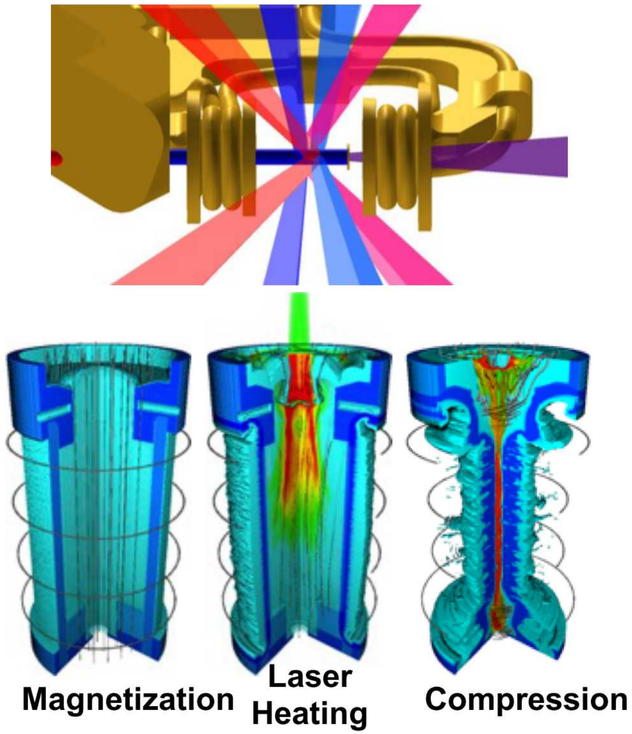
SAND2018-12259PE

Exceptional service in the national interest



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

2018 *ARPA-E ALPHA Program Annual Review*

Sandia National Laboratories
Albuquerque, NM, USA

Laboratory for Laser Energetics
Rochester, NY, USA

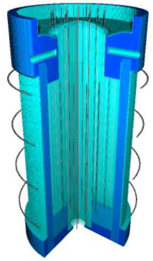
CHANGING WHAT'S POSSIBLE

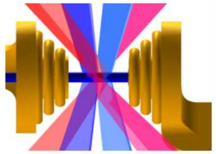
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

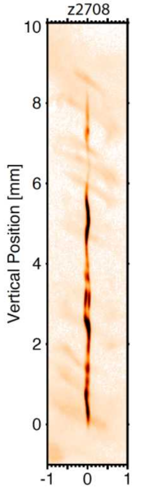
Project Objective and desired outcomes

- *Develop and demonstrate the essential elements of MIF*
- *Validate simulation tools and models* ***<u>at fusion conditions</u>*** *with* ***driver scales differing*** *by* ***two orders of magnitude***
- *Mature scientific platforms and understanding enables rapid development of technology*

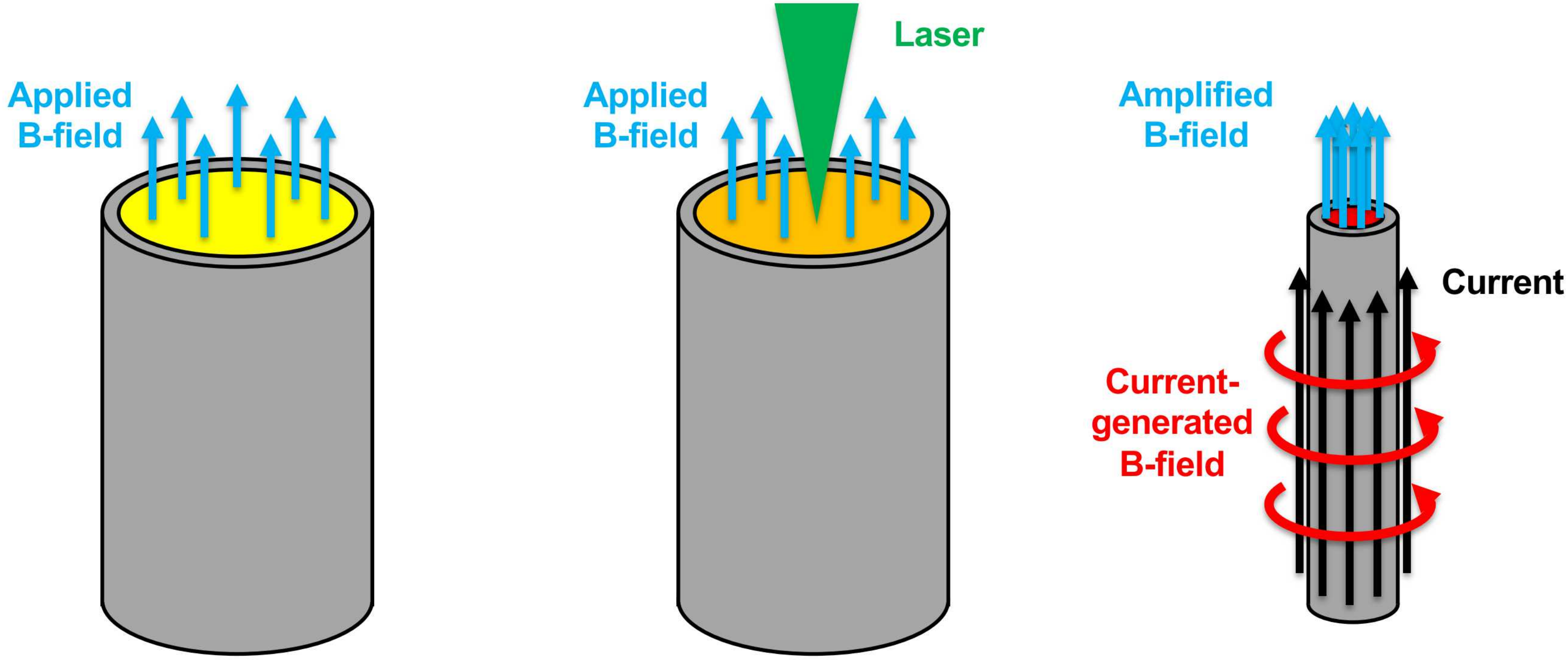
- *Potential to demonstrate fuel gain >1 (50-100 kJ DT) on Z facility*
- *Provides* ***strong*** *MIF credibility and motivates investments in MIF concepts as alternative to MCF and ICF*





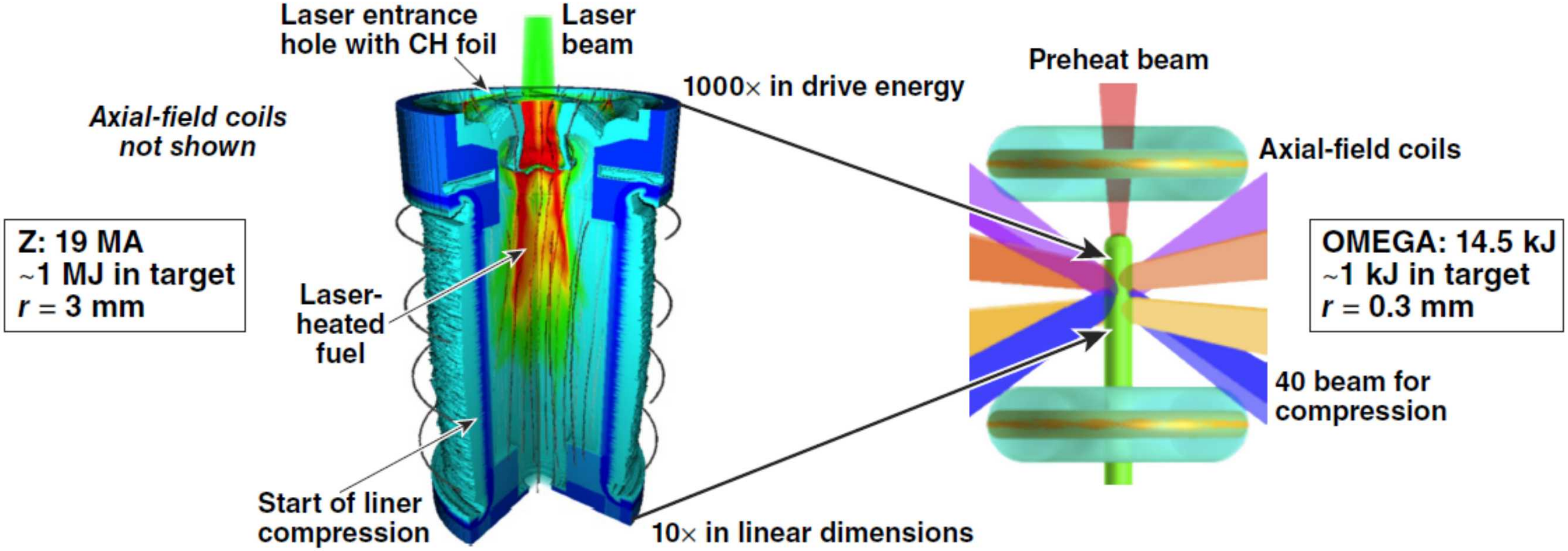


Magnetized Liner Inertial Fusion (MagLIF) relies on three stages to produce fusion relevant conditions

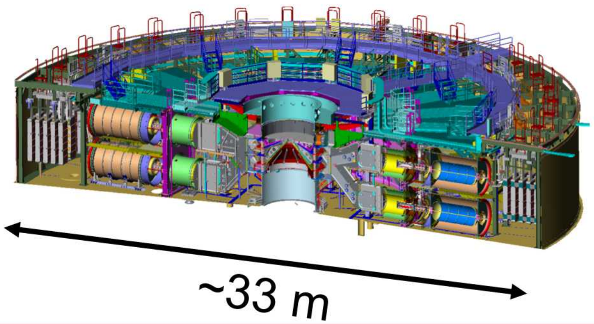


Apply axial magnetic field **Heat the magnetized fuel (e.g., with a laser)** **Compress the heated and magnetized fuel**

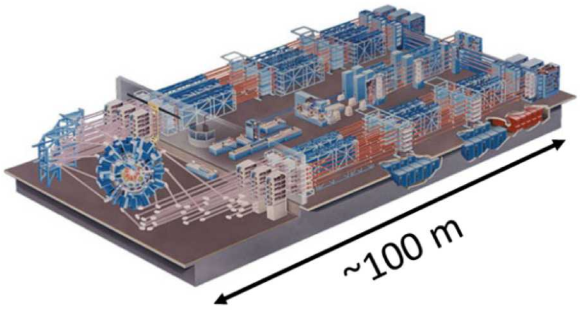
We developed a scaled-down laser driven MagLIF platform on OMEGA that enables key scaling keys and rapid assessment of physics



Z Facility



Omega Facility



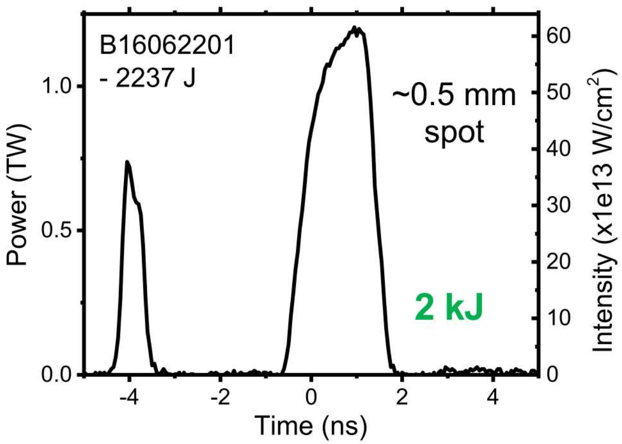
Accomplishments and ARPA-E Impact

- *Developed a laser driven MagLIF platform (OMEGA) and successfully tested scaling at **1000x** lower energy*
- *Significantly improved laser energy coupling to the fuel on Z from ~300J to 1.4kJ and developed a validated modeling capability*
- *Demonstrated **6X improvement** in fusion performance on Z (2.5kJ DT equivalent)*
- *11 publications in peer reviewed scientific journals*

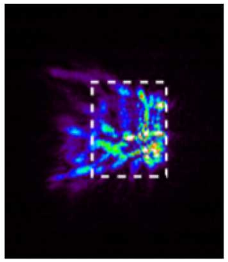
Our initial experiments had significant uncertainty in the coupled laser energy due to poor beam quality

- No beam smoothing was employed (Z-Beamlet only used for radiography before MagLIF)
- Laser configuration produced significant laser plasma interactions (LPI) not modeled in our codes
- Several independent laser heating experiments suggested low (200-500J) preheat coupling

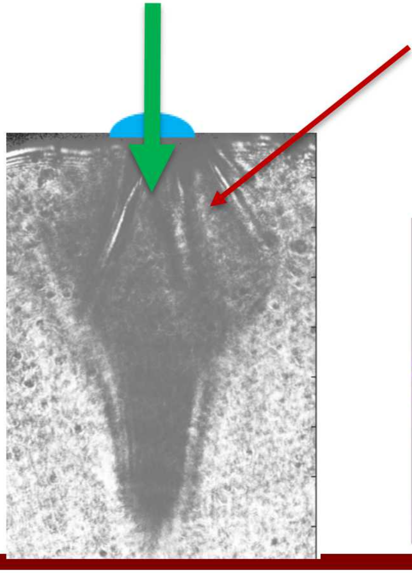
Original MagLIF laser pulse



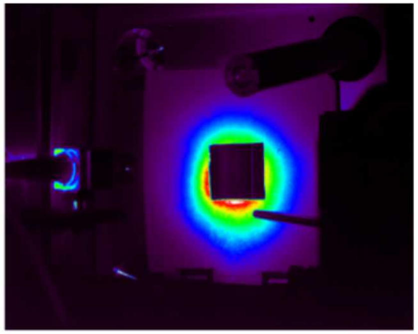
Beam Profile



filamentation

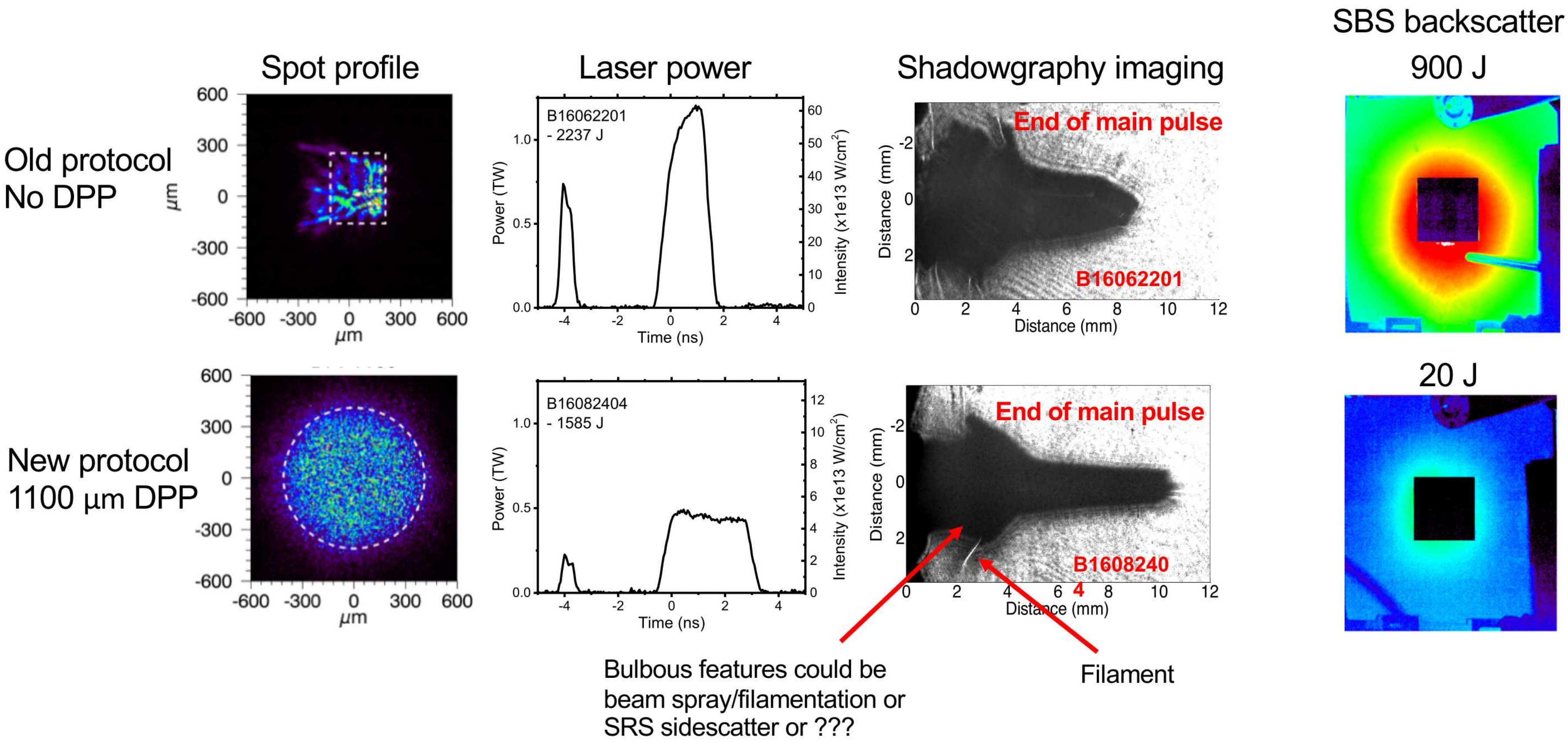


Stimulated Brillouin Scattering: 900J !



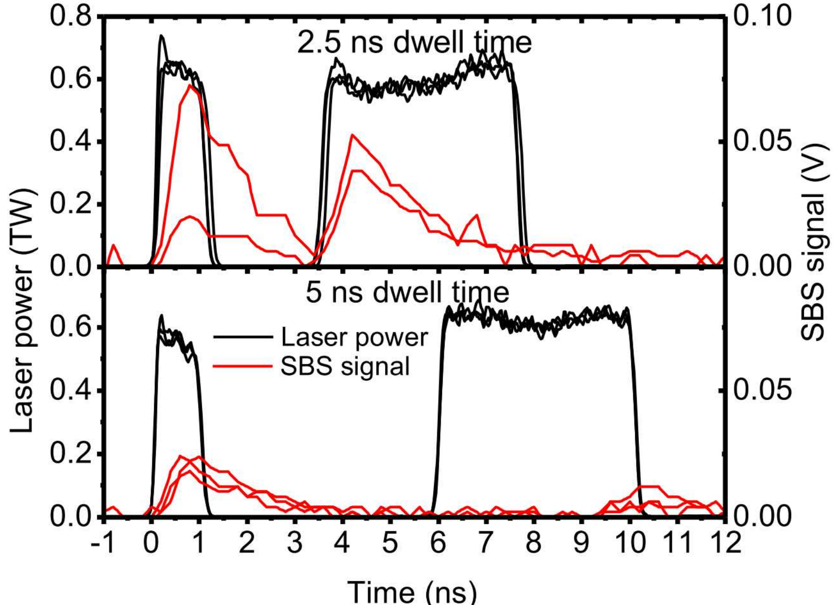
M. Geissel *et al.*, Proc. SPIE 9731 (2016); M. Geisel *et al.*, Phys. Plasmas 22 (2018).

New laser heating protocols were developed for Z-Beamlet that significantly reduced LPI and modeling uncertainties

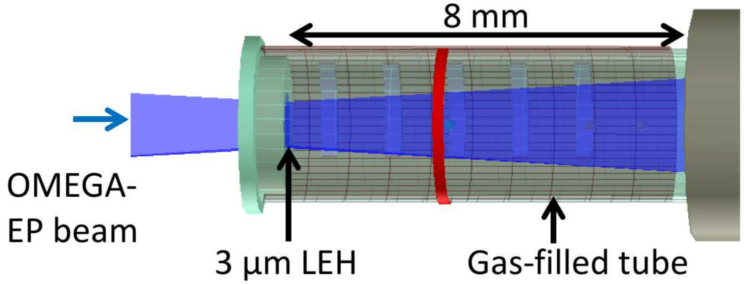


M. Geissel *et al.*, Proc. SPIE 9731 (2016); M. Geisel *et al.*, Phys. Plasmas 22 (2018).

OMEGA-EP experiments showed increased dwell time between laser pre-pulse and main pulse was needed



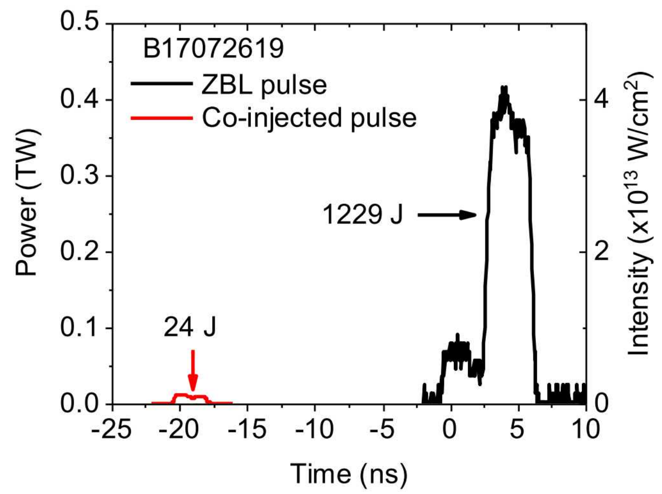
Laser power and SBS signals for two different pulse shapes



A.J. Harvey-Thompson et al., POP (2015), PRE (2016)

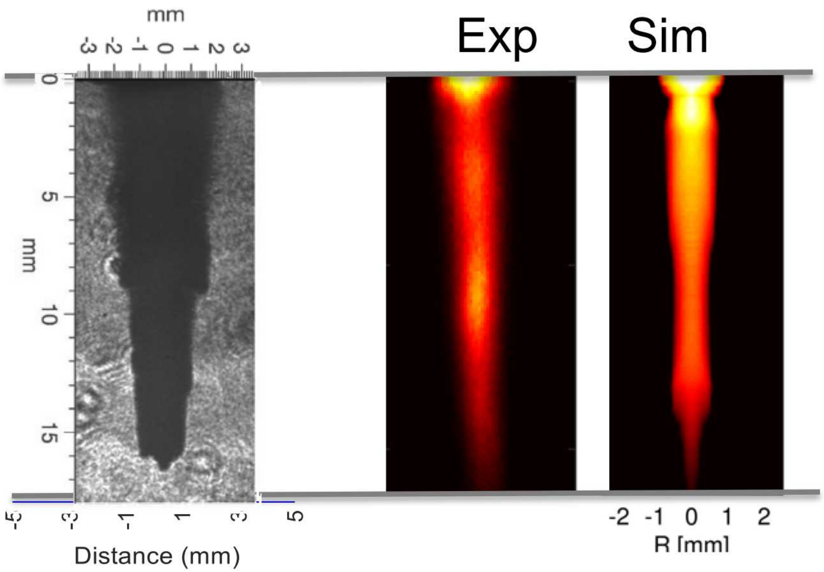
Longer delay times were recently enabled by co-injection of the Z Petawatt laser

- Utilize 10-20J Z-Petawatt laser pulse to disassemble window
- Entire 6 ns ZBL laser window available for fuel heating
- Significantly improved energy coupling and reduced LPI effects



Optical Shadowgraph @ +20ns

Time integrated pinhole camera

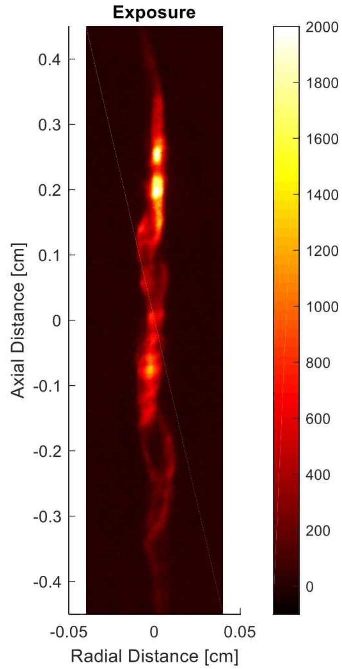


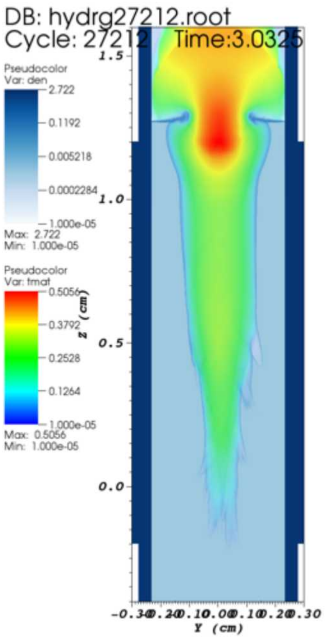
A. Thompson, M. Geissel, M. Weis, J. Schwarz, I. Smith

A 6x increase in neutron yield (1.1e13 DD neutrons) was observed due to improvements to preheating and liner stability

	z3236 (preheat 18A)
Main pulse laser energy	261 + 2240 J
Gas pressure	90 psi (1 mg/cc)
LEH window	2 mm diam. 1.77 um
Dopant	1 nm Co on LEH
DD	1.1e13 ± 20%
DD/DT	100 +/- 28%
Tion (Ntof)	3.1 keV +/- 20%

10T, 17 MA Current Pulse



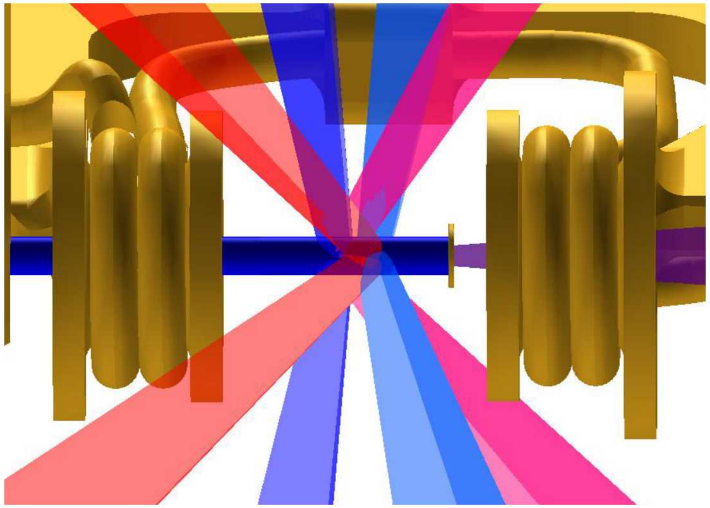


- AR9 Coated/Stabilized Liner
- Higher density fuel (1.0 mg/cc)
  - Lower convergence
- Greater coupled preheat energy
  - 1.5kJ with co-injection

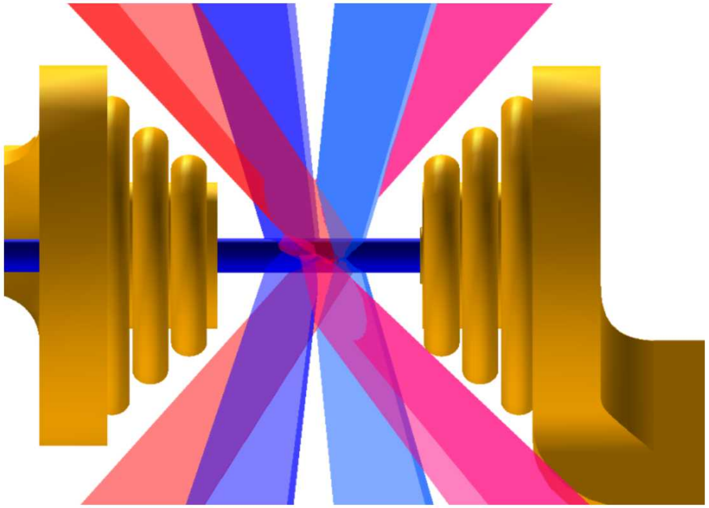
M. Weis, A. Harvey-Thompson

Initial laser driven MagLIF experiments showed that the initial axial magnetic field was insufficient. The field was increased to 27 T using 2 MIFEDS and several design improvements

Old design single MIFEDS 9 T

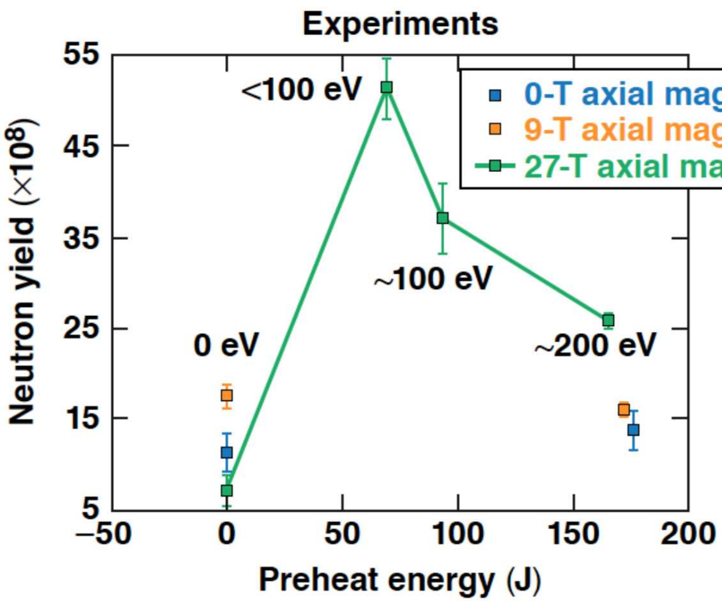


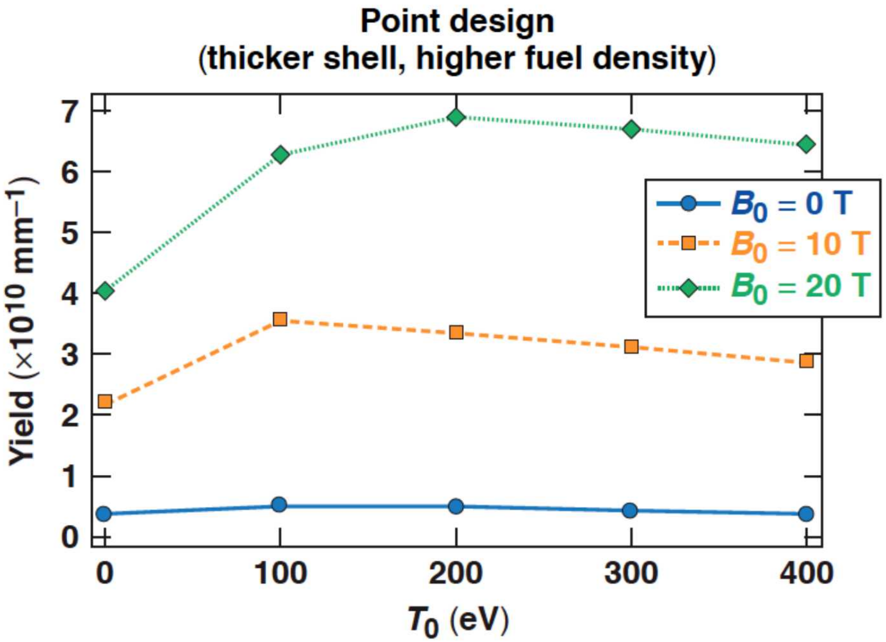
New design dual MIFEDS 27 T



VisRad from J. Peebles

Optimum preheat is lower than expected and the fall in yield above optimum preheat is faster than expected

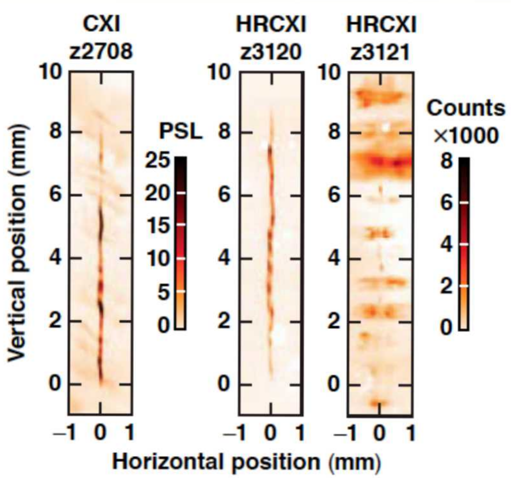




Compared to Z experiments the yield enhancements due to magnetization and preheating are lower because the compression-only baseline is more stable

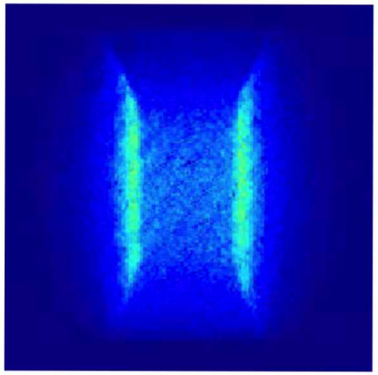
Z baseline experiments		
	$B_z = 0$ T	$B_z = 10$ T
No preheat	0.003×10^{12} ~1 keV	0.01×10^{12} ~1 keV
Preheat	0.04×10^{12} ~1 keV	3×10^{12} 2.5 keV

OMEGA baseline experiments		
	$B_z = 0$ T	$B_z = 10$ T
No preheat	1×10^{9} 2.0 keV	1.8×10^{9} 2.6 keV
Preheat	1.4×10^{9} 2.1 keV	1.6×10^{9} 2.3 keV



27839

Any type of shot on OMEGA

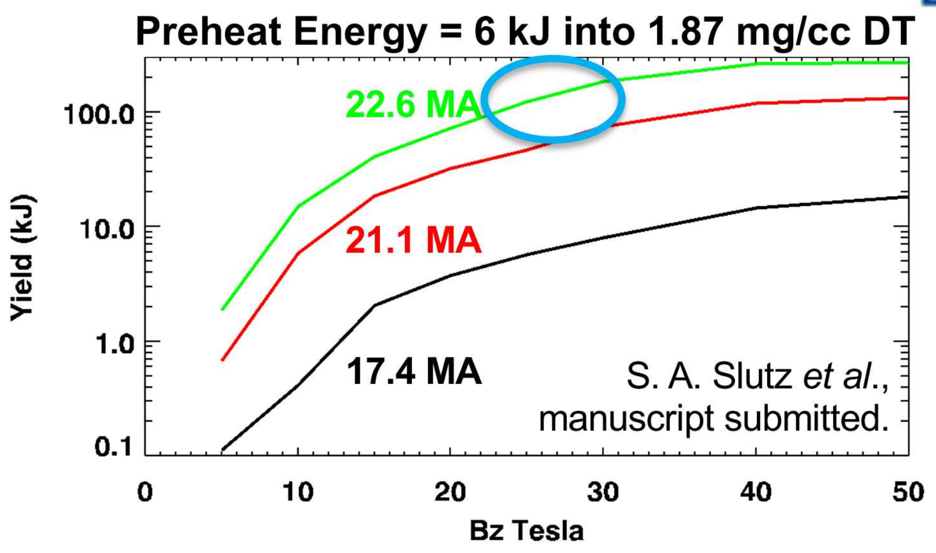


Future Plans

- *Develop enhanced platform for testing scaling predictions on Z (22 MA, 20-25T, 6kJ) by 2020. Demonstrate >50 kJ DT yield equivalent on a time scale commensurate with funding*
- *Perform detailed physics and scaling tests (>35T) with laser driven MagLIF platform, validate codes*
- *Develop science based scaling to support investment in a future facility capable of large fusion yields and gain*
- *Evaluate alternative magnetization and preheat schemes that are more suited to fusion energy*

Our goal on Z is to produce a fusion yield of ~100 kJ DT-equivalent

- 2D simulations indicate a 22+ MA and 25+ T with 6 kJ of preheat could produce ~100 kJ
- Presently, we cannot produce these inputs simultaneously.

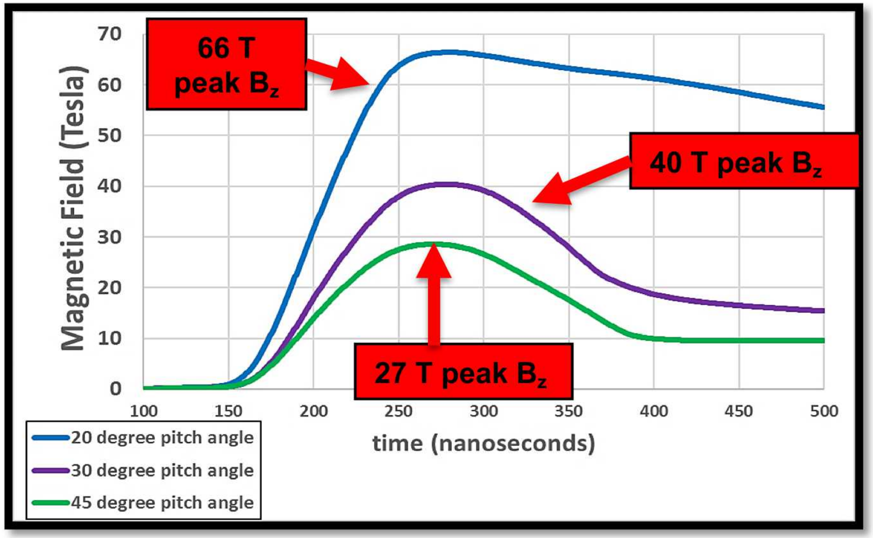


Date	Liner	Fill (D2)	Current	Bfield	Preheat	Yield (DT-eq.)
2014	AR=6	0.7 mg/cc	17-18 MA	10 T	~0.3 kJ?	0.2-0.4 kJ
Aug. 2018**	AR=6	1.1 mg/cc	19-20 MA	15 T	~1.2 kJ**	~2.4 kJ**
2020 Goal	TBD	~1.5 mg/cc	20-22 MA	20-30 T	2-4 kJ	~10 kJ
Final Goal	TBD	1.5 mg/cc	22 MA	25-30 T	6 kJ	100 kJ

** M.R. Gomez *et al.*, preliminary analysis

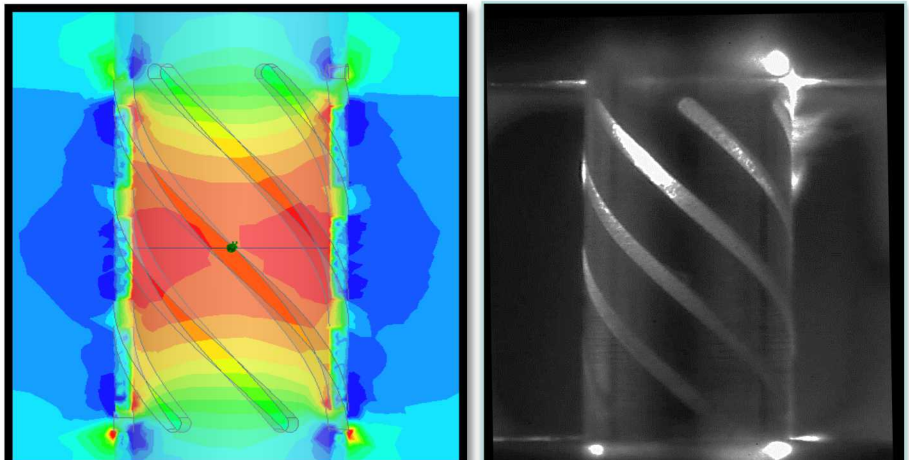
We are exploring alternative magnetization and preheating schemes that are more suitable to fusion energy

- **Slotted helical auto-magnetizing MagLIF liners (AutoMag) have demonstrated ~100 Tesla fields**
- **Motivation**:
  - *<u>Eliminate field coils!</u>*
  - higher initial magnetization
  - increase current through lower inductance
  - lower cost



On-axis field measured inside AutoMag liners

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



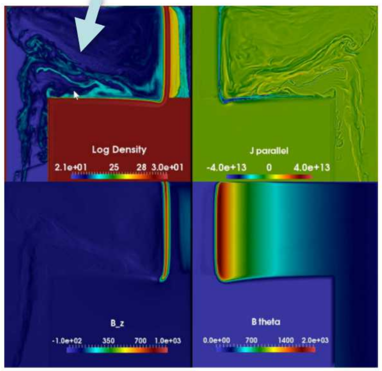
Simulation of internal B_z (left), iCCD image (right)

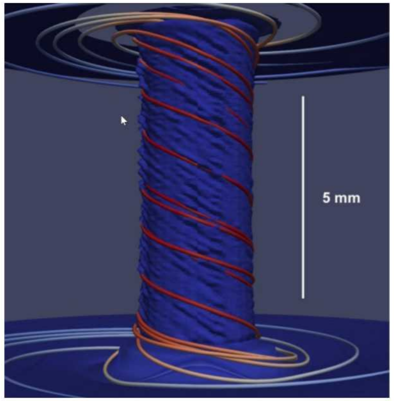
We are developing new tools to address identified shortcomings in simulation models

- **PERSEUS** – generalized Ohm's Law(XMHD), FORTRAN90, Discontinuous Galerkin (DG) code, originally developed at Cornell (Martin,Seyler) and licensed to SNL with numerous publications demonstrating the need for XMHD physics in the modeling of pulsed power systems

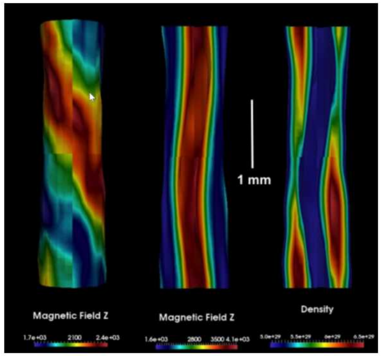
- **FLEXO** – new C++ XMHD code (Flux Limited EXtended Ohm's law) based on PERSEUS, developed under SNL LDRD with new capabilities: multi-material equation of state(EOS), adaptive mesh refinement(AMR), and scalable DG radiation transport, all compatible with advanced architectures (GPU) to enable a predictive simulation capability for design work on Z and future pulsed power facilities

1) Feed plasma transport requires XMHD due to low densities





2) XMHD predicts helical instability in 3D calculations due to feed plasma driving flux compression in MagLIF



3) Low density feed plasma (~10^18/cc) changes morphology and stability of liner stagnation

Development path towards commercial fusion

- **Demonstrate robust fusion gain**
  - Take easy path, not necessary an optimized driver path.
  - Focus on physics and understanding of technical challenges.
- **Share key findings with MIF community**
- **Fully develop alternative pre-heating and pre-magnetization schemes more suitable for fusion energy**

What's needed now?

- Improve Z platform capabilities, test target scaling
- Laser upgrades (improve energy coupling, LPI mitigation)
- Investigate physics scaling at OMEGA and validate simulation codes
- Invest in higher fidelity MHD (xMHD) and improve low beta physics in simulation codes