Magnetic Field Coil Designs for MagLIF

MagLIF Workshop
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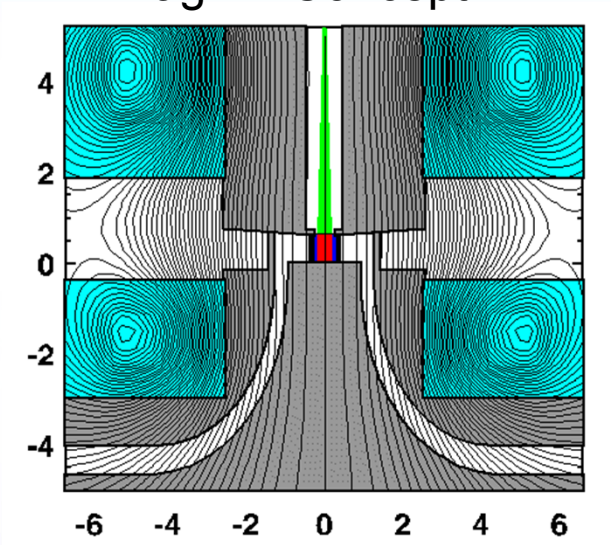
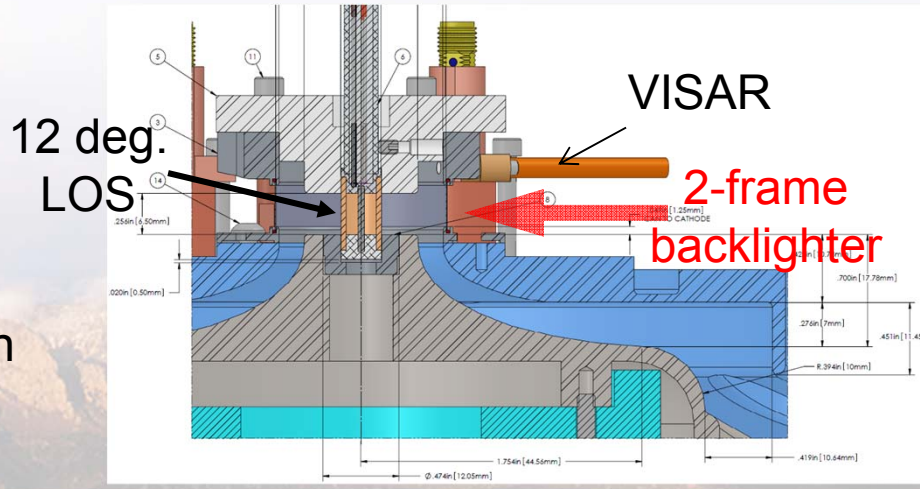
MagLIF coil system goals and requirements

- **Field strength goals:**
  - Goal is 10-T with full diagnostic access
    - Must provide access for 2 frame backlighter, VISAR and 12 deg. LOS
  - Goal is 20 – 30 T for limited or no-access design
    - Main diagnostic is neutron yield
- **Pulse length requirements:**
  - Must be able to magnetize the liner/fuel
  - Must not crush or buckle the target
  - Goal is to minimize induced forces on load and feed hardware
- **Minimize the increased inductance due to raised feed**
  - Thou shalt not add more inductance than necessary

MagLIF Concept

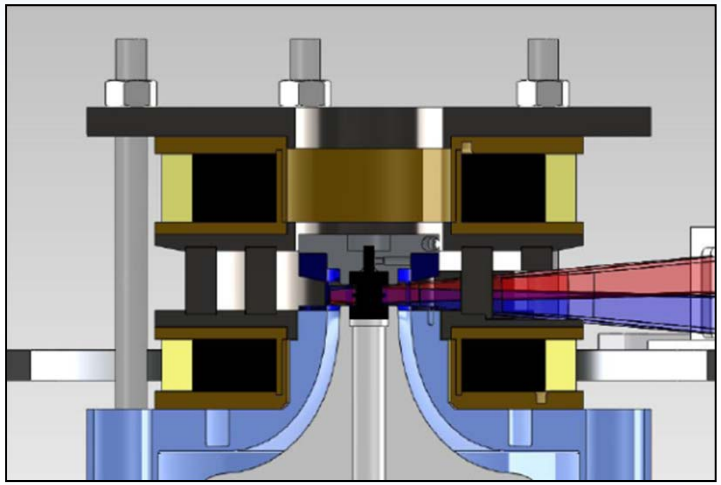


Standard Experimental Configuration

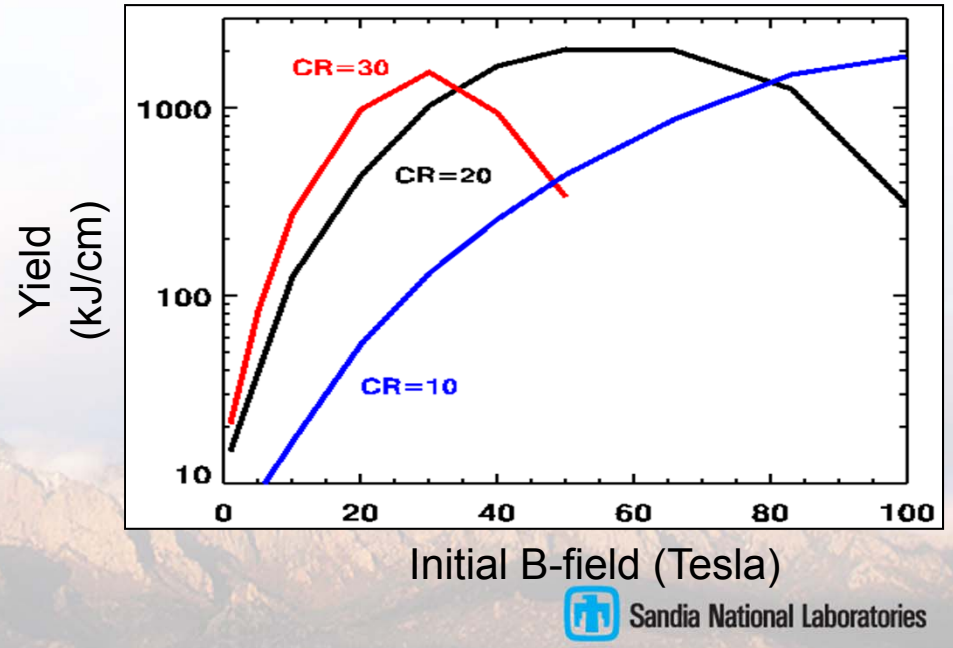


Field requirements for MagLIF

- **Modest field requirements of 1 – 10 T are required for initial experiments**
  - Test flux compression
  - Provide full access to diagnostics
  - Assess power feed loss with applied magnetic field



- **Ultimate field requirements for MagLIF are guided by theory***
  - 20 – 30T could produce interesting *DT-equivalent* yields on Z
  - Root for liner stability team to deliver CR = 30



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

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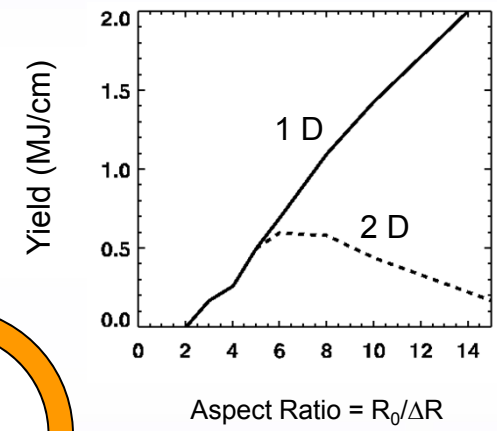
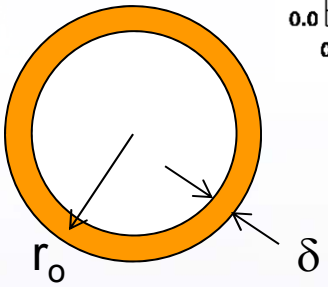
MagLIF pulse length and uniformity requirements

- **Physics requirements for uniformity have not been specified**
  - Point design goal < 1%
- **Pulse length requirements for MagLIF are determined by diffusion and target integrity**
  - Field needs to penetrate
  - Avoid crushing or buckling
    - Table lists minimum values for 30 T
- **Pulse length requirements for buckling may be most restrictive**

Aspect ratios of interest: 4 - 12





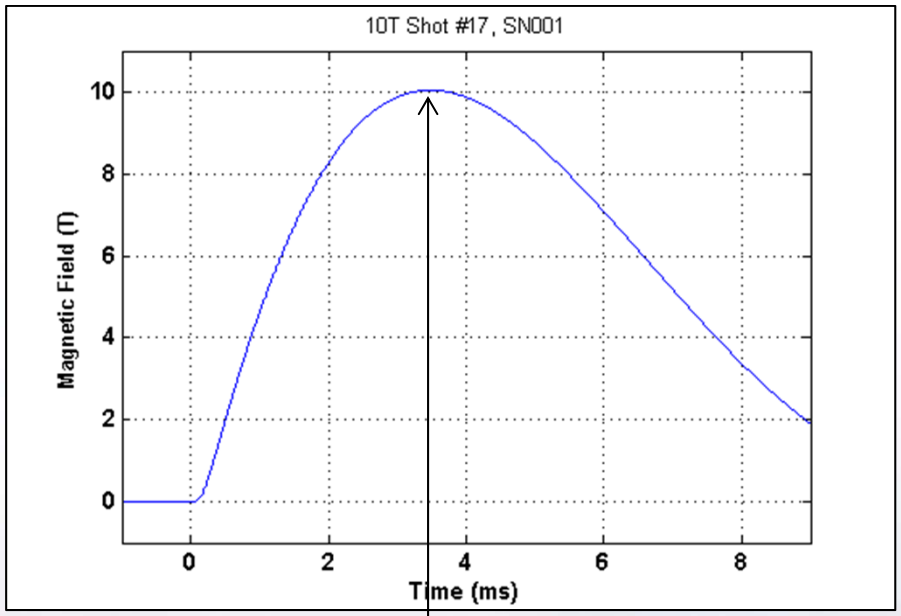
Material	Buckling t_p (ms) (r_o/δ=10)	Buckling t_p (ms) (r_o/δ=6)	Crushing t_p (ms)	Diffusion $t_p>4\tau_o$ (ms)
Be S-65H	0.35	0.09	0.38	0.11
Al 1100	2.26	0.48	0.84	0.16
Al 7075-T6	1.23	0.27	0.15	0.09

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

Engineering safety factors for MagLIF targets

- Time to peak for 10 Tesla point design = 3.49 ms (measured)
- Time to peak for 30 Tesla point design = 6.65 ms (estimated)
- Yield / buckling safety factors:
  - 82.7 / 89.7 for 10 T with Be
  - 37.4 / 13.9 for 10 T with Al-1100
  - 17.5 / 19.0 for 30 T with Be
  - 7.9 / 2.9 for 30 T with Al-1100
- Verify analysis with high fidelity experiments on Systems Integration Test Facility

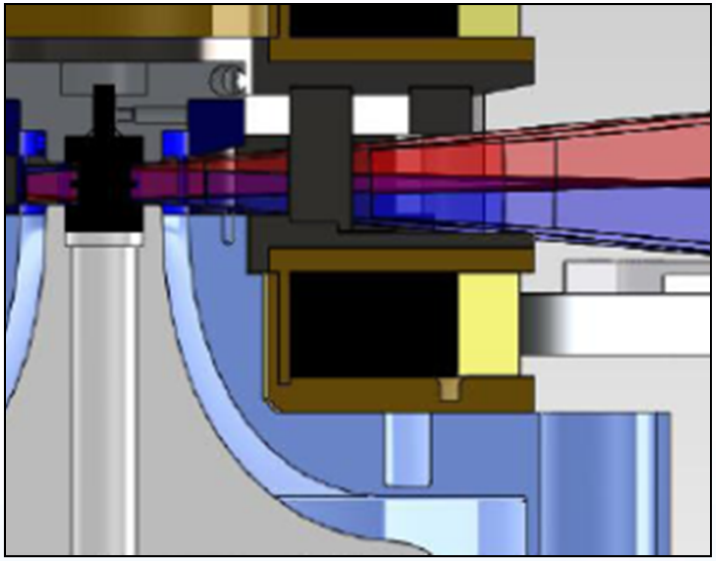
Measured 10 Tesla point design pulse
On-axis measured field



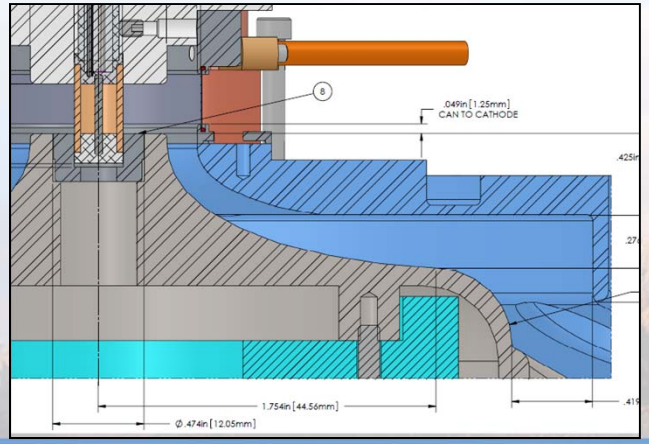
Time to peak field = 3.49 ms

In March we plan to assess the impact of the feed geometry change on feed loss and convolute loss

MagLIF feed geometry



Standard feed geometry



MagLIF inductance

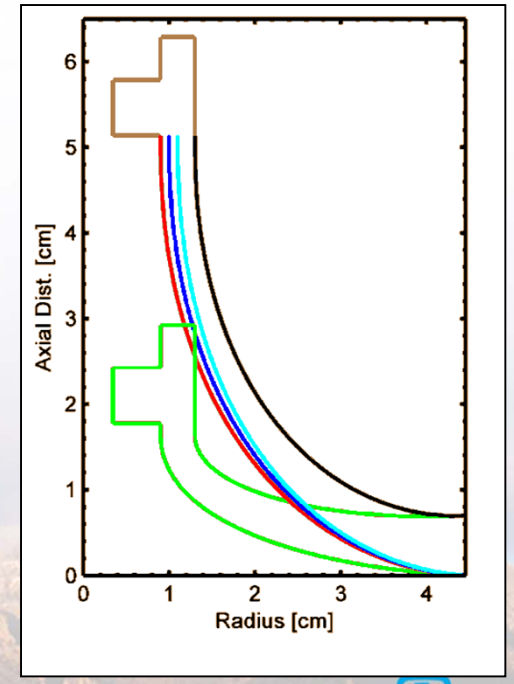
Feed 1: 5.52 nH (7 mm to 4 mm)

Feed 2: 4.82 nH (7 mm to 3 mm)

Feed 3: 4.18 nH (7 mm to 2 mm)

Standard feed inductance:

Feed = 3.97 nH (7 mm to 4 mm)



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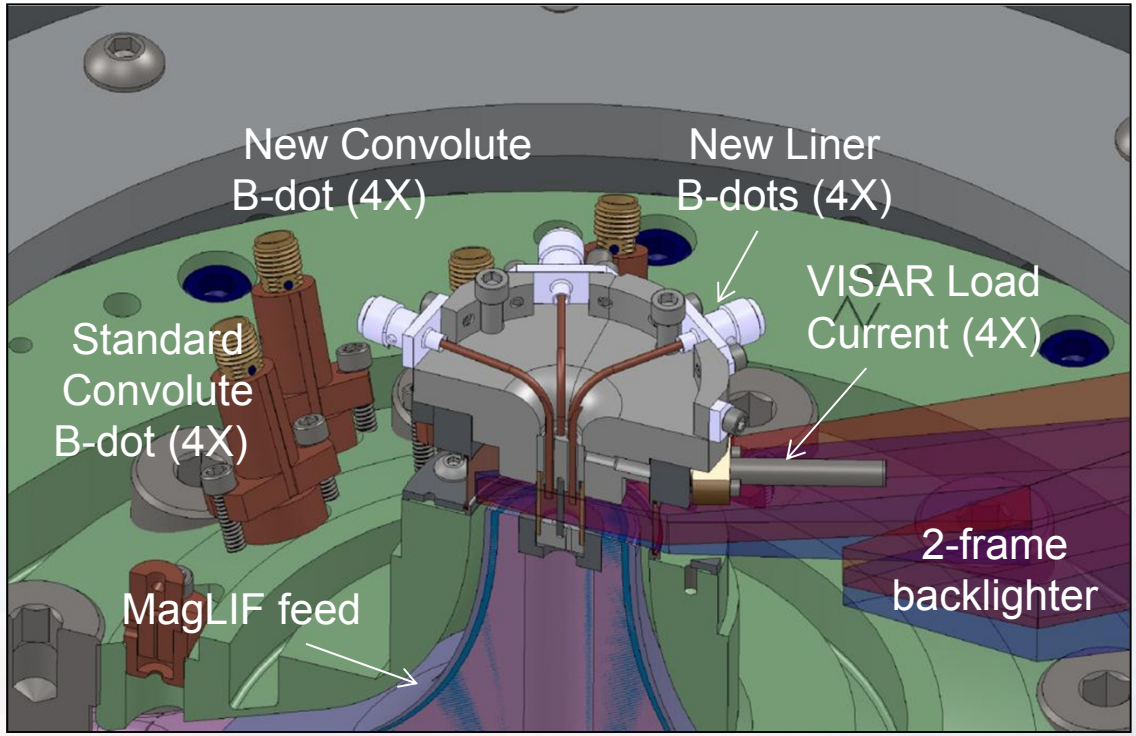
The experimental series in March is designed to assess current loss with the MagLIF feed geometry without magnetic coils

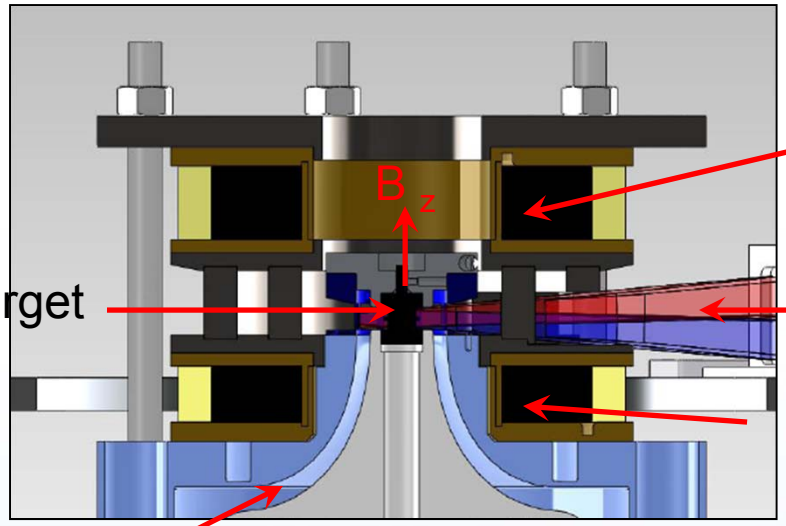
- Convolute loss measured by 8 B-dots
- Feed loss measured by load current VISAR and radiographic measurements of load position
- New liner B-dot monitors (John Greenly) will try to detect B_θ getting past the liner
- Plans are to use similar B-dots for initial flux compression measurements

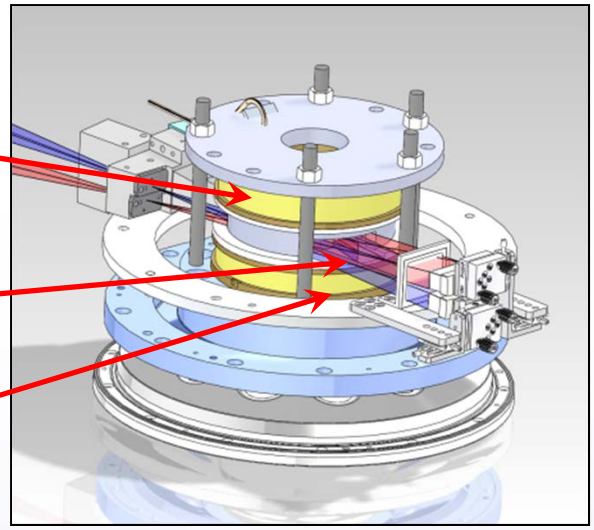


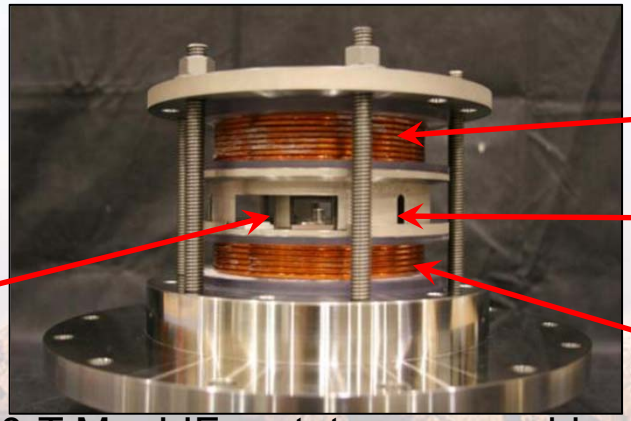
The load / target region is a busy place !

We have designed, fabricated, and tested a prototype 10-T MagLIF magnetic coil system

10 T MagLIF design with access for 2 frame backlighter







10-T MagLIF prototype assembly with test windings of coils

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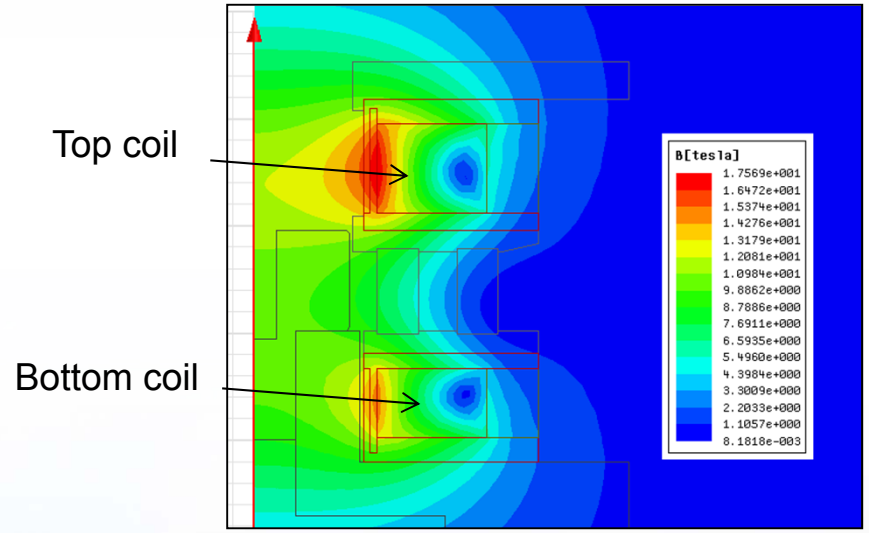
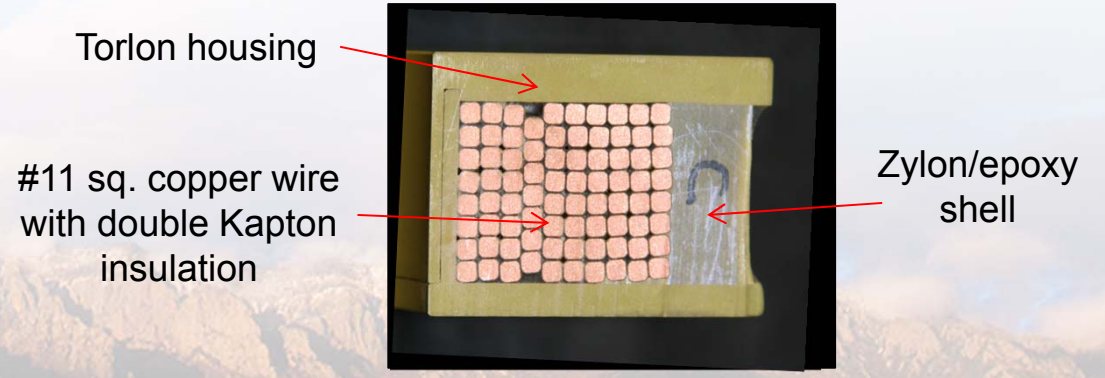
Engineering challenges for 10-T design (by the numbers)

- Peak field on the coils is 17.6 T
- Peak attractive force pulling the coils together:
  - 145 kN (33,000 lbf)
- Peak repulsive force pushing the coil assembly away from MITLs:
  - 25 kN (5,600 lbf)
- Peak equivalent radial pressure acting on the Zylon/epoxy composite shell:
  - 136 MPa (19,700 psi)
- Final coil temperature:
  - 88 deg. C

Plot of magnetic field for 10-T design



Cross section of un-shot top coil



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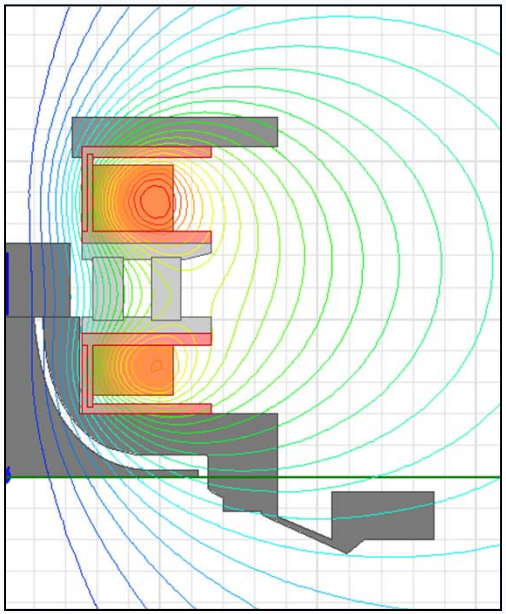
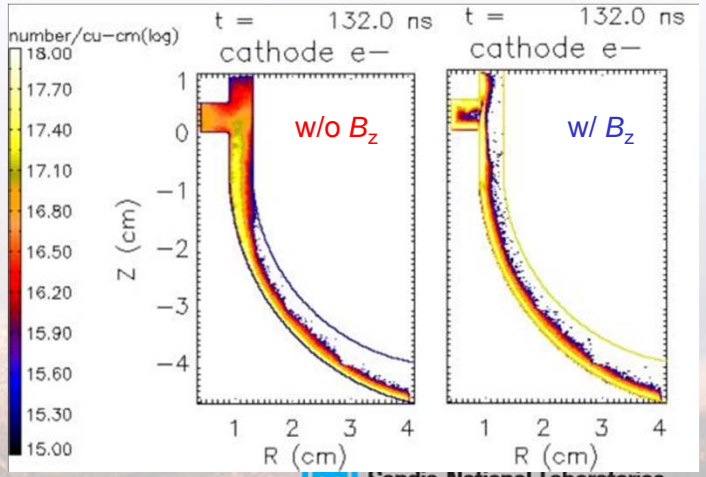
We do not believe that the applied magnetic field will cause significant additional feed loss

- **PIC simulations by Adam Sefkow suggest that there is not a problem**
  - Applied field may even help insulate
- **Electron flow in gap is small**
- **B_θ eventually >> B_z**
- **Early plasma formation tamped by B_θ pressure**





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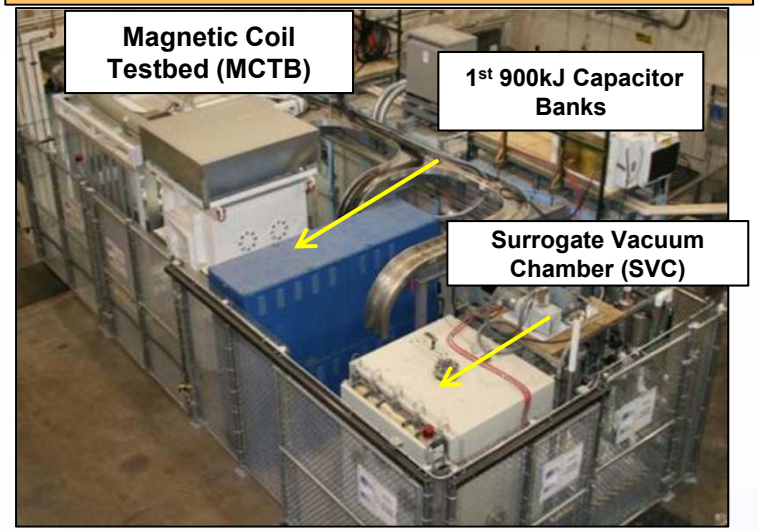
We have been using a 900 kJ capacitor bank to test the coils in our Systems Integrated Test Facility (SITF)

- **Two 900 kJ units allows for identical systems at Z and in 970**
  - 8mF, 15kV, 900kJ
- **We believe 900 kJ is enough to meet our short and long term goals**
- **SITF has a large robust coil test bed for testing coils to failure**
- **The vacuum chamber will be used to do high fidelity experiments**
  - Large enough to hold convolute hardware and 2 ft. transitions

The SITF Testbed in Bldg. 970



2nd 900 kJ bank ready for 983

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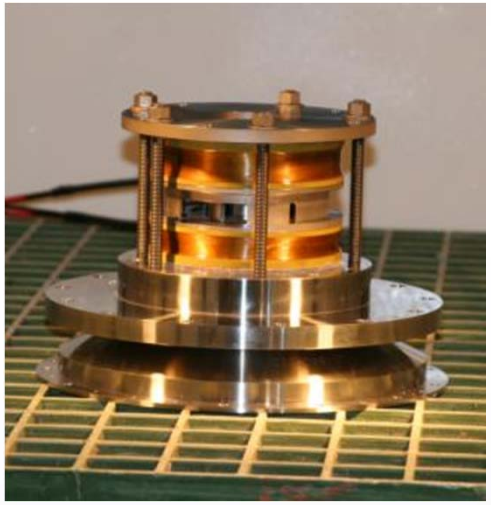
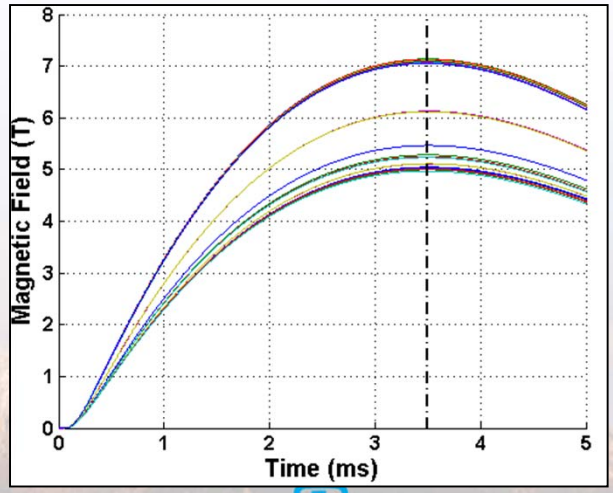
Recently we starting characterizing the lifetime and reliability of our 10-T prototype design

- **Three 10-T MagLIF coil pair prototypes have been built and tested**
  - SN001 failed after 17 pulses at 10 T
  - SN002 failed on 2nd 10-T pulse
    - Early failure likely caused by fabrication issues
  - SN003 had similar fabrication issues
    - To date, successfully tested for 37 pulses
    - 25 @ 5 T
    - 2 @ 6 T
    - 10 @ 7 T

- **On-axis field measurements show timing and magnitude are very repeatable for given charge voltage**
  - SN003 data
  - 7-T data are all at 3.9 kV

10-T MagLIF prototype in SITF test chamber





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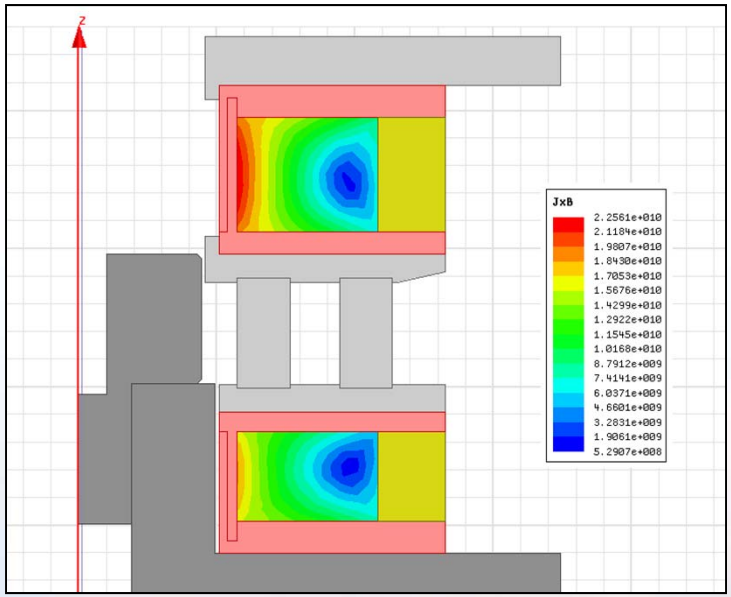
Based on a simple jxB loading comparison, we believe the 10-T geometry ~ 20 T with no access

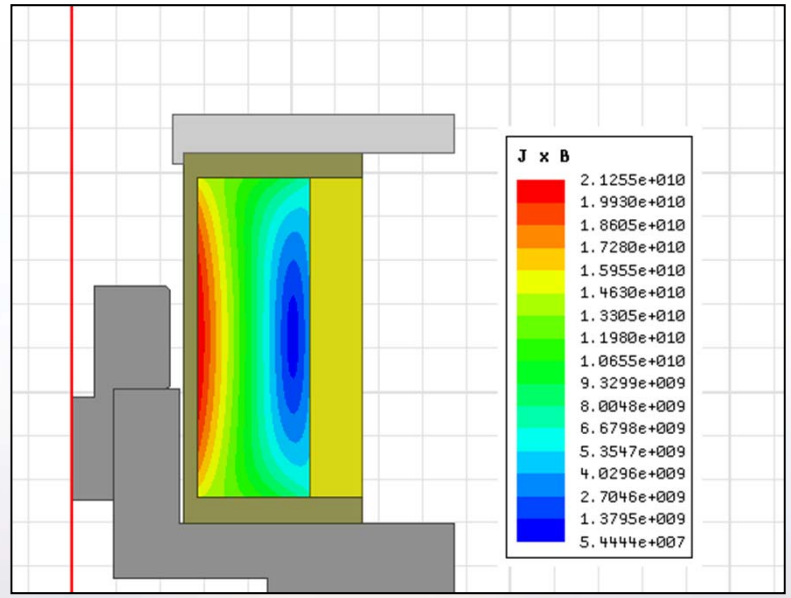
Plot of jxB loading on coils for 10-T “full-access” design

Peak = 2.26 x 10^{10} N/m^3



Plot of jxB loading on coils for 20-T design “no-access” design

Peak = 2.13 x 10^{10} N/m^3



Higher reliability and higher fields will require us to reinvigorate our coil engineering efforts

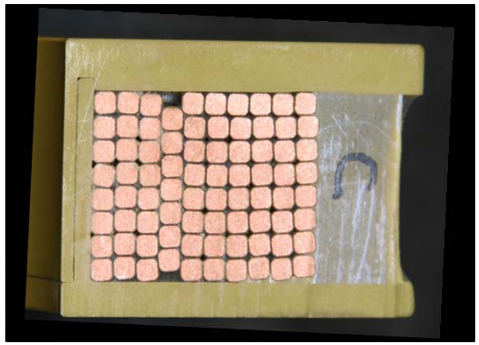
Short-term

- **Need more experience**
  - Coil failures can be subtle
- **Need to improve our fabrication techniques**
  - SN002 that failed on 2nd 10-T pulse had known fabrication issues
- **Need to eliminate epoxy voids in the coil winding**

Longer-term

- **Need more mechanical design analysis, e.g. FEA**
- **Need to consider using high field design techniques**
  - Stronger wire, e.g. Glidcop, CuNb
  - Nested coil construction
  - Internally reinforced coil

Un-shot top coil cross section



Cross sections of SN001

Bottom coil suffered soft electrical failure during 18th 10-T pulse

Top coil

Bottom coil

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Summary

- **We have established an integrated test facility for developing and testing our coil systems**
  - Uses identical capacitor bank system planned for Z
- **We have developed and tested a 10-T prototype design with diagnostic access**
  - We believe it is solid at 7 T
  - More development/necessary to qualify at 10-T
- **We believe that using this same coil technology we can achieve 20 T in a no access design**
- **Increasing the reliability and getting to higher fields will require us to reinvigorate our coil engineering and development efforts**

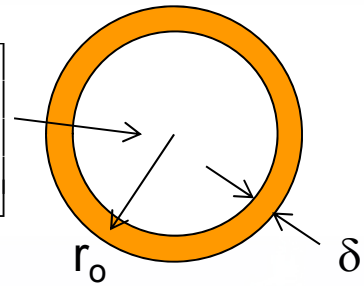
Backup Slides

Will the magnetic field penetrate the MagLIF fusion targets?

Internal field

$$B_i = \frac{B_o}{1+(\tau_o \frac{\pi t}{2t_p})^2}\left[\sin\frac{\pi t}{2t_p} + \frac{\pi\tau_o}{2t_p}\left(\exp^{-\frac{t}{\tau_o}} - \cos\frac{\pi t}{2t_p}\right)\right]$$

$$\tau_o = \frac{1}{2}\mu_o r_o \delta \sigma_e$$



External field

$$B_e = B_o \sin\frac{\pi t}{2t_p}$$

r_o = 3.18e-03 m
δ = 5.9e-04 m

Requirement for time to peak field t_p for < 1% loss from field penetration: $t_p > 4\tau_o$

Material	σ_e	τ_o (μs)	$t_p > 4\tau_o$ (ms)
Be S-65H	2.33e7	27	0.11
Al 1100	3.33e7	39	0.16
Al 7075-T6	1.92e7	22	0.09

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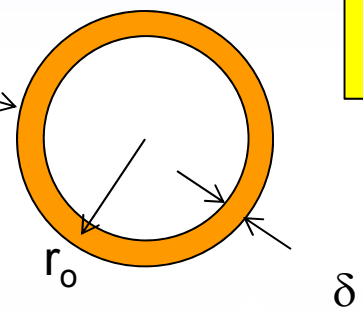
Will the magnetic field deform or crush the MagLIF fusion targets?

Peak magnetic pressure

$$P_{mag} \le \frac{B_o^2}{2\mu_o}\frac{\pi\tau_o}{2t_p}$$

$$\tau_o = \frac{1}{2}\mu_o r_o \delta \sigma_e$$

Approx. valid for $\pi\tau_o/(2t_p) \le 1$



Mechanical yield stress on thin wall cylinder

$$P_Y = \sigma_Y \frac{\delta}{r_o}$$

$$P_Y \ge P_{mag}$$

$$t_p \ge \frac{\pi}{8} B^2 r_o^2 \frac{\sigma_e}{\sigma_Y}$$

Requirement on time to peak field t_p for $P_Y > P_{mag}$ (30 Tesla)

Material	σ_e	σ_Y (MPa)	t_p (ms)
Be S-65H	2.33e7	217	0.38
Al 1100	3.33e7	141	0.84
Al 7075-T6	1.92e7	453	0.15

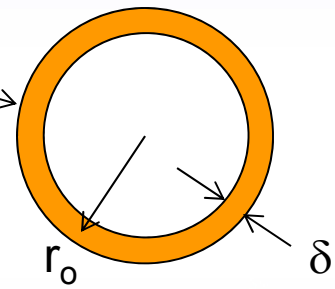
Mechanical yield much more restrictive than field penetration

Will the magnetic field pressure cause a buckling instability on the MagLIF fusion targets?

Peak magnetic pressure

$$P_{mag} \le \frac{B_o^2}{2\mu_o}\frac{\pi\tau_o}{2t_p}$$

$$\tau_o = \frac{1}{2}\mu_o r_o \delta \sigma_e$$



Buckling stress on thin wall cylinder

$$P_B = f\,\frac{1}{4}\frac{E}{1-\nu^2}\left(\frac{\delta}{r_o}\right)^3$$

f~0.5 for real items

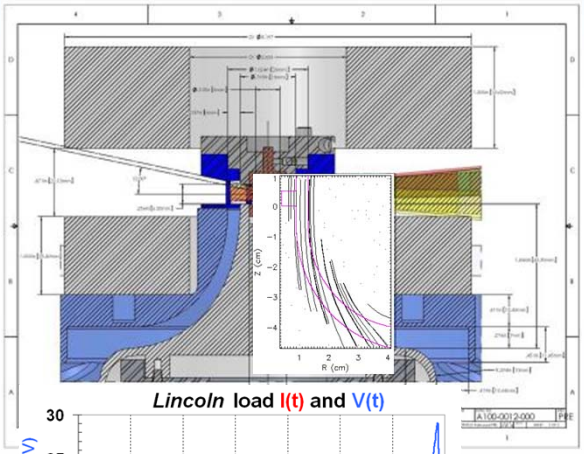
$$P_B \ge P_{mag}$$

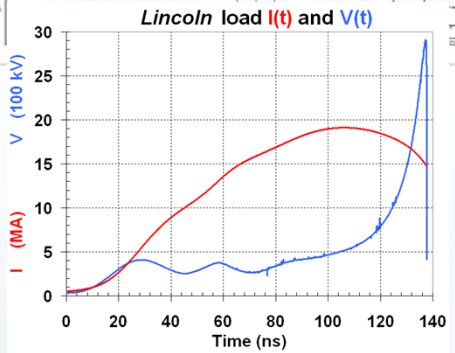
Requirement on time to peak field t_p for $P_B > P_{mag}$ (30 Tesla, f = 0.5)

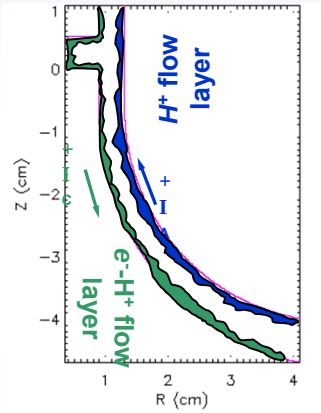
Material	σ_e	E (GPa)	ν	t_p (ms) (r_o/δ=10)	t_p (ms) (r_o/δ=6)
Be S-65H	2.33e7	303	0.12	0.35	0.09
Al 1100	3.33e7	69	0.33	2.26	0.48
Al 7075-T6	1.92e7	71.5	0.33	1.23	0.27

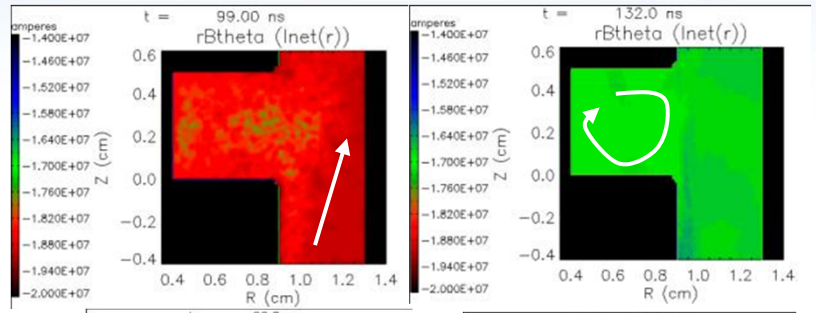
Buckling could be more restrictive than field penetration or yield

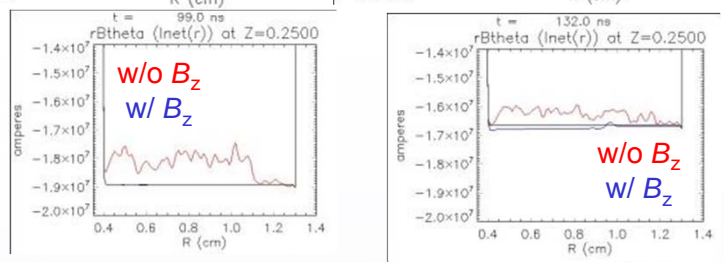
PIC simulations predict no significant current loss in MagLIF feed due to external B_z field

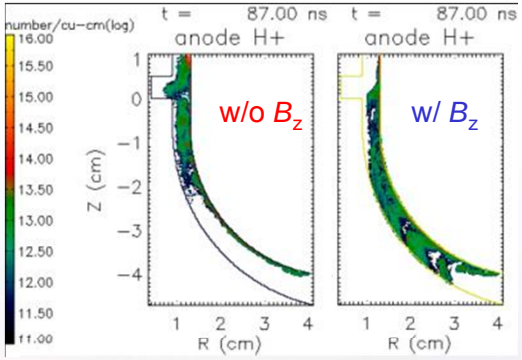


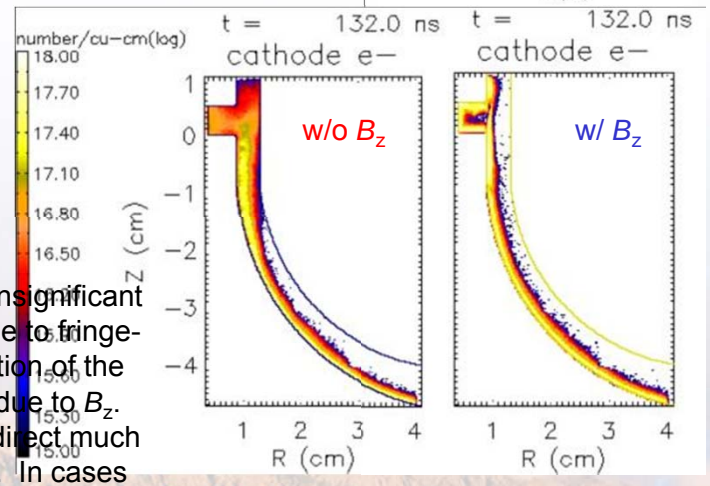












MODEL: Fully explicit and electromagnetic, 3D {r,θ,z}, collisional, neutral desorption from conductors, energy deposition and heating of electrodes, solenoid B_z

PARTICLE SOURCES: [1] Field-stress space-charge-limited e^- emission (from K); [2] Neutral H^0 thermal desorption of adsorbed monolayers at 1 ns^{-1} (rate needs to be measured); [3] Ionization of e^- H^- plasma; [4] Thermal H^+ ion emission (from A) at T=400K.

PREDICTIONS so far: Insignificant early-time power loss due to fringe-fields. Magnetic insulation of the A-K plasma is not lost due to B_z. A-K plasma does not redirect much current away from load. In cases without B_z where shorting occurs due to A-K plasma, the case with 30T B_z does not short and late-time losses are suppressed. Back EMF may enhance late current ($dI/dt<0$).

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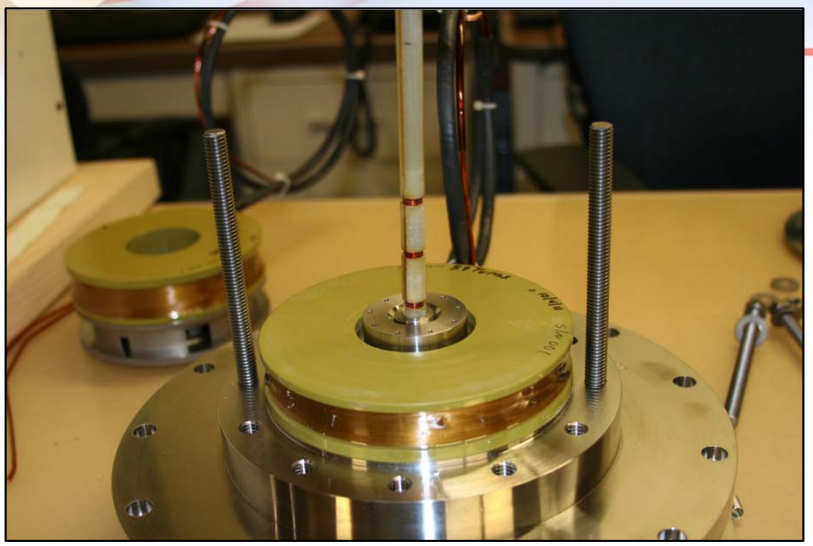
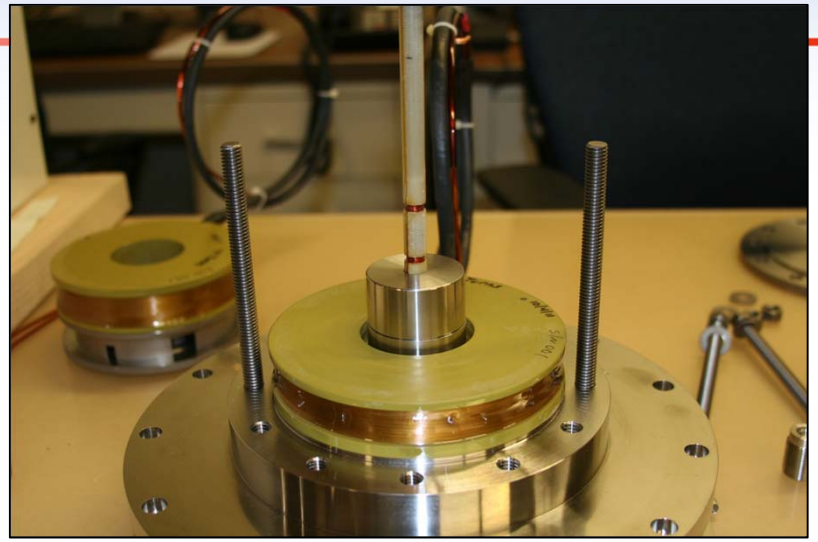
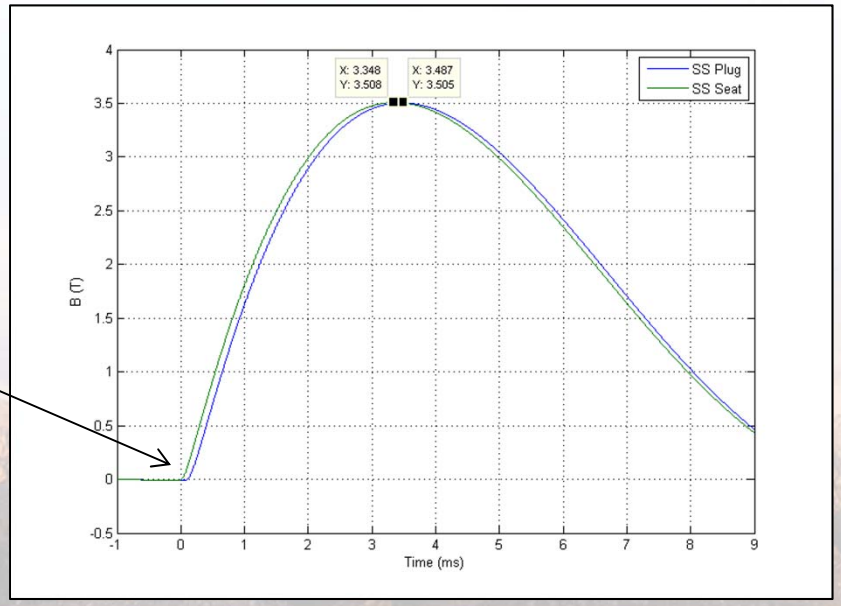
Test configuration without SS Plug



Test configuration with SS Plug



On-axis measured field shows diffusion delay due to SS plug



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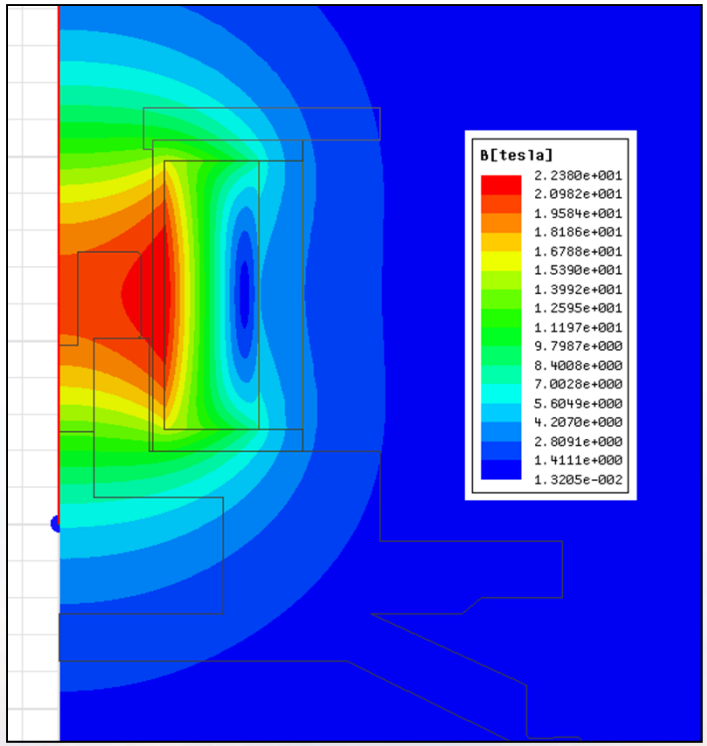
Magnetic field plot of 20-T point design

Peak field at coil inner radius is 22.4 T