SAND2023-04079C

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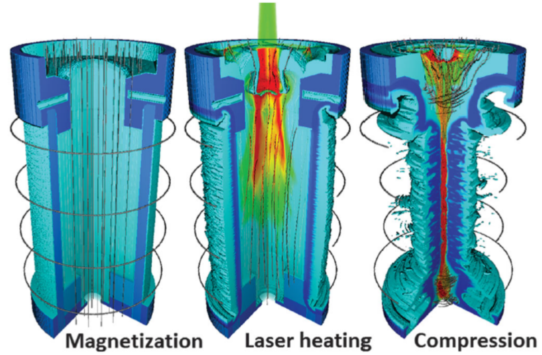
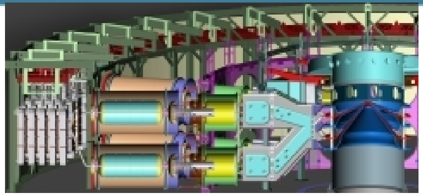
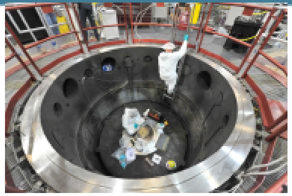
Investigating the formation and scaling of helical structures in axially magnetized magnetically driven implosions







Matthew R. Gomez, M.R. Weis, M.B. Adams, T.J. Awe, N.D. Hamlin, C.A. Jennings, M.R. Martin, G.A. Shipley, J.M. Woolstrum, E.P. Yu, L.N. Shulenburger, D.J. Ampleford

Presented at the 50th International Conference on Plasma Science

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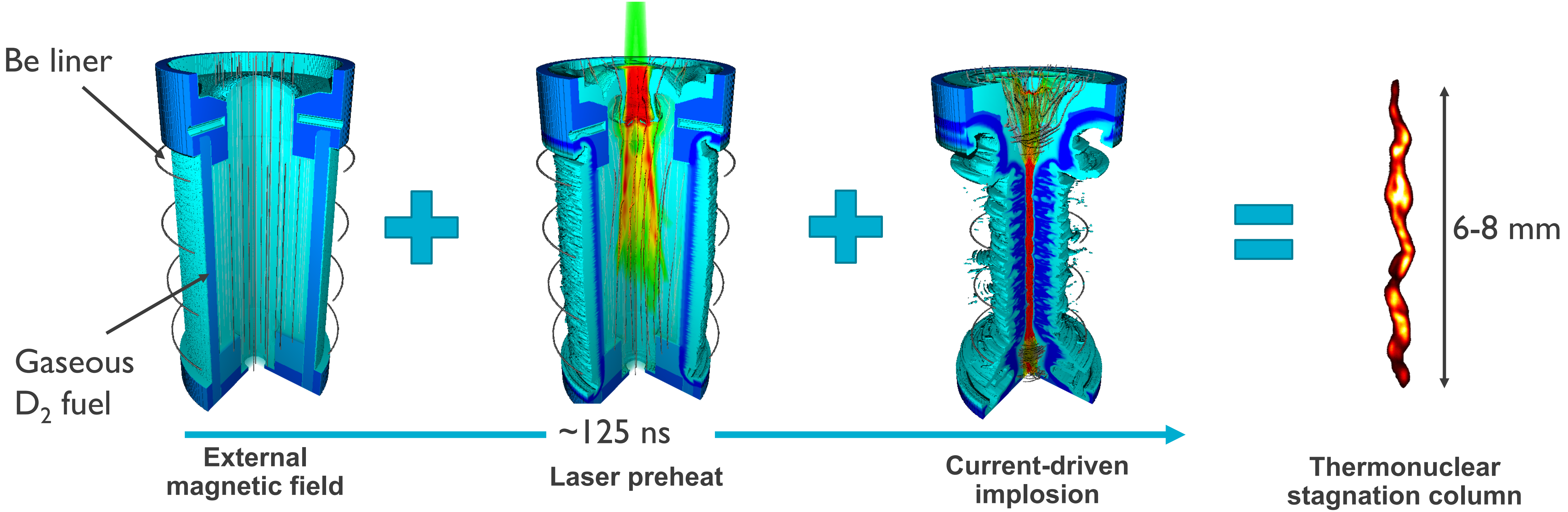
MagLIF is utilizes an applied axial magnetic field, laser preheat, and a magnetically driven implosion to reach fusion conditions



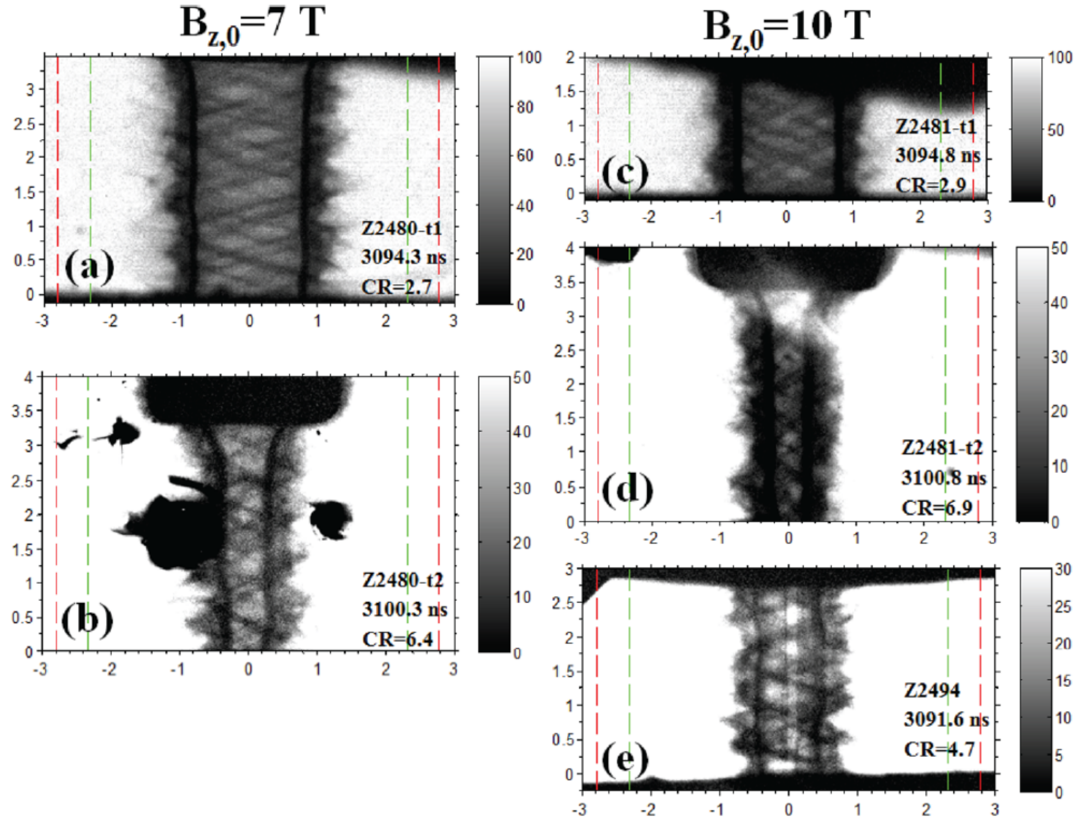
- Preheat raises the adiabat of the fuel allowing quasi-adiabatic compression to keV temperatures
- Applied field reduces thermal conduction losses from fuel to wall during implosion and traps charged fusion products

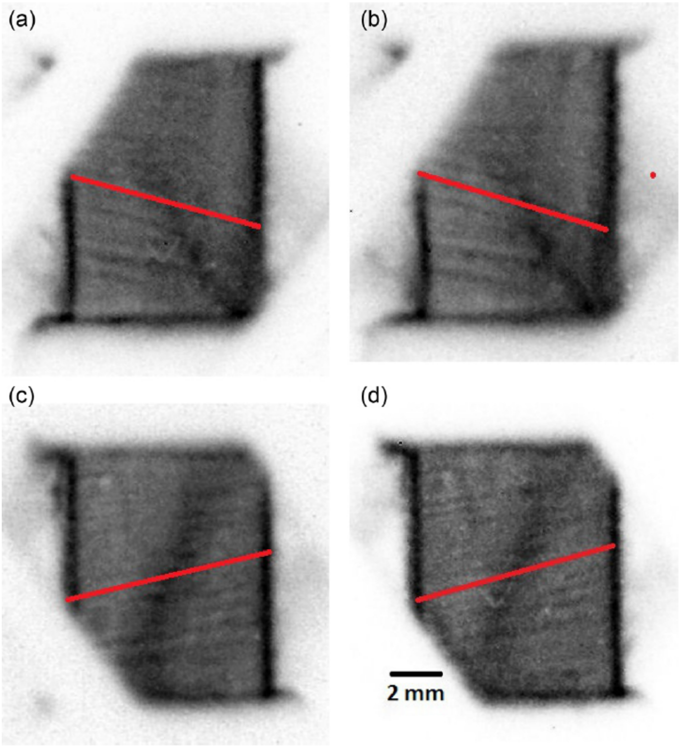
S.A. Slutz et al., Phys. Plasmas **17**, 056303 (2010).

M.R. Gomez et al., Phys. Rev. Lett. **113**, 155003

Helical structures have been observed in axially magnetized, magnetically-driven liner implosions

- The axial applied magnetic field combined with the azimuthal drive field results in helical structures
- Helical structures have been observed on the 1 MA and 20 MA scales
- Helical structures have been observed radiographically and in self-emission

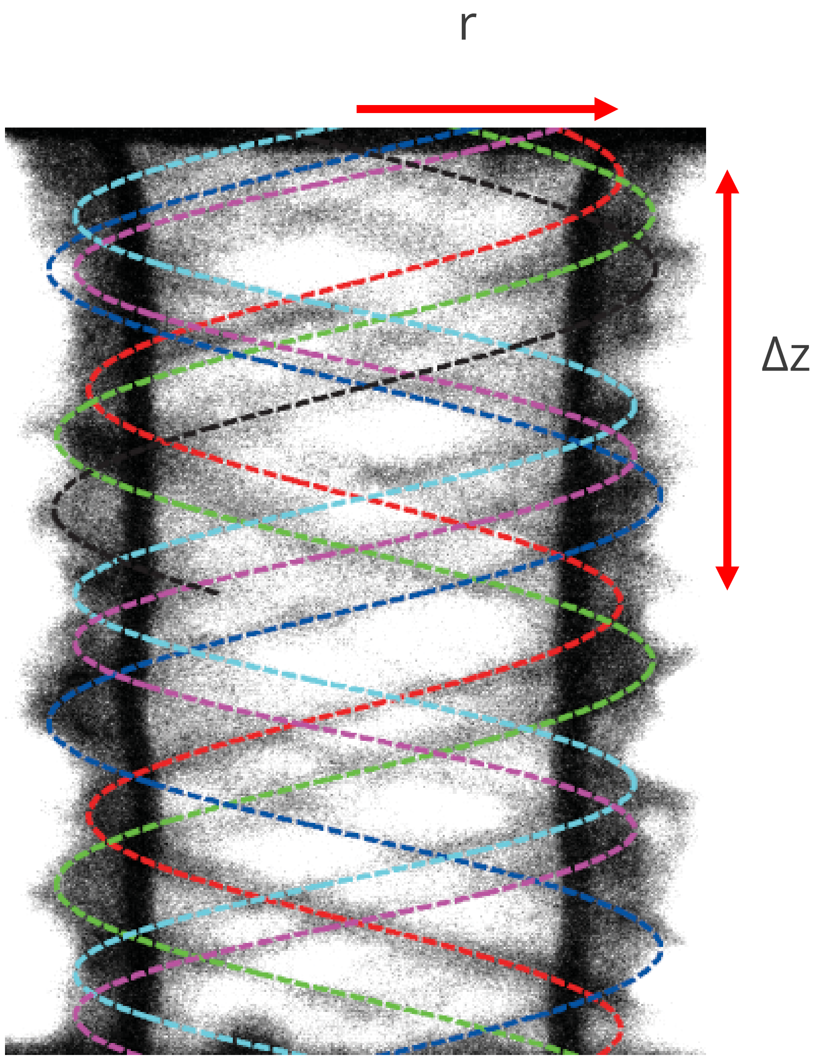




T.J. Awe et al., Phys. Plasmas **21**, 056303 (2014).

L. Atoyan et al., Phys. Plasmas **23**, 022708 (2016).

The angle of the helical structures is observed to increase with (1) the initial applied field and (2) the convergence of the target



$$\theta_{pitch} = atan\left(\frac{\Delta z}{2\pi r}\right)$$

- Assuming Δz remains fixed, θ_{pitch} increases as r decreases

- Helices are observed only in experiments with B_z
- Angle of helices increases with increasing B_z
- Geometric argument about helical magnetic field

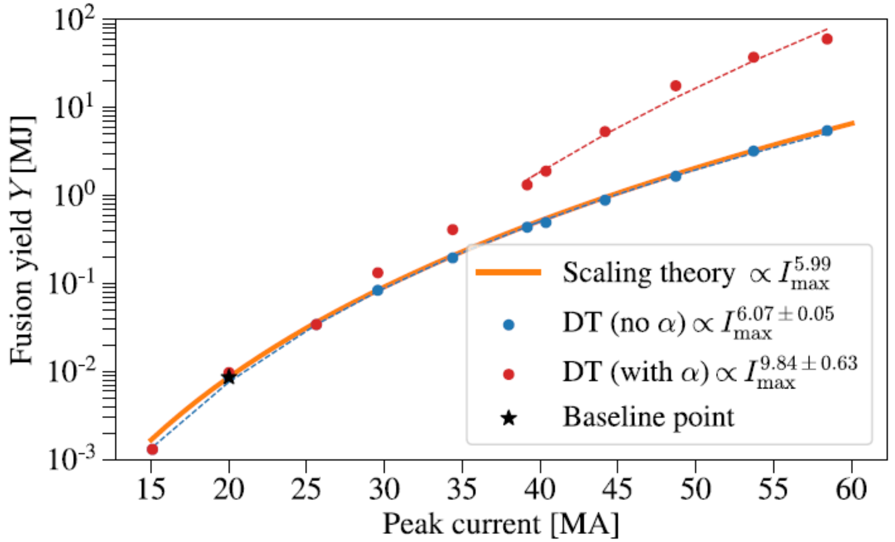
$$\theta_{pitch} \overset{?}{\propto} atan\left(\frac{B_z}{B_\theta}\right)$$

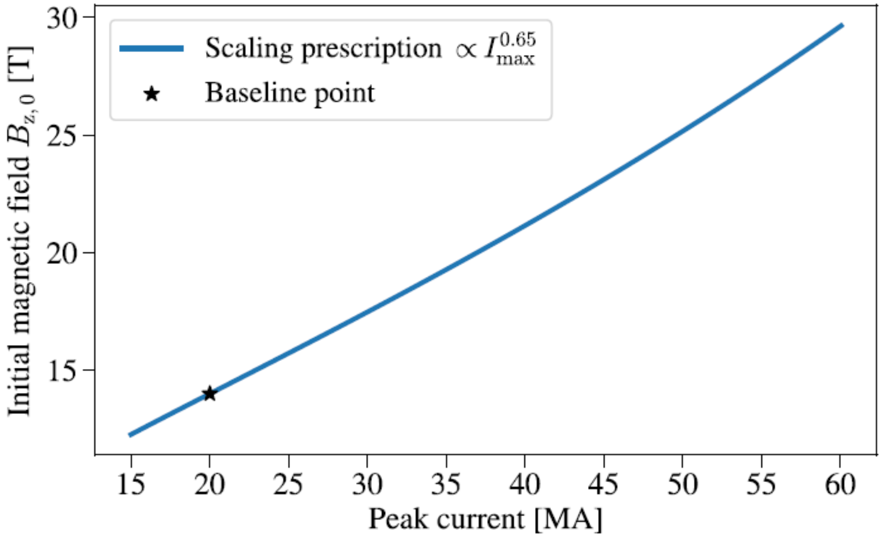
T.J. Awe et al. Phys. Rev. Lett., **111**, 235005 (2013).

T.J. Awe et al., Phys. Plasmas **21**, 056303 (2014).

Understanding the formation of helical structures is critical to scaling MagLIF to higher currents and larger magnetic fields

- Efforts to understand MagLIF scaling are underway
- High currents and magnetic fields are necessary to reach high yields
  - 16-20 MA → ~60 MA
  - 10-15 T → ~30 T
- Implosion stability can significantly impact the predicted performance in MagLIF
- We need to understand how helical structures form and scale



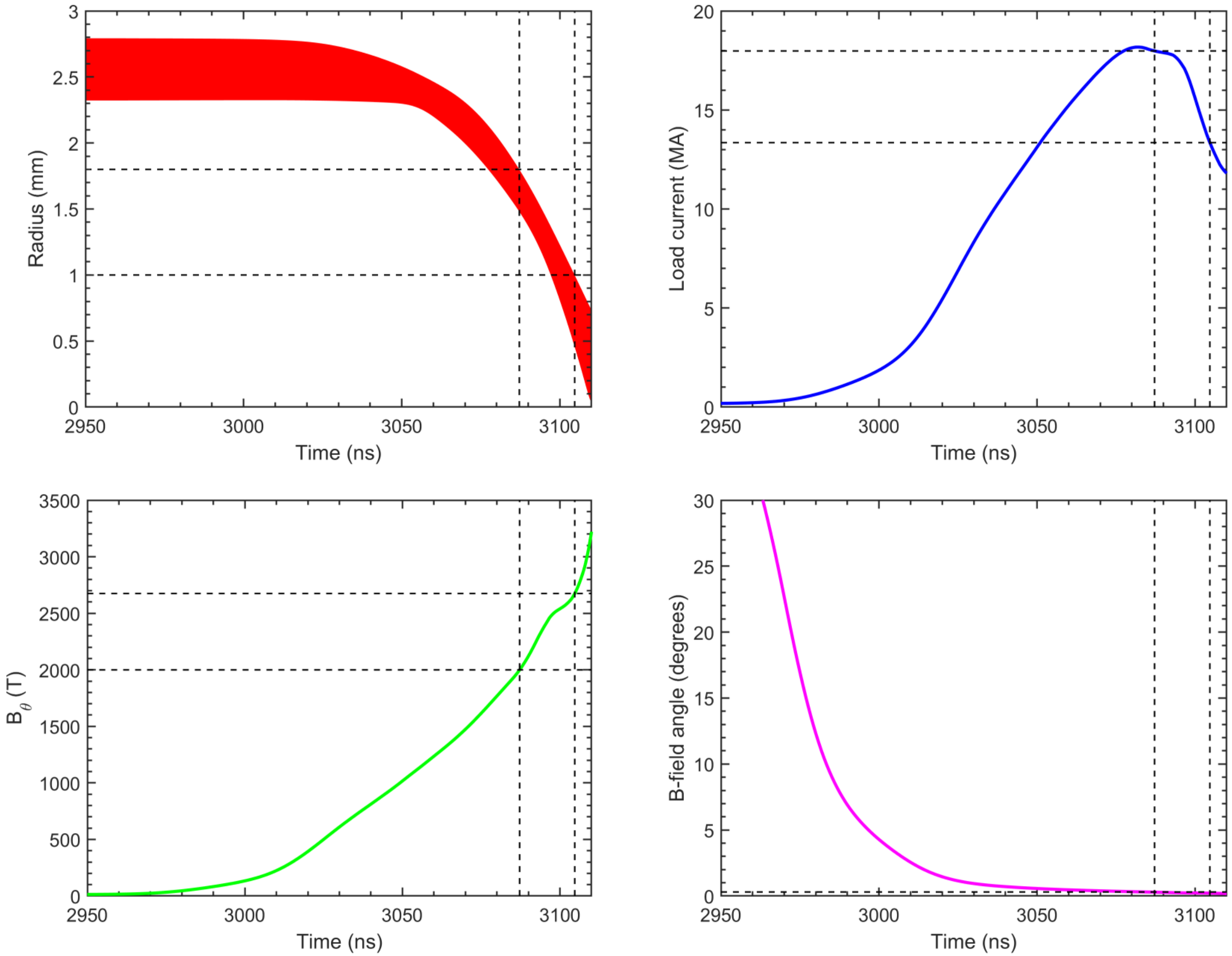


S.A. Slutz et al. Phys. Plasmas, **111**, 022702 (2016).

D.E. Ruiz et al., Phys. Plasmas, **30**, 032708 (2023).

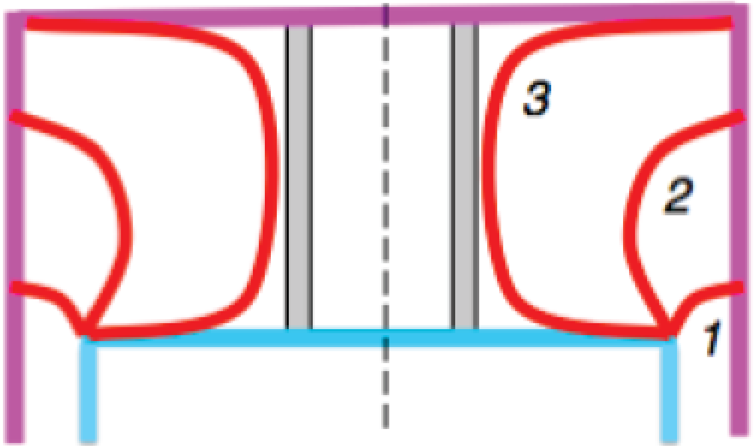
The helical structures were unexpected because the azimuthal field dwarfs the applied axial field when the images are captured

- At radiography time range:
  - Current ≈ 13-18 MA
  - $B_\theta \approx 2000\text{-}2700$ T
- Assuming $B_Z = 10$ T, the magnetic field angle < 0.3°
  - Observed angles > 10°
- Are the helical structures seeded early in time when fields are comparable?
- Is the axial magnetic field higher than we think?



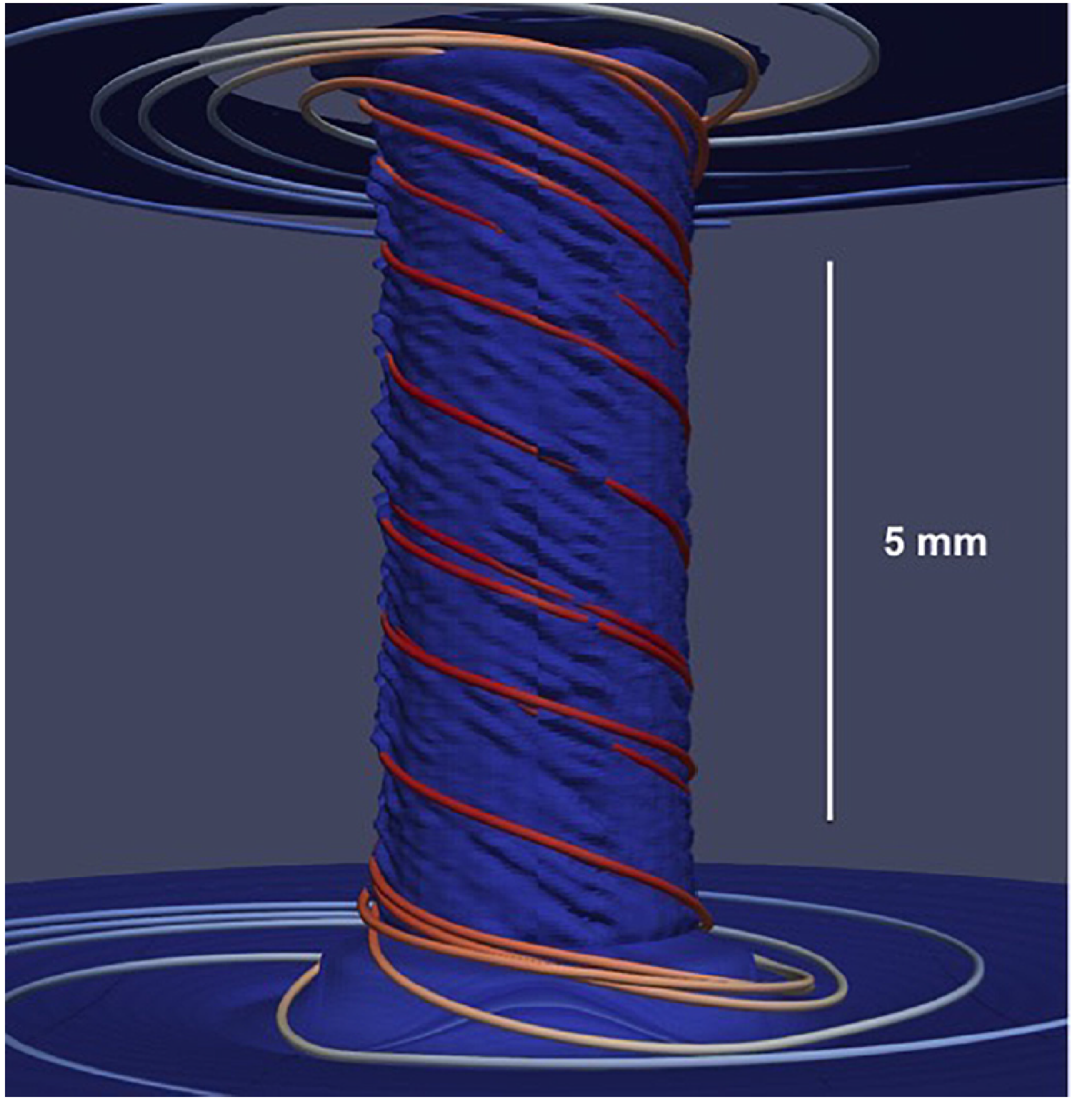
T.J. Awe et al. Phys. Rev. Lett., **111**, 235005 (2013). T.J. Awe et al., Phys. Plasmas **21**, 056303 (2014). R.D. McBride and S.A. Slutz, Phys. Plasmas **22**, 052708 (2015).

One proposed mechanism for generating helical structures is flux compression of the applied magnetic field



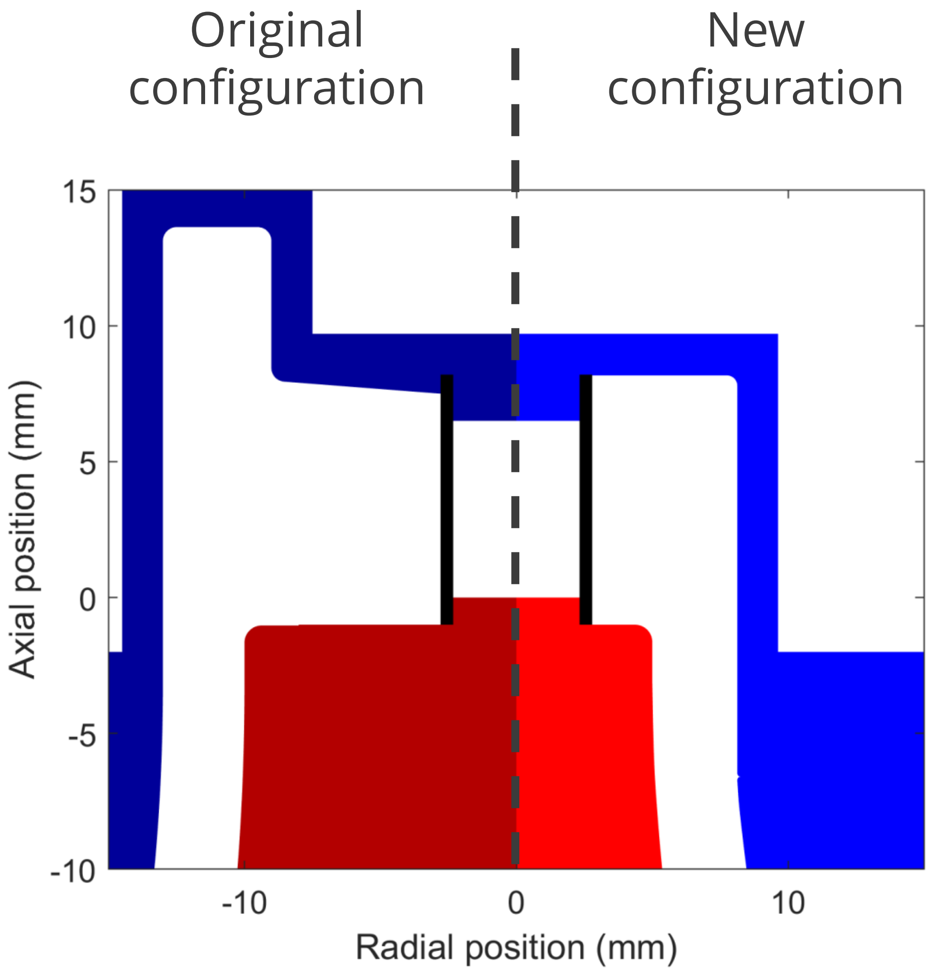
- Plasma from the final transmission line sweeps up magnetic flux within the return can and compresses it onto the target
- Flux compressed axial magnetic field comparable to azimuthal magnetic field, enabling helical structures to grow
- This requires that the plasma be conductive enough to sweep up the field

D.D. Ryutov et al. AIP Conf. Proc. **1639**, 63 (2014).



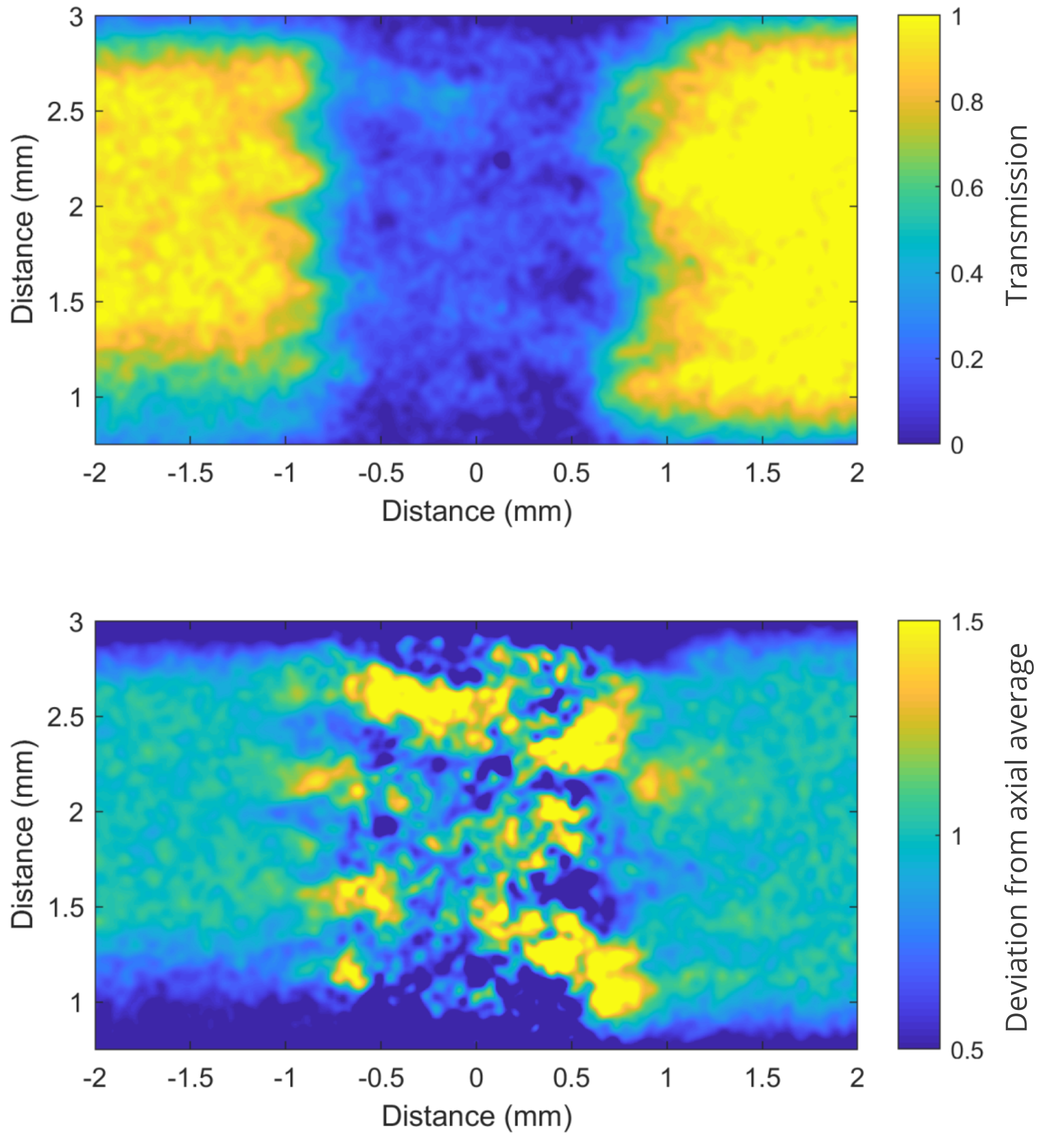
C.E. Seyler et al., Phys. Plasmas **25**, 062711 (2018).

To test this hypothesis, experiments were conducted with reduced magnetic flux and fixed magnetic field amplitude



- Anode radius 13 mm → 8 mm cathode radius 10 mm → 5 mm
  - Available flux outside target was reduced by a factor of 2.8-5.4
- Applied magnetic field of 10 T in both cases
- Maintain the same current drive/ azimuthal magnetic field
  - The target geometry was held constant
  - Initial inductance held constant

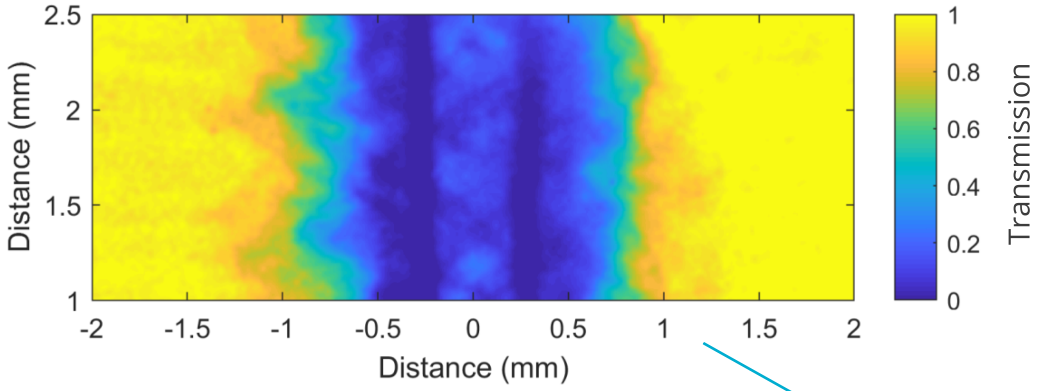
Increased background presented a challenge, but helical structures were identified and pitch angle was determined

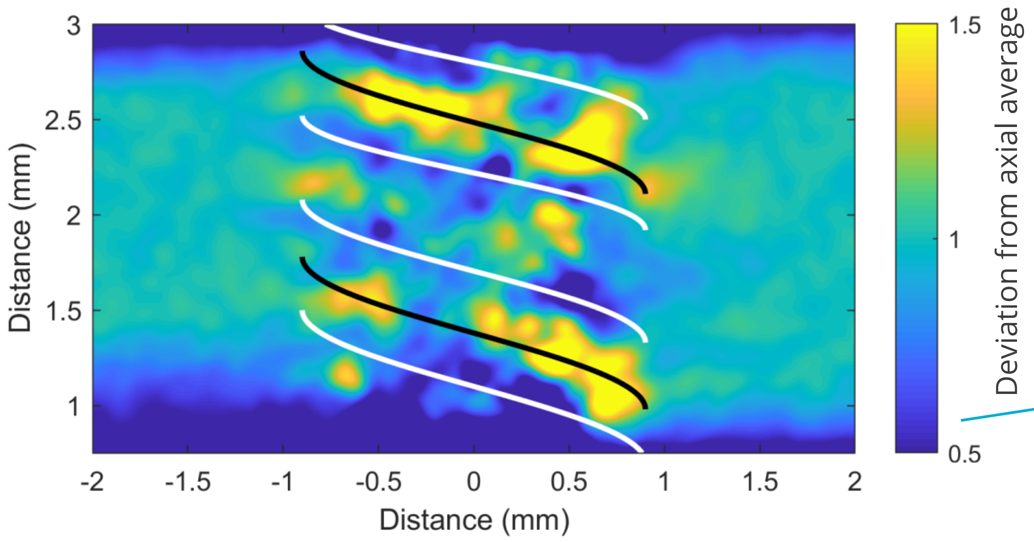


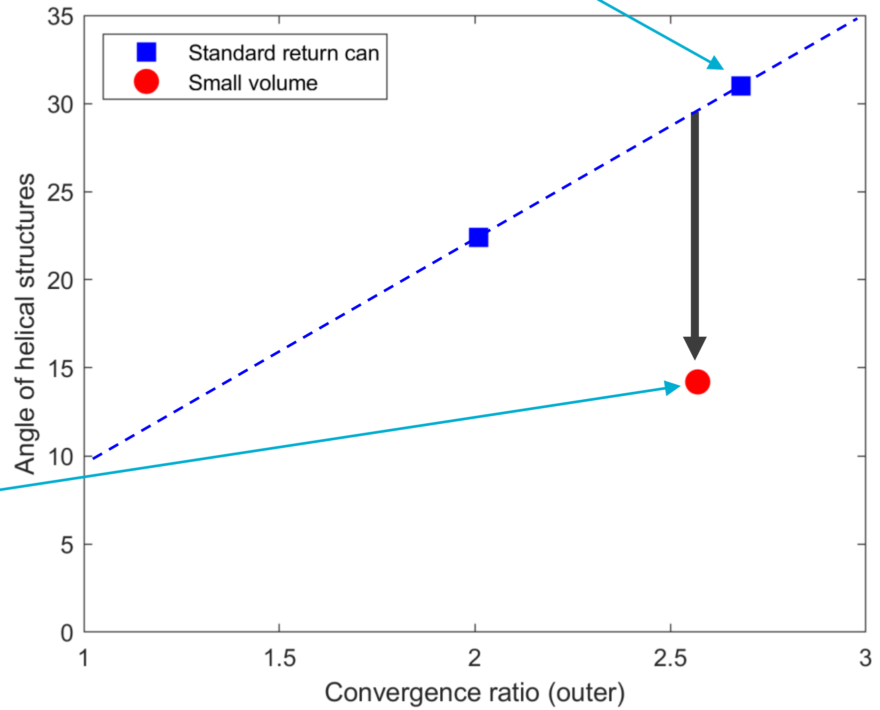
- Background level was ~2x backlighter signal level
  - Self-emission from load was significantly brighter and longer lasting for the small return can experiments
- Instability structures at the edges of the target are clearly visible in radiography
  - Difficult to identify helical structures in the middle of the target
- Image divided by axial average of target transmission to highlight the regions that deviated from the average
  - Helical structures more clearly visible

Reduced angle structures for the smaller return can suggest flux compression plays a role in helical structure development

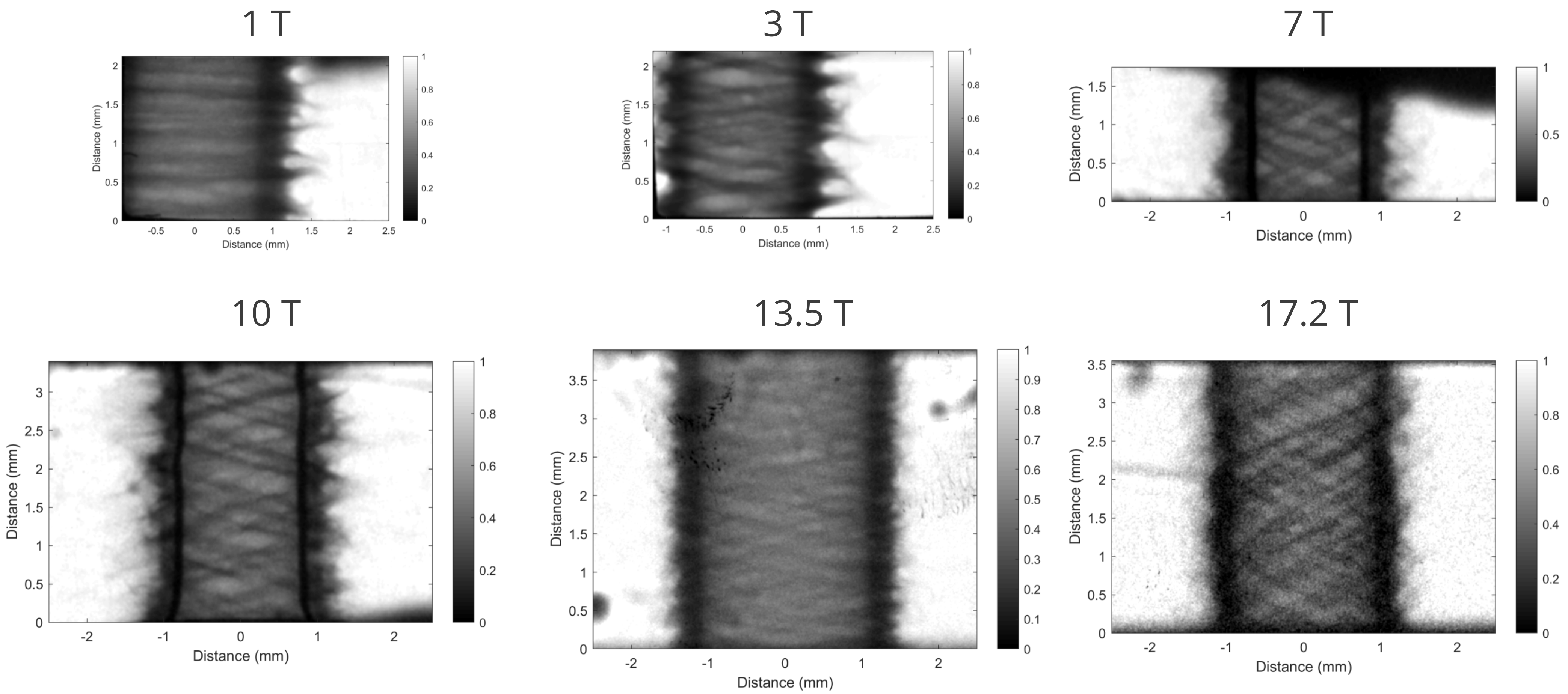
- Simple geometric arguments suggests 3-5x reduction in angle expected if flux compression plays a dominant role
  - >2x reduction observed
- Rigorous comparison with simulations planned





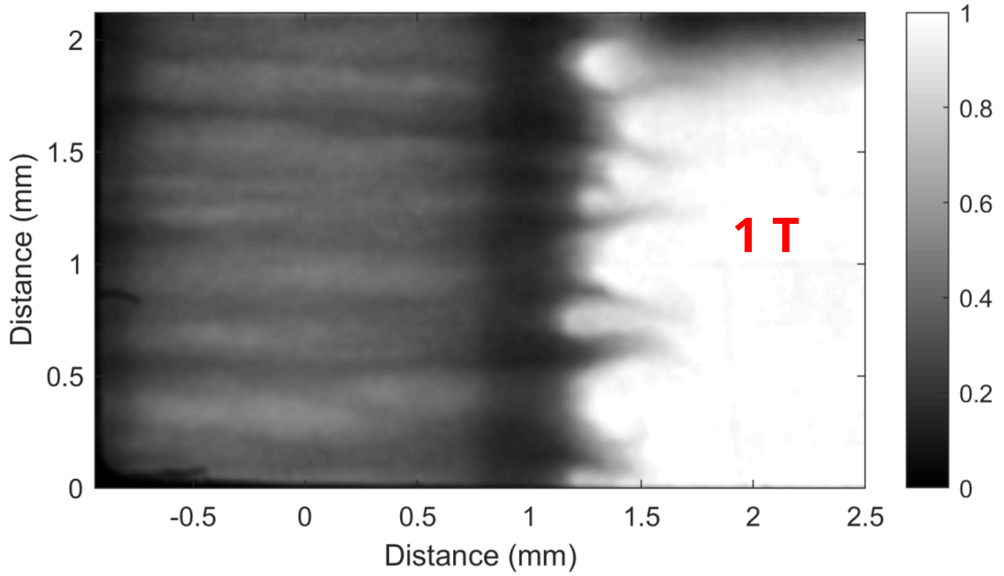


We have begun to characterize the scaling of helical structures with amplitude of the applied magnetic field

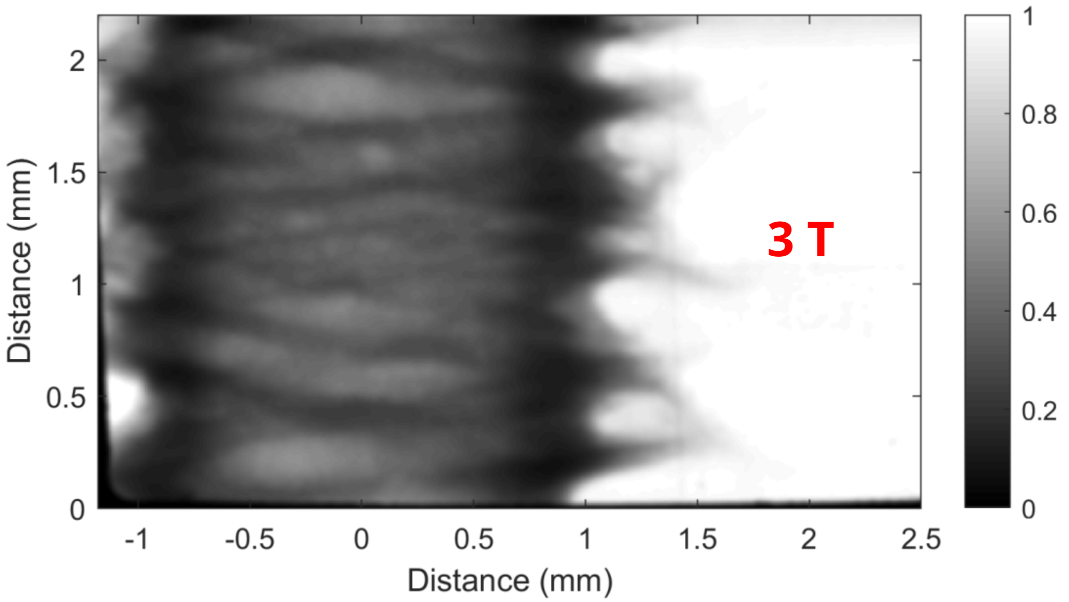


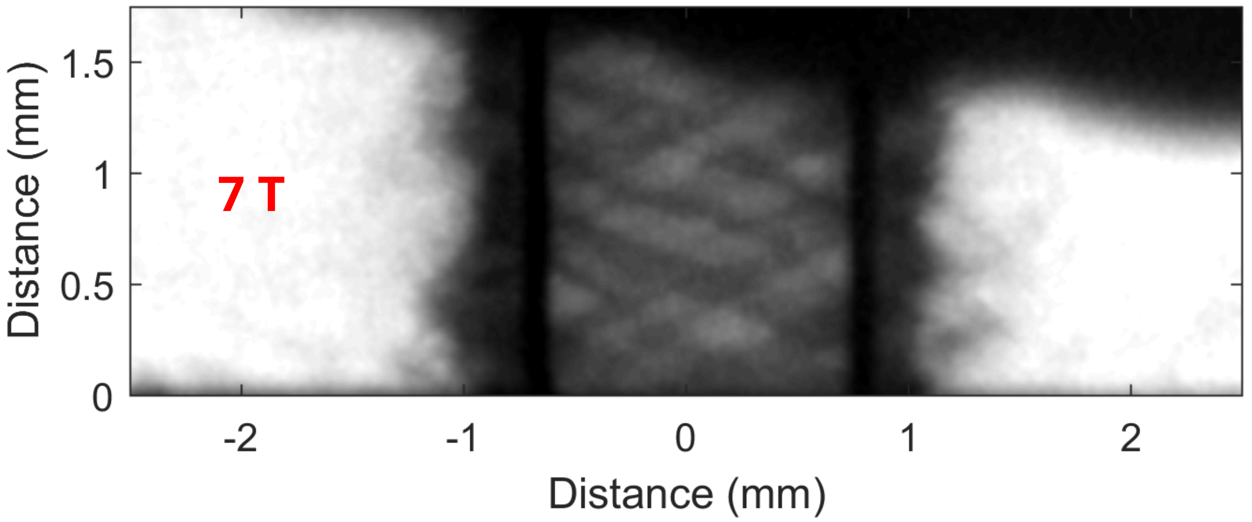
- Radiographs at similar convergence ratio for 0, 1, 3, 7, 10, 13.5, and 17.2 T

We have begun to characterize the scaling of helical structures with amplitude of the applied magnetic field



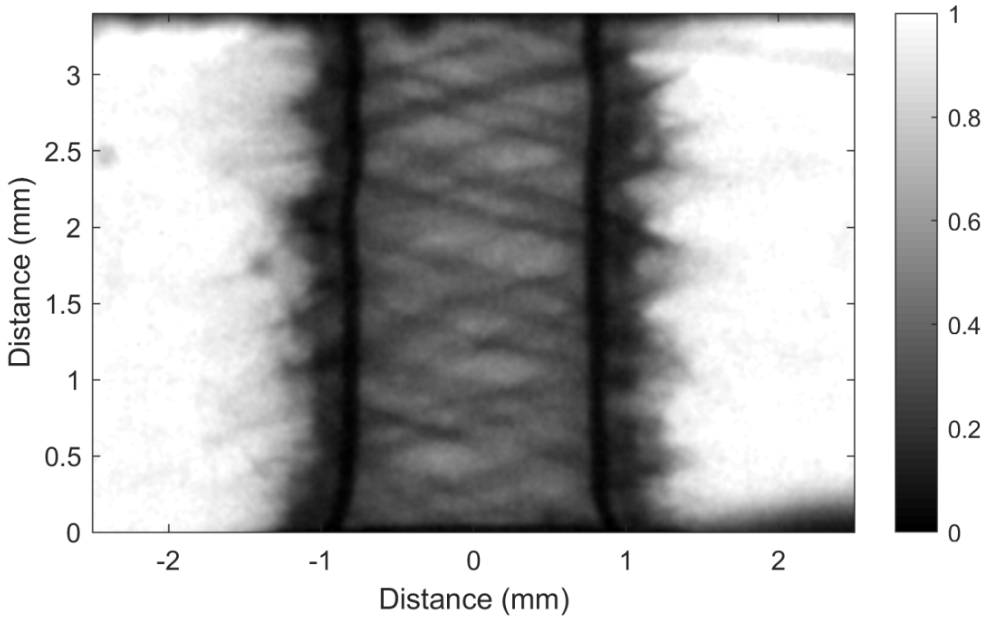
- Nearly azimuthal structures at 1 T, but clearly helical at 3 T
- Angle of structures increases significantly between 3 T and 7 T



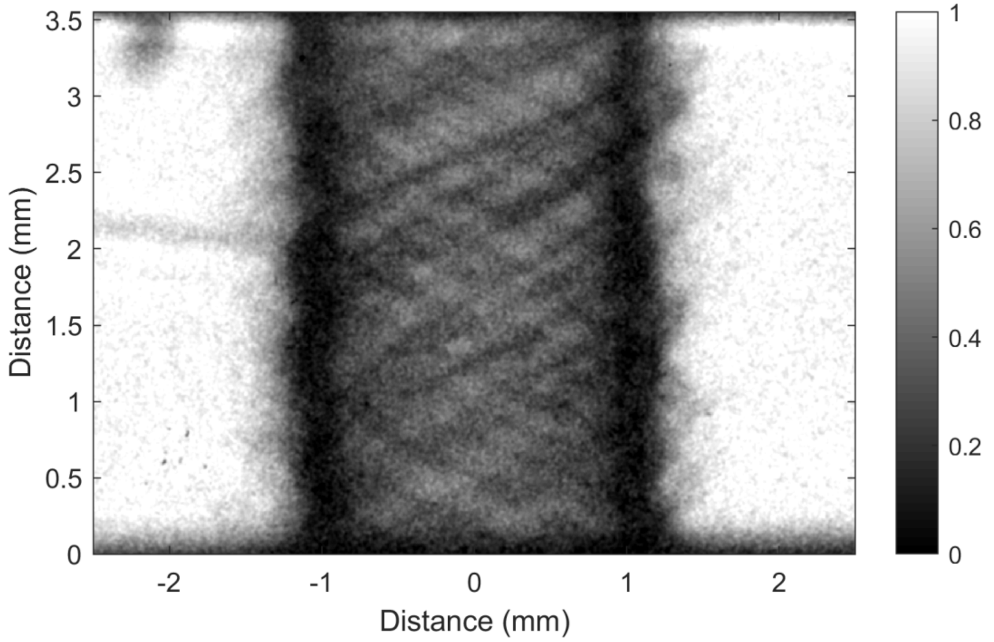


We have begun to characterize the scaling of helical structures with amplitude of the applied magnetic field

10 T



17.2 T



- Change in angle from 10 T to 17.2 T is perhaps smaller than expected
  - Helical pitch angle as a function of applied B-field needs to be rigorously quantified

Summary and future work

- Helical structures are observed in axially-magnetized implosions like in MagLIF
- Magnetic flux compression proposed to explain observed helical instability structures
- Experiments with reduced magnetic flux and fixed magnetic field indicate a significant reduction in helical pitch angle
  - Analysis of self-emission images and direct flux compression probe measurements is next priority
- Scaling of helical structures with applied magnetic field is underway
  - Interesting behavior in both the low and high field limits