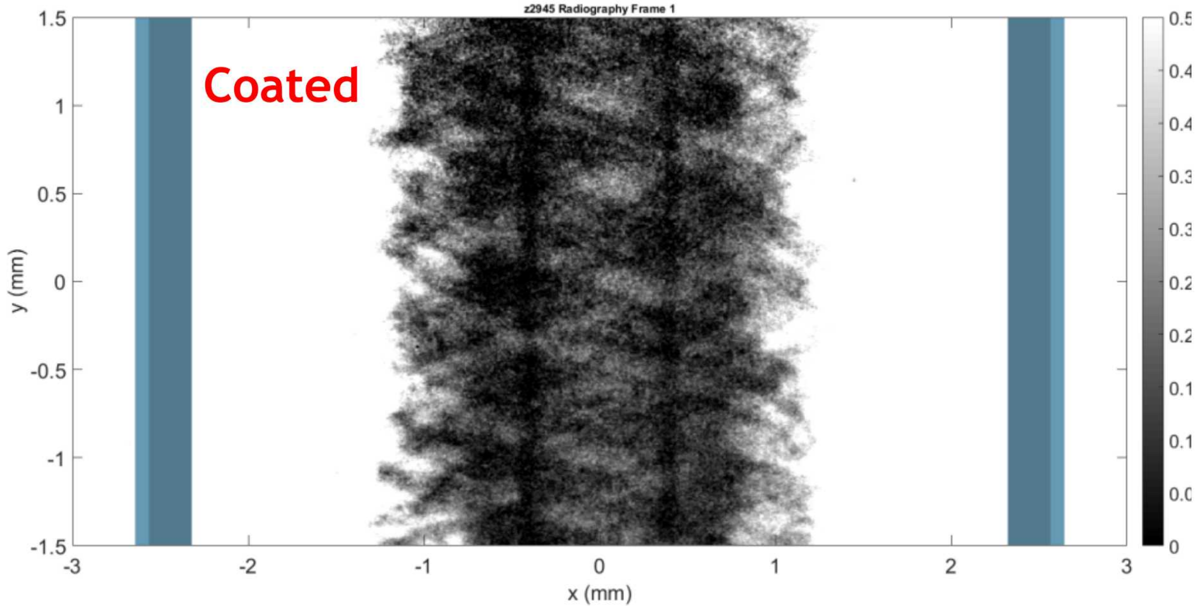
Late in time data indicates very good implosion stability with coatings

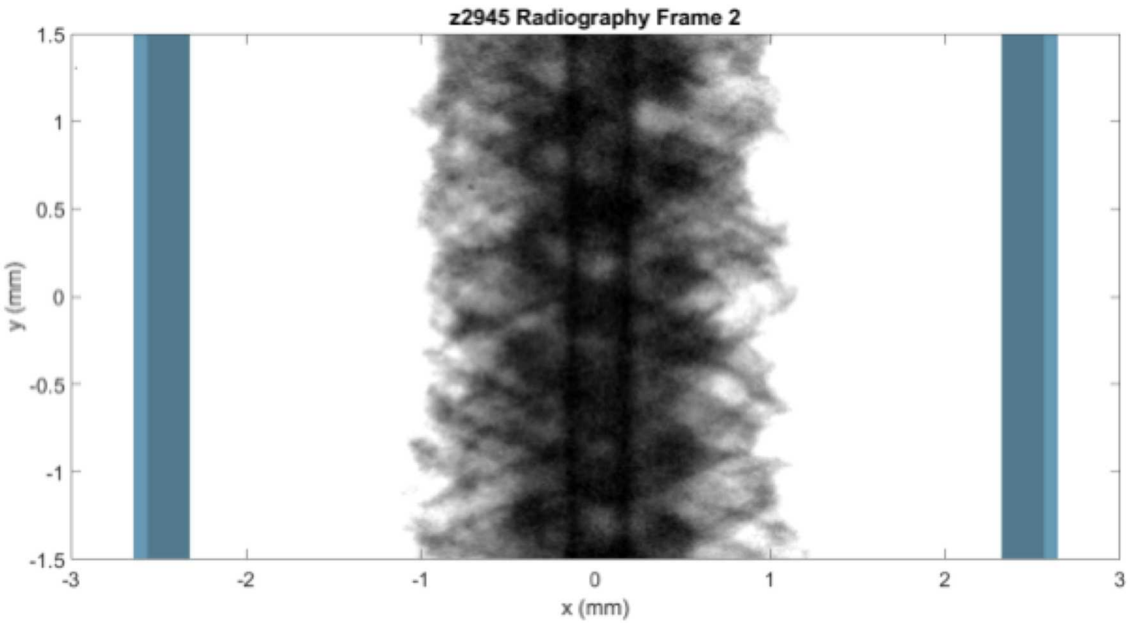
AR9 data



Stability looks good at very late time

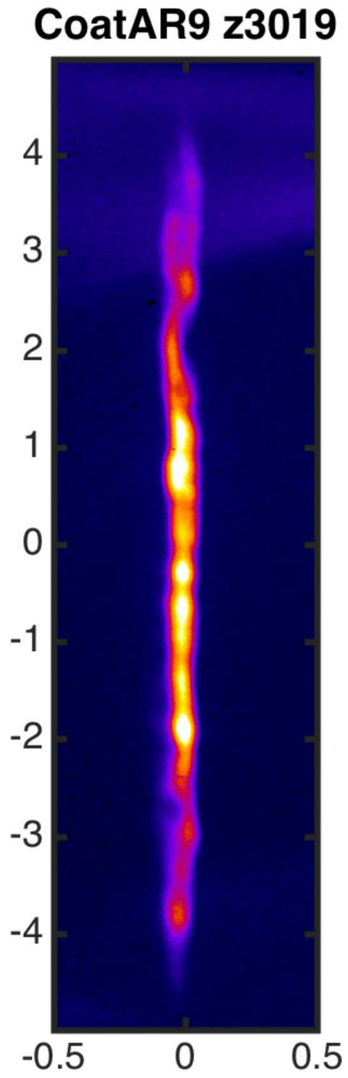
- Convergence ratio ~ 17





We have demonstrated a uniform stagnation column by reducing this ETI seed

Taking these high-aspect-ratio liners to stagnation we can produce a quasi-uniform stagnation column

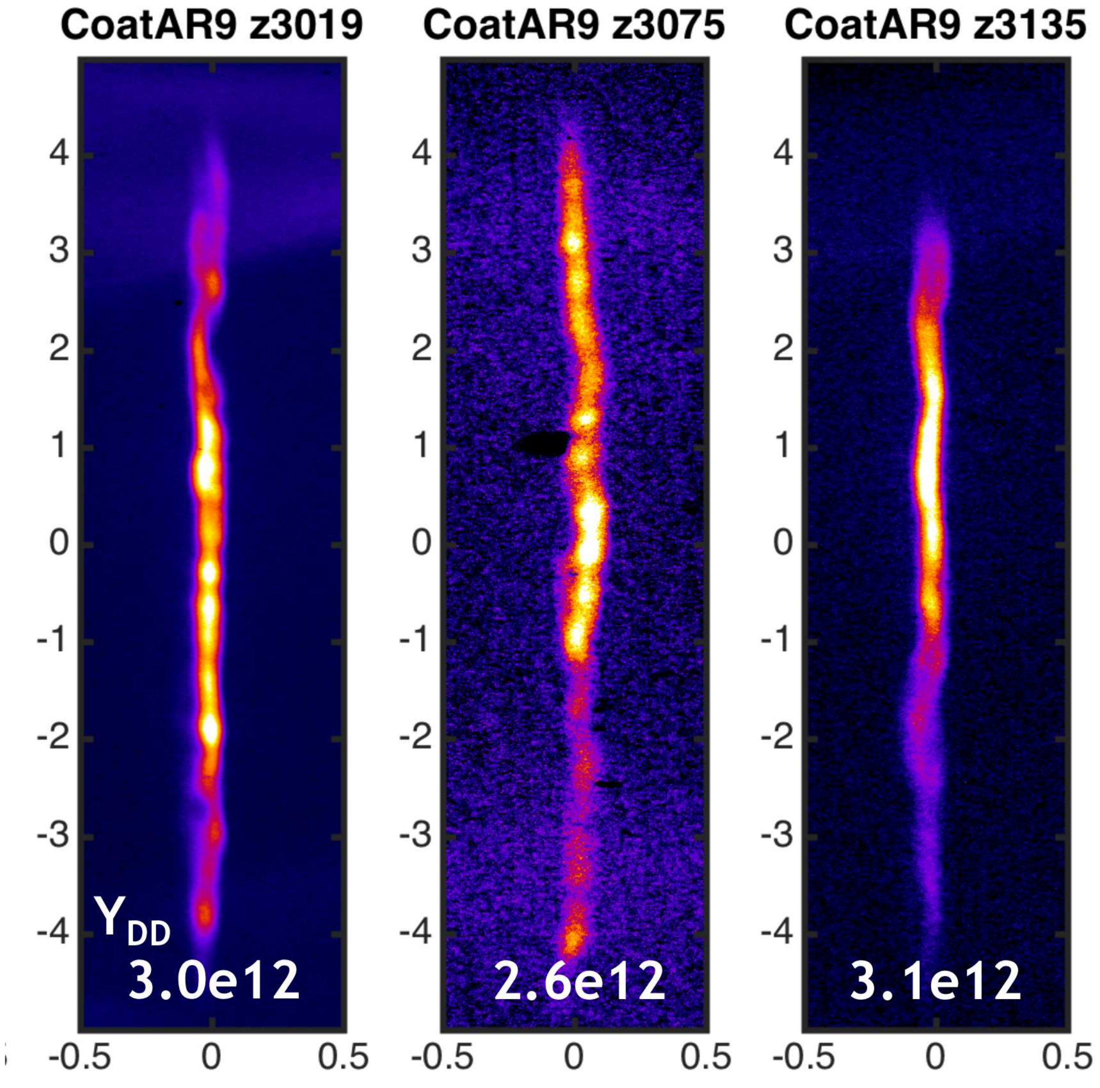


Taking the coated AR9 implosion thought to stagnation (i.e. now with preheat) we reach a uniform stagnation column

- >4 mm of bright, continuous x-ray emission
- Minimal (if any) residual helical structure

Yield Y_{DD} ~3e12 is equivalent to our uncoated AR6 experiments

Over multiple shots we get similar stagnation morphologies

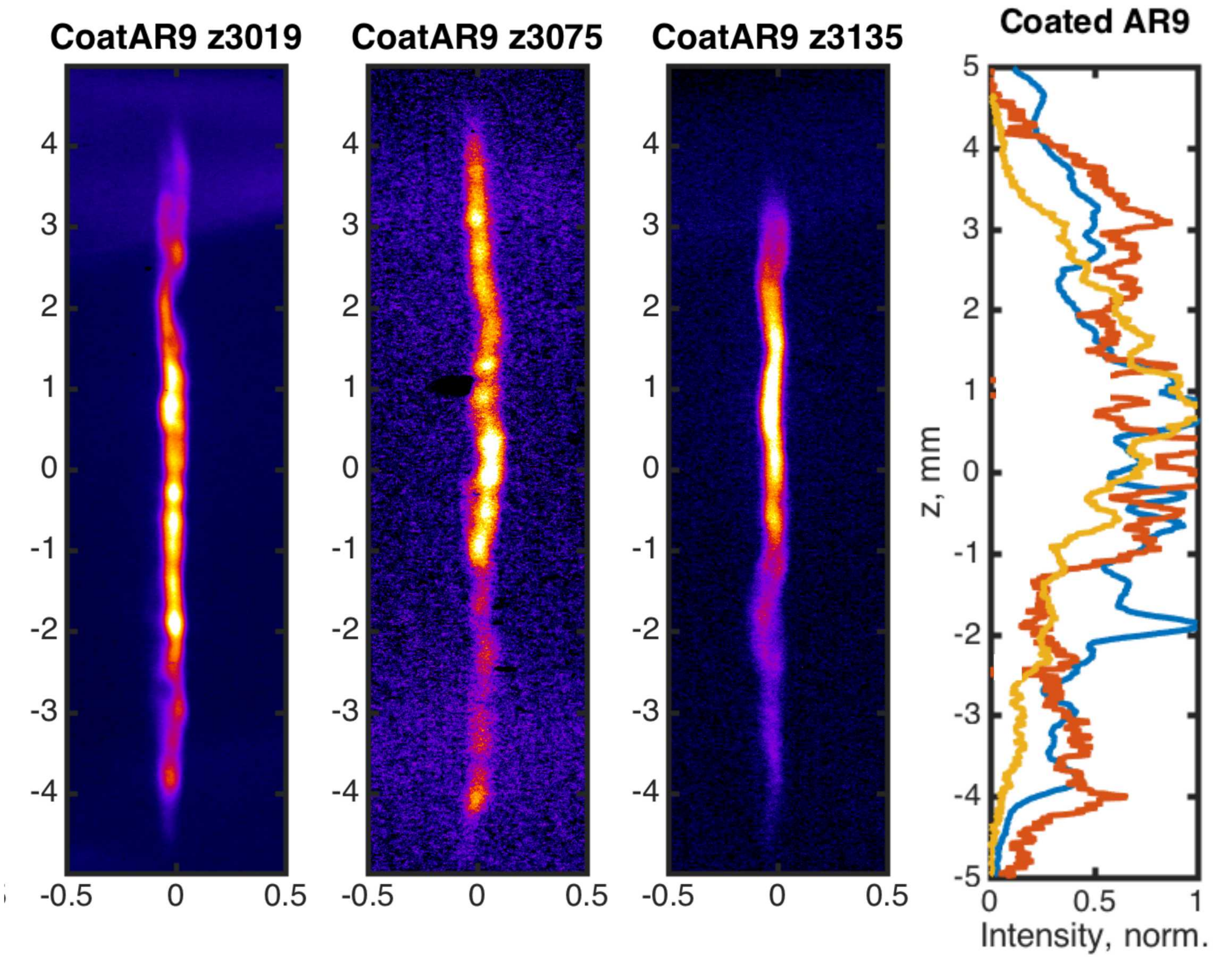


Taking the coated AR9 implosion thought to stagnation (i.e. now with preheat) we find we obtain a uniform stagnation column

- >4 mm of bright, continuous x-ray emission
- Minimal (if any) residual helical structure

Over multiple experiments we obtain reasonably uniform stagnations

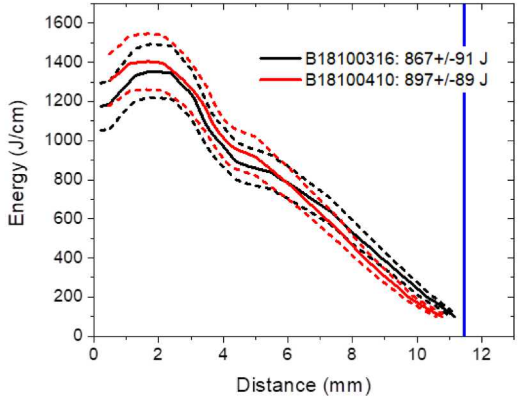
The axial x-ray emission structures look similar



The axial structure of the x-ray emission is broadly similar

- Brighter for upper ~5 mm
- Lower emission near at lower end of stagnation
- Could be consistent with axial gradient in laser deposition

~880 J coupled to fuel
- 55% of input energy



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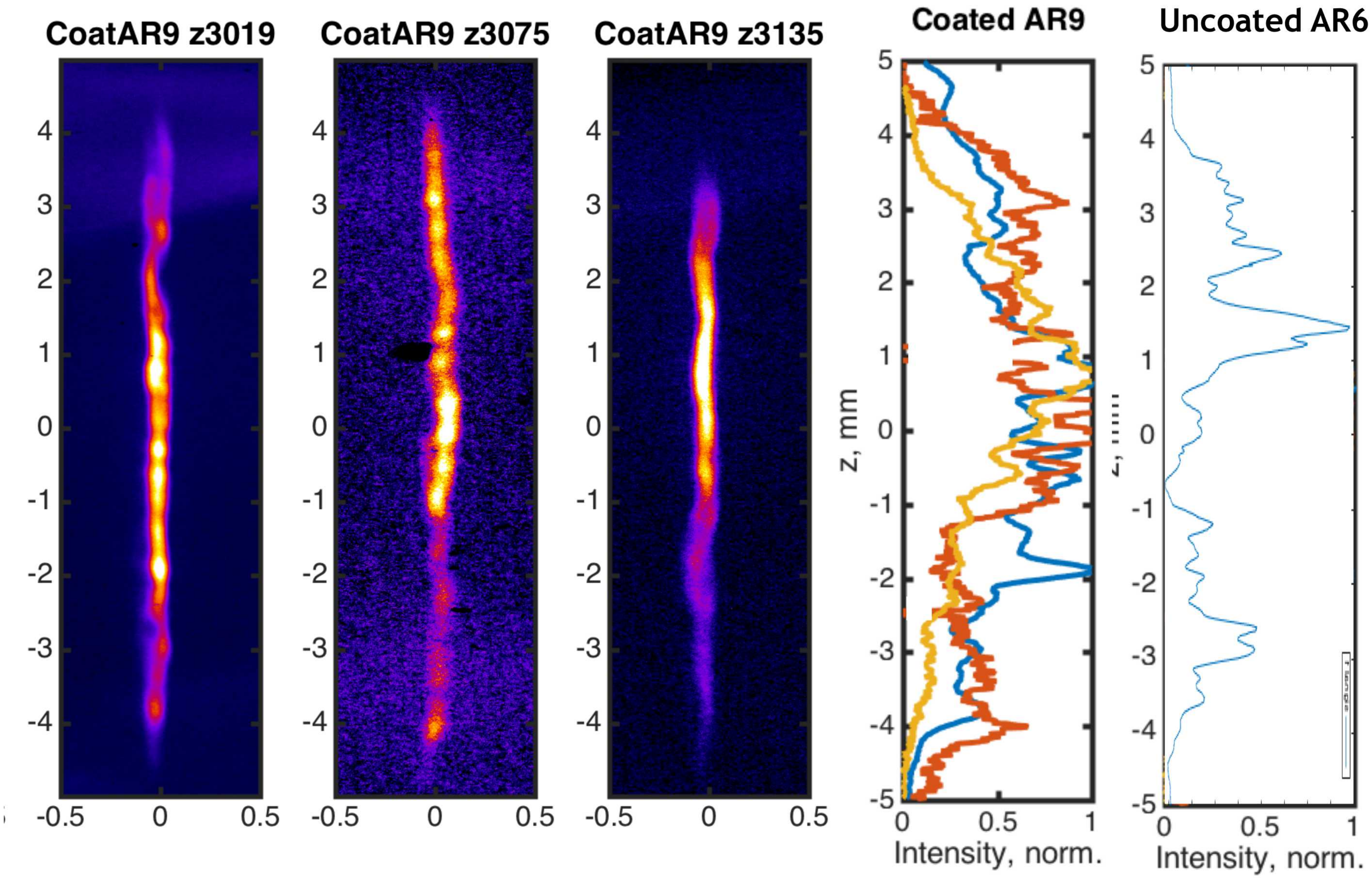

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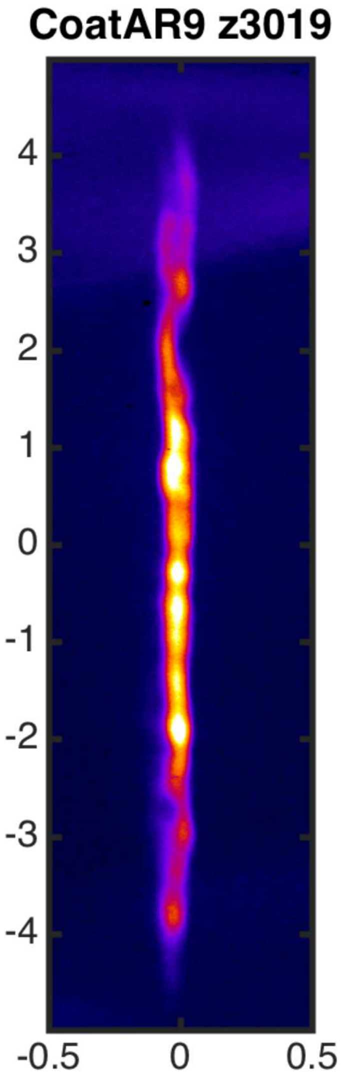
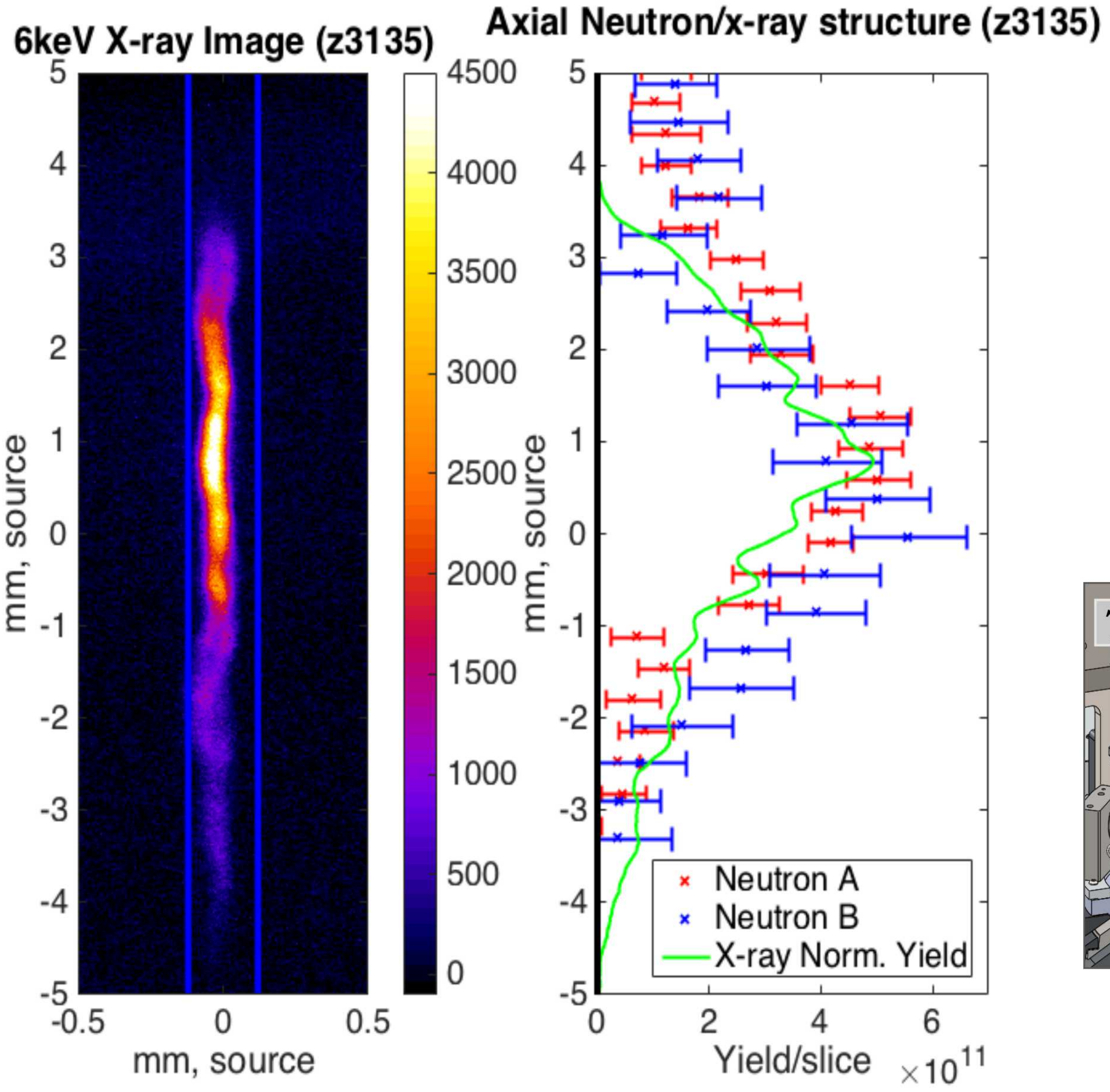
Uncoated AR6 data shows significantly more axial variation in emission

Of course, there's more to stagnation than an image



- X-ray emission structure
- Neutron emission structure
- Time resolved structure
- Neutron spectrum (nTOF)
  - Ion temperature
  - Magnetization
- Primary DD yield
- Secondary DT yield

The axial neutron emission structures look uniform

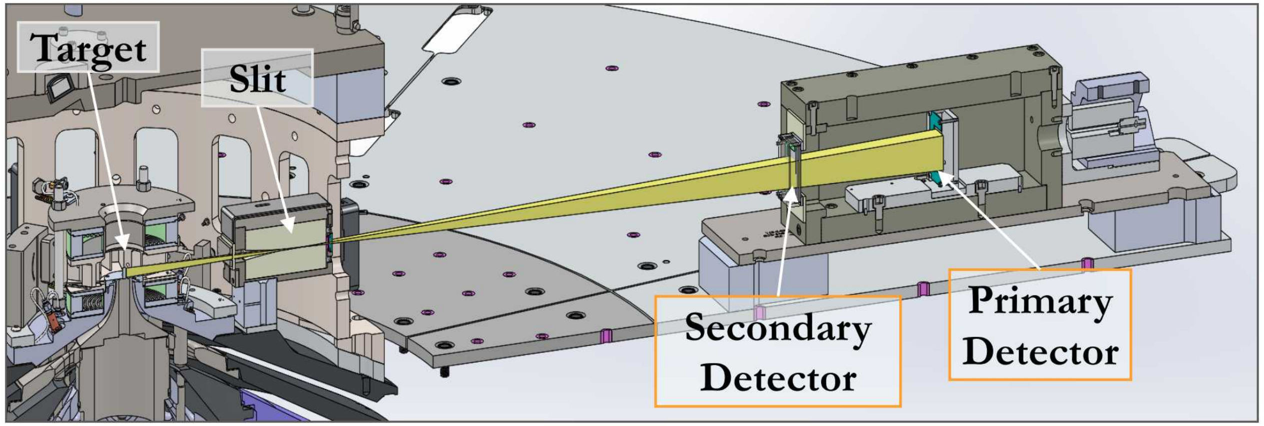


We recently developed a one-dimensional neutron imager for Z

- Uses tungsten rolled edge slit to image onto CR39

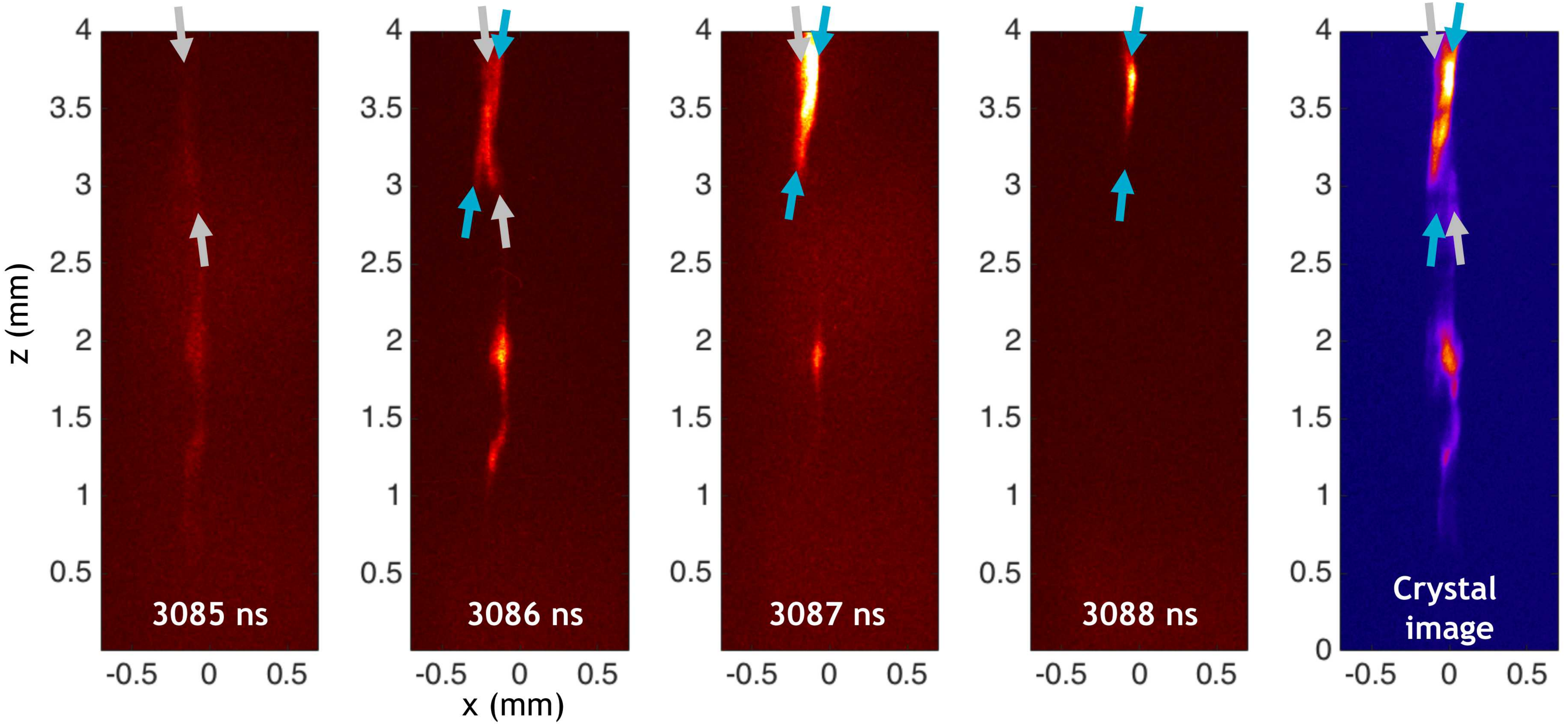
Initial data indicates the neutron emitting regions is also quasi-uniform

- For this case good correlation between neutron and x-ray emitting regions



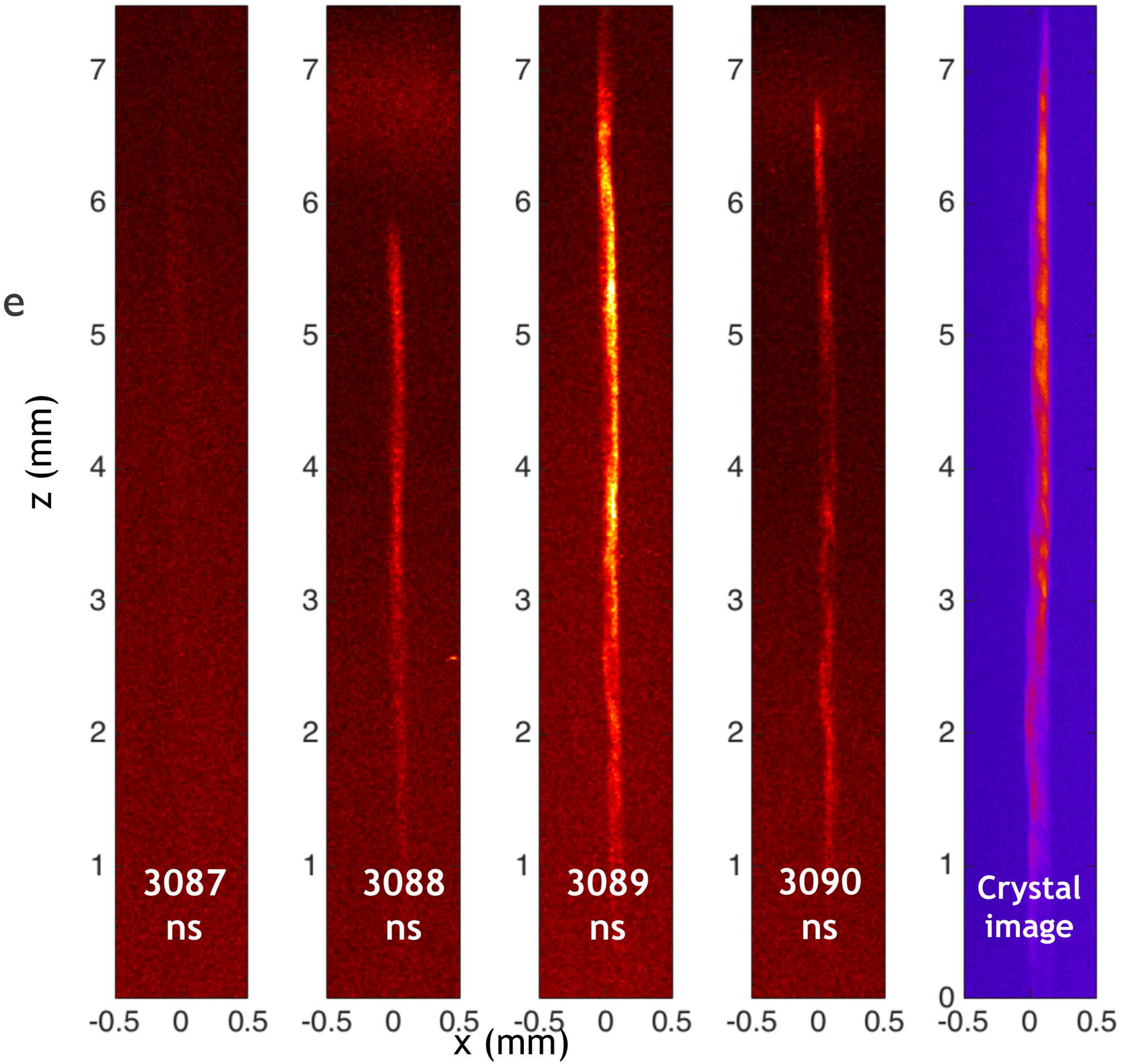
J.D. Vaughan *et al.*, Rev. Sci. Instrum. **89**, 10I121 (2018)
D.J. Ampleford *et al.*, Rev. Sci. Instrum. **89**, 10I132 (2018)
See posters: **GP11.00132** (Vaughan), **GP11.00094** (Ampleford)

We have recently developed a time-resolved imaging capability for MagLIF: For AR6 stagnations we see very non-uniform stagnation



TiGHER Pinhole Camera:
Developed by T. Webb *et al.*

With Coated AR9 liners we see a significantly more uniform stagnation over time

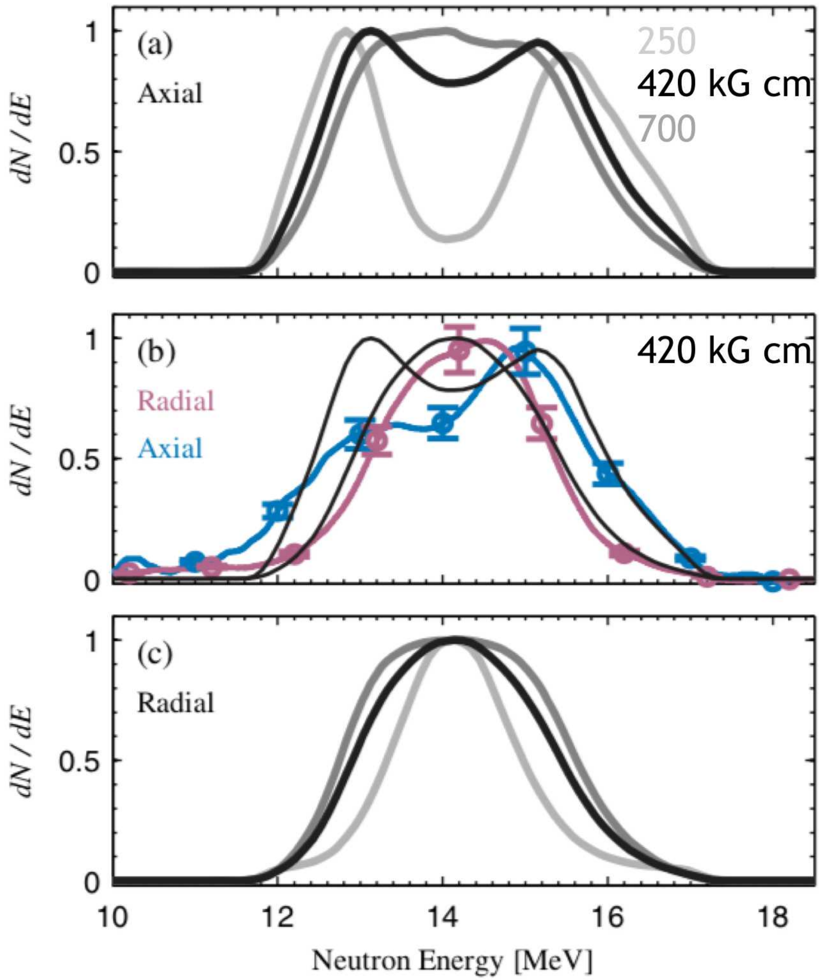


TiGHER Pinhole Camera: Developed by T. Webb *et al.*

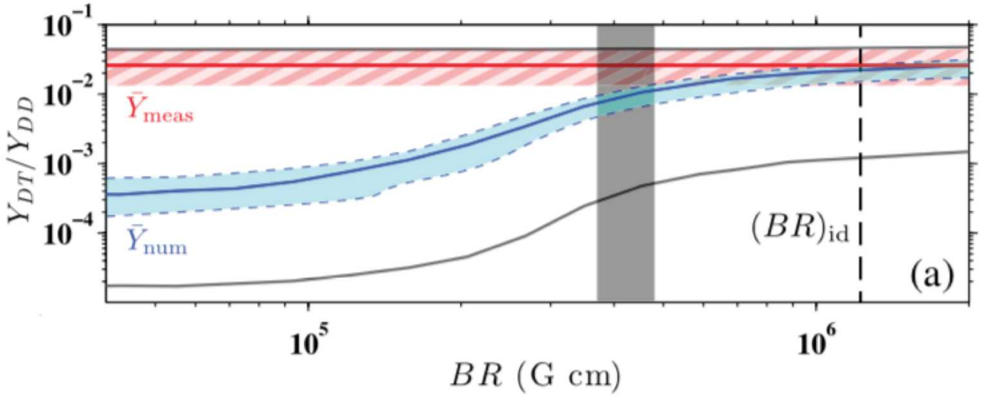
We can use the spectrum of the secondary DT neutrons as a diagnostic of magnetization at stagnation

AR6 data

Magnetic field consistent with flux compression

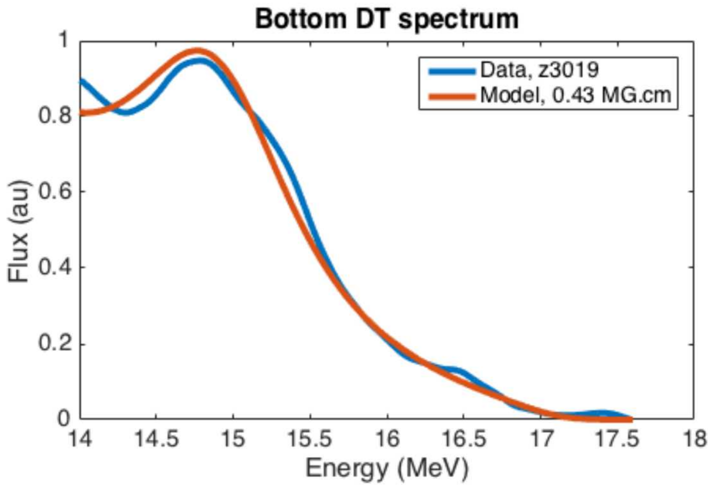


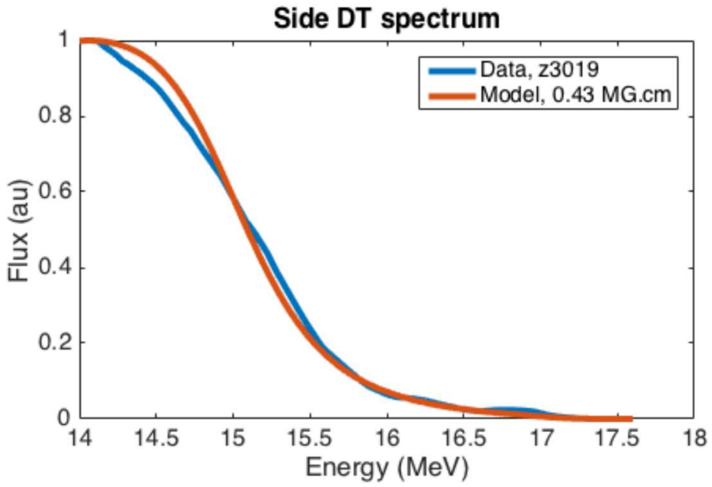
Relationship between DT and DD yield varies with magnetization



P.F. Schmit *et al.*, Phys. Rev. Lett. **113** 155004 (2014)

For the coated high aspect ratio liners we have very clean measures of magnetization at stagnation



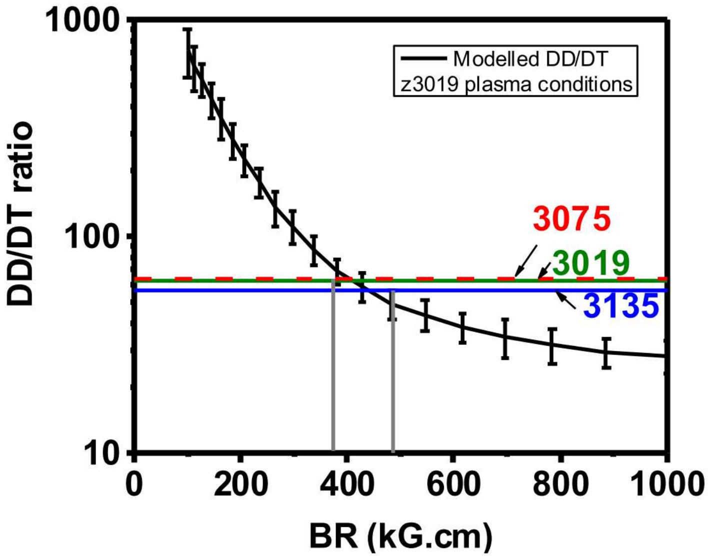


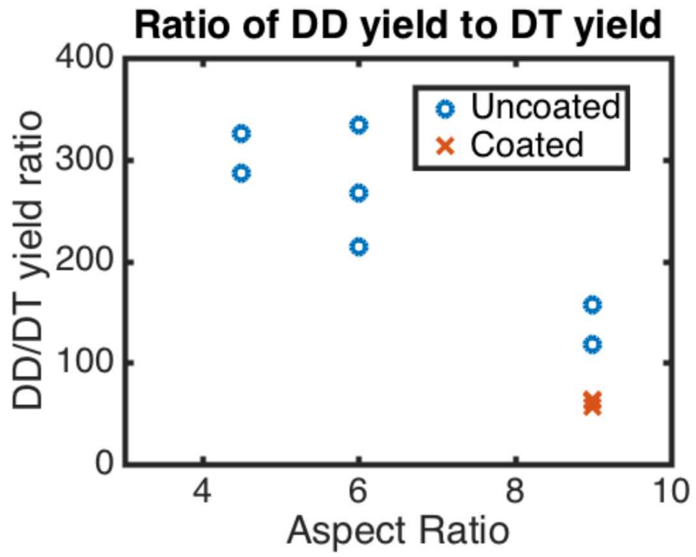
For AR9 dataset

- Both BR diagnostics indicate
  BR ~ 400 kG.cm
- This is on the high end of the BR from the AR6 dataset
  - Better than best performing AR6 shots
- Agreement between two metrics is better than for AR6

For coated AR9 setup we have shown assumption of long neutron producing region is valid

Coated AR9 data





Analysis method based on
P.F. Schmit *et al.*, Phys. Rev. Lett. **113** 155004 (2014)

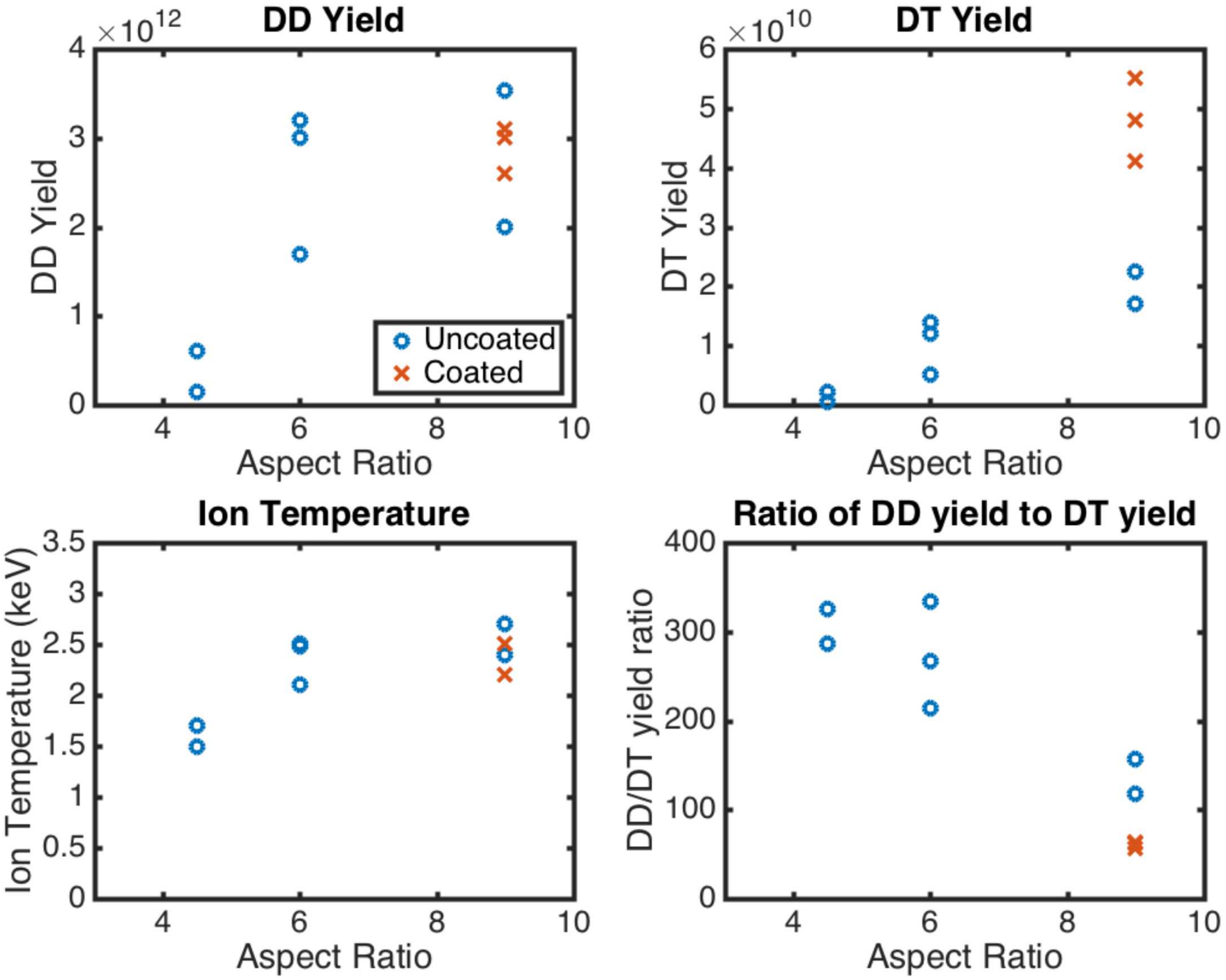
Many key stagnation parameters, including yield, are reproducible

These three, nominally identical coated AR9 experiments have exhibited very similar behavior

- Similar Primary DD yields
- Similar Ion temperatures
- Similar DT yields

While going to the coated AR9 platform hasn't improved MagLIF performance

- Performance hasn't been diminished
- Reproducibility is better



This platform enables detailed scaling studies

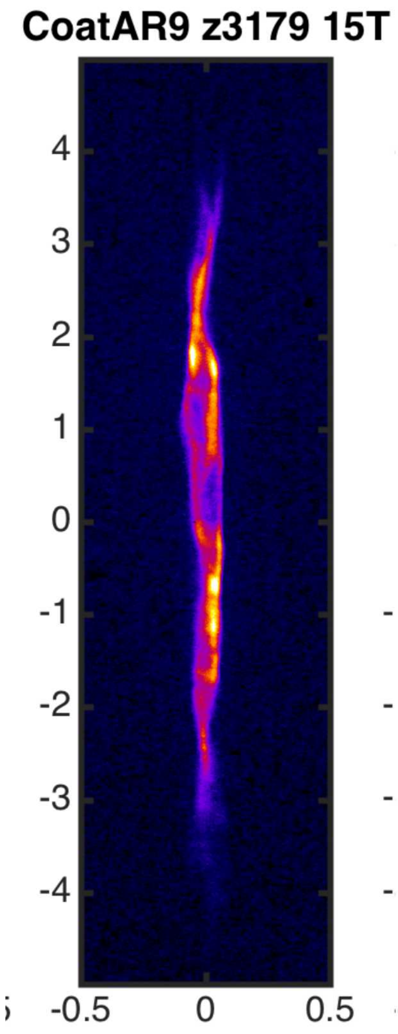
Initial experiment at 15T demonstrated ability to scale MagLIF with initial axial magnetic field

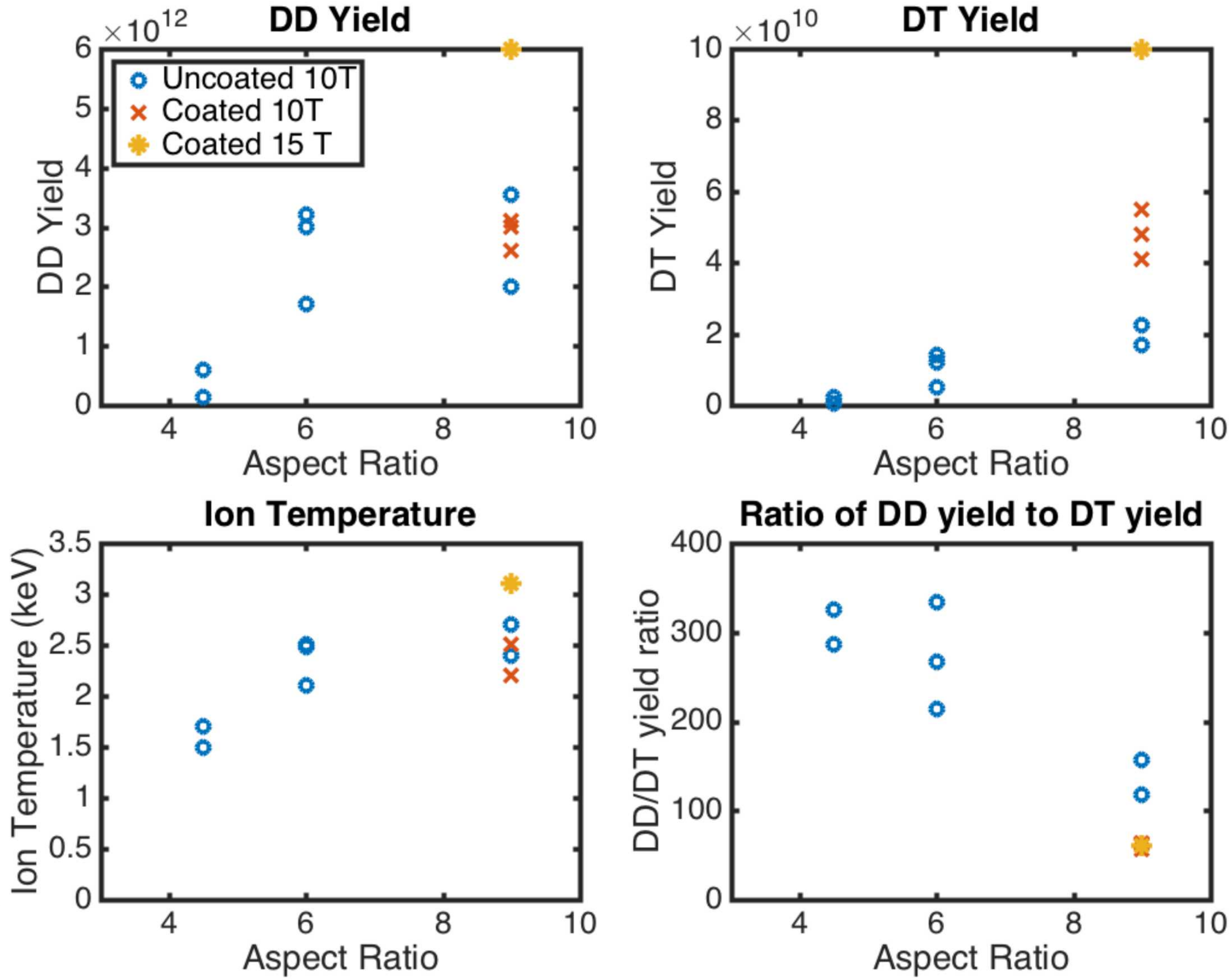
By taking our coated AR9 experiments to 15T we have seen considerable gain in

- ion temperature,
- DD yield
- DT yield
- Electron temperature

All other inputs kept fixed

- Preheat
- Fuel density
- Drive current





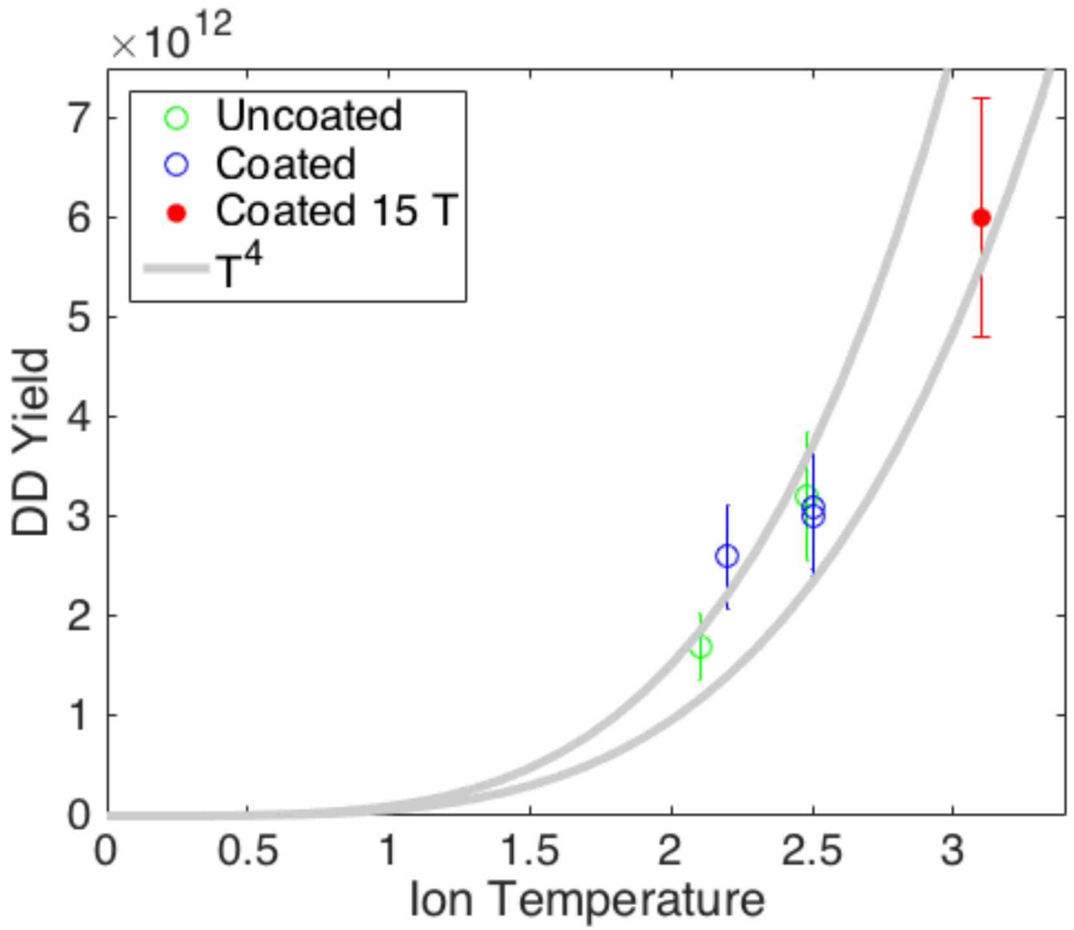
This 15T experiment also demonstrated scaling with ion temperature

Significant enhancement in ion temperature is matched by significant change in DD yield

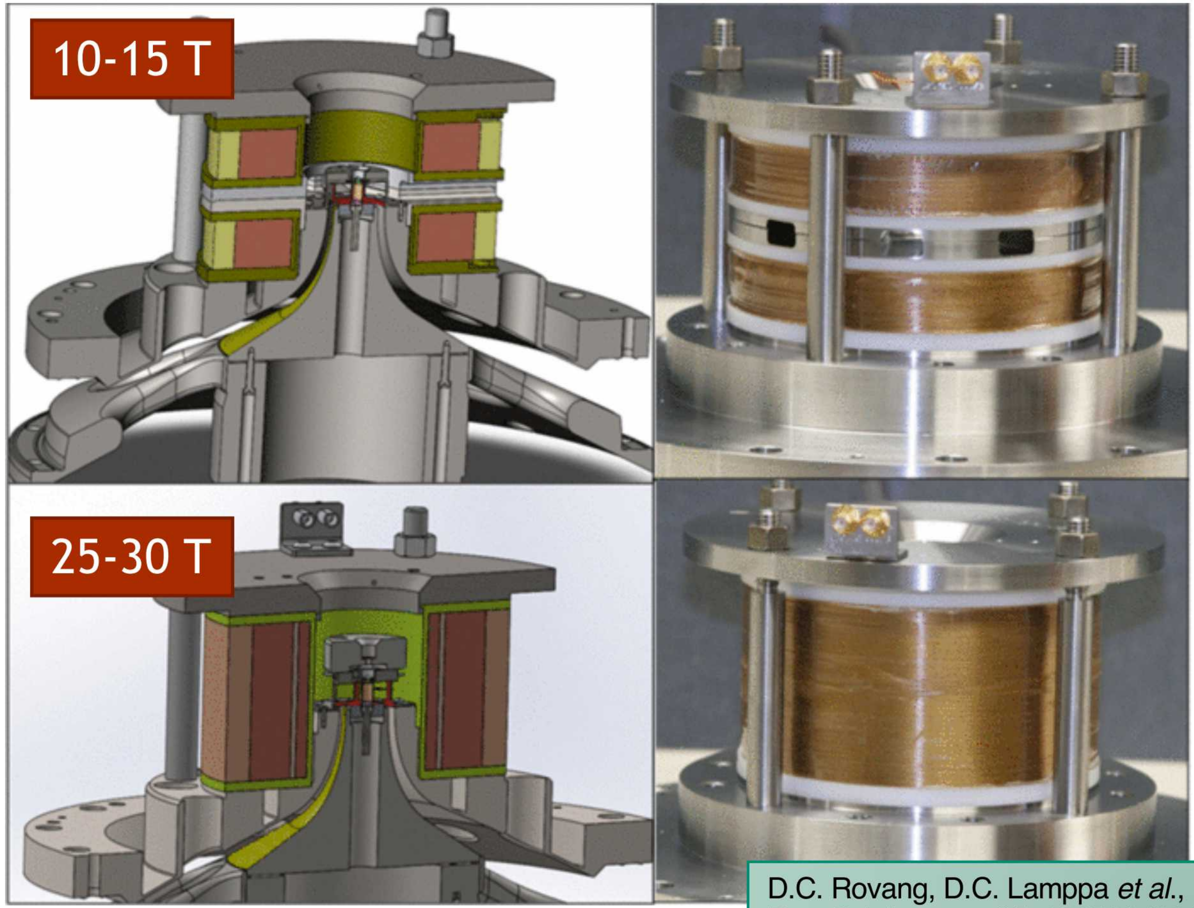
Within uncertainties in yield, data is following T^4 scaling

In a parallel effort, this coated AR9 platform is being used to study new preheat platforms

- See next talk by Adam Harvey-Thompson



We are planning to use the coated AR9 platform to further study scaling with initial axial magnetic field



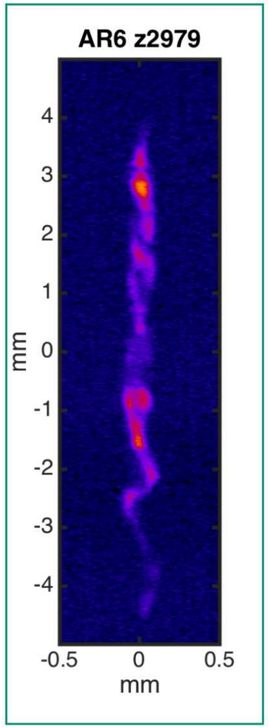
D.C. Rovang, D.C. Lamppa *et al.*, Rev. Sci. Instrum. **85**, 124701 (2014)

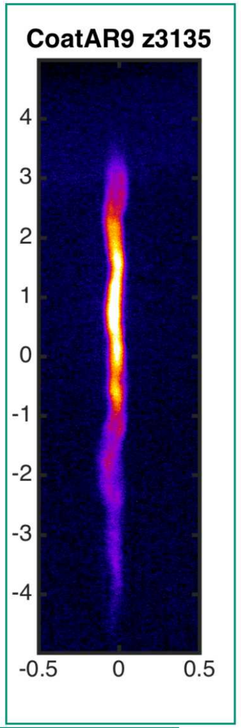
Experiments to date have concentrated on 10-15 T initial fields

We are planning experiments next year to study B_z scaling outside this range

- Evaluate performance at B < 10 T
  - Reduce current in existing coils
- Use different coil configuration to driving fields in the 25-30 T range
  - Requires sacrificing x-ray diagnostic access

Overview: By reducing the seed of instabilities, we have developed a uniform, reproducible MagLIF platform





MagLIF stagnations exhibit complex helical structures

- These can impact performance, reproducibility and comparisons to simulations
- By varying the liner geometry we can conclude that these are initiated on the outer surface of the liner

We can significantly reduce the seed of these instabilities

- Previous work has shown seed is early-time electro-thermal instability – we have techniques to reduce

We have demonstrated a uniform stagnation column by reducing this ETI seed

- Helical mode significantly reduced, more uniform brightness axially (in x-rays and neutrons)
- Reproducibility is improved when structure is improved
- Stagnation column is uniform across burn time

This platform enables detailed scaling studies

- Scaling with initial applied axial field