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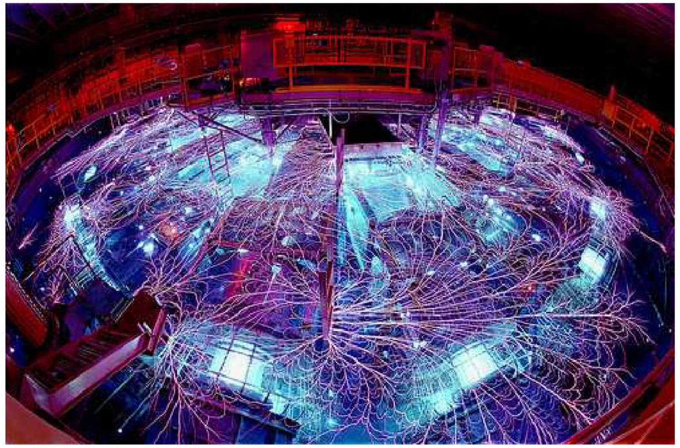

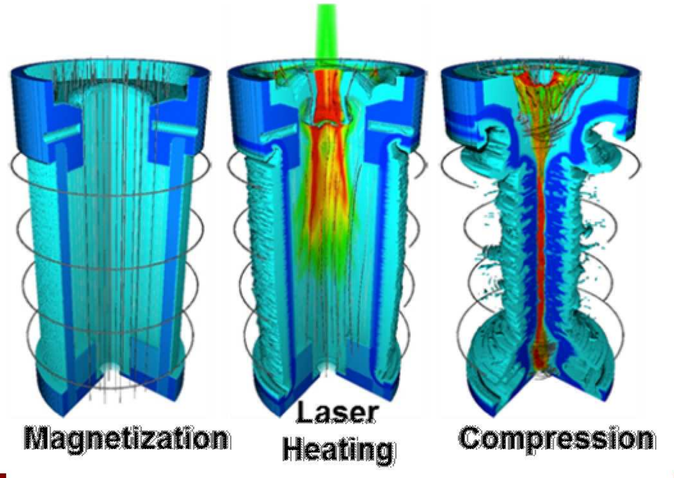

Electromagnet Designs on Low-Inductance Power Flow Platforms for the Magnetized Liner Inertial Fusion (MagLIF) Concept at Sandia's Z Facility

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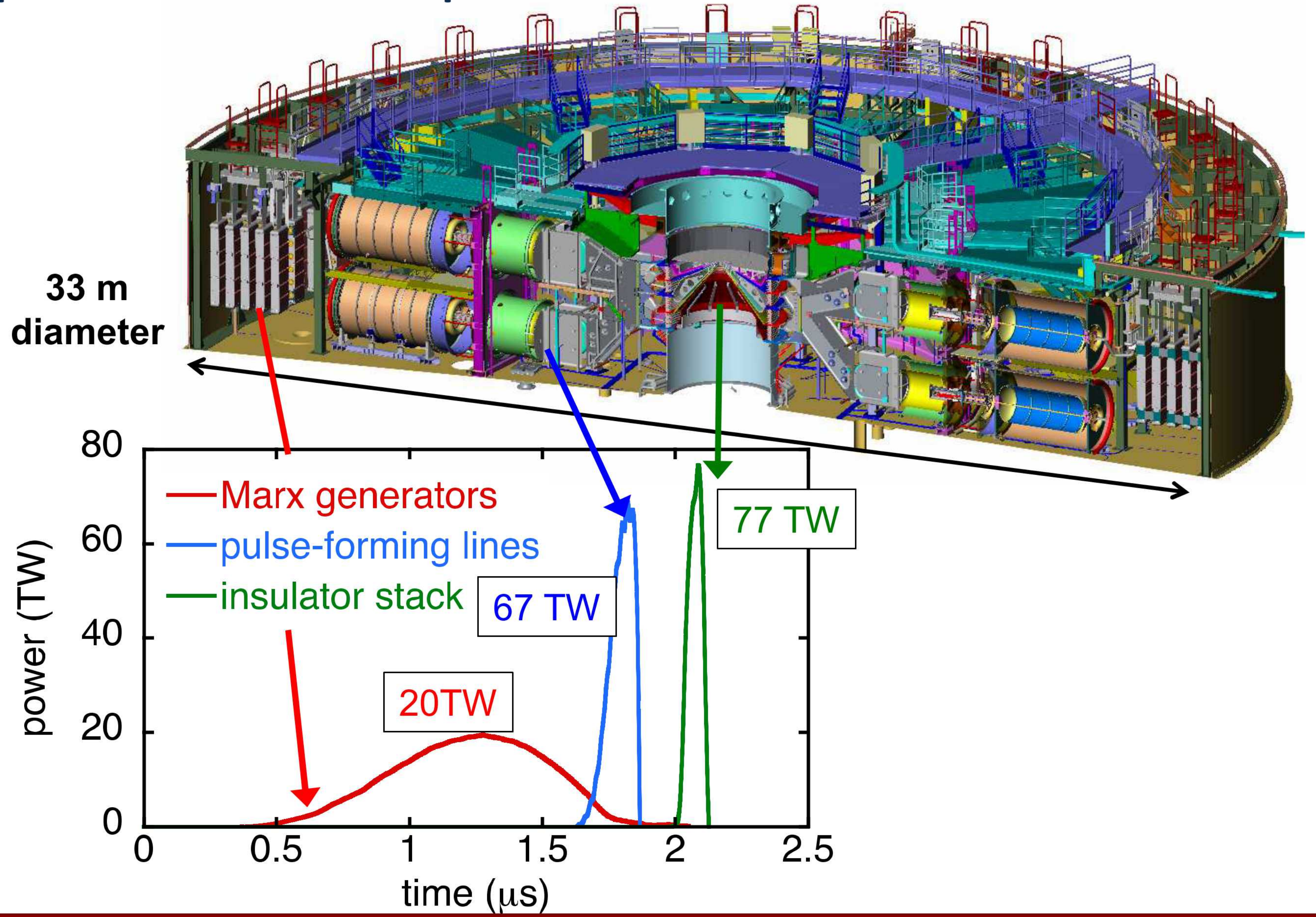
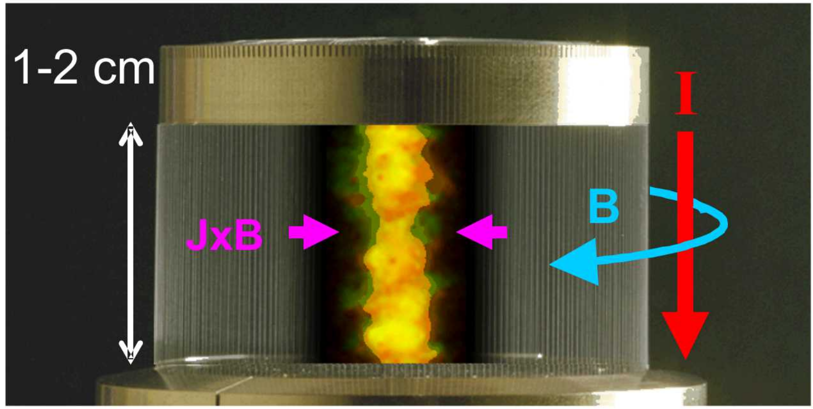
Outline of today's discussion

- Sandia's Z Machine and the MagLIF concept
- Pre-magnetizing the fusion fuel with the Applied B on Z (ABZ) system
- Making a more efficient inefficient coil: Designing an electromagnet for Low-L
- The path forward to 20 – 25 T

SANDIA’S Z MACHINE AND THE MAGLIF CONCEPT

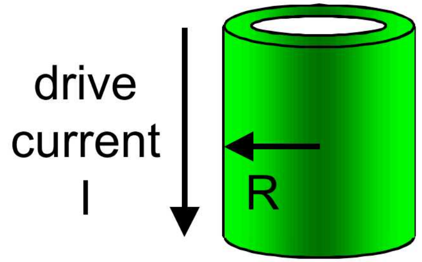
Sandia's Z Machine uses large currents (>25MA) to generate 100-MBar pressures for HEDP experiments





Magnetically-Driven Implosion

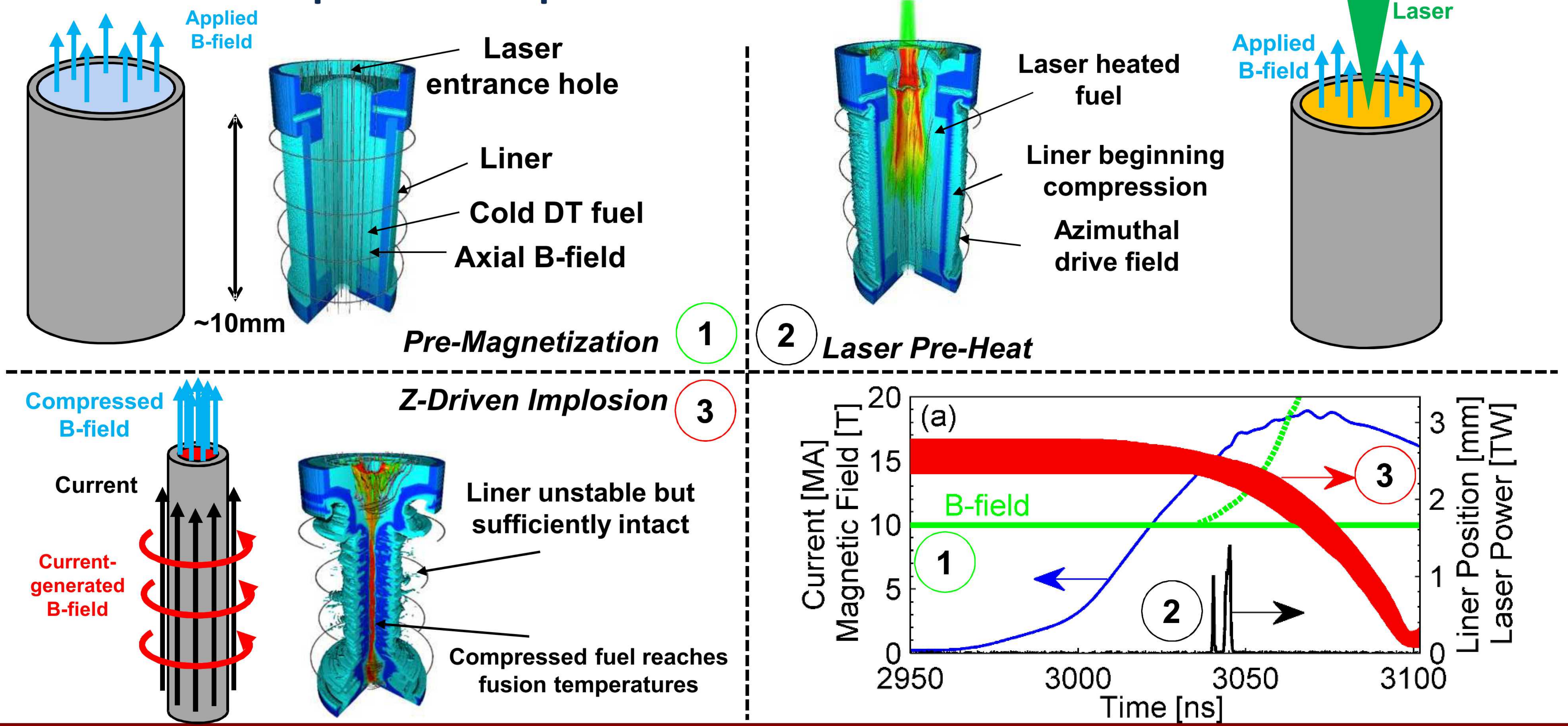
$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$



100 MBar at 26 **MA and 1 mm**

Implosion time ~50 ns; stagnation ~0.1-1 ns

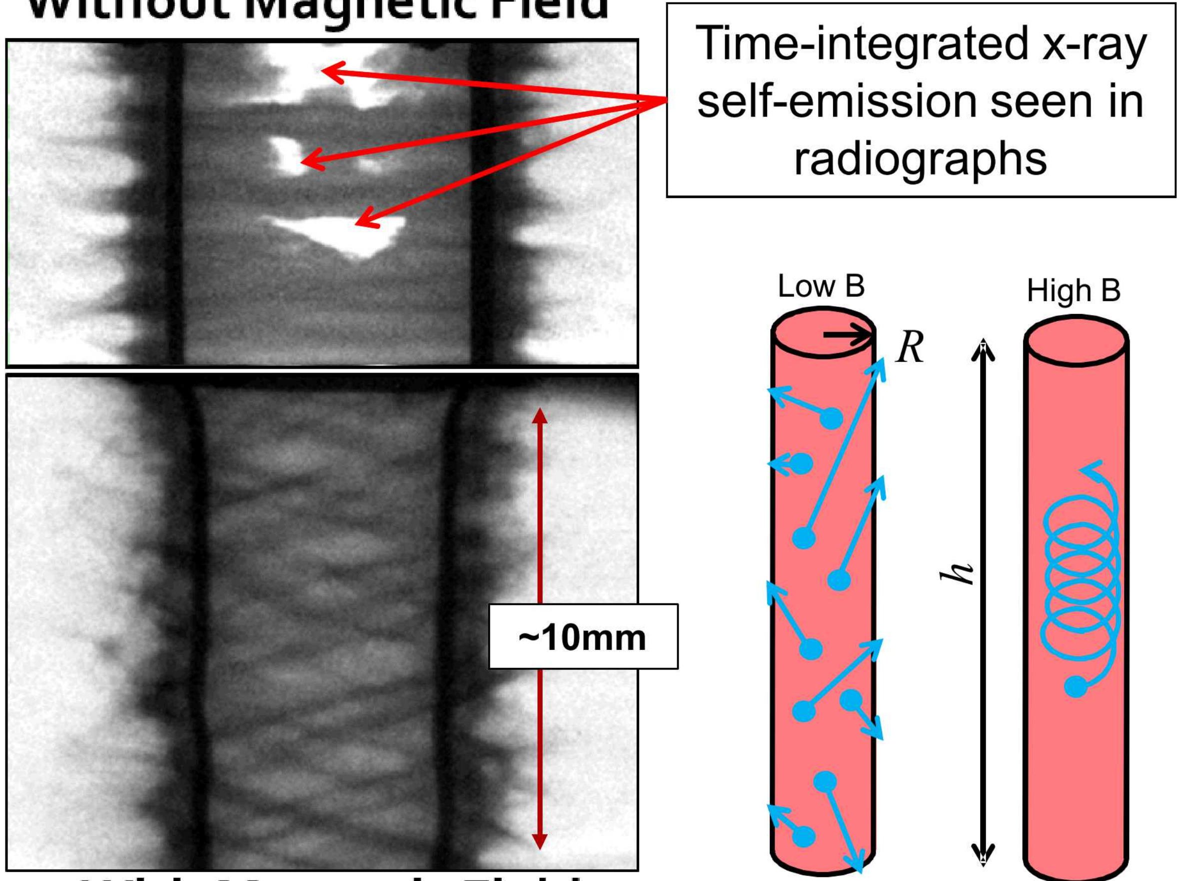
Magnetized Liner Inertial Fusion (MagLIF) combines three stages that reduce fuel compression requirements to achieve fusion conditions



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

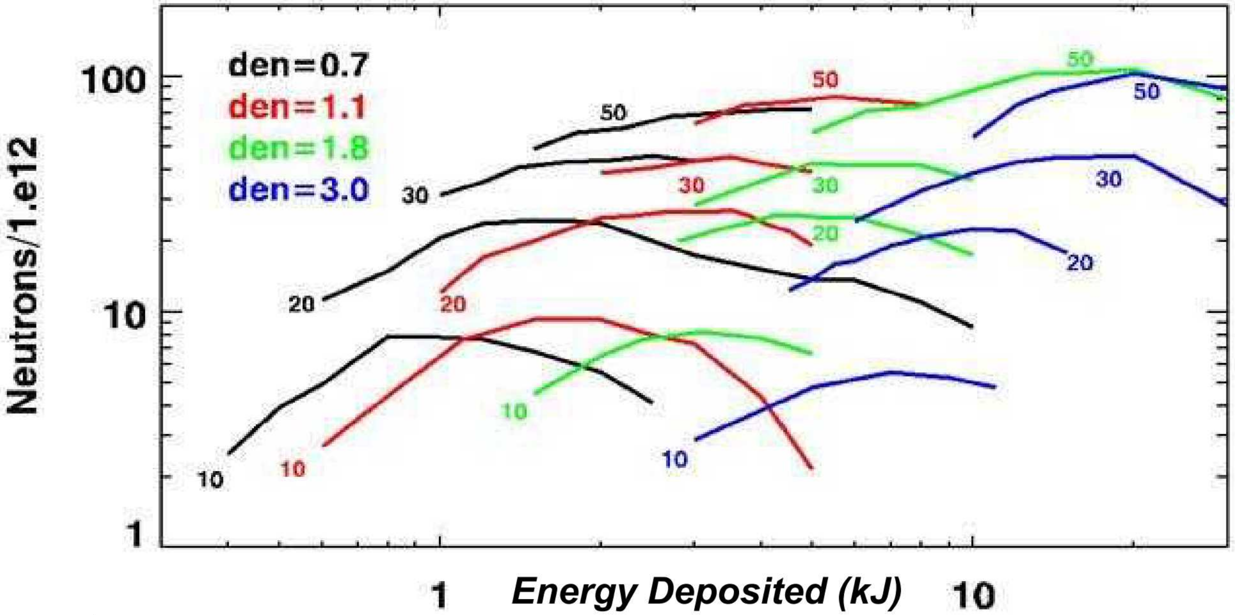
Pre-Magnetization relaxes implosion convergence requirements by helping confine heated fuel

Without Magnetic Field



With Magnetic Field

When magnetized, MagLIF Liners have reduced x-ray self emission (left) and particles are confined within fuel on cyclotron orbits (right)



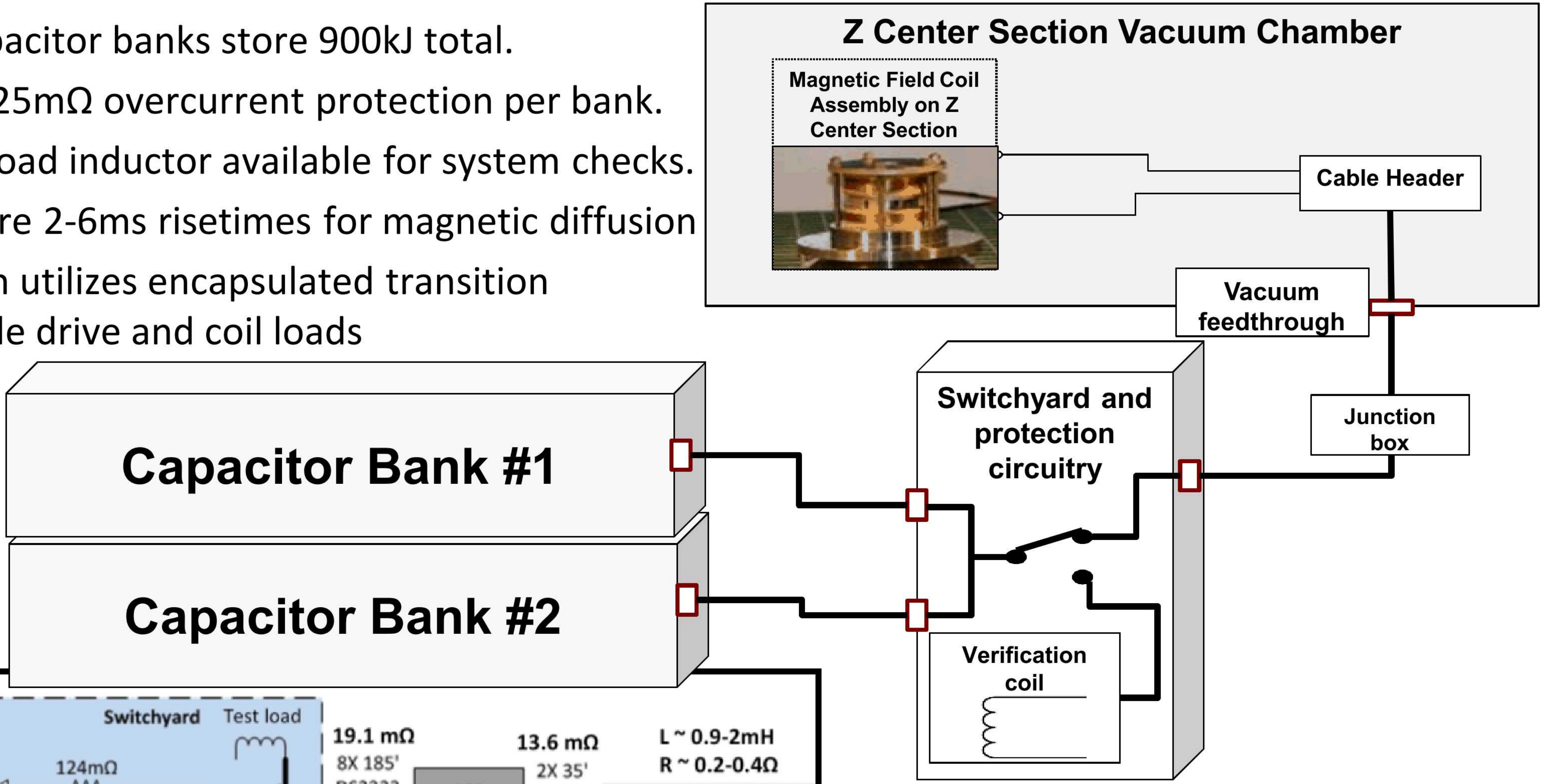
Fusion yield trends for various fuel density, laser preheat energy benefit from increased magnetic flux density

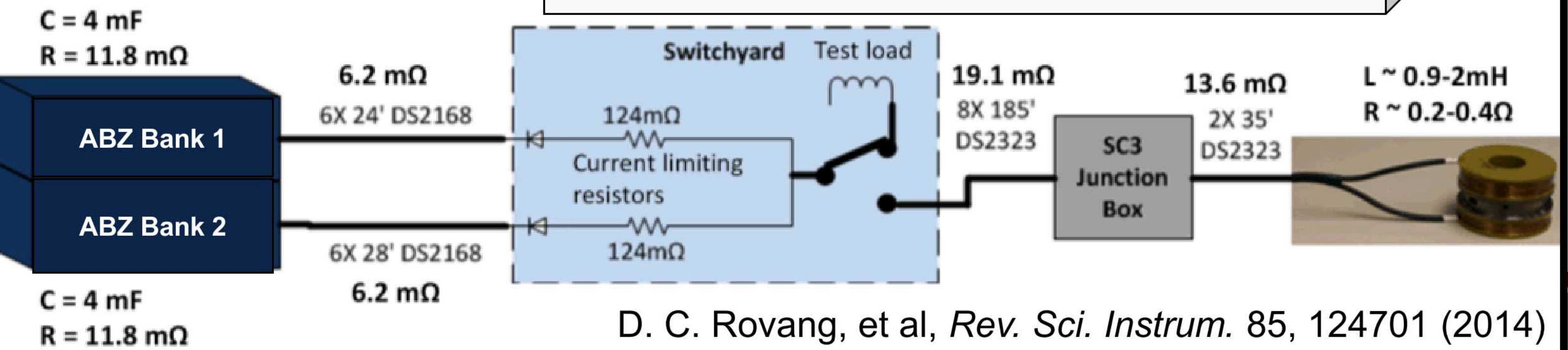
- A highly magnetized fuel inhibits loss by trapping electrons to axial field lines and reducing radial thermal conduction to cold liner wall
- The usual azimuthal MRT instability becomes helical; initial B-field may stabilize the liner during compression to improve fusion conditions

PRE-MAGNETIZING THE FUSION FUEL WITH THE APPLIED B ON Z (ABZ) SYSTEM

The Applied B on Z (ABZ) capacitor and coil system designed to provide 10 – 30 T within liner volume

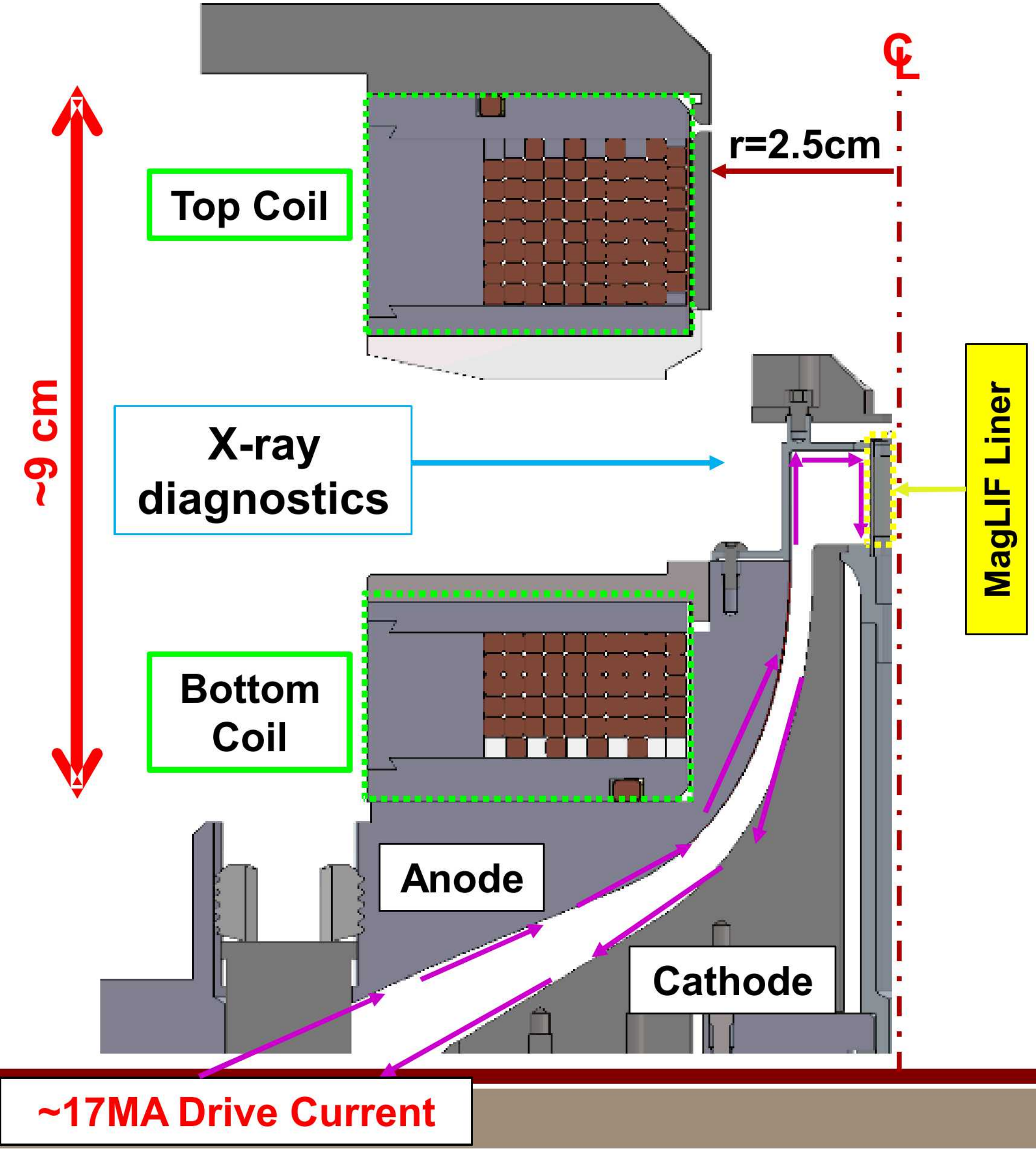
- Two 4-mF, 15-kV capacitor banks store 900kJ total.
- Paralleling diodes, 125mΩ overcurrent protection per bank.
- Switchyard dummy load inductor available for system checks.
- 0.8 – 3mH coils ensure 2-6ms risetimes for magnetic diffusion
- Vacuum feedthrough utilizes encapsulated transition between coaxial cable drive and coil loads



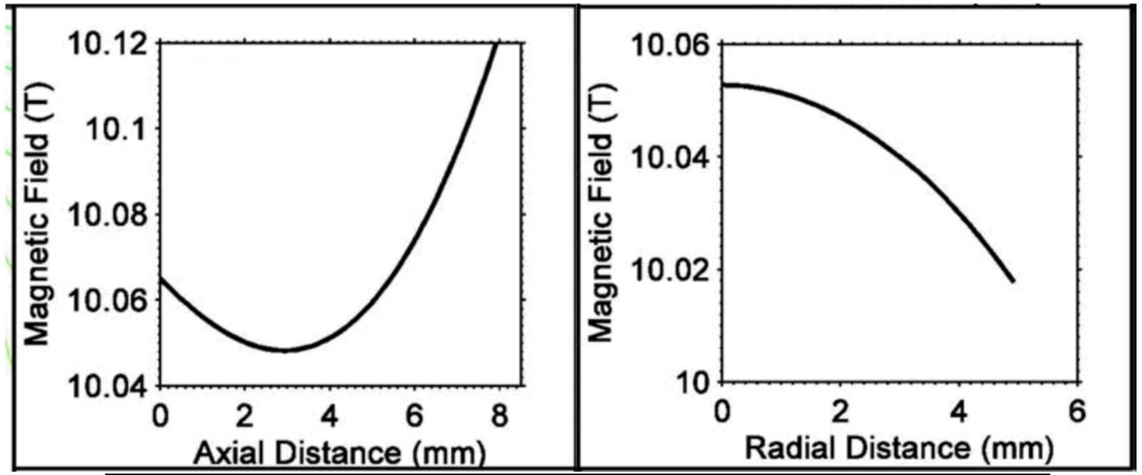


D. C. Rovang, et al, *Rev. Sci. Instrum.* 85, 124701 (2014)

Integrating electromagnets onto the target geometry requires changes in Z power flow

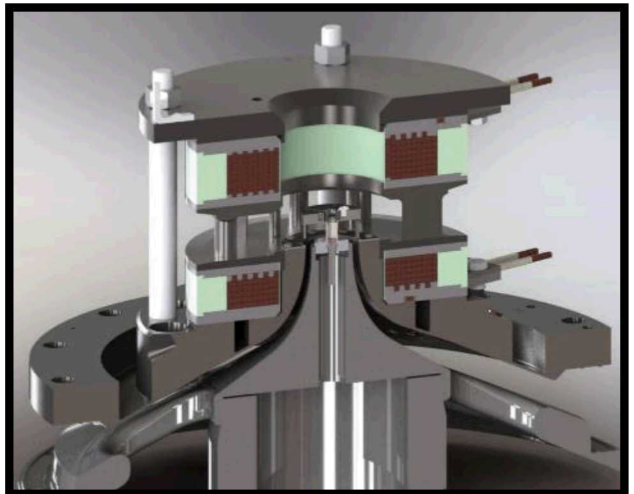


- Initial guidance was to prioritize radial diagnostic access and field uniformity in liner
  - We designed coil pairs with 1-2.5cm axial spacing
- An Extended Power Feed was needed to raise target above the bottom coil of a split pair into uniform field region
- ABZ coil pairs consist of an 80-turn top coil and either a 60- or 80-turn bottom coil
  - Helmholtz-like pairs provide <1% field uniformity
- 5cm-bore coils magnetize ~75cm^3 region to 10 – 20 T



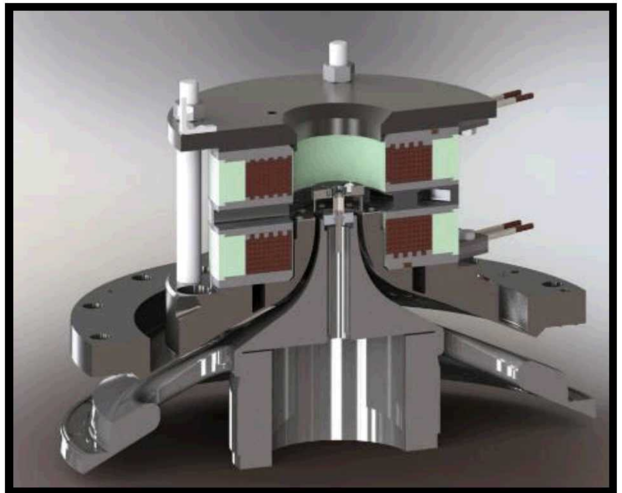
2D Transient magnetic calculations axial and radial lineouts showing ~1% field variation within liner

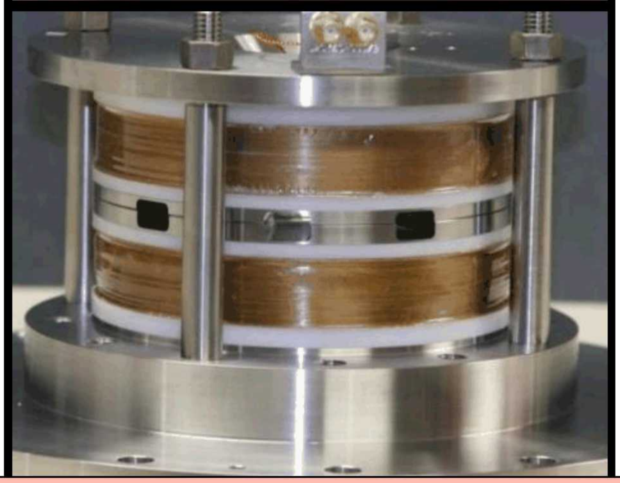
The Extended Power Feed platform was designed with three coil configurations in mind



Full-Access Spacing (60-80)

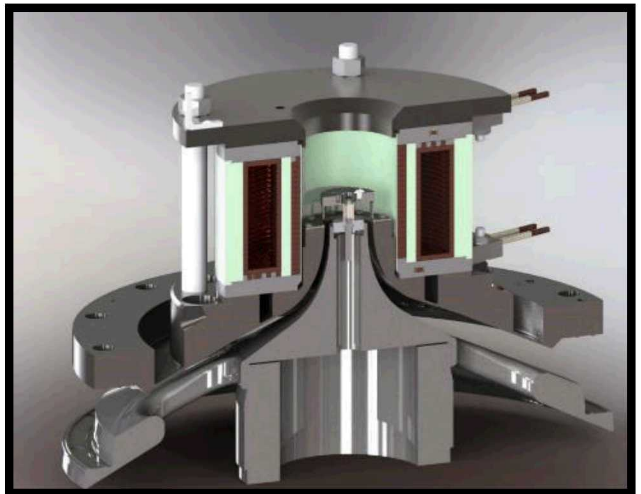
- 10-T Operating point
- ~25-30mm coil spacing for radial diagnostic access
- 90+ shots on Z since 2013





Limited-Access Spacing (80-80)

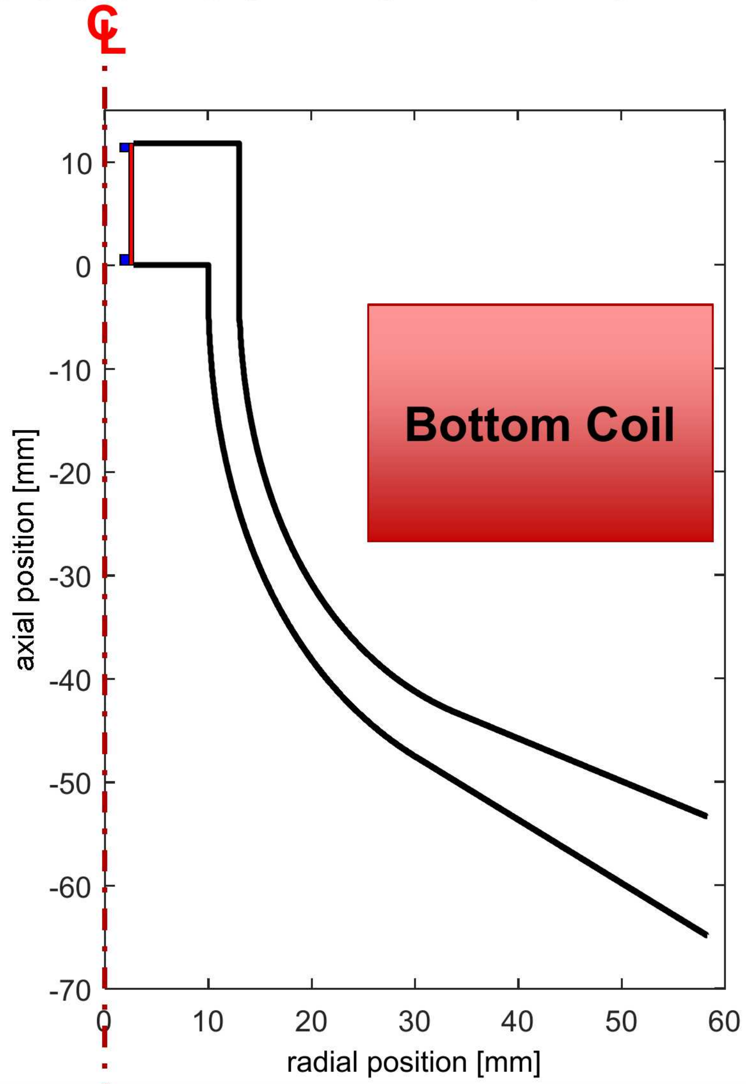
- 15-T Operating point
- ~10-14mm coil spacing for radial diagnostic access
- 15+ shots on Z since 2013



No-Access Spacing (230-turn)

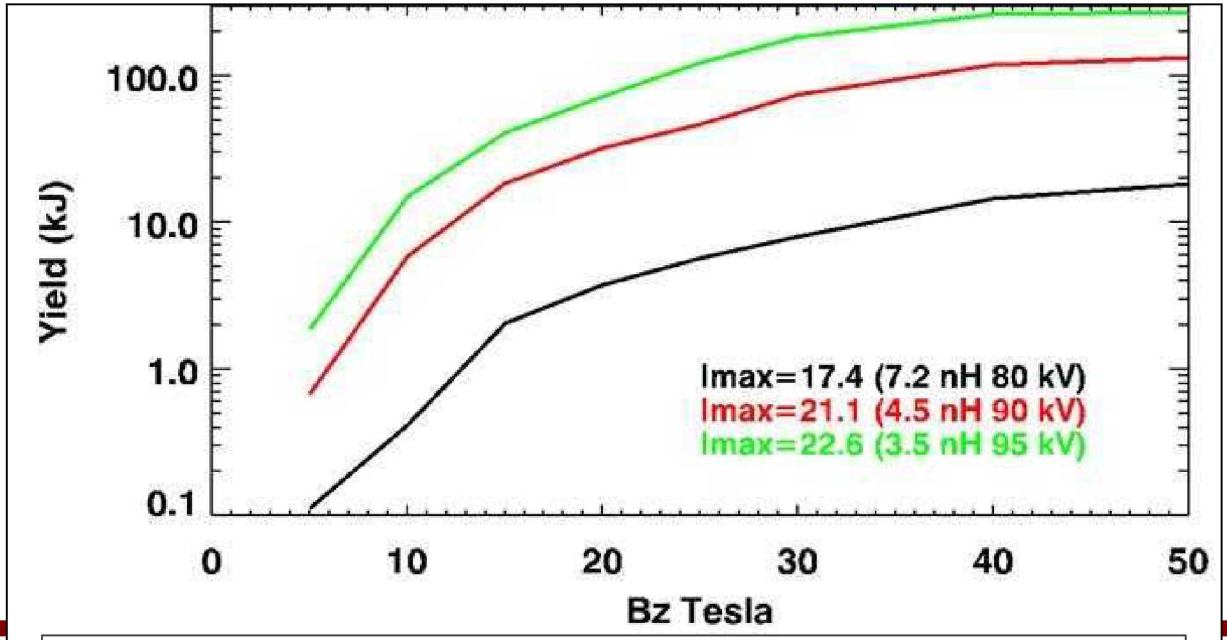
- 20-25-T Operating point
- No radial diagnostic access
- Never shot on Z in this configuration …

The Extended Power Feed limits achievable drive pressures from the Z current pulse



The extended power feed results in initial load inductance of 7.2nH

- **Each additional nH of initial feed inductance reduces deliverable machine current by ~0.8 MA**
  - Higher power feed voltage drives nonlinear loss mechanisms
- **Z's magnetic drive pressure should increase in step with ABZ field and laser preheat energy to maintain liner convergence**
- **We are also already near the Z Facility's peak charge voltage**



Fusion yield increases with magnetic field and drive current

By reducing feed inductance, Z can deliver more current to a MagLIF liner

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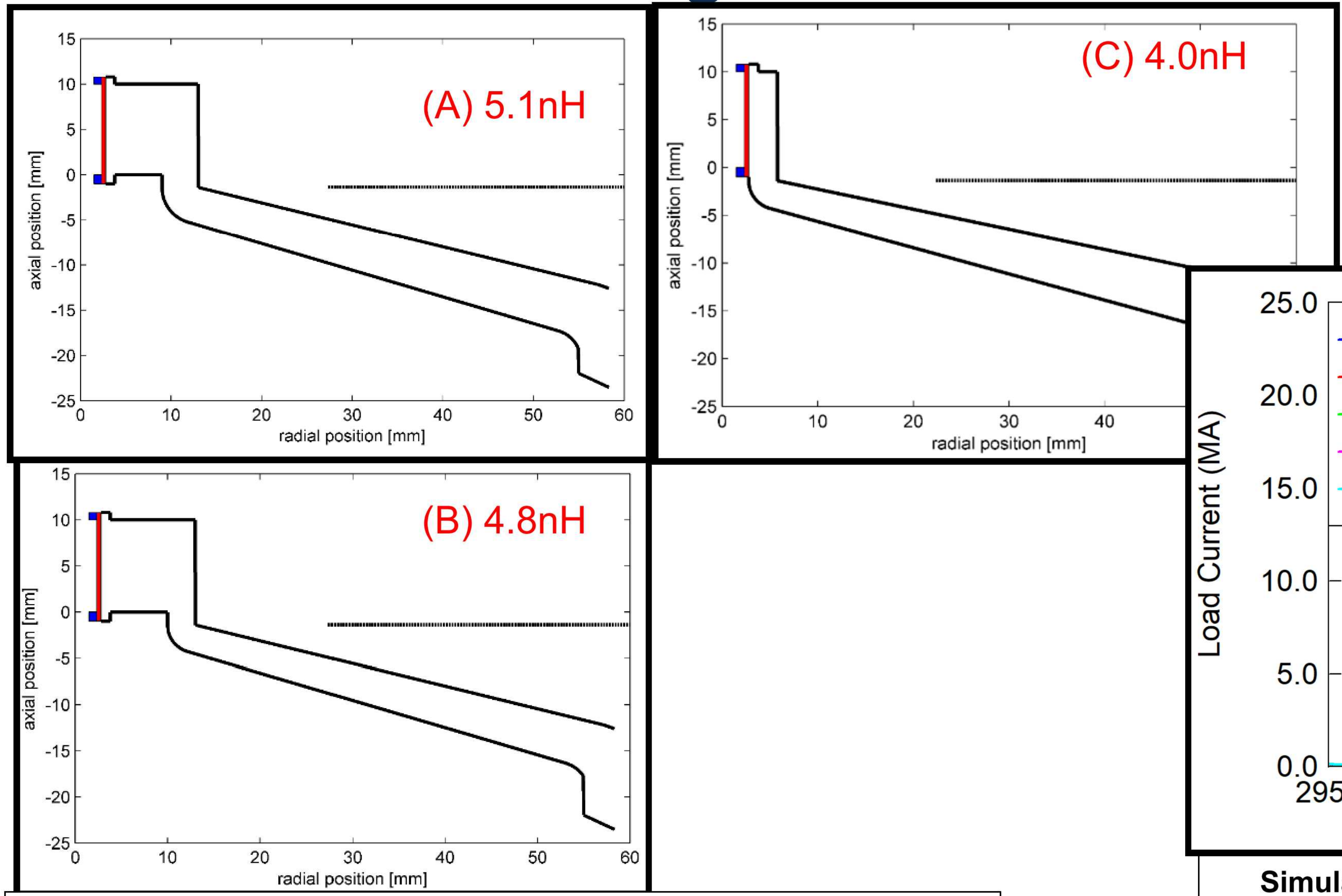
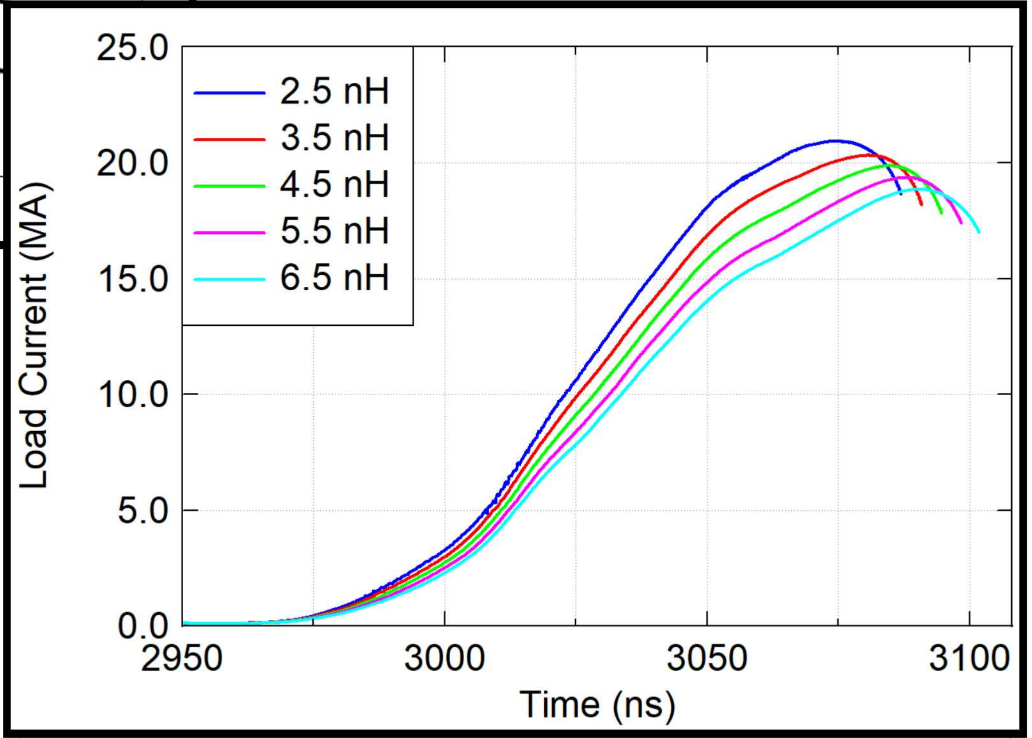


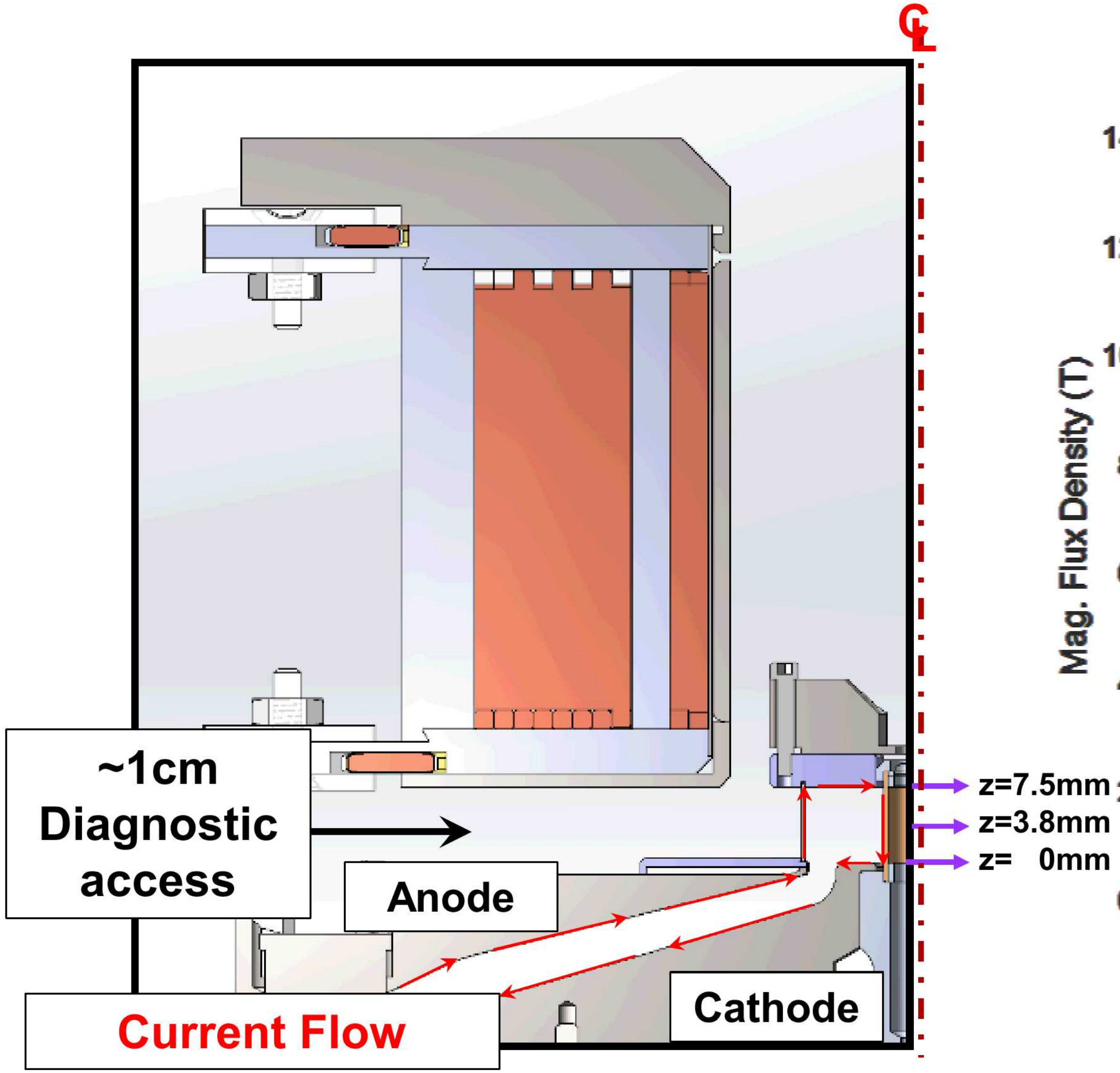
Initial inductance is reduced by lowering axial extent of feed (A), reducing power feed A-K gap (B), and return can volume (C)

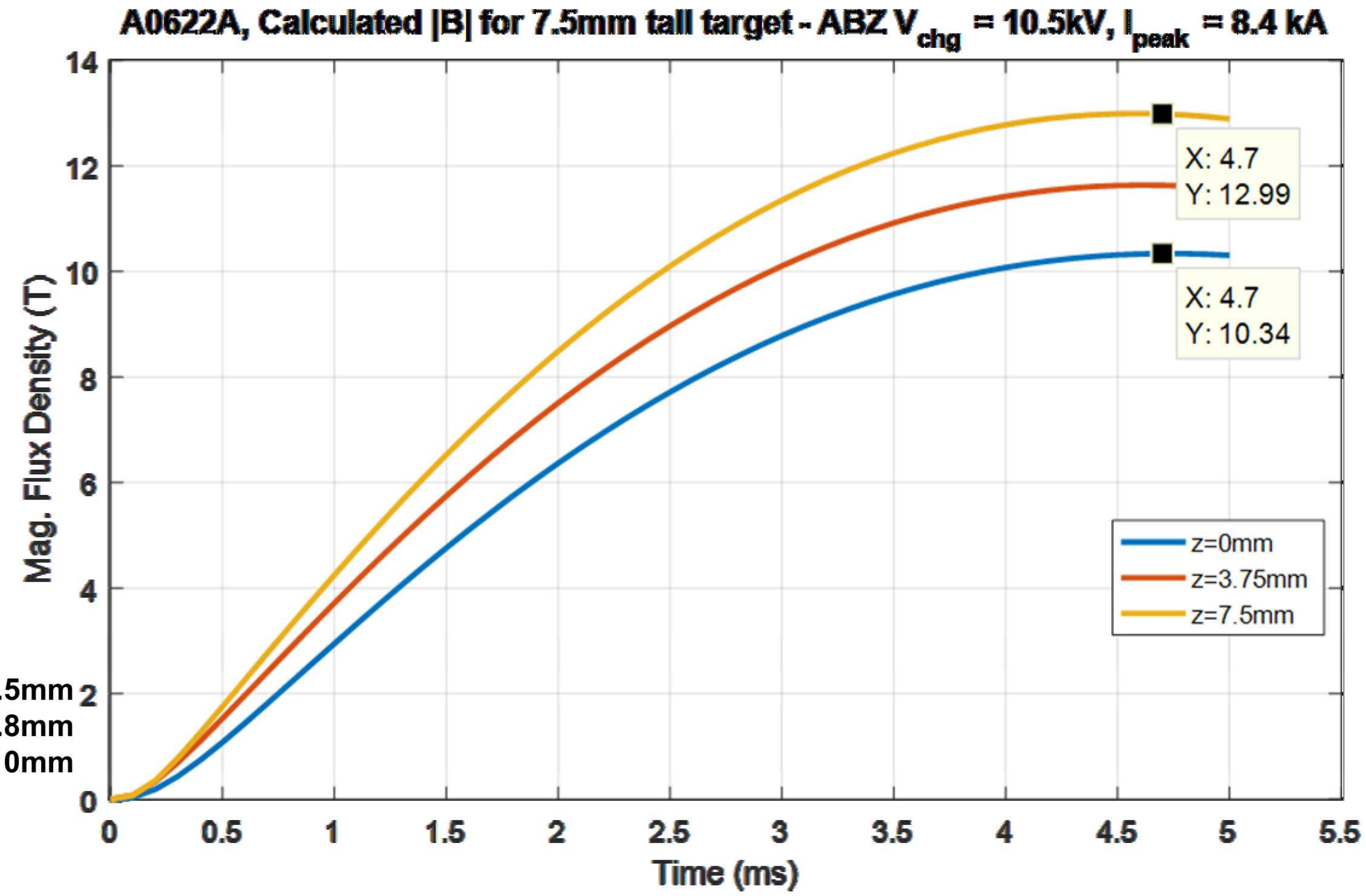


Simulated load current profiles for varying final power feed inductances and imploding MagLIF liner

Hutsel, et al., PhyRev AccelBeams, 21, 030401 (2018)

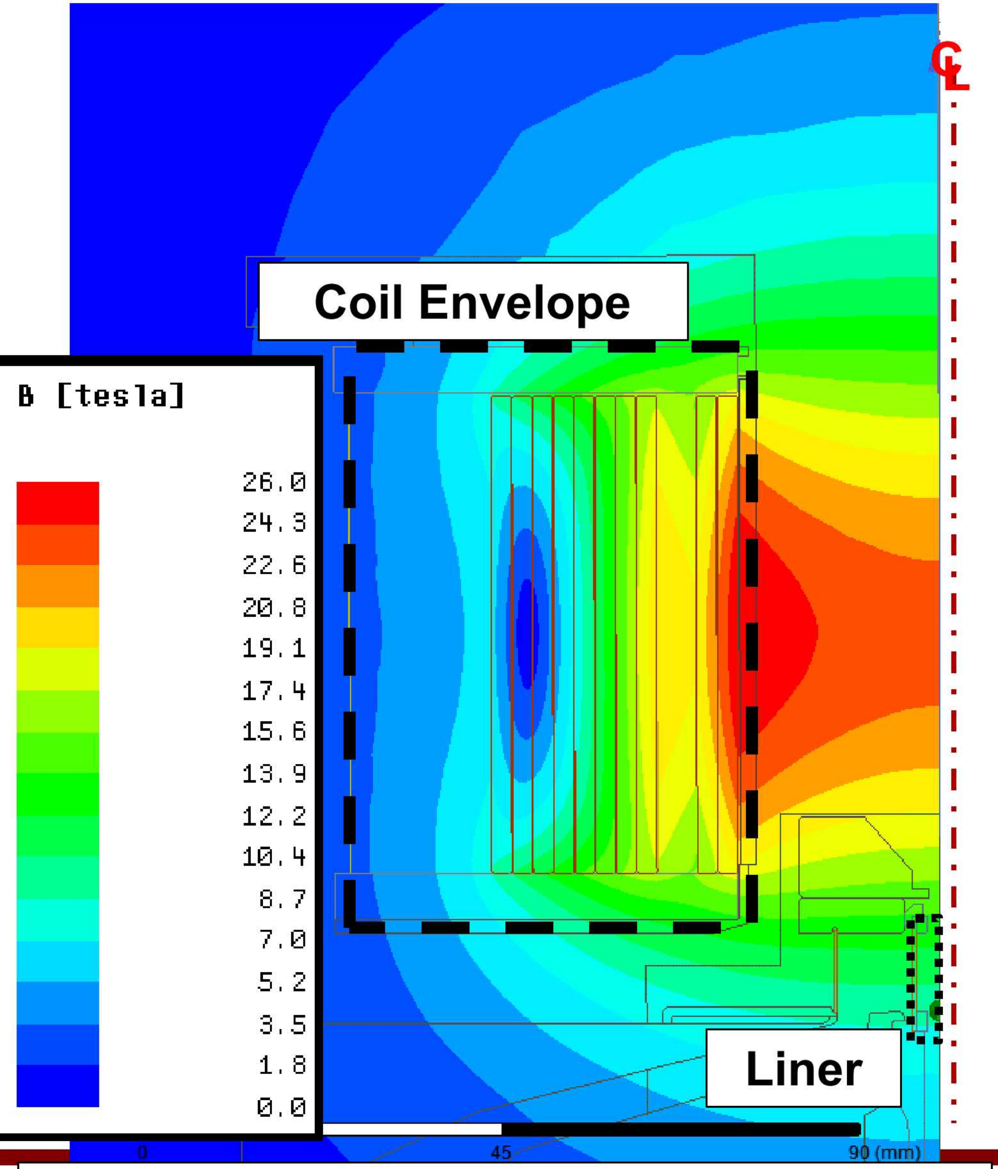
The ~5.1nH Low-Inductance (Low-L) platform uses 230-turn coil to magnetize MagLIF liner





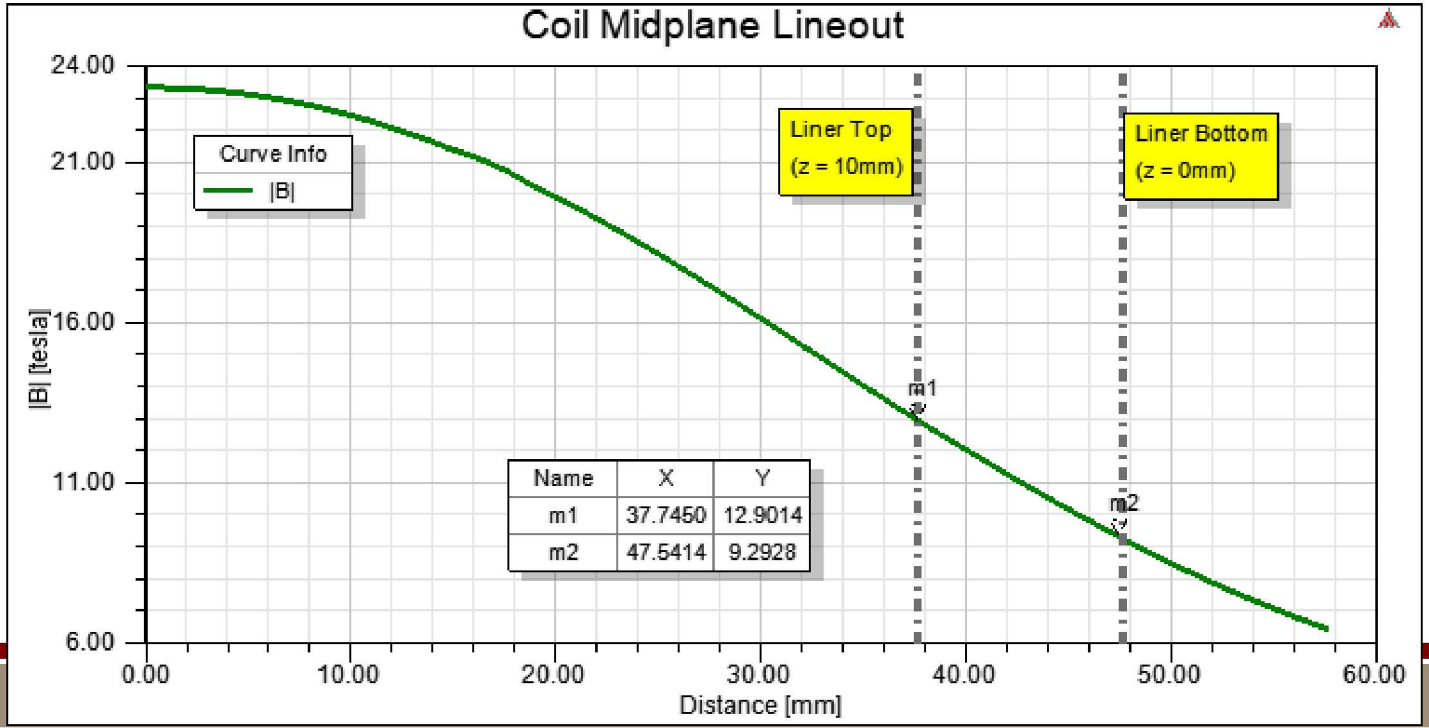
ANSYS Maxwell Transient-Magnetic calculations predict ~23% axial variation of field in 7.5mm tall target (above); ~32% for 10mm tall target

It is remarkably inefficient to utilize the external field of the 230-turn coil like this



Field distribution at 4.2ms (time of Z trigger)

- Coil was designed to produce 25-T at coil midplane for No Access configuration
- Not enough headroom in bank voltage for B_{z_avg} > 12-T
- By reducing coil height by 50% (230 → 115 turns), average B_z at target drops by only ***6%!***
- Adding 2 outer radial layers would increase field by 18%!
- **We can design a better coil for this application.**



MAKING A MORE EFFICIENT INEFFICIENT COIL: DESIGNING AN ELECTROMAGNET FOR LOW-L

Program guidelines dictate ABZ coil design path

The MagLIF program looks to increase constituent parameters in lockstep

- Integration by September 2018:
  - ABZ field between 15 – 20 T
  - Z Machine delivering 19 – 20 MA
  - Laser preheat of 1 – 2 kJ

- Integrated by September 2020:
  - ABZ field between 20 – 25 T
  - Z Machine delivering 20 – 22 MA
  - Laser preheat of 2 – 4 kJ

Coil Design Requirements

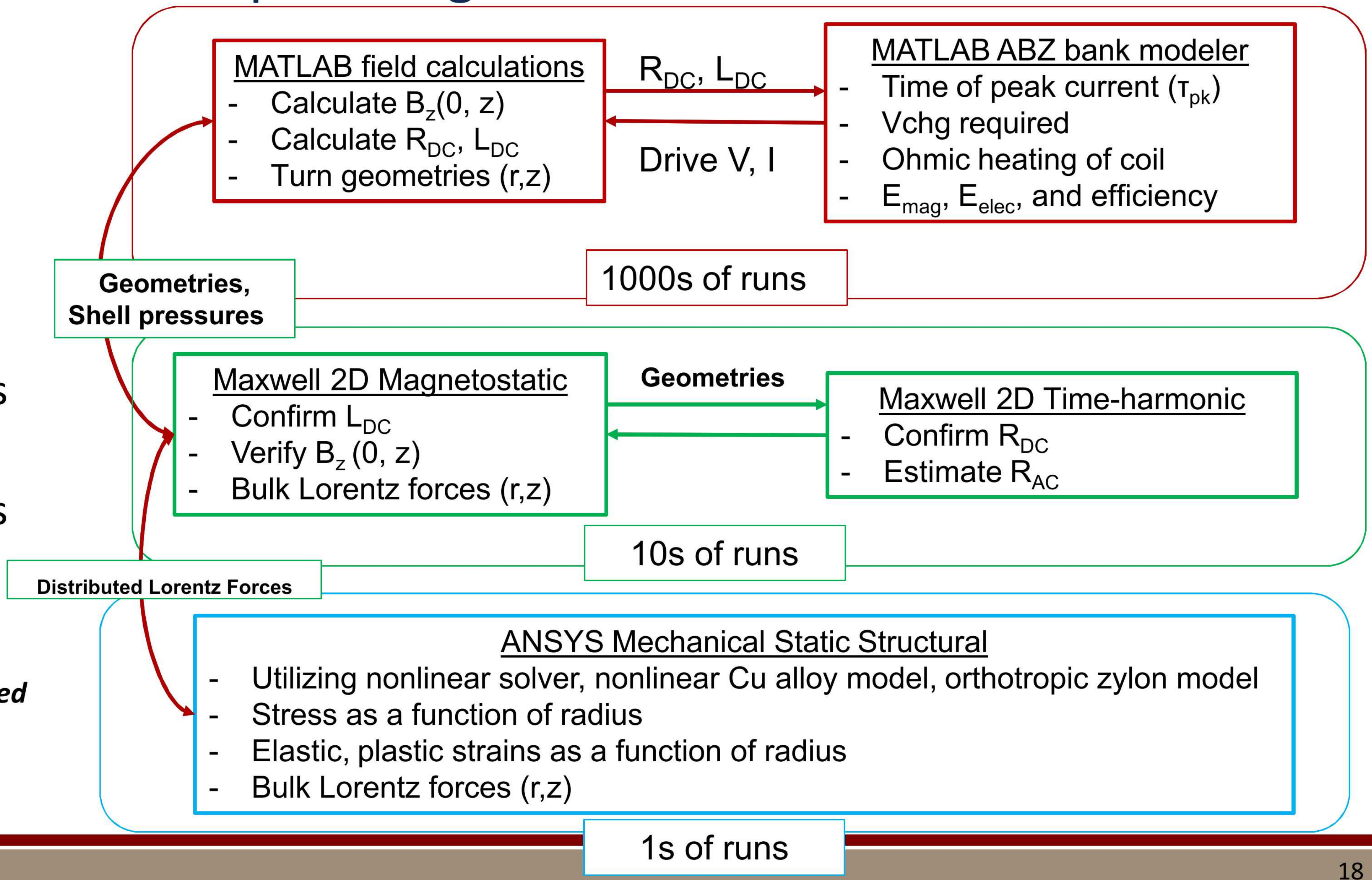
- **Flux Density:**
  - Low-L Coil shall be able to magnetize target to ***15-T average across the liner***.
  - Low-L Coil should be able to magnetize target to 20-T average field across the liner.
- **Liner Uniformity:** Equal or lower than existing Low-L platform: ~32% across 10mm target.
  - This is a lower priority than flux density.
- **Bank Dynamics:**
  - Rise time should be < 6.1 ms
  - Low-L Coil shall achieve requirements with one-bank operation at 13.5kV max (limits coil inductance)
- **Lifetime and pulsed behavior:**
  - Low-L Coil should achieve required field strengths using ~10kA current
    - Enables coupling to 60- and 80-turn coils
  - Demonstrate ***coil lifetime of n=10 shots*** at required field strengths

Loosely constrained parameter space required staged analysis approach to "optimize" output design

Parameters

- Initial coil diameter
- Axial layers (how "tall" is it)
- # of zylon internal reinforcement shells
- Thickness of zylon reinforcement shells
- Outer coil radius

Surveyed parameter space yielded ~3400 design variants



3- and 4-shell variants of 13-axial-layer coil advanced to detailed design

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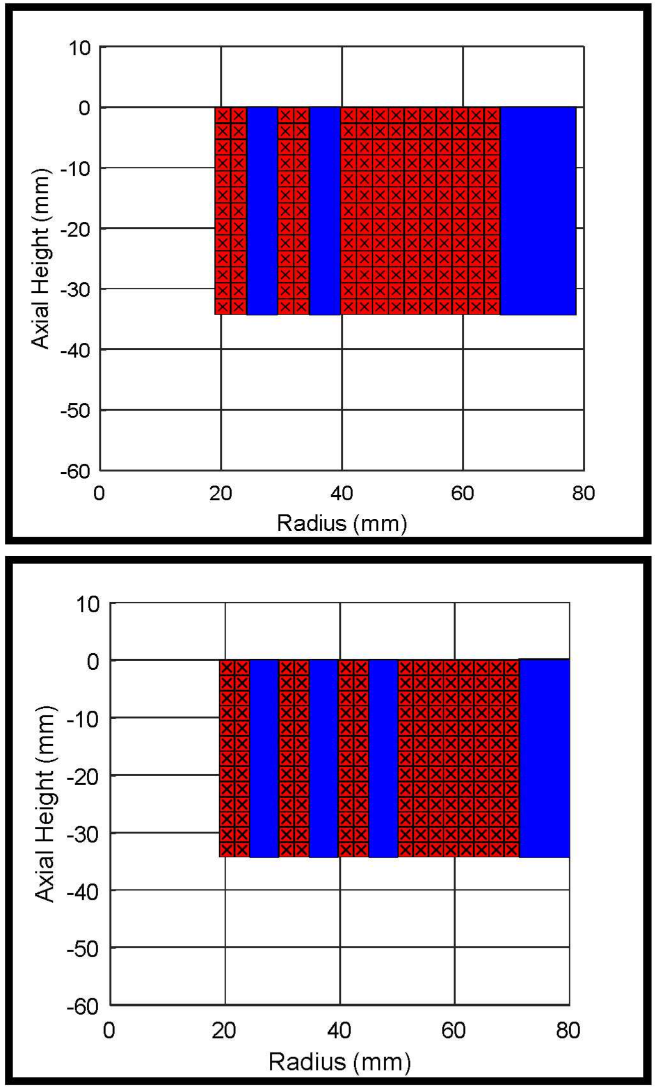
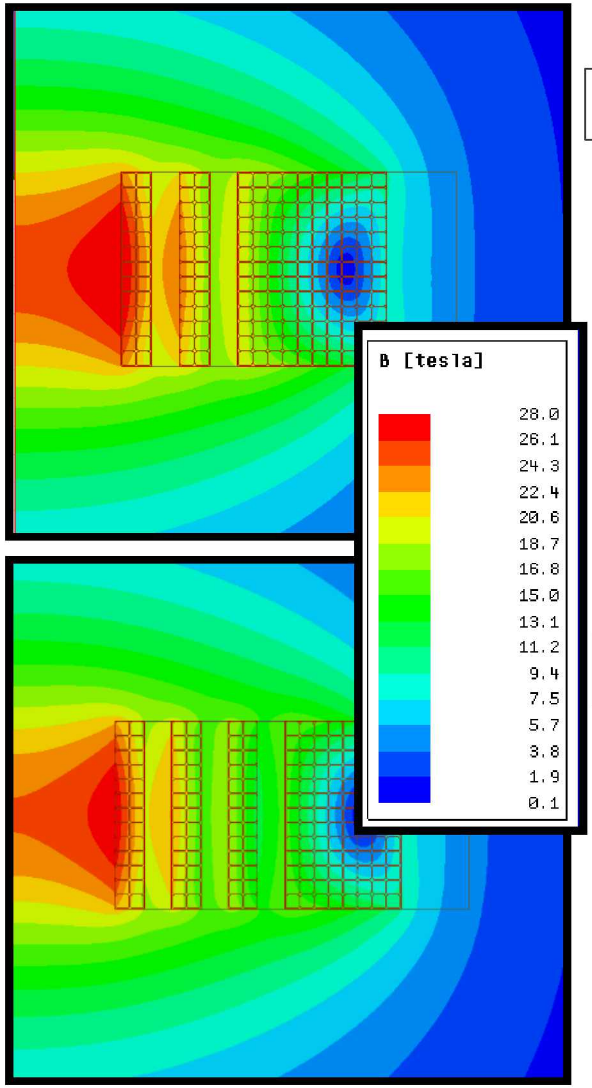
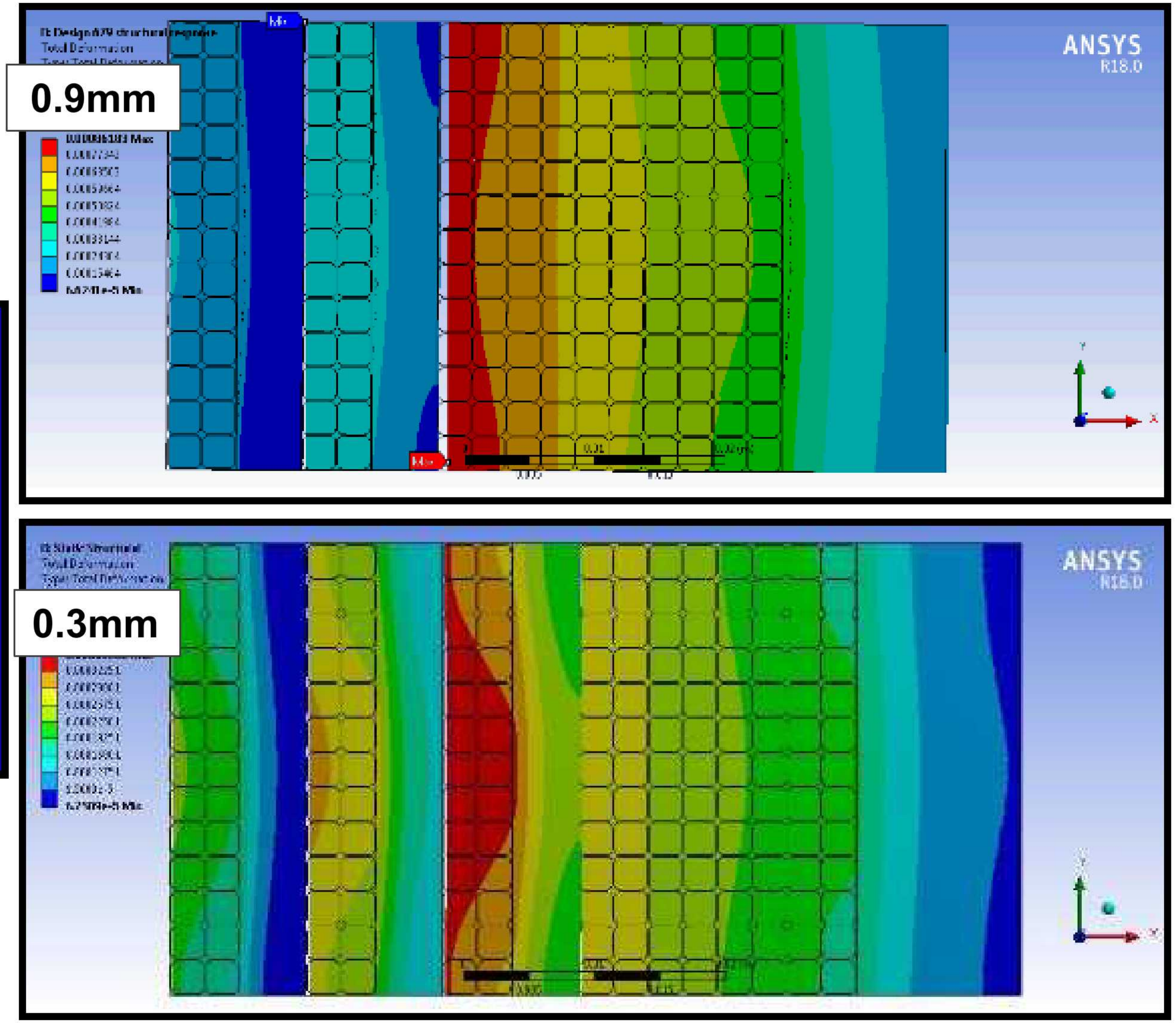


MATLAB-generated 3-shell and 4-shell Low-L coil geometries

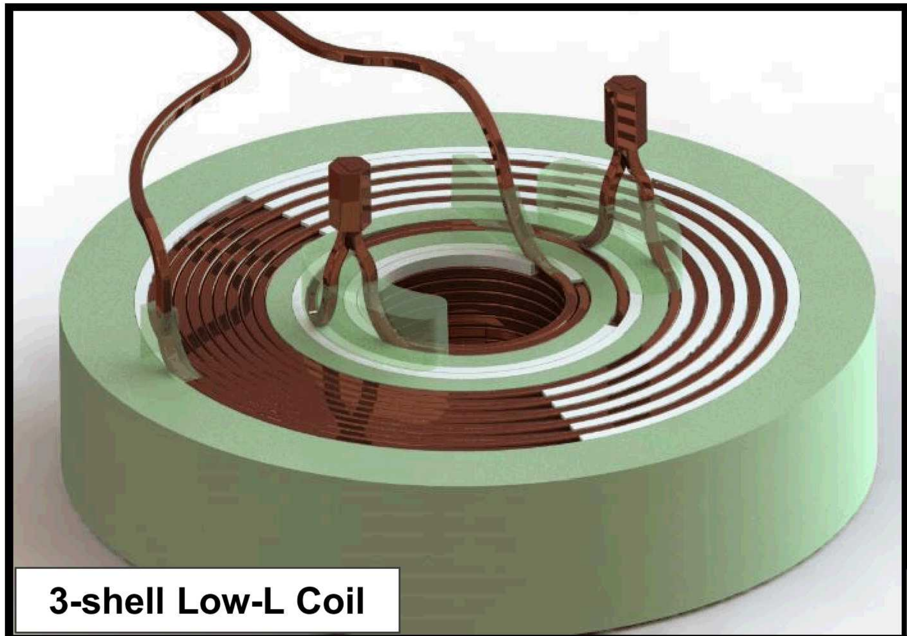


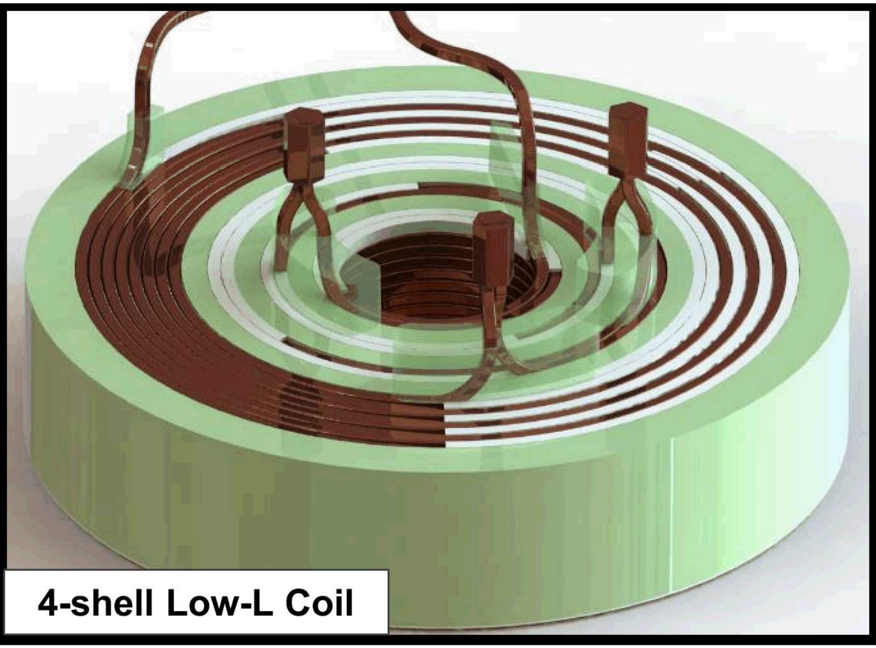
ANSYS Maxwell-Generated magnetic field strengths and JxB distributed force loadings

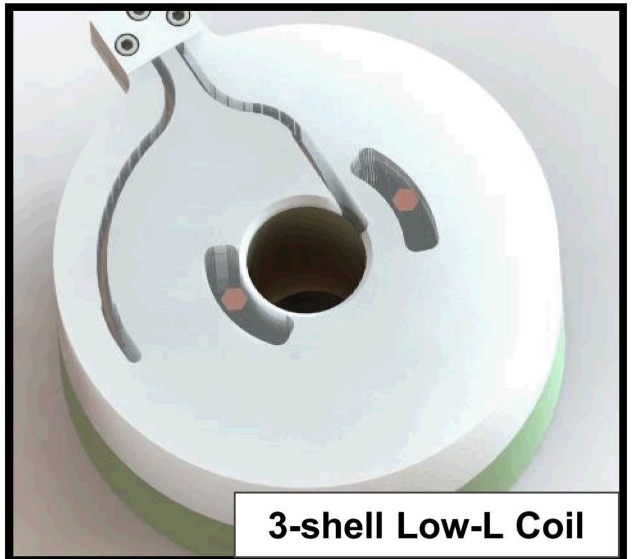


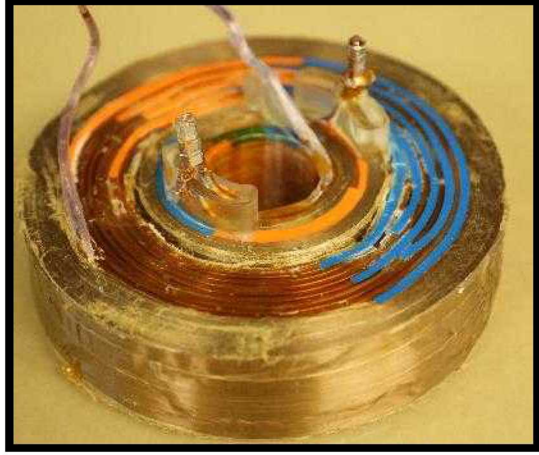
ANSYS Mechanical-generated total deformation using elastic-plastic nonlinear copper model for 20-T average field at liner location

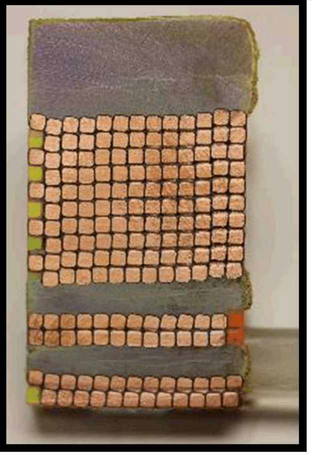
Z hardware imposes unique winding requirements to enable novel internal reinforcement, coil connection scheme


3-shell Low-L Coil


4-shell Low-L Coil


3-shell Low-L Coil





- Designs minimize material below coil
- Inter-coil connections made via crimps above coil in lower-field regions
- Requires a “down-wind” and “up-wind” to get wire out of way for zylon
- Allows for internal reinforcement around clean breaks in conductor wind

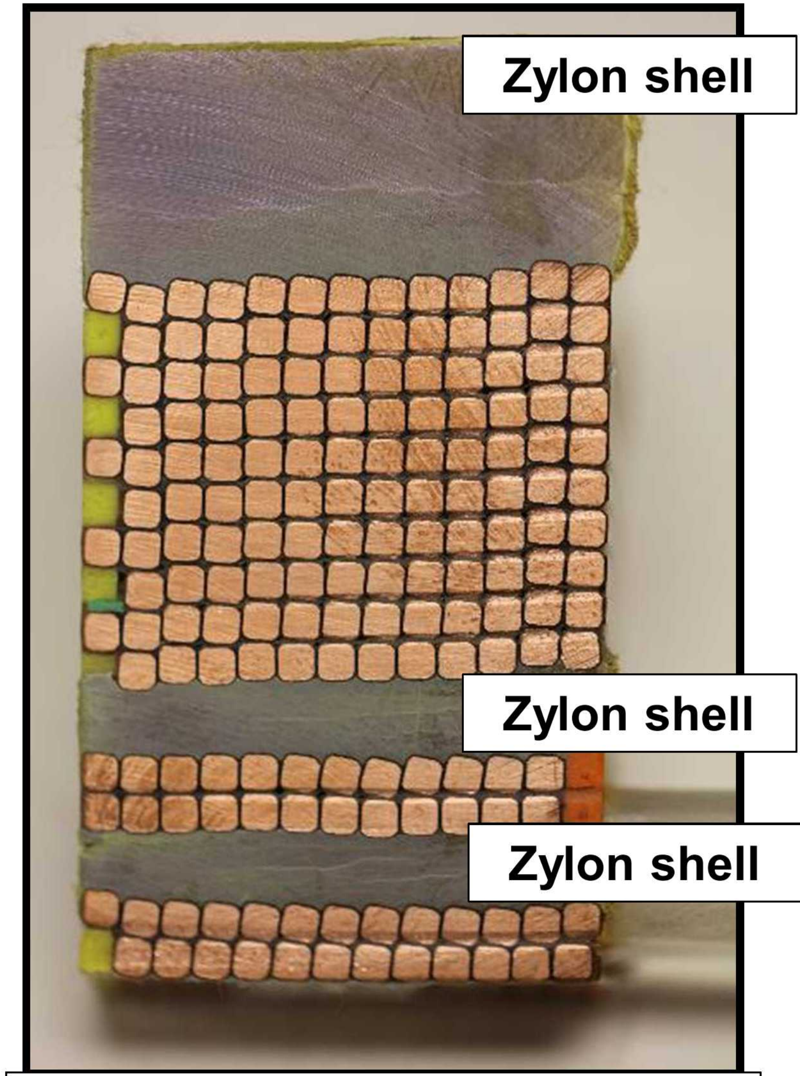

Delrin flange captures coil transitions and leads for final epoxy encapsulation process

3-Shell and 4-Shell Low-L Coils perform similarly in simulation

Parameter	3-Shell	4-Shell
Coil Inductance	2.14mH	2.27mH
DC Resistance	143mΩ	153mΩ
Drive current to achieve 15-T avg.	9.05kA	9.3kA
1-Bank Voltage V_{chg} for $\mathbf{B_{avg}}$ = 15-T	9.9kV	10.5kV
Field Uniformity for 10mm liner	30%	29%
Shell 1 Zylon Peak Stress	1.15 GPa	1.16 GPa
Shell 2 Zylon Peak Stress	1.12 GPa	1.10 GPa
Shell 3 Zylon Peak Stress	1.10 GPa	1.04 GPa
$\mathbf{B_{avg}}$ linearly scaled to 13.5kV max $\mathbf{V_{chg}}$	20.5 T	19.3 T
Shell 1 Zylon Peak Stress at 13.5kV $\mathbf{V_{chg}}$	**2.14 GPa**	1.66 GPa
Shell 2 Zylon Peak Stress at 13.5kV $\mathbf{V_{chg}}$	**2.08 GPa**	1.57 GPa
Shell 3 Zylon Peak Stress at 13.5kV $\mathbf{V_{chg}}$	**2.04 GPa**	1.48 GPa

Shell 4 0.62 GPa

Shell 4 0.88 GPa



3-shell sectioned prototype shows well-filled zylon reinforcement shells, tightly-packed winding journals

Zylon fibers measured to have 3.3 GPa ultimate tensile strength for 77.5% fill fraction [Y.K. Huang et al / Composites: Part B 33 (2002)]. We assume we have less than this fill fraction.

3-Shell Low-L coil seems superior to 4-shell in theory, but …

- Passing orthotropic “thick-shell” zylon ultimate tensile strength calculations is necessary for “good” designs
  - But not sufficient to predict coil failure.
  - We’ve never failed a zylon shell.
  - 3rd coil conductors are observed to move.
- Observed failures *always* occur at wire-to-wire interfaces
  - Predicting lifetime would require 3D modeling based on local wire loading
  - Also need to consider 3D effects on layer-to-layer transition, lead-to-wire

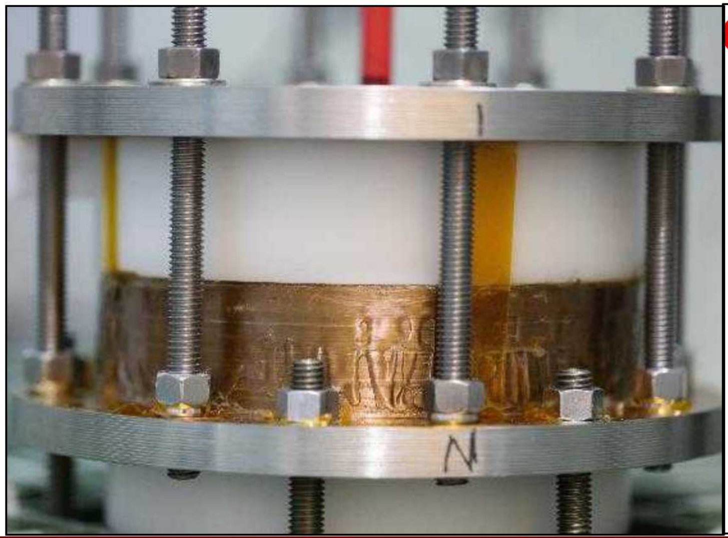
- **A third internal reinforcement shell:**
  - Reduces field 5% (1T out of 20T)
  - Increases inductance (lower I_{pk} at 13.5kV)
  - More complex to produce per unit
- **But it also:**
  - Reduces calculated peak wire strain by 67%
  - Reduces compliance in winding journal and resultant deformation
  - Is likely necessary for higher-field shots (>15-T)

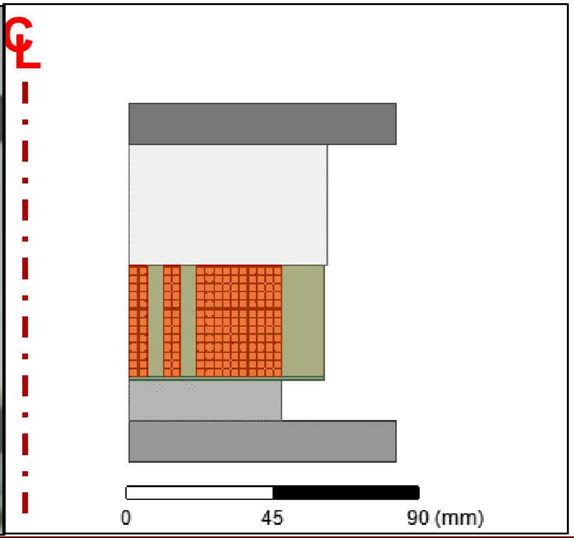
First 3-shell coil prototype (Delrin flange removed) after 10 shots at 17-T average B-field.

Prototype 3-shell coils have demonstrated n~10 for B_{avg} > 15-T

- **15-T B_{avg} → 100% design stress**
- **Test coil 1:**
  - 1 shot each at 50%, 70%, 80%, 100%, 120%
  - **10 shots at 133%**
  - (Dissected after 10^{th} shot)
- **Test coil 2:**
  - 1ea. at 50%, 3ea. at 67%, 1ea. 85%, 100%
  - **14 shots at 120%**
  - Soft failure of 14^{th} shot
- **Test coil 3:**
  - 1ea. at 50%, 67%, 85%, 100%
  - **9ea. at 120%**
  - Soft failure on 9^{th} shot (after peak current)

Prototype 1 pulsed ten times at 10.4kA (B_{avg} ~ 17T) before post-mortem

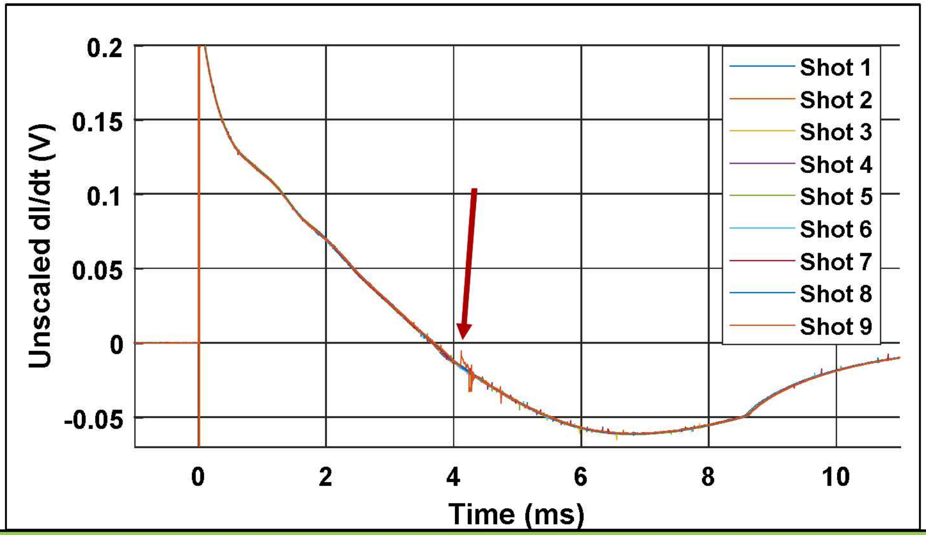




Coils tested in surrogate geometry that mimics Z hardware

Observed failures have been "soft"; result from conductor movement shorting between layers during pulse

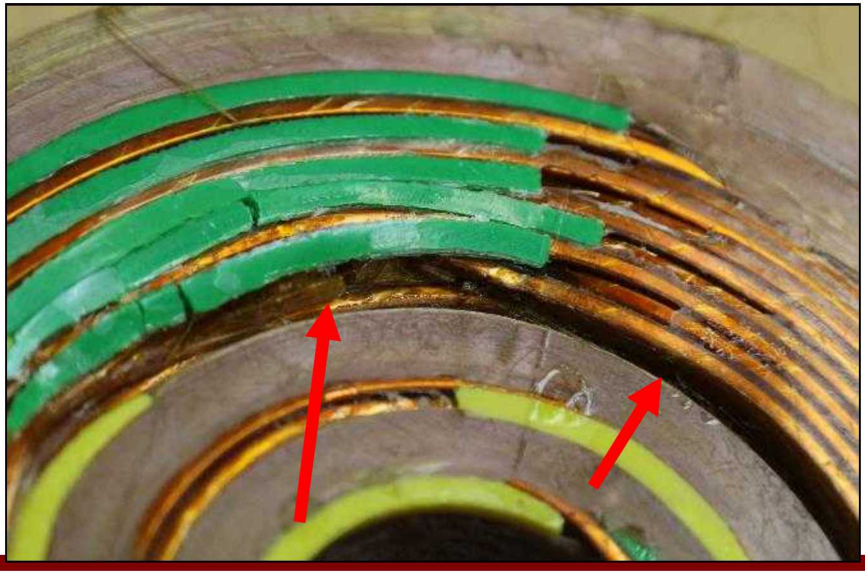
- **3-shell Low-L coil is observed to accumulate large radial displacement in outer coil**
  - This trend is observable in coil inductance ($L_{eq} \propto d$)
  - The two nested 2-layer coils see no change throughout testing
- **This movement eventually shorts out turns during pulse**
  - Typically occurs after peak current (peak mechanical strain)
  - Does not destroy the coil (it remains intact for post-mortem)



Rogowski probe (di/dt diagnostic) shows gentle short after I_{pk} on shot 9

Shot	Inner Coil 21.6 µH	Middle Coil 33.9 µH	Outer Coil 1.554 mH	Full Assembly 1.98 mH
1	100.0%	100.0%	**100.0%**	100.0%
2	99.7%	100.0%	**100.3%**	100.2%
3	100.4%	100.3%	**100.6%**	100.4%
4	100.2%	100.2%	**100.9%**	100.6%
5	100.1%	100.0%	**101.1%**	100.7%
6	100.3%	100.2%	**101.3%**	100.9%
7	99.7%	100.2%	**101.6%**	101.1%
8	99.4%	100.1%	**101.7%**	101.2%
9	99.8%	100.2%	**101.9%**	101.3%
10	99.5%	100.2%	**102.0%**	101.4%

Test coil 1's nested and total coil inductance change per shot



Turn movement (left arrow) and increase in inner diameter (right arrow)

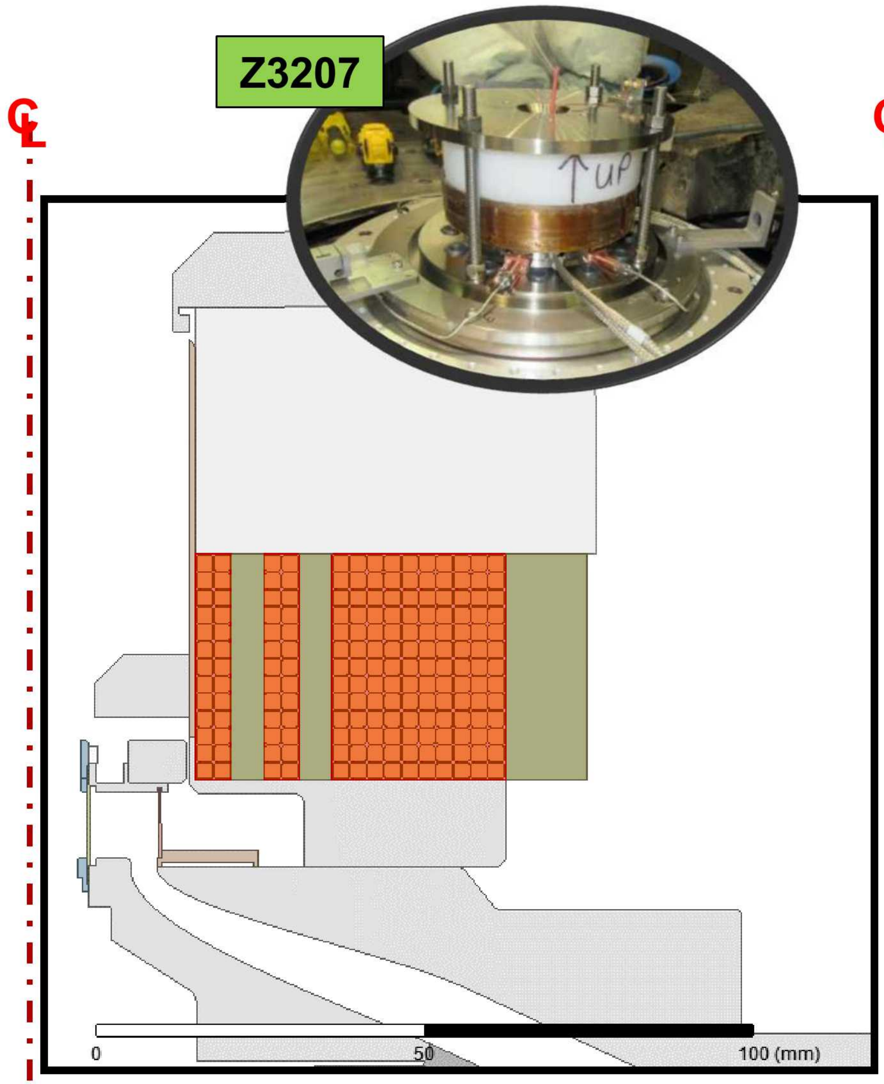
The 3-Shell Low-L coil has been fielded for 10-T Z experiments, ready for 15-T B_{avg}

Experiment Z3207 (05Feb2018) utilizing 3-Shell coil on Low-L platform for MagLIF experiment

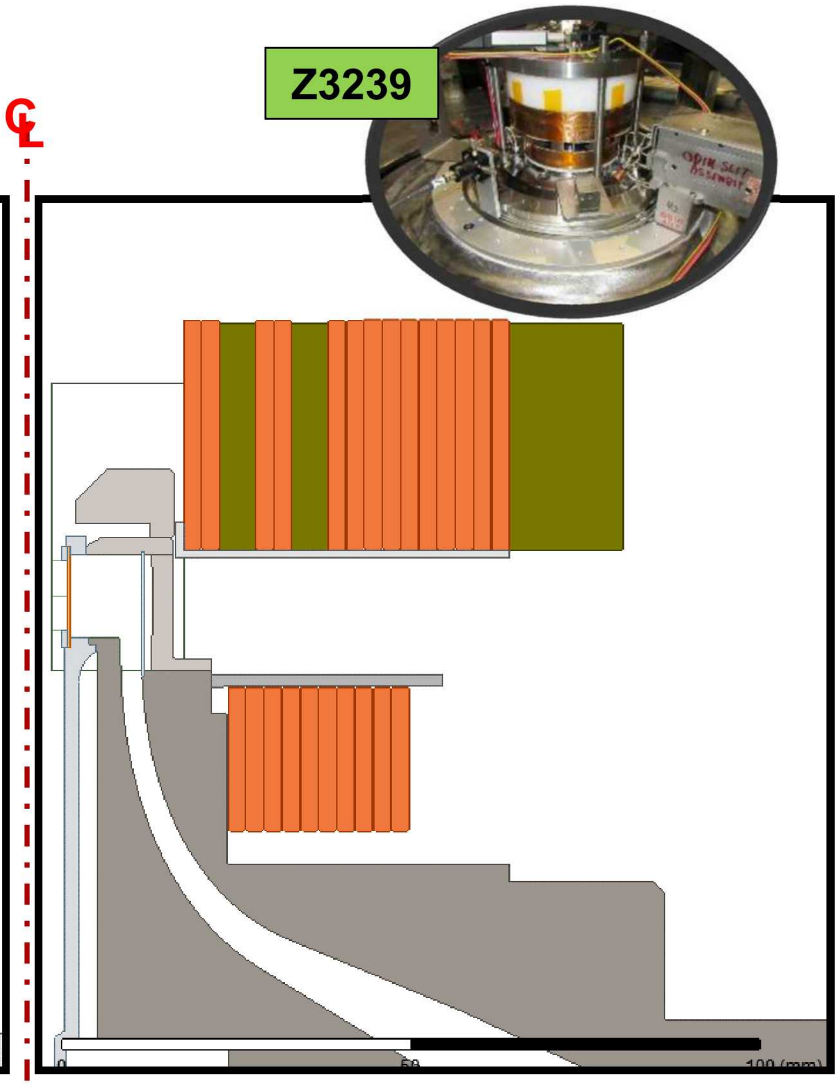
- **We have fielded these coils on Low-L platform Z experiments at 10-T**
  - Experiments performed in February 2018
- **15-T average field experiments currently scheduled for July 2018**
  - The lifetime data with the 3-shell prototypes gives us confidence in our readiness
- **We can increase pre-magnetization field level in standard feed experiments**
  - Replacing 80-turn coil with 3-Shell Low-L coil to increase from 15 to 20T

THE PATH FORWARD TO 20 – 25 T

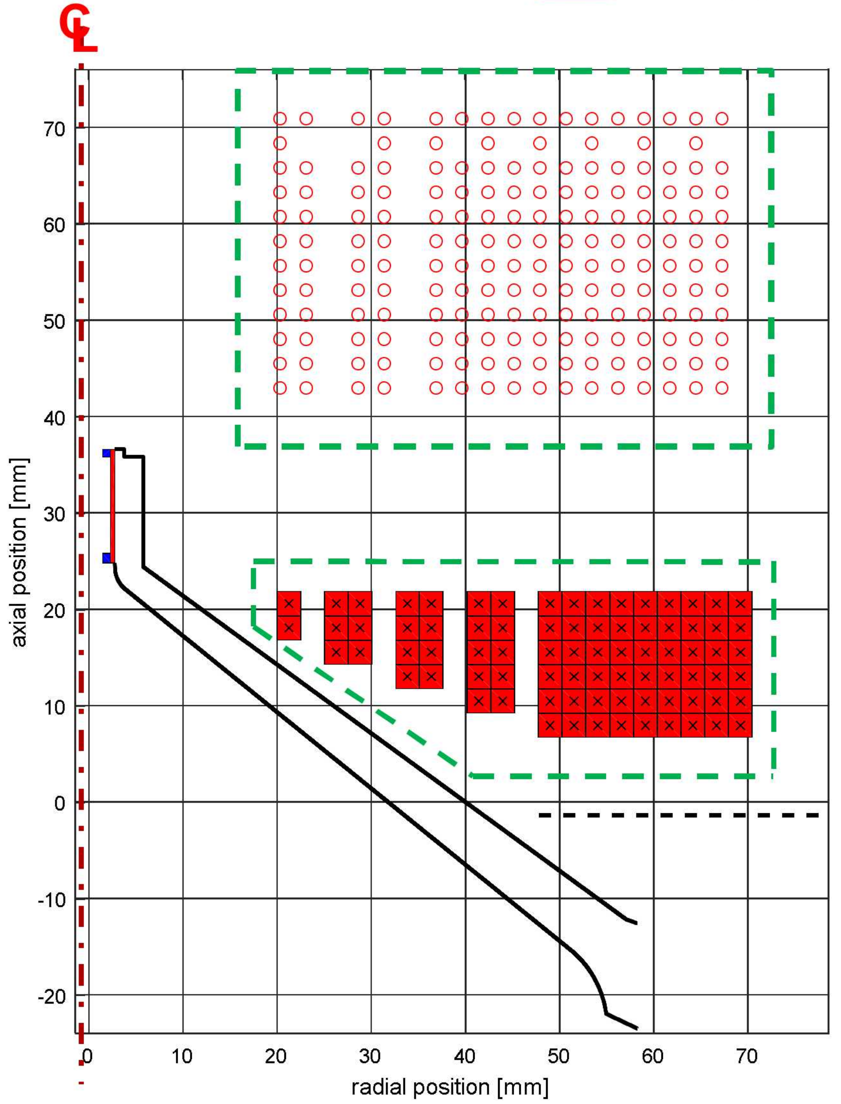
Low-L coil provides three configurations for MagLIF scaling studies



Low-L Coil on Low-L Platforms
15 – 20T avg. field
with 19-20MA feed designs

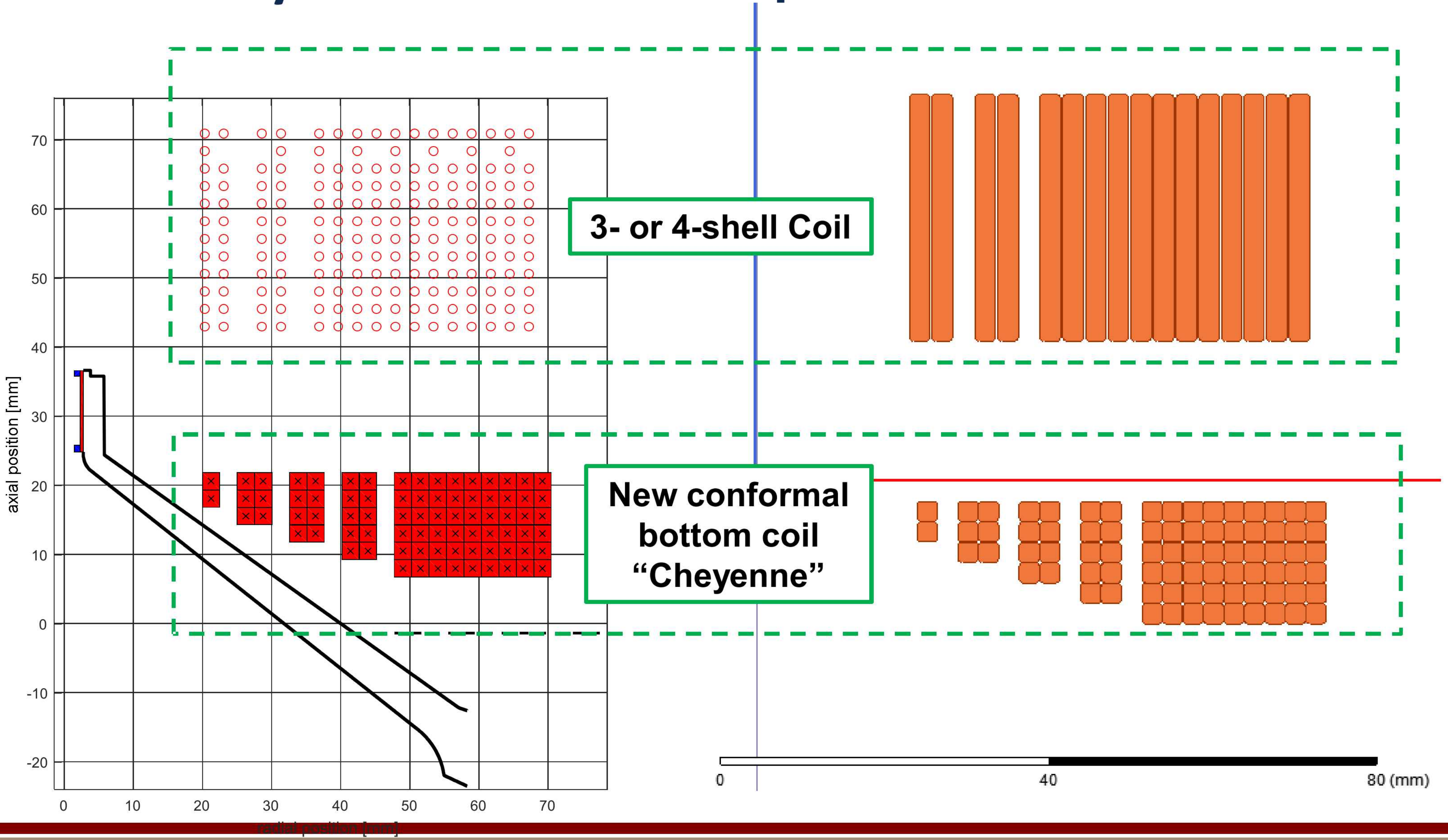


80-turn Coil + Low-L Coil
20 – 22T avg. field in Standard Feed
(~17 MA drive current)

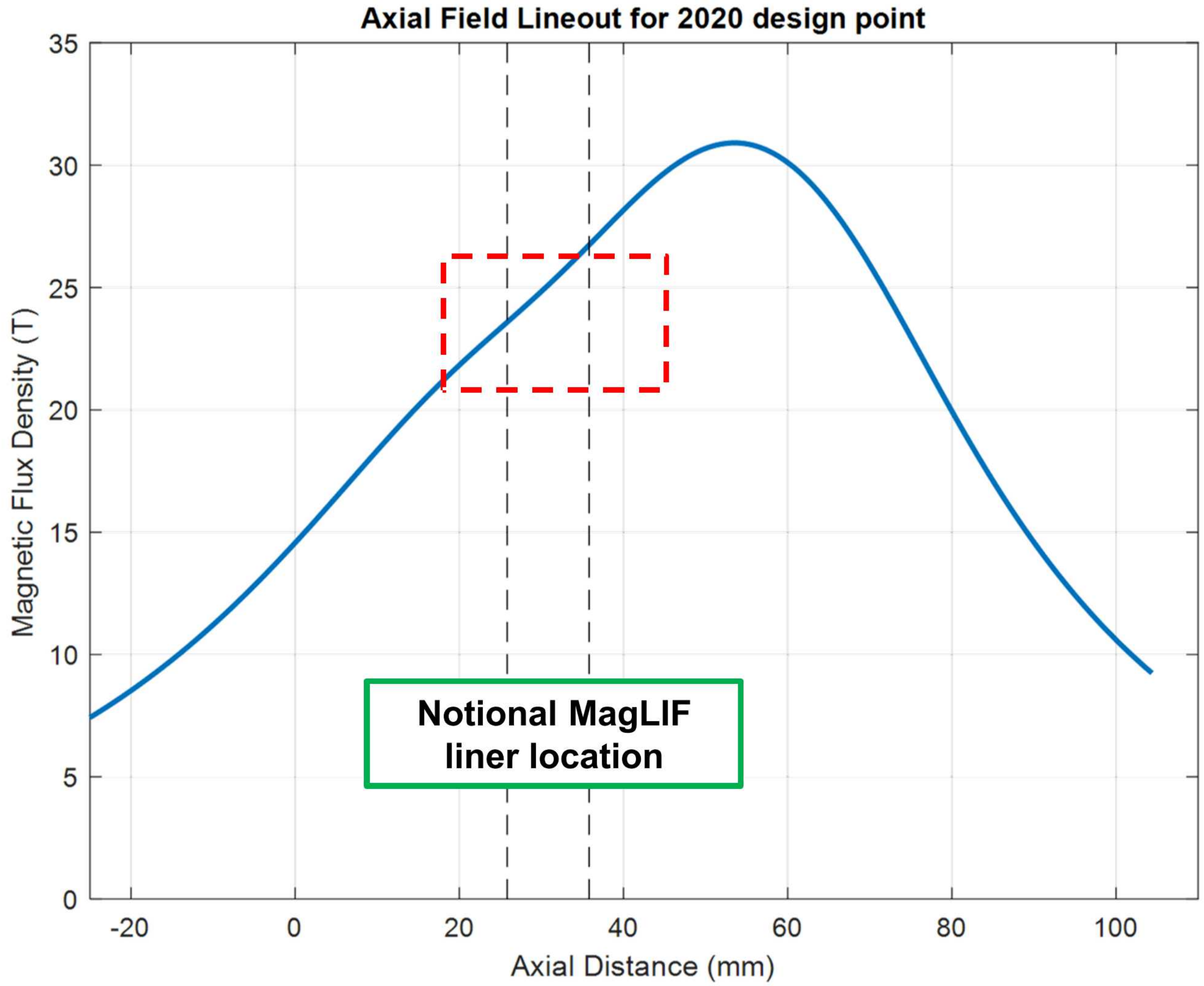


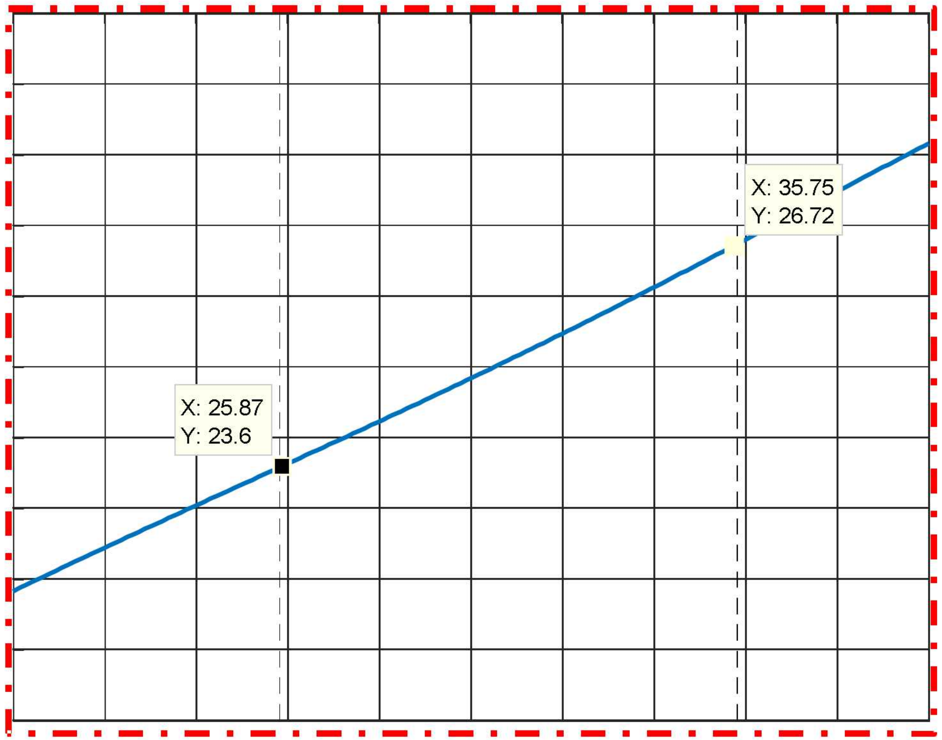
New conformal bottom coil to increase field, provide better field uniformity for 20-30T goal

Design underway to complement Low-L coil with new bottom coil "Cheyenne" for 20-30 T operation



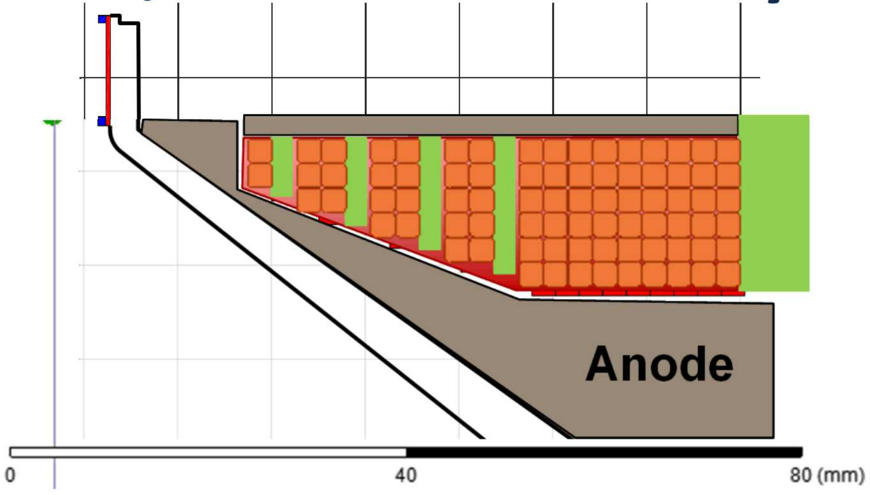
Superposition of calculated coil fields look encouraging for ~25T experiments in 2020



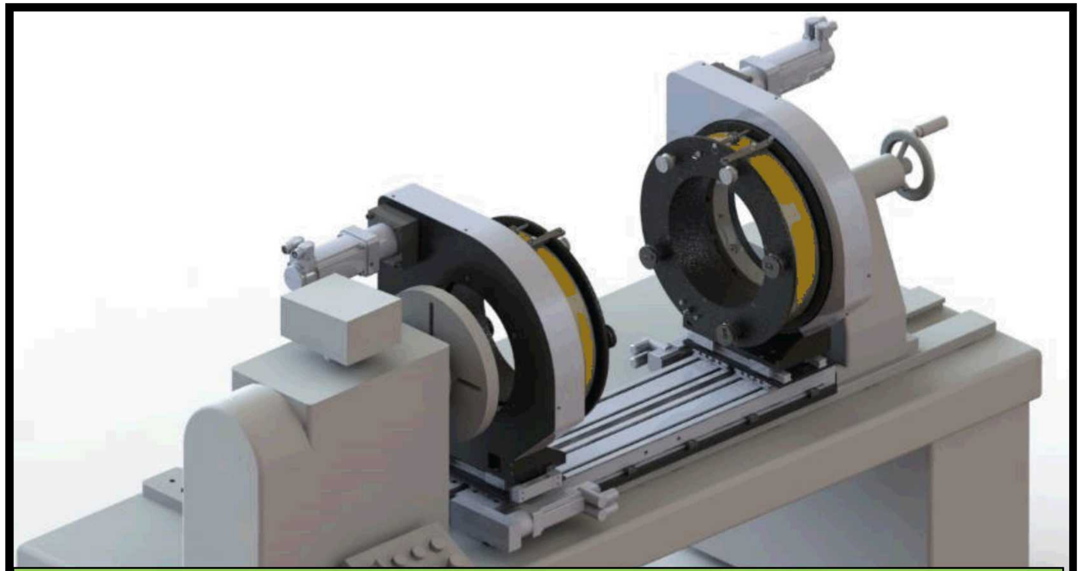


- Conceptual coil pair can generate 25.2-T average field at the same operating current (10kA) as the existing Low-L coil
- Need to evaluate transient coil self-forces, coil attraction, and repulsion from anode

Cheyenne concept requires new winding capability, fabrication process, and detailed analysis to converge on design



Conceptual coil design with support flange and notional internal reinforcement shells



Machine with orbital winding functionality currently in fabrication by collaborators at Milhous Company

- **Tight geometric constraints prevent coil-coil transitions like in Low-L coil**
- **Coil cross-section must follow power flow contour**
  - Minimize Z power feed inductance
  - Maximize field strength per turn
- **Power feed and bottom coil must be designed in tandem to achieve optimized performance for both**

- Space constraints require the ability to wind zylon while maintaining conductor feed under tension
- Zylon winding heads must “orbit” stationary coil mandrel while wire feed remains unbroken
- Orbiting heads must be preloaded with zylon
- Hoping for Cheyenne prototypes by February 2019

Summary of today's discussion

- **Sandia's MagLIF program on Z requires electromagnets to pre-magnetize the fusion fuel**
  - The magnetic field reduces thermal conduction losses in fuel, relaxes convergence requirements
  - The ABZ subsystem on Z regularly delivers 10 – 15 T to Z experiments with ~16-17 MA machine current.

The ABZ team works to meet program goals for integrated MagLIF experiments:

- **19-20 MA machine current, 15 – 20T pre-magnetization, 1-2kJ laser preheat**
  - The Low-L platform increases machine current by dropping extended power feed, reducing load inductance
  - We have designed an internally reinforced magnet that can deliver 15 – 17 T average field in MagLIF liner
  - Coil prototypes have demonstrated acceptable lifetime and are ready for Z experiments
  - Our first 15-T experiments are scheduled for July 2018 on Z

- **20-22 MA machine current, 20 – 30T pre-magnetization, 2-4kJ laser preheat**
  - Our team is designing a coil pair to meet this field requirement also while providing radial diagnostic access
  - A coupled design effort for the Z power feed and bottom ABZ coil is required to optimize performance
  - A new winding methodology is currently in development to enable production of Cheyenne prototypes

Questions?