SAND2016-0296C

Development of a Cryogenically-Cooled Platform for Magnetized Liner Inertial Fusion (MagLIF) Experiments

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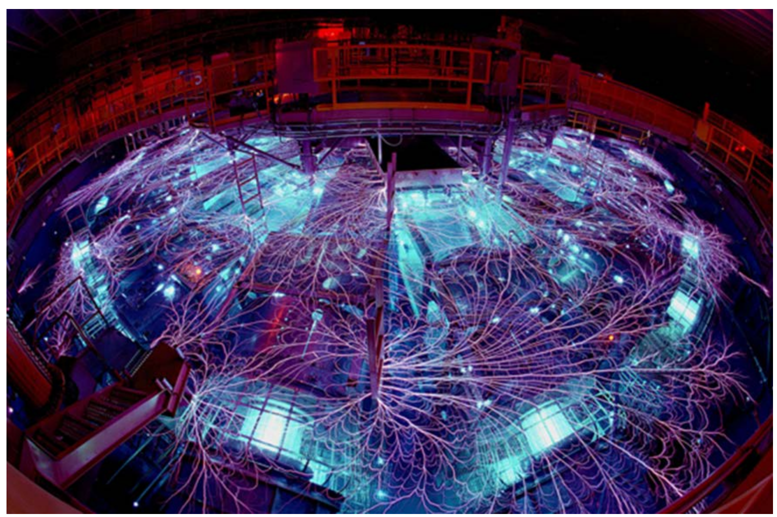

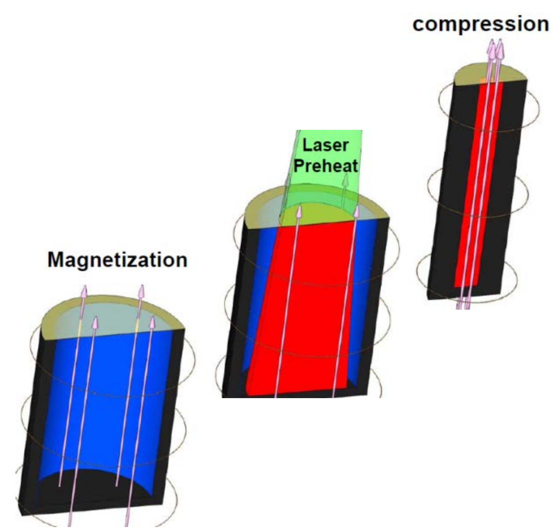

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Many thanks to those who have contributed to this ongoing work

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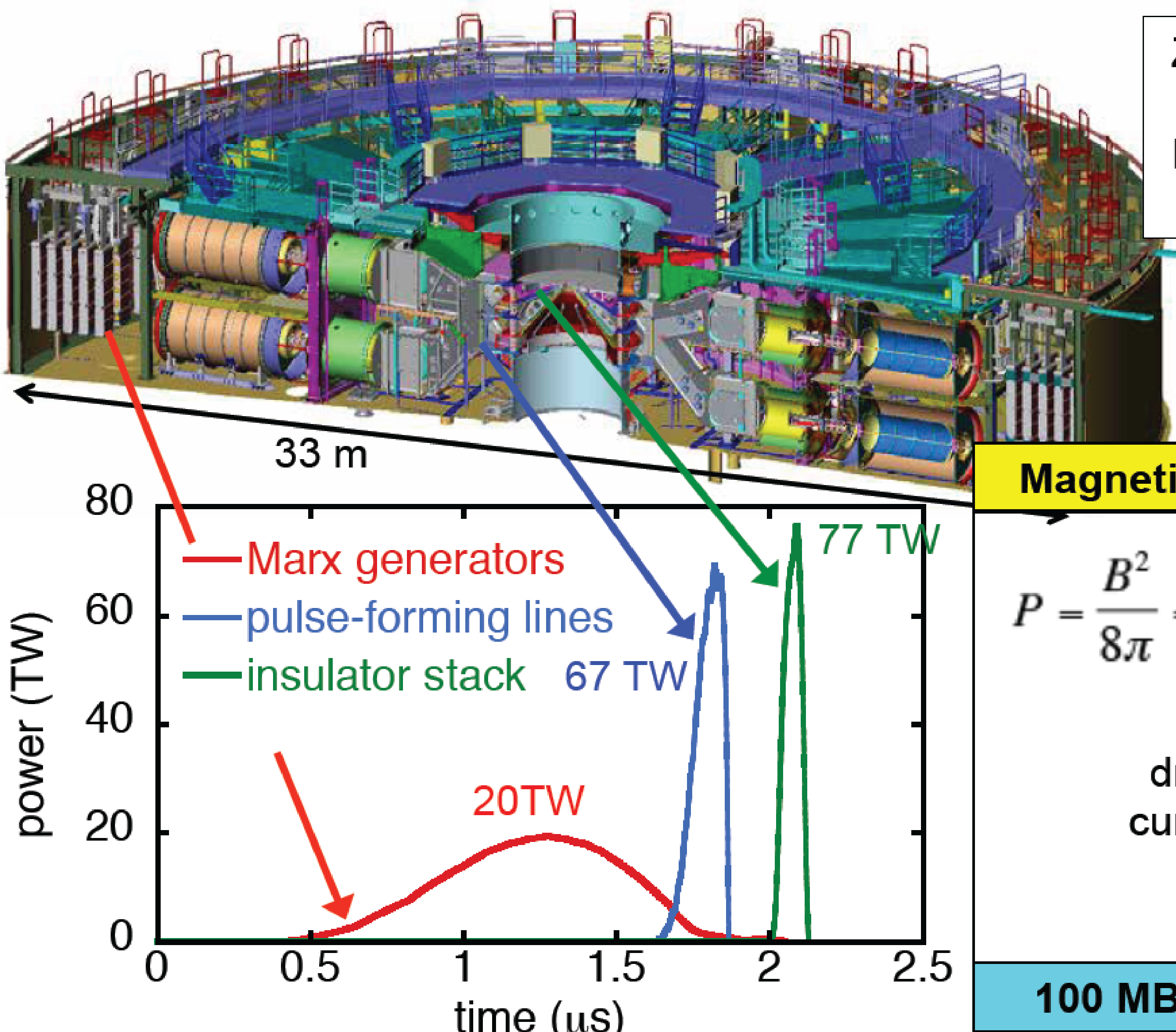
Presentation Outline

- Overview of the MagLIF concept
- Enabling infrastructure and scientific advancements
- Results from initial experiments with low preheat-energy coupling
- Results from experiments with increased laser energy
  - → *Motivation for cryogenic platform*
    - → *Unique challenges*
- Preliminary cryogenic hardware design and performance

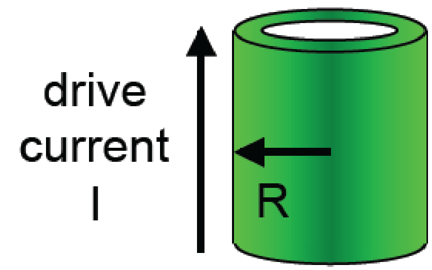
"Magnetic direct drive" is based on the idea that we can efficiently use large currents to create high pressures



Z today couples ~0.5 MJ out of 20 MJ stored to MagLIF target (0.1 MJ in DD fuel).

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

(1 atm = 1 bar = 10^5 Pascals)

We are evaluating a Magnetized Liner Inertial Fusion (MagLIF)* concept that is well suited to pulsed power drivers and that may reduce fusion requirements

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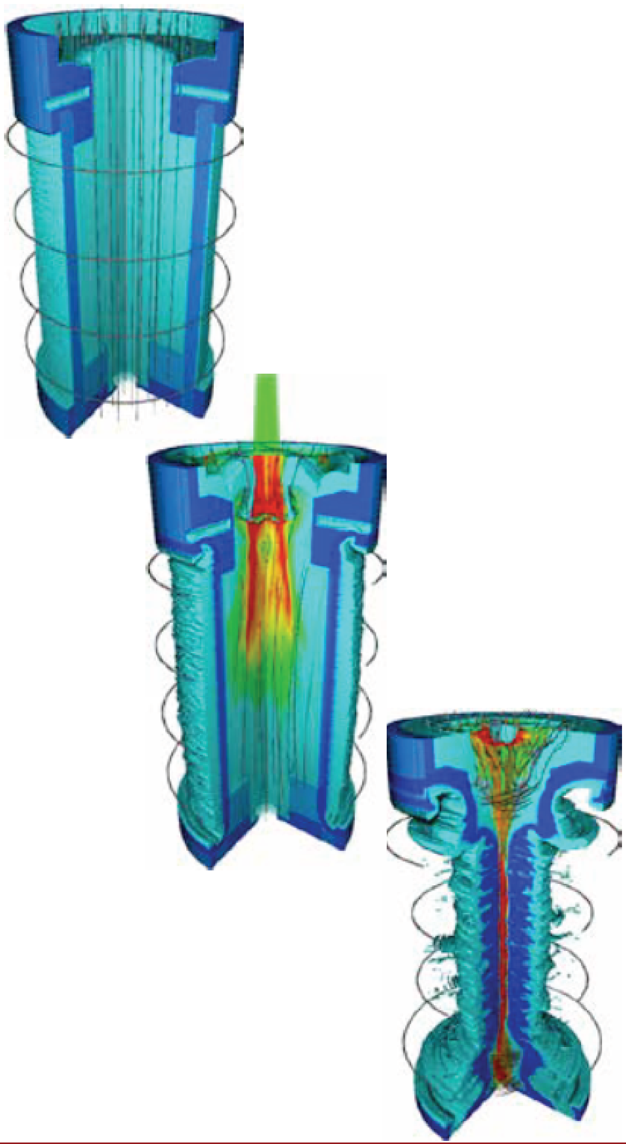


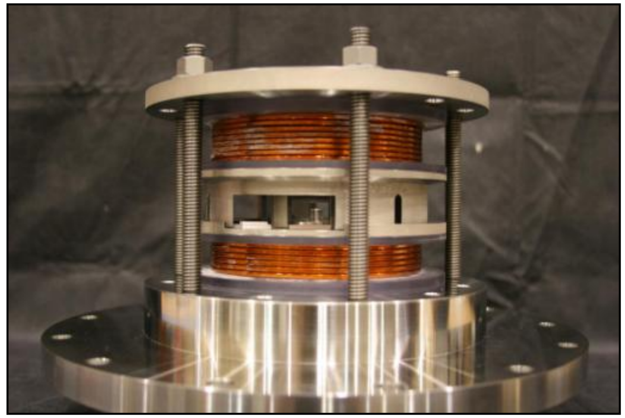
- Axial magnetization of fuel/liner (B_{z0} = 10-30 T)
  - Inhibits thermal conduction losses, may help stabilize liner compression, ions magnetized too (β: 5~80; $\omega\tau$>200)
- Laser heating of fuel (2-10 kJ)
  - Reduces amount of radial fuel compression needed to reach fusion temperatures (R_0/R_f = 23-35)
- Liner compression of fuel (70-100 km/s, ~100 ns)
  - "Slow", quasi-adiabatic compression of fuel
  - Low velocity requirements allow use of thick liners ($R/\Delta R$~6) that are robust to instabilities (need sufficient ρR at stagnation to inertially confine fuel)
- Combination allows fusion at ~100x lower fuel density than traditional ICF (~5 Gbar vs. 500 Gbar)
- DD equivalent of 100 kJ DT yield may be possible on Z in future—requires upgrades from our initial setup e.g., 10 T → 30 T; 2 kJ → >6 kJ; 19 MA → >24 MA

*S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

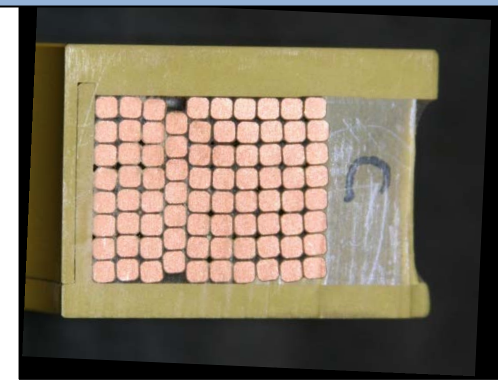
B_z=10 T coils maintain full diagnostic access. Higher fields can be applied (B_z=30 T), but diagnostic access is reduced

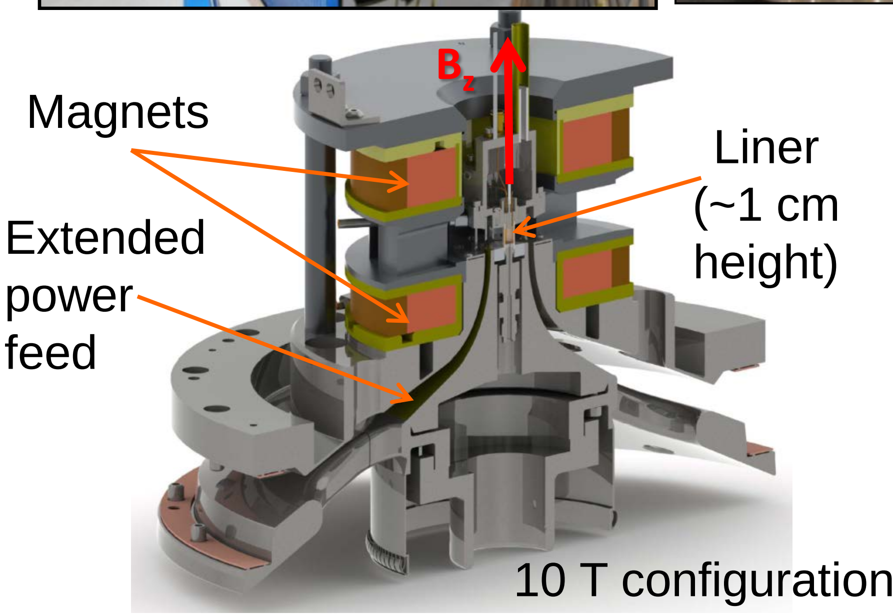
Capacitor bank system on Z
900 kJ, 8 mF, 15 kV (Feb. 2013)

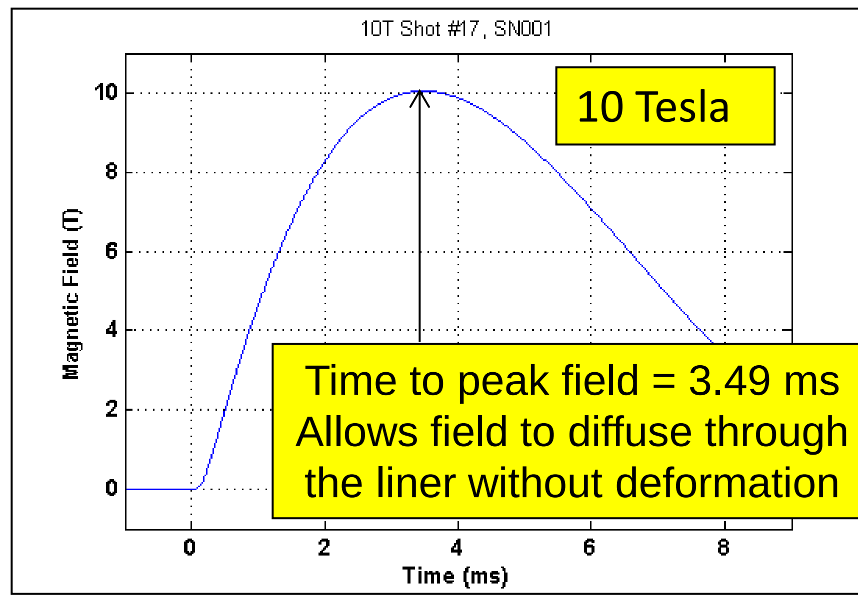
Example MagLIF coil assembly with copper windings visible



Cross section of coil showing Cu wire, Torlon housing, and Zylon/epoxy reinforcement

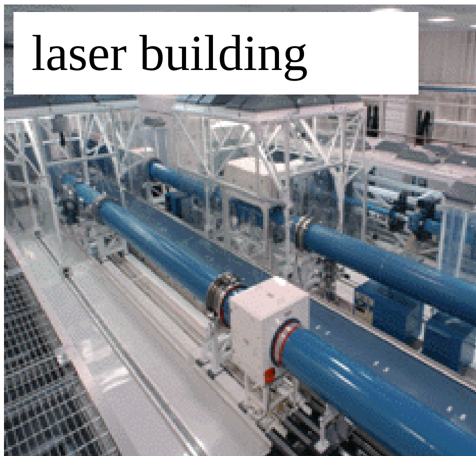






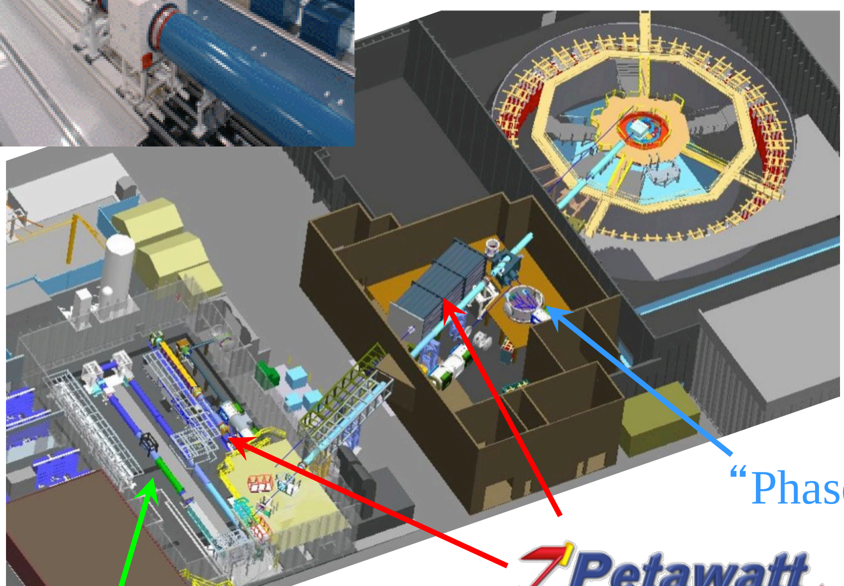
D.C. Rovang, D. Lamppa *et al.*, Rev. Sci. Instrum. (2014).

The Z-Beamlet Laser (ZBL) is primarily used for radiography, but can be used to pre-heat fusion fuel

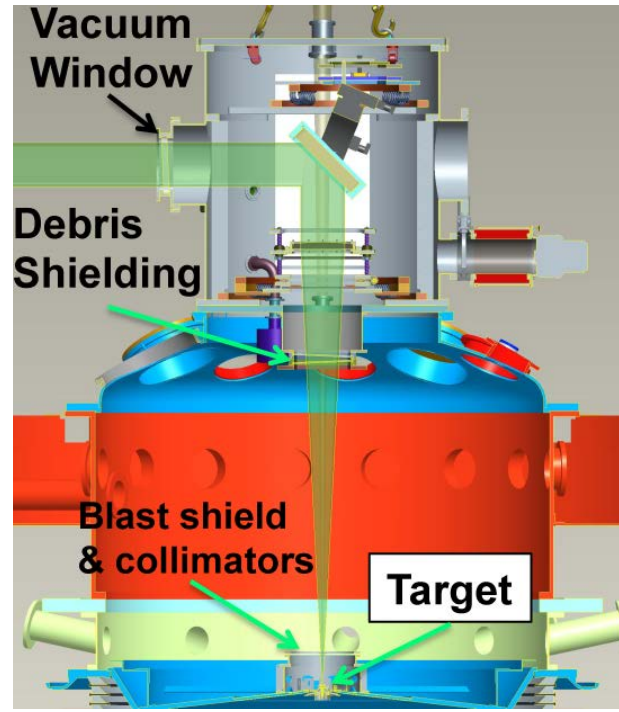


ZBL routinely used to deliver ~2.4 kJ of 2ω light in 2 pulses for target radiography

Recent upgrade—now delivers 4 kJ (2ω) in 4 ns



A new vacuum FOA protect ZBL from implosion generated debris

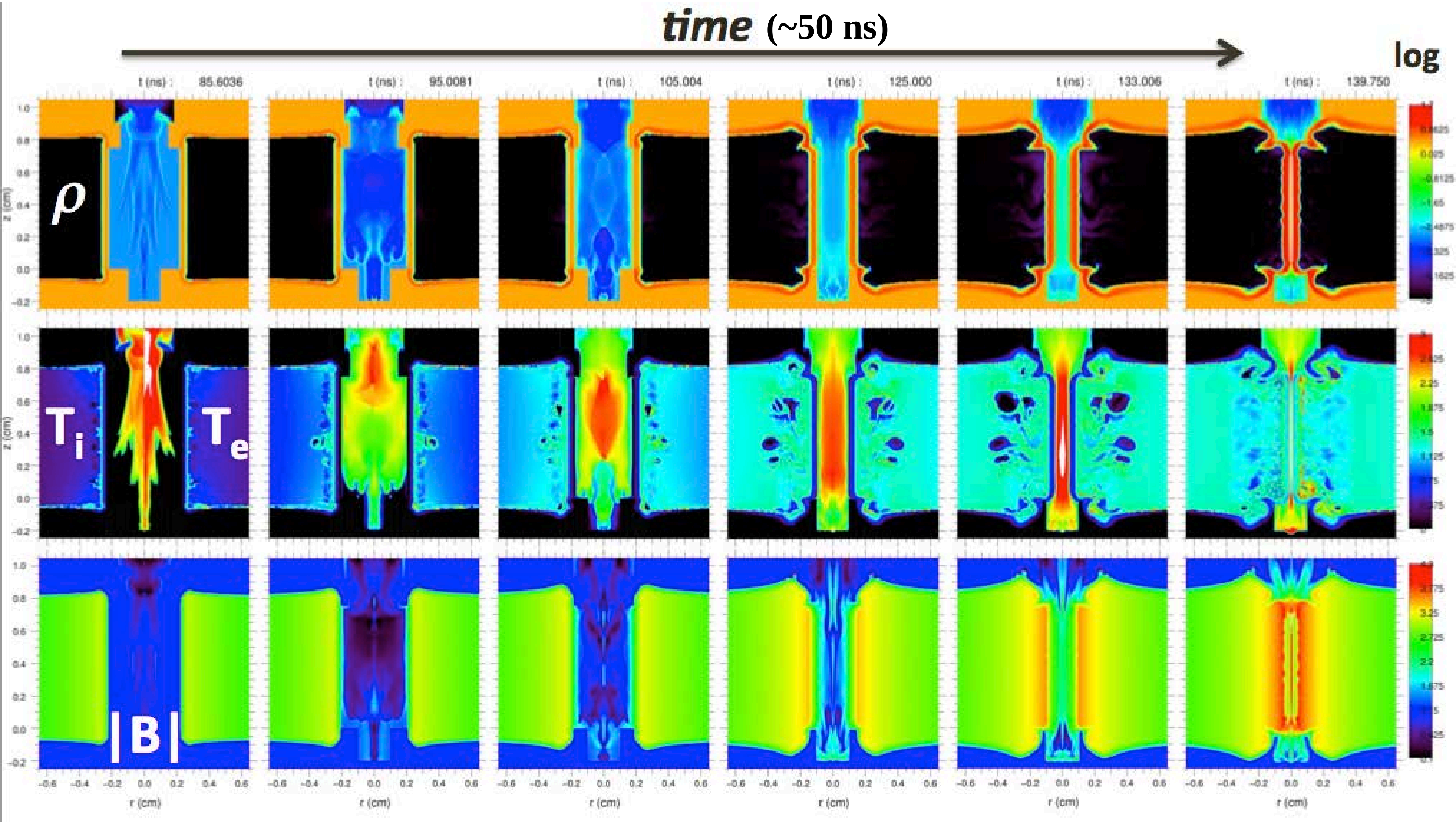


Future Advancements (in progress):

- Laser wavefront smoothing
- Higher energy delivery (6-8 kJ)
- Enhanced beam pointing precision
- Laser backscatter diagnostics
- Z-Petawatt co-injection

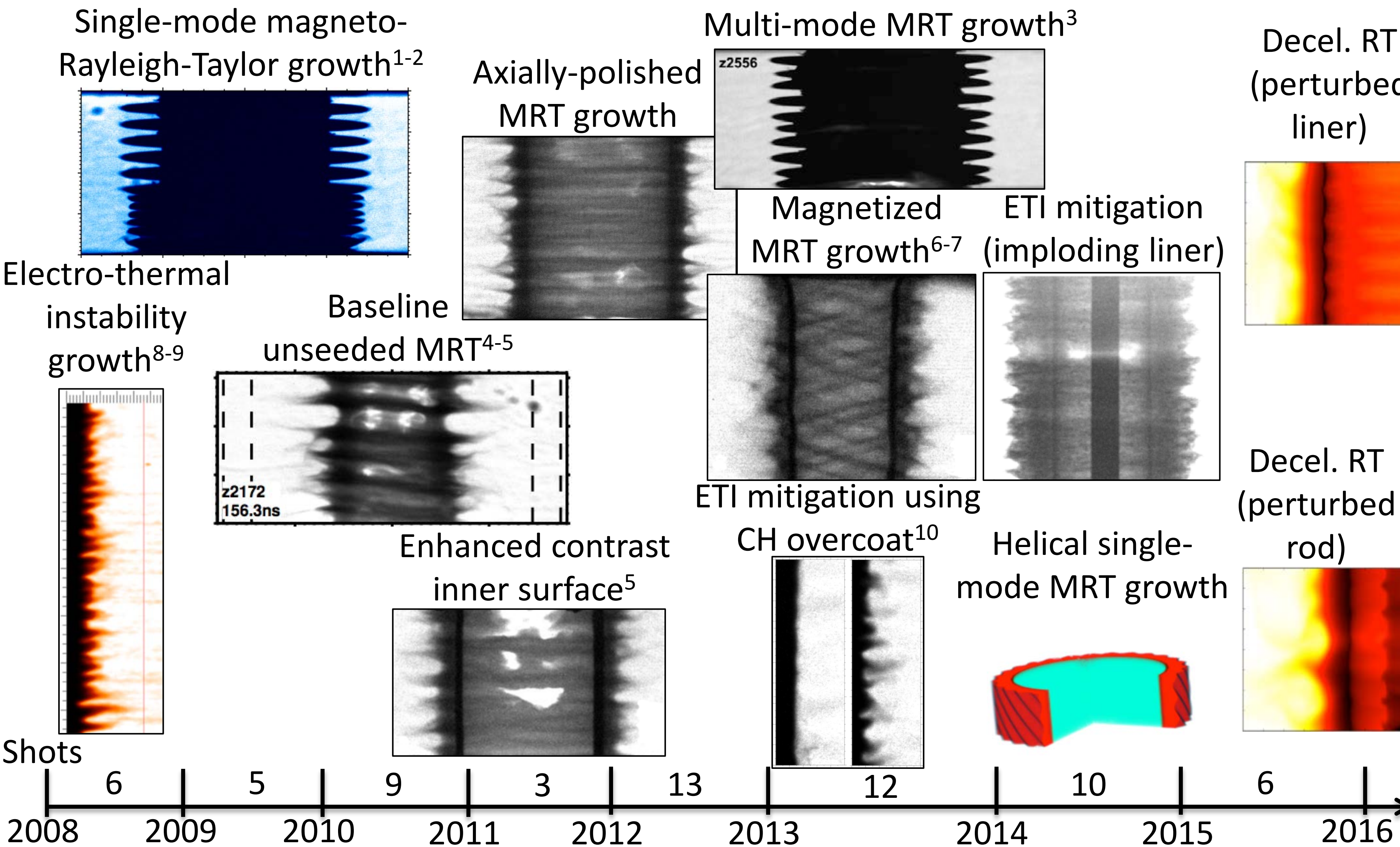
* P. K. Rambo *et al.*, Applied Optics **44**, 2421 (2005).

HYDRA calculations of near-term Z experiments (19 MA, 10 T, 2 kJ) illustrate the stages of a MagLIF implosion



A.B. Sefkow, S.A. Slutz *et al.*, Phys. Plasmas 21, 072711 (2014).

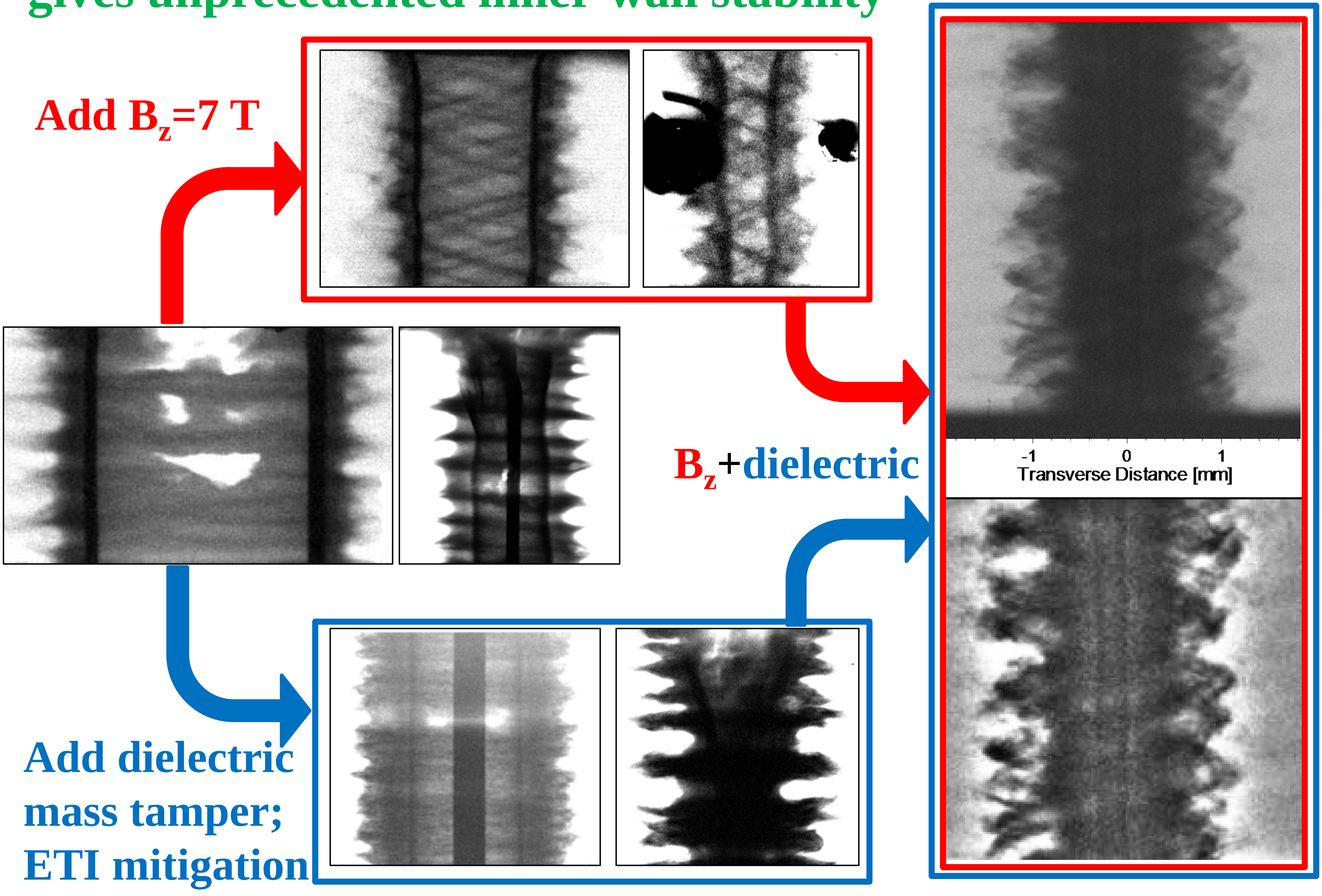
Our biggest uncertainty in 2008 was our ability to model liner dynamics—Rapid progress has been made in our ability to **study, modify, and mitigate** MHD instabilities



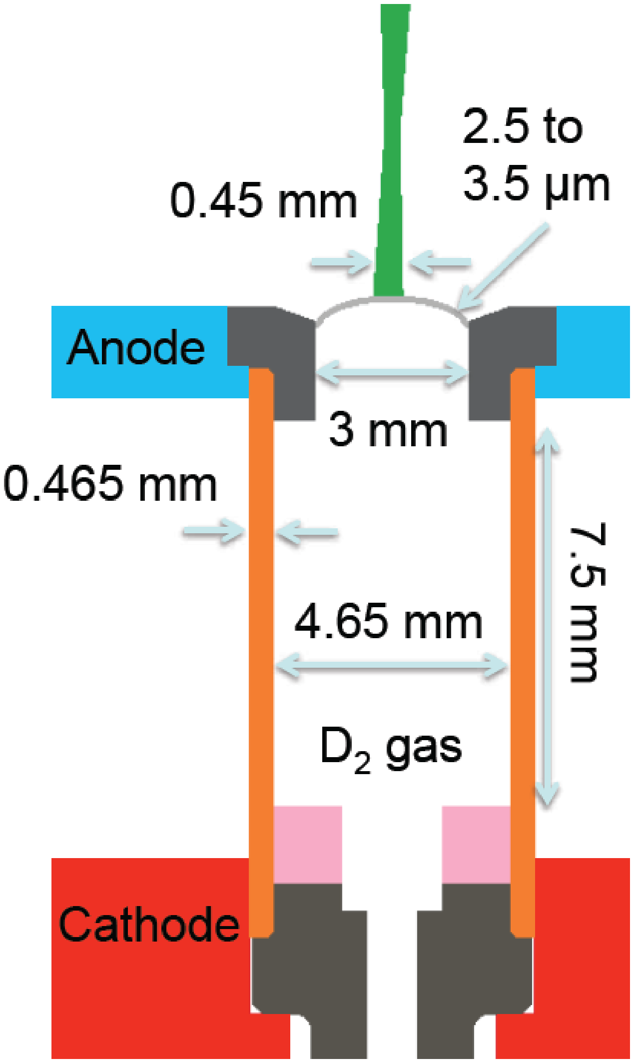
Publications to date include 4 PRLs, 5 PoPs, more in prep.

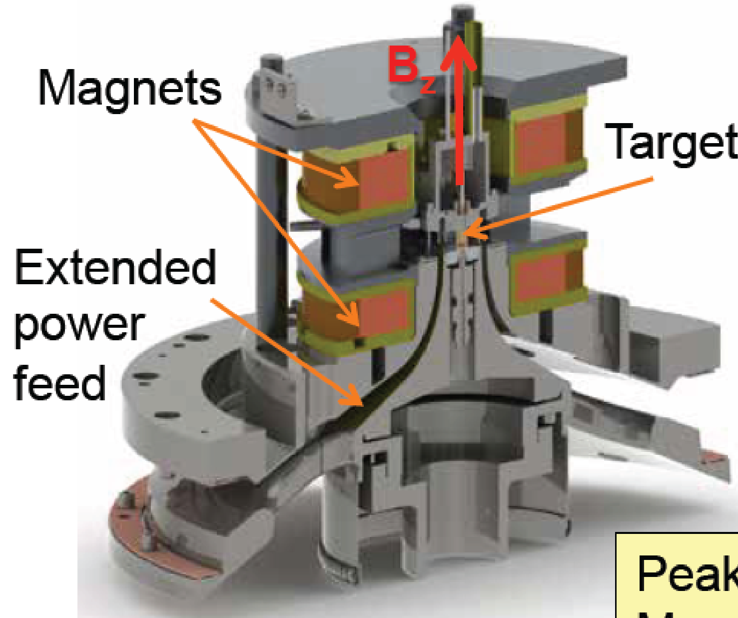
B_z with mass tamping (ETI mitigation) gives unprecedented inner-wall stability

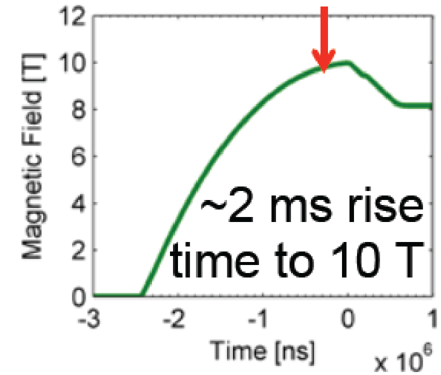
$CR=R_{in}(t=0)/R_{in}(t)=21$!



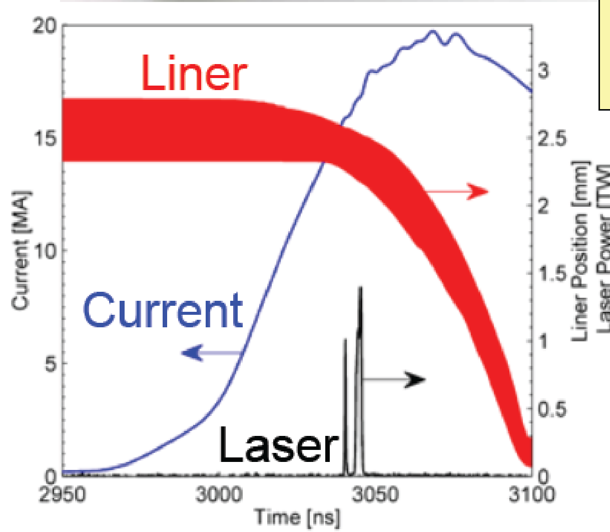
The initial experiments used 10 T, 2.5 kJ laser energy, and 19-20 MA current to drive a D_2 filled (0.7 mg/cc) Be liner

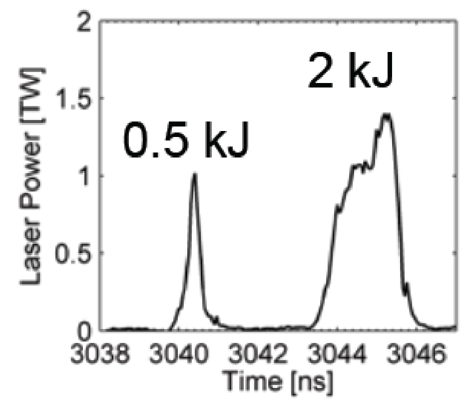






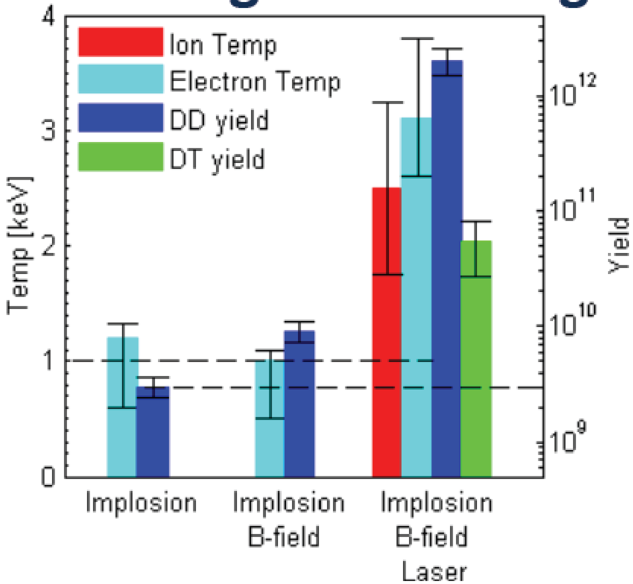
Peak current is 19 MA
Magnetic field is 10 T
Total laser energy is 2.5 kJ

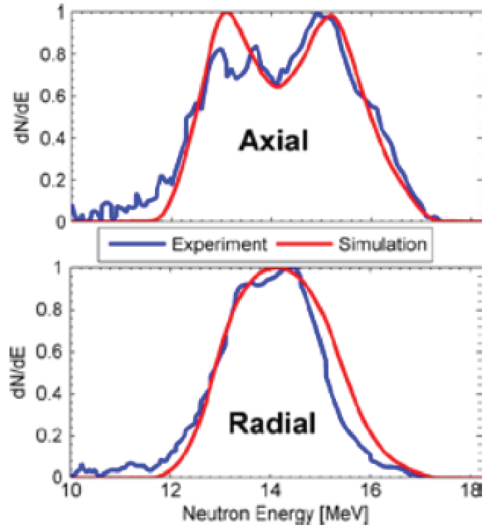


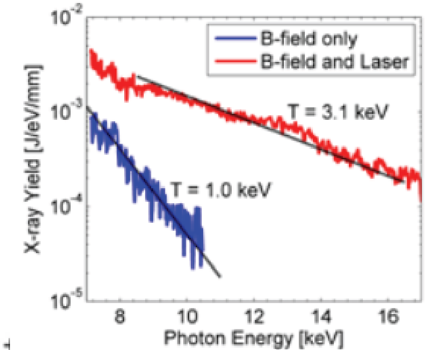


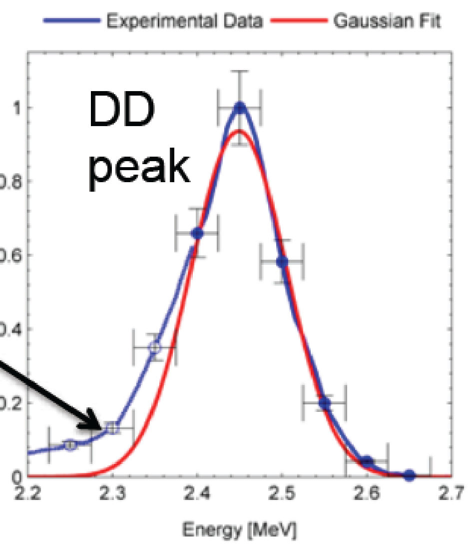
M.R. Gomez *et al.*, Phys. Rev. Lett. 113, 155003 (2014).

Our initial MagLIF experiments successfully demonstrated fusion yield consistent with a thermonuclear origin and with significant magnetization of the fusing plasma

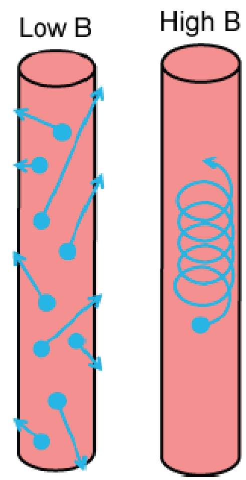


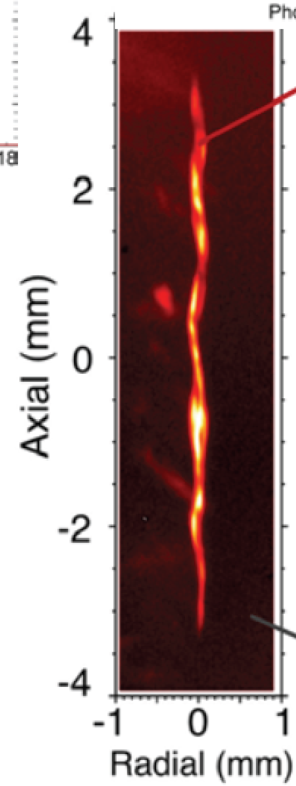






n scatter off Be liner around hot fuel





Stagnating plasma

$\langle T \rangle = 3 \pm 0.5$ keV

$T(r) = T_0[1 - (r/R)^2]$

$t_{burn} = 1.5 \pm 0.5$ ns

$f_{Be} = 5 \pm 3$ %

$z = 5 \pm 2$ mm

$R = 50 \pm 20$ µm

$\rho_D = 0.3 \pm 0.1$ g/cm^3

$P(z) = 1 \pm 0.2$ Gbar

$\rho R \sim 1.5$ mg/cm^2

$BR \sim 0.4$ MG·cm

Confining liner

$\rho r_{liner} = 0.9$ g/cm^2

M.R. Gomez *et al.*, Phys Rev Lett 113, 155003 (2014); P.F. Schmit *et al.*, Phys Rev Lett 113, 155004 (2014).

After early experiments, target performance plateaued

Lower than predicted coupling of laser energy to the fusion fuel was a leading hypothesis: Original MagLIF data can be modeled by assuming no mix and 200-300 J in fuel

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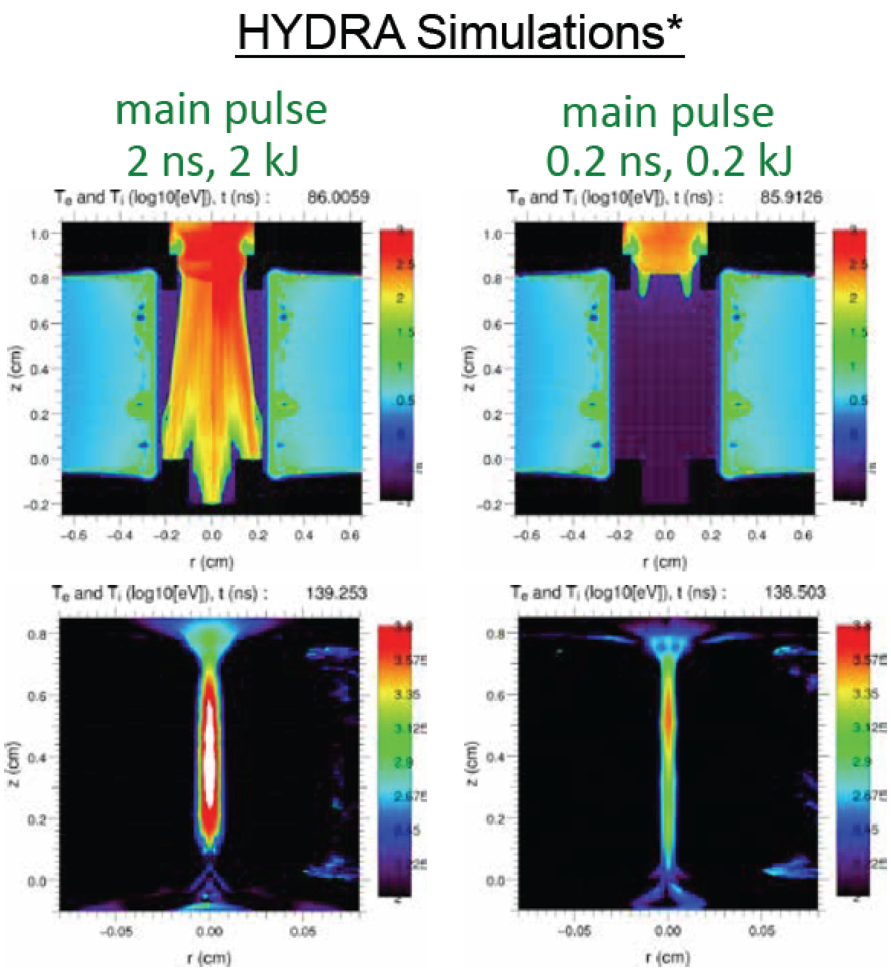
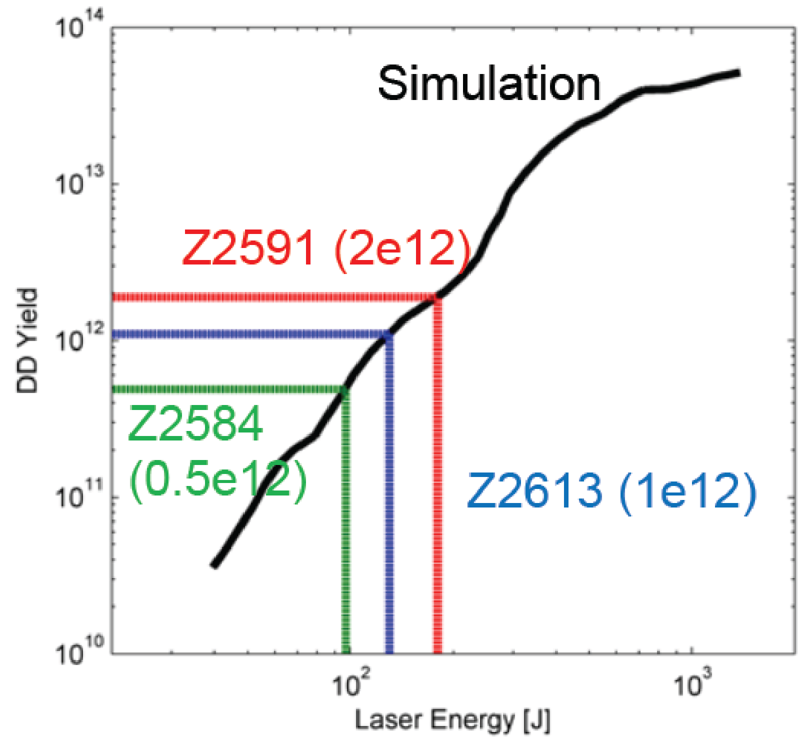
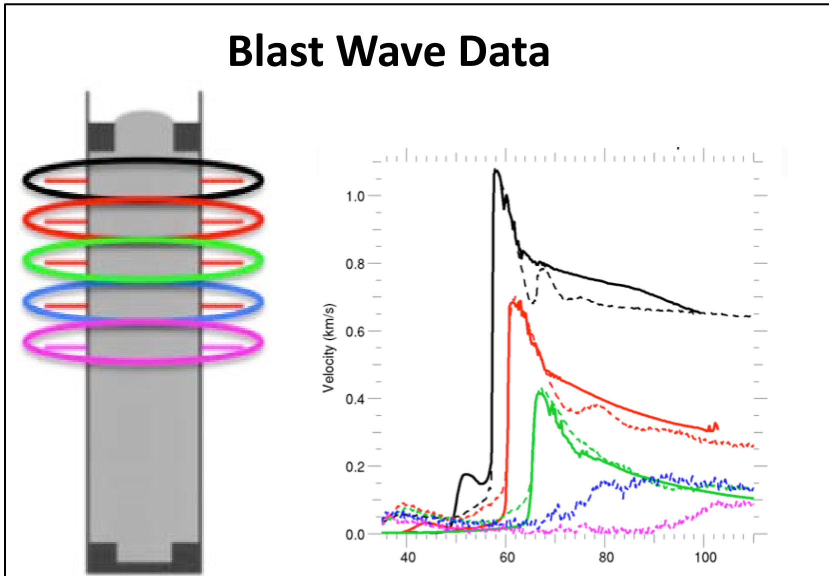


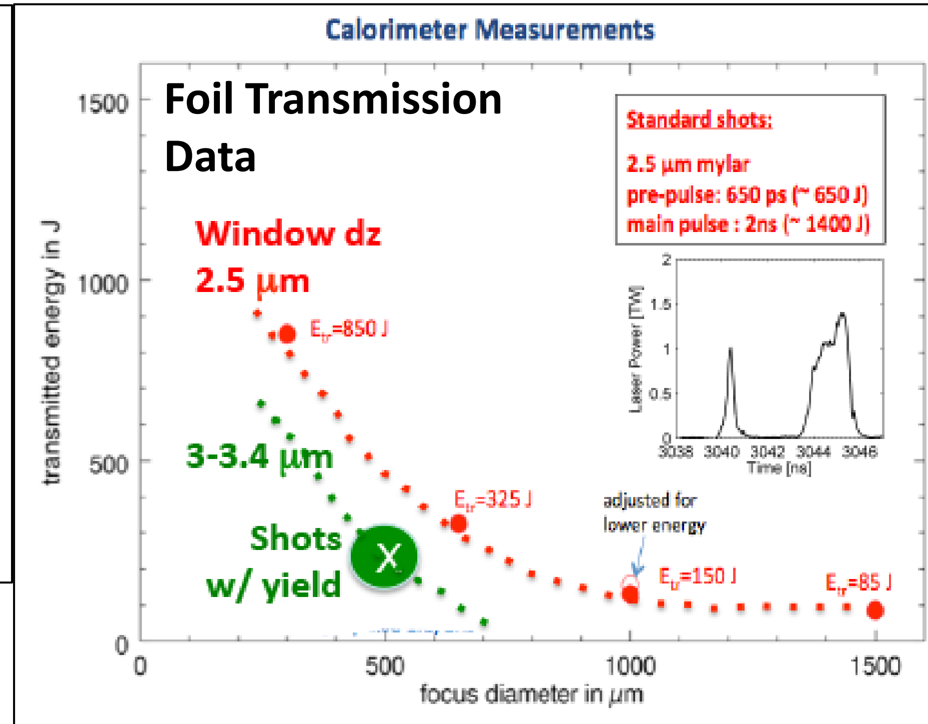


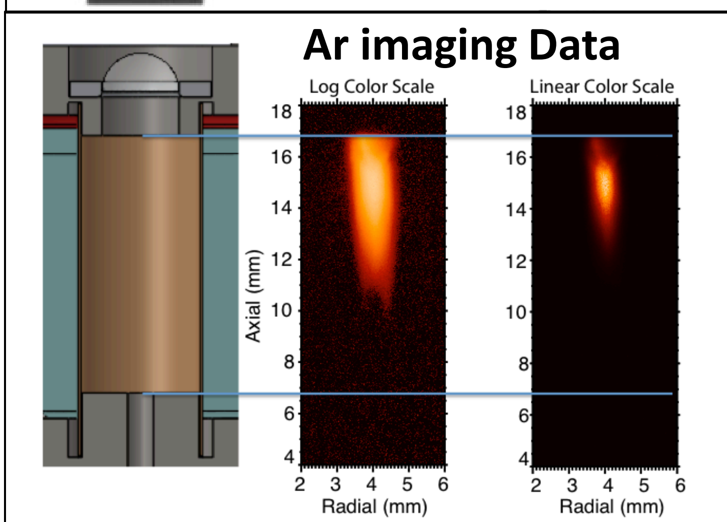
e.g., A.B. Sefkow *et al.*, Phys. Plasmas (2014).

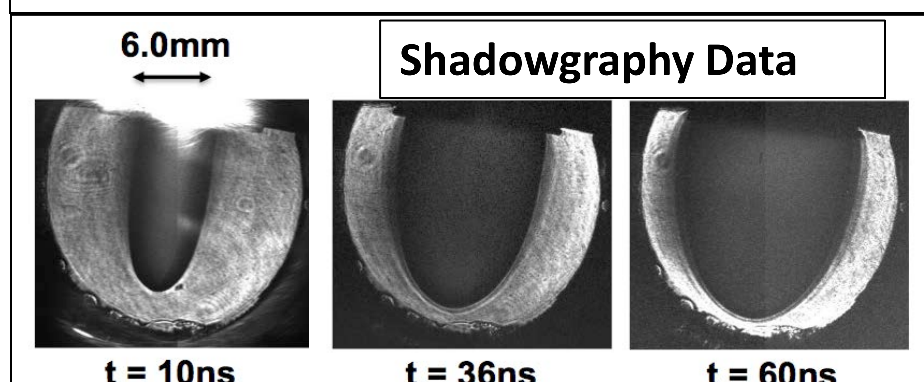
Simulations with 200 J match not only the yield, but other parameters measured in the experiments (temperature, shape, BR, etc.)

Laser-only experiments support that laser-fuel coupling is a concern; Multiple data are consistent with 200-600 J fuel out of >2000 J



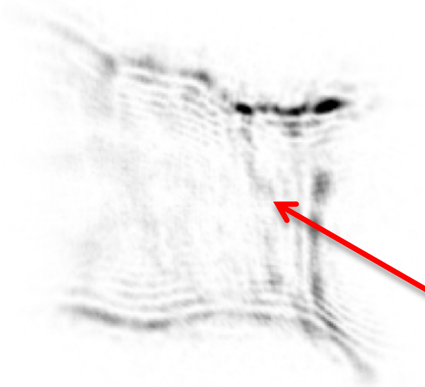






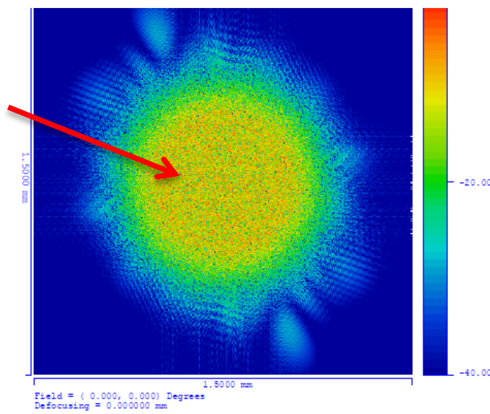
Poor beam spot quality may be one reason that we are struggling to couple well to the fusion fuel

Z-Beamlet currently does not use any beam smoothing techniques adopted by the laser community

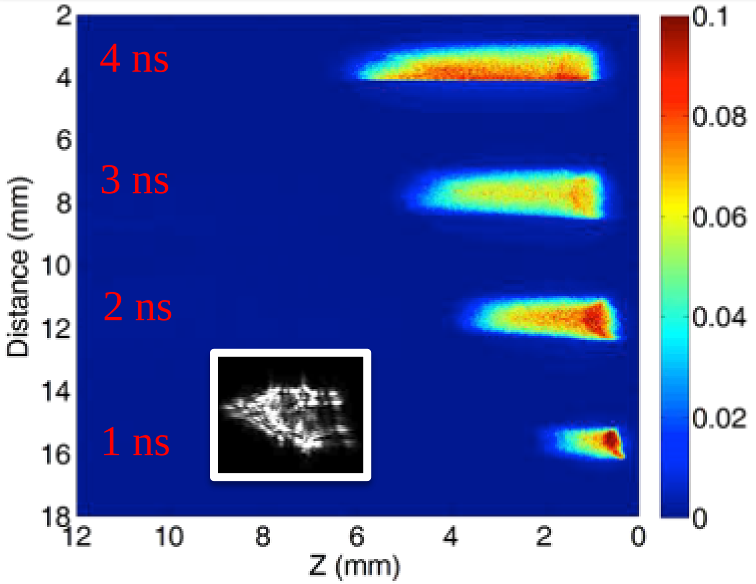


ZBL: No DPP (representative)

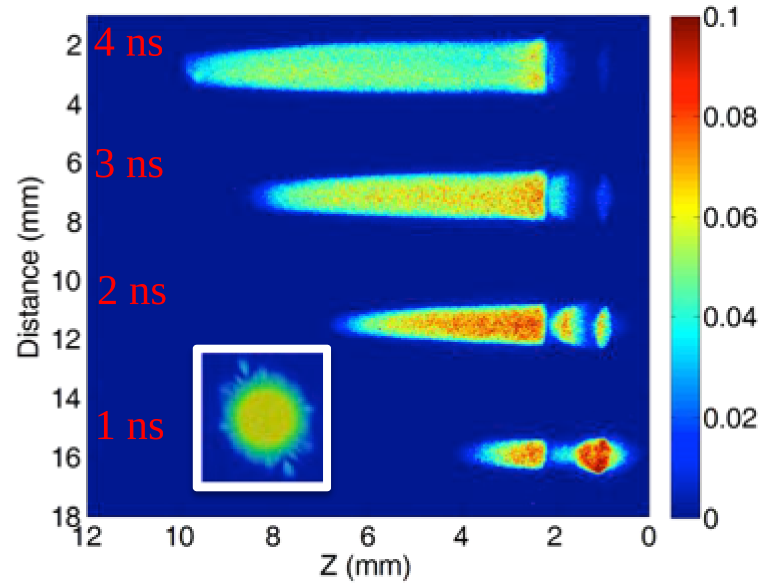
OMEGA-EP 750um DPP



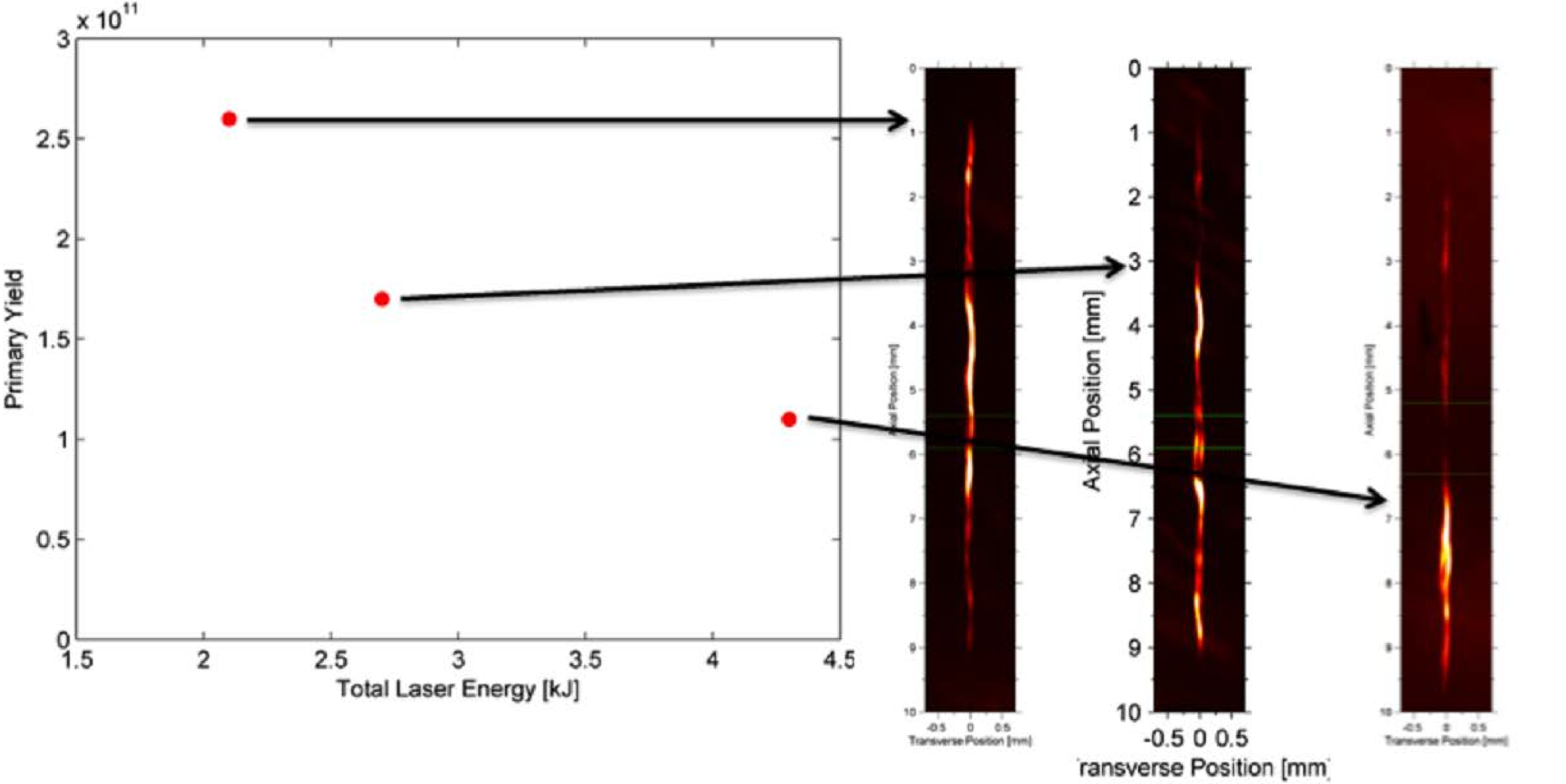
4 ns/2.93 kJ, 2 μm LEH, no prepulse without DPP (SNL Omega-EP data)



4 ns/3.1 kJ, 2 μm LEH, no prepulse with DPP (SNL Omega-EP data)

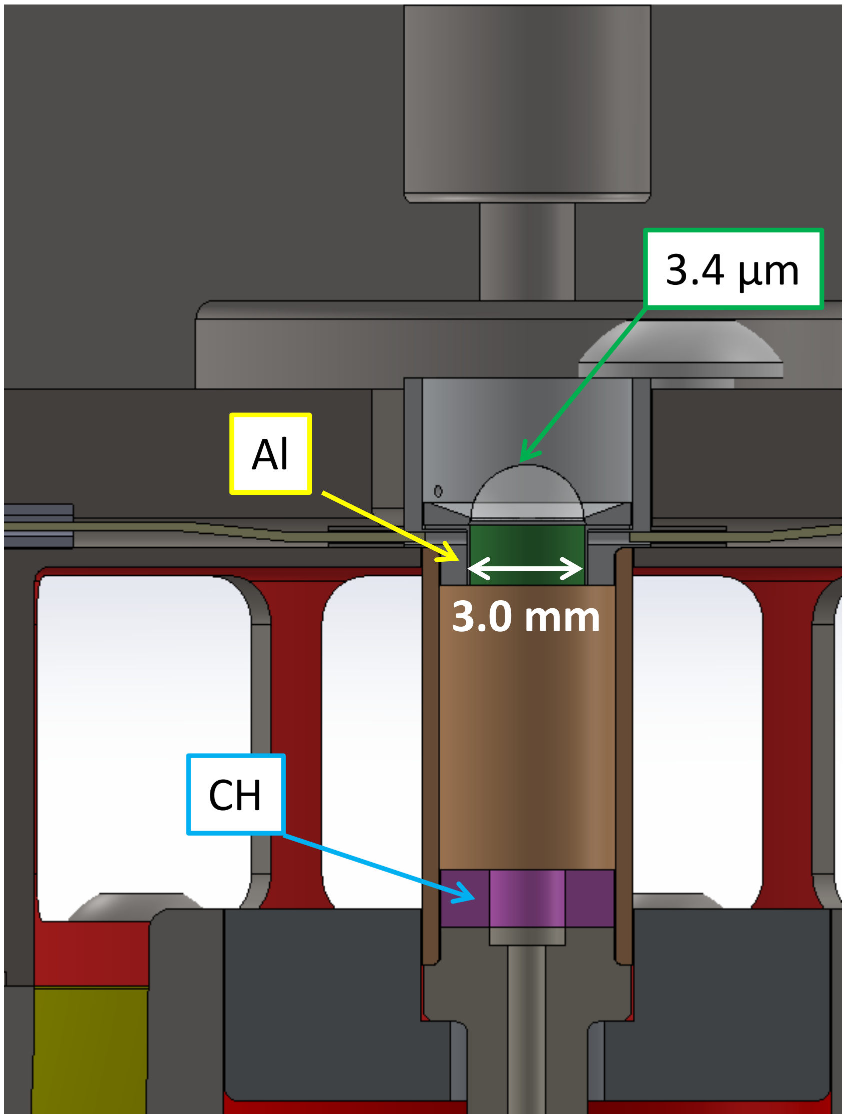


Stagnation column (3.1 keV) self emission suggest radiative cooling from high-Z contamination near LEH



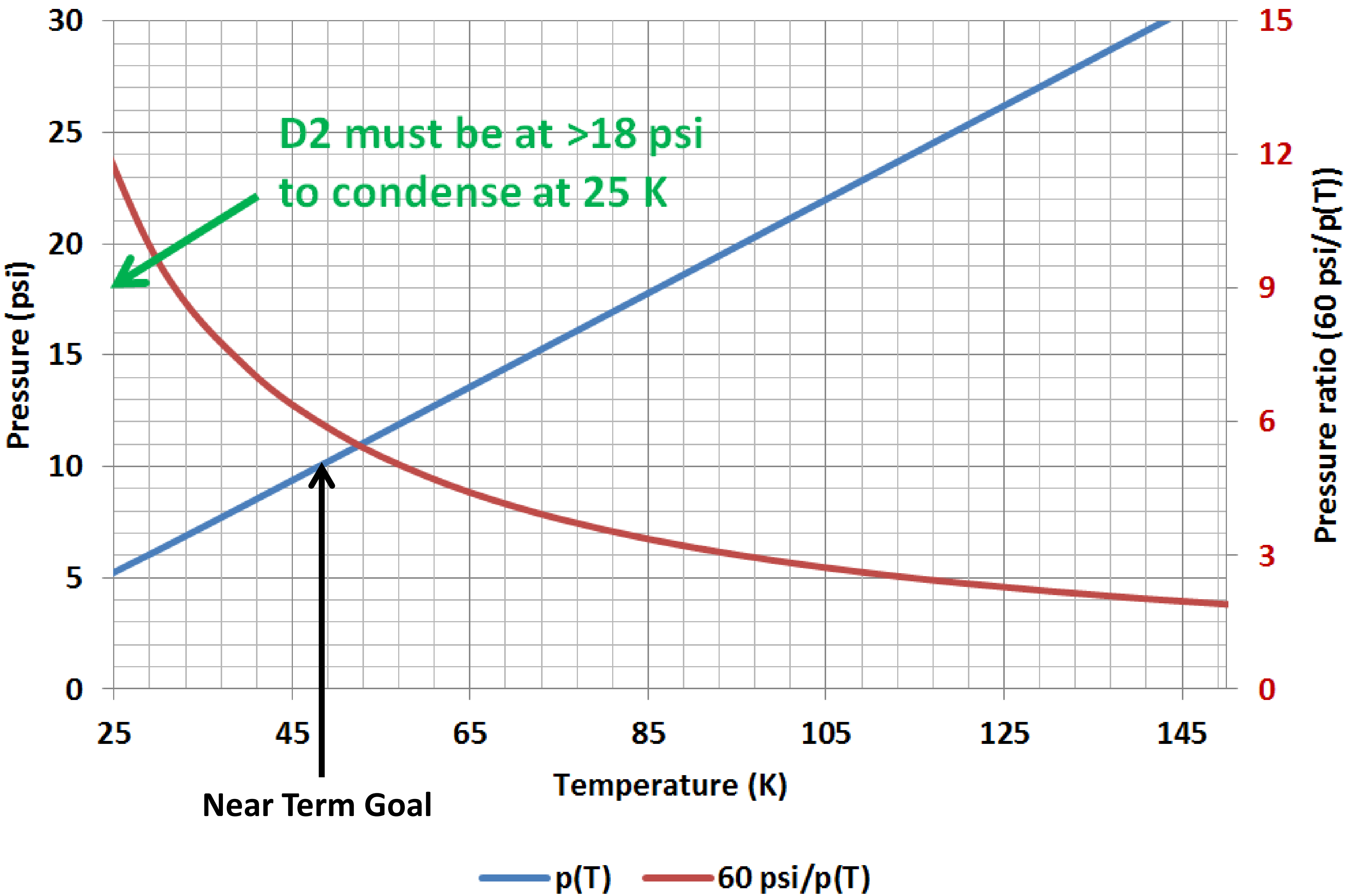
Yield decreased with increasing laser energy
Top portion of target has reduced emission with increased laser energy
Consistent with increased laser induced mix with increasing laser energy

Multiple target features exacerbate our lack of predictive understanding of the laser preheat process



- Unsmoothed beam enhances LPI and unpredictable laser filamentation.
- LEH window is too thick & too small diameter, but is required to hold the 60 psi room temperature gas fill
- The thick window increases LPI concerns and provides a large ρΔz source of high Z mix to the hottest region of fuel.
- Small diameter window challenges the pointing accuracy of the laser
- Al LEH channel sources contamination the hottest region of fuel.
- CH bottom cap may introduce mix into the imploding region if sufficient laser-preheat energy reaches the bottom of the target.

Cryogenically cooling the target to ~50 K gives ρ=0.7 mg/cc at 10 psi, enabling use of a thin window



LUXEL polyimide windows increase in strength when cooled. At 50 K, ρ=0.7 mg/cc and 10 psi, a 400-nm-thick window can span the full ID of the target

Expected Maximum Use Pressure for LUXFilm™ Polyimide at 25 Kelvin

LUXEL

Polyimide Thickness/ Aperture Diameter	250nm	300nm	350nm	400nm
4.65mm	5.3	6.50	7.98	9.8
4.45mm	5.59	6.85	8.39	10.29
4.25mm	5.9	7.22	8.83	10.8

Pressures in PSI

Pressure applied on polyimide side against radiused washer

Windows proofed at 1psi at room temperature

Burst failure rate criterion is ~1%

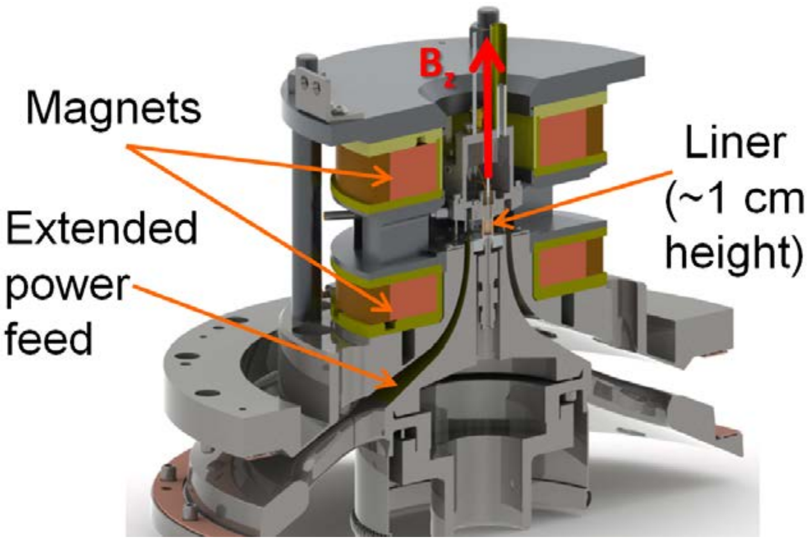
Pressures listed in black are estimated from polyimide properties

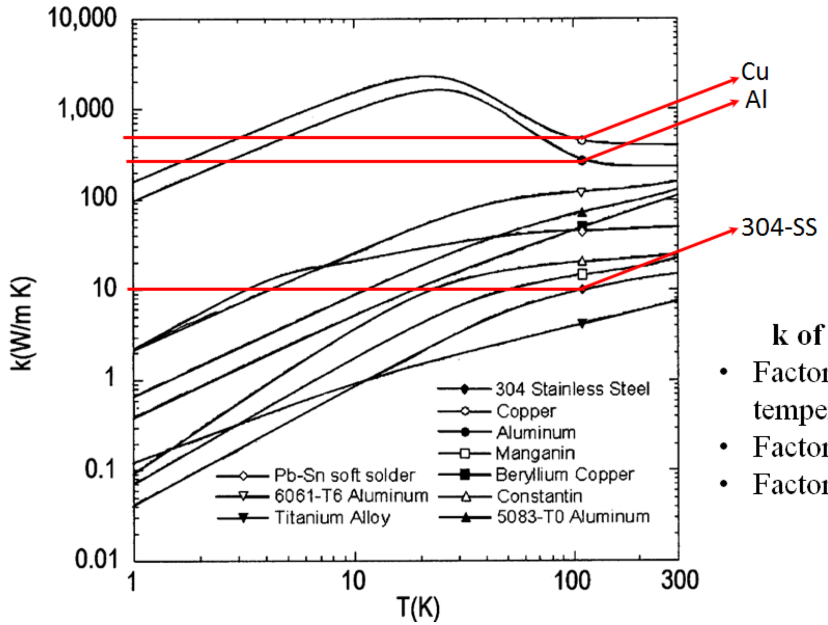
Pressures listed in red are interpolated

LEH channel is eliminated to further take advantage of large diameter window

Cooling a MagLIF Target Presents Unique Challenges

- Cryogenic system must be compatible with the applied axial magnetic field coils (ABZ). Cooling generally applied through high thermal/electrical conductivity oxygen free Cu, which is incompatible with ABZ B_z diffusion.
- Conductivity of Cu/Al greatly increases at cryogenic temperatures





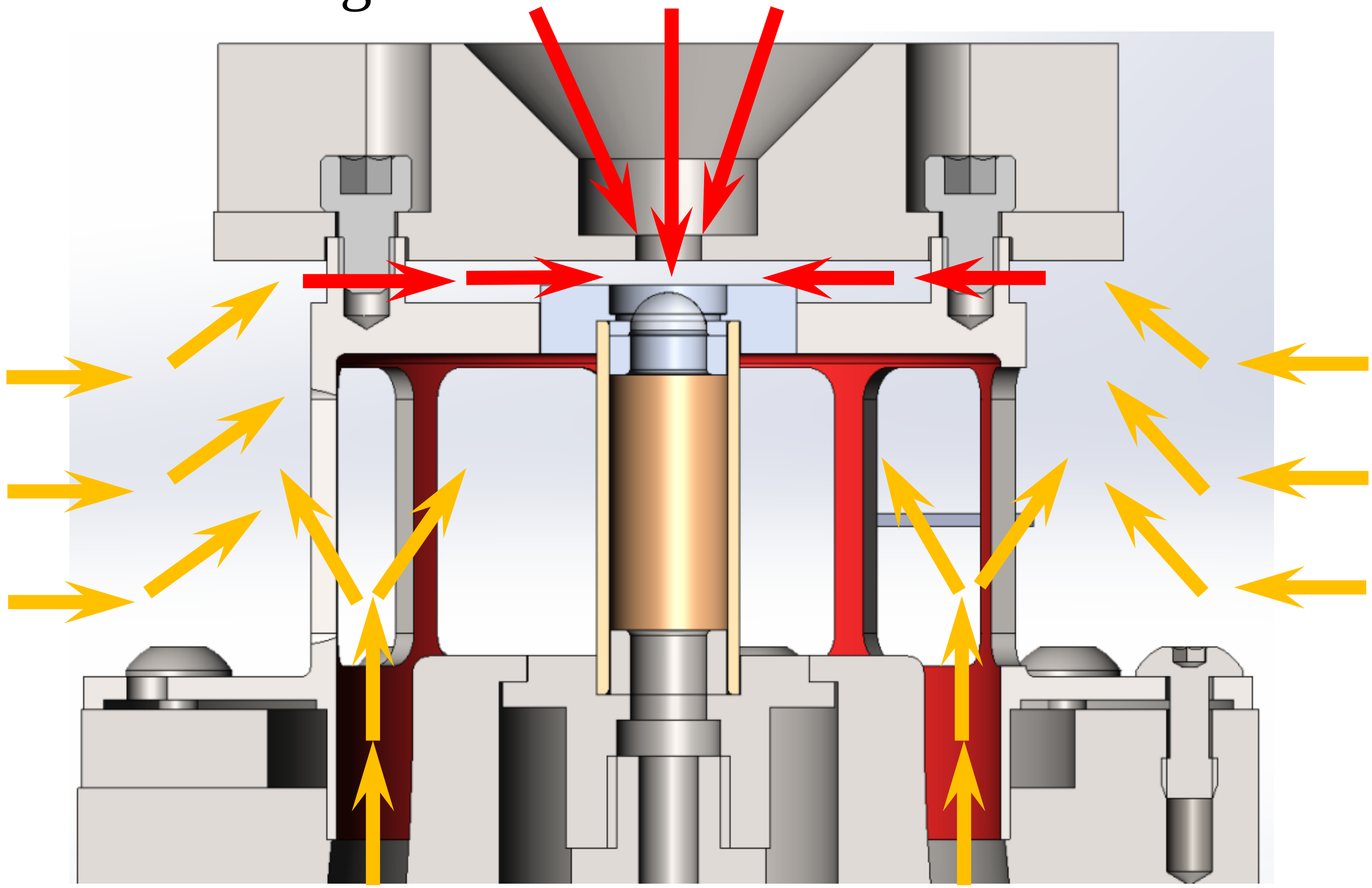
k of Cu versus SS

- Factor of ~20 at room temperature
- Factor of ~40 at 100 K
- Factor of ~1000 at 30 K

Solution: Bring liquid helium directly to target via stainless steel (resistive) cryostat, which mates to target's top cap.

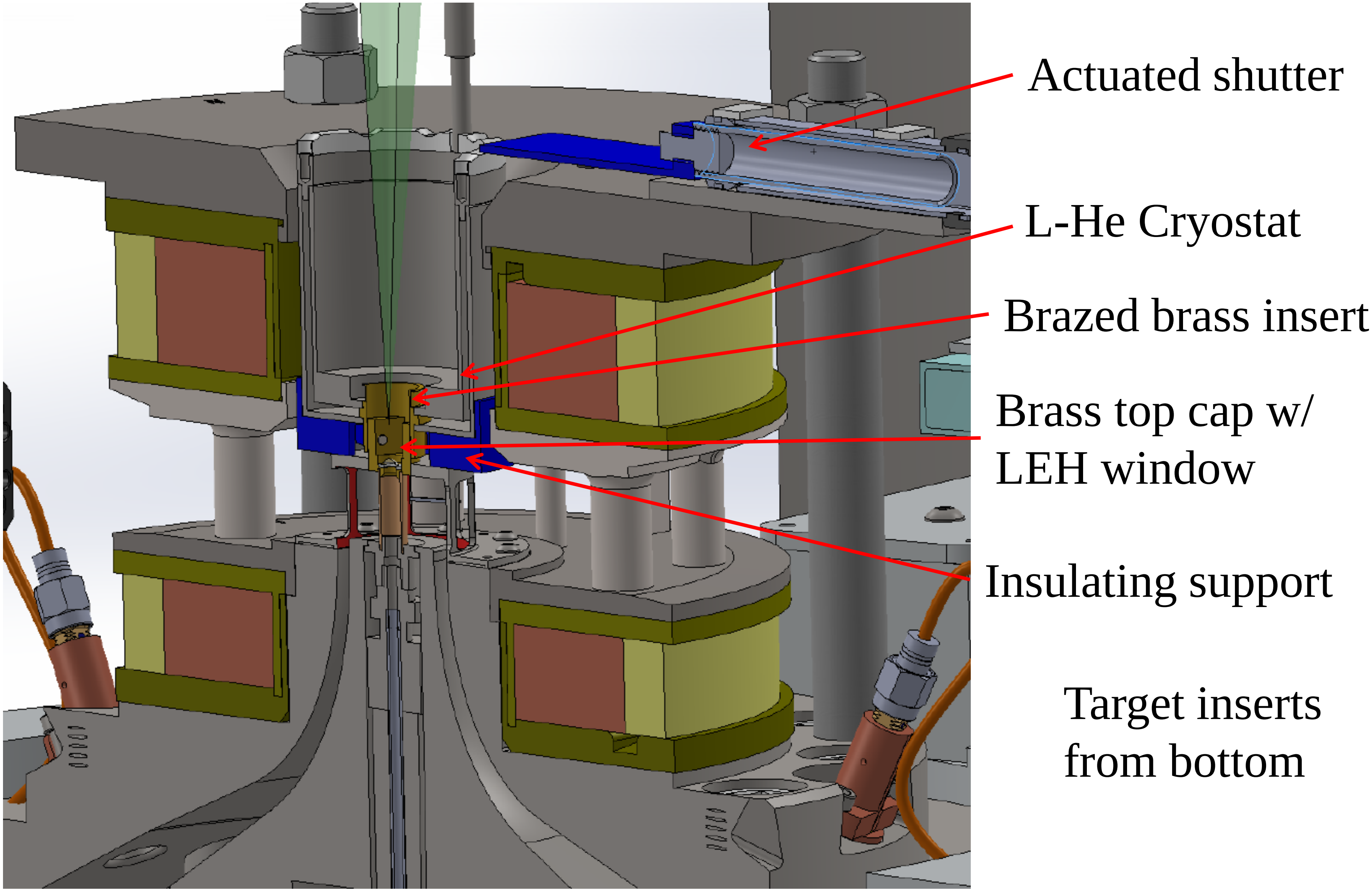
Cooling a MagLIF Target Presents Unique Challenges

- LEH window must be protected from condensation of vacuum contaminants during cool down.

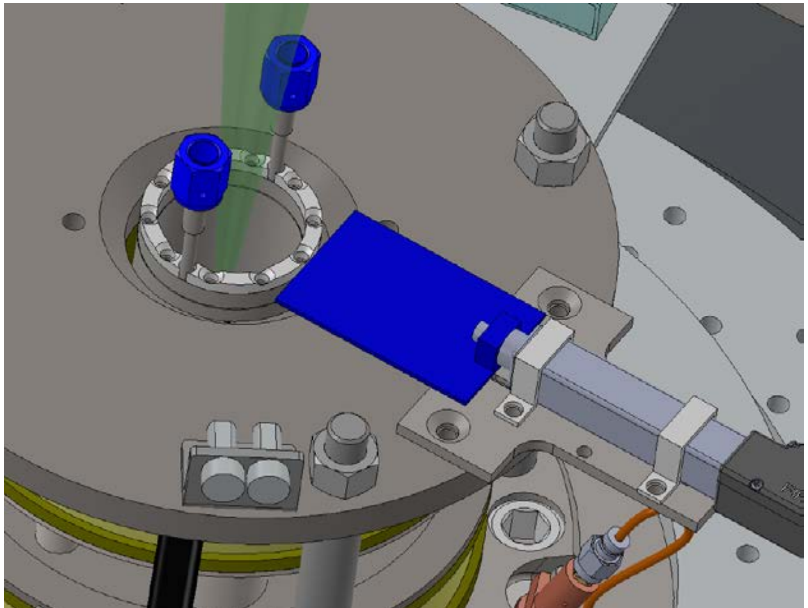


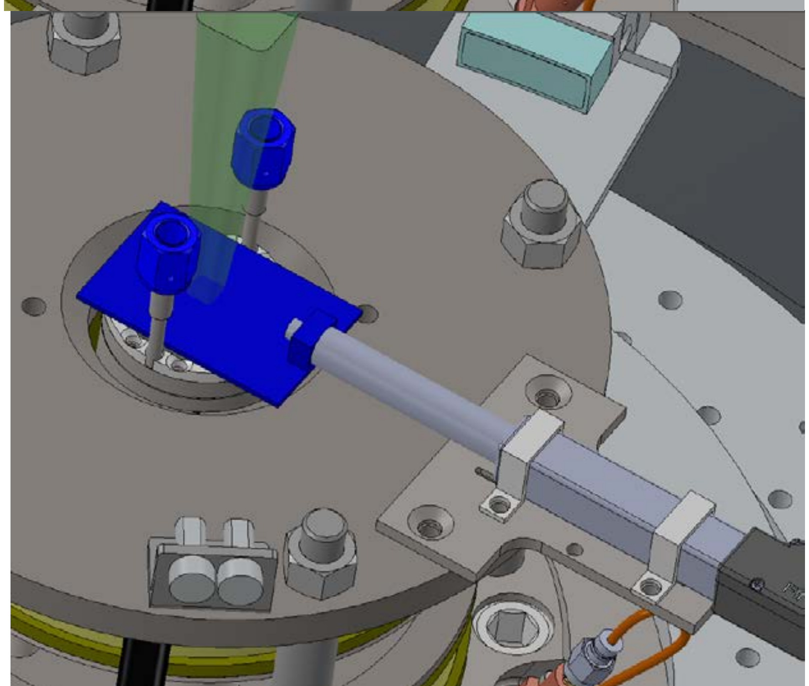
Solution: Add shutter to cryostat. Differentially pump volume surrounding LEH. Open shutter before ZBL fires.

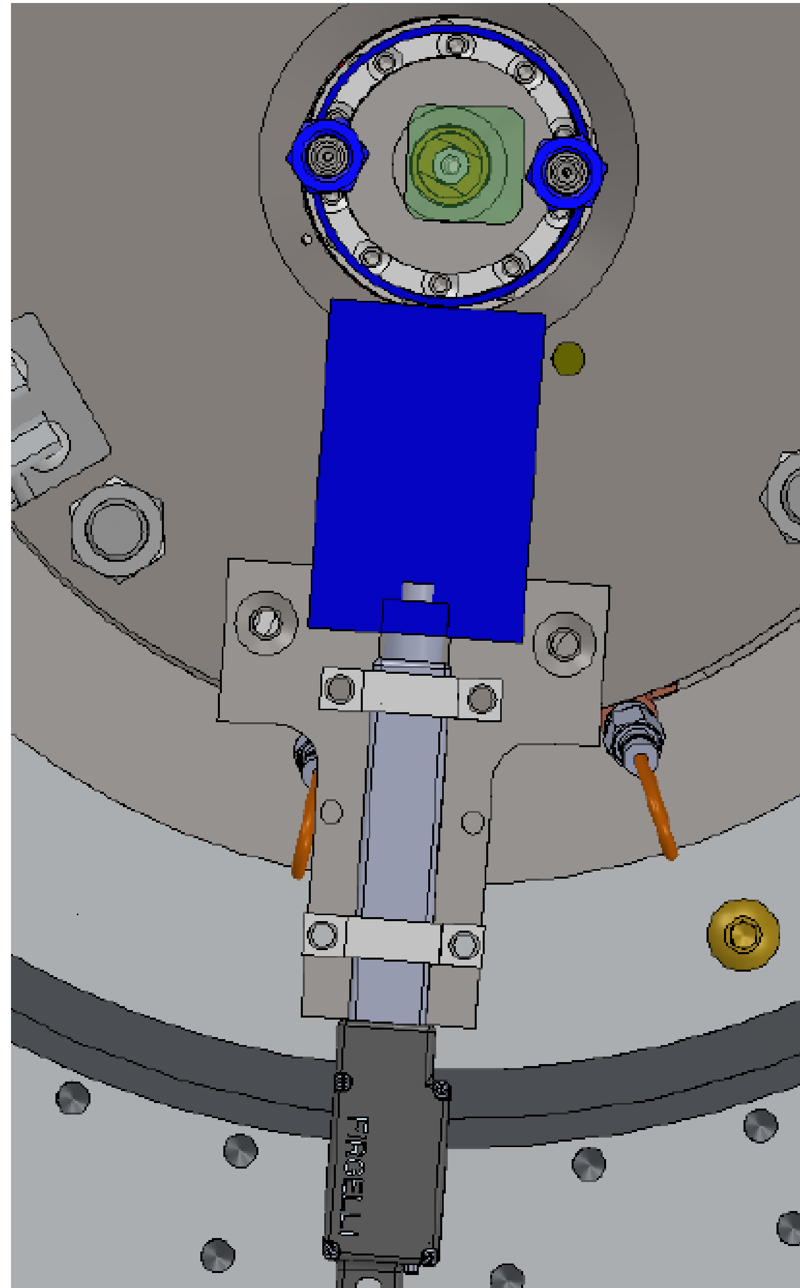
Liquid He cryostat inside ABZ coil cools target's top cap; shutter protects LEH window from ice build-up



Shutter (not valve!) assembly mounts to ABZ top plate







Cooling Process takes advantage of differential pumping inside of cryostat

- Pump vacuum chamber to $<10^{-5}$ Torr with gate valve open and target at room temperature
- Evacuate target (fill/purge process)
- Close gate valve
- Cool target to desired temperature
  - Most water should freeze to cryostat/cold finger as they will cool much earlier than the LEH window
  - Slowly add deuterium; fill to desired density
- Begin charging Z
- Open gate valve only seconds before firing

Cryogenics-Lab testing provided data that resulted in several design modifications

- Cryostat/cold finger get suitably cold (<30K) in an acceptable amount of time
- SS cold finger too resistive → Use Brass
- Return can is large heat sink → Insulating break must be used
- Largest thermal resistance between cold finger and target top cap → Change to one-piece design
- Cryostat flow restrictions observed → Open up restriction near cold finger
- 70 K achieved in target → Sufficient for July 2015 experiments. Likely will improve with hardware modifications

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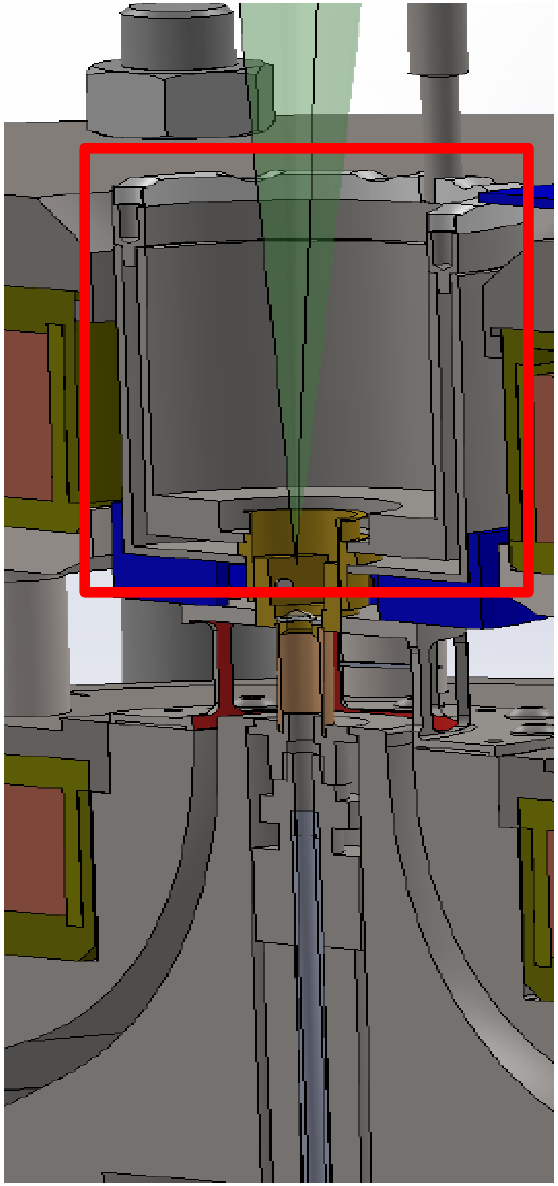

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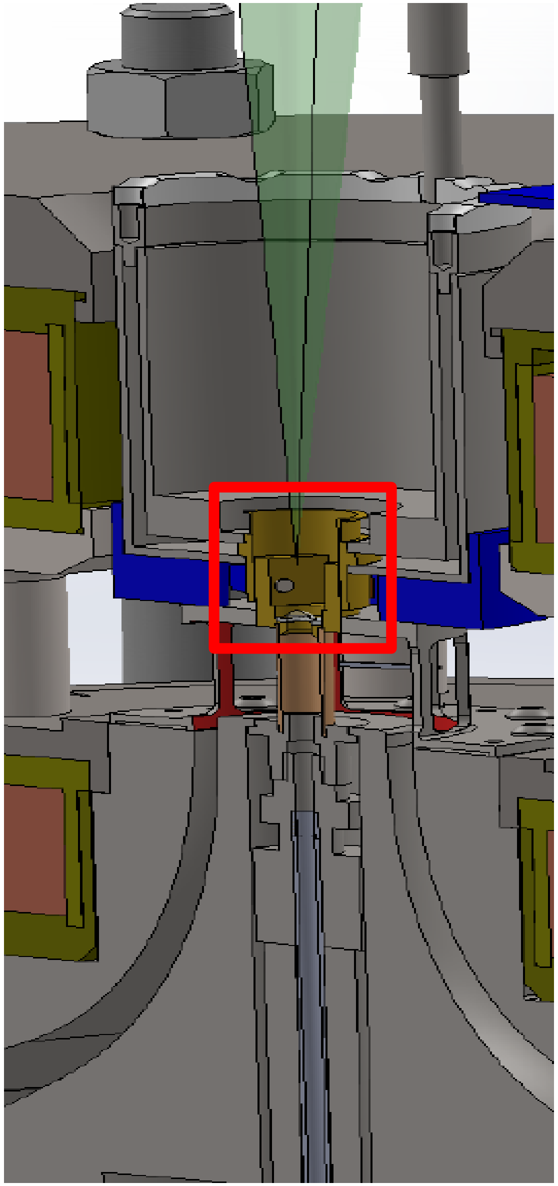

- Cryostat/cold finger get suitably cold (<30K) in an acceptable amount of time
- SS cold finger too resistive → Use Brass
- Return can is large heat sink → Insulating break must be used
- Largest thermal resistance between cold finger and target top cap → Change to one-piece design
- Cryostat flow restrictions observed → Open up restriction near cold finger
- 70 K achieved in target → Sufficient for July 2015 experiments. Likely will improve with hardware modifications

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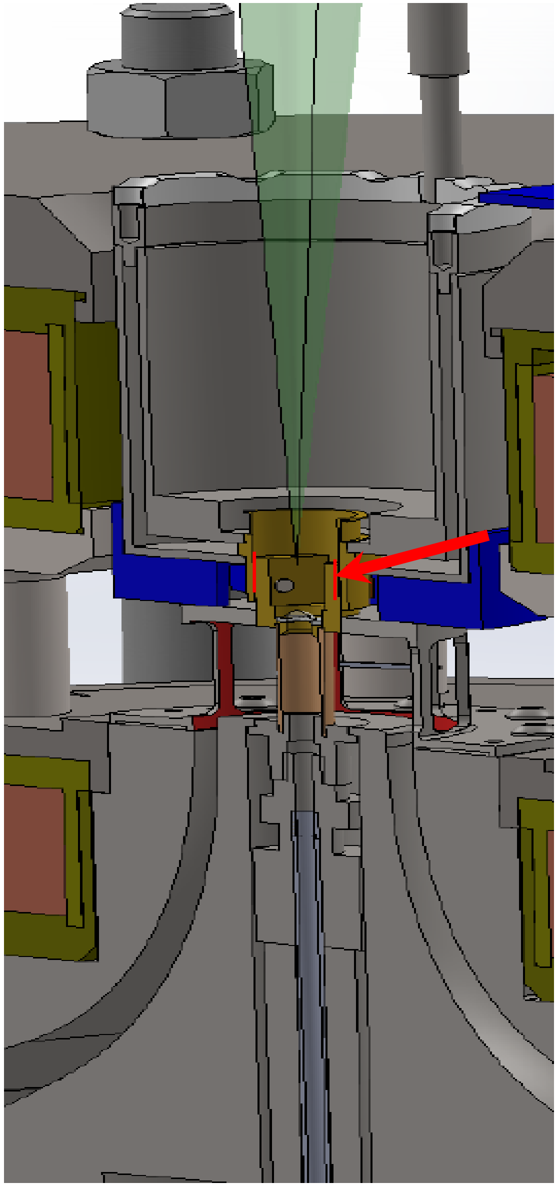

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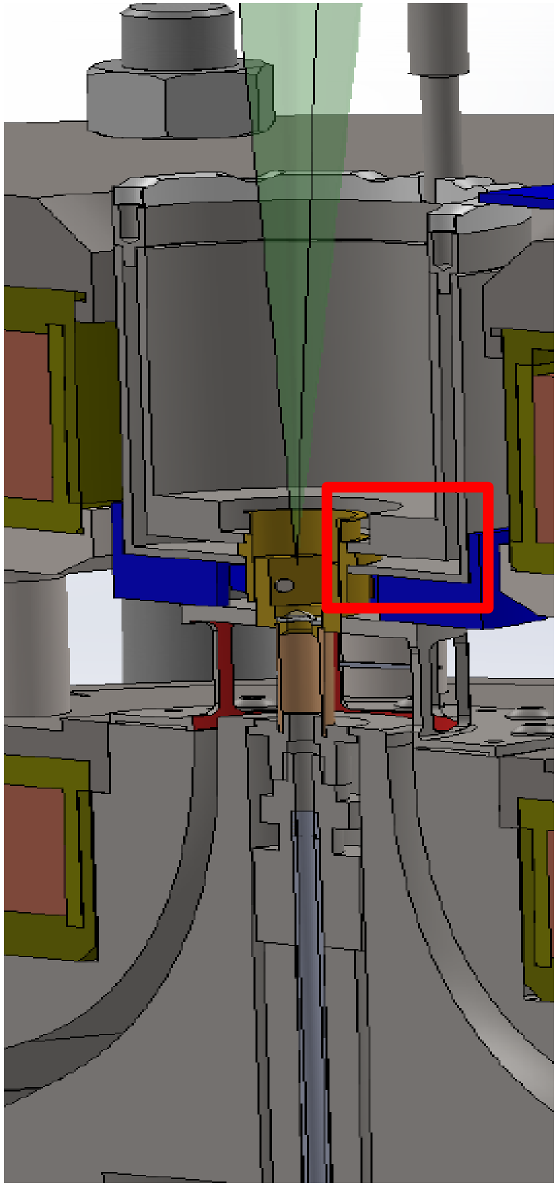

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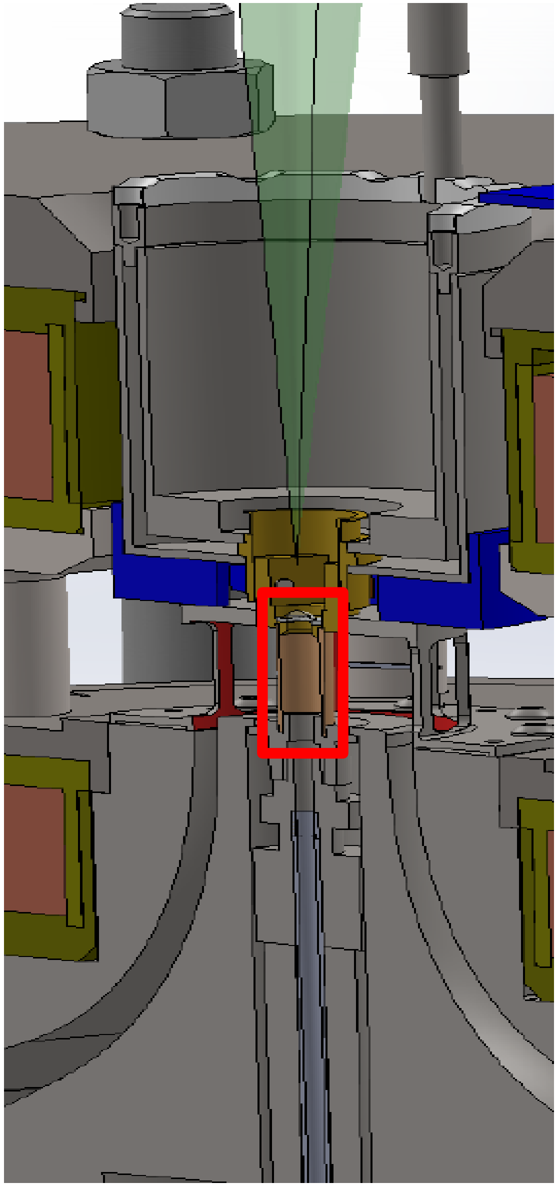

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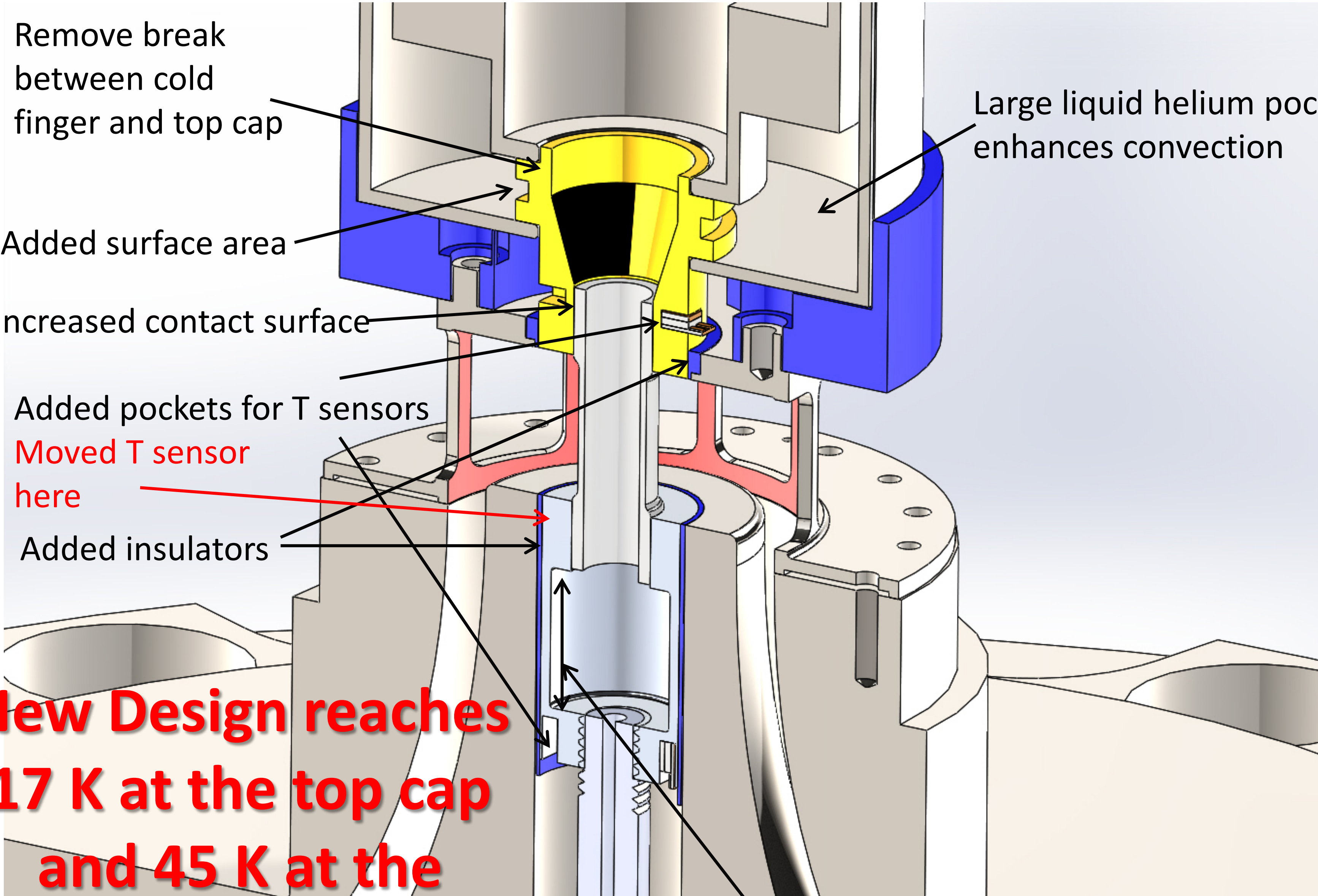
Cryo Lab Testing Informs Mod2 Target Design

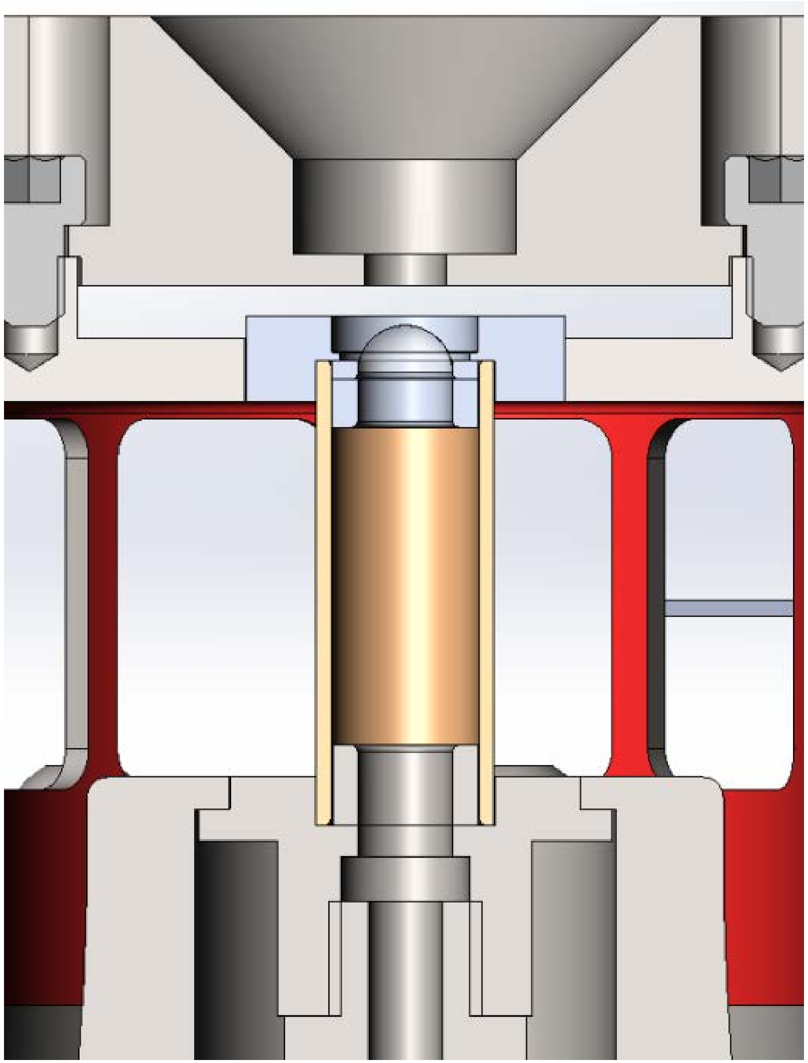


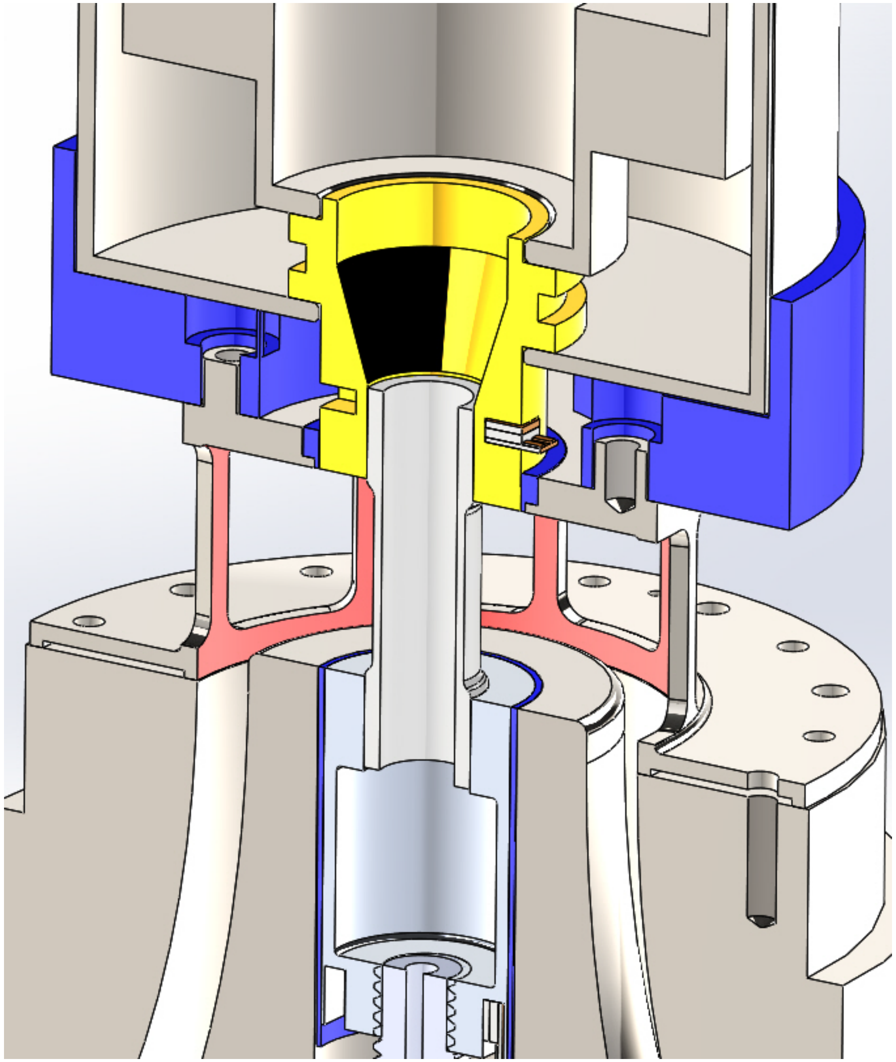
New Design reaches 17 K at the top cap and 45 K at the bottom cap!

Cryo Design Enables Many MagLIF "Firsts"

- **4.5 mm LEH window diameter** (largest to date has been 3.0 mm)
- **400-nm-thick LEH window** (thinnest to date has been 1.5 microns)
- **<u>NO</u> high-Z material in contact with hot plasma**
  - Be LEH washer (4.5 mm ID)
  - No LEH channel
  - No end caps inside of liner (requires shaped liner for electrode instability mitigation)
  - Large diameter laser focusing surface (avoid beam clipping)
- **"Laser Only" experiments will measure preheat energy deposition**
- **Fully integrated experiments will evaluate target performance**

Thank you for your attention!





Questions?