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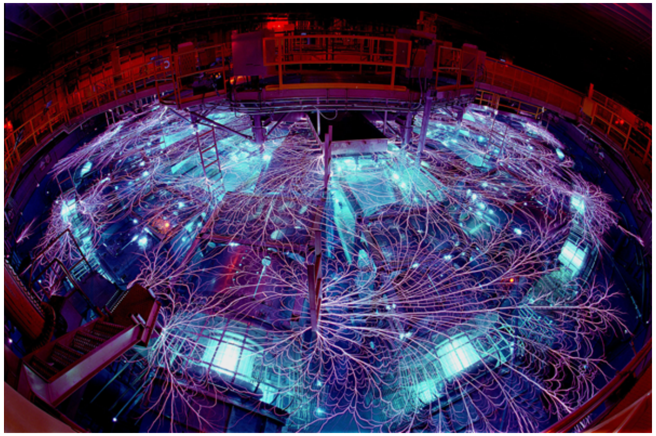

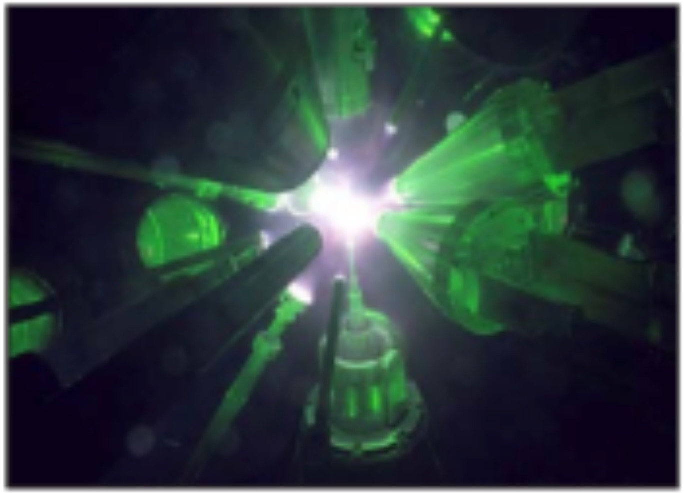

# Demonstrating Fuel Magnetization and Laser Heating Tools for Low-Cost Fusion Energy

**Kyle Peterson[1], Jonathan Davies[2]**

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*Rochester, NY, USA*

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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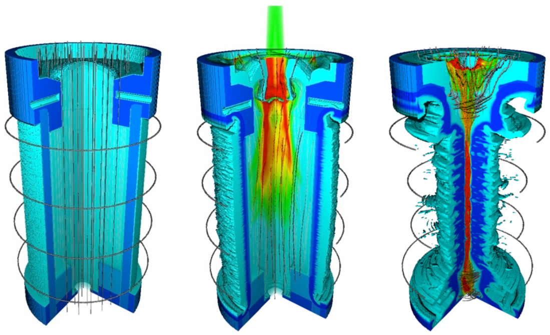
# This project is a collaboration between Sandia and the University of Rochester

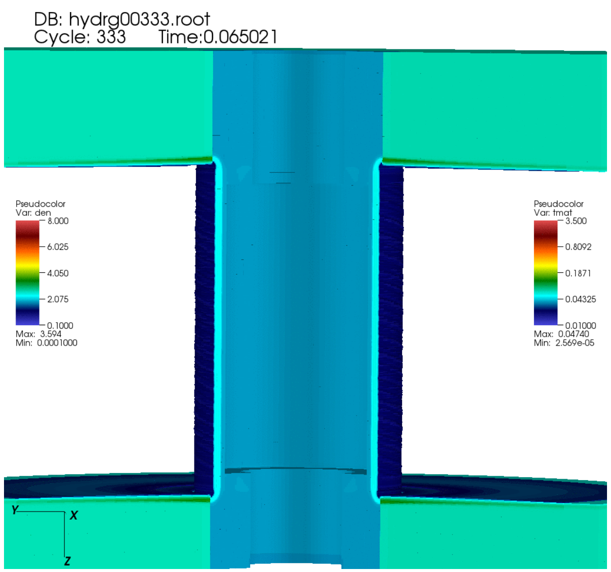
- **Sandia National Laboratories, Albuquerque, NM**
  - Daniel Sinars, Senior Manager, Radiation & Fusion Physics Group
  - Kyle Peterson*, Manager, ICF Target Design Department
  - John Porter, Manager, Laser Operations & Engineering
  - Matthias Geissel, Principal Member of Technical Staff
  - Adam 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






3D HYDRA Simulation, A. Sefkow

- **Axial magnetization of fuel/liner ($B_{z0}$ = 10-30 T)**
  - Inhibits thermal conduction losses and traps alphas ($\beta$: 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 $\rho R$ at stagnation for inertial confinement
- $\tau$ ~ 1-2ns, ~100x lower fuel pressure than traditional ICF (~5 Gbar vs. 500 Gbar)

**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).

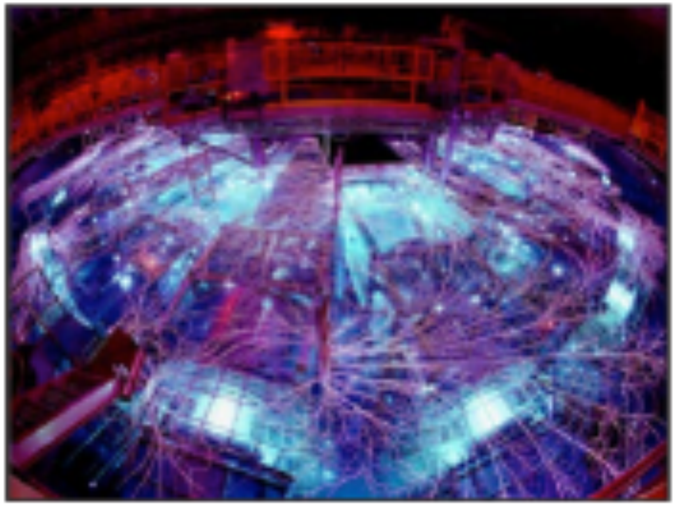
# This project is using existing capabilities at both institutions to demonstrate magneto-inertial fusion scaling

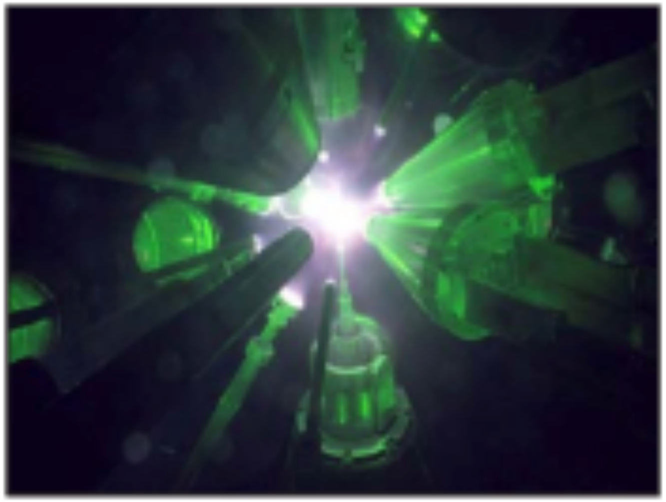
**Sandia National Laboratories**

- 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





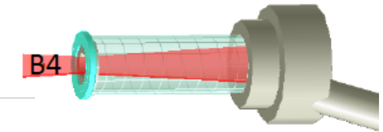


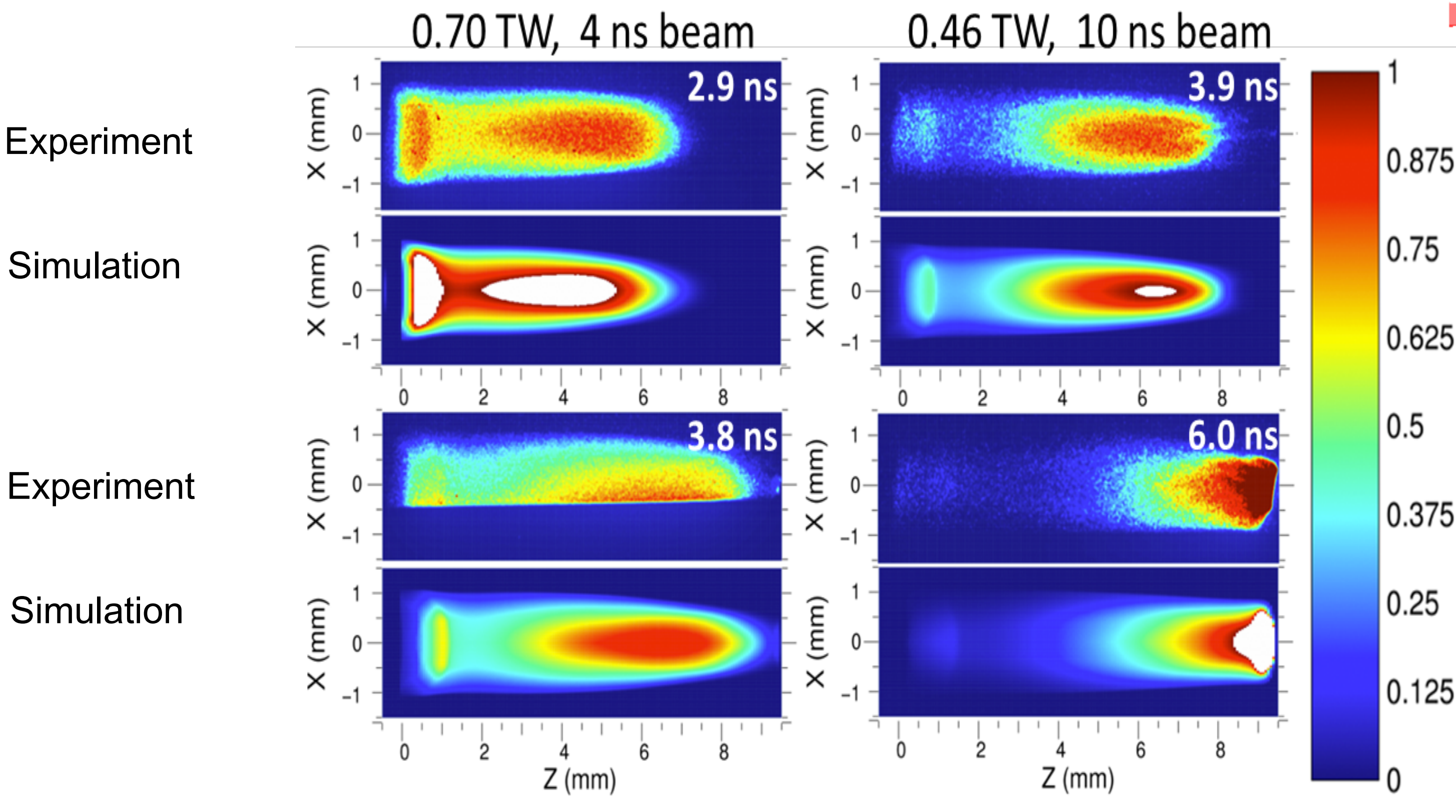
* All facilities are multi-user, multi-program facilities funded by the NNSA

# 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

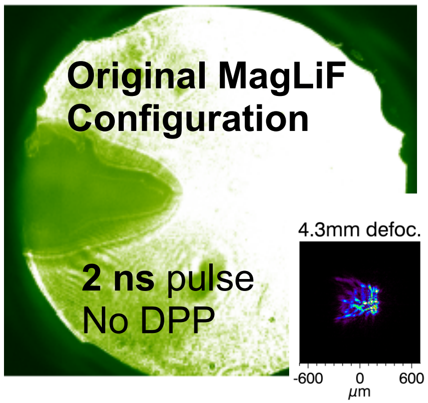


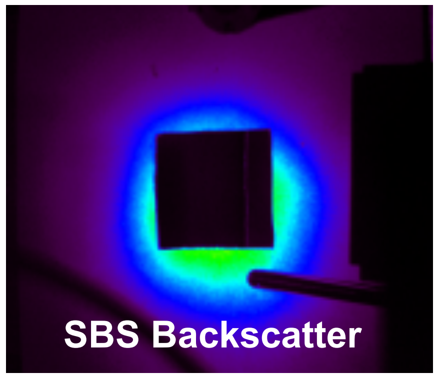



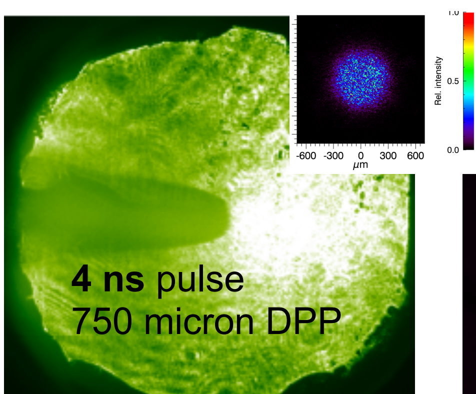

- Effect of B field (underway)
- Effect of pre-pulse (complete)
- Effect of laser intensity (complete)
- Window mix (next year)
- 2ω **vs** 3ω surrogacy (next year)
- LPI (underway)

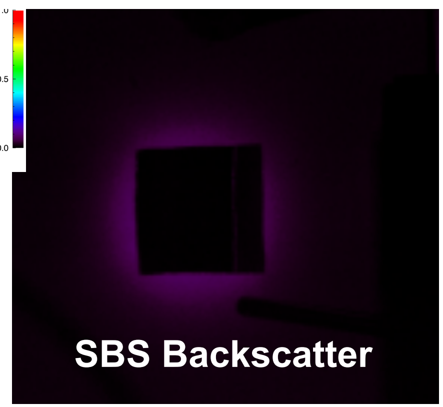
# Recent preconditioning experiments have provided key data for the development of a new preheat platform

## Optical Blastwave Measurements



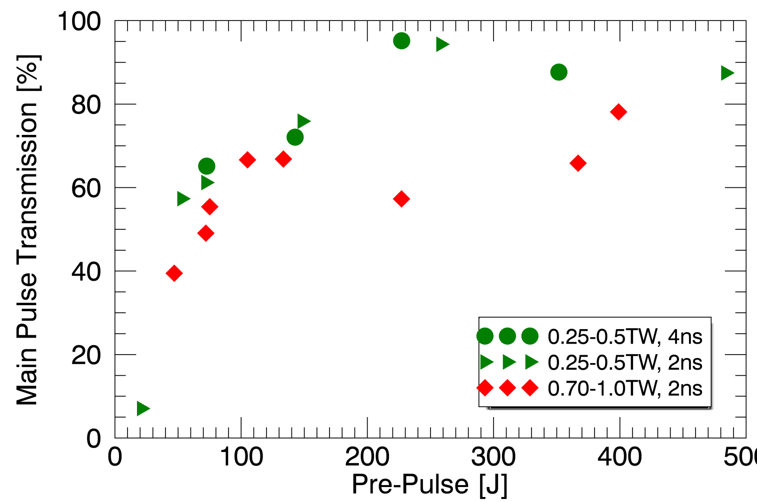




54psi He, 250J/1350J

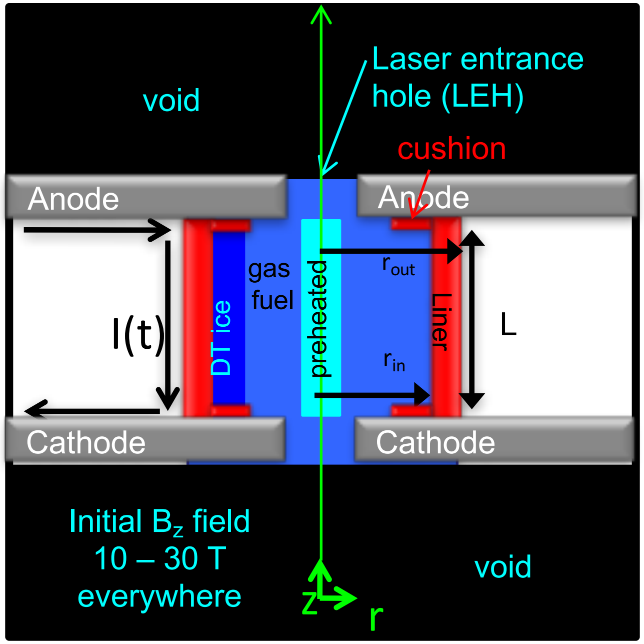
## Key Accomplishments

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

## LEH Window Transmission

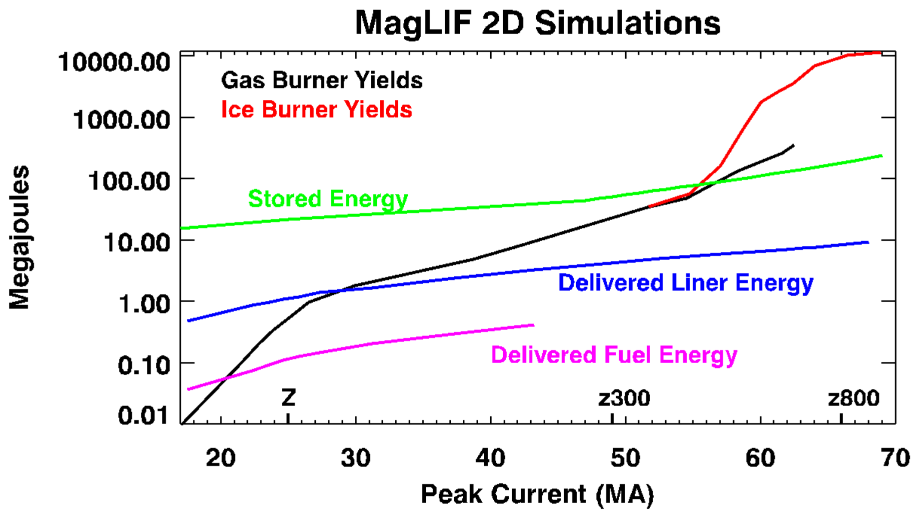


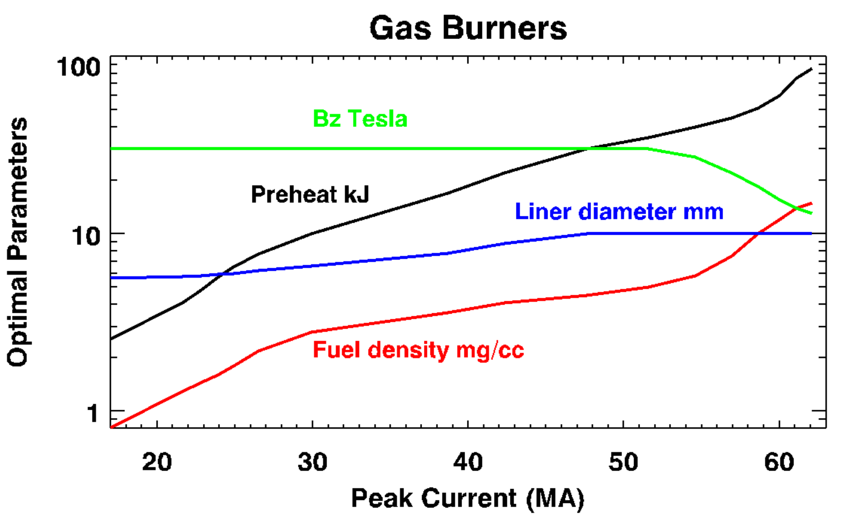
# MagLIF scaling study is complete for AR6 targets over a wide range of current and time scales*




Simulation Configuration

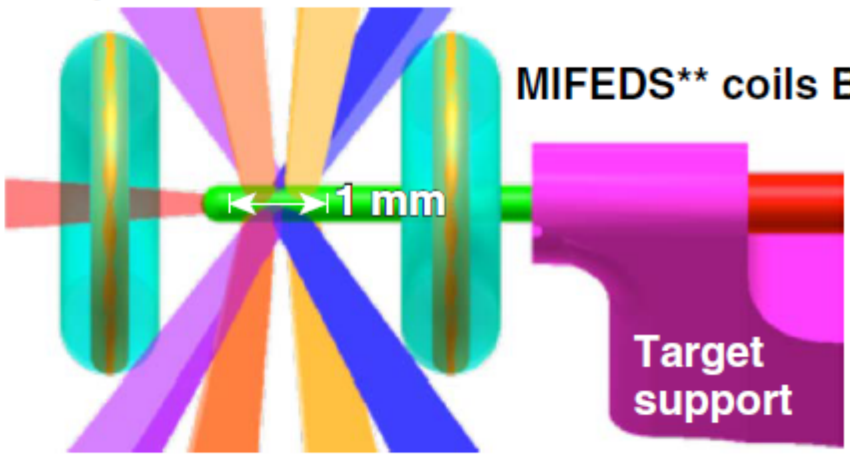
A broad study of the MIF parameter space is now underway. Results will be reported soon.




* ~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



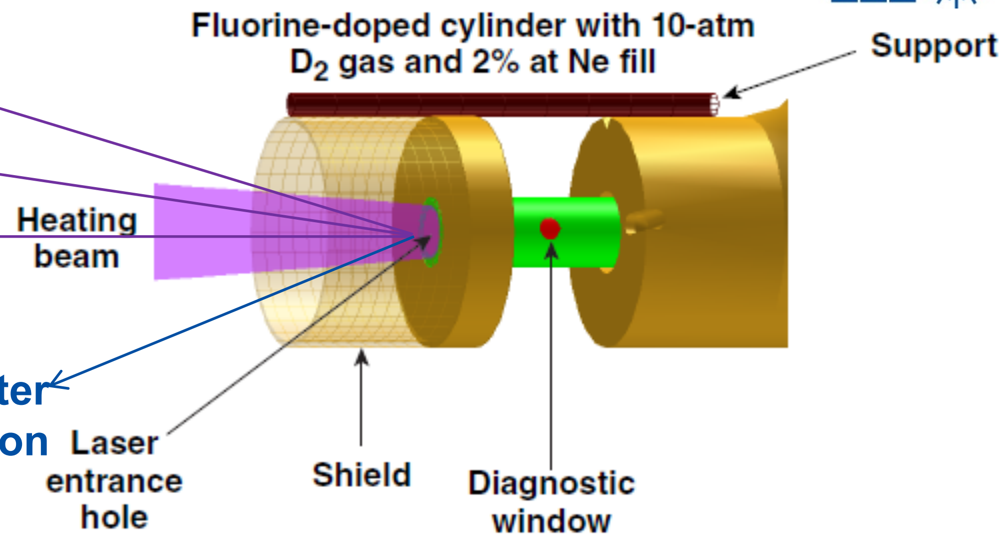

| | $r$ (mm) | $\Delta r$ (mm) | $r/\Delta r$ | $\rho_{fuel}$ (mg/cm$^3$) | $B_0$ (T) | $T_0$ (eV) | $V_{imp}$ (km/s) | Convergence ratio | $T_{max}$ (keV) |
|---|---|---|---|---|---|---|---|---|---|
| Z * | 3.48 | 0.58 | 6 | 3 (DT) | 30 | 250 | 70 | 25 | 8.0 |
| OMEGA | 0.30 | 0.03 | 10 | 2.4 ($D_2$)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

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

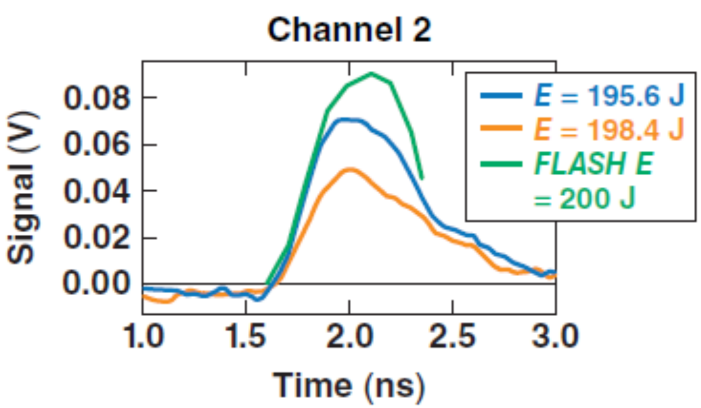
TC12449a

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

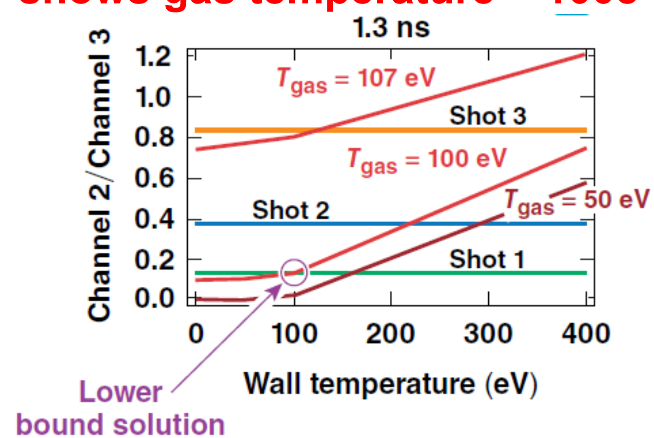
Total laser backscatter < 1% with no backscatter from the gas




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)
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 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 μm**

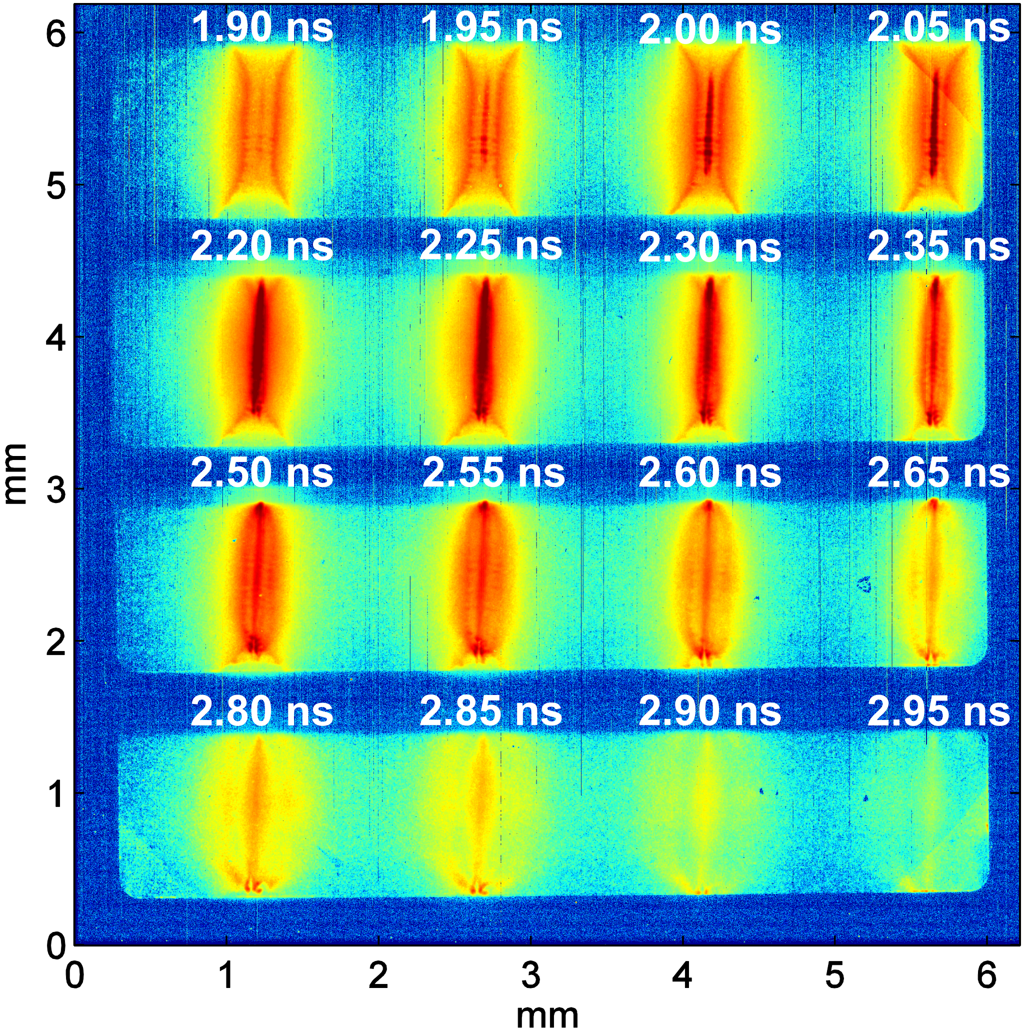
**$D_2$ density: 1.80 mg/cc**

**Laser energy: 13.0 kJ**

**Pulse length: 2.0 ns**

**Neutron yield: $2.53 \times 10^7$**

**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 ≥ $10^7$



| Shell thick. (μm) | $D_2$ 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 3ω 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

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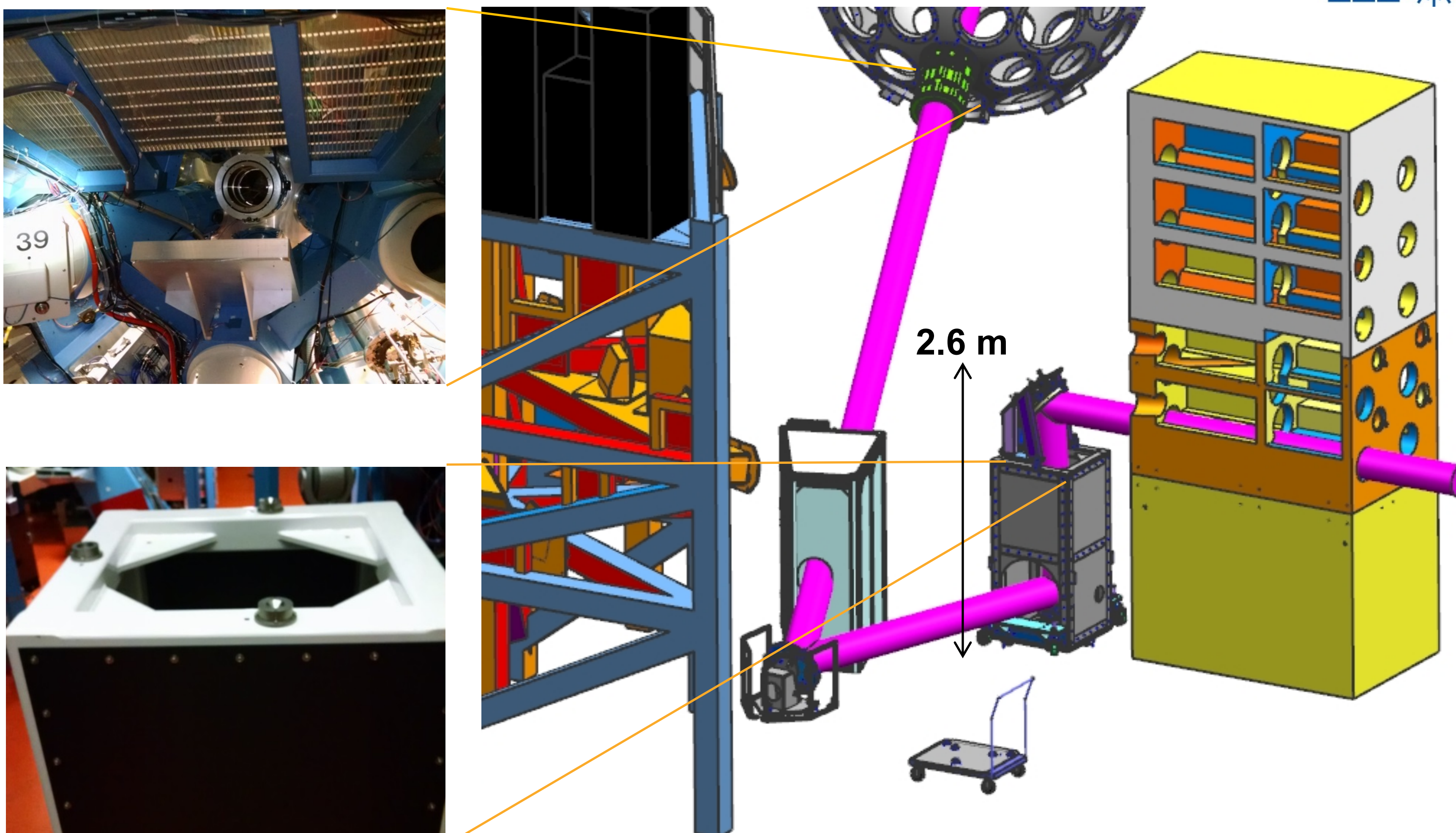
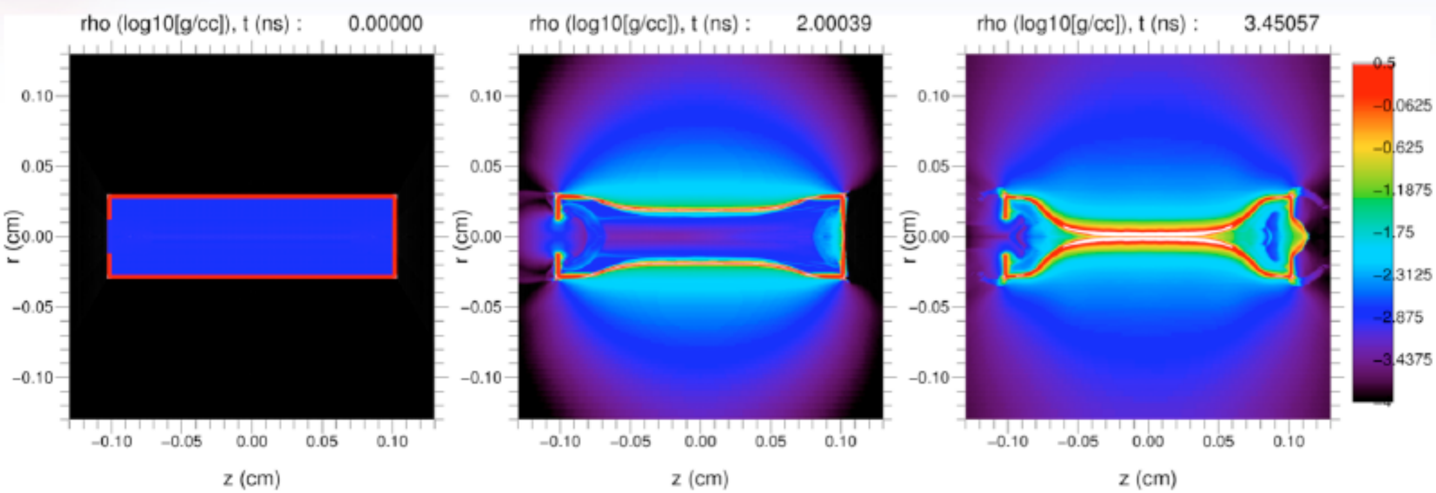


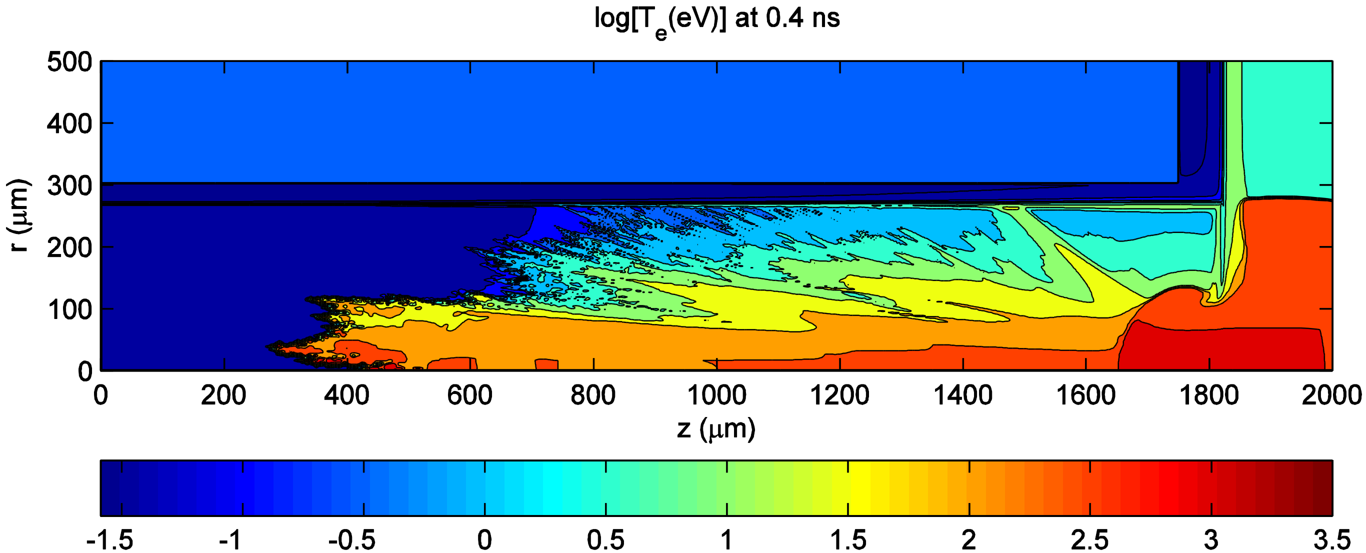

**Mirror hardening shots up to full energy have been performed**

# 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**



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

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- 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

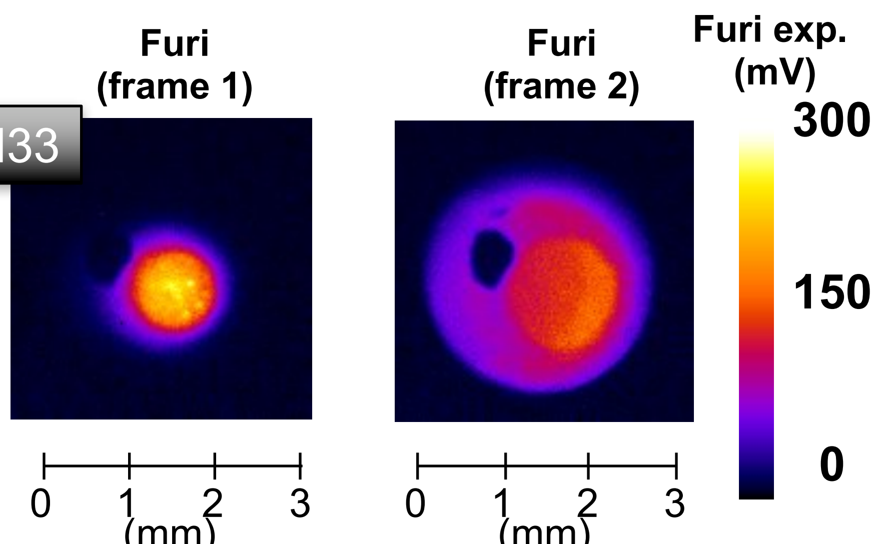
- Magnetic field system has been developed for PECOS chamber (up to 5 T)
- Near back & forward scatter imaging (SBS) capability complete on PECOS
- New distributed phase plates installed for PECOS
- New pressure test stand for PECOS targets is complete (60 psi, He)
- New targets that provide much better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

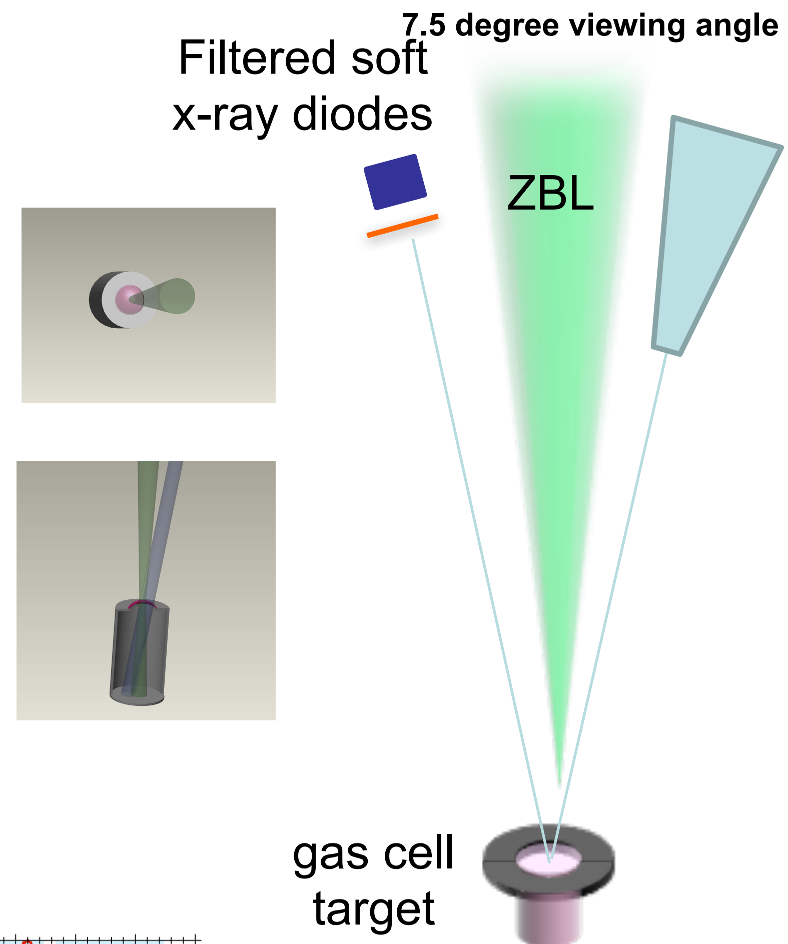
# We are making good progress in developing an in-situ Te measurement for Z

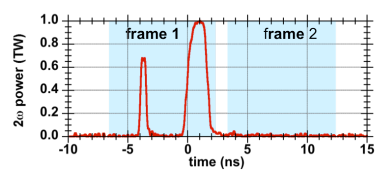
WBS 2.4

- **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

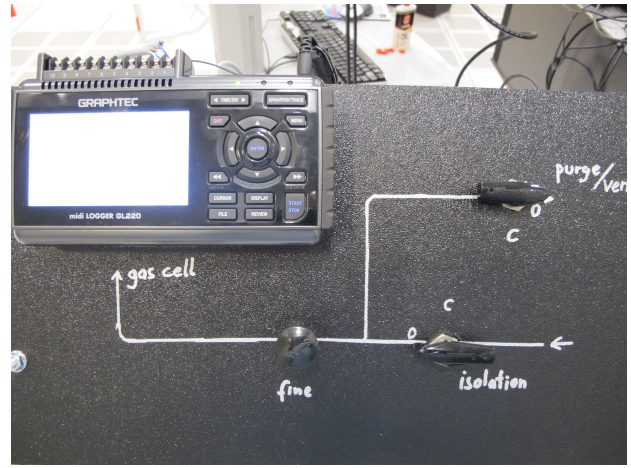
H33

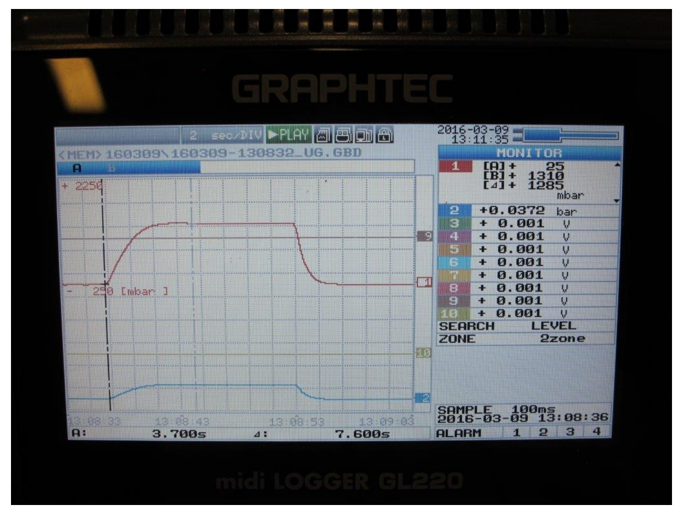


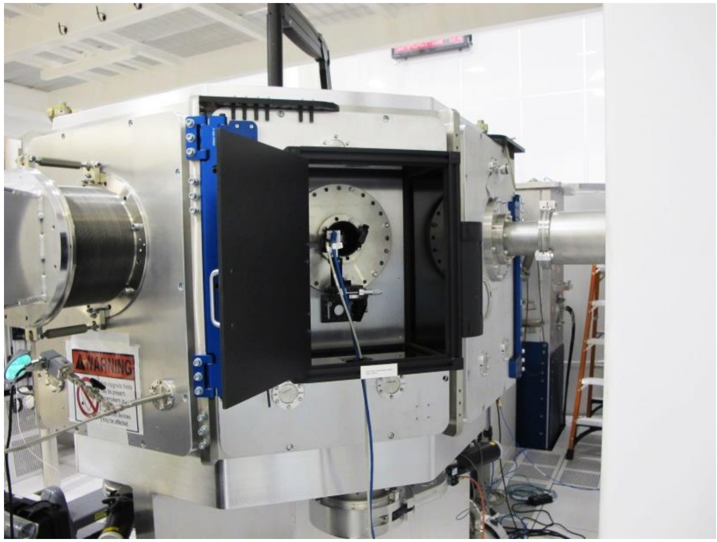



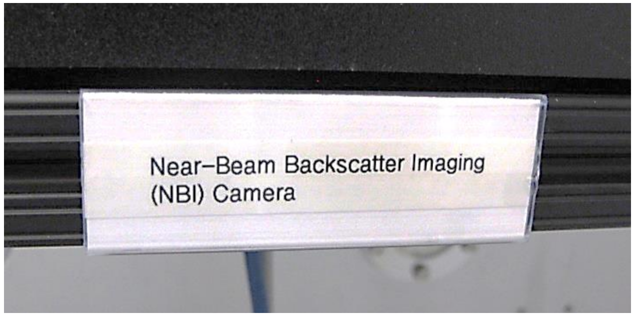
# Gas Cell Test Stand

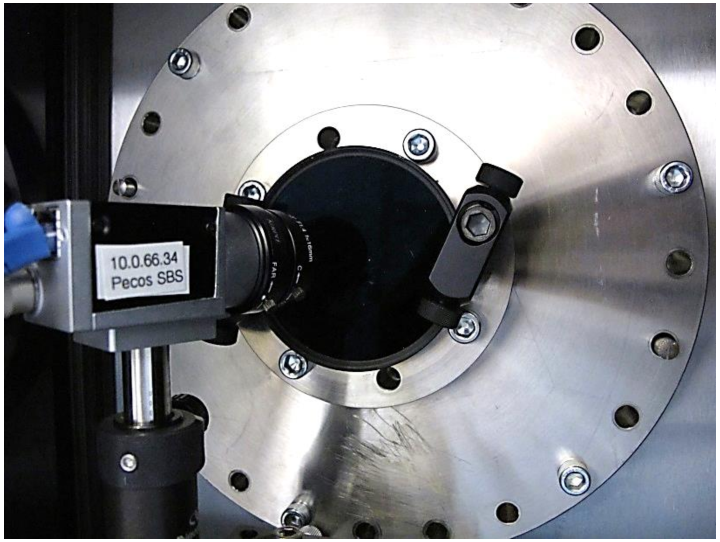



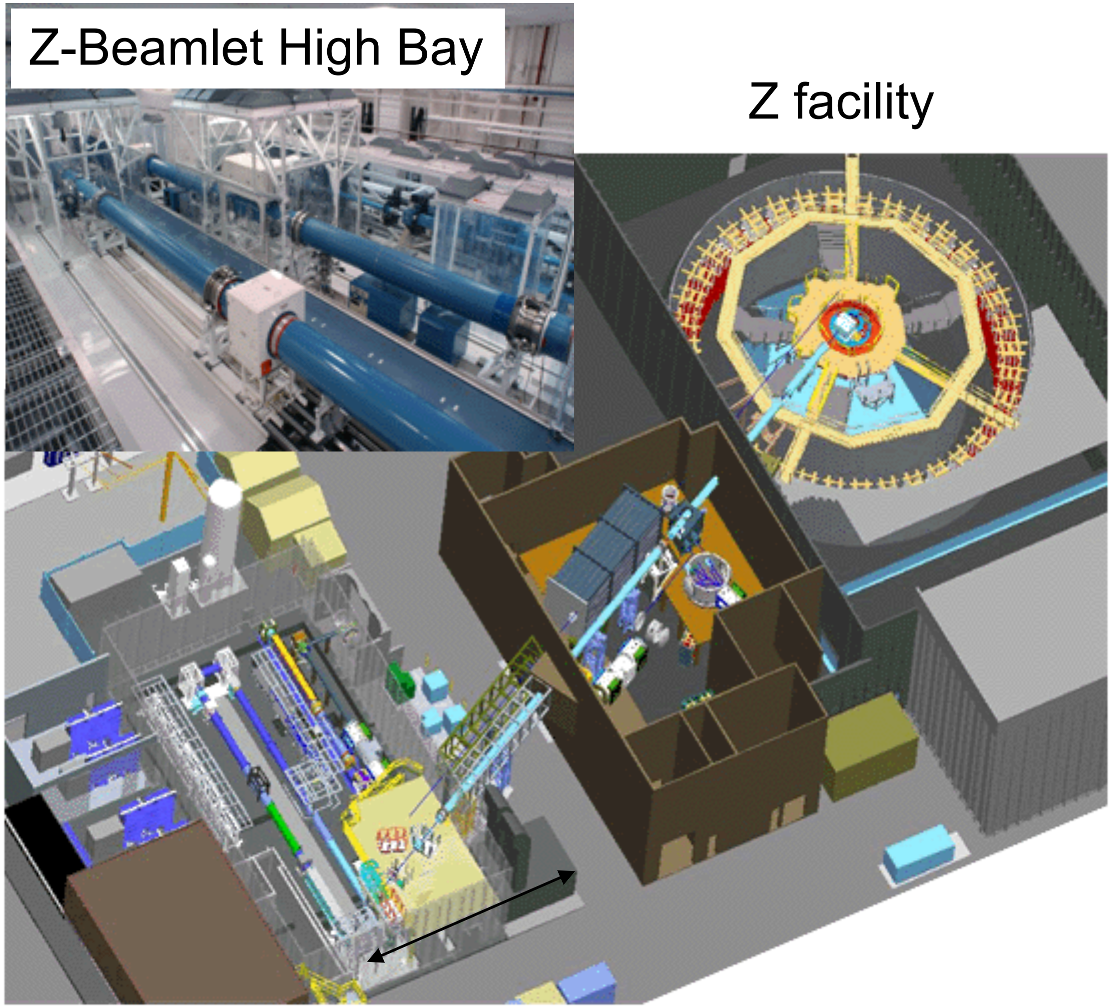
# SBS Station


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 2$\omega$ light in 2 pulses for backlighting experiments on Z

In 2014 we added bandwidth to the laser; can now deliver ~4.5 kJ of 2$\omega$ 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 2$\omega$

* 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