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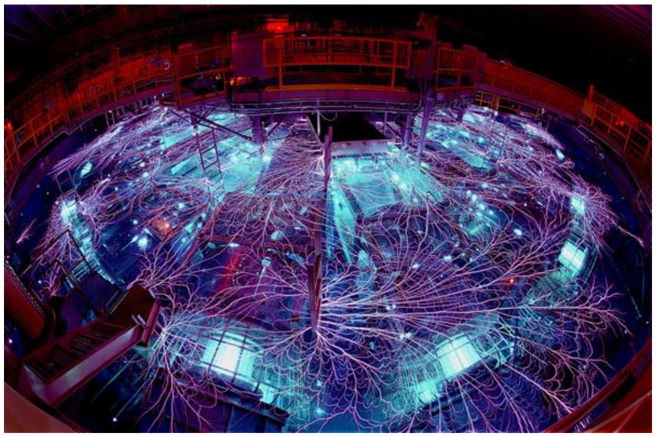

Demonstrating Fuel Magnetization and Laser Heating Tools for Low-Cost Fusion Energy

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ARPA-E ALPHA Annual Meeting
August 8-11, 2016
Seattle, WA, USA

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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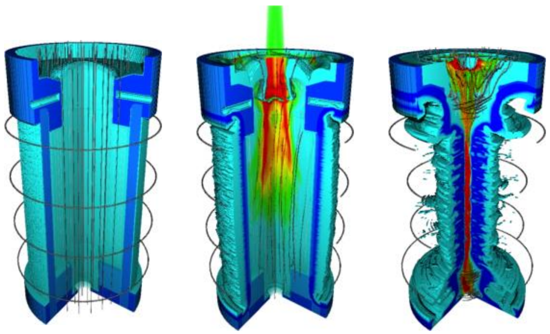
This project is a collaboration between Sandia and the University of Rochester

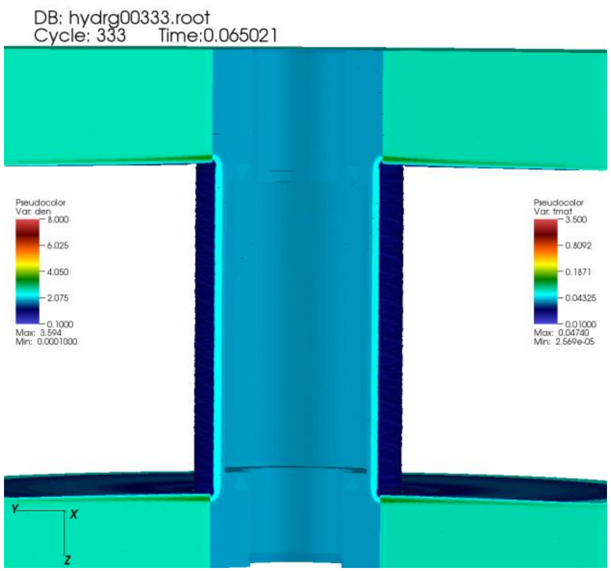
- **Sandia National Laboratories, Albuquerque, NM**
  - Daniel Sinars, Senior Manager, Radiation & Fusion Physics Group
  - Kyle Peterson*, Manager, ICF Target Design Department
  - John Porter, Manager, Laser Operations & Engineering
  - Matthias Geissel, Principal Member of Technical Staff
  - Adam Harvey-Thompson, Research Scientist
  - Stephen Slutz*, Distinguished Member of Technical Staff
  - Matt Weis, Senior Member of Technical Staff
- **University of Rochester, Rochester, NY**
  - Jonathan Davies*, Research Scientist
  - Dan Barnak, Graduate Student
  - Riccardo Betti*, Professor of Mechanical Engineering
  - Mike Campbell*, LLE Deputy Director
  - Sean Regan, Experimental Group Leader
  - Vladimir Glebov, Research Scientist
  - Jim Knauer, Research Scientist

* In attendance today

This project is centered around the Magnetized Liner Inertial Fusion (MagLIF) target design for Z



- **Axial magnetization of fuel/liner (B_{z0} = 10-30 T)**
  - Inhibits thermal conduction losses and traps alphas (β: 5~80; $\omega\tau$>200 at stagnation)
- **Laser heating of fuel (2 kJ initially, 6-10 kJ planned)**
  - Reduces radial fuel compression needed to reach fusion temperatures (R_0/R_f about 25, T_0=150-200 eV)
- **Liner compression of fuel (70-100 km/s, ~100 ns)**
  - Low velocity allows use of thick liners ($R/\Delta R$~6) that are robust to instabilities and have sufficient ρR at stagnation for inertial confinement
- τ ~ 1-2ns, ~100x lower fuel pressure than traditional ICF (~5 Gbar vs. 500 Gbar)



3D HYDRA Simulation, A. Sefkow

Goal is to demonstrate scaling: *Y (B_{z0}, E_{laser}, I)*
DD equivalent of 100 kJ DT yield possible on Z

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).

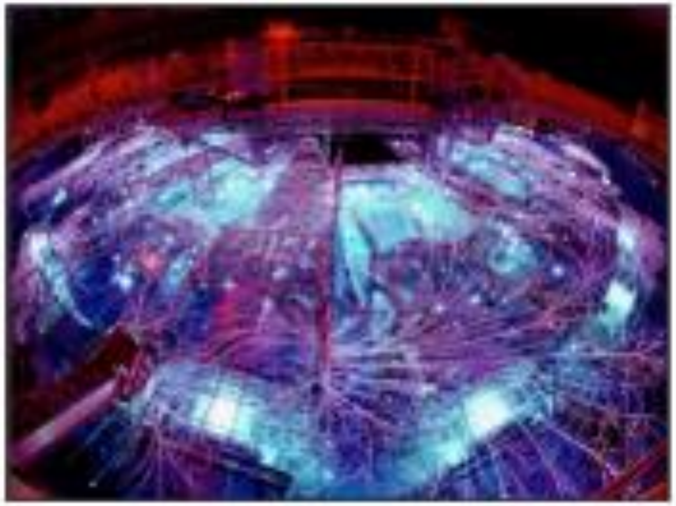
This project is using existing capabilities at both institutions to demonstrate magneto-inertial fusion scaling

Sandia National Laboratories

- 80-TW, 20 MJ Z pulsed power facility
- 1-TW, multi-kJ Z-Backlighter laser facility
- 10 T B-field system

Laboratory for Laser Energetics

- 60-beam, 30-TW, 30 kJ, OMEGA laser facility
- 4-beam, TW to PW, multi-kJ OMEGA-EP laser facility
- 10 T B-field systems

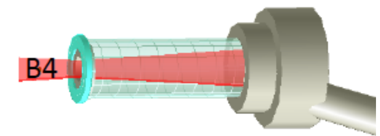


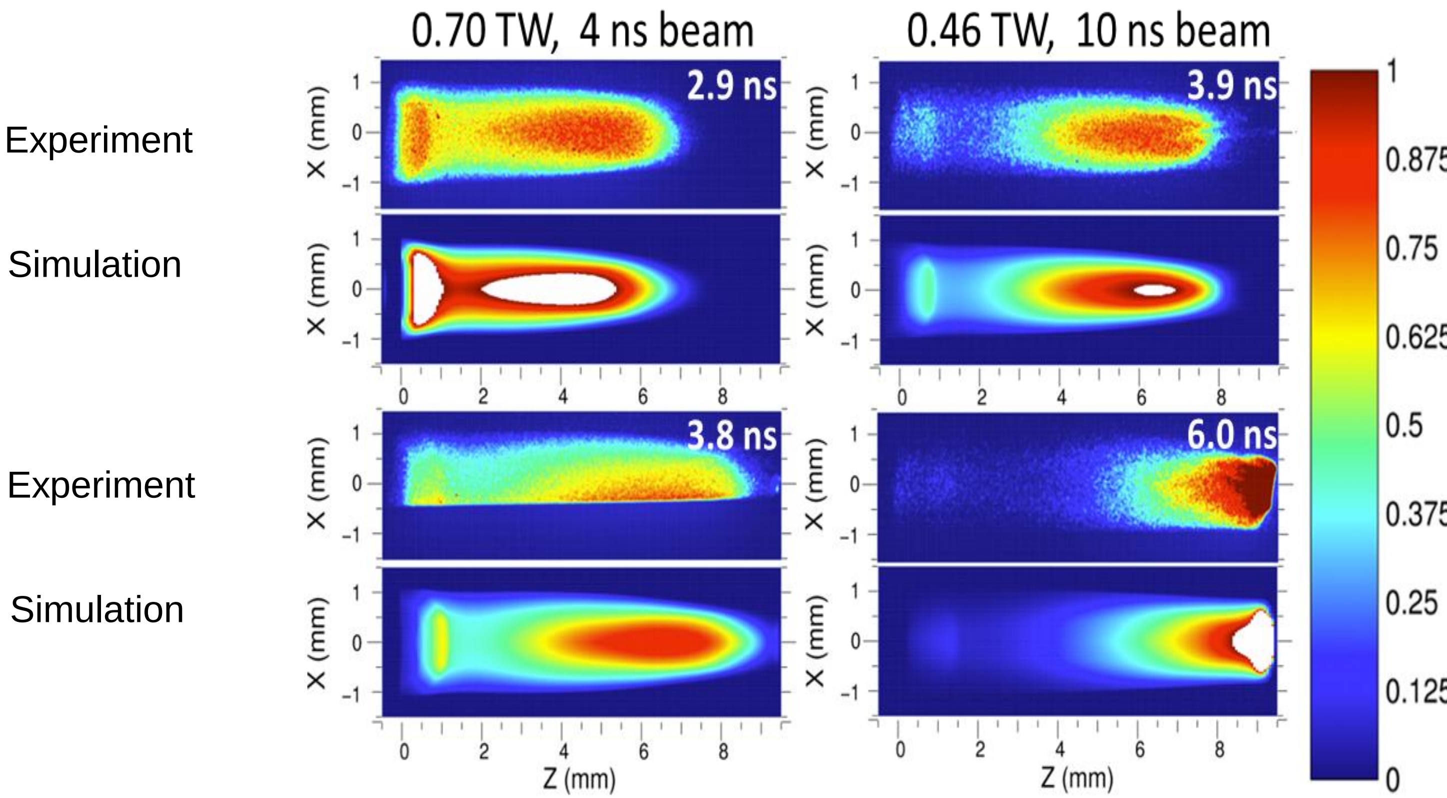
* All facilities are multi-user, multi-program facilities funded by the NNSA

We are working to demonstrate magneto-inertial fusion in relatively high-density, short-duration plasmas, and study the scaling of magneto-inertial fusion using modeling

- **Target pre-conditioning experiments**
  - Utilize Omega, Omega-EP, Z, Z-Backlighter (PECOS) to understand initial conditions and validate simulation codes
  - Determine a set of conditions needed to achieve functional fuel pre-conditioning (i.e., laser and magnetic field configurations)
- **Laser-driven MagLIF experiments on OMEGA**
  - Develop a platform to predict and scale the performance of magneto-inertial fusion targets over a wide range of size, time scale, and available energy (e.g., ~10 kJ to ~1 MJ absorbed)
- **Numerical Modeling & Theory**
  - Improve & refine simulation models using data collected
  - Examine not only MagLIF scaling, but also the general MIF parameter space over a broad range configurations using validated simulations
- **Tech transfer & Outreach activities**

OMEGA-EP experiments are providing key data at 3ω that cannot be obtained with ZBL



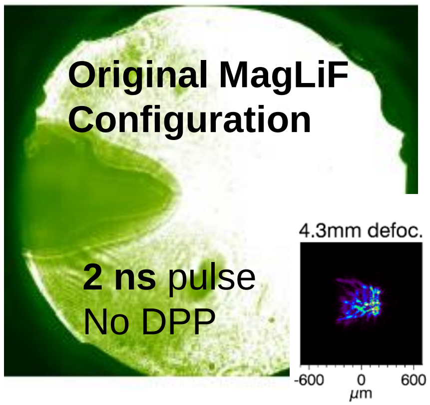


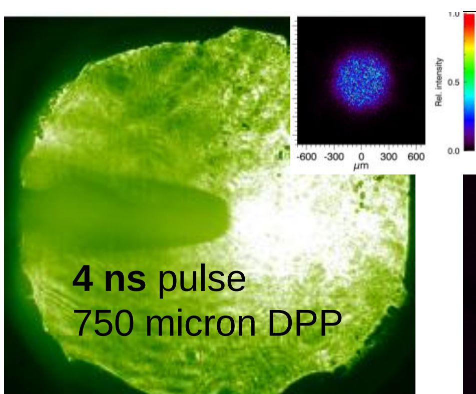
- Effect of B field (underway)
- Effect of pre-pulse (complete)
- Effect of laser intensity (complete)
- Window mix (next year)
- 2ω **vs** 3ω surrogacy (next year)
- LPI (underway)

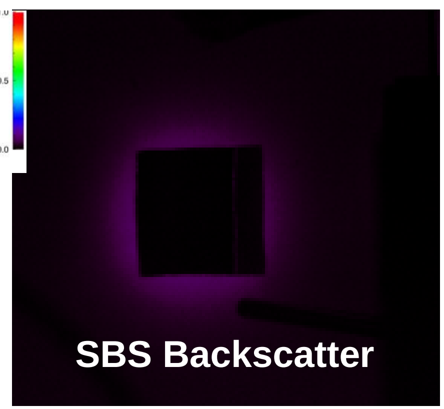
Harvey-Thompson *et al.*, Recently submitted for publication

Recent preconditioning experiments have provided key data for the development of a new preheat platform

Optical Blastwave Measurements





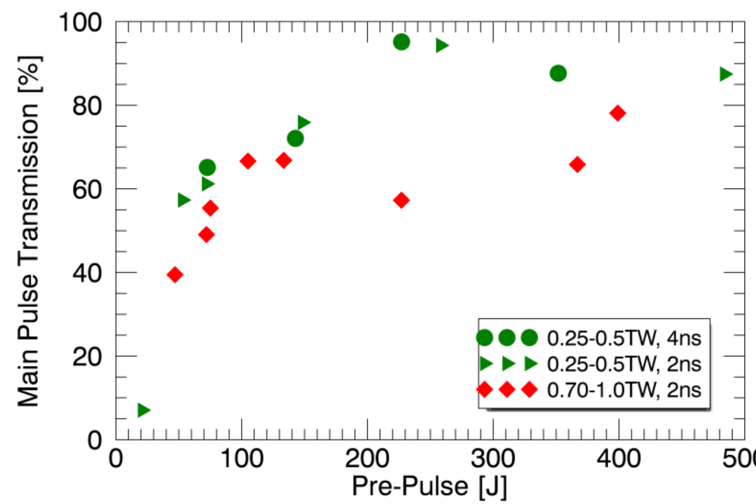


54psi He, 250J/1350J

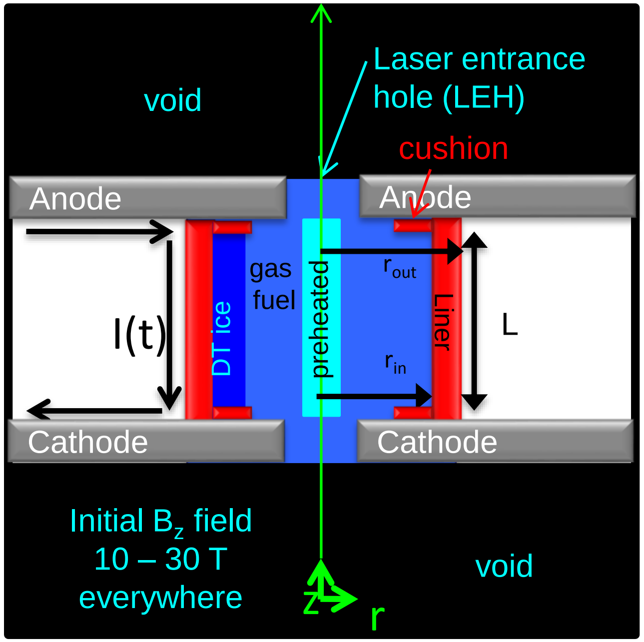
Key Accomplishments

- Dramatically Improved Transmission
- Determined pre-pulse requirements
- Dramatically reduced LPI
- New Diagnostics & Capabilities

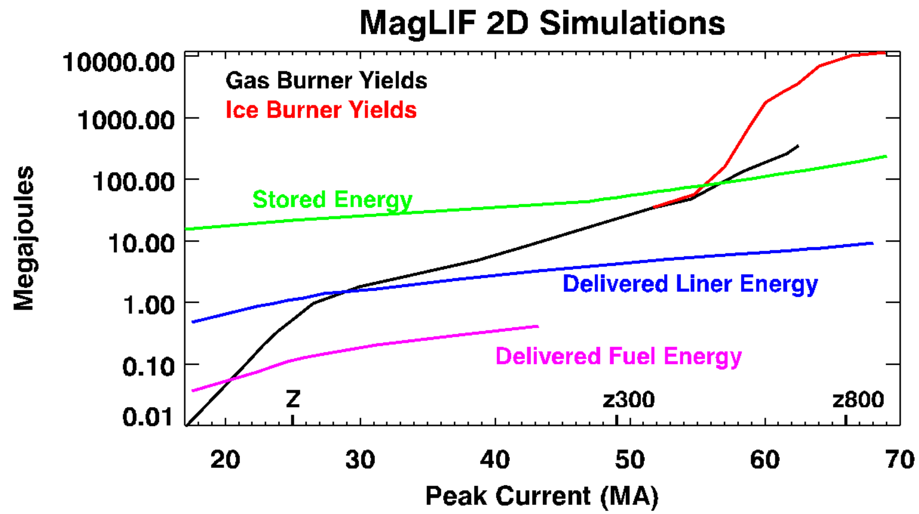
LEH Window Transmission

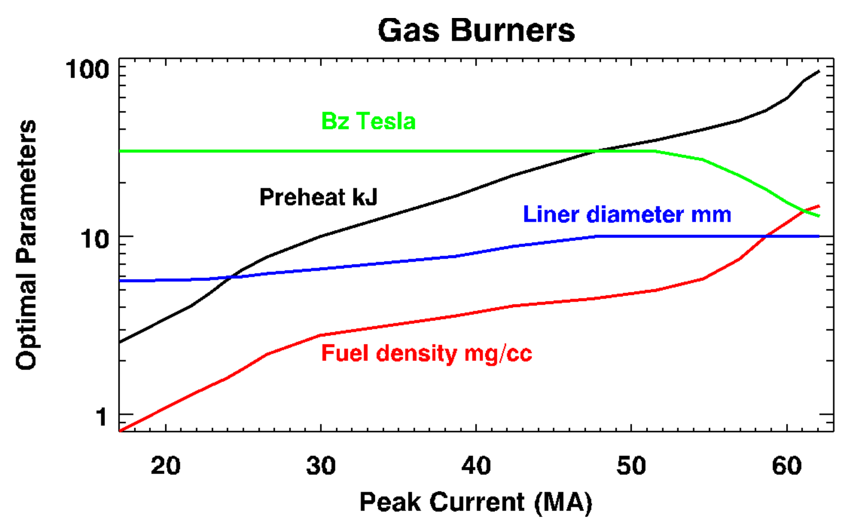


MagLIF scaling study is complete for AR6 targets over a wide range of current and time scales*



Simulation Configuration

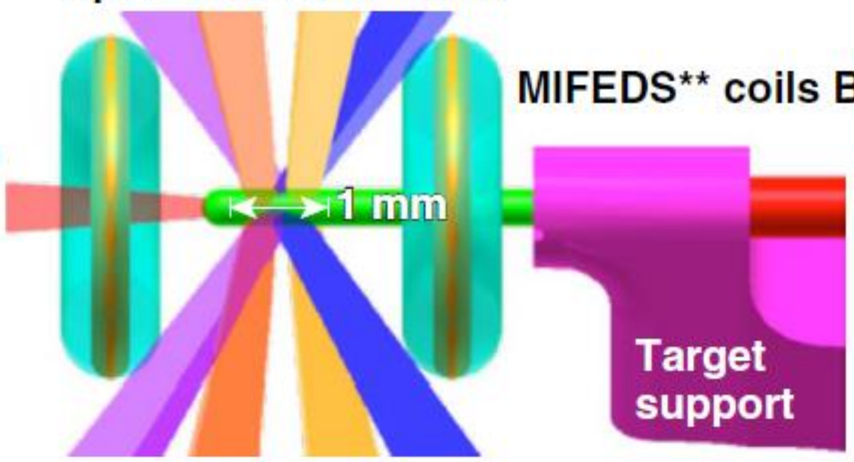




A broad study of the MIF parameter space is now underway. Results will be reported soon.

* ~100ns results shown here

Laser-driven MagLIF on OMEGA is providing scaling data over a factor of 1000 in energy and more shots with more diagnostics than Z



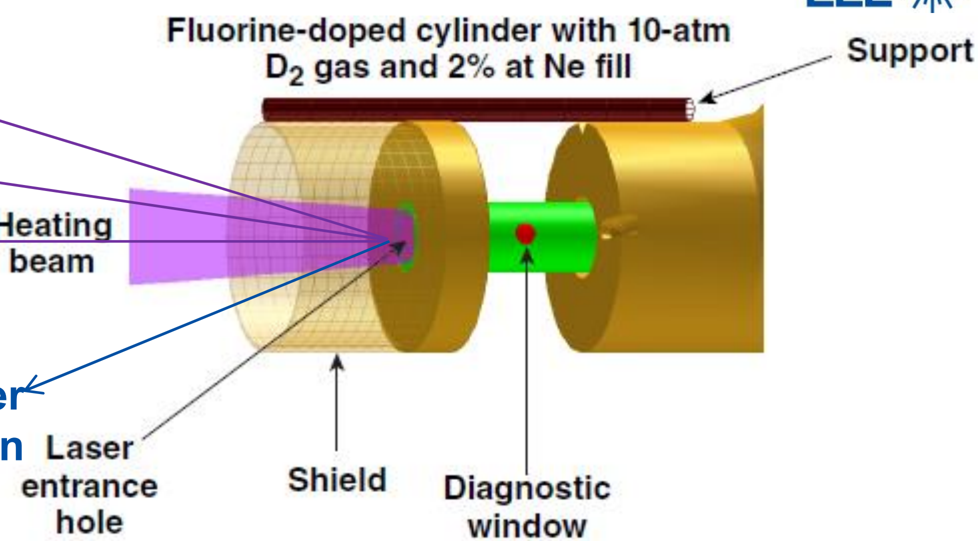
	r (mm)	Δr (mm)	$r/\Delta r$	ρ_{fuel} (mg/cm^3)	B_0 (T)	T_0 (eV)	V_{imp} (km/s)	Convergence ratio	T_{max} (keV)
Z *	3.48	0.58	6	3 (DT)	30	250	70	25	8.0
OMEGA	0.30	0.03	10	2.4 (D_2)	10	200	154	26	2.9

*S. A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).
**MIFEDS: magneto-inertial fusion electrical discharge system

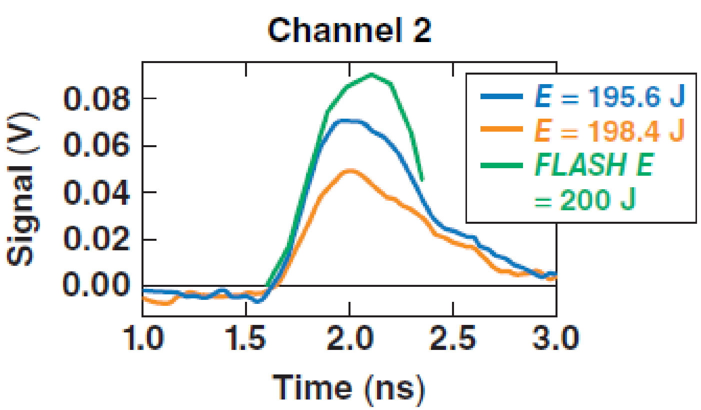
TC12449a

The objective of laser preheating of D_2 gas to > 100 eV was demonstrated in preliminary OMEGA experiments

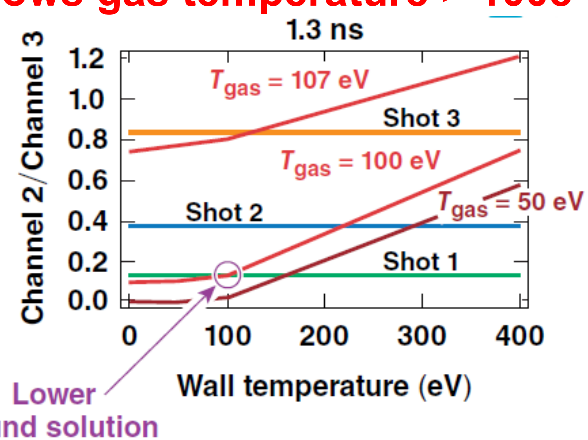
Total laser backscatter < 1% with no backscatter from the gas



Time-resolved soft x-ray spectrometer shows window, gas and wall emission



3-channel soft x-ray framing camera shows gas temperature > 100e V



Streaked optical emission shows uniform heating along length of interest

A nine shot day program (> 100 shots) was drawn up for the ALPHA program

1. Optimize ring 3 – ring 4 energy balance without preheat (1 Sept 15)
2. Optimize ring 3 – ring 4 energy balance and reduce shell thickness without preheat (24 Nov 15)
3. Optimize preheat timing and vary preheat energy (19 July 16)
4. Complete B/no-B and preheat level data set (22 Sept 16)
5. B-field 1: measure axial B-field evolution using D^3He protons with H_2 fill to avoid proton production from target and with preheat (8 Nov 16)
6. B-field 2: use EP if D^3He unsuccessful or extend data set (7 Feb 17)
7. B-field scan: include a higher value if possible with 2 MIFEDS and/or transformer coil (under development) with preheat (16 May 17)
8. Fill density and shell thickness scans with B and preheat (1 Aug 17)
9. Contingency: fill in missing data, address unforeseen issues or extend data set

The first two shots days have been successfully executed

1. Optimize ring 3 – ring 4 energy balance without preheat (1 Sept 15) ✓
2. Optimize ring 3 – ring 4 energy balance and reduce shell thickness without preheat (24 Nov 15) ✓
3. Optimize preheat timing and vary preheat energy (19 July 16)
4. Complete B/no-B and preheat level data set (22 Sept 16)
5. B-field 1: measure axial B-field evolution using D^3He protons with H_2 fill to avoid proton production from target and with preheat (8 Nov 16)
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8. Fill density and shell thickness scans with B and preheat (1 Aug 17)
9. Contingency: fill in missing data, address unforeseen issues or extend data set

The objectives of uniform compression over 0.6 mm at a velocity of ~ 150 km/s have been demonstrated

<u>X-ray framing camera data</u>

0.05 ns temporal resolution

Shell thickness: 20 ∝m

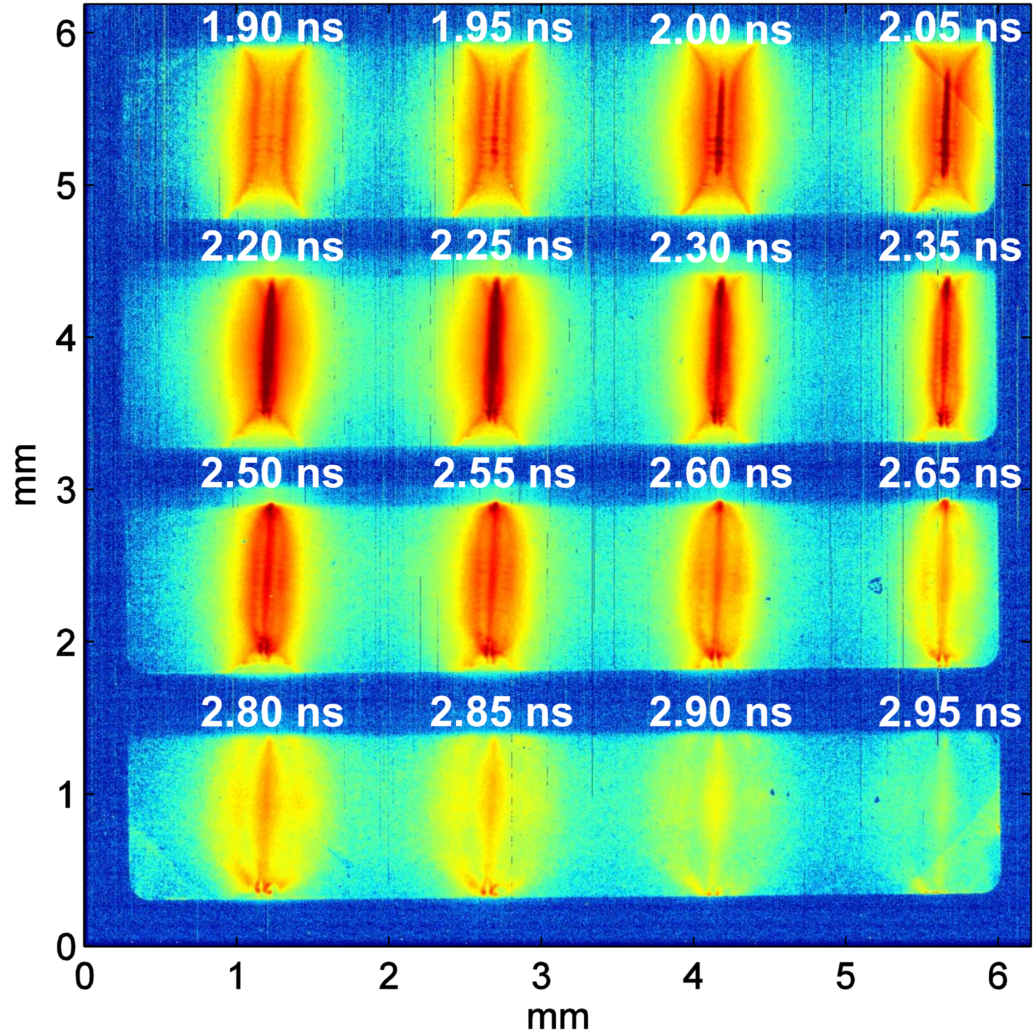
D_2 density: 1.80 mg/cc

Laser energy: 13.0 kJ

Pulse length: 2.0 ns

Neutron yield: 2.53×10^7

No B, no preheat



The 3rd shot day was not executed as planned because the lens for the preheating beam was not delivered

1. Optimize ring 3 – ring 4 energy balance without preheat (1 Sept 15) ✓
2. Optimize ring 3 – ring 4 energy balance and reduce shell thickness without preheat (24 Nov 15) ✓
3. Optimize preheat timing and vary preheat energy (19 July 16)
4. Complete B/no-B and preheat level data set (22 Sept 16)
5. B-field 1: measure axial B-field evolution using D^3He protons with H_2 fill to avoid proton production from target and with preheat (8 Nov 16)
6. B-field 2: use EP if D^3He unsuccessful or extend data set (7 Feb 17)
7. B-field scan: include a higher value if possible with 2 MIFEDS and/or transformer coil (under development) with preheat (16 May 17)
8. Fill density and shell thickness scans with B and preheat (1 Aug 17)
9. Contingency: fill in missing data, address unforeseen issues or extend data set

The shot day was used to obtain additional neutron data without preheat and without magnetic field

1. Optimize ring 3 – ring 4 energy balance without preheat (1 Sept 15) ✓
2. Optimize ring 3 – ring 4 energy balance and reduce shell thickness without preheat (24 Nov 15) ✓
3. Obtain neutron data without preheat and without B (19 July 16)
4. Complete B/no-B and preheat level data set (22 Sept 16)
5. B-field 1: measure axial B-field evolution using D^3He protons with H_2 fill to avoid proton production from target and with preheat (8 Nov 16)
6. B-field 2: use EP if D^3He unsuccessful or extend data set (7 Feb 17)
7. B-field scan: include a higher value if possible with 2 MIFEDS and/or transformer coil (under development) with preheat (16 May 17)
8. Fill density and shell thickness scans with B and preheat (1 Aug 17)
9. Contingency: fill in missing data, address unforeseen issues or extend data set

A new neutron time of flight diagnostic allowed neutron averaged ion temperatures to be determined at neutron yields $\geq 10^7$

Shell thick. (∝m)	D_2 density (mg/cc)	Laser energy (kJ)	Pulse length (ns)	Neutron yield (10^5)	2D HYDRA	N. avg. T_{ion} (keV)
40	1.82	10.4	2.5	3.2	NA	NA
30	1.80	14.3	2.0	58.6	NA	NA
20	1.80	13.1	2.0	159.0	NA	NA
30	1.58	14.7	1.5	527.0	1216	1.24
20	1.94	14.9	1.5	5610.0	8604	2.48

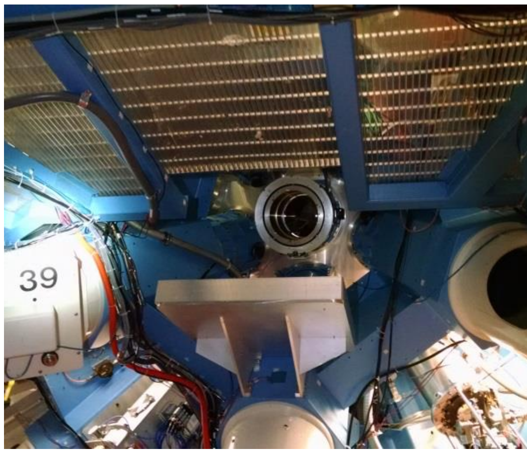
An extra shot day has been scheduled to carry out the first integrated shots with magnetization and preheat

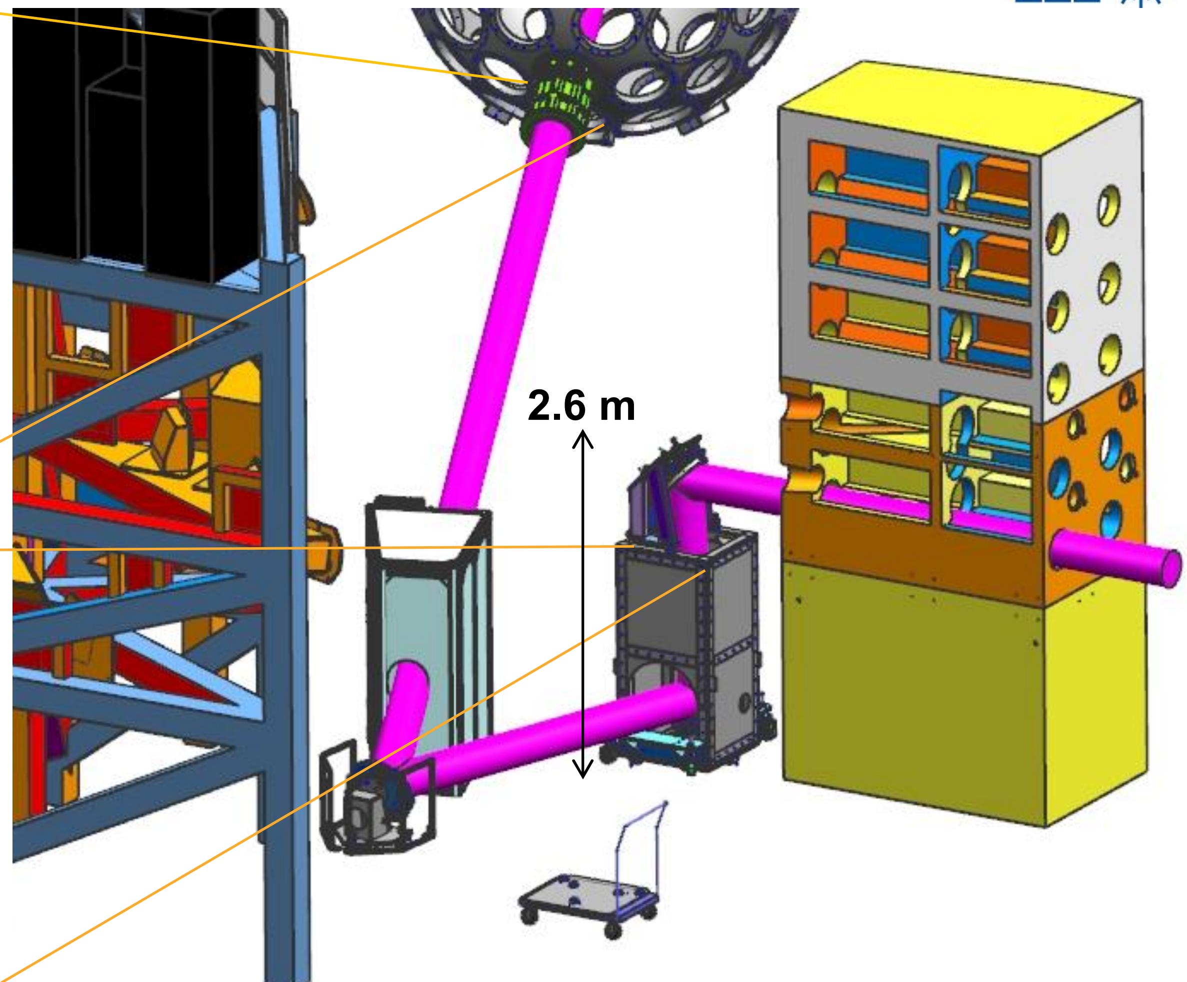
1. Optimize ring 3 – ring 4 energy balance without preheat (1 Sept 15) ✓
2. Optimize ring 3 – ring 4 energy balance and reduce shell thickness without preheat (24 Nov 15) ✓
3. Obtain neutron data without preheat and without B (19 July 16)

3b. Optimize preheat timing and vary preheat energy (25 Aug 16)

4. Complete B/no-B and preheat level data set (22 Sept 16)
5. B-field 1: measure axial B-field evolution using D^3He protons with H_2 fill to avoid proton production from target and with preheat (8 Nov 16)
6. B-field 2: use EP if D^3He unsuccessful or extend data set (7 Feb 17)
7. B-field scan: include a higher value if possible with 2 MIFEDS and/or transformer coil (under development) with preheat (16 May 17)
8. Fill density and shell thickness scans with B and preheat (1 Aug 17)
9. Contingency: fill in missing data, address unforeseen issues or extend data set

A 3w beam not required for compression will be available from P9 by Aug 25 using either a new lens or a new lens mount for a standard OMEGA lens

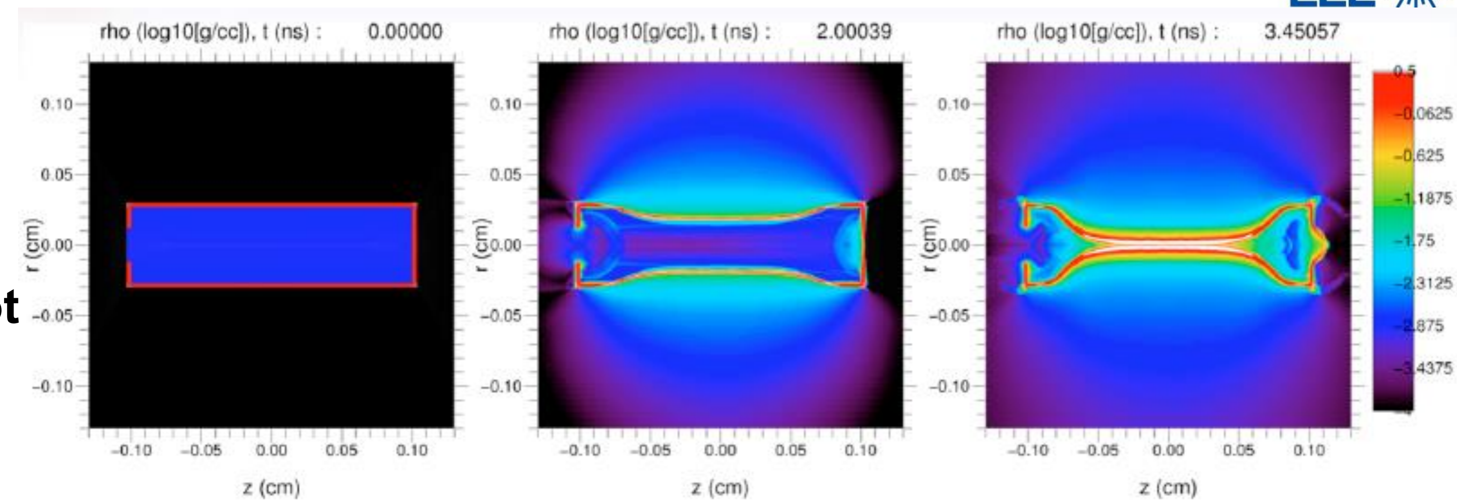




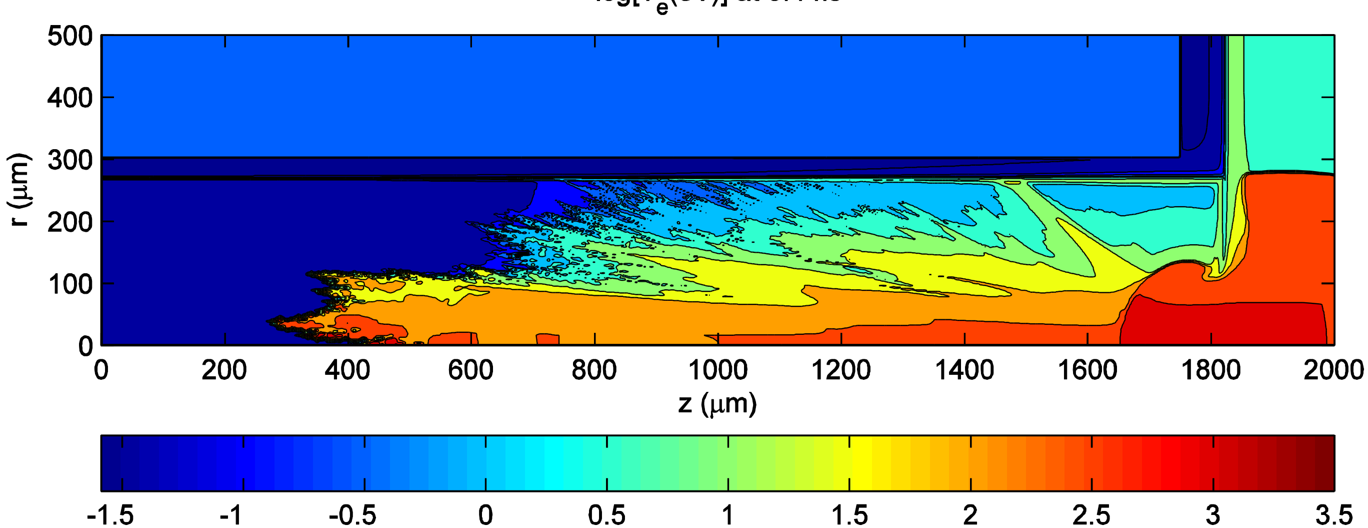
Mirror hardening shots up to full energy have been performed

The OMEGA and Z experiments are being modeled with a number of MHD codes in 1, 2 and 3D

2D HYDRA
SNL
Integrated shot



2D DRACO
LLE
Preheat shot



UNIVERSITY of ROCHESTER

Summary

Laser-driven MagLIF on OMEGA is providing scaling data over a factor of 1000 in energy and more shots with more diagnostics than Z

- The same codes are being used to model OMEGA and Z experiments
- Laser preheating and implosion have been successfully tested independently
- ALPHA funds have been important in providing an optimal preheating capability on OMEGA for these experiments
- The first integrated laser-driven MagLIF experiment will be carried out on 25 Aug 2016

Questions?

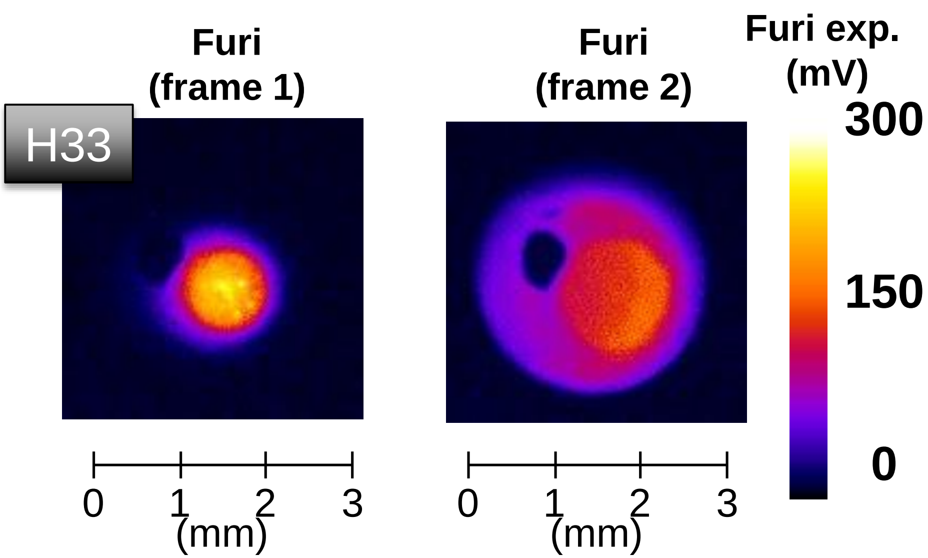
ZBL/PECOS Upgrades

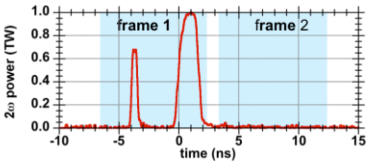
- Magnetic field system has been developed for PECOS chamber (up to 5 T)
- Near back & forward scatter imaging (SBS) capability complete on PECOS
- New distributed phase plates installed for PECOS
- New pressure test stand for PECOS targets is complete (60 psi, He)
- New targets that provide much better surrogacy to Z experiments
- Significant Improvements in ZBL shot rate

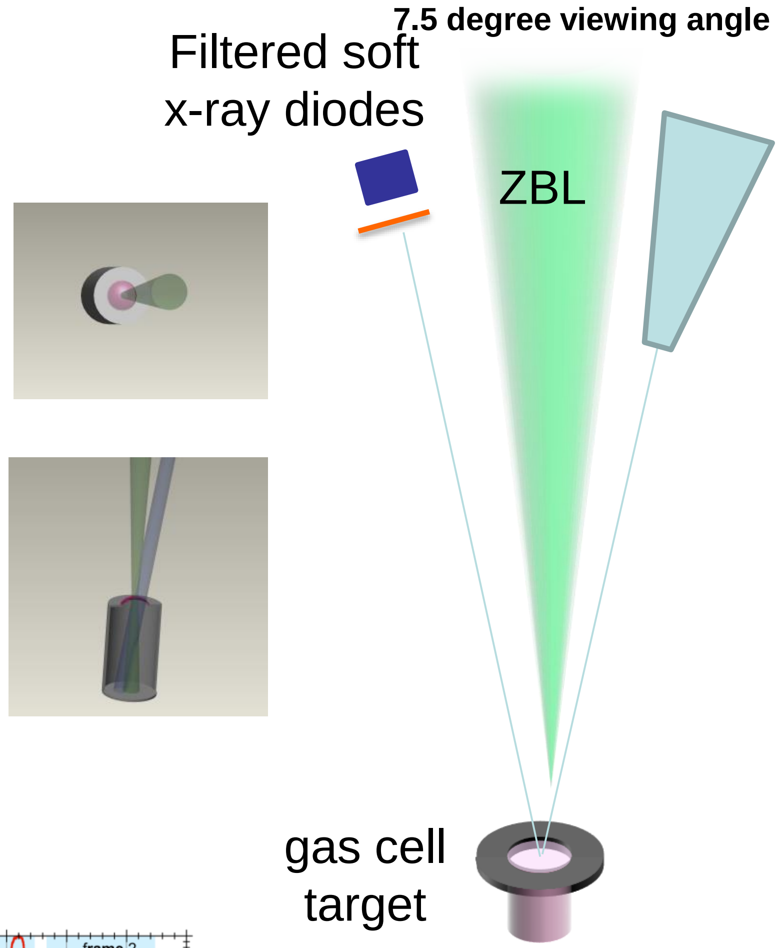
We are making good progress in developing an in-situ Te measurement for Z

WBS 2.4

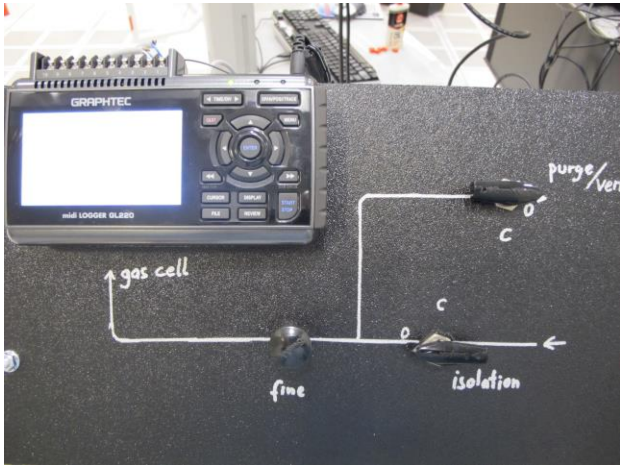
- **Important for understanding preheat conditions in a MagLIF implosion & validating simulation models**
- First time resolved axial pinhole camera images of laser only experiments on Z have been obtained
- Development happening concurrently on PECOS & Z

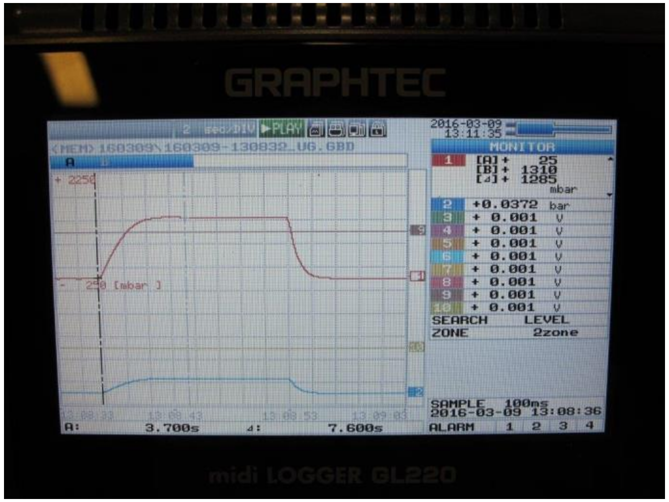






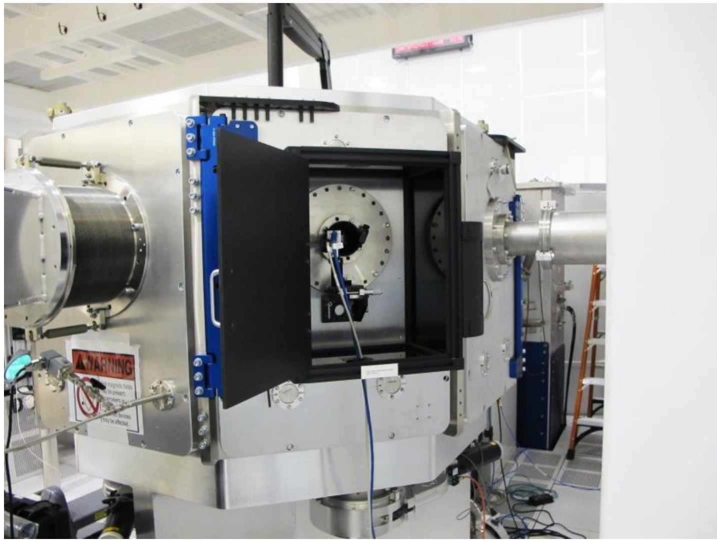
Gas Cell Test Stand

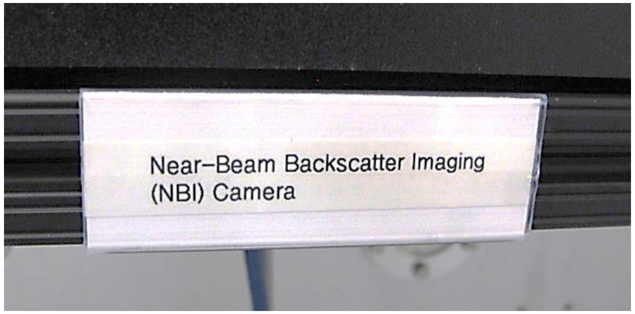


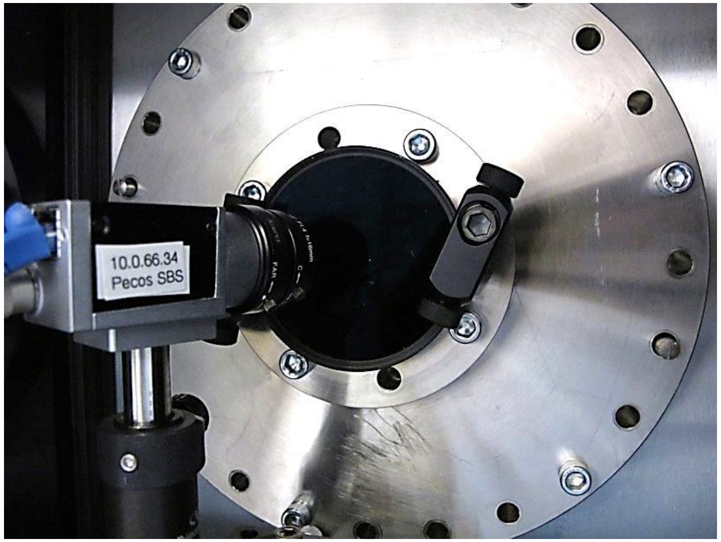


SBS Station

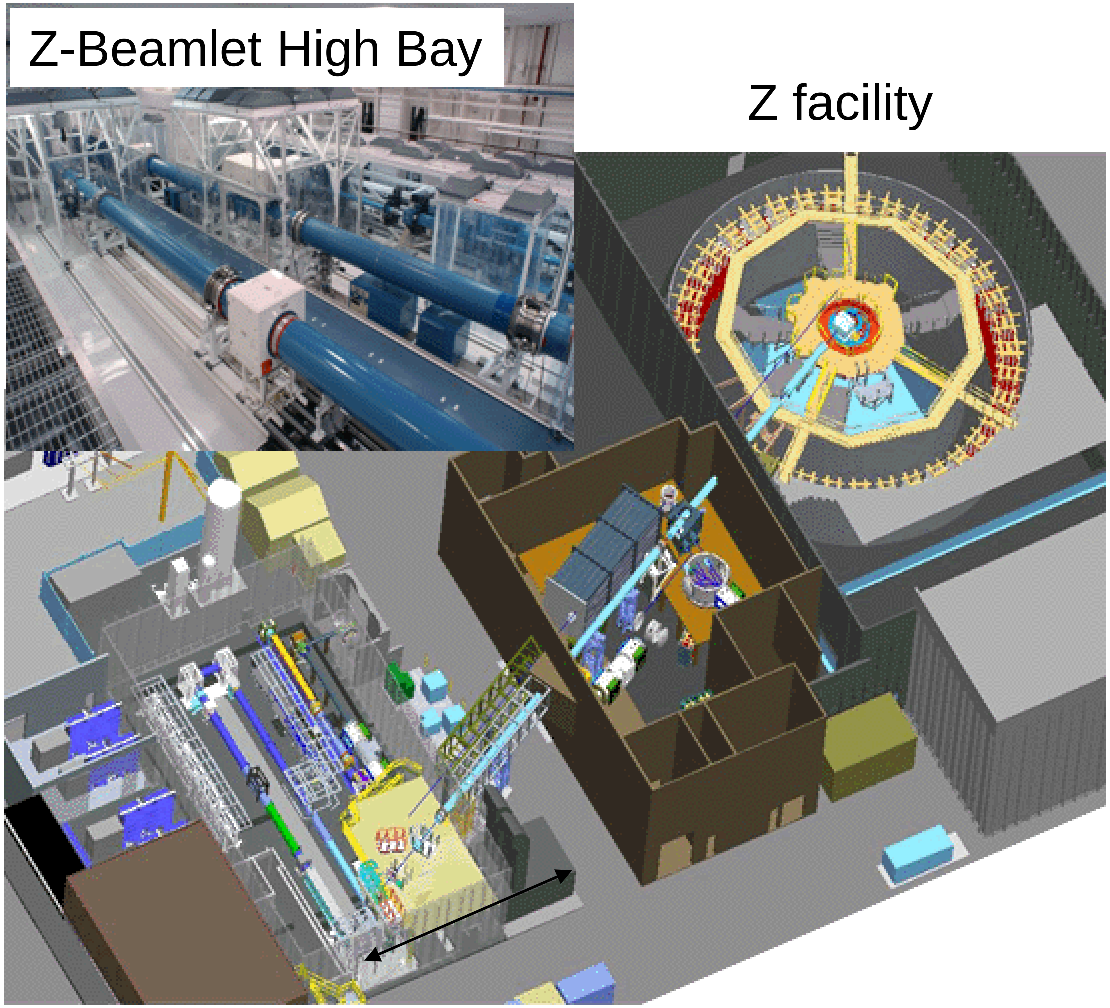

WARNING


WARNING


Near–Beam Backscatter Imaging
(NBI) Camera


10.0.66.34
Pecos SBS

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



Z-Beamlet and Z-Petawatt lasers

Z-Beamlet (ZBL) is routinely used to deliver ~ 2.4 kJ of 2ω light in 2 pulses for backlighting experiments on Z

In 2014 we added bandwidth to the laser; can now deliver ~4.5 kJ of 2ω in a 4 ns pulse.

It should be possible to reach 6-10 kJ of laser energy (e.g., as on the NIF)

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

Typical MagLIF initial fuel densities correspond to 0.10 to 0.30 x critical density for 2ω

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

Our major milestones focus on demonstrating magneto-inertial fusion scaling experimentally and using modeling

- **Target pre-conditioning experiments (Z, ZBL, OMEGA, OMEGA-EP)**
  - Demonstrate a set of functional laser pre-heating parameters (laser pulse shape, focal spot size, window thickness) to provide > 1 kJ of laser heating to the fusion fuel in an integrated MagLIF shot on Z
  - Determine the time-dependent Te history in a Z MagLIF experiment
- **Laser-driven MagLIF experiments (OMEGA)**
  - Confirm >100 eV and low-mix preheat
  - Symmetrically implode cylindrical target containing preheated fuel with > 1 kJ/cm of kinetic energy
  - Demonstrate > 30% increase in Te (as compared to unmagnetized target) in axially symmetric target compression over > 0.6 mm length
- **Numerical Modeling & Theory (Sandia, U. Rochester)**
  - Results from integrated OMEGA experiments agree with Flash and Hydra to within 20% of hydrodynamic variables and a factor of two in neutron yield
  - Report on key dependencies across the MIF parameter space for generalized scaling laws, and highlight most promising regimes; analysis to include both near-term and long-term fusion power cases