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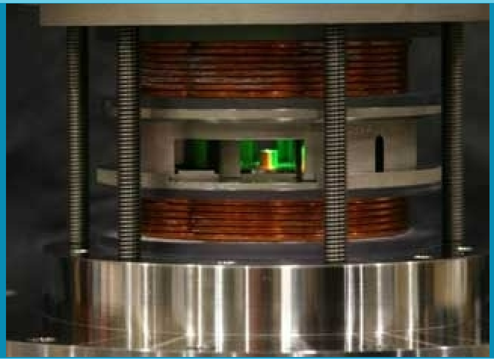
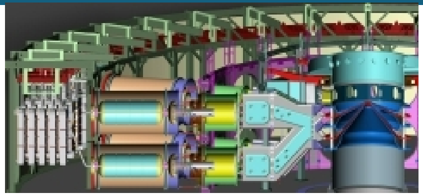
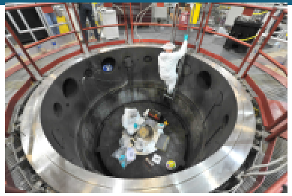
Assessing the Origins of the Helical Instability in Axially Magnetized Liner Implosions







PRESENTED BY

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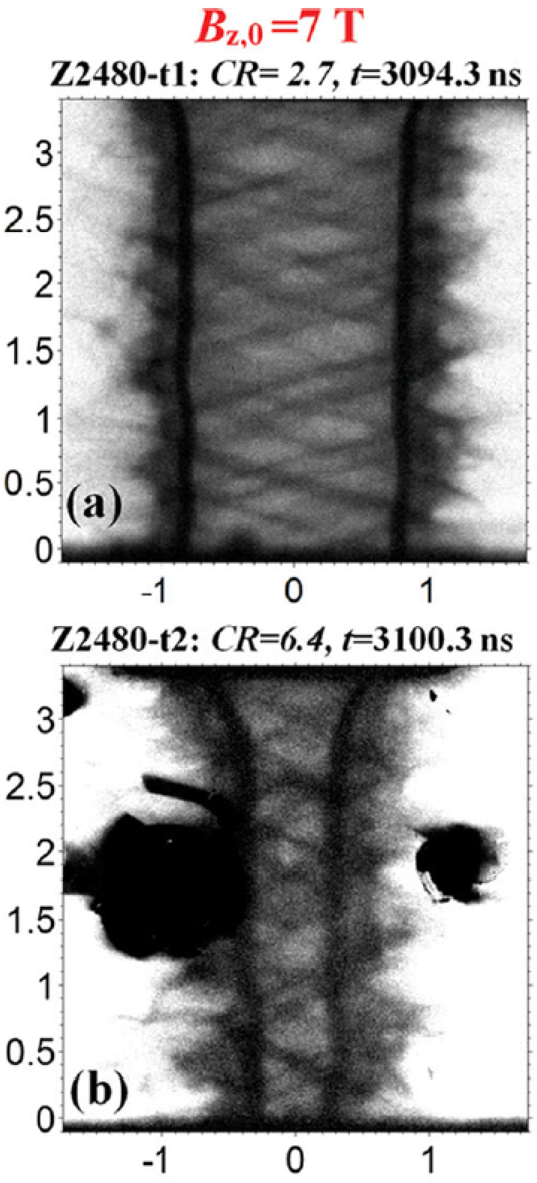
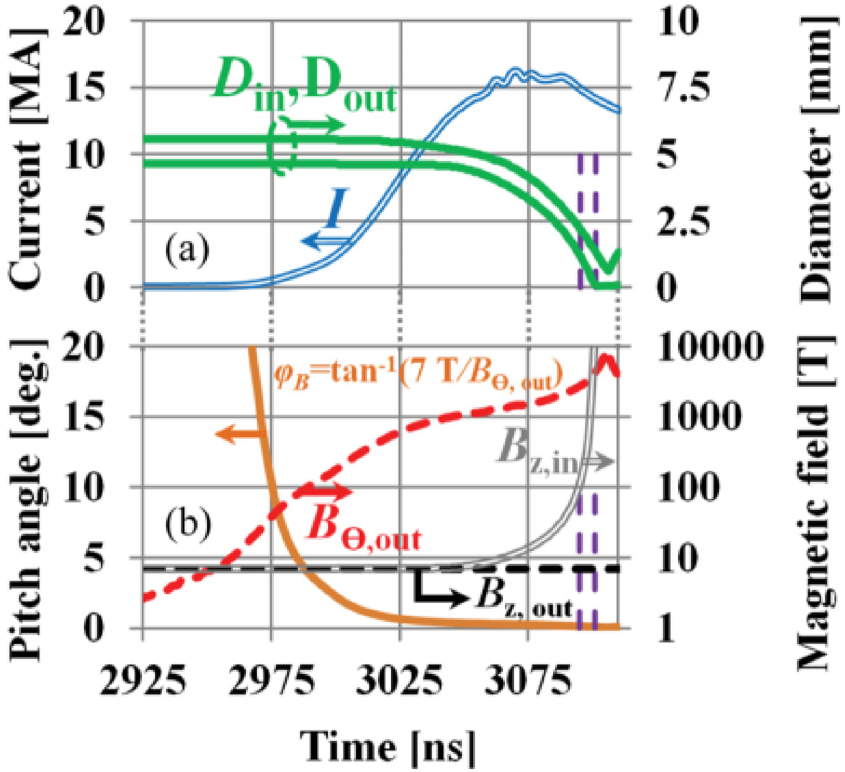
Helical instability structures were unexpectedly observed in axially-magnetized liner implosions

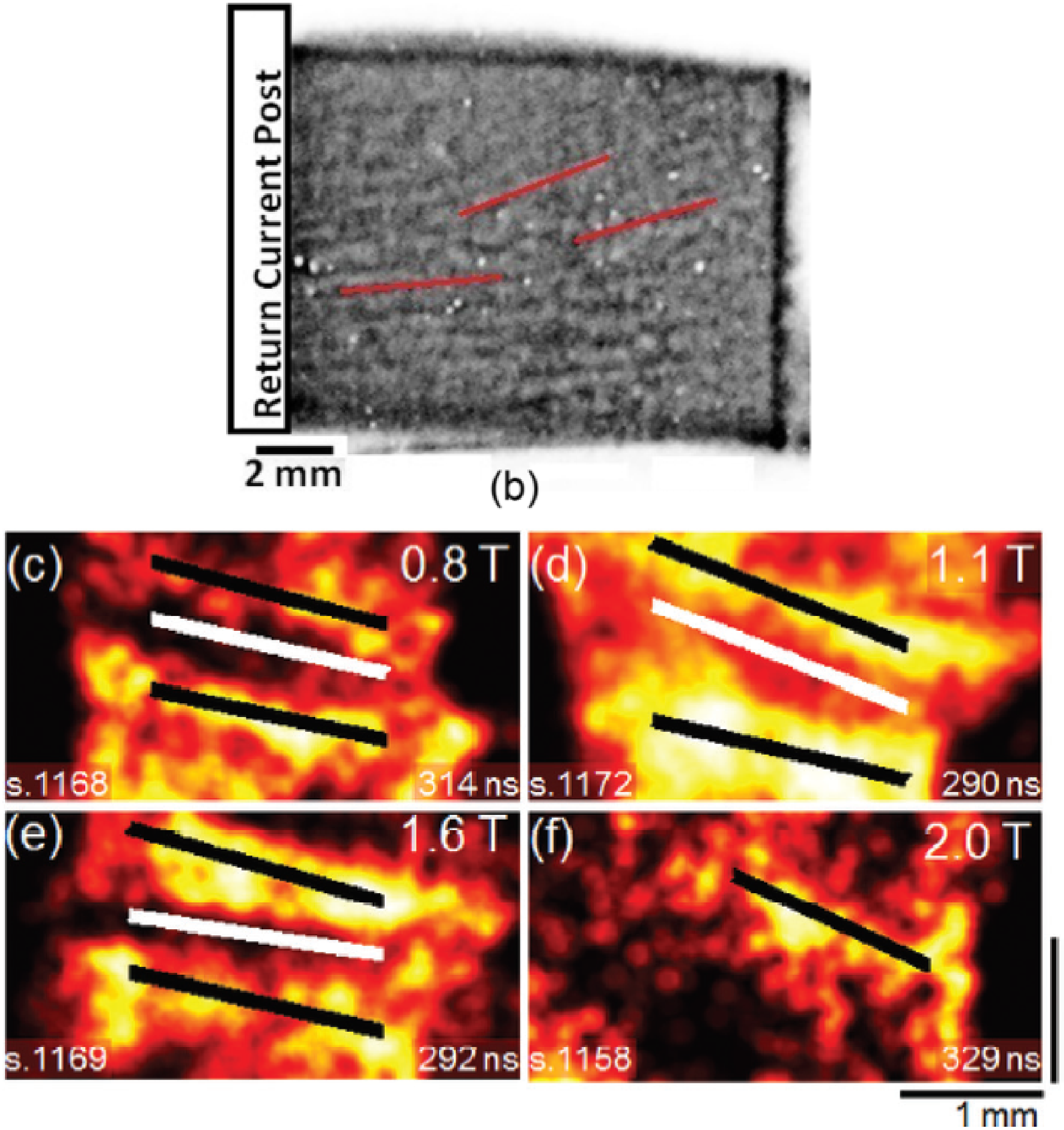


- The first observation of this behavior is documented in T.J. Awe, et al., *Phys. Rev. Lett.* **111**, 235005 (2013) with additional detail given in T.J. Awe, et al., *Phys. Plasmas* **21**, 056303 (2014)
- The applied axial field was 7 or 10 T, and the azimuthal field at the time the liner began moving was 100s of T
  - The ratio of the applied field to the drive field is inconsistent with the observed pitch of the helical structures



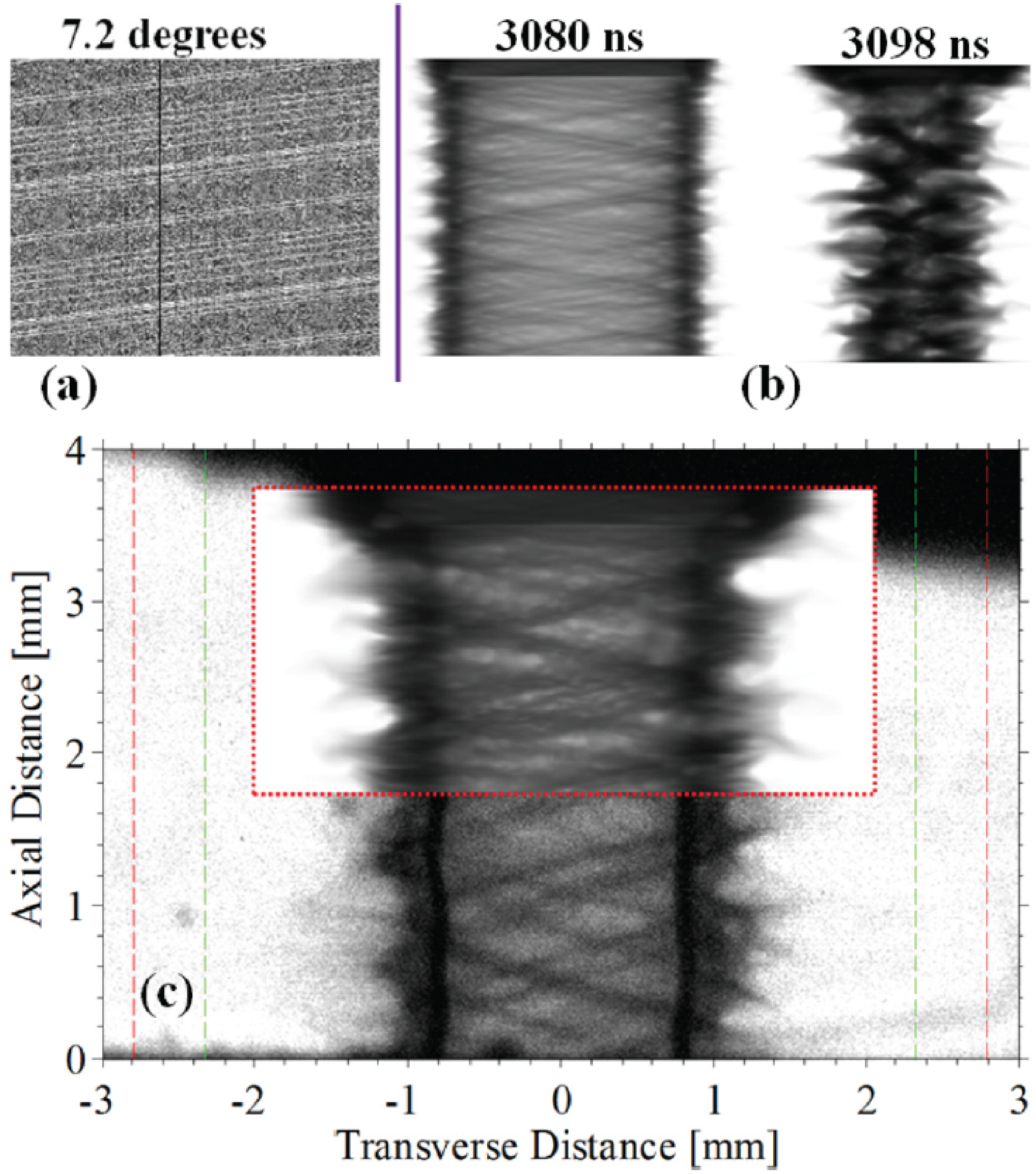
Similar structures have been observed in experiments conducted on smaller drivers with applied axial B-fields

- With a 1.5 T applied B-field, helical structures developed on a 16 mm diameter, 4 µm thick foil driven by the 1 MA COBRA generator as reported in L. Atoyan, et al., *Phys. Plasmas* **23**, 022708 (2016).
- With various B-fields, helical structures developed on a 3.3 mm diameter, 0.4 micron thick foil driven by ~0.6 MA on the MAIZE generator as reported in D. Yager-Elorriaga, et al., *Phys. Plasma* **23**, 124502 (2016).
  - Helical structures were observed with as little as 0.2 T
  - The mode number was observed to increase with increasing axial B-field



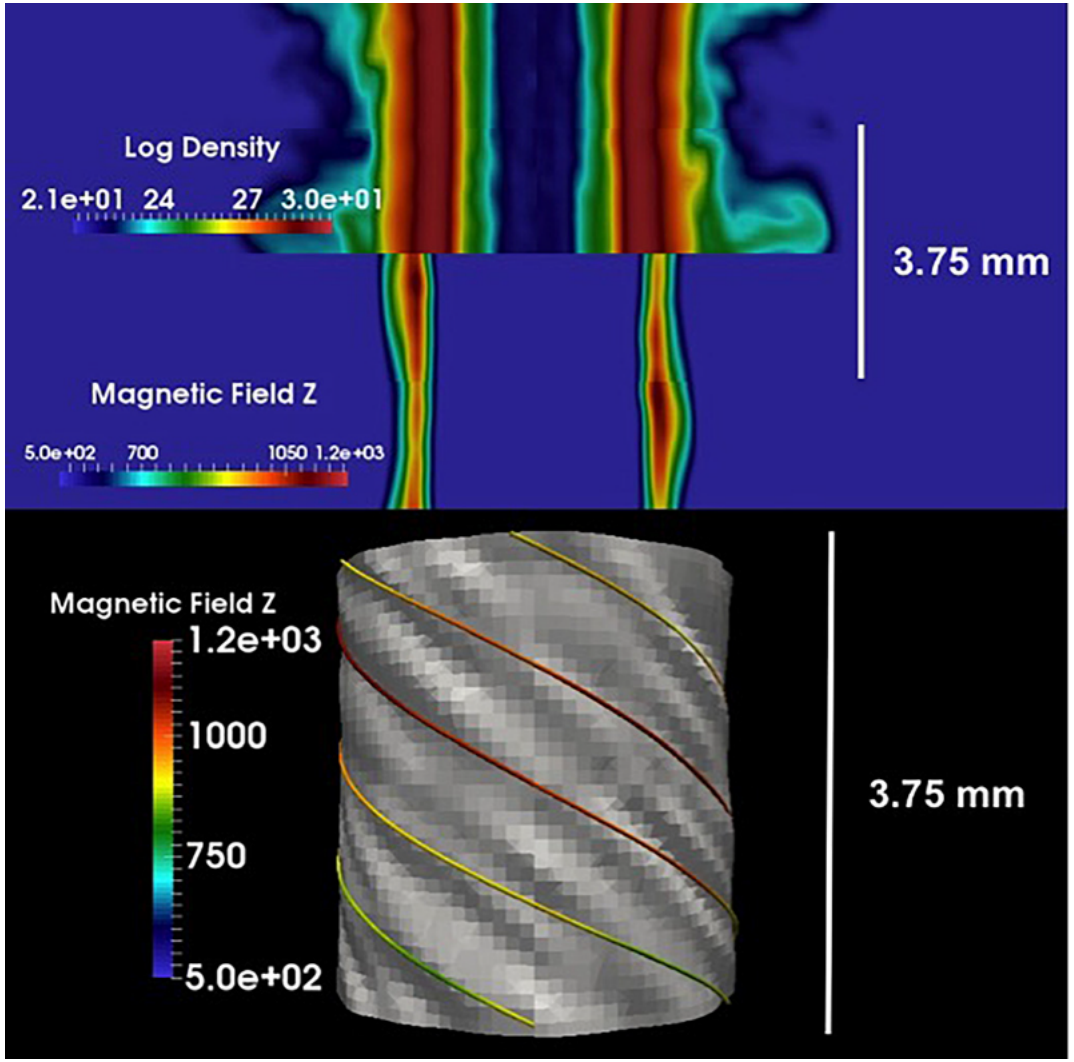
MHD simulations show that imposed helical structures will persist without an axial B-field to reinforce them

- As reported in T.J. Awe, et al., *Phys. Plasmas* **21**, 056303 (2014), simulations in the MHD code GORGON are able to reproduce the experimental helical structures, though a pre-imposed helical seed needed to be applied
- Additional simulations were conducted to understand the hydrodynamic impact of the axial field
  - Two simulations were conducted, one with 10 T and one with 0 T
  - The same helical structure was pre-imposed on the liner in both simulations
  - After the liners were imploded, the helical structure was imperceptibly different for the two simulations indicating a helical structure established early in time may persist without continued helical drive

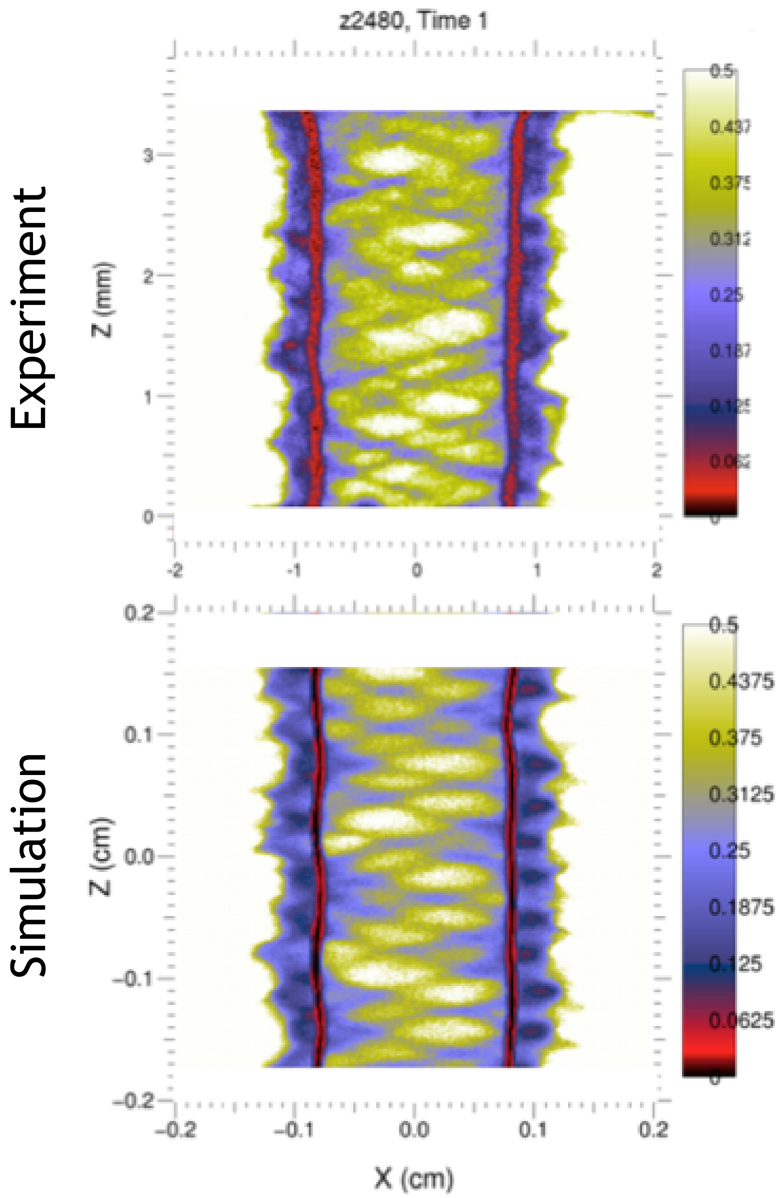


Extended MHD simulations indicate flux compression of the axial field could create helical structures

- It was observed that compression of the axial field onto the target surface could increase the axial component of the magnetic field, providing a helical drive consistent with the observed structures in D.D. Ryutov, et al., *AIP Conf. Proc.* **1639**, 63 (2014).
- Simulations in the extended MHD code PERSEUS demonstrated this effect as reported in C.E. Seyler, et al., *Phys. Plasmas* **25**, 062711 (2018).
  - In simulations including the terms required to accurately evolve low density plasmas, the plasma formed in the final transmission line sweeps up into the return can and compresses the axial field onto the target surface.
  - The axial field can reach ~1000 T, which is comparable to the azimuthal field even at late times, creating a helical drive field roughly consistent with the helical structures observed in experiments



PIC simulations show that plasma bombardment of the liner at early times could seed a helical mode



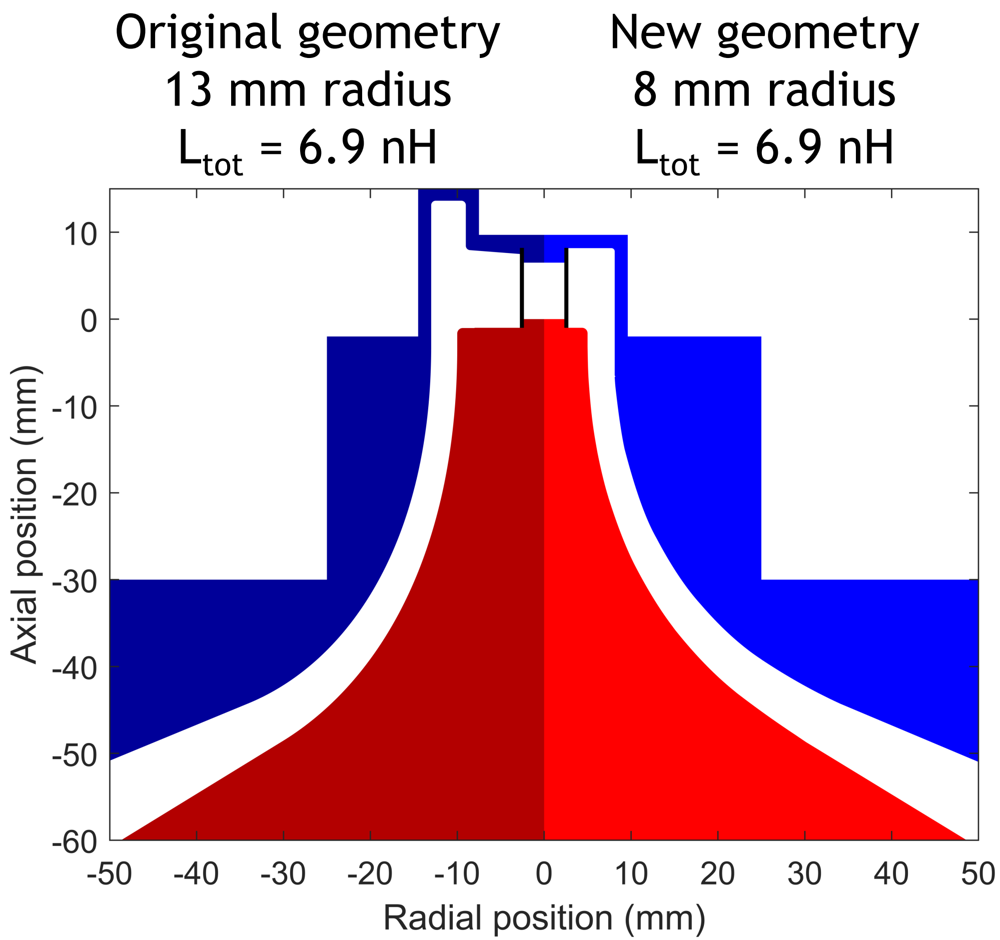
- As was presented in A.B. Sefkow's invited talk at the 2016 APS-DPP (BAPS.2016.DPP.UI3.6), PIC simulations in LSP show that plasma bombards the liner surface early in time
  - The plasma oscillates with at the upper-hybrid mode, which is helical due to the comparable magnitude of the applied axial B-field and the azimuthal drive field at early times
  - The plasma heats the surface of the target, causing melt to occur slightly earlier than it would through joule heating alone
  - Melt initiates with a helical structure, and this is reinforced through the electrothermal instability
  - The helical structure seeded into the liner is input into MHD simulations in HYDRA, which show helical instability structures in synthetic radiographs
- This mechanism also can explain the significant correlation of azimuthal structure in unmagnetized experiments

The leading hypotheses for the origin of the helical structure in magnetized targets differ on a key point

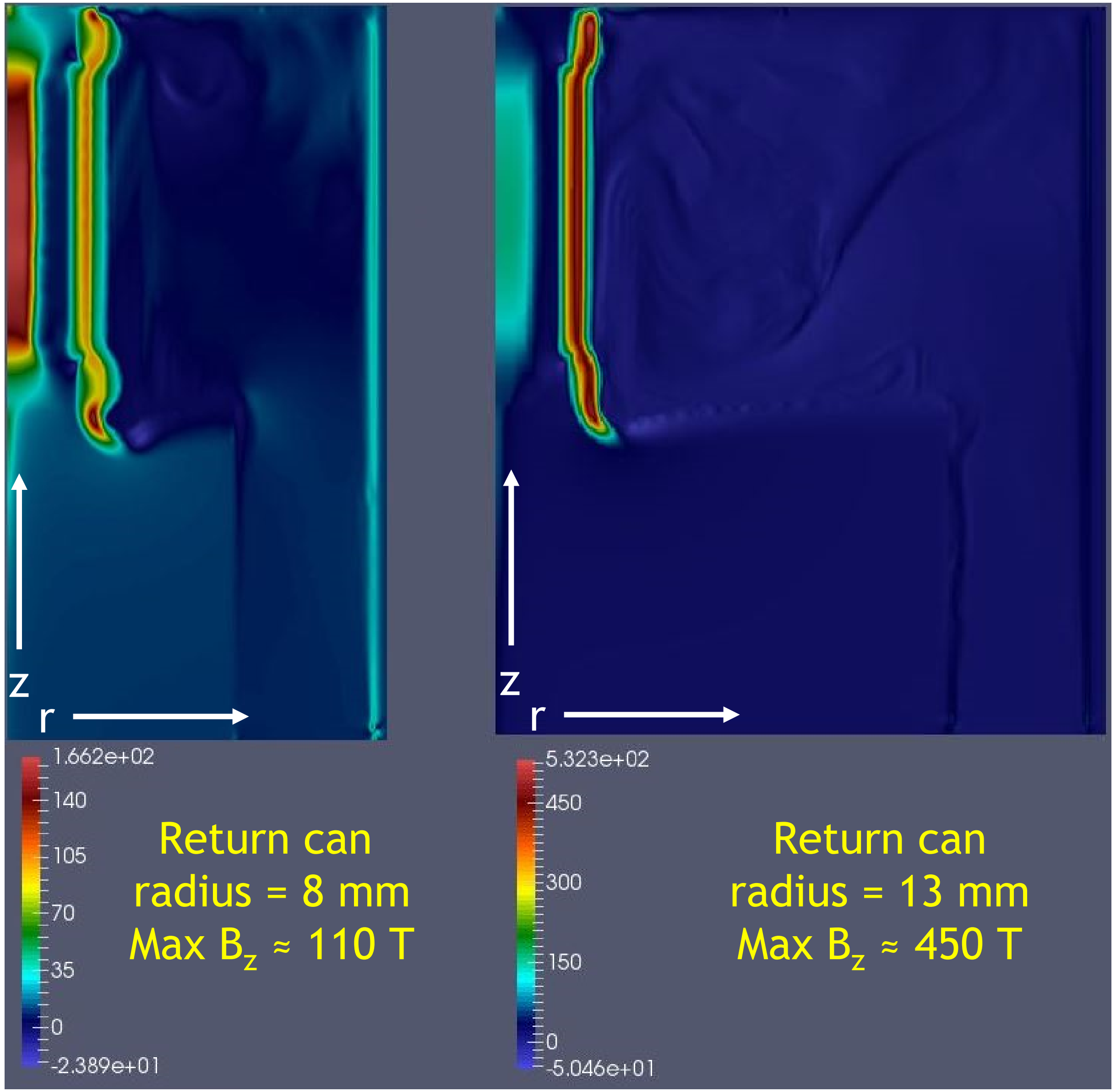
- The flux compression hypothesis (Ryutov, et al., and Seyler, et al.)
  - Relies on plasma formation in the final transmission line and transport into the load region
  - Generates large axial field at the target surface by sweeping up the flux in the load volume
    - Axial magnetic field within the return can is depleted since it is all compressed on the target
  - The pitch of the helical instability is expected to scale with the amplitude of the applied axial field
  - The pitch of the helical instability is expected to scale with the magnetic flux available for compression
- The plasma bombardment hypothesis (Sefkow)
  - Relies on plasma bombardment of the target
  - Generates large axial field at the target surface due to helical current flow within the target, which is the result of the helical structure seeded at early times
    - Axial magnetic field within the target is not depleted
  - The pitch of the helical instability is expected to scale with the amplitude of the applied axial field
  - The pitch of the helical instability is NOT expected to scale with the magnetic flux available for compression
- We can start to differentiate between these hypotheses with an experiment that maintains the same axial field magnitude but changes the flux available for compression

The load was redesigned to reduce the volume within the return can, reducing the available flux

- The overall inductance of the experiment was intentionally matched to that of the standard return can experiments
  - The inductance within the return can was reduced significantly, but the inductance of the final transmission line increased
  - The target geometry is identical between the two designs
  - With matching initial inductance and target configurations, the load current for the new design was expected to match that of the old design



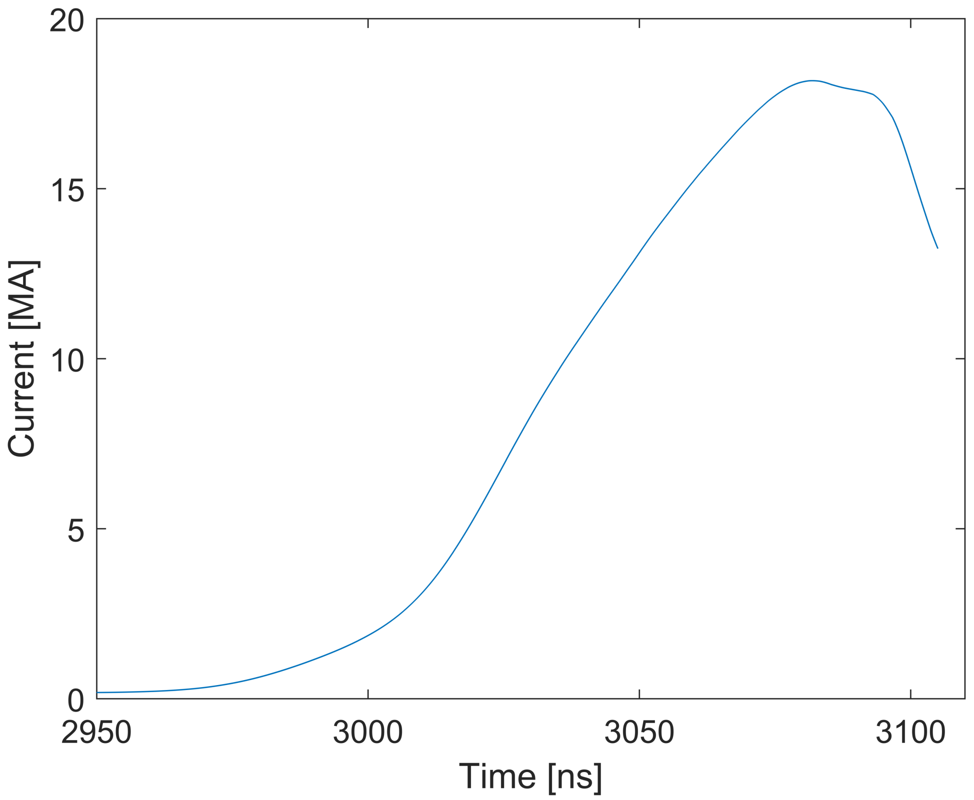
significant change in the flux compressed onto the target



- The return can radius was reduced from 13 mm to 8 mm
  - The cross-sectional area of the return can was reduced to 35% of its original value
- The radius of the cathode at the entrance of the return can was reduced from 10 mm to 5 mm
  - The area of the cathode within the return can was reduced to 19% of its original value
- 2D Perseus simulations indicate the flux was reduced to 24% of its value for the standard return can diameter
- Previously we were able to observe a difference between B_z = 7 T and 10 T, indicating that we should be able to diagnose a factor of ~4 change in field

The initial test of the small diameter return can geometry demonstrated good current delivery

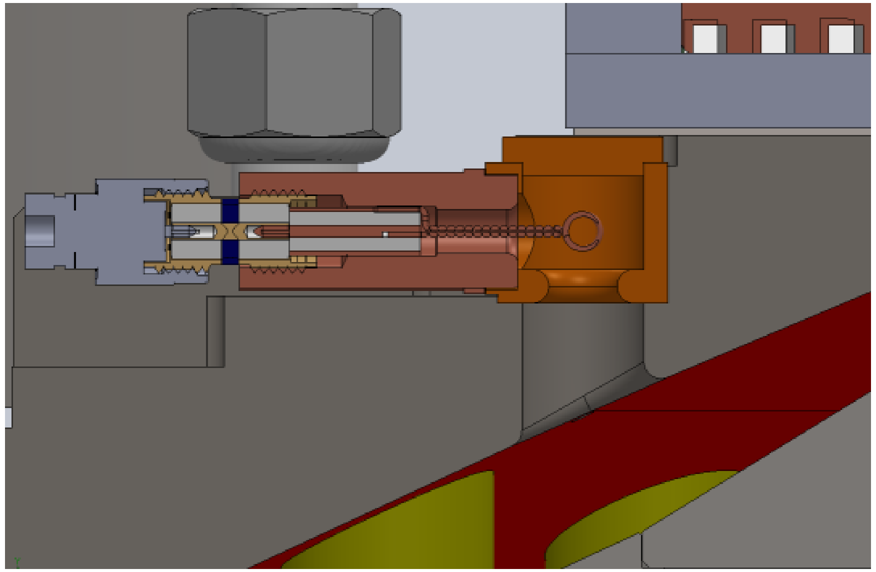
- Current delivery was good with the new transmission line design
  - Peak current was just over 18 MA, consistent with expectations based on matching the total inductance to the previous configuration
  - Constraining the load current, especially at early times, is critical to accurately model the plasma bombardment hypothesis
- Unfortunately the radiographs had a very poor signal to noise
  - An unexpected high background signal was observed on this experiment, which caused the poor S/N
  - No conclusions about the helical pitch can be made from the available data set

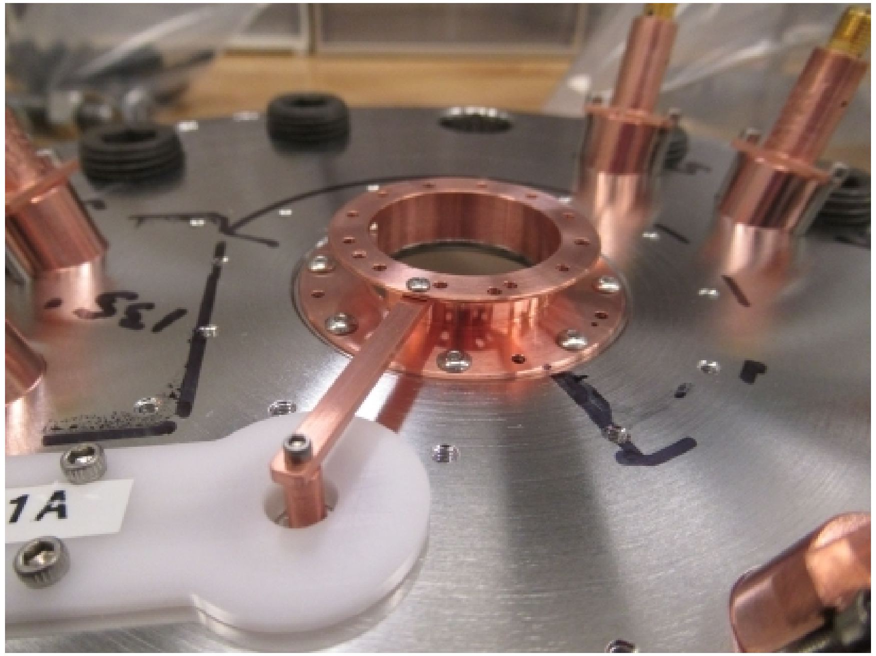


Note measurement made through load current velocimetry, which very accurately constrains peak current, but does not constrain early time current very well

There is another opportunity to test this change in geometry coming up soon

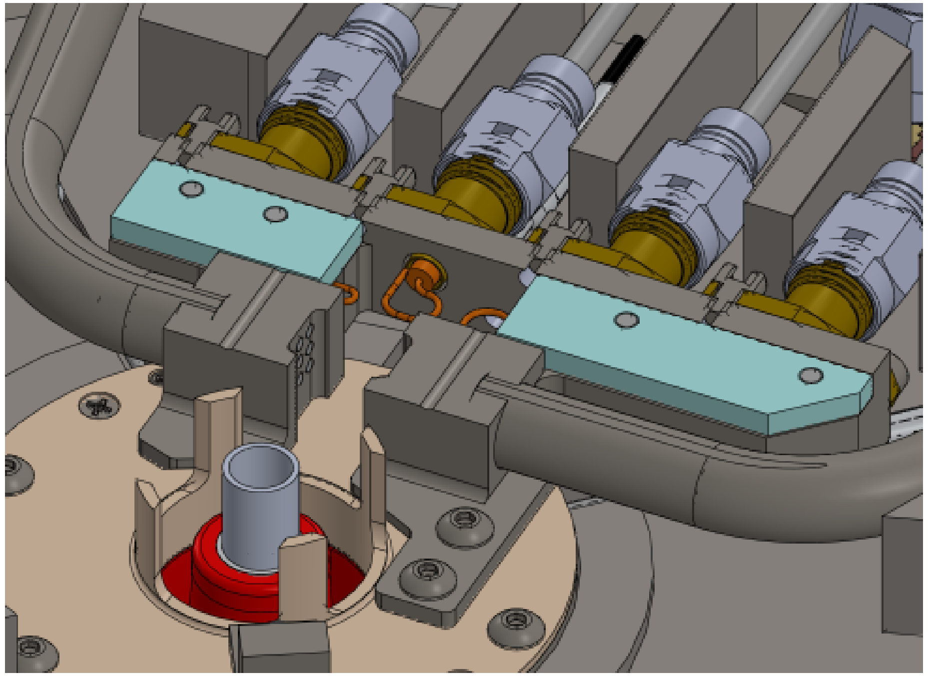
- This experiment will retain the transmission line and return can geometry successfully demonstrated in the first experiment
- Improvements to the load current diagnostics have been implemented with a focus on measurements early in the current pulse
  - The inner-MITL B-dots (r = 59 mm) have been redesigned
    - Previously the applied B-field coils prevented these probes from being fielded at the proper location
  - A Rogowski coil has been designed for use on an extended return can post
    - The return can post is designed to inductively limit the current through the post to ~10 kA, which can easily be measured with the Rogowski coil
    - Simulations are used to relate the current through this post to the total current in the load
    - Initial tests indicate that this probe functions throughout the full current pulse including through the inductive dip

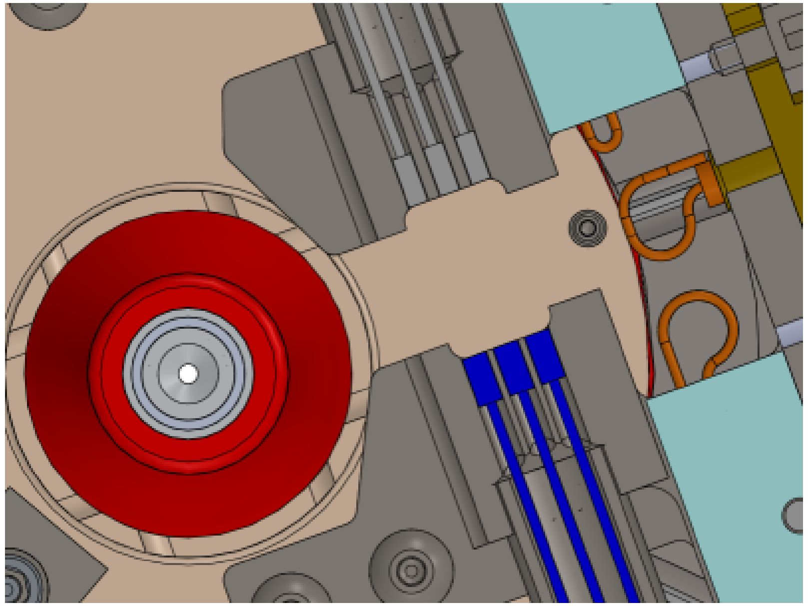




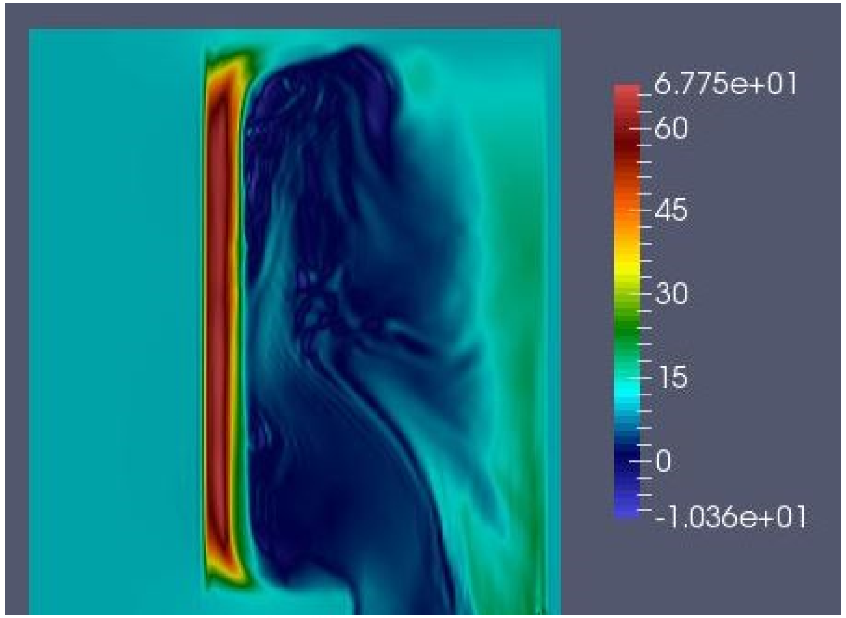
A diagnostic to directly measure flux compression has been designed

- Flux compression at the surface of the target would be extremely challenging to measure
  - Plasma conditions make optical measurements unlikely
  - Field levels change too quickly for B-dot probes
- luckily, in simulations, flux compression occurs both on the outer surface of the target and on the inner surface of the return can
  - With a slotted return can, some plasma streams out of the can, bringing magnetic flux with it
- This diagnostic sits just outside of the slotted return can
  - A series of optical probes are used to diagnose the arrival time and velocity of plasma
  - A series of B-dot monitors are used to detect changes in the axial flux within the probe cavity

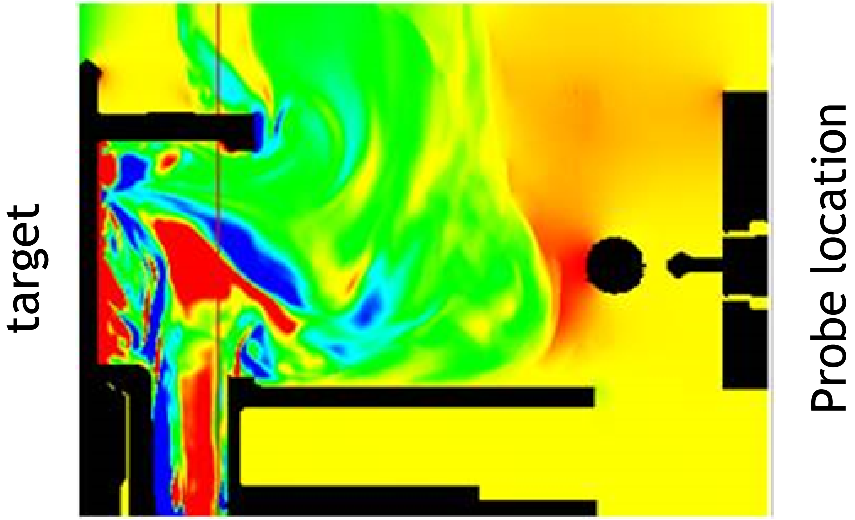




Simulations indicate this probe could be used to demonstrate flux compression



Bz (-20 to +20)



- In simulations that showed significant flux compression on the surface of the target, measurable magnetic flux was also observed within the probe
- If signs of flux compression are observed with this diagnostic, it will significantly bolster the argument for flux compression on the target surface
  - A lack of flux compression signatures in the diagnostic will not necessarily disprove the hypothesis though – it is possible that the plasma streaming out of the return can will drop in conductivity sufficiently to no longer compress flux

Experimental evidence to support one of the hypotheses for the origins of the helical instability may be obtained soon

- The observation of helical structures in magnetized targets was puzzling due to a very low ratio of applied axial B-field to azimuthal drive field
- The flux compression hypothesis suggests that plasma from the final transmission line streams into the load region and sweeps up flux onto the surface of the target
- The plasma bombardment hypothesis suggests that a helically-structured plasma wave interacts with the surface of the target, causing it to melt with a helical pattern, which is reinforced through the electrothermal instability, and supported by helical current flow
- Changing the diameter of the return can while maintaining the same applied axial field will change the flux available to compress on the surface of the target
  - The flux compression hypothesis predicts this will change the helical pitch
  - The plasma bombardment hypothesis predicts this will not impact the helical pitch, assuming the current drive remains constant
- An experimental geometry to test this hypothesis has been developed
  - New diagnostics to directly measure flux compression and improve our understanding of the load current will be included to better enable a separation of the two hypotheses