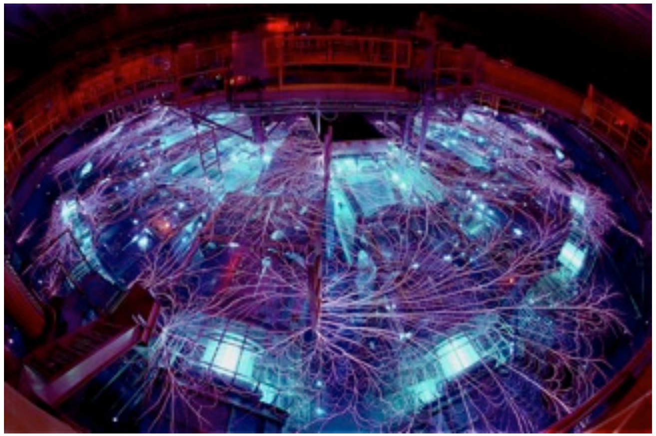
Exceptional service in the national interest

Sandia National Laboratories



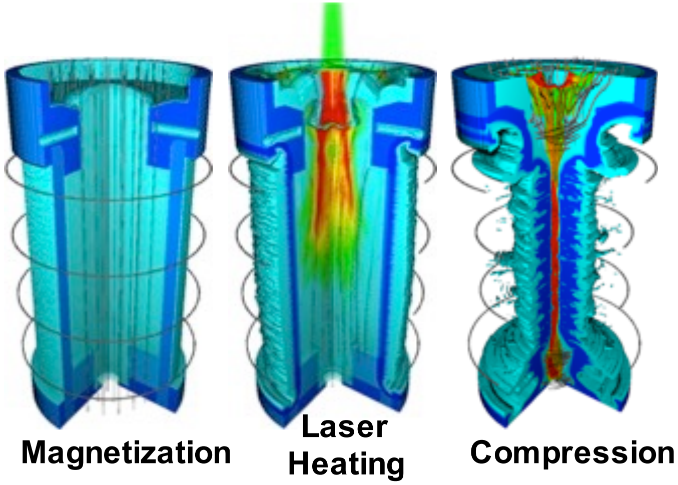
MagLIF Update

Daniel Sinars

Sandia National Laboratories,

Albuquerque, NM, USA

Fusion Power Associates, Dec. 14, 2016



U.S. DEPARTMENT OF ENERGY

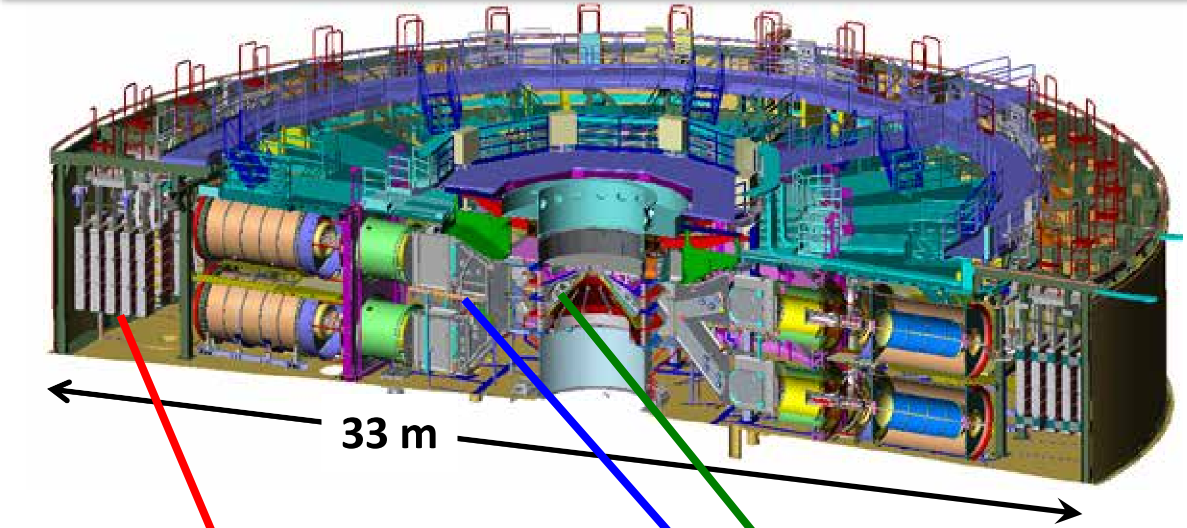
NNSA

GENERAL ATOMICS

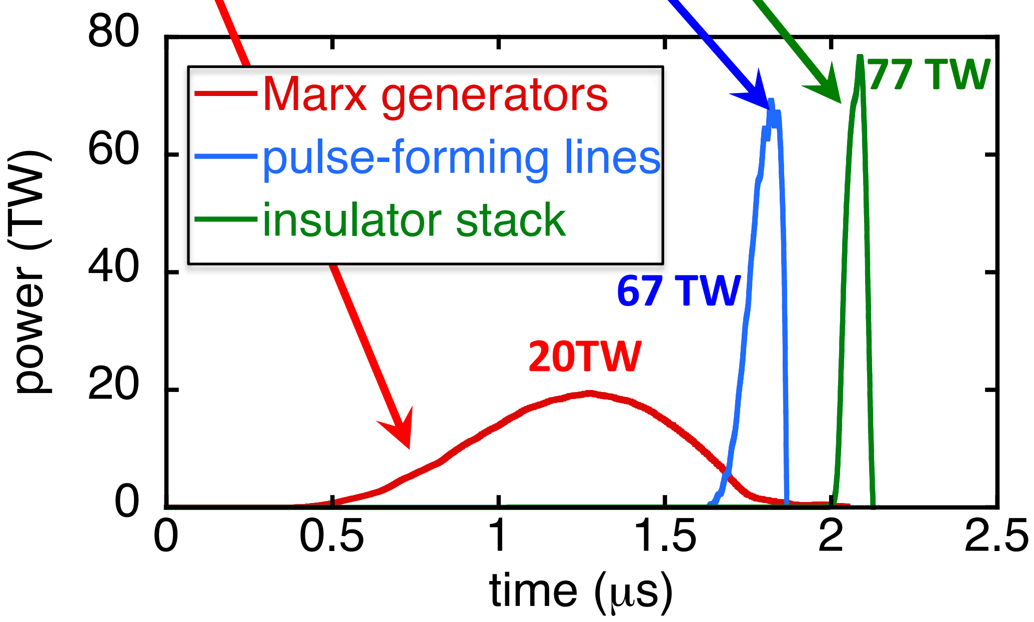
UR LLE

Lawrence Livermore National Laboratory

Magnetic direct drive on Z is based on efficient use of large currents to create high pressures

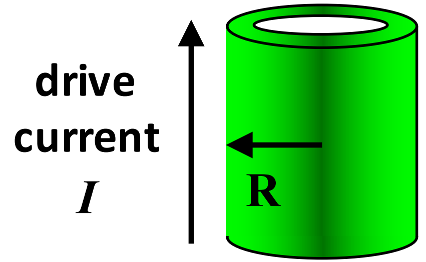


Z today couples ~0.5 MJ out of 20 MJ stored to magnetized liner inertial fusion (MagLIF) target (0.1 MJ in DD fuel).



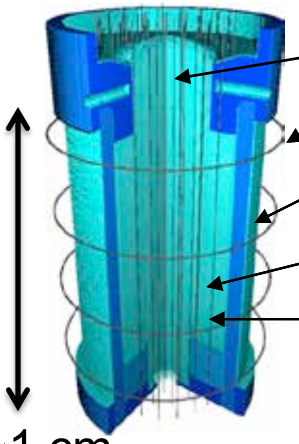
Magnetically Driven Implosion

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



100 MBar at 26 MA and 1 mm

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



Laser entrance hole

Azimuthal drive field

Liner (Al or Be)

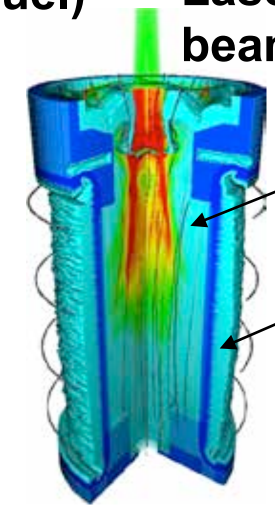
Cold DT gas (fuel)

Axial magnetic field

~1 cm

1. A 10–50 T axial magnetic field is applied (~3-ms rise time) to inhibit thermal conduction losses and to enhance alpha particle deposition.

*S.A. Slutz *et. al*., PoP (2010)
S.A. Slutz and R. A. Vesey, PRL (2012)
M.R. Gomez *et. al*., PRL (2014)
P.F. Schmit *et. al*., PRL (2014)
A.B. Sefkow, *et. al*. ,PoP (2014)
M.R. Gomez, *et. al*., PoP (2015)
S.B. Hansen, *et. al*. , PoP (2015)
R.D. McBride, *et. al*., PoP (2016)



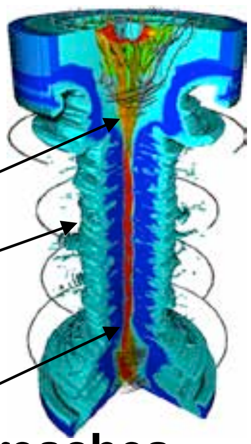
Laser beam

Laser heated fuel

Liner beginning compression

2. ZBL preheats the fuel to ~100–250 eV, reducing the required final convergence ratio to CR 20–30.

3. The Z-pinch drive current implodes the liner at 50–100 km/s, compressing the fuel and Bz field by factors of 1000.

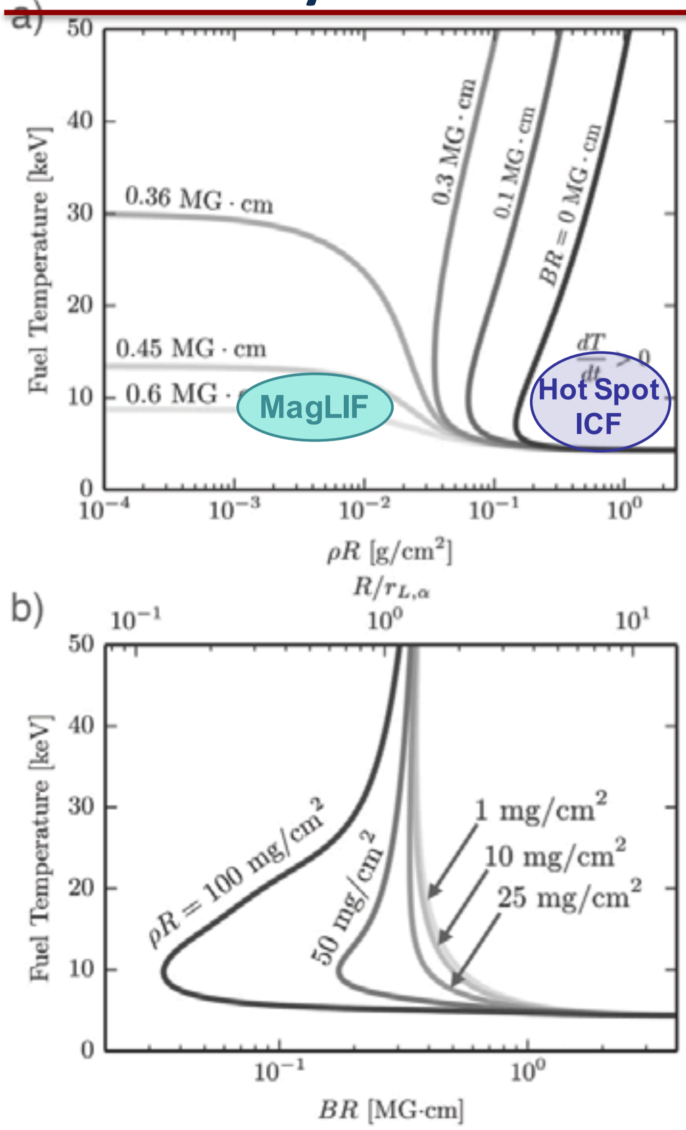


Compressed axial field

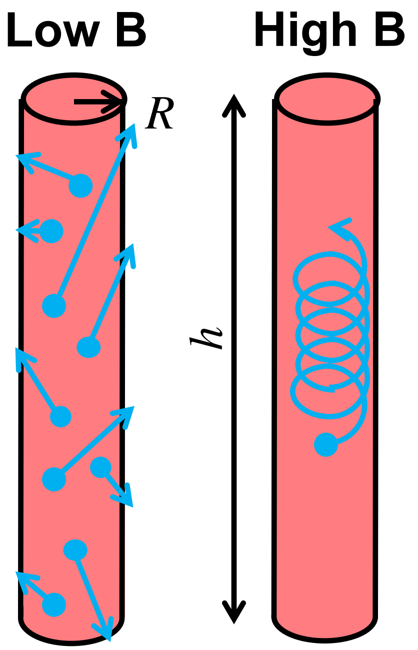
Liner unstable but sufficiently intact

Compressed fuel reaches fusion temperatures

Magnetization (*BR*) can be used to reduce *ρR* requirements and reduce electron heat losses, lower density also reduces bremsstrahlung radiation losses



- **Initial 10-30 T field greatly amplified during the implosion through flux compression**
- **Too much field is inefficient—want to stagnate on plasma pressure, not magnetic pressure**



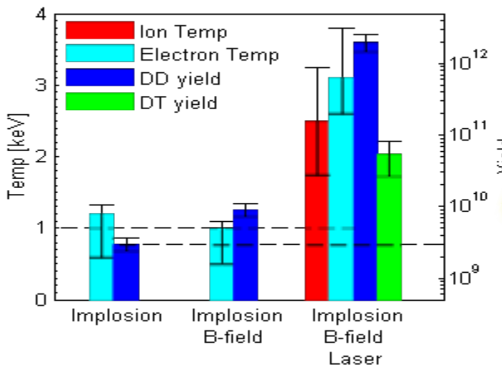
$$\frac{R}{r_\alpha} \approx 4BR\ [MG \cdot \mathrm{cm}]$$

- **Fraction of trapped tritons (or α's) a function of *BR***
- **Effects saturate at *BR* > 0.6 MG-cm**
- **Measurements to date suggest *BR* of 0.4 MG-cm**

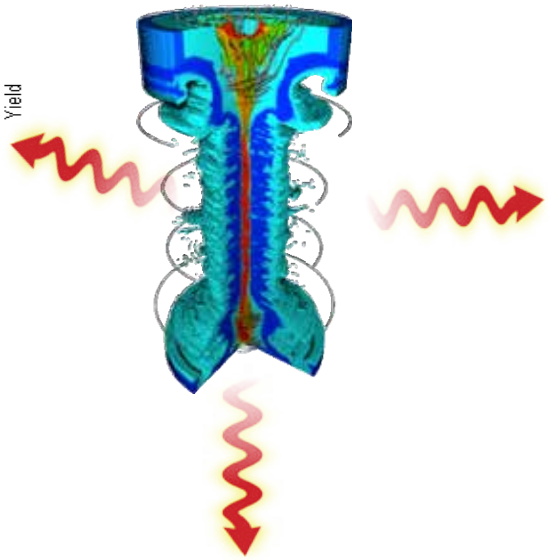
Basko *et al*. Nuclear Fusion 40, 59 (2000); P.F. Knapp *et al.*, Phys. Plasmas (2015).

An ensemble of measurements from our first MagLIF experiments are consistent with a magnetized, thermonuclear plasma!

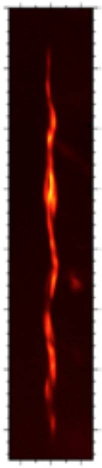
Nuclear Activation (yield)



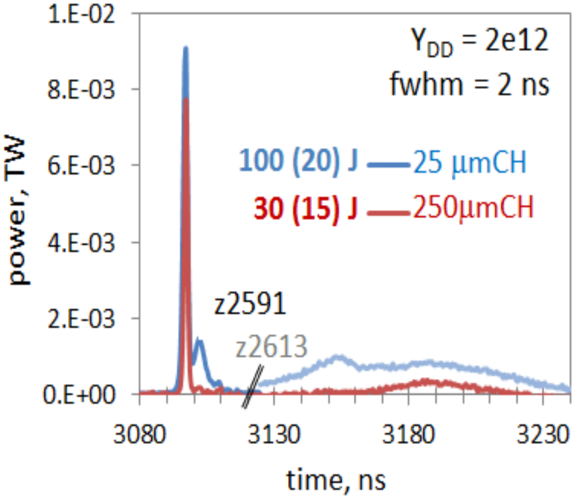
MagLIF Z pinch



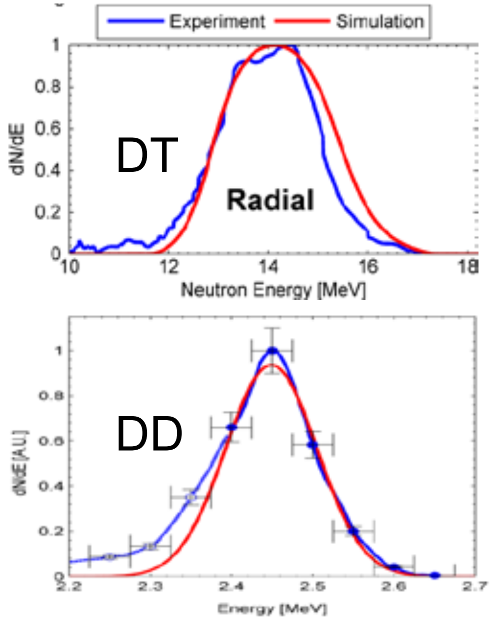
X-ray Imaging (hot plasma shape)



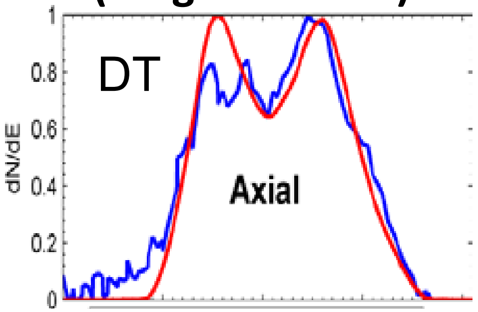
X-ray Power (duration)



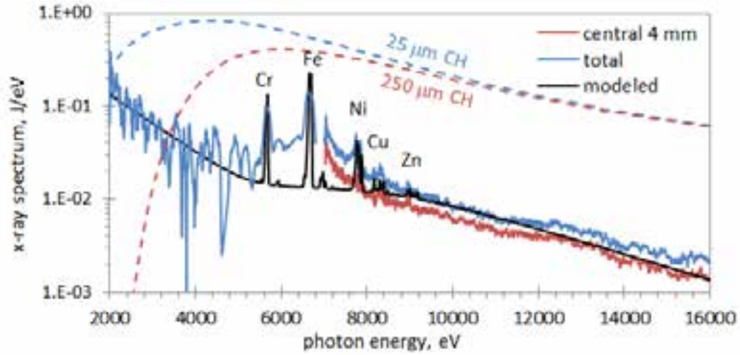
Neutron spectra (Tion)



DT Neutron spectra (magnetization)



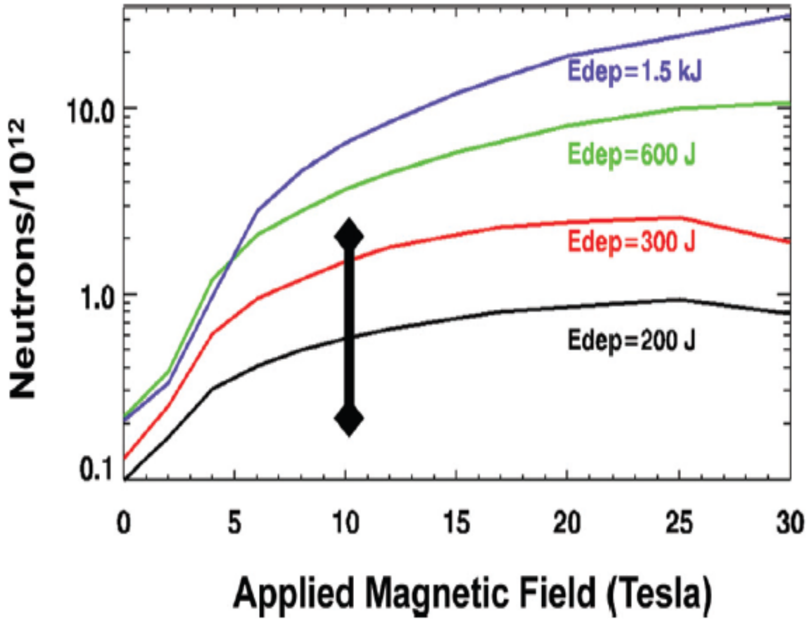
X-ray Spectra (Te, mix)



The main hypotheses for the discrepancies between experiments and models involve preheat, mix, and morphology

- **Ineffective Preheat**
  - Pecos experiments indicate we are over an intensity cliff
  - Omega and NIF show potential for a predictable preheat condition
- **Radiative cooling from Be walls and/or LEH window**
  - Long interval time (~50ns) between preheat and stagnation
  - Mix may get worse with increased laser energy
- **Liner implosion stability and resulting stagnation morphology**
  - 3-D stagnation column

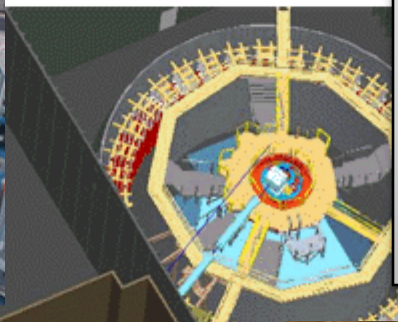
S.A. Slutz *et al.*, Phys. Plasmas 2016



Even so, we are only ~4x away from the predicted optimum yield for this platform.

The Z-Beamlet laser at Sandia* is being used to radiograph liner targets and heat fusion fuel

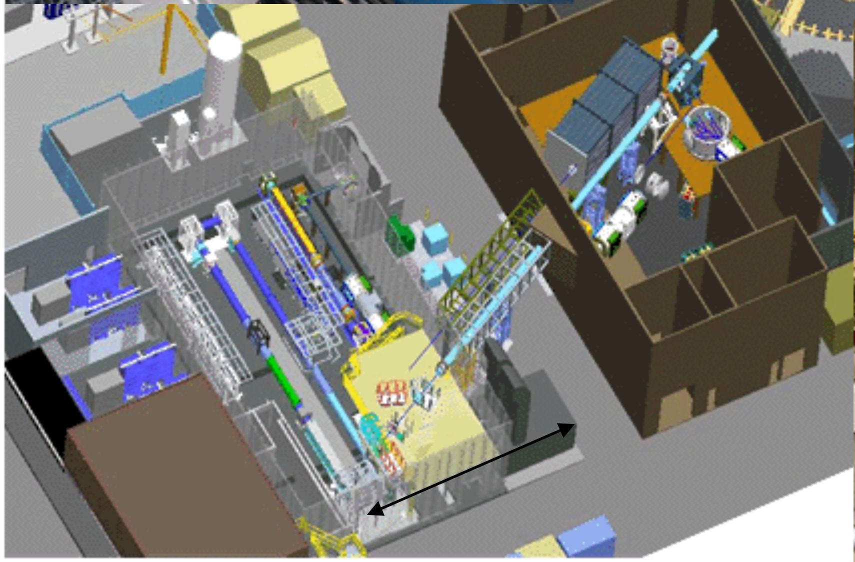
Z-Beamlet High Bay



Z facility

Z-Beamlet (ZBL) is now routinely used to deliver up to 4.5 kJ of 2ω light in a 6 ns time window

An advantage of laser heating is that it can be studied and optimized without using Z



Z-Beamlet and Z-Petawatt lasers

---

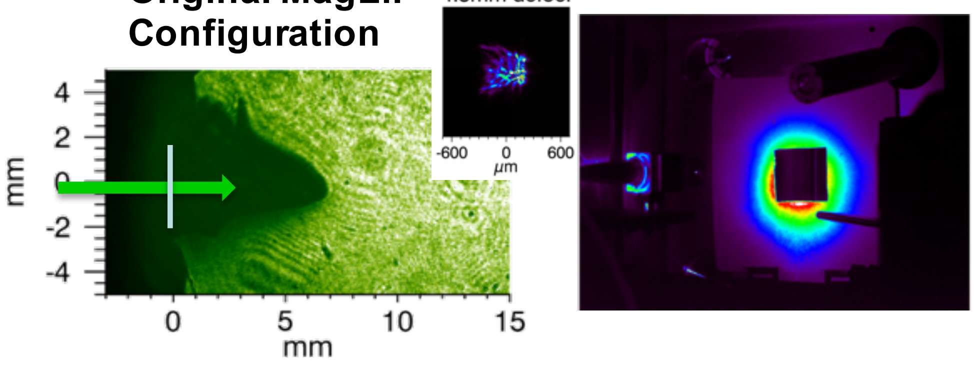
* P. K. Rambo *et al.*, Applied Optics 44, 2421 (2005).

Recent progress on ZBL (PECOS) has demonstrated dramatically lower backscatter losses, higher window transmission, and better simulation predictability

Optical Blastwave & SBS Measurements

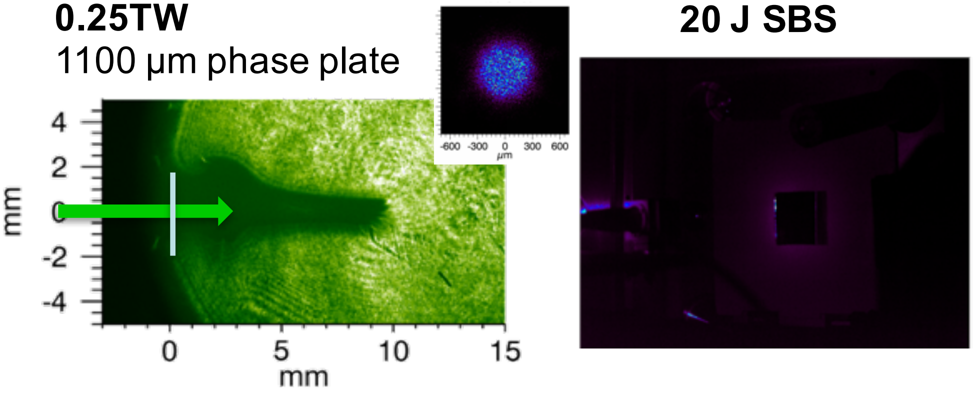
Original MagLiF Configuration

900 J SBS!



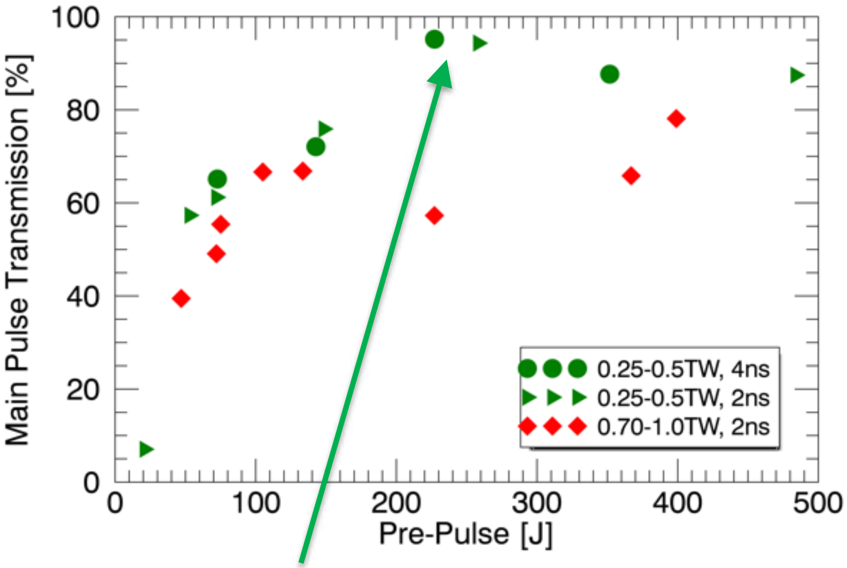
0.25TW
1100 µm phase plate

20 J SBS



54psi He

LEH Window Transmission



Integrated experiments planned for February 2017 will attempt to use a better laser configuration

The main hypotheses for the discrepancies between experiments and models involve preheat, mix, and morphology

- **Ineffective Preheat**
  - Pecos experiments indicate we are over an intensity cliff
  - Omega and NIF show potential for a predictable preheat condition
- **Radiative cooling from Be walls and/or LEH window**
  - Long interval time (~50ns) between preheat and stagnation
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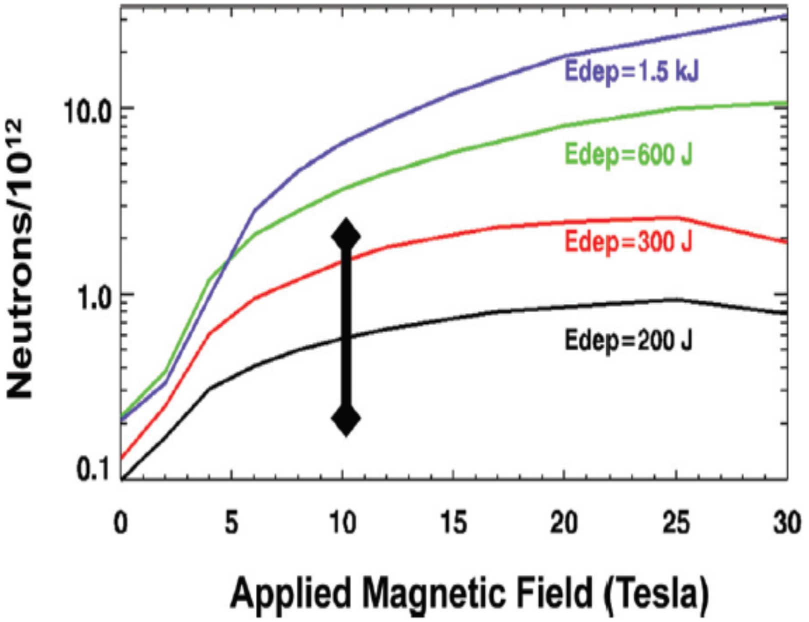
  - 3-D stagnation column

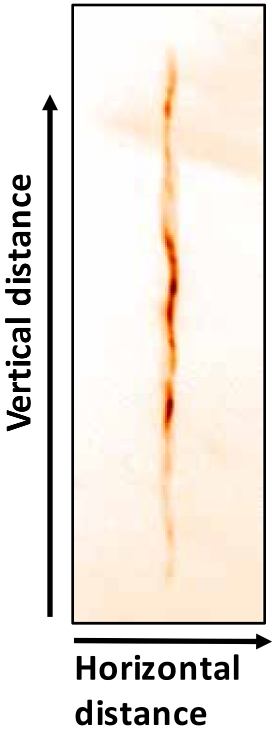
S.A. Slutz *et al.*, Phys. Plasmas 2016



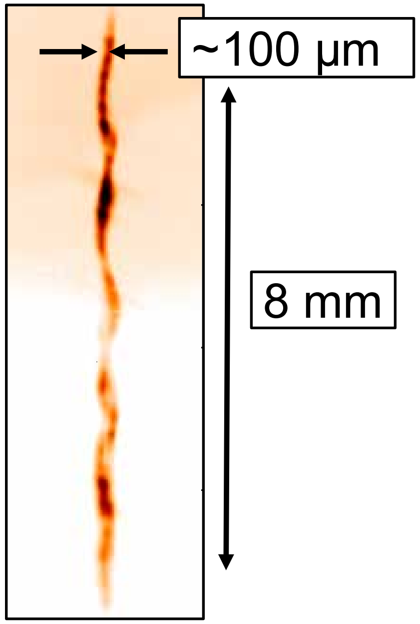
Even so, we are only ~4x away from the predicted optimum yield for this platform.

Experiments with DD neutron yields >10^{11} all show a narrow column of x-ray emission, albeit with structure

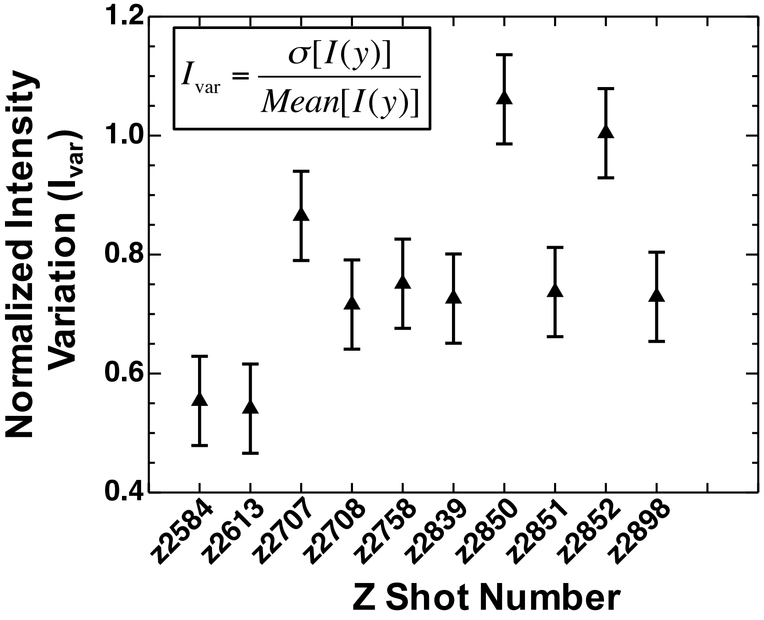
Shot z2707
Y_{DD} = 2.8e11



Shot z2839
Y_{DD} = 3.2e12

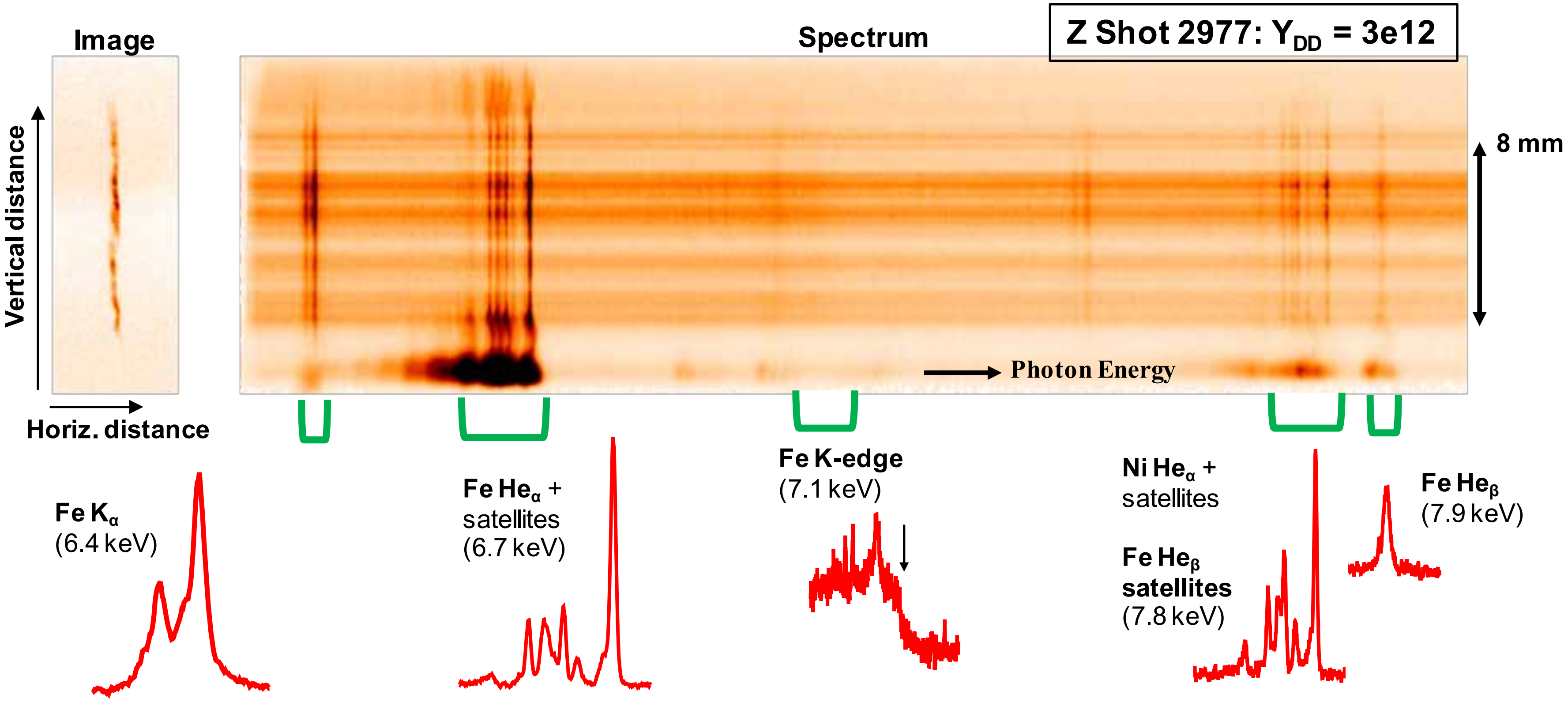


Vertical Intensity Variation vs. Shot Number



Vertical intensity variations can be as large as the mean intensity

Recent experiments obtained high-quality Fe spectra that enable a detailed analysis at many axial locations



Z Shot 2977: Y_{DD} = 3e12

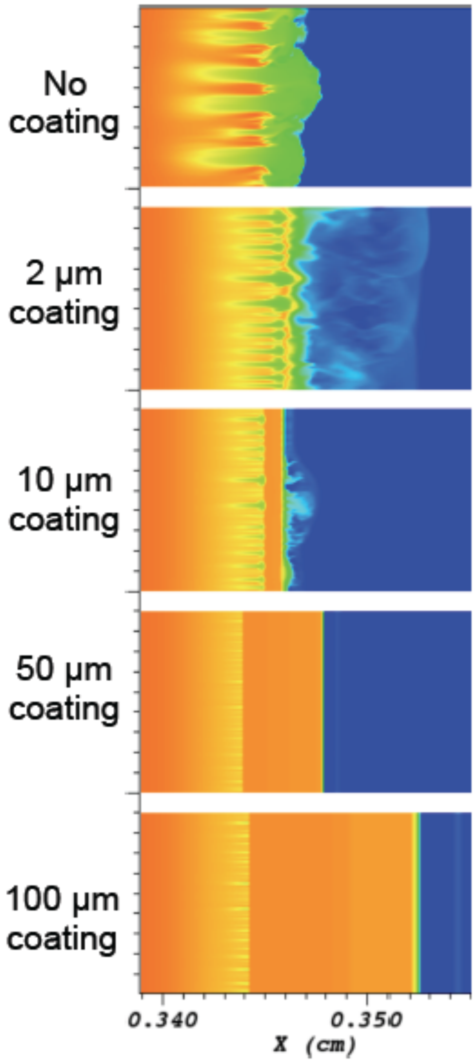
Conditions vary vertically in the range T_e = 1.4to 2 keV, n_e = 5e22 to 2.5e23 cm^{-3}

Fluorescence and K-edge absorption→ Be liner: T_e=10 eV with ρR=0.8 g/cm^2

Estimate mix fraction→ Be mix = 4-10% uniform atomic fraction assuming t = 2 ns

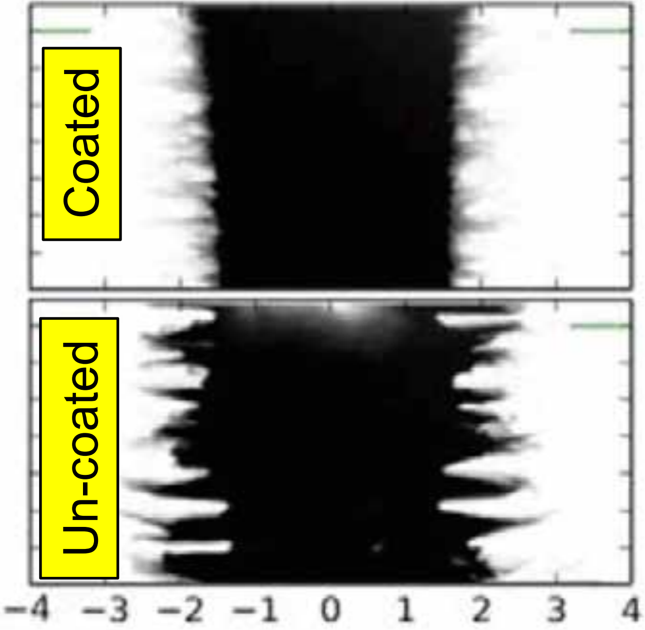
Variations in brightness correlated with T_e and n_e values, suggesting compression uniformity could be the cause

The electro-thermal instability can seed the MRT instability, and can be mitigated using dielectric coatings



Thick dielectric coatings suppress liner instabilities that are seeded by the electro-thermal instability

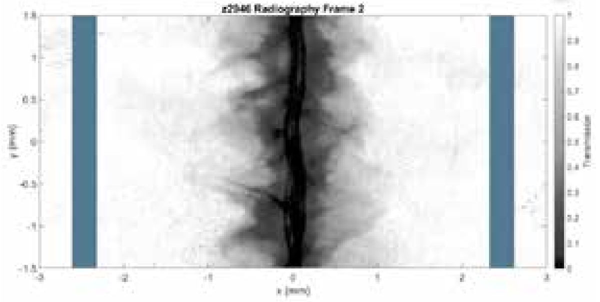
T.J. Awe *et al.,* Phys. Rev. Lett. (2016).

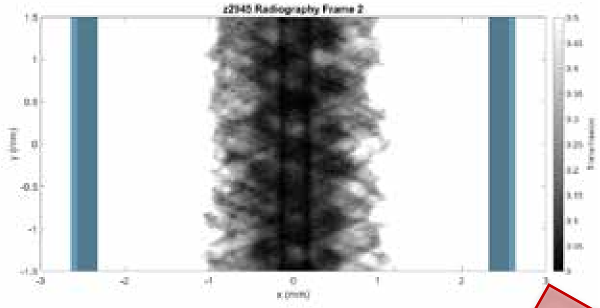


K. J. Peterson *et al*., Phys. Plasmas **19**, 092701 (2012);
K. J. Peterson *et al*., Phys. Plasmas **20**, 056305 (2013);
K. J. Peterson *et al*., Phys. Rev. Lett. **112**, 135002 (2014).

We have demonstrated the ability to impact the stagnation morphology through controlling the implosion

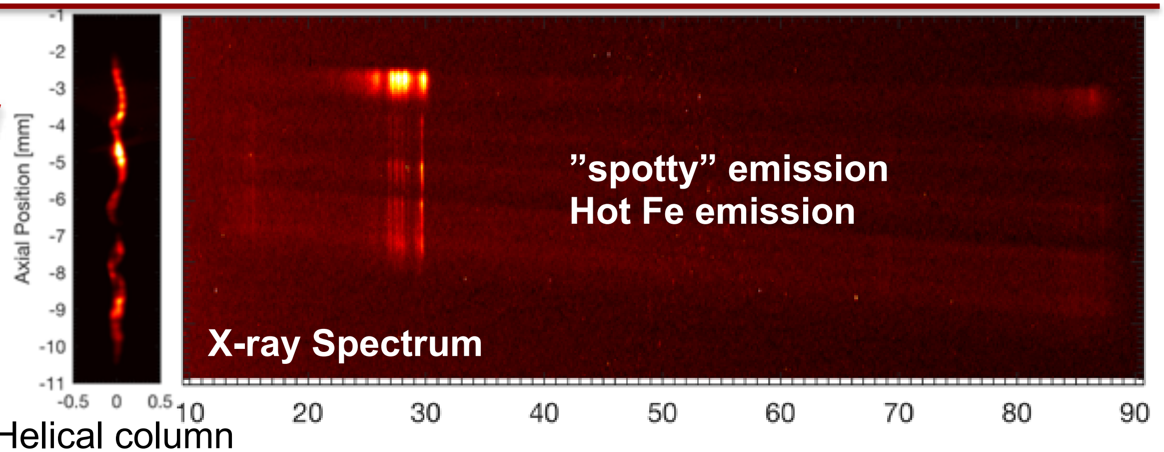
No coating





w/ dielectric coating

Implosion only experiments



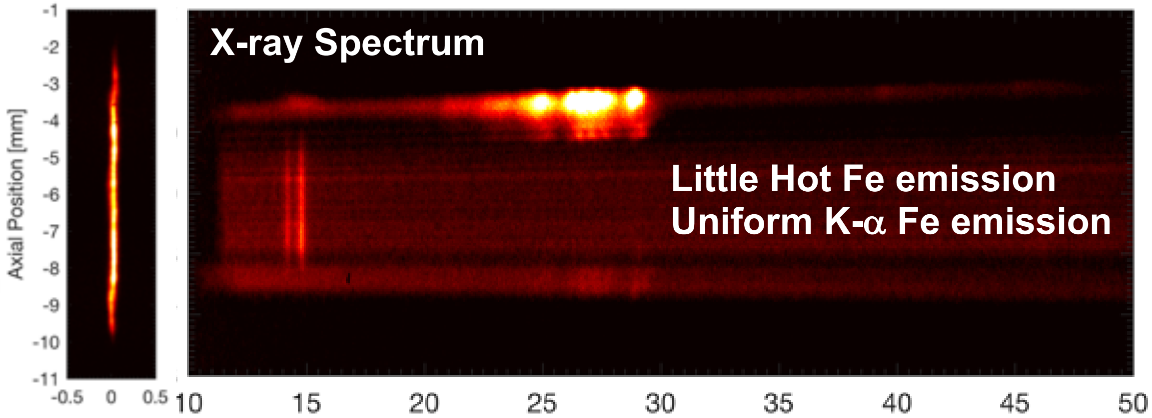
X-ray Spectrum

”spotty” emission
Hot Fe emission

Helical column
Highly variable intensity

Despite ”improved” morphology, neutron yield and ion temperature decreased

Much straighter column
Uniform brightness



X-ray Spectrum

Little Hot Fe emission
Uniform K-α Fe emission

Integrated experiments

Radiographs provided by Tom Awe and Dave Ampleford

Over the next 4 years we have an aggressive set of programmatic goals to evaluate the science of MagLIF and establish credible requirements for ignition and high yield

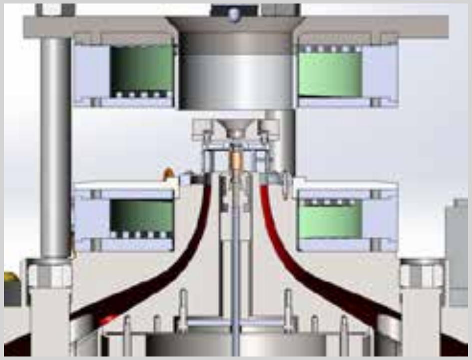
FY17

- Develop a methodology for inferring B-r and P-τ as quantitative performance metrics from integrated MagLIF experiments.
- Demonstrate >1 kJ of laser energy coupled to the MagLIF fuel
- Develop and characterize a new MagLIF baseline at ≥20 T, ≥20 MA, and ≥2 kJ
- Quantify the amount and relative origins of Mix
- Develop and characterize an enhanced MagLIF baseline at 30 T, 22-24 MA, and ≥6 kJ
- Provide credible physics extrapolation to ignition
  - **Demonstrate 30 kJ heating on NIF**
  - **Achieve a BR > 0.5 MG-cm ($R/r_\alpha > 2$)**
  - **Achieve fuel pressure > 5 Gbar and Pτ > 5 Gbar-ns**

FY20

We are developing two new integration platforms to provide enhanced capability for MagLIF on Z

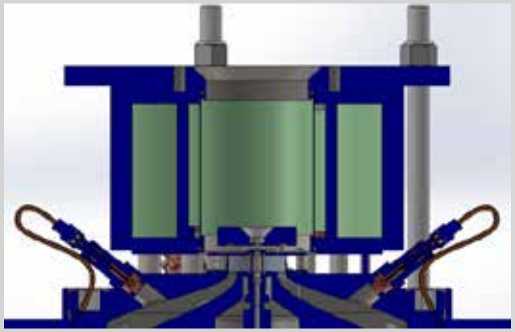
Rev 0 (FY13)



Demonstrated Capability

- 6.5 nH Load Inductance
- 18 MA Peak Current
- 0.4 MJ Energy Delivered
- 10-20 T Uniform Bz
- Full diagnostic access

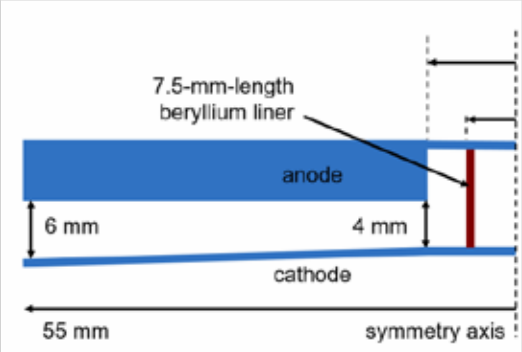
Low-L (FY18)



Design Goals

- 4.3 nH Load Inductance
- 22 MA Peak Current
- 0.55 MJ Energy Delivered
- 15-20 T Non-uniform Bz
- Full diagnostic access

Ultra Low-L (FY20)

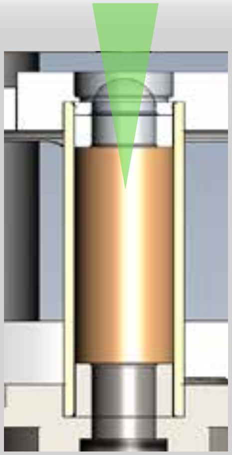


Design Goals

- ~3 nH Load Inductance
- >24 MA Peak Current
- >0.65 MJ Energy Delivered
- Up to 30 T Bz
- May have limited diagnostic access

We are evaluating two laser preheat platforms and are exploring windowless concepts

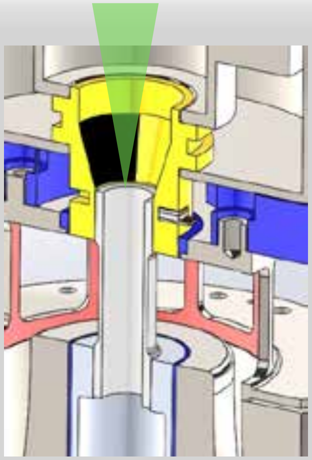
Warm Gas



Key Characteristics

- 1.5-3 um Windows
- Few Hundred Joule Pre-Pulse
- DD Gas < 1 mg/cc for thinnest windows
- Simplest Implementation

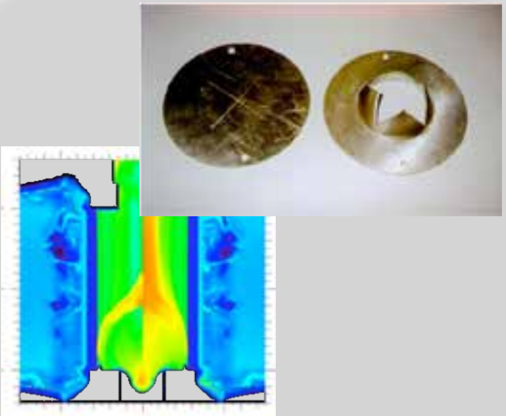
Cryo Gas



Key Characteristics

- ~0.1 um Windows
- May not require a pre-pulse
- DD Gas up to a few mg/cc
- Most complex implementation

Windowless (Conceptual)

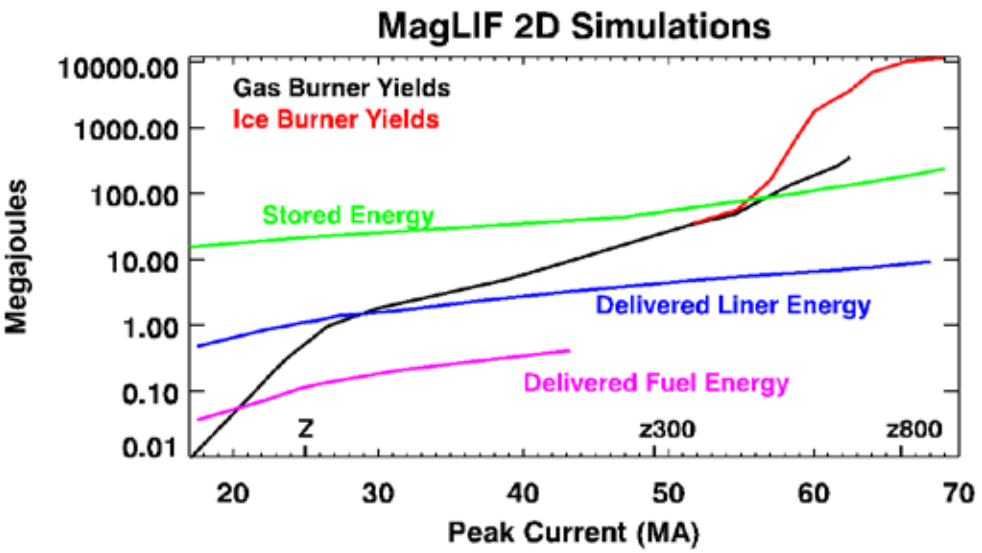


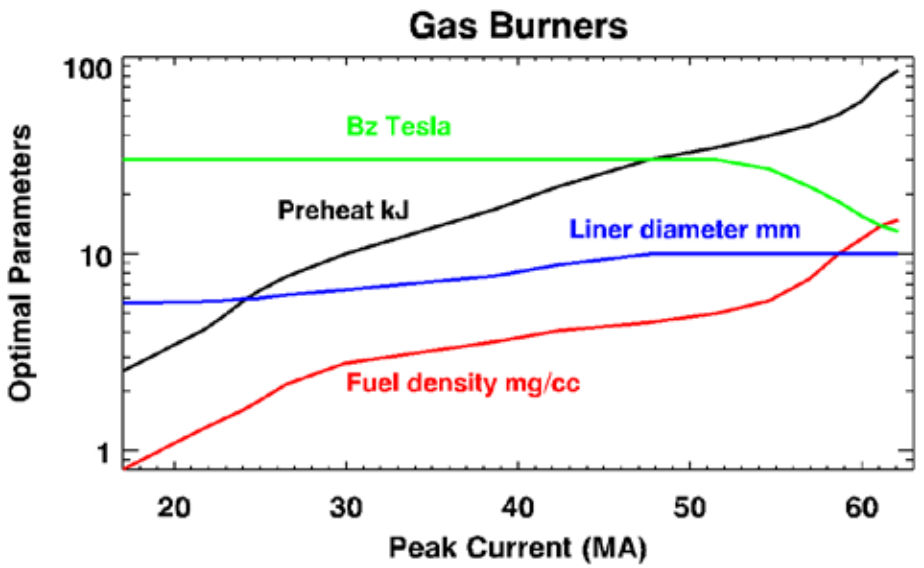
Key Characteristics

- No window
- Could use a perforated thick window or a cryo liquid pool
- May require very early (~μs) pre-pulse to perforate thick window

Ultimately, we would like to define the requirements to reach 10-30 MJ single-shot yields on a “Z-Next”

- Today’s MagLIF experiments couple 17-18 MA (~0.4 MJ) to the target
- At **24 MA**, an optimized target design with **30 T** and **>6 kJ** of preheat is predicted to produce **>100 kJ DT yield**
  - Obtaining all of these parameters simultaneously on Z will be a challenge!
- Larger scale designs don’t require larger Bz or scaled line designs, but do require **higher fuel density** and **more preheat**


MagLIF 2D Simulations


Gas Burners

S.A. Slutz *et al.*, Phys. Plasmas 23, 022702 (2016).