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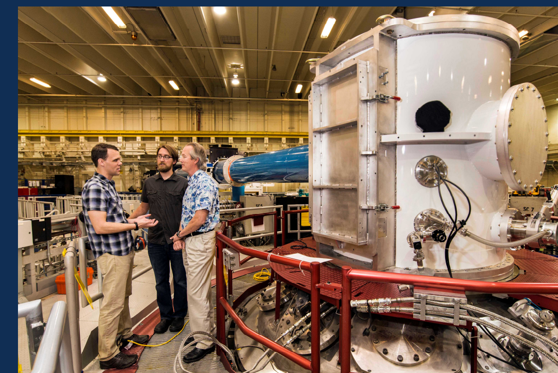

Progress in Preconditioning MagLIF fuel and its Impact on Performance

Kyle Peterson

A.J. Harvey-Thompson, T.J. Awe, D.E. Bliss, Matthias Geissel, M.E. Glinsky, M.R. Gomez, E. Harding, S.B. Hansen, C. Jennings, M.W. Kimmel, P.F. Knapp, S.M. Lewis, K. Peterson, M. Schollmeier, J. Schwarz, A. B. Sefkow, J.E. Shores, S.A. Slutz, D.B. Sinars, I.C. Smith, C.S. Speas, R.A. Vesey, M.R. Weis, and J.L. Porter

47th Annual Anomalous Absorption Conference

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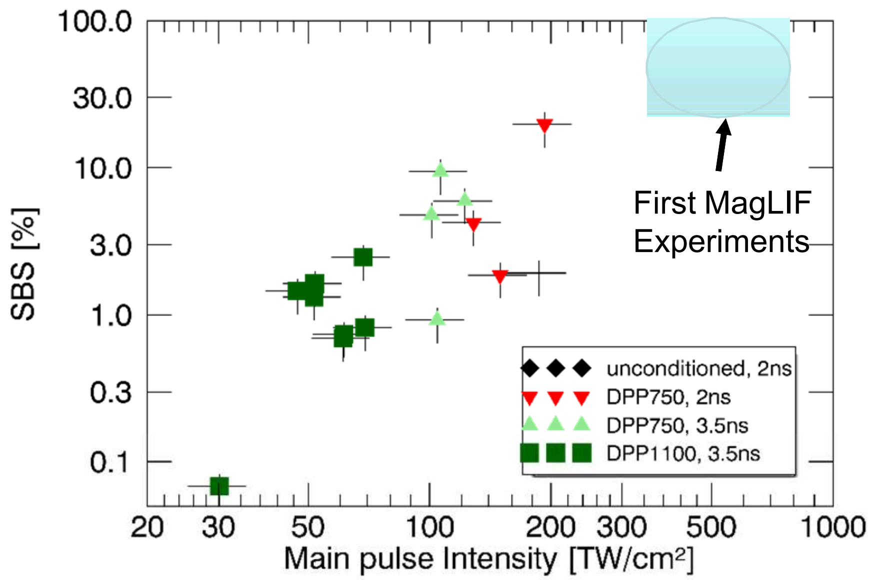
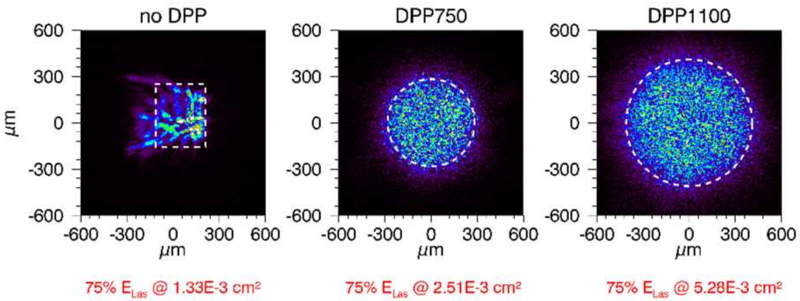
While the initial MagLIF experiments were highly successful, the laser pre-heating was not ideal

- **There is strong evidence for poor laser energy coupling in the original MagLIF experiments.**
- **Initial efforts to increase coupled energy (thinner windows, higher delivered laser energy) did not improve target performance. Data is consistent with increased mix.**
- **SBS backscatter of almost 50% of beam energy has been observed.**
- **Current effort is focused on improving understanding & predictability, minimizing LPI, and developing a scalable platform.**

SBS on ZBL (PECOS) Preheating experiments



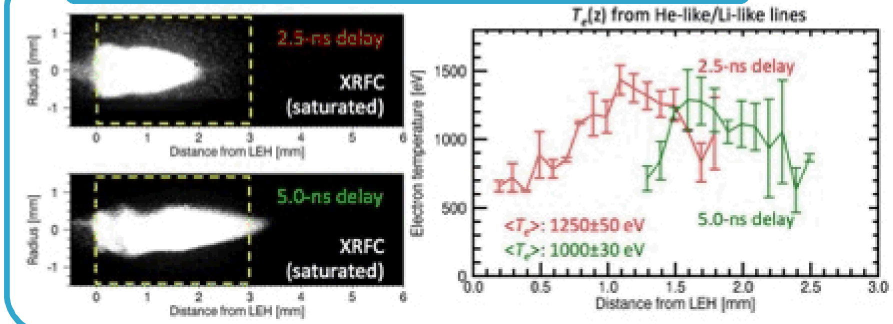


We have made significant progress in our understanding of laser heating deuterium fuel for MagLIF

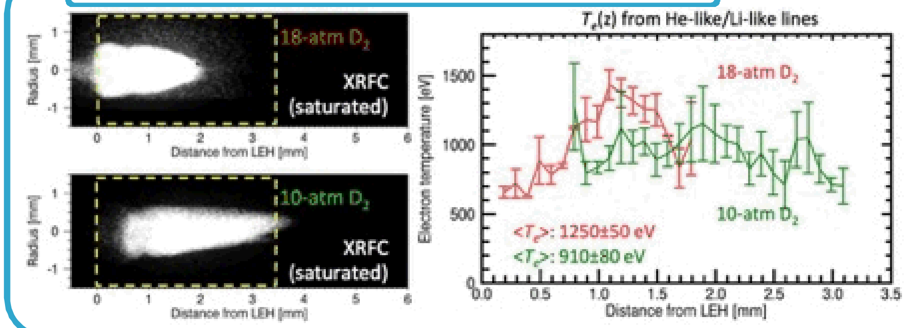
- Experiments at OMEGA-EP, OMEGA, NIF, and on ZBL (PECOS) have provided insight into improving preheating of MagLIF targets
- We have developed a new, significantly better understood, low LPI laser preheating platform that has produced record MagLIF performance (~50% of clean 2D)
- Some fraction of window and upper end cap material is mixing into the fuel during MagLIF implosions.
- Demonstrated predictable unmagnetized laser coupling in a surrogate gas at 30kJ

We have gained valuable insight into what factors influence laser heated plasma conditions using Ar spectroscopy at OMEGA-EP

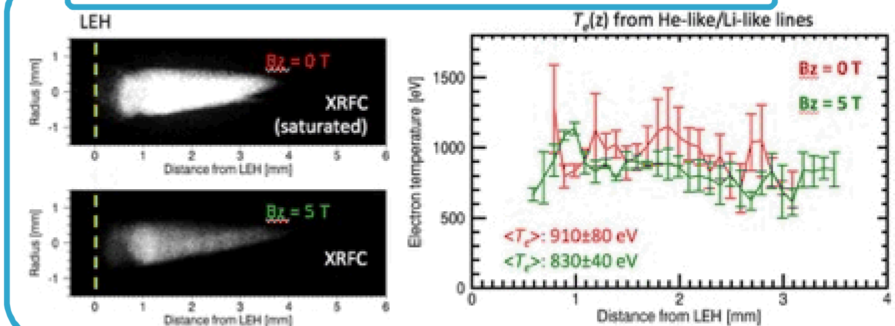
Main-pulse delay drops $\langle T_e \rangle$



Lower gas pressure drops $\langle T_e \rangle$



No clear indication of 5T Bz effects



- When main pulse is delayed, the gas expands more and density drops
- As density drops, beam propagates farther and <Te> is lower
- No significant differences in inferred plasma conditions with 5 T – insufficient magnetization?

T. Nagayama, A. H. Thompson, M. Wei

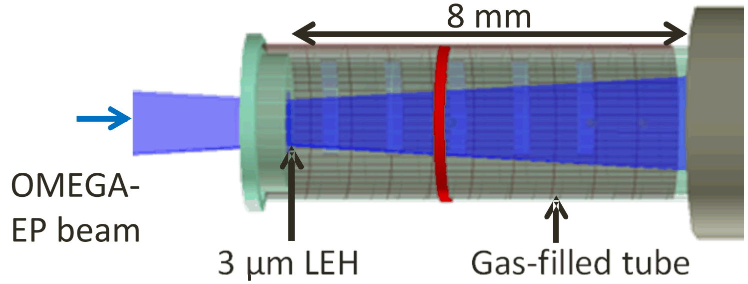
SBS has been substantially reduced by increasing dwell time between pre-pulse and the main laser pulse

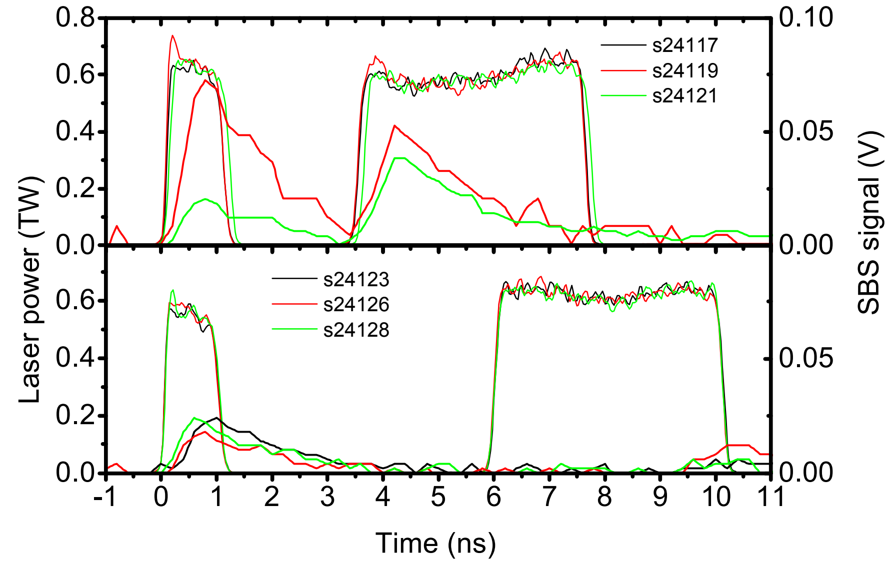
- **OMEGA-EP experiments with similar laser pulses to ZBL exhibit significant SBS during <u>both</u> the pre-pulse interaction with window and the main laser pulse**

- **SBS during the main pulse was insignificant when dwell time was doubled to 5 ns.**

- **On ZBL without co-injection, the maximum pulse window on ZBL is ~6ns which puts practical limits on dwell time of ~2ns**

All shots use n_e=0.055n_c D_2 gas

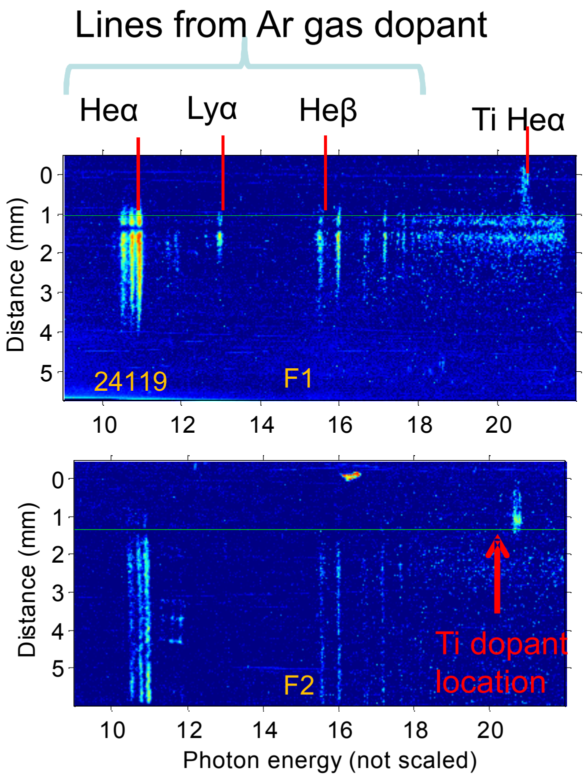


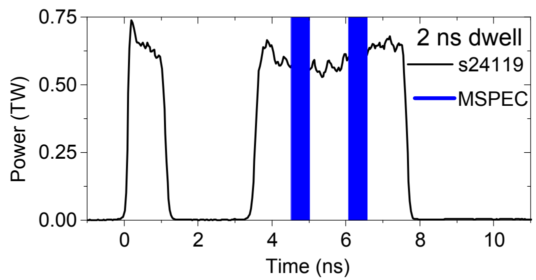


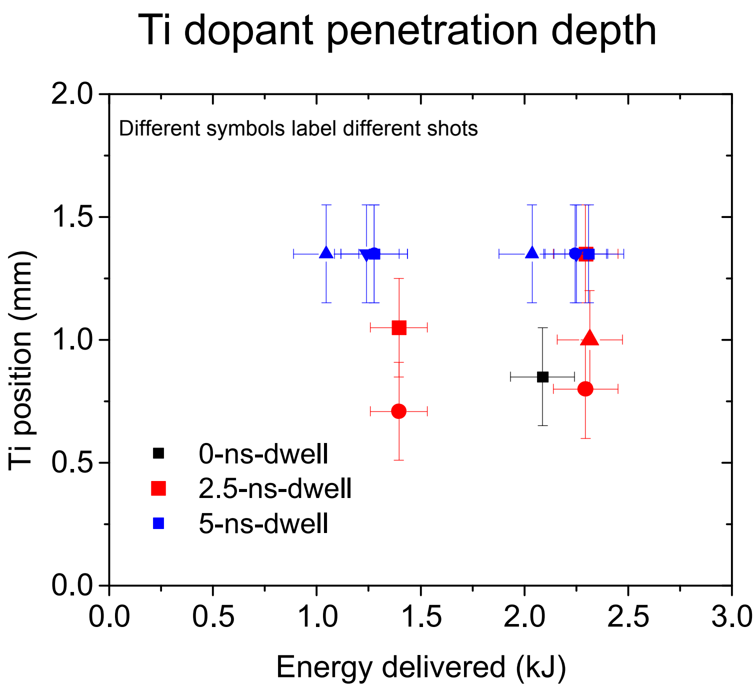
Laser power and SBS signals for two different pulse shapes

A. H. Thompson, M. Wei

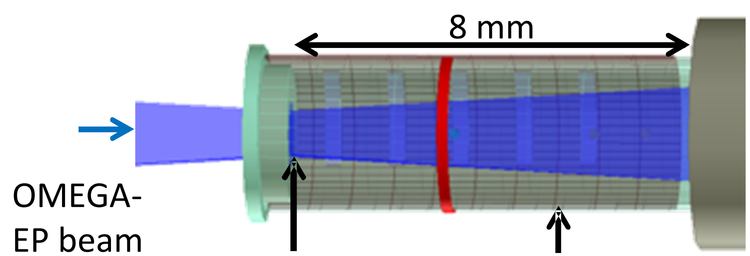
Increasing dwell time also pushes window material deeper into the target



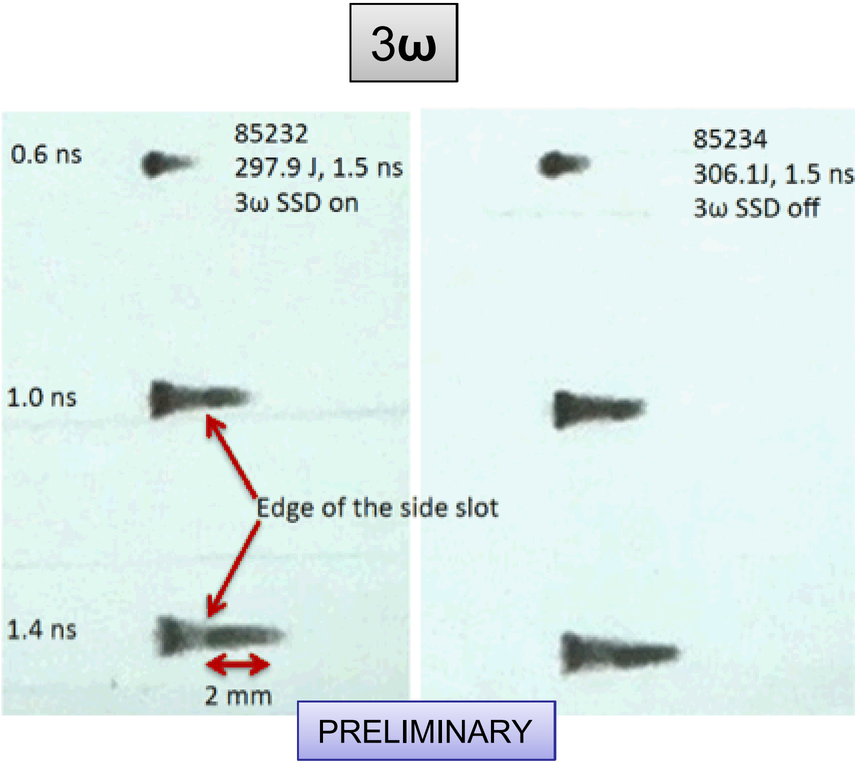


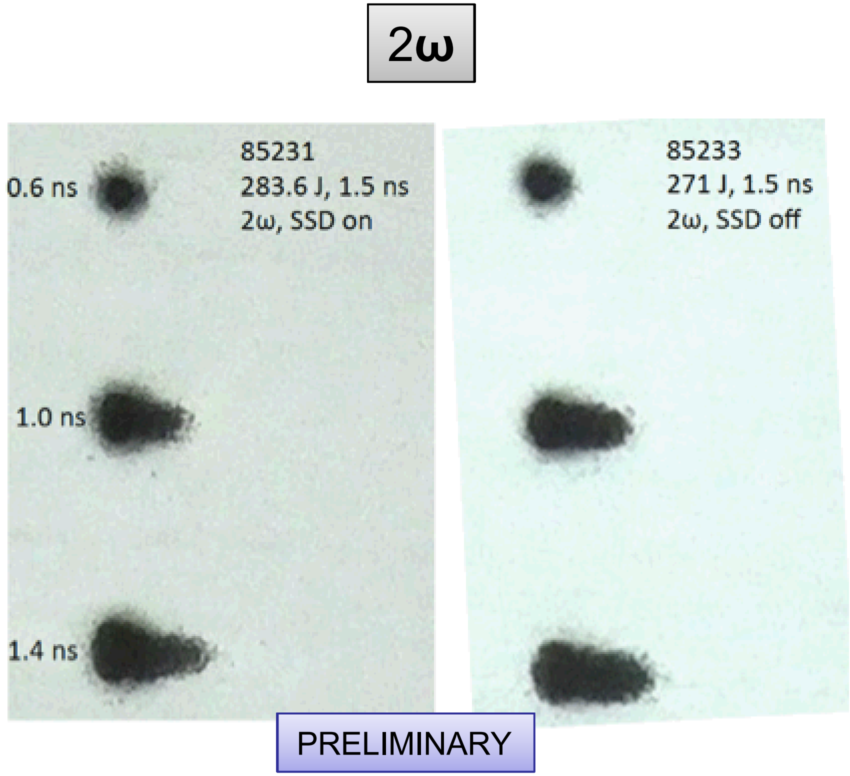


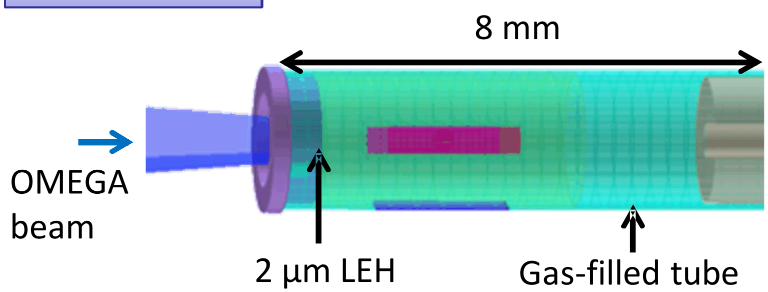
All shots use $n_e=0.055n_c$ D_2 gas



Significant differences were observed between 2ω and 3ω light on experiments at OMEGA



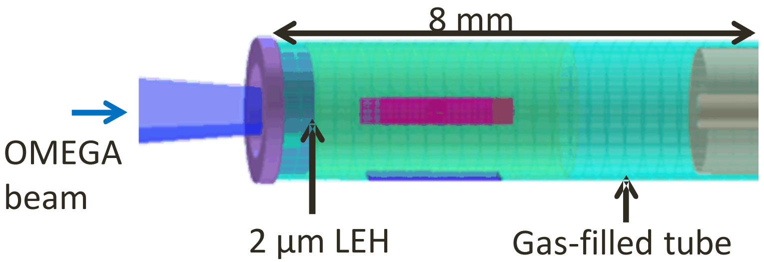




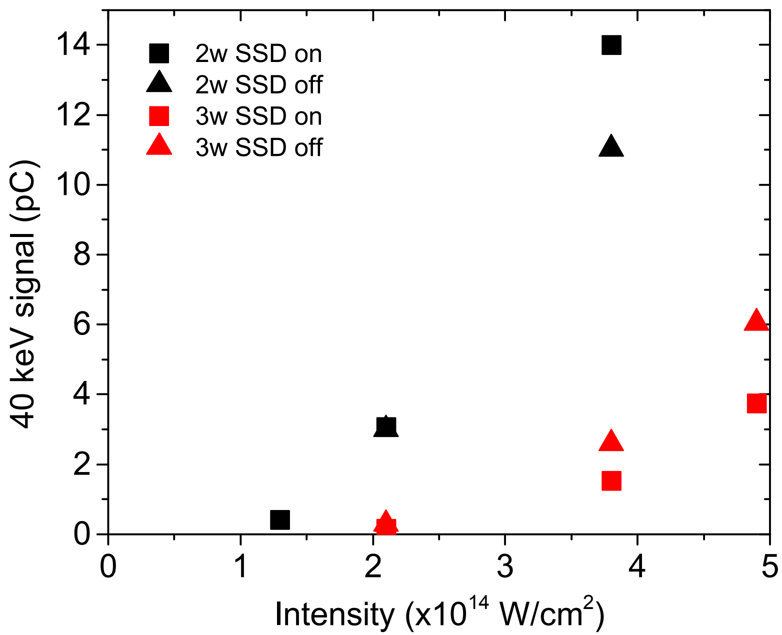
All shots use n_e=0.05n_c D_2 + Ar gas

Inferred SRS was significantly less with 3ω vs 2ω, as expected

All shots use n_e=0.05n_c D_2 + Ar gas

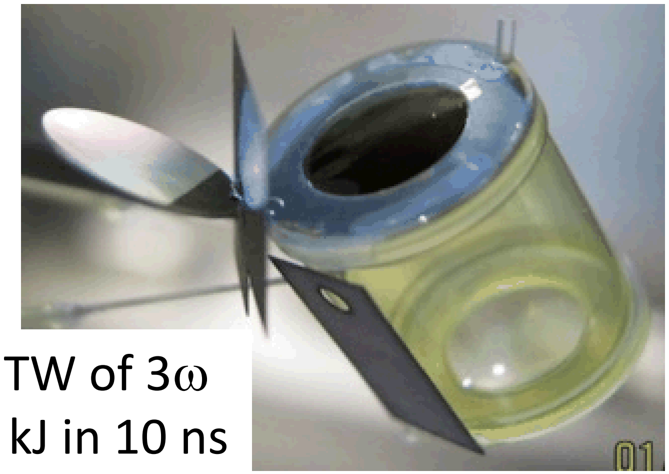


- **SSD only marginally reduced level of hard x-rays with 3ω**
- **In order to maintain similar levels of low backscatter, ZBL's 2ω light puts severe constraints on the operating intensities and the amount of energy delivered to fuel**
  - **Is 3ω on ZBL required to effectively deliver more energy to targets on Z?**
  - **Would STUD pulses on ZBL be a cheaper and/or more effective option?**
  - **SSD - probably not worth investment**



Hard x-ray signals indicative of stimulated Raman scattering

HYDRA pre-shot simulations predicted time dependent laser propagation remarkably well in our first 30kJ preheating experiments at the NIF

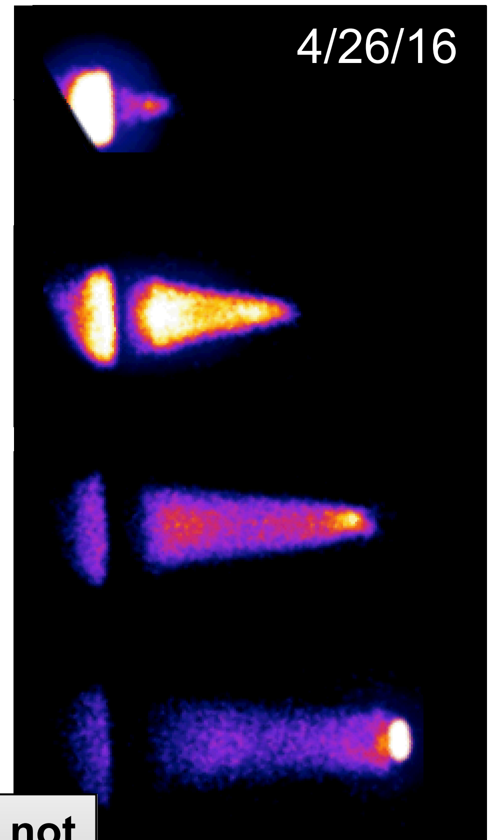


3 TW of 3ω
30 kJ in 10 ns

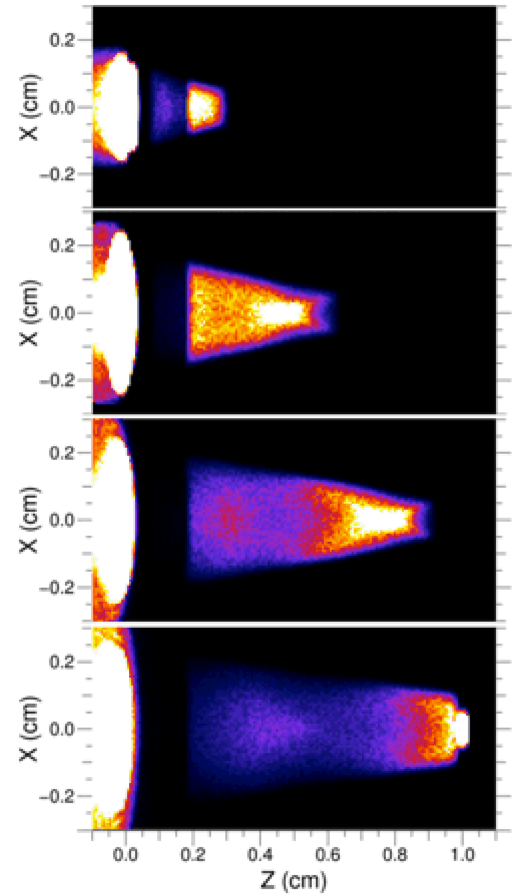
- 1 cm long by 0.845 cm gas pipe
- Gas fill: 1 atm of C_5H_{12} at 300K, doped with 1% *Ar*
- 100 μm thick epoxy tube
- 0.75 μm polyimide LEH window

Primary Objective: Assess whether or not laser preheating is a viable scaling path for magnetized target fusion (MagLIF)

GXD Data



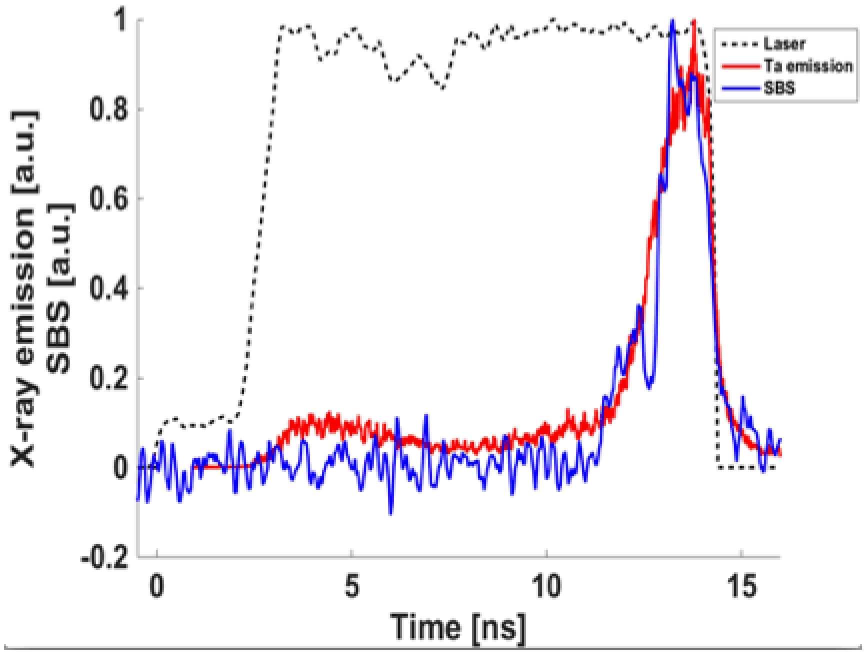
Hydra Sim

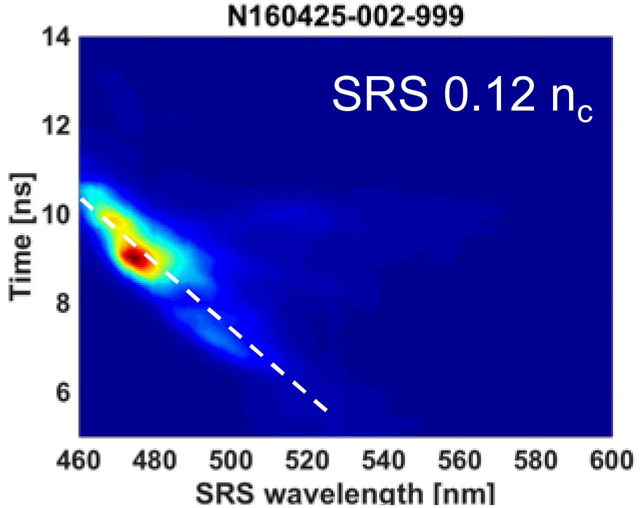


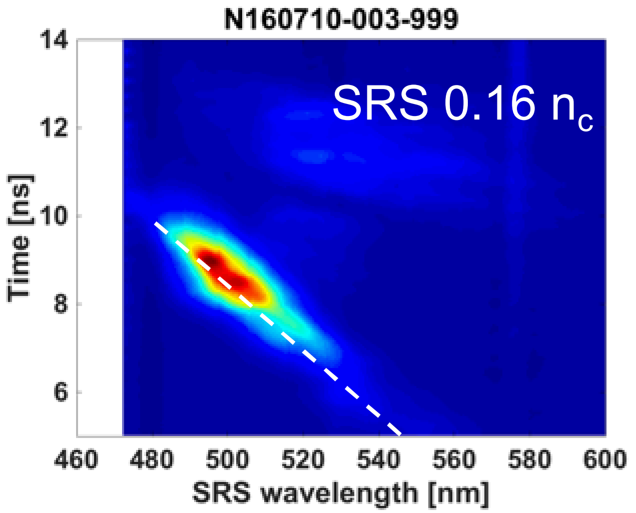
A. B. Sefkow, B. Pollock, C. Goyon, J. Moody

NIF experiments demonstrated that effective and predictable coupling can occur over relatively large time scales (~10ns)

SBS time history







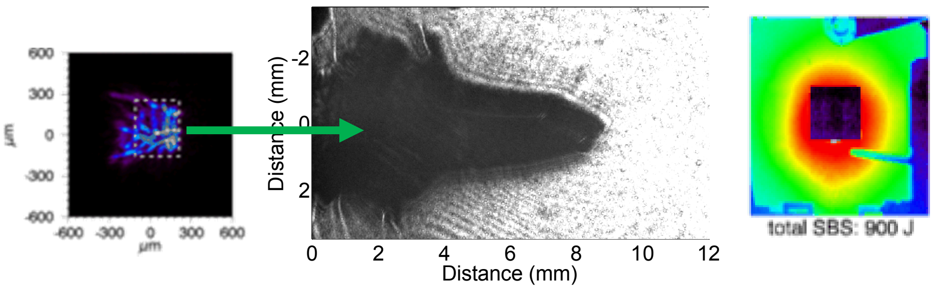
Estimated coupling is (98.6 +/- 0.2) % within gas-pipe

Experiments later this year will test propagation in cryo cooled deuterium

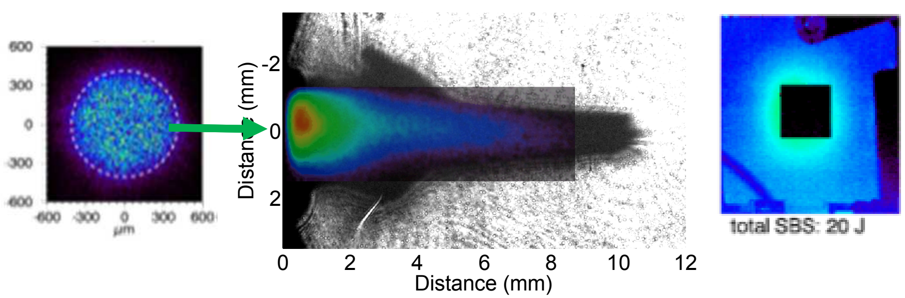
A new laser preheating platform has been developed with significantly less LPI for MagLIF experiments on Z

Optical Blastwave Measurements

Original MagLiF Configuration (2.5kJ)

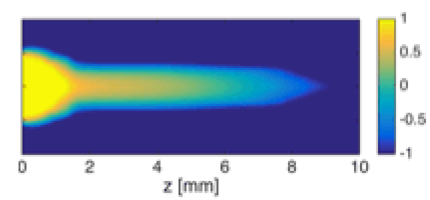


New preheating platform – Rev 1



- 1100 μm Distributed Phase Plate
- Lower laser intensity
- 80 J pre-pulse, 1500J 4ns main pulse

- Reduced SBS from ~50% to <3%
- Enhanced penetration depth with **<u>reduced</u>** laser energy
- Less conical and more cylindrical energy deposition
- ~600J deposited in gas
- *Going forward, fuel density will be increased to couple more energy to fuel*



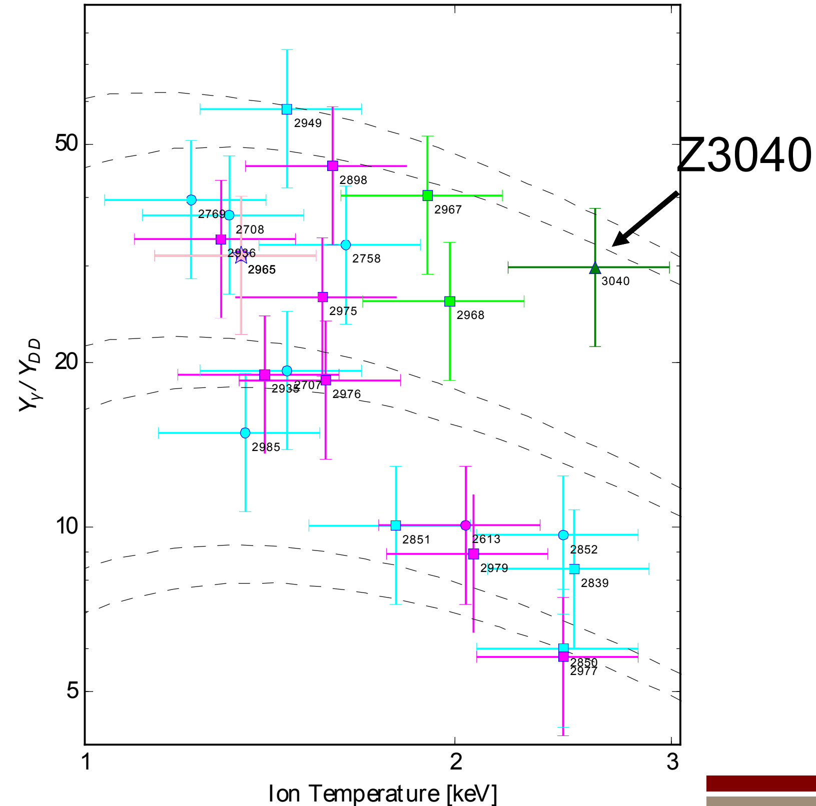
Simulated time-integrated X-ray image

M. Geissel, A. H. Thompson, M. Weis

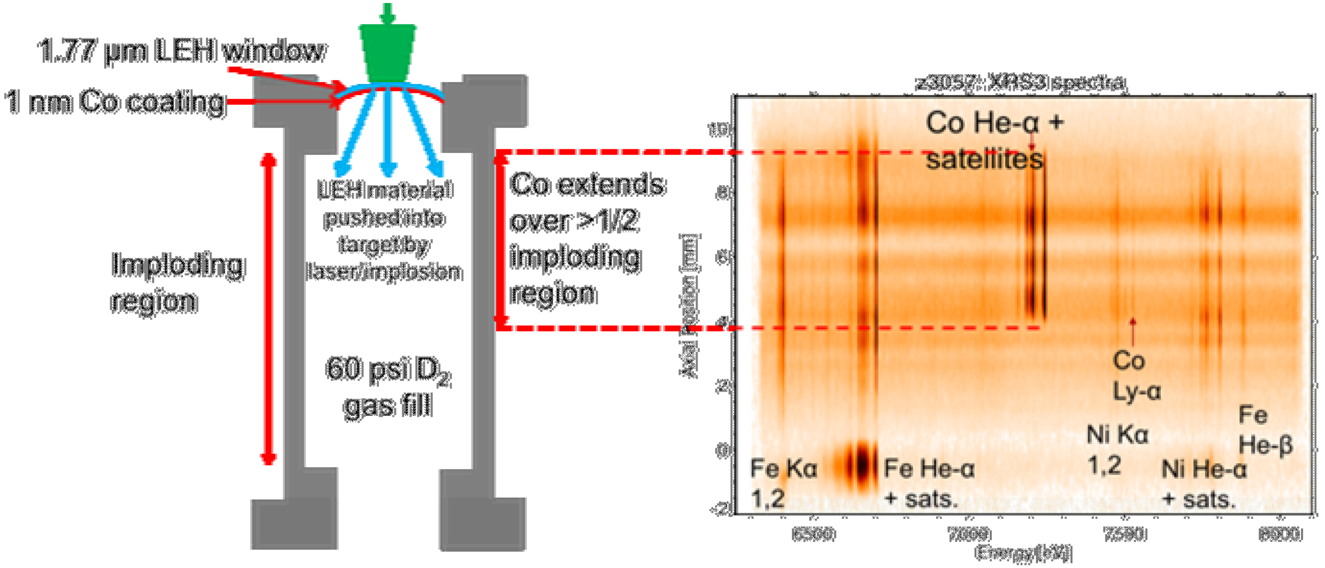
The new laser preheat configuration has produced the highest MagLIF integrated yields thus far, but questions remain about reproducibility

	z3040	Z3041	z3057
Laser energy	70 + 1460 J	73 + 1534 J	103 + 1283 J
Y_{DD}	4.1e12 ± 20%	3.2e11 ± 20%	2.0e12 ± 20%
Comments	**~50% of clean 2D**	Direct repeat of z3040.	Co coating on LEH

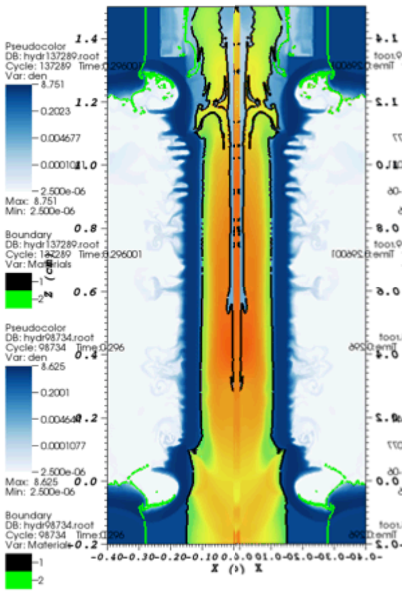
- Neutron yield of nominally identical shots has varied by more than 10X
- What is the source of variation?
  - Dust?
  - Mix Cliff?
  - High convergence (CR 40+)?
- Repeat shots in PECOS of laser configuration show no significant shot-to-shot variations
  - Limited statistics
  - Incomplete diagnostics
  - Imperfect surrogacy



Over the past year, We have made significant progress in diagnosing and understanding mix in MagLIF implosions on Z

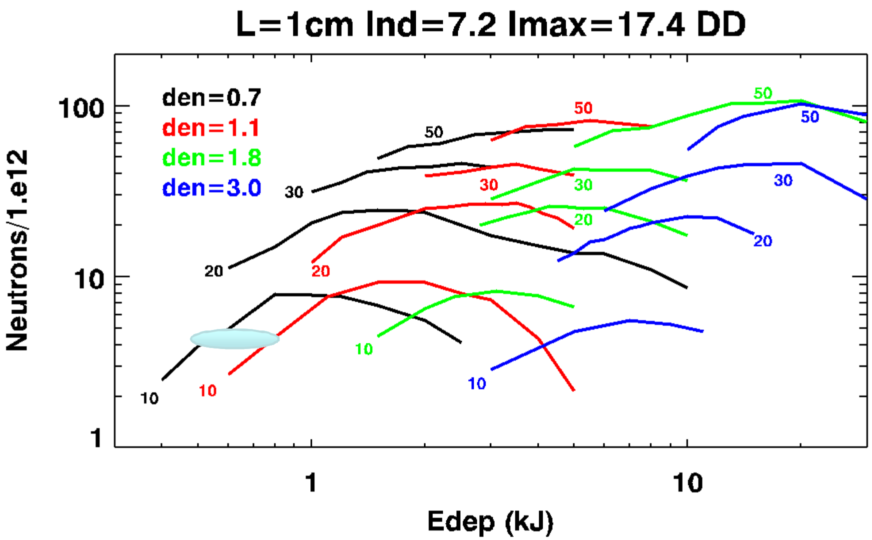


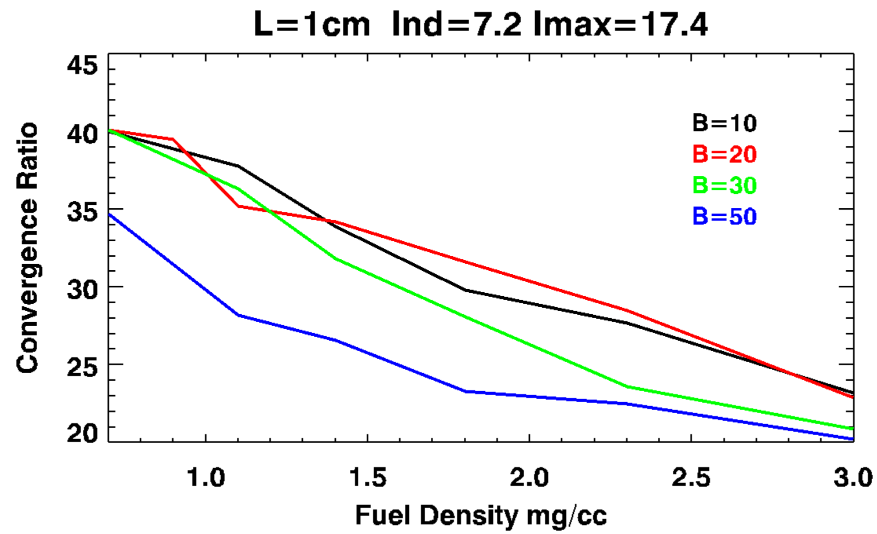
HYDRA



- Both window and upper endcap material has been observed to mix into fuel at stagnation
- The amount of mixed mass is still unclear as well as the relative impact of liner vs laser induced mix on stagnation performance
  - Target performs ~50% of clean 2D regardless of preheat energy deposited
  - Spectroscopic analysis (uniform mix assumption) infers catastrophic levels of C and Be in the fuel (recent Co and Kr dopants will help further constrain)

Improving laser heating alone is not sufficient to realize significant increase in performance of MagLIF targets on Z

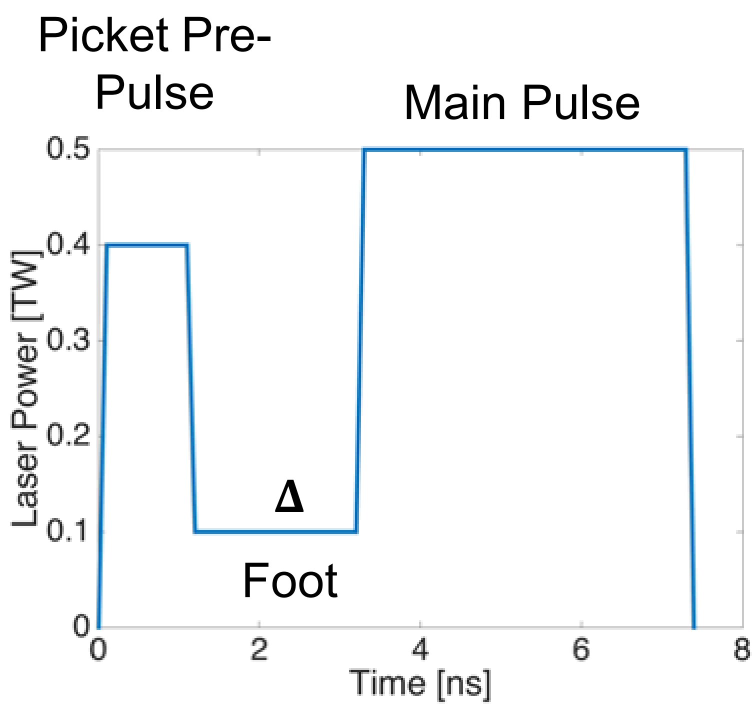


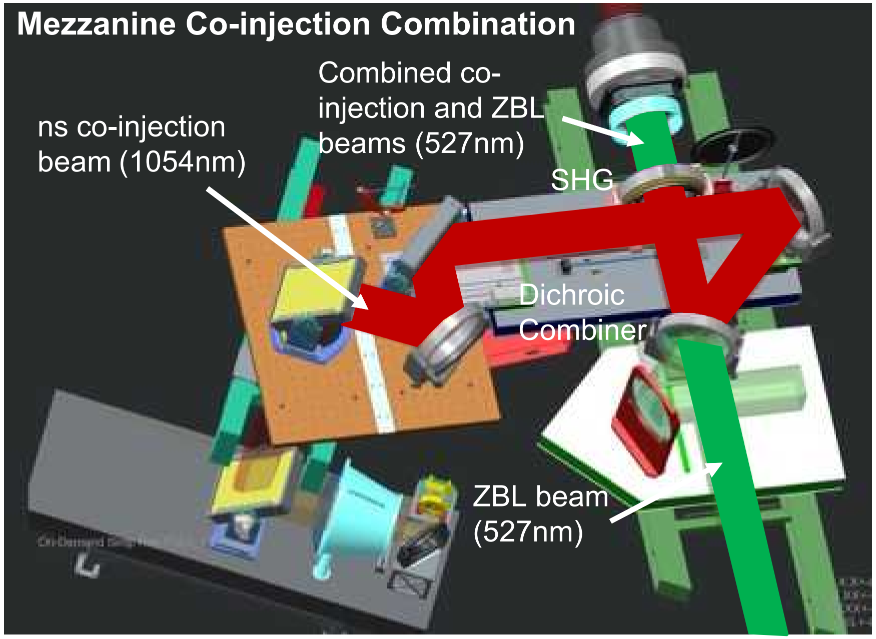


- Larger fields increase the burn time
- Higher fuel densities lower convergence
- Lower inductance feed increases current

Larger initial magnetic fields are needed!!

Co-injection of Z-Petawatt is now fully operational and will be used to mitigate the impact of the window as well as increase deposited energy



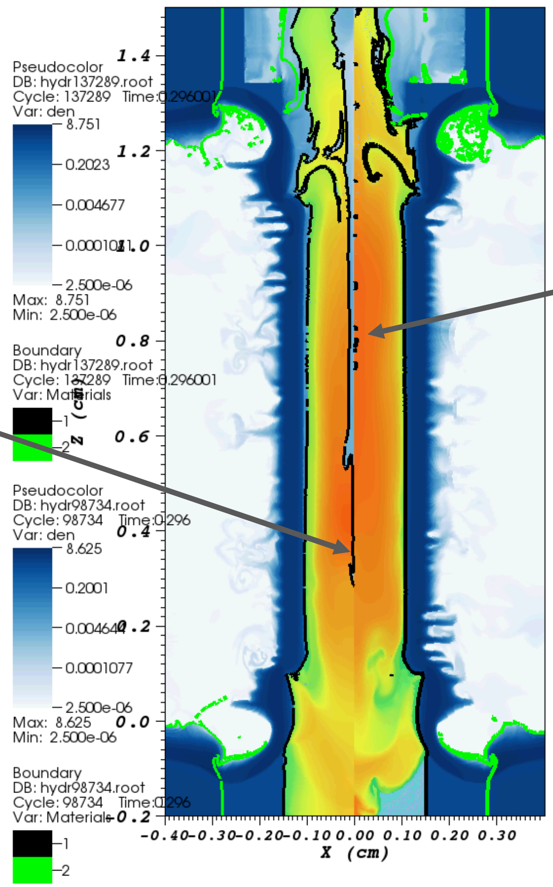


Fixed ZBL temporal window limits dwell time and total energy at fixed laser power

ZPW adds up to 400 J in 2 ns at any arbitrary time which frees ZBL to use the full pulse length

Co-injection is predicted to significantly reduce mix and enhance coupling

Standard Pulse Shape	**Co-injection Pulse Shape**
0.7 kJ in gas	1.6 kJ in gas (90 psi)

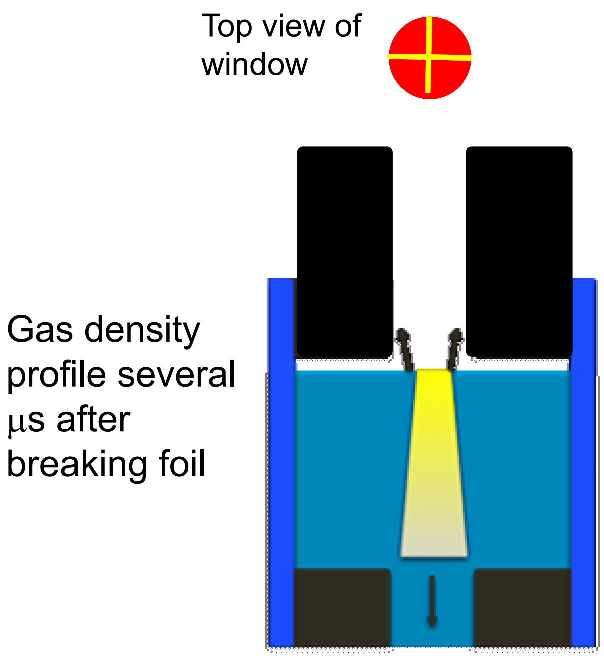


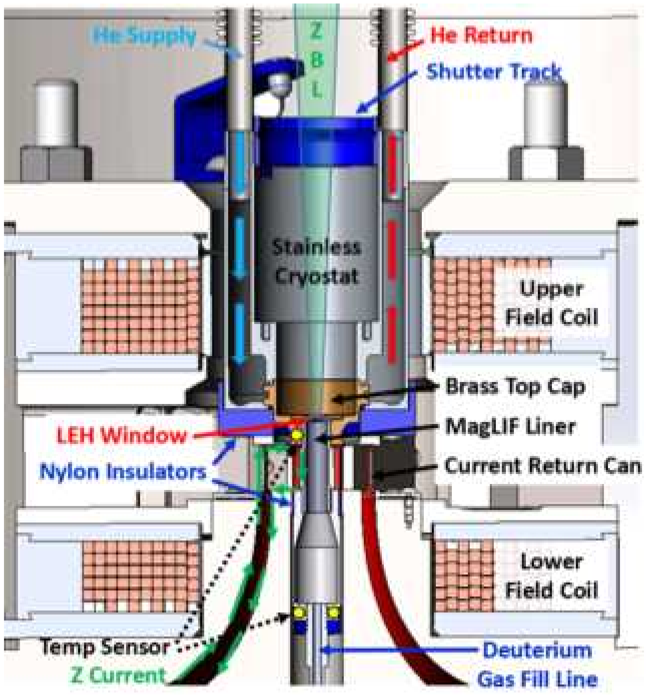
Simulated Window Mix

Simulated Window Mix

We are working to minimize the window mass which is expected to improve performance and predictability

- **Lasergate**
  - Window designed to fold open in controllable manner (e.g. shocktube)
  - Rarefaction wave propagates downward at ~1 mm/μs, voiding the tunnel region.
  - Effort is just starting up
- **Cryo**
  - Ice-mitigation features including protective shroud isolating target
  - New 6x faster cryostat
  - New compact cryogenic deuterium fiber extruder





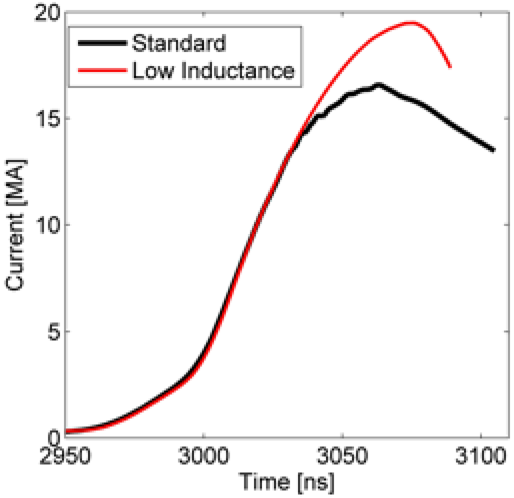
We have made significant progress in our understanding of laser heating deuterium fuel for MagLIF

- **Progress**
  - Experiments at OMEGA-EP, OMEGA, NIF, and on ZBL (PECOS) have provided insight into improving preheating of MagLIF targets
  - We have developed a new, significantly better understood, low LPI laser preheating platform that has produced record MagLIF performance (~50% of clean)
  - Some fraction of window and upper end cap material is mixing into the fuel during MagLIF implosions.
  - Demonstrated predictable unmagnetized laser coupling in a surrogate gas at 30kJ
- **Going Forward**
  - Determine source if source of variability is laser in integrated experiments.
  - Better quantify mix and relative impact on performance
  - Ramp up efforts to minimize or eliminate the laser entrance window
  - Assess whether laser heating is a viable scaling path (NIF)

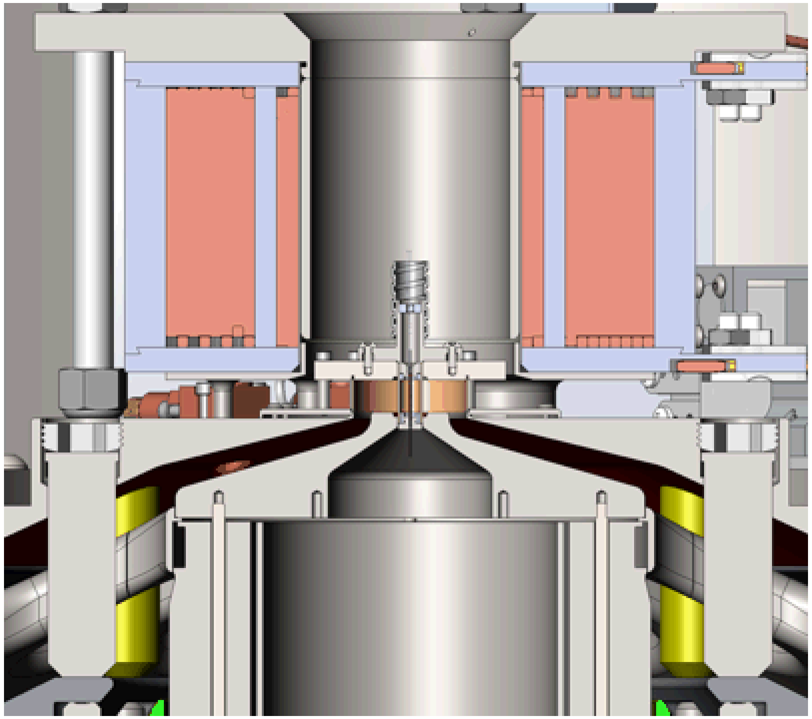
Backups

New integrated platforms have been developed and are now being tested in order to produce conditions required for scaling

- Original coil design has failed in two attempts to deliver >10T
- New Low-L configuration has been developed with 10-20% increase in peak current has been demonstrated with 10 T
- Integrated tests will be performed later this summer



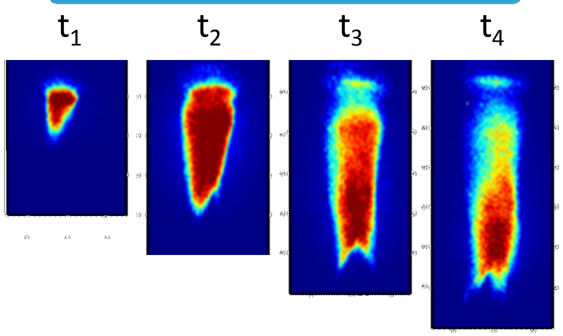
Low-L monolithic coil



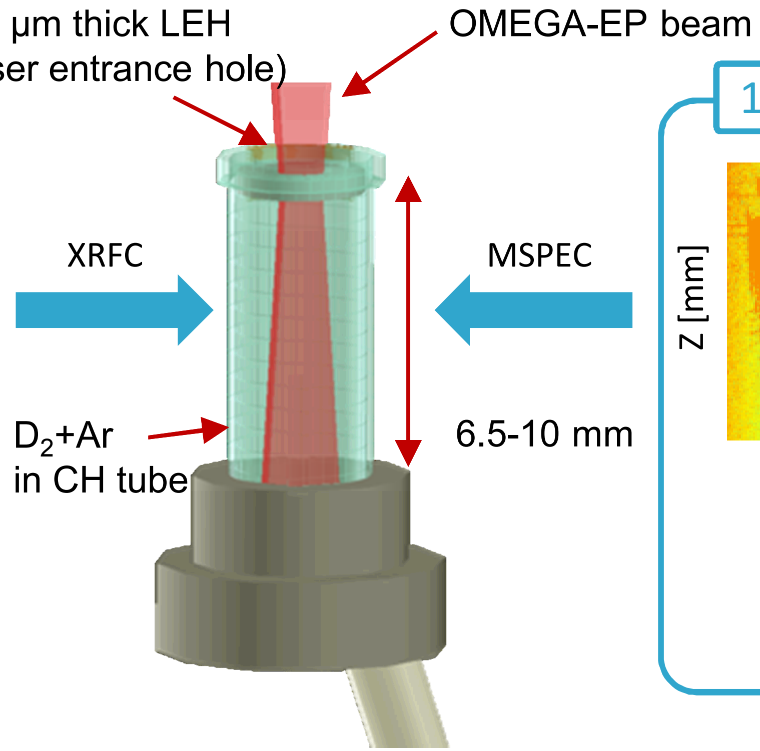
Capable of ~20 MA, 15-20T fields (non-uniform)

MagLIF preconditioning is being investigated at OMEGA-EP facility with various diagnostics

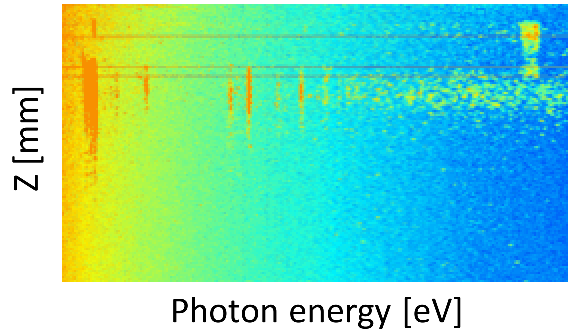
2D image with XRFC



- Laser propagation
- 2D intensity structure
- Beam split



1D spectra with MSPEC



- Laser propagation
- $T_e(z)$

T. Nagayama, Anomalous Absorption 2016

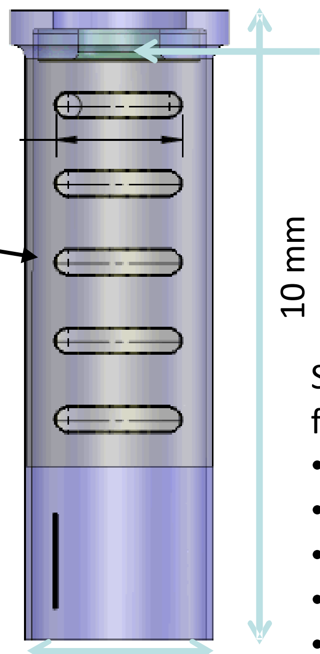
We are working towards trying to diagnose plasma lifetimes on OMEGA-EP by measuring Ne continuum emission

<u>MSPEC was reconfigured* with a new RbAP crystal to record Ne K-shell line emissions</u>

Multi-slit window design

Slit dimension 2 mm x 0.3 mm

film

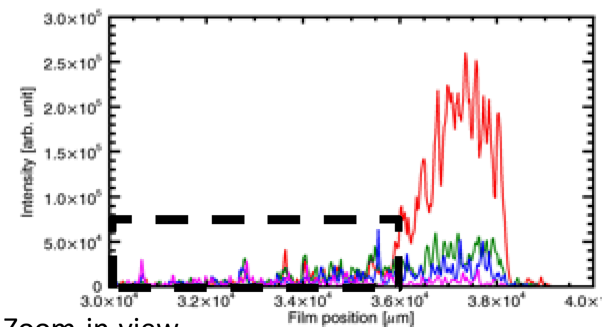


LEH washer with 1.3 mm diameter, 3um-thick window

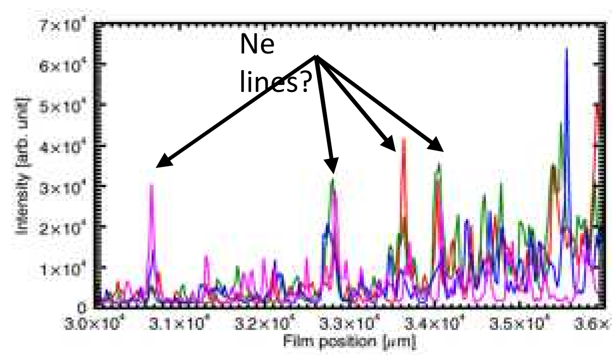
Slit distance from LEH:

- 0.7 mm
- 1.95 mm
- 3.2 mm
- 4.45 mm
- 5.7 mm

10 atm D2 with 2.5% Ar + 0.2 atm Ne



Zoom-in view



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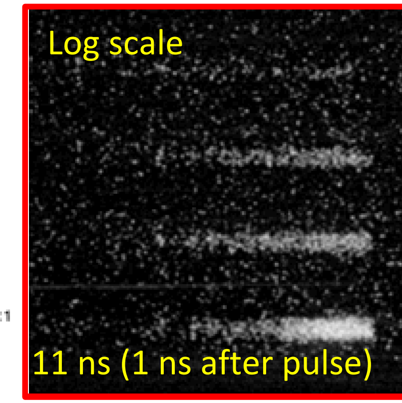
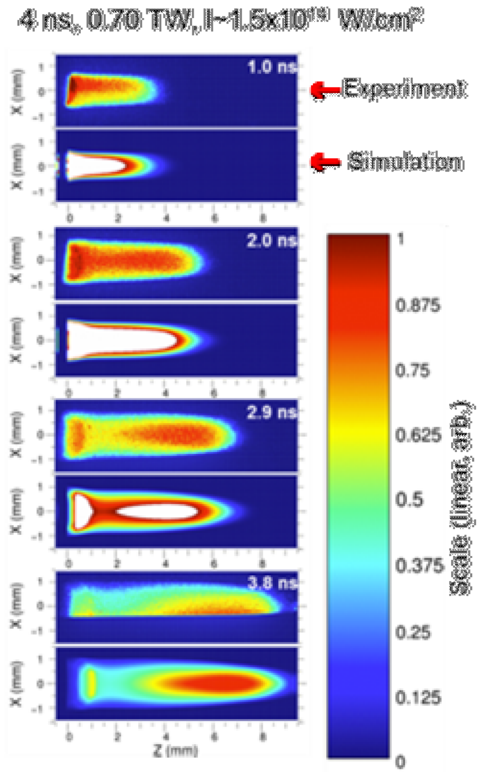


*Design courtesy of Bob Heeter and Jim Emig

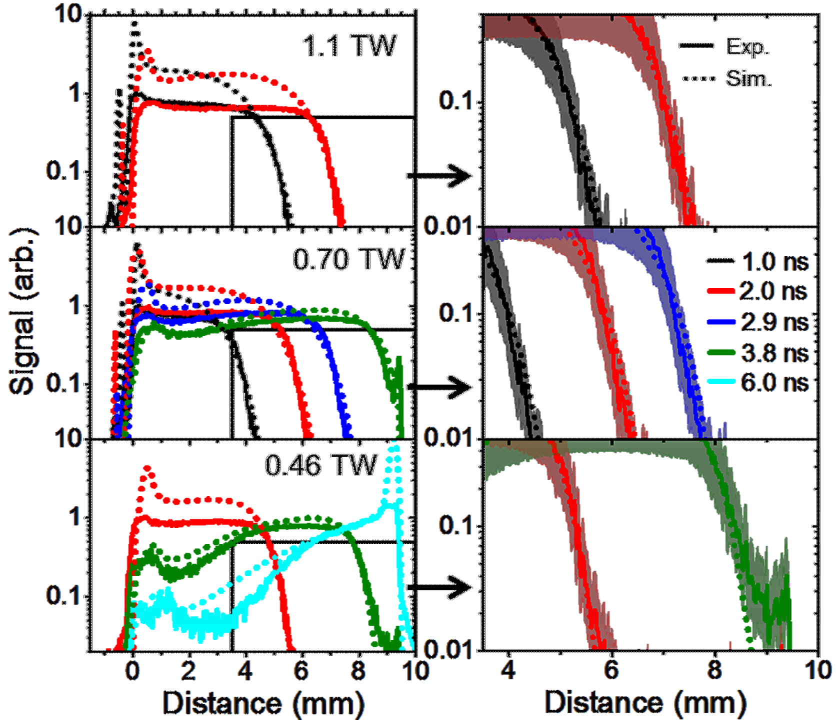
MSPEC analysis by Tai Nagayama

2D HYDRA simulations match propagation in pure Ar

XRFC image comparison



XRFC lineout comparison



Experimental parameters:

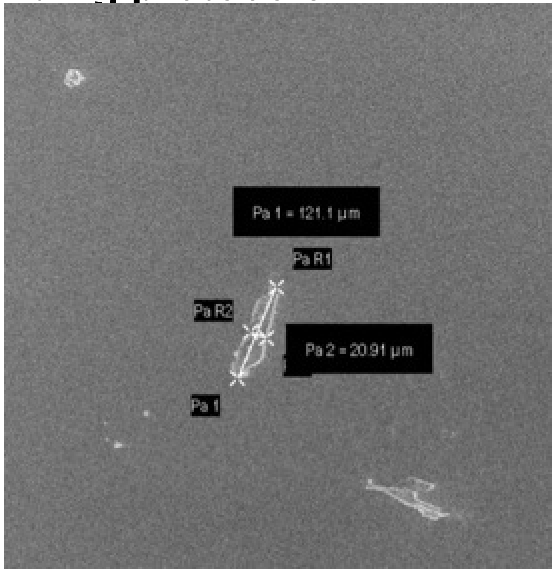
- **1 μm LEH**
- **1 atm pure Ar (n_e~$0.045n_c$)**
- **750 μm DPP**

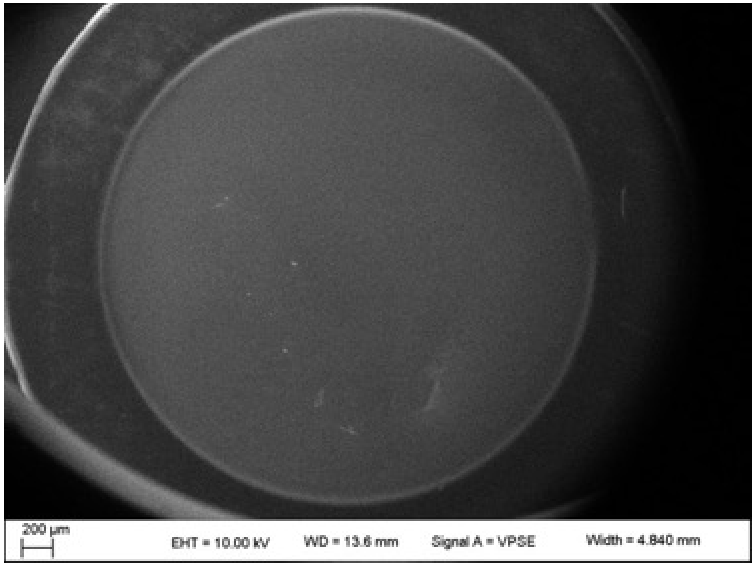
HYDRA simulations for laser propagation and heating in D2 fuel is under way

Harvey-Thompson et al, Phys. Plasmas (2015); Phys. Rev. E (2016).

Dust is now being investigated as a potential source of variability laser heating

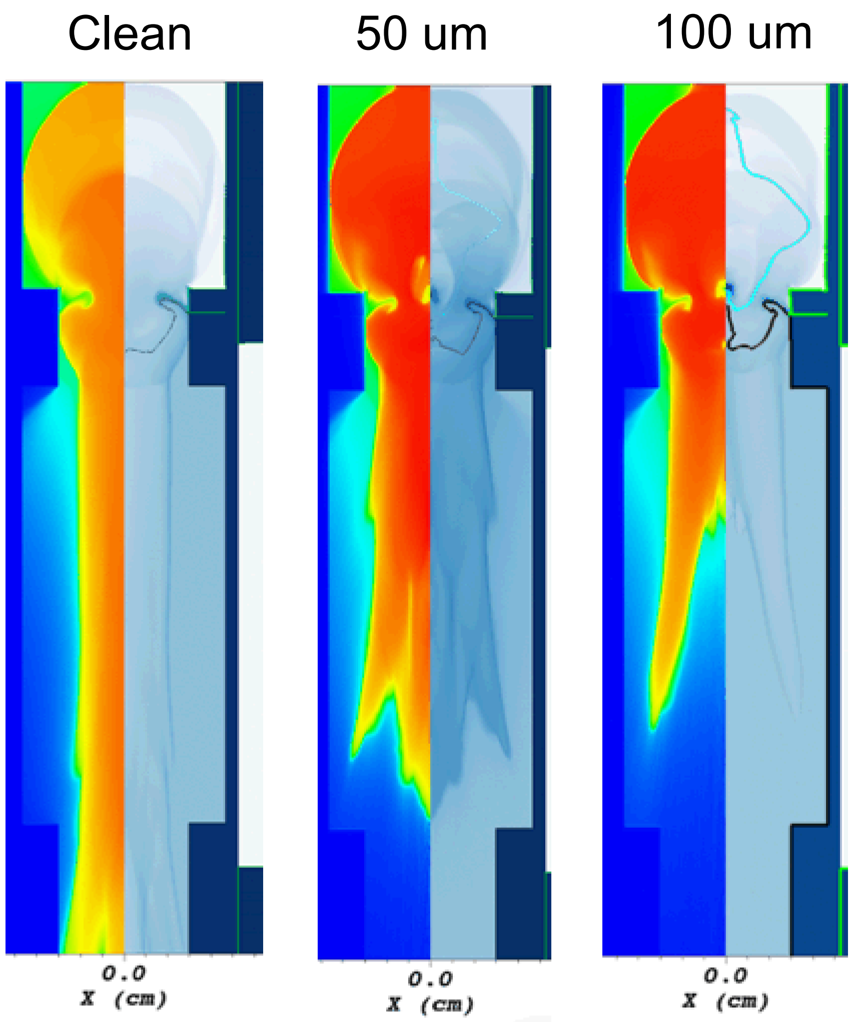
- **Dust particles ~ 10-100 um have been observed on LEH windows**
  - **Dust can be accumulated before target assembly, in the high-bay, and potentially after lids are placed (also observed on Pecos windows)**
  - **Phase plate illuminates a larger portion of the window and could potentially interact with more particles**
  - **Specific tests are planned, better characterization and handing protocols**



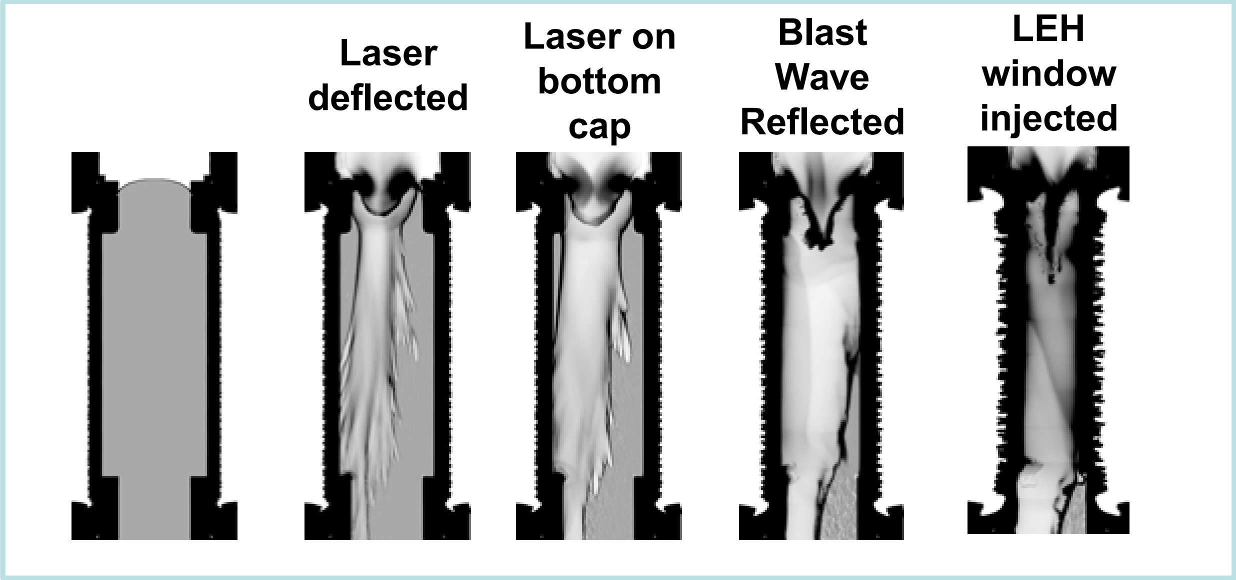


HYDRA Simulations suggest dust particles >50µm are problematic

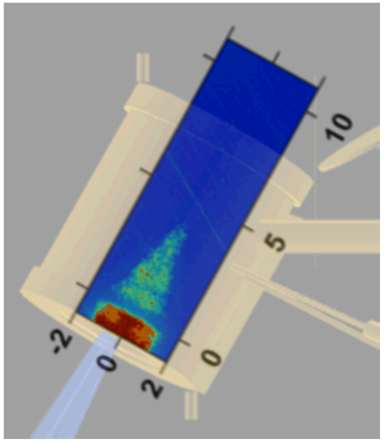
- Large dust particles ~ 50 to 100 um can cause beam deflection and significantly change the energy deposition pattern
- Ablation of the dust particle can drive additional window mix

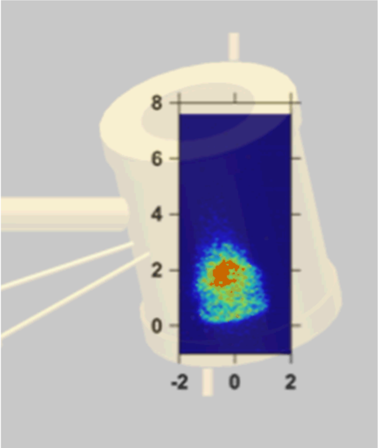


In FY18, a major focus will be to begin assessing the potential for mix induced as a result of the laser heating process



We have already begun using Ti window coatings to examine LEH window mix





25 um poly + 5 um Ti

Comparison between the 2 GXD views at t = 5 ns

Minimizing Scatter Losses in MagLIF Pre-Heat

- **Motivation**: Large-angle forward scatter and Brillouin backscatter reduce the coupling efficiency in pre-heat and can cause mix by heating cold, high-Z boundaries.

- **Approach**: Measure both forward and backscatter at the PECOS target area and optimize by spatial and temporal laser pulse shaping.

- **Outcome**: By implementing distributed phase plates, stretching the laser pulse temporally, and optimizing the pre-pulse a reduction of a factor 1000 in stimulated Brillouin Scatter was observed.

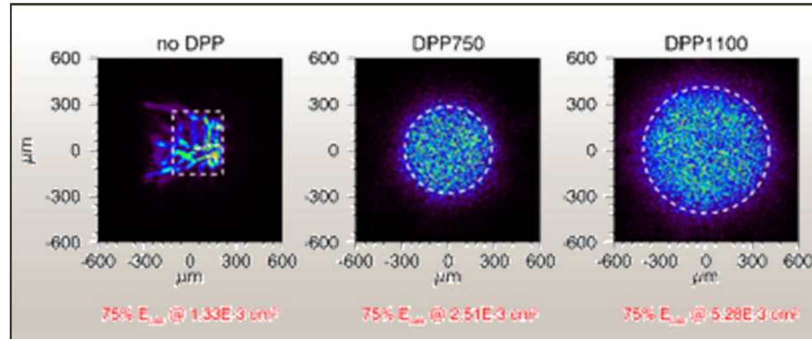
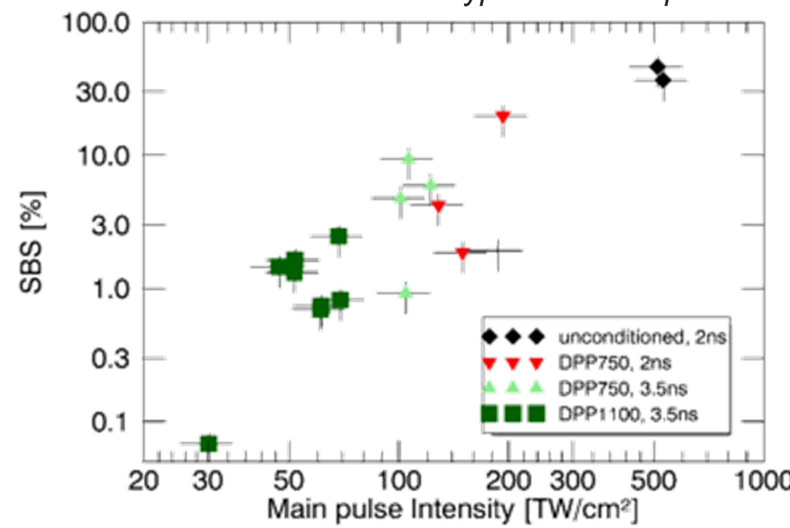


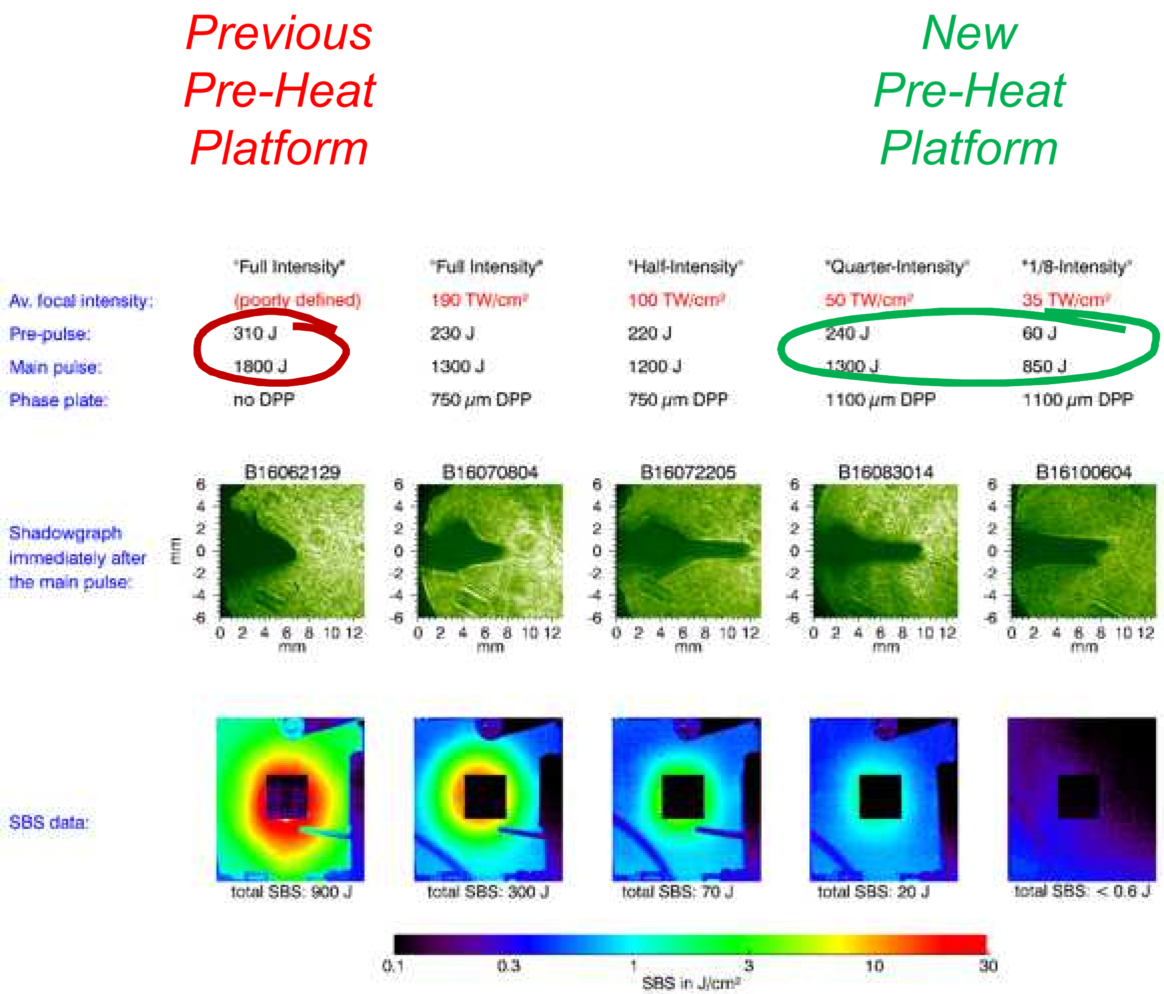
Illustration of focus homogeneity and indication of characteristic spot size

Stimul. Brillouin Scatter vs. focus type and main pulse length



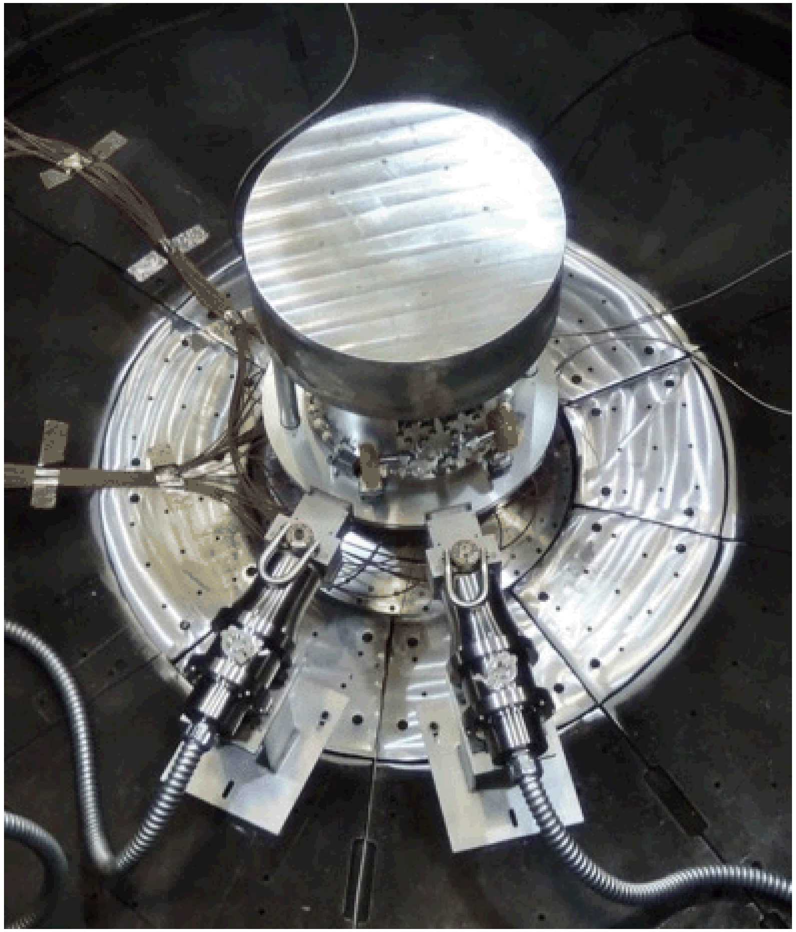
PECOS Pre-Heat Progress Summary

- **Brillouin Backscatter**: Essentially eliminated.
- **Laser heating**: Heated region optimized from highly conical to near-cylindrical.
  -> Less mix potential.
- **Efficiency**: Laser penetration depth increased or maintained with REDUCED energy investment.
  -> Less mix potential.
- **Impact in Z:** Closer to simulation and new YIELD RECORD.



First ever tritium experiment was conducted on Z in August 2016

- **Motivation**: We need to develop experience with tritium and it can benefit our scientific understanding through higher yields (50 -100x) and higher energy spectrum neutrons (14 MeV)
- **Approach**: We safely conducted a tritium experiment on Z using a trace amount of tritium (0.1% T), applied engineering controls (e.g. containment) and thorough planning
- **Outcome**: Neutron diagnostics measured a primary DT neutron signal for the first time on Z and tritium was not detected above background levels using surface and airborne monitoring techniques

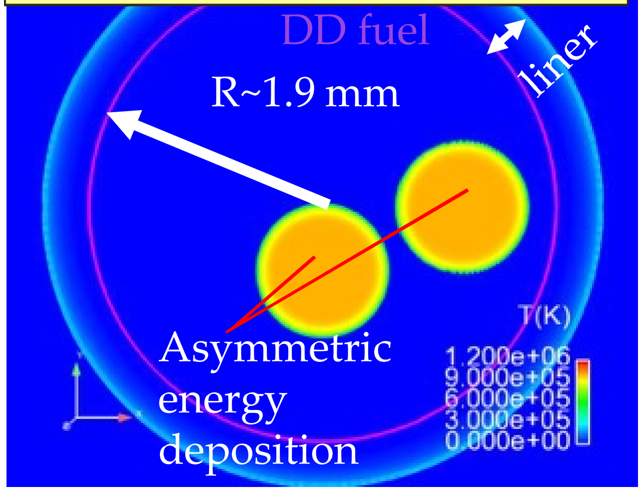


Experimental configuration for first ever tritium experiment on Z

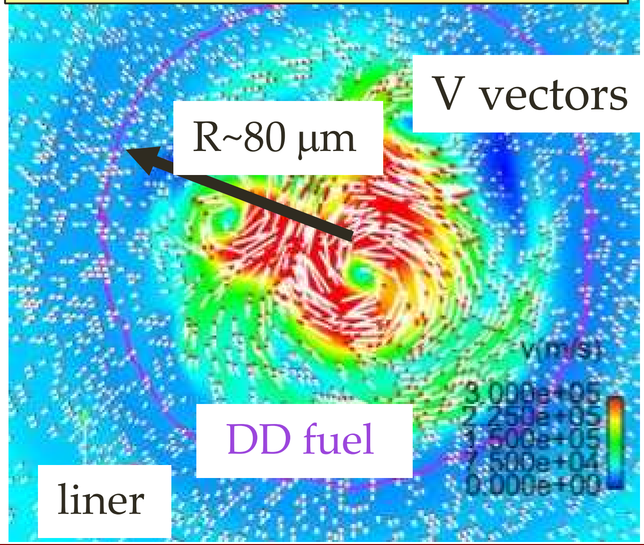
Demonstration of vortex generation and amplification in MagLIF

- **Motivation**: Most MagLIF simulations assume an azimuthally symmetric laser energy deposition, but experiment shows a filamented, non-uniform beam. What additional physics does this introduce?
- **Approach**: We used a 2D (r,θ) MHD simulation to study the implosion and stagnation of a MagLIF-like liner when energy is deposited in 2 off-centered beams (see a).
- **Outcome**: Oblique shocks generated by asymmetric energy deposition result in vortices, which are amplified during implosion, due to (approximate) conservation of angular momentum. Vortex velocities can be ~4X liner implosion velocities (see b), and deform the liner from the inside-out, rather than from outside-in (e.g. MRT feedthrough).

a) Temperature at initial energy deposition

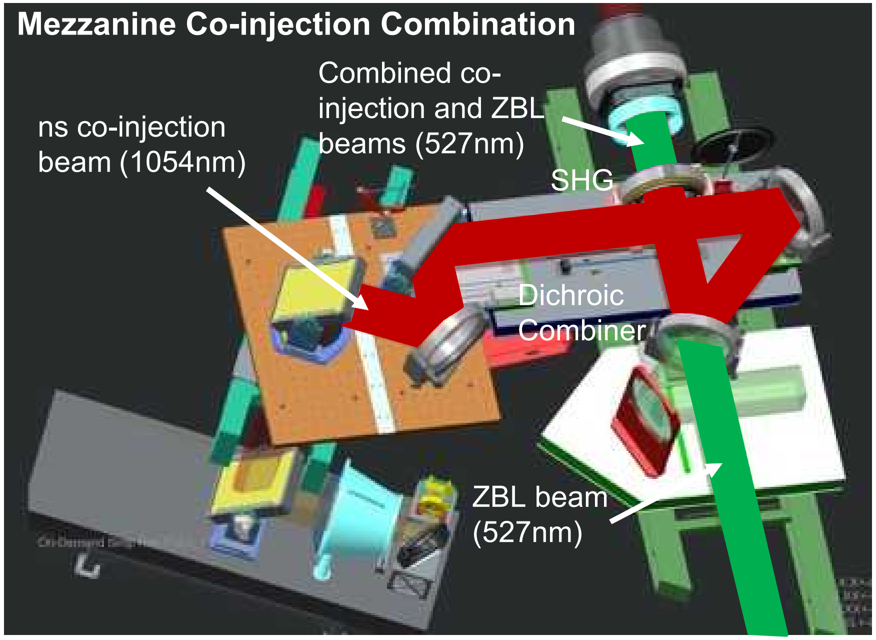


b) Velocity near stagnation



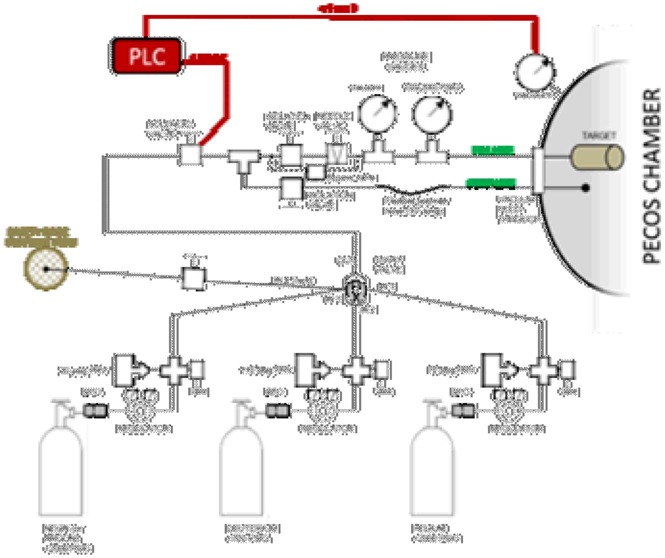
Activation of Co-injection Beam

- **Motivation**: Provide a 2^{nd} ZBL like beam for:
  - Having an arbitrarily variable temporal pre-pulse to "blow-off" the MagLIF laser entry hole,
  - Providing additional pre-heat for MagLIF, and
  - Allowing for the possibility of developing a backlighting capability for laser heated MagLIF experiments.
- **Approach**: We modified the existing Z-Petawatt short-pulse laser to operate in long pulse (ns) mode. The beam is then co-injected with a dichroic combiner and frequency doubled.
- **Outcome**: We demonstrated 200J at 527nm long pulse mode and are currently in the commissioning phase, having already shot into a ZBL target chamber.

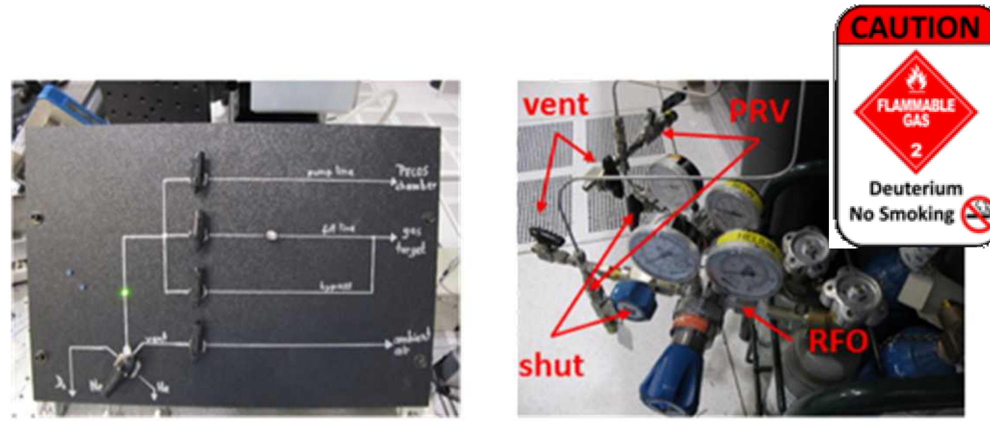


Co-Injection Efforts

PECOS Deuterium Implementation



Implementation Photographs

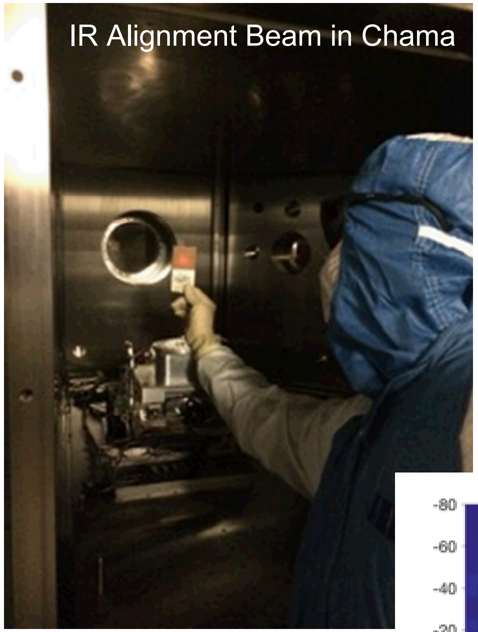


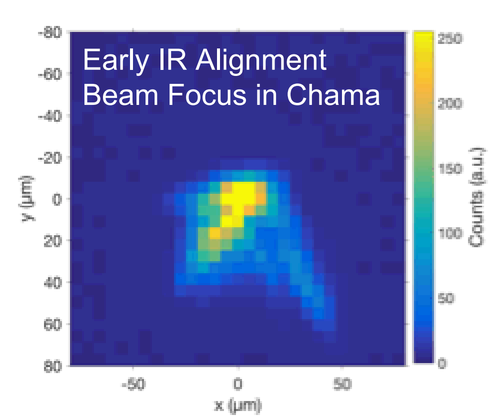
- **Safety Assessment Topics Finished**
  - ✓ multiple work-meetings and reviews
  - ✓ including 10 subject-matter-experts
  - ✓ Radiological issues (neutron generation)
  - ✓ fire safety (auto-ignition, LEL, electrical compatibility, fire extinguishers)
  - ✓ pressure safety (hydrogen embrittlement)
  - ✓ industrial hygiene (asphyxiation, failure mode analysis with process map)
  - ✓ ES&H, vacuum equipment compatibility

- **Implementation Progress**
  - ✓ New D_2 compatible manifold and control panel
  - ✓ Programmable Logic Controller for safety solenoid-valve (completed) with LabView Interface (in progress)
  - ✓ Deuterium Safety Memo, Job Safety Analysis
  - ✓ Additional (turbo-molecular) pump installed (PLC contr.)
  - ✓ Safety Case Write-up (under review)
  - ✓ D_2 regulator and custom-fill lecture bottle acquired
  - ✓ Pressure Safety Data Package (reviewed, not yet signed)
  - ✓ Safety signs (defined/designed, on order)

Activation of the Chama Target Chamber

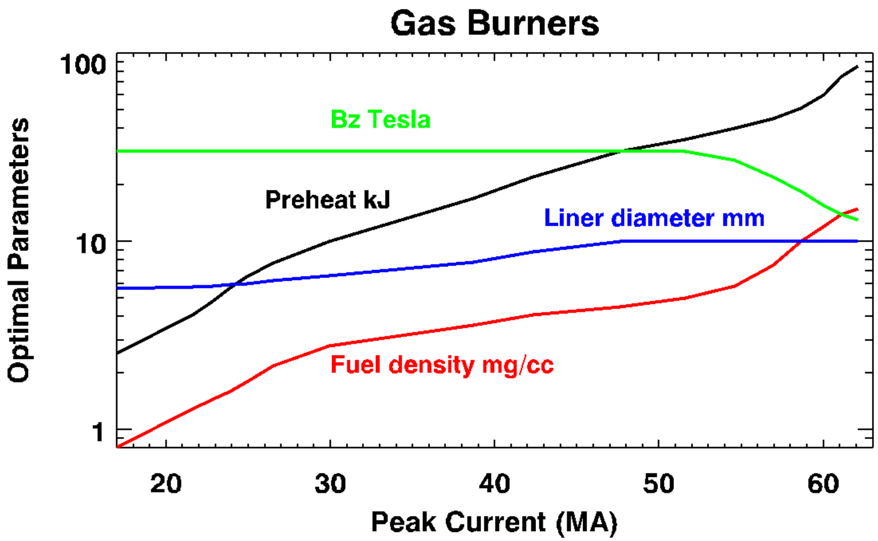
- **Motivation**: Activate the last of five high energy laser target chambers in order to perform combined Z-Beamlet (ZBL) and Z-Petawatt (ZPW) experiments.
- **Approach**: Using an existing beam line, we steered the ZPW beam to the Chama chamber utilizing custom meter scale mirror mounts and in-house coated optics.
- **Outcome**: ZPW has been focused at target chamber center. This enables a large range of novel experiments, such as prototyping of dynamic diffraction experiments on the Z-machine (ongoing LDRD).





Initial Chama Chamber Alignments

Our program plan is to develop platforms that enable testing of optimal configurations for scaling



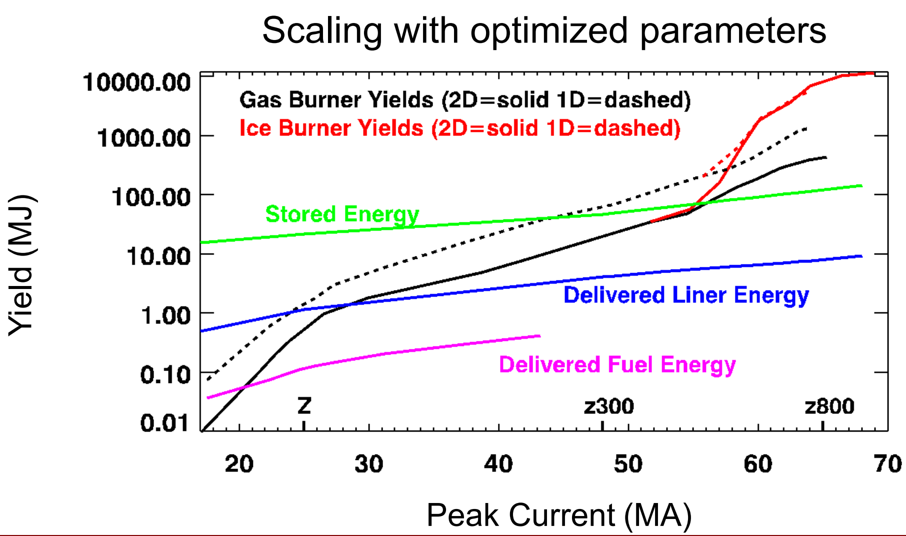
Our present experimental configuration is far from optimal

B-field=10 Tesla (optimum >30 Tesla)

Fuel density=0.7 => **high convergence**

Preheat energy < 1 kJ

Feed inductance 7.2 nH => **I_{max}~17.4 MA**



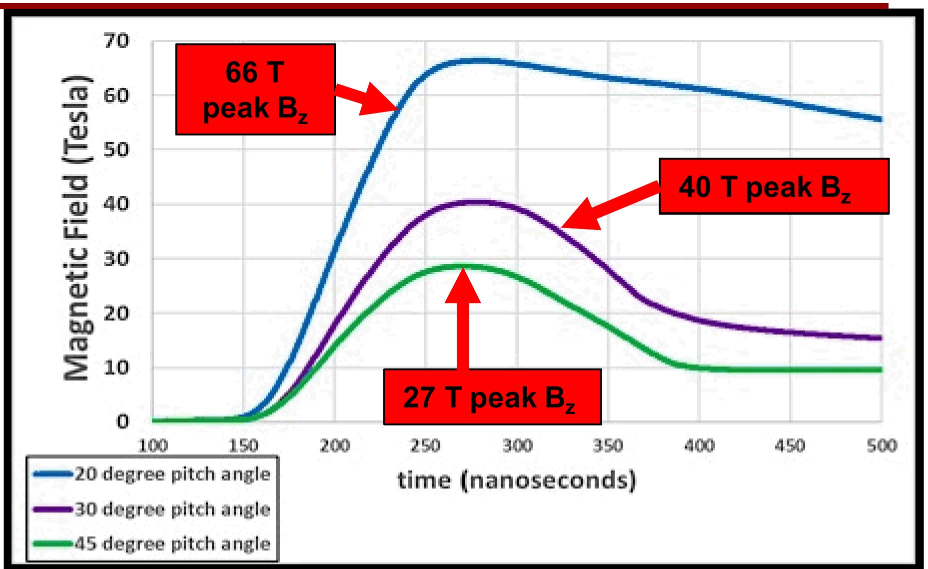
Simulations predict favorable scaling of yield with drive current[1] when MagLIF parameters are optimized

[1] S.A. Slutz et al. Phys. Plasmas 23, 022702 (2016)

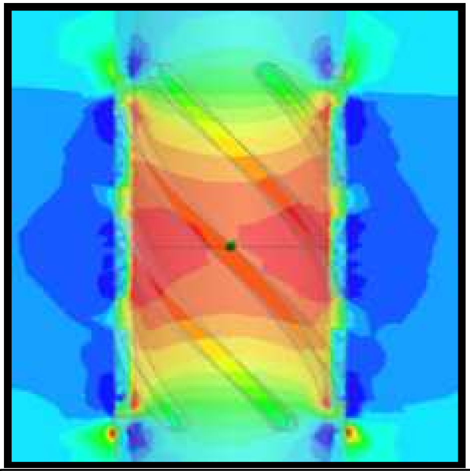
Slotted helical auto-magnetizing MagLIF liners (AutoMag) have demonstrated 66 Tesla fields in a recent LDRD project

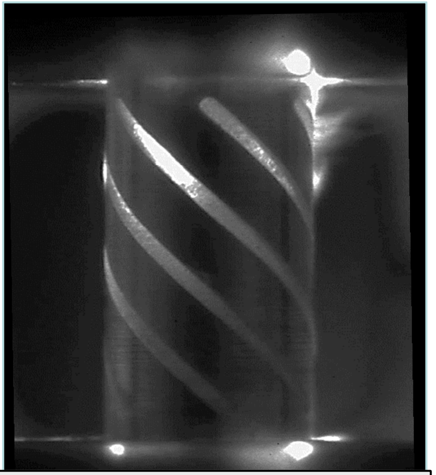
- **Motivation:**
  - ***Eliminate field coils!***
  - **higher initial magnetization**
  - **increase current through lower inductance**
  - **lower cost**
- **500 kA in 100 ns pulse on the MYKONOS Linear Transformer Driver machine used for testing**
- **Initial results have been promising with no breakdowns observed in 15 shots, but significant challenges**

AutoMag liners designed to generate on-axis 27 T (left) 38 T (center) 65 T (right)



On-axis field measured inside AutoMag liners





Simulation of internal B_z (left), iCCD image (right)