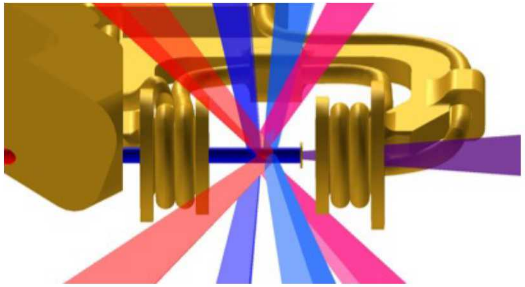
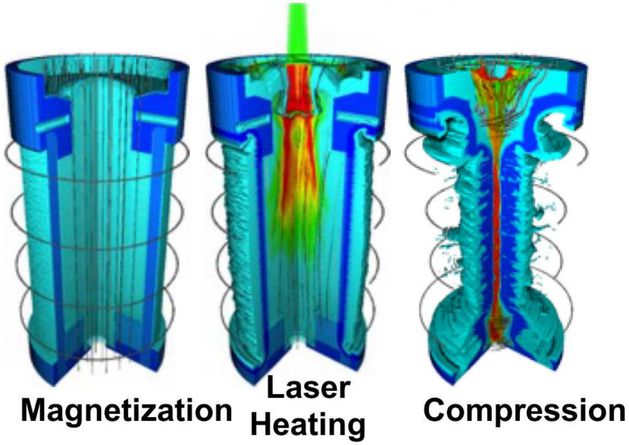
SAND2018-12674C

Exceptional service in the national interest





Progress in Magnetized Liner Inertial Fusion Research

2018 *American Physical Society Division of Plasma Physics Meeting*

Mini-Conference on Magneto-inertial Fusion Science and Technology II

November 5–9, 2018; Portland, Oregon

Sandia National Laboratories, Albuquerque, NM, USA

Laboratory for Laser Energetics, Rochester, NY, USA

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.

Acknowledgements

M. R. Gomez, P. F. Knapp, E. C. Harding, D. J. Ampleford, T. J. Awe, A. J. Harvey-Thompson, C. A. Jennings, C. E. Myers, K. J. Peterson, G. A. Rochau, D. B. Sinars, M. R. Weis, and D. A. Yager-Elorriaga, M. Geissel, C. A. Jennings, M. R. Weis, D. J. Ampleford, G. A. Chandler, R. Fasano, J. R. Fein, B. Galloway, M. E. Glinsky, M. R. Gomez, K. D. Hahn, S. B. Hansen, E. C. Harding, M. Kimmel, L. Perea, K. J. Peterson, J. L. Porter, P. K. Rambo, G. K. Robertson, G. A. Rochau, D. E. Ruiz, J. Schwarz, J. E. Shores, D. B. Sinars, S. A. Slutz, I. C. Smith, C. S. Speas, K. Whittemore, D. Woodbury

Sandia National Laboratories

J. R. Davies, J. Peebles, D. Barnak, M. Wei, R. Betti, E. M. Campbell, S. Regan, V. Glebov, J. Knauer, A. B. Sefkow

Laboratory for Laser Energetics

B. Pollock, J. Moody, D. Strozzi, C. Goyon

Lawrence Livermore National Laboratory

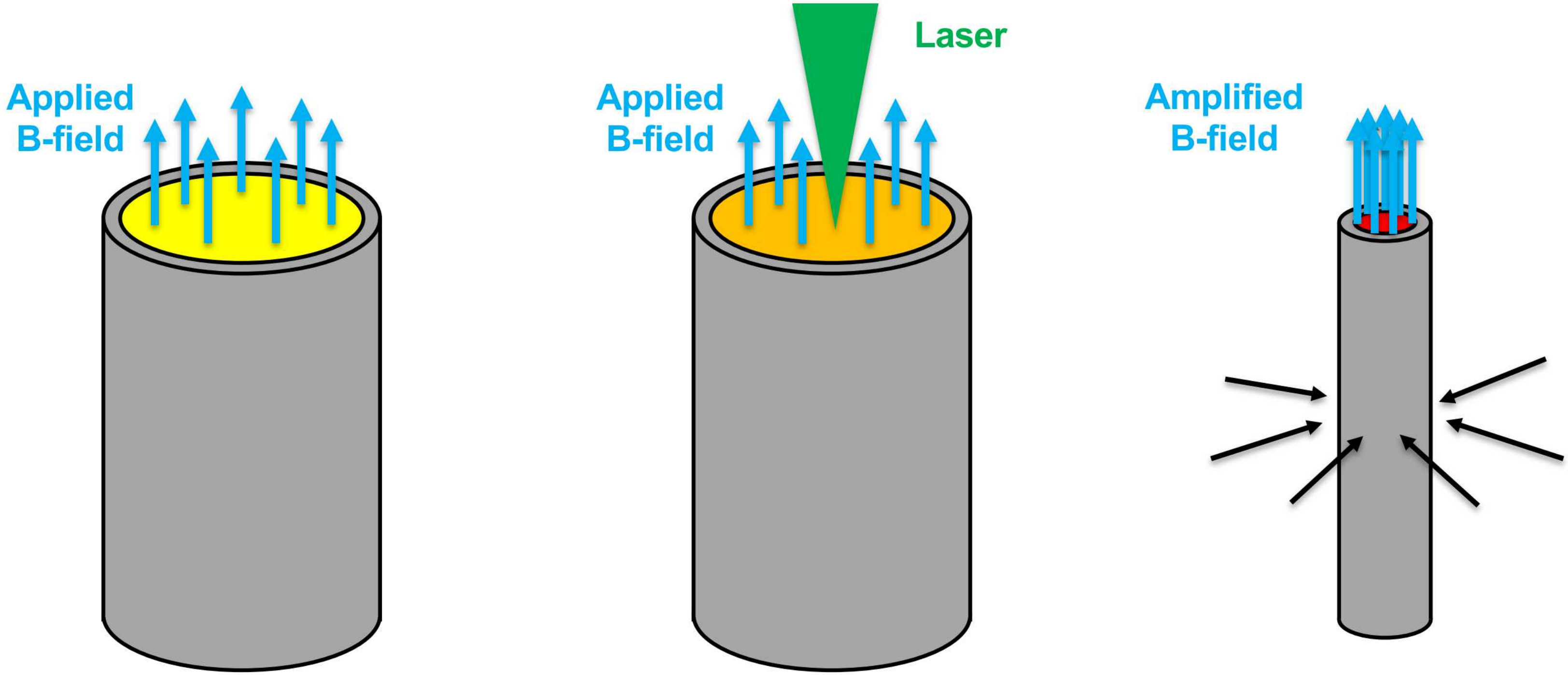
R. R. Paguio, G. E. Smith

General Atomics

Conclusions & Highlighted Progress

- Significantly improved laser energy coupling to the fuel, reduced laser plasma interactions, reduced mix, and improved modeling capability
- Demonstrated **6-10X improvement** in fusion performance on Z (2.5kJ DT equivalent) over initial MagLIF experiments, consistent with 2D simulations
- We are developing new platforms capable of delivering more drive current, higher initial magnetic fields, and more preheat energy simultaneously to test performance scaling on Z
- Significant variability is observed in some of our experiments as we improve performance, we are working to understand this
- We are evaluating ignition scale laser energy coupling (30kJ) at NIF

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



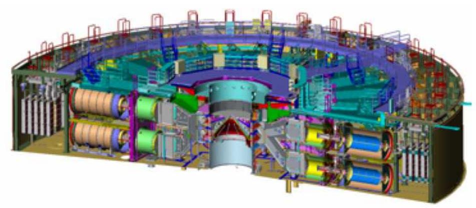
Apply axial magnetic field

Heat the magnetized fuel (e.g., with a laser)

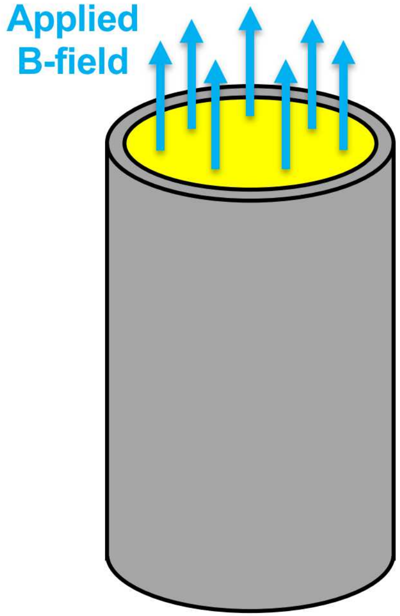
Compress the heated and magnetized fuel

S. A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).

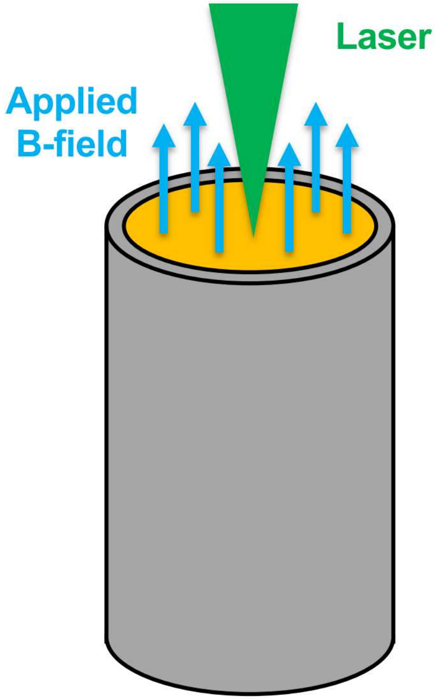
Magnetized Liner Inertial Fusion (MagLIF) relies on three stages to produce fusion relevant conditions



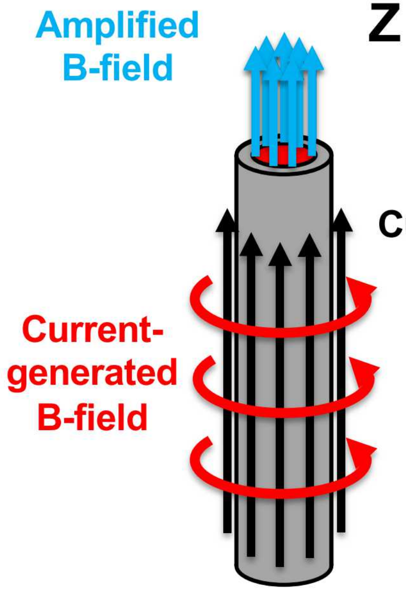
Z Facility



Apply axial magnetic field



Heat the magnetized fuel (e.g., with a laser)



Compress the heated and magnetized fuel

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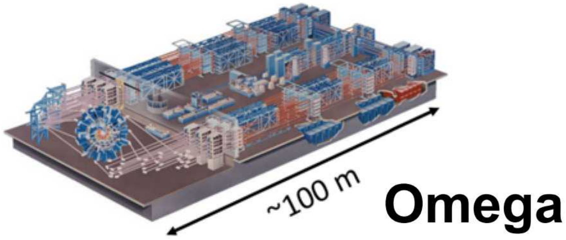
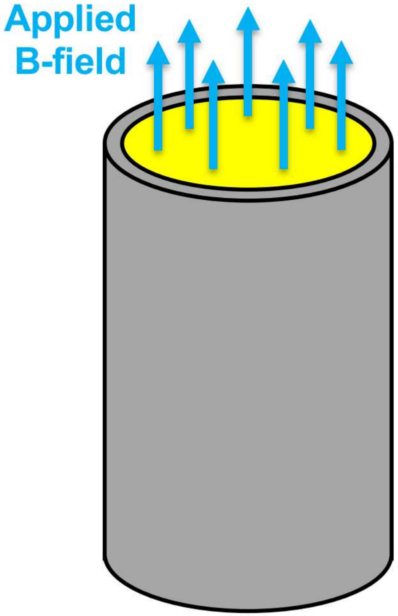
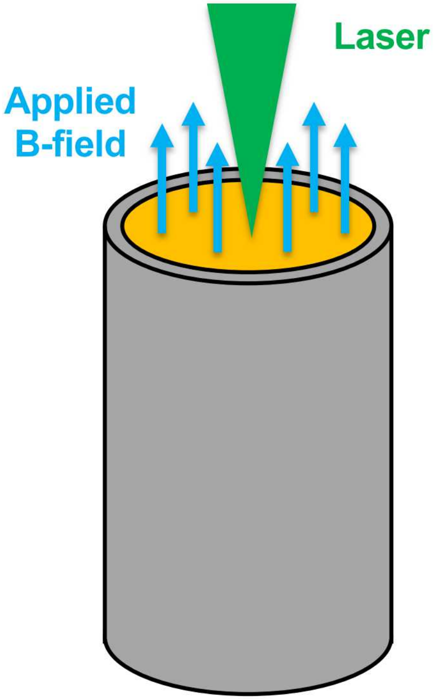
Magnetized Liner Inertial Fusion (MagLIF) relies on three stages to produce fusion relevant conditions

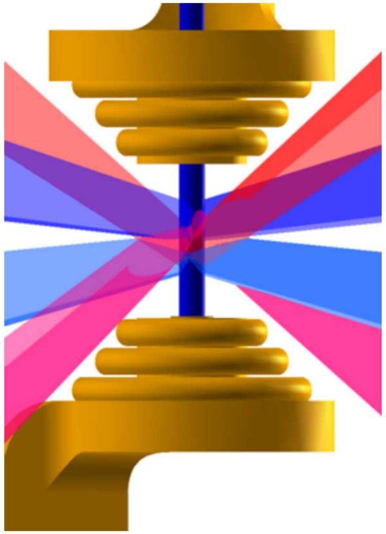




Apply axial magnetic field



Heat the magnetized fuel (e.g., with a laser)



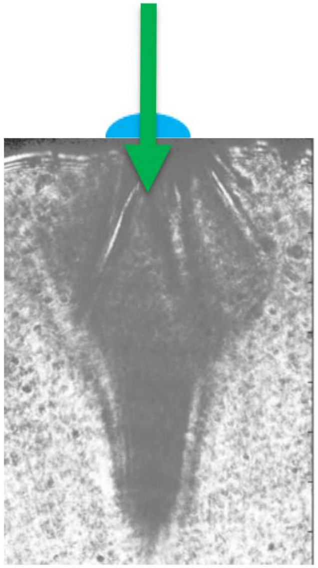
Compress the heated and magnetized fuel

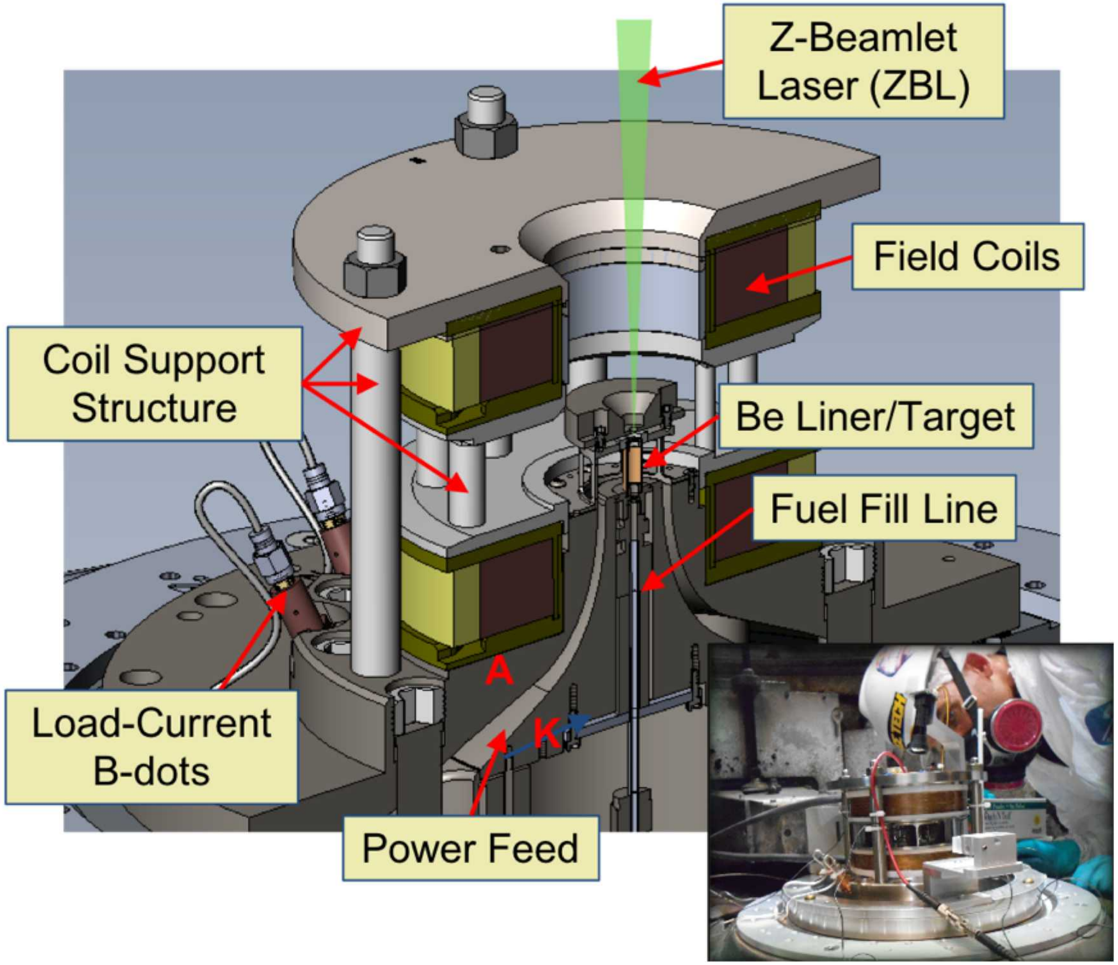
CM9.00003 - Peebles
KI3.00004 - Davies

S. A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).

While the initial MagLIF experiments were successful, they were far from optimal

Poor laser coupling (LPI),
Laser Induced Mix

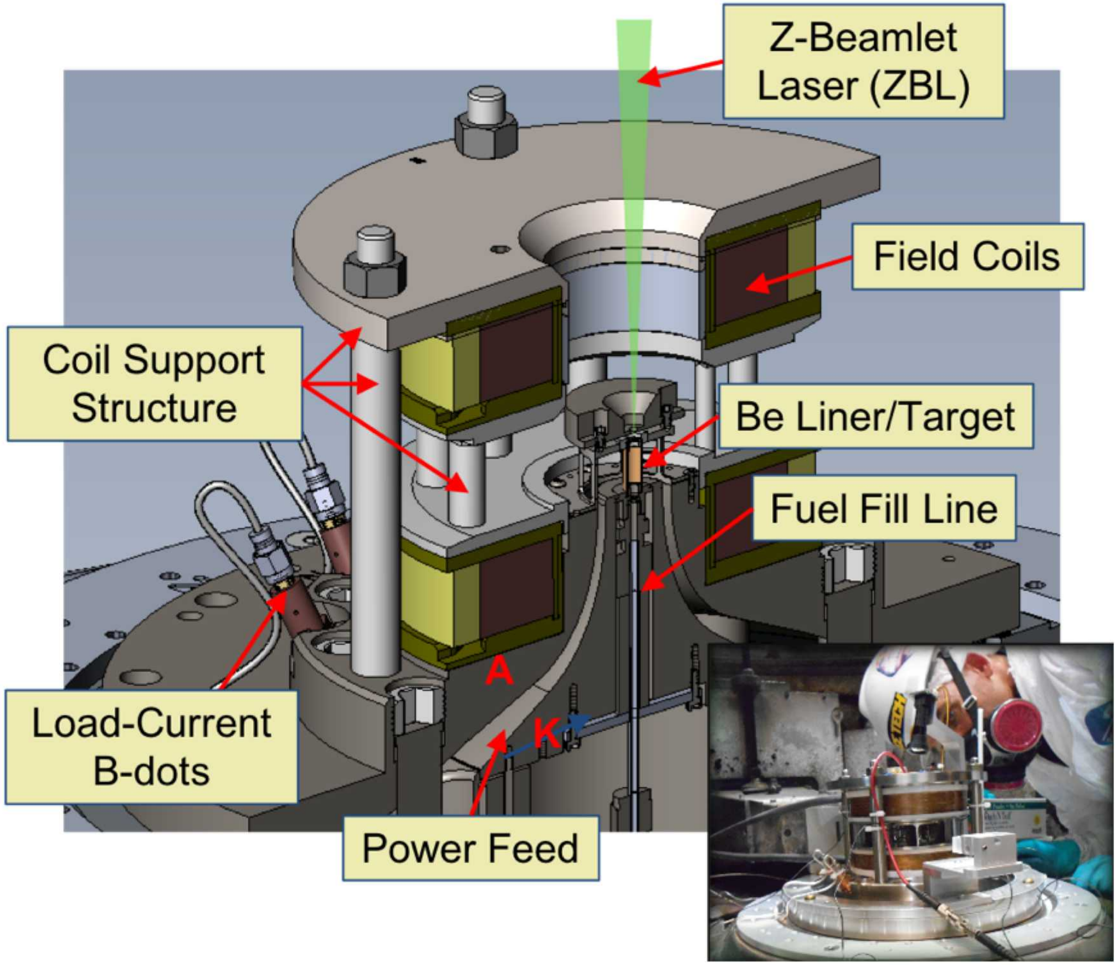




Poor simulation capability

While the initial MagLIF experiments were successful, they were far from optimal

Low fuel density,
High convergence, CR > 40



Z-Beamlet Laser (ZBL)

Field Coils

Coil Support Structure

Be Liner/Target

Fuel Fill Line

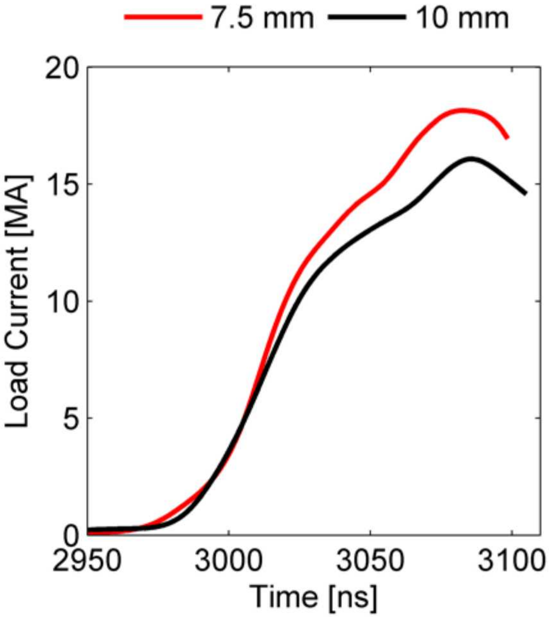
Load-Current B-dots

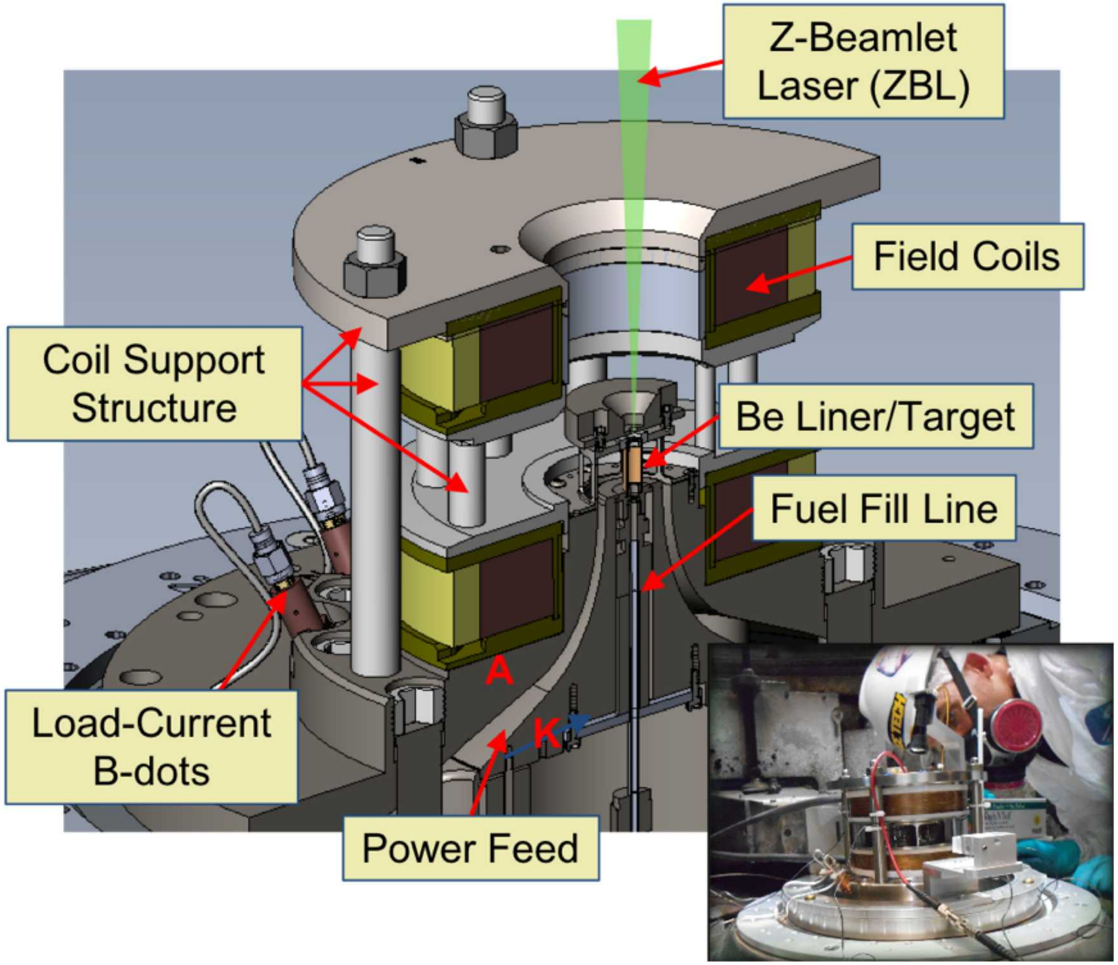
Power Feed

Effect of 3D asymmetry?

While the initial MagLIF experiments were successful, they were far from optimal

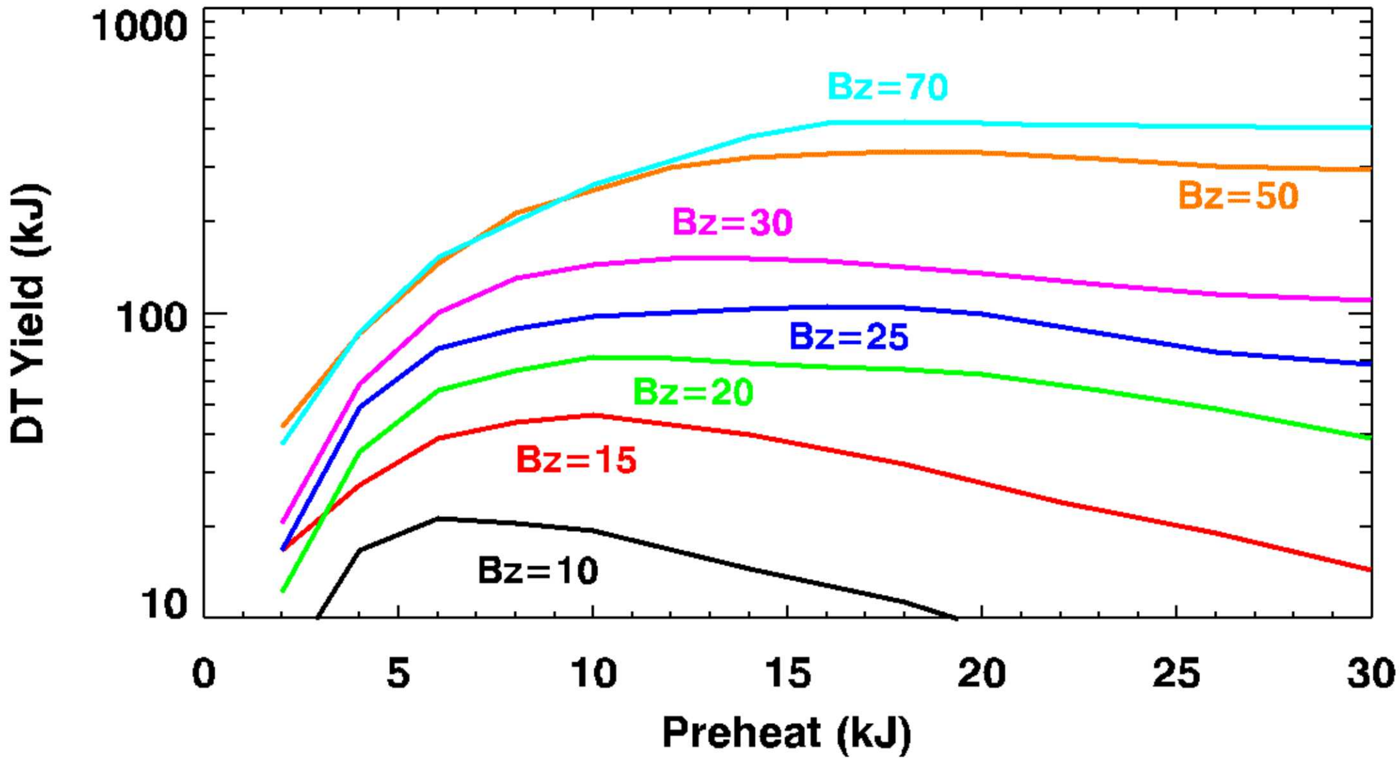
Low Drive Current
(High Inductance)





While the initial MagLIF experiments were successful, they were far from optimal

Initial B_z field too low for optimal performance

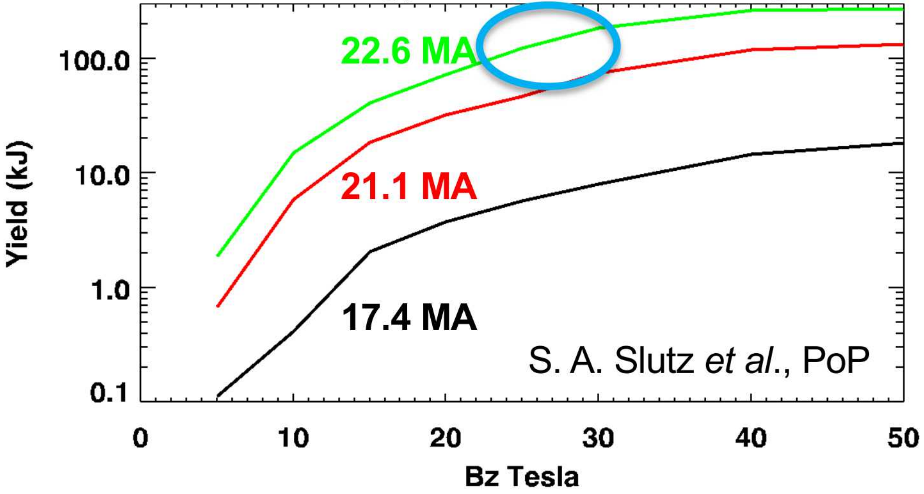


~100X lower for D2 fuel

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.

Preheat Energy = 6 kJ into 1.87 mg/cc DT

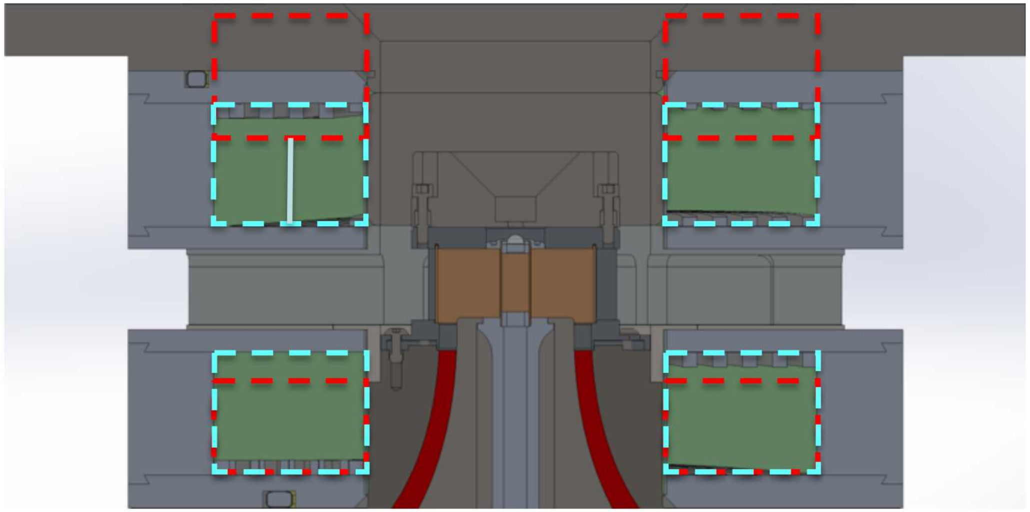


S. A. Slutz *et al.*, PoP

Date	Liner	D2 Fill (mg/cc)	Current (MA)	Bfield (T)	Preheat (kJ)	Yield with DT Fuel (kJ)
2014	AR=6	0.7	17-18	10	0.3-0.6?	0.2-0.4
Aug. 2018**	AR=6	1.1	19-20	15	1.2**	2.4**
2020 Goal	TBD	1.5	20-22	20-25	2-4	10
Beyond 2020	TBD	1.5	22-23	25-30	6	~100

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

Axial B-field was increased with modest change in coil configuration resulting in record performance



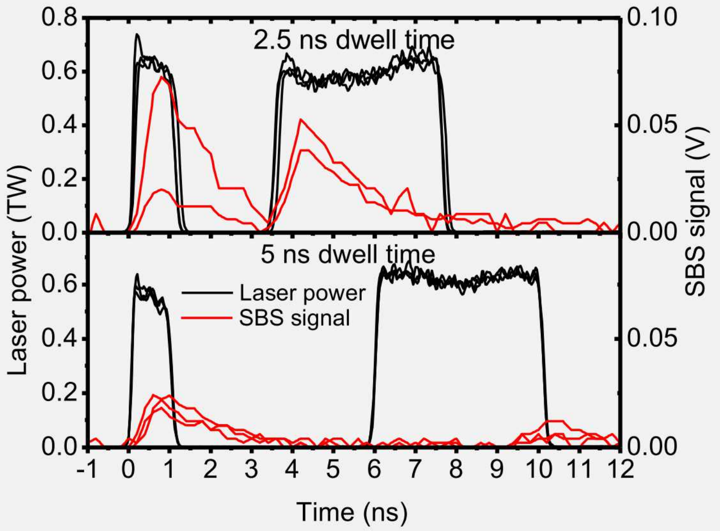
- Bottom coils increased from 60 turns to 80 turns
- Top coils lowered by 15 mm, eliminating 12 degree x-ray diagnostic access

- Applied B-field was increased from 10 to 15 T
- Simulations predicted an increase in primary neutron yield between 1.5-2x
- Experimental yield nearly doubled from 3.1e12 to 5.5e12
- Evidence of increased magnetization at stagnation

D. C. Rovang, et al., Rev. Sci. Instrum. **85**, 124701 (2014).
Experiments by D. J. Ampleford and C. A. Jennings

Laser preheating experiments at OMEGA-EP and OMEGA identified several potential issues in our integrated experiments – 2 examples

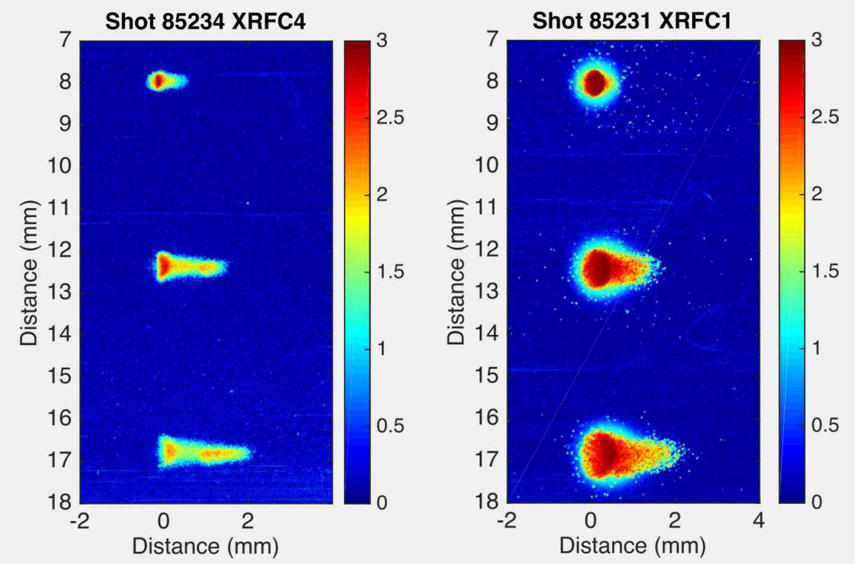
OMEGA-EP experiments showed increased dwell time between laser pre-pulse and main pulse was needed



Laser power and SBS signals for two different pulse shapes

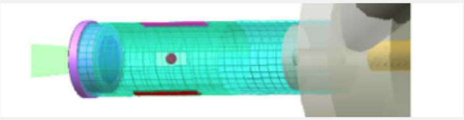
A.J. Harvey-Thompson et al., POP (2015), PRE (2016)

OMEGA experiments show dramatic differences in 2ω/ 3ω laser propagation



3ω, **1.5 ns**
2.1×10^{14} W/cm^2

2ω, **1.5 ns**
~2×10^{14} W/cm^2



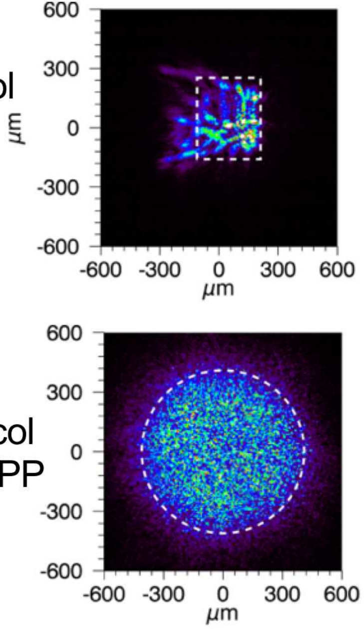
M. Wei et al., in preparation

Laser propagation into the fuel was improved using a new pulse shape and a phase plate to smooth the beam

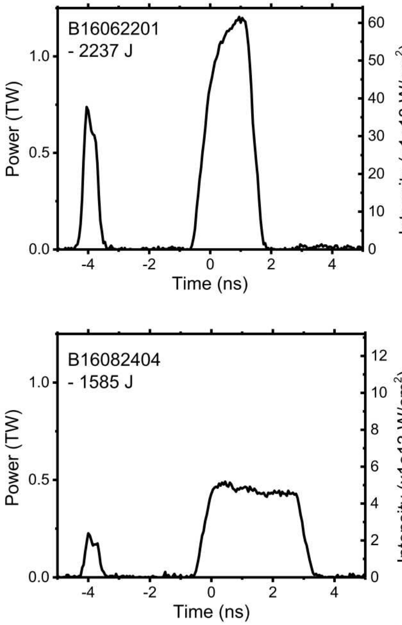
Old protocol
No DPP

New protocol
1100 μm DPP

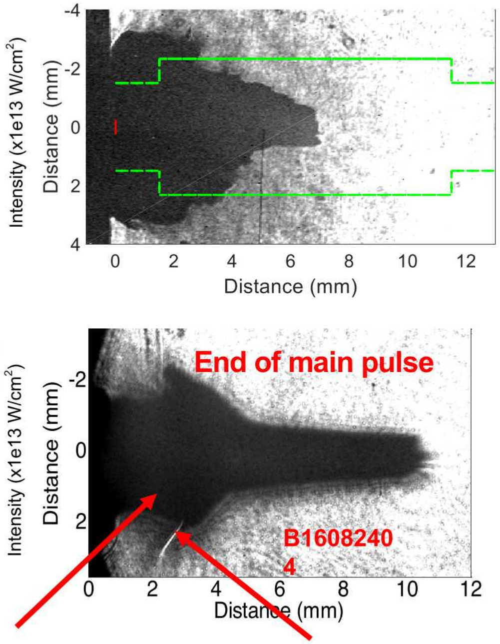
Spot profile



Laser power



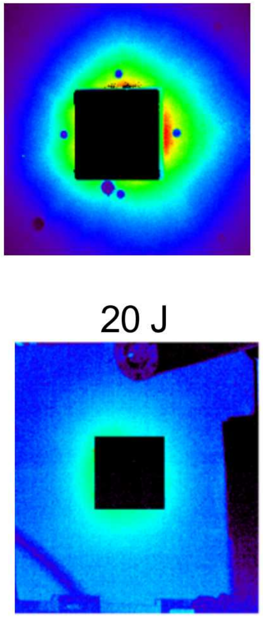
Shadowgraphy imaging



Bulbous features could be beam spray/filamentation or SRS sidescatter or ???

Filament

SBS backscatter
~650 J !!

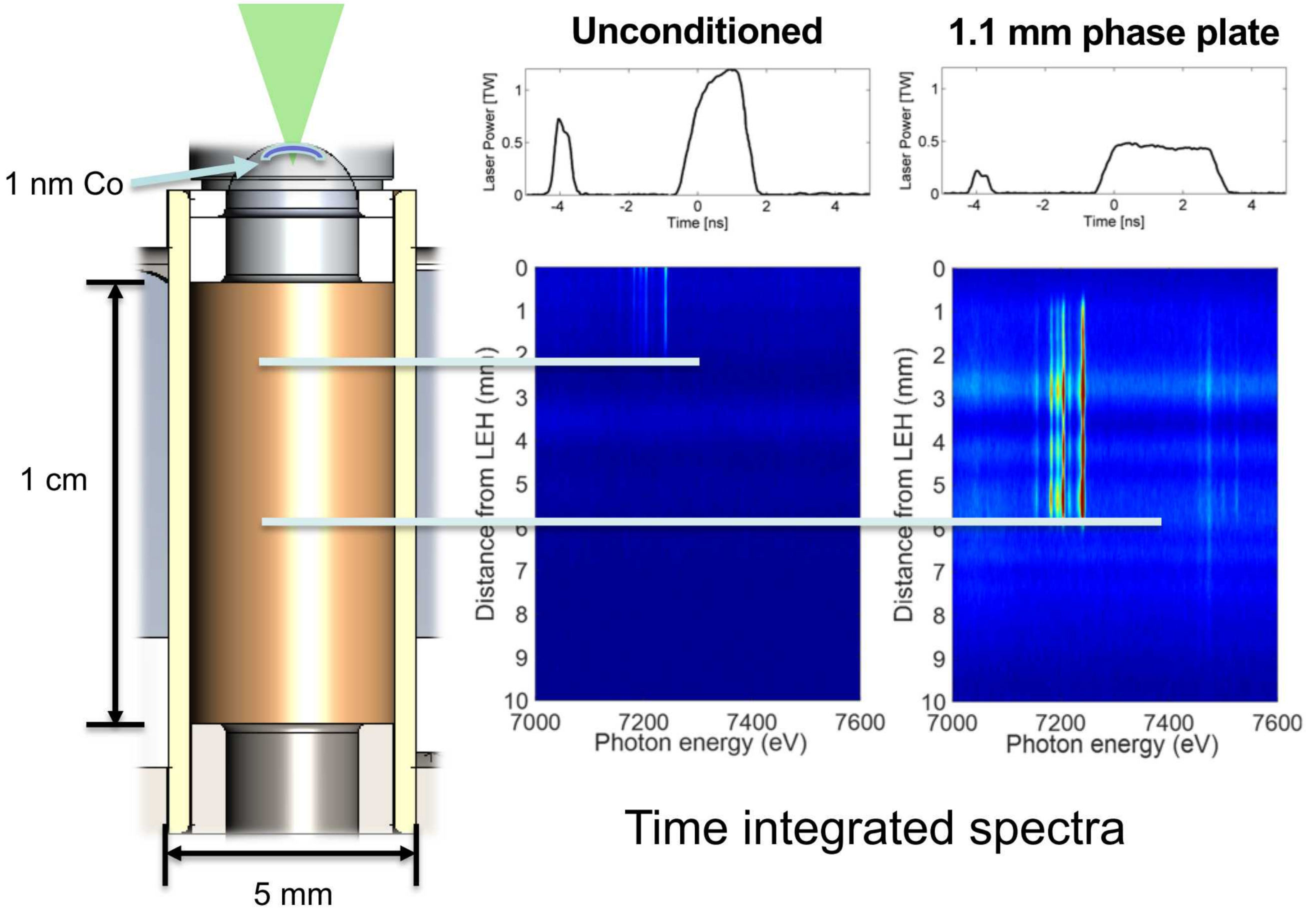


20 J

KI3.00002 Harvey-Thompson
YO6.00008 Weis
GP11.00134 Weis
GP11.00126 Geissel
YO6.00009 Fein

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

Spectroscopic diagnostics demonstrated that the phase-plate configuration drove more window material (mix) into the fuel



Time integrated spectra

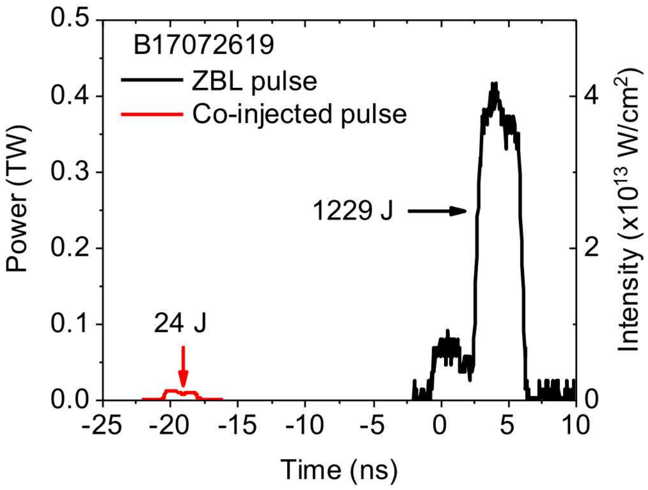
Cobalt emission from tracer vs. height

KI3.00002 Harvey-Thompson
CM9.00002 - Knapp

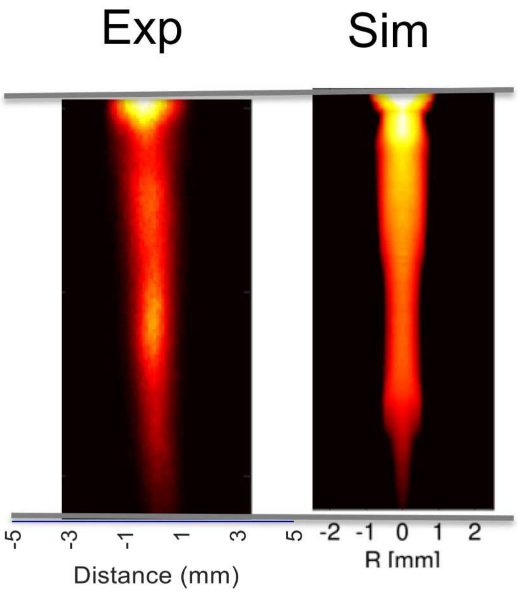
A. J. Harvey-Thompson *et al.*, Physics of Plasmas, 2018

Longer delay times were enabled by co-injecting the Z Petawatt laser in the same beamline

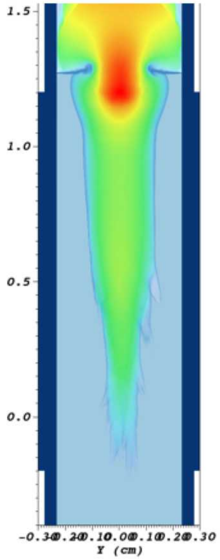
- 10-20 J Z-Petawatt (long-pulse mode) laser pulse to disassemble window
- Improved simulation modeling
- Entire 6 ns ZBL laser window available for fuel heating



Time integrated pinhole camera

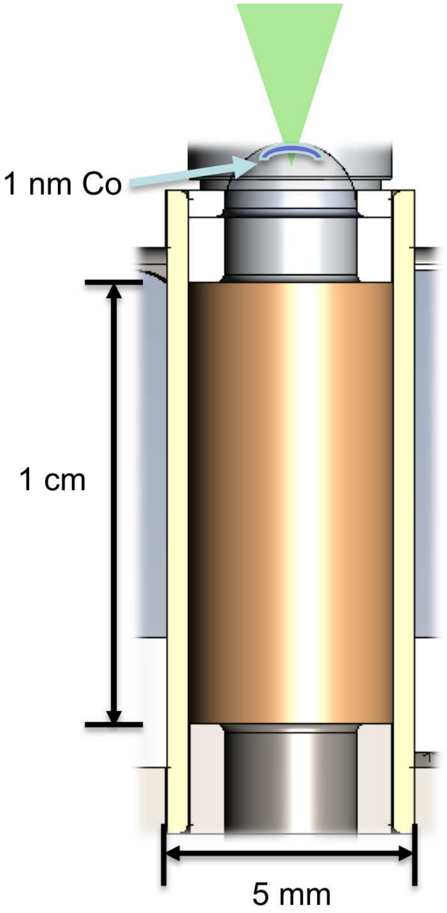


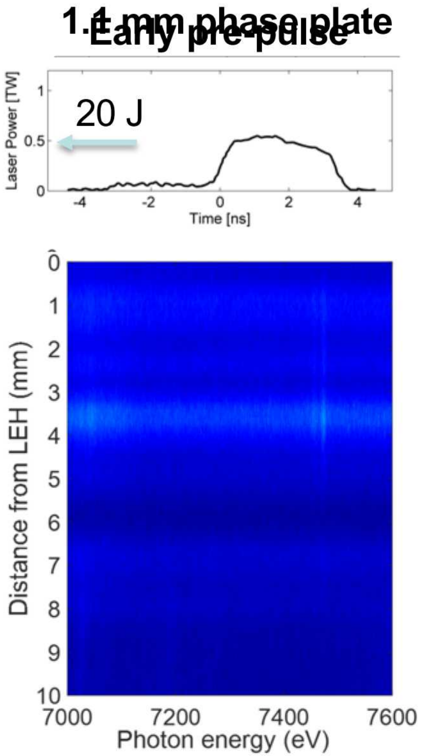
3D Hydra Sim

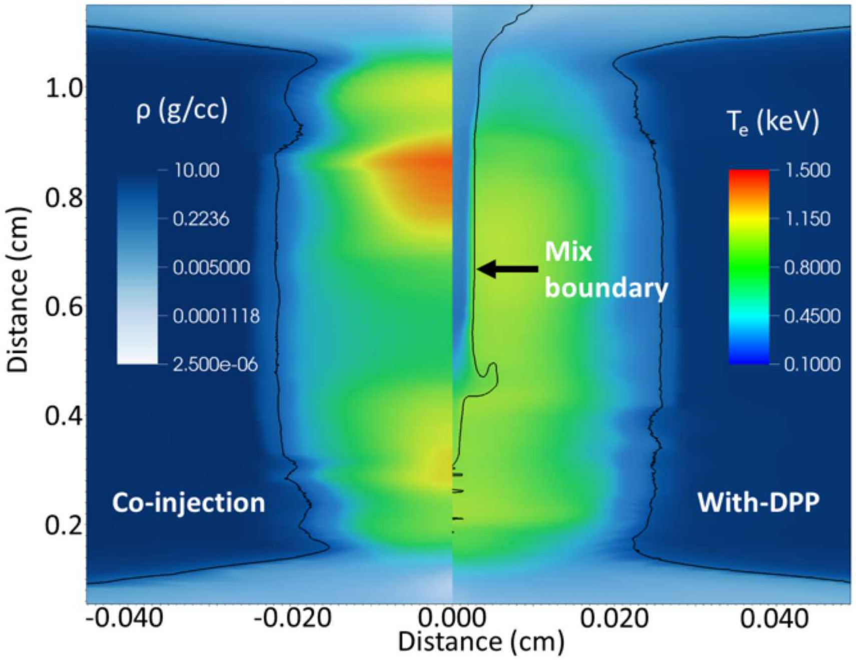


KI3.00002 Harvey-Thompson

Co-injection was also predicted to mitigate mix which was later demonstrated







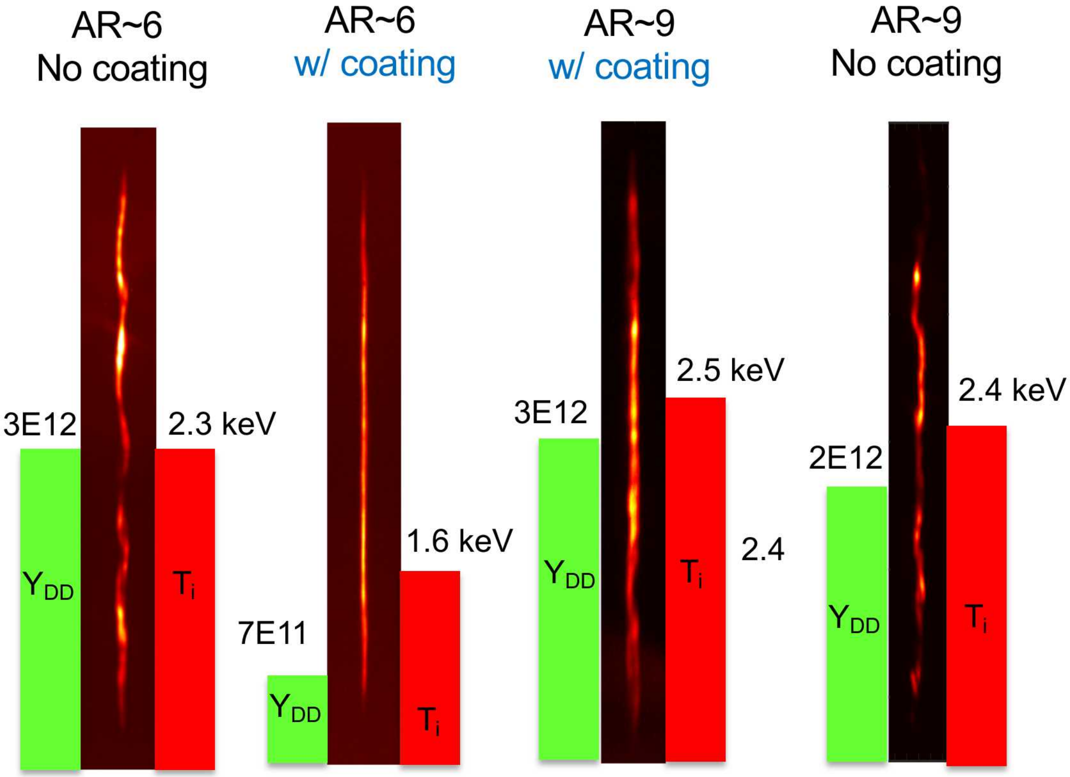
KI3.00002 Harvey-Thompson
YO6.00012 Slutz

A. J. Harvey-Thompson *et al.*, manuscript submitted.

Significant improvements in liner stability have been demonstrated with thick dielectric coatings

- Thick plastic coatings applied to outside surface mitigate electro-thermal instability growth
- Coated AR-9 targets have shown excellent stability and shot-to-shot reproducibility (~15%)
  - Higher magnetization observed BR ~ 400 kG cm
- **New time resolved measurements show a dynamically evolving hot spot (axial variation with time) without a coating and a no variation with a coating**

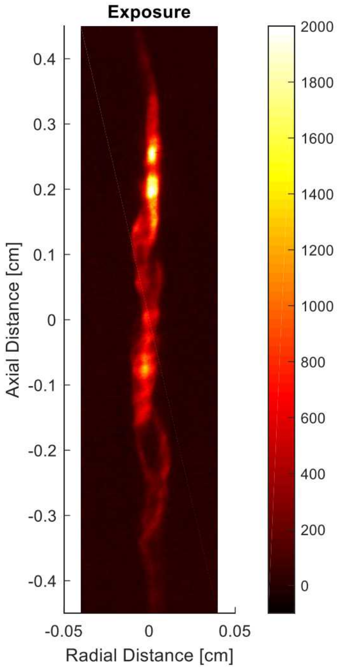
>6keV X-ray self-emission stagnation images



KI3.00001 Ampleford

Improvements to preheating and liner stability have increased neutron yields to 1.1e13 DD, consistent with 2D simulations

	z3236 (preheat 18A)	Simulated
Main pulse laser energy	261 + 2240 J	261 + 2240 J (~1.4 kJ in fuel)
Stagnated B field	~25kT	30kT
DD	1.1e13 ± 20%	1.2e13
Stagnation Presure	~1 Gbar	1.3 Gbar
Tion (Ntof)	3.1 keV +/- 20%	3.0 keV



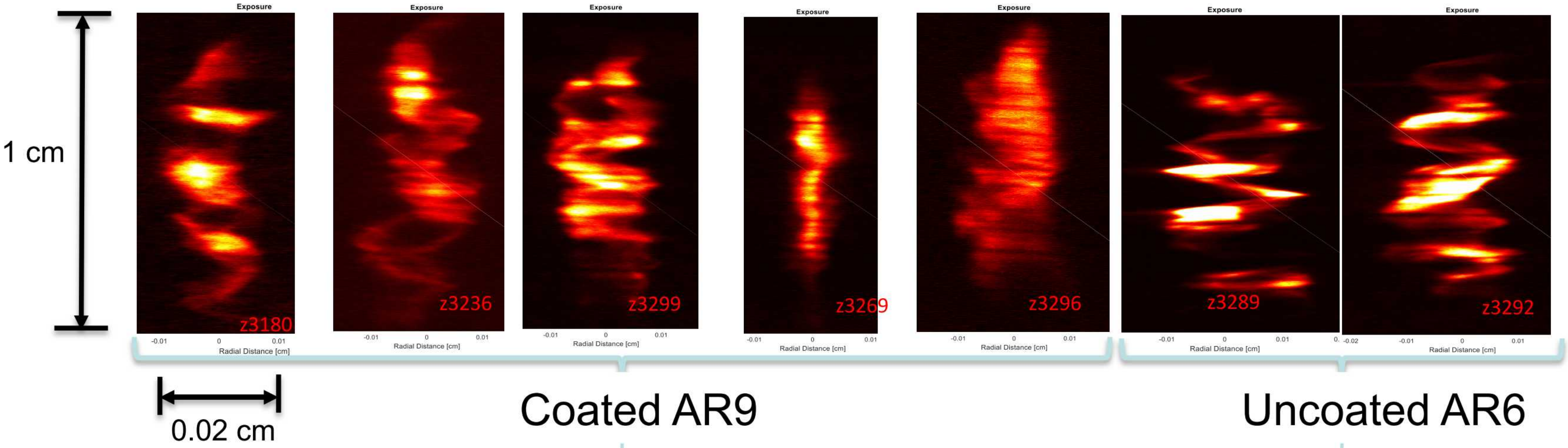
Liner: AR9, coated liner
Initial Bz field:10T
Peak Drive Current: 17 MA Current Pulse
Window: 2 mm diameter, 1.77 um thick, 1 nm Co on LEH
Fuel: 90 psi (1 mg/cc) Deuterium

M. Weis, A. Harvey-Thompson

Stagnation morphology can vary considerably from shot to shot with no obvious correlation to performance

KI3.00001 Ampleford

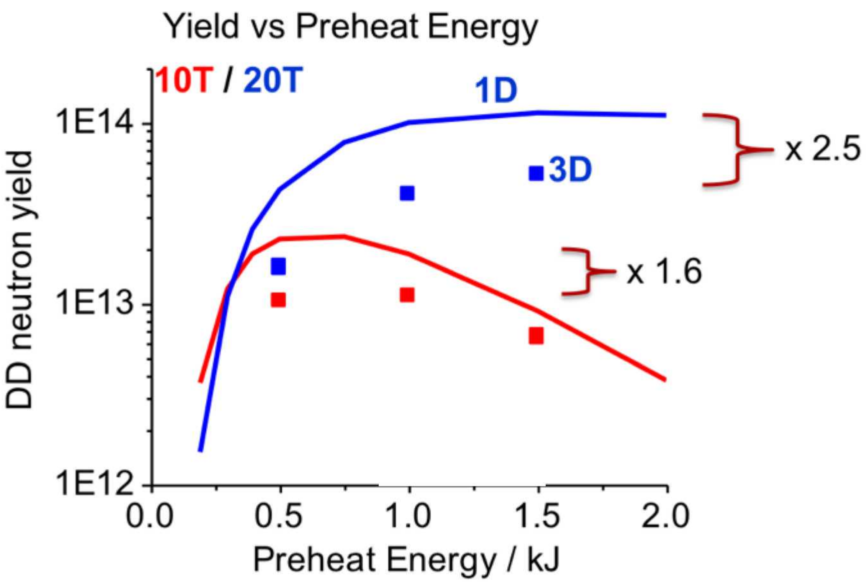
	z3180	z3236	3299	z3269	3296	3289	3292
Liner	Coated AR9	Coated AR9	Coated AR9	Coated AR9	Coated AR9	AR6	AR6
Laser Energy (J)	(153) + 1712	(294) + 2240	(258) + 2338	(291) + 1391	(320) + 2711	(357) + 1872	(366) + 2171
B field	10 T	10 T	10 T	10 T	15 T	15 T	15 T
DD Yield	3.3e12	1.1e13	2.28e12	1.3e12	1.19e12	1.11e13	5.25e12

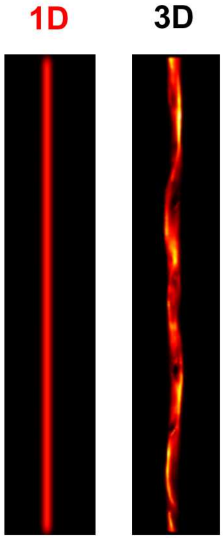


Note: images are stretched radially for comparison

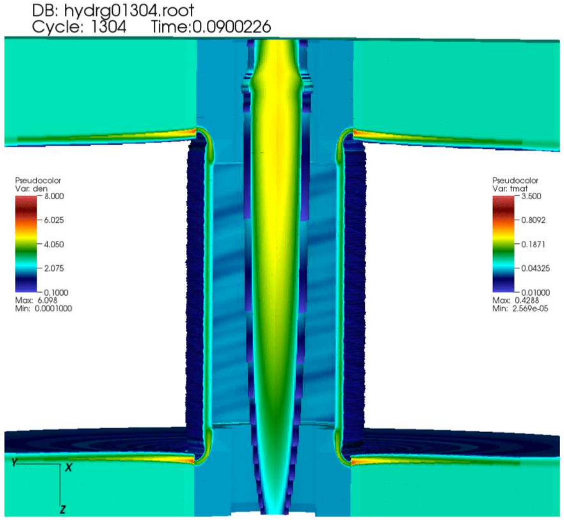
3D simulations suggest asymmetries have a slight impact on performance, but that impact increases as magnetic insulation improves

3D Gorgon



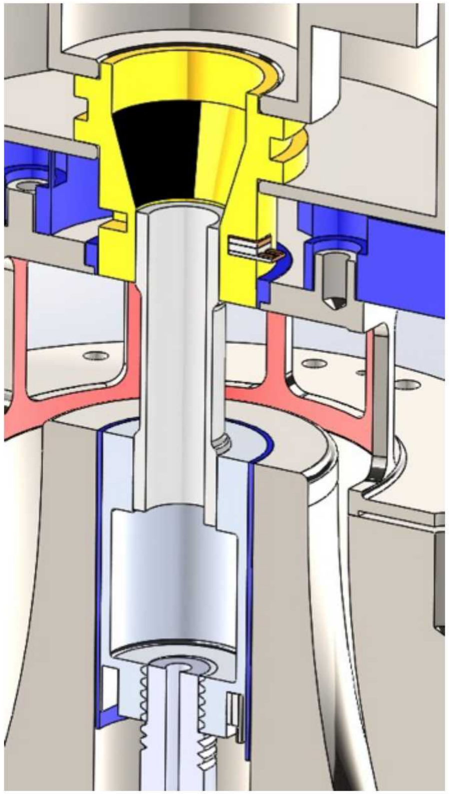


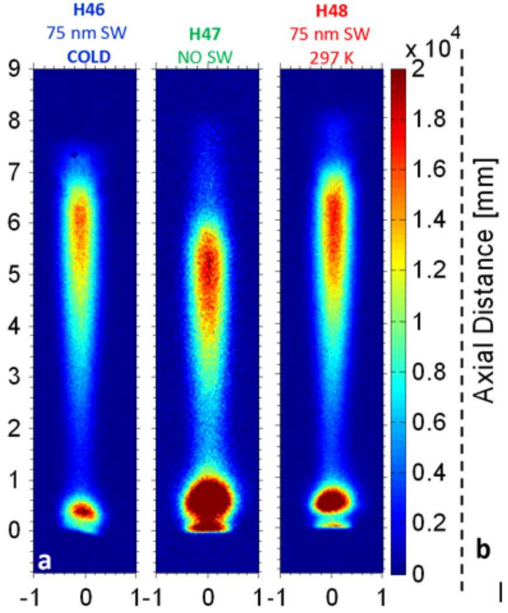
3D Hydra



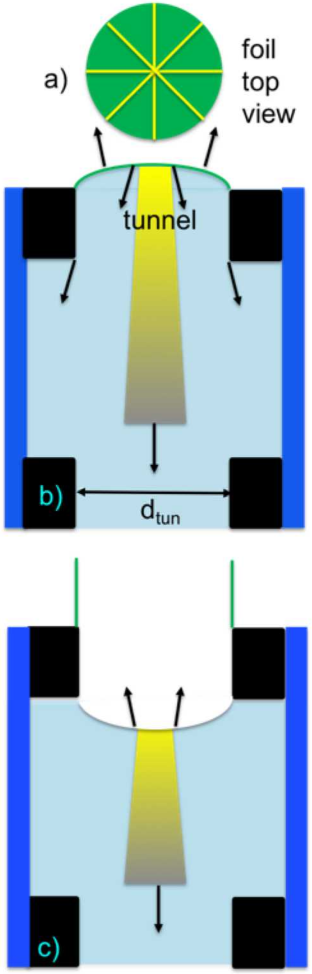
We are developing two different approaches in order to deposit >2kJ of laser energy in the fuel

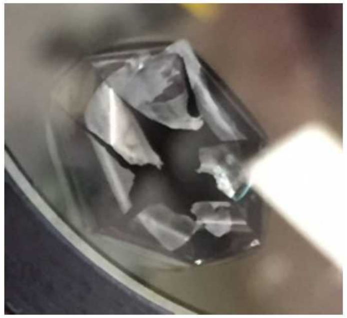
Cryogenic Targets





Lasergate



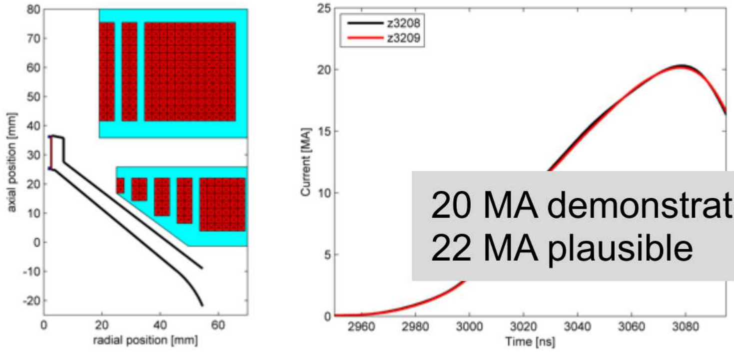


T. Awe, M. Weis, M. Glinsky, K. Shelton, A. York

S. Slutz, J. Schwarz

We are actively developing new platform capabilities for MagLIF on Z

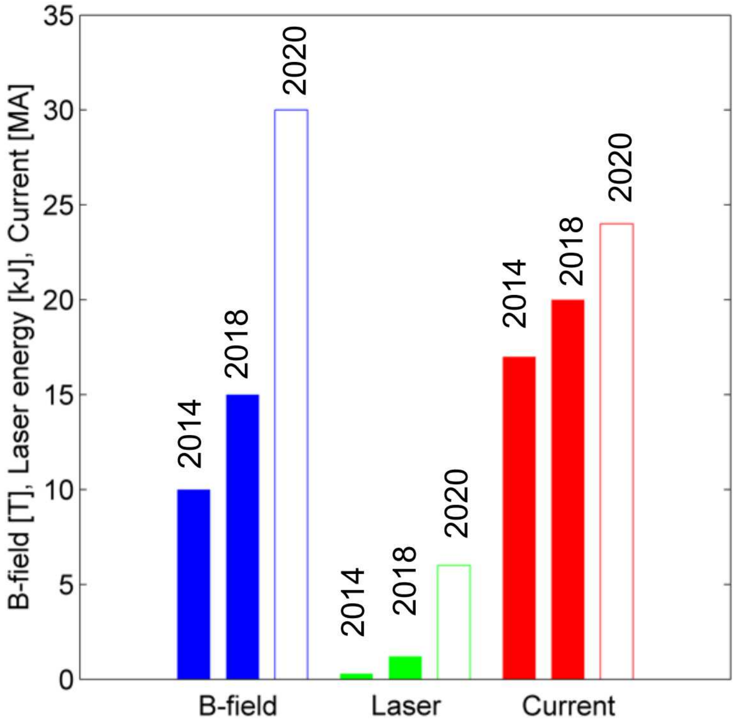
Modifications to the inner-MITL are being that reduce load inductance and increased load current



20 MA demonstrated
22 MA plausible

New coil designs could allow 25T operation without giving up diagnostic access

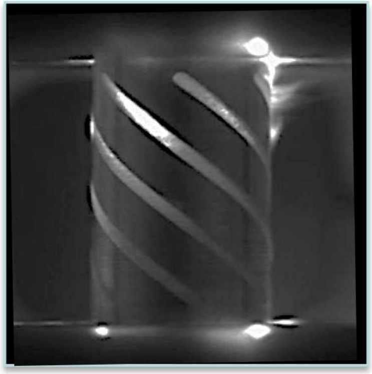
80-turn Coil + Low-L Coil
20 – 22T avg. field in
Standard Feed



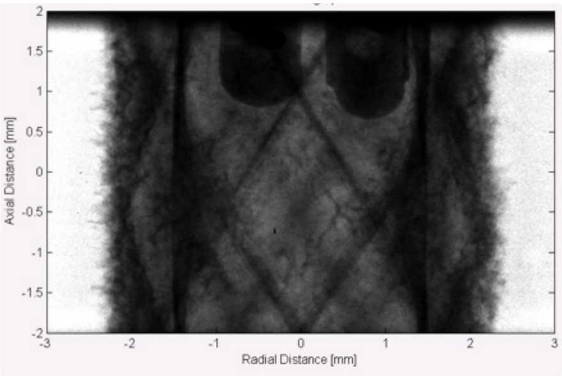
GP11.00125 Gomez

We are also exploring alternative magnetization schemes that may be more suitable for scaling

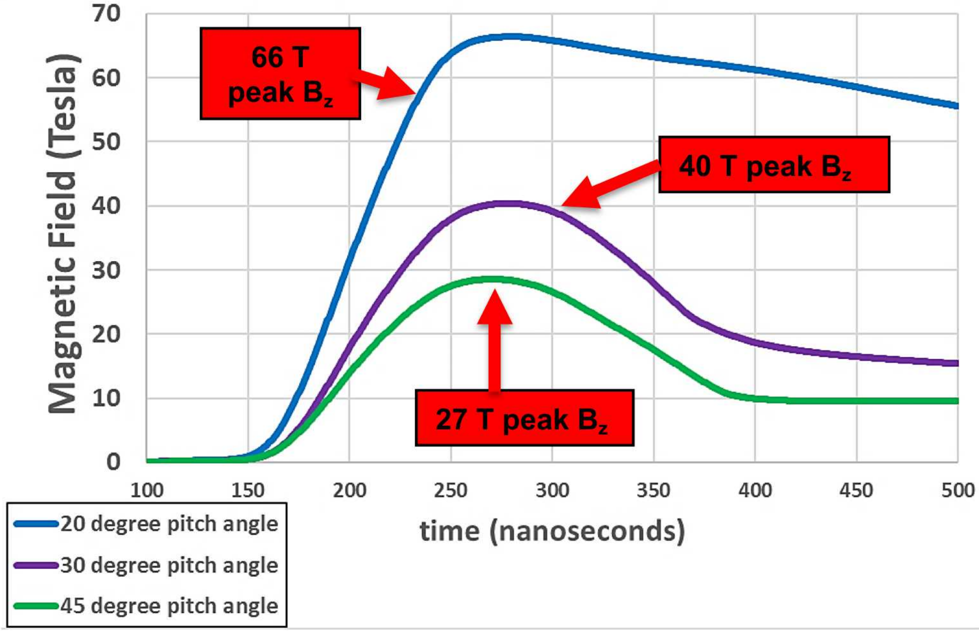
Visible Emission



Liner Implosion Experiment
6.1 keV Radiography



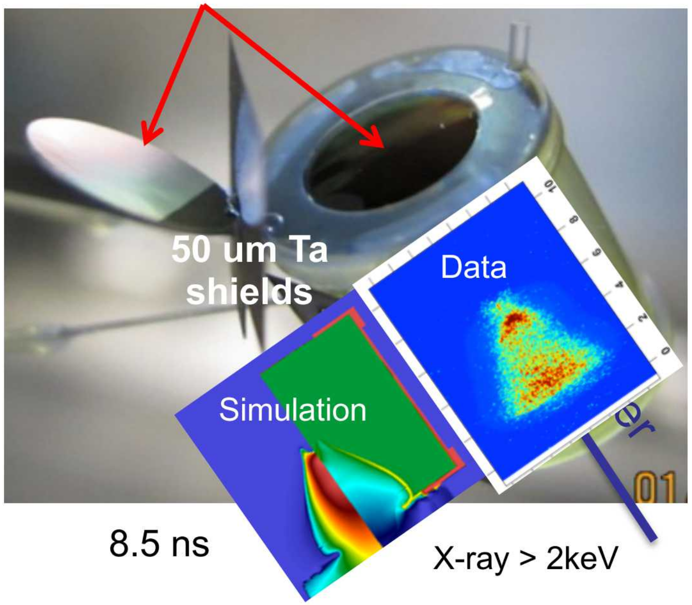
Slotted helical liners “Automag”



KI3.00003 Shipley

G. Shipley, T. Awe

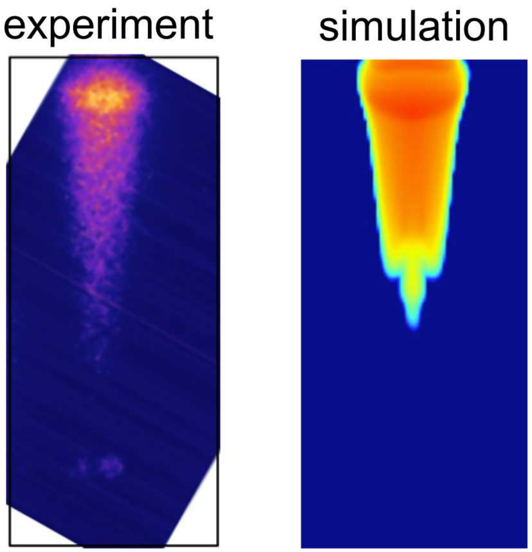
Experiments testing ignition scale preheating at NIF have been encouraging



Time dependent laser propagation is in remarkable agreement with pre-shot simulation predictions

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

3.2 mg/cc cryogenic D2



- Demonstrated 24 kJ absorption into warm hydrocarbon surrogate
- Demonstrated 16 kJ into 4.8 mg/cc D2

CP11.00183 Glinsky

B. Pollock (LLNL), A. B. Sefkow, M. Glinsky

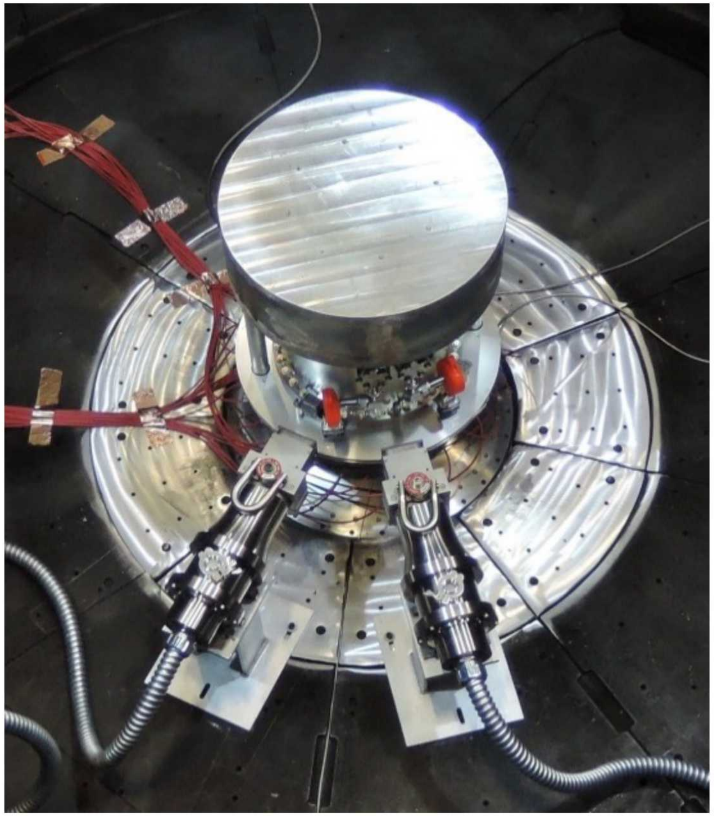
Conclusions & Highlighted Progress

- Significantly improved laser energy coupling to the fuel, reduced laser plasma interactions, reduced mix, and improved modeling capability
- Demonstrated **6-10X improvement** in fusion performance on Z (2.5kJ DT equivalent) over initial MagLIF experiments, consistent with 2D simulations
- We are developing new platforms capable of delivering more drive current, higher initial magnetic fields, and more preheat energy <u>simultaneously</u> to test performance scaling on Z
- Significant variability is observed in some of our experiments as we improve performance, we are working to understand this
- We are evaluating ignition scale laser energy coupling (30kJ) at NIF

Backups

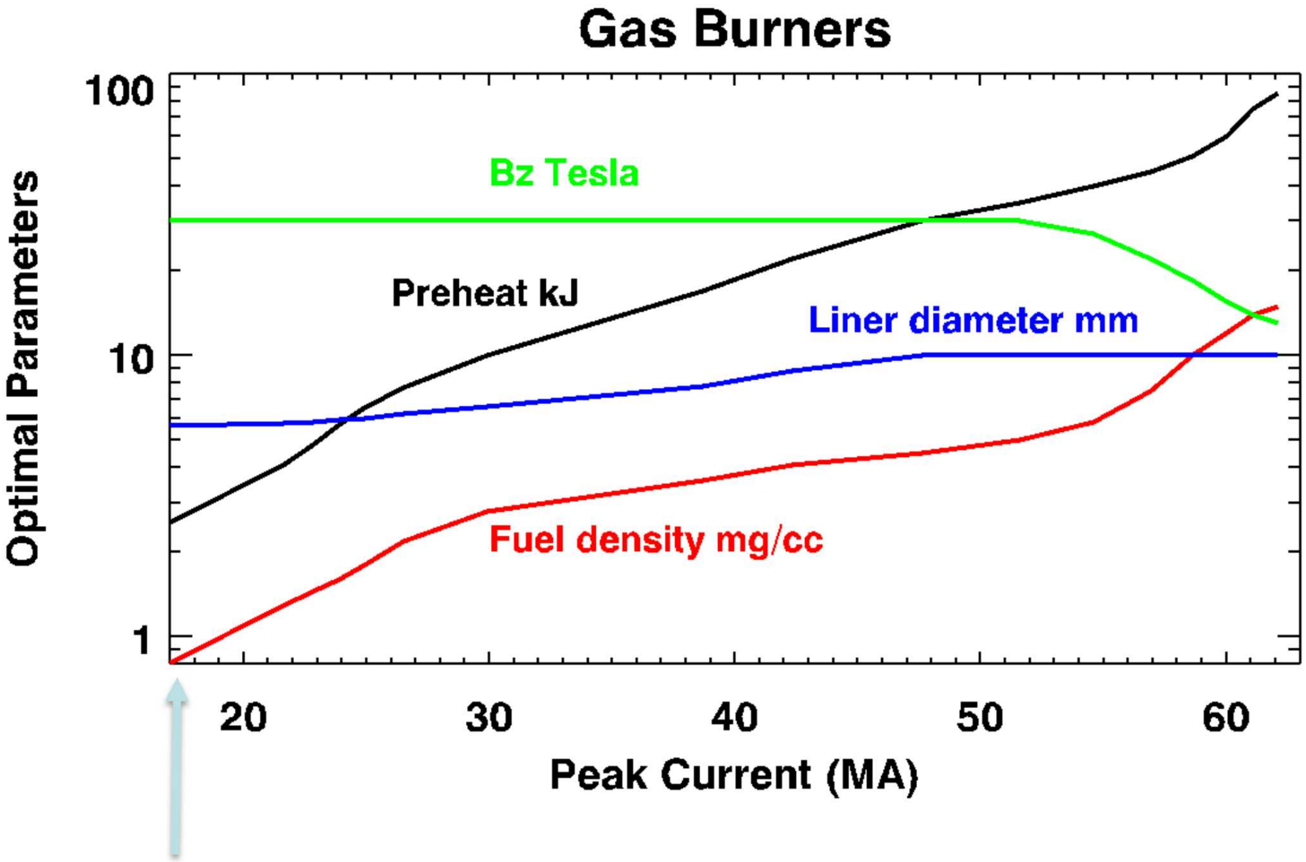
First ever tritium experiment was conducted on Z in August 2016, we have subsequently been testing chamber confined tritium in small amounts

- **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

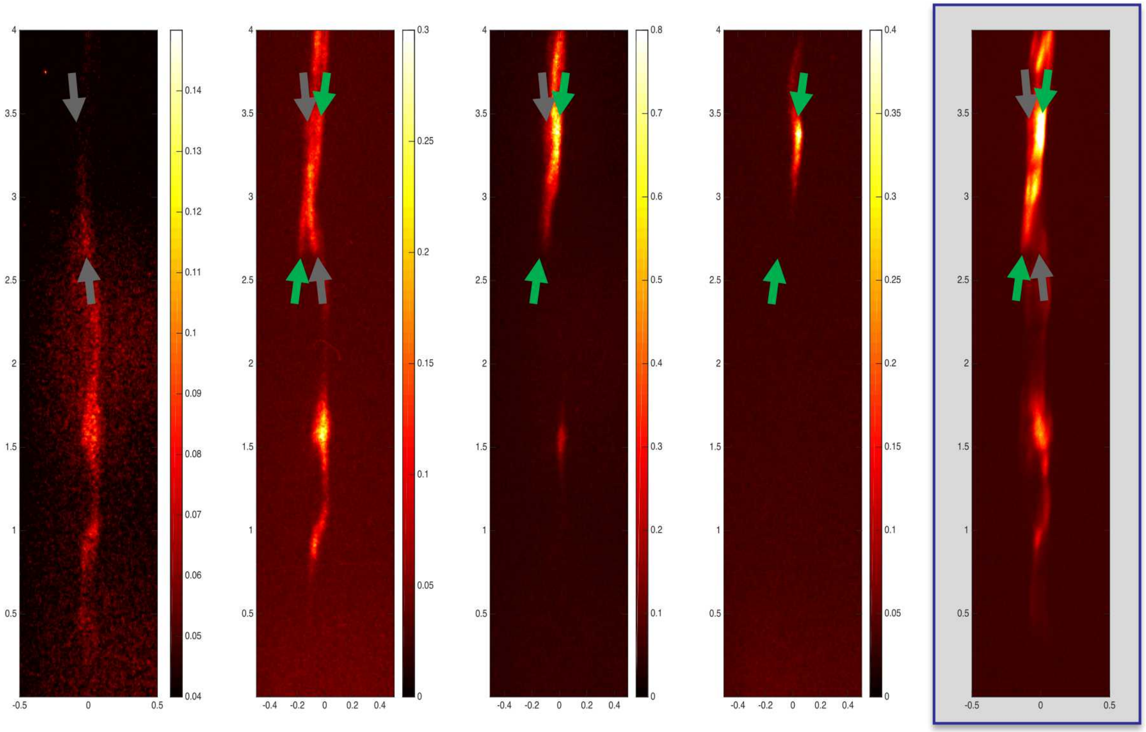
Performance optimized scaling is only achieved when field, fuel density, preheat energy, and current are all scaled simultaneously



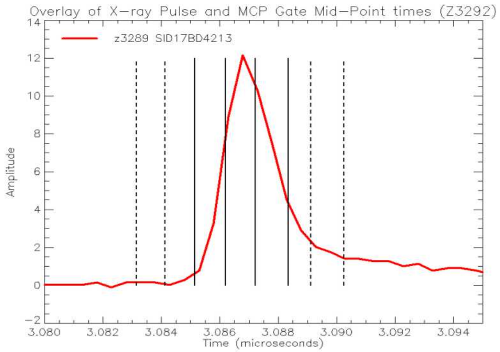
According to simulations, we have not yet tested optimal conditions on Z

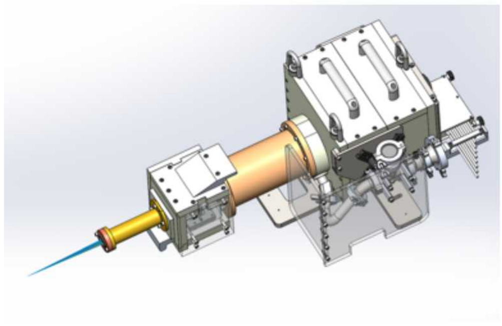
Simulations courtesy of S. A. Slutz

New time resolved measurements show a dynamically evolving hot spot

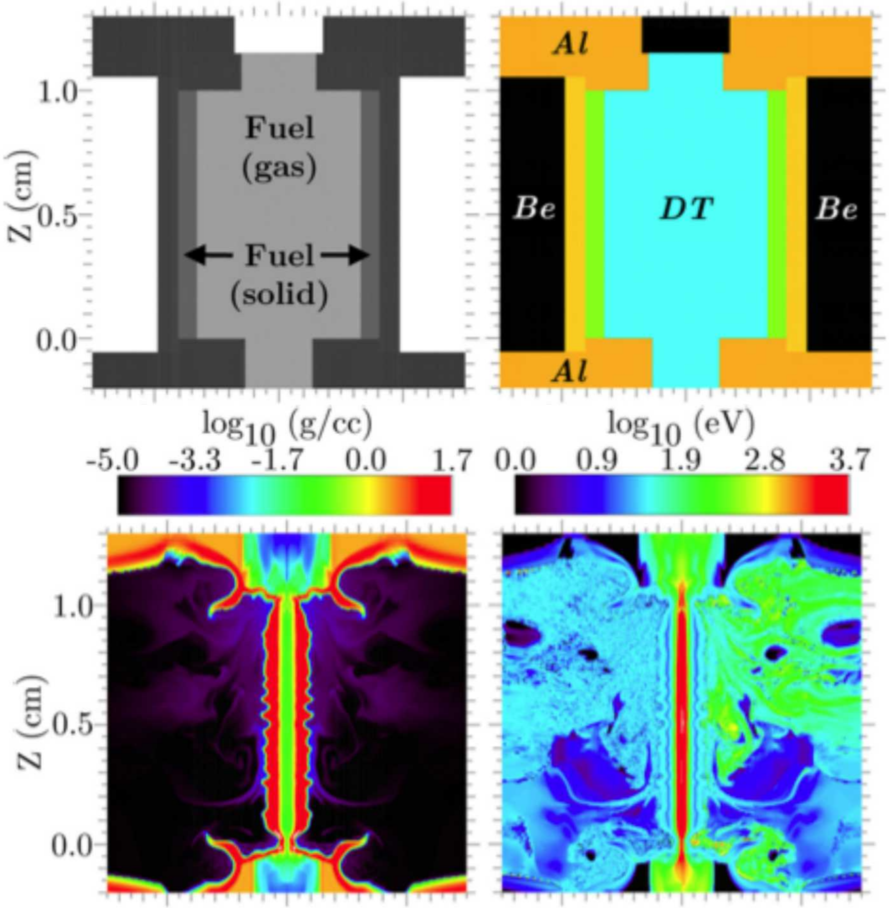


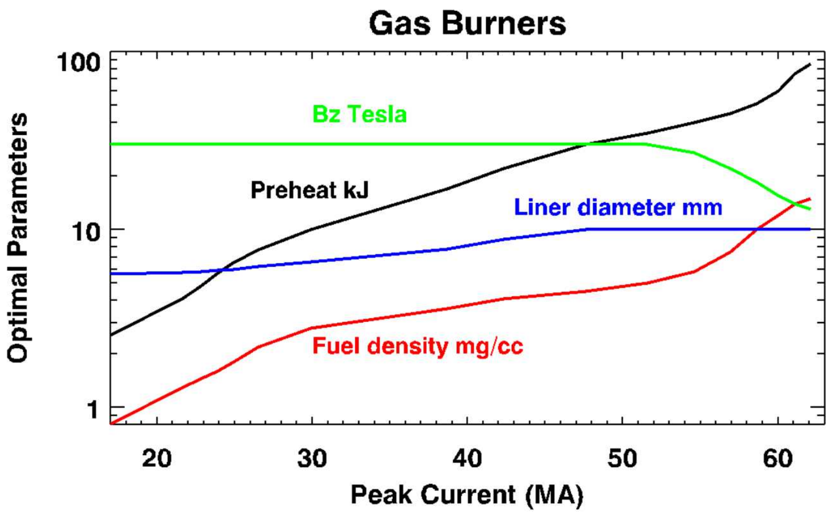
Time Integrated
High resolution crystal spectrometer image

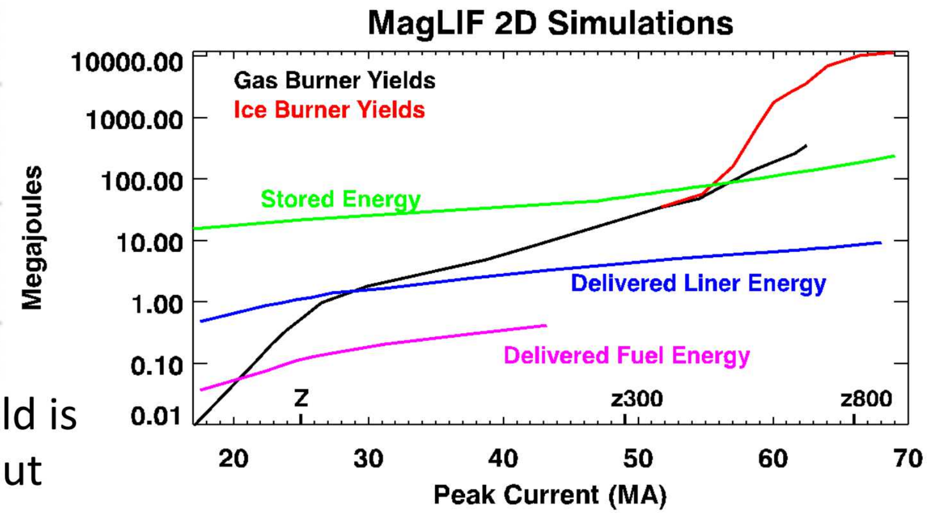




Achieving alpha heating and ignition may be possible on a future facility. A cryogenic DT layer could enable up to ~1 GJ yield.







An intermediate regime exists wherein the B_z field is

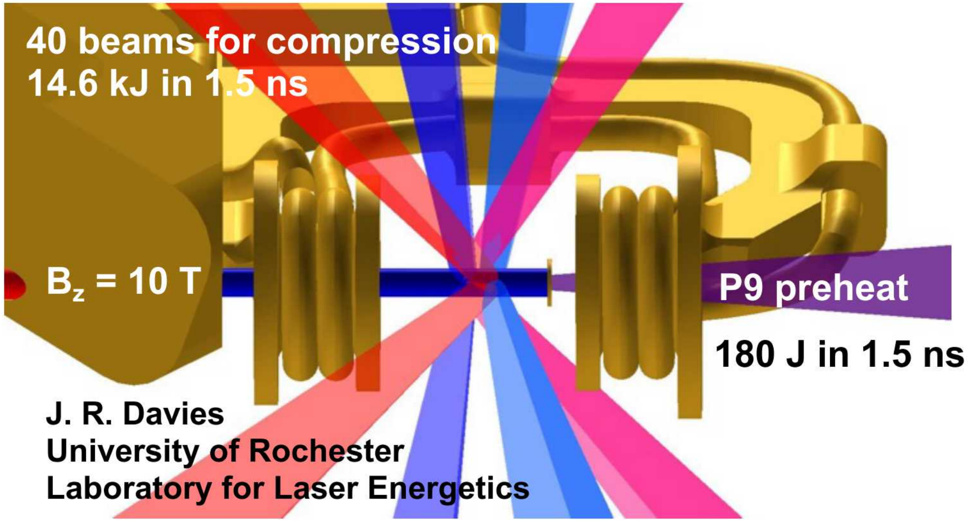
- *strong enough* to reduce conduction losses, but
- *weak enough* not to inhibit the α deflagration wave

S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

Sandia is also collaborating with LLE to develop a scaled MagLIF platform on OMEGA which strongly complements research done at Z

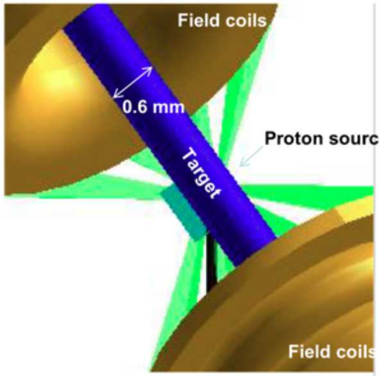
Laser-driven MagLIF on OMEGA

- 10× smaller (test platform scaling)
- More data: 2 shot days on OMEGA returns more data than a years worth of shots on Z
- Access to diagnostics with greater dynamic range
- Ability to probe magnetic field with proton radiography (impossible on Z)

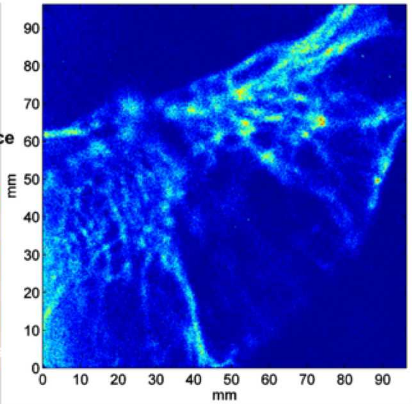


J. R. Davies
University of Rochester
Laboratory for Laser Energetics

Experimental Setup
Showing only beams on proton source



Proton Radiograph
Reveals electric and magnetic fields



14 MeV protons generated by D-^{3}He fusion are used to probe the electric and magnetic fields in the compressed, magnetized target on Omega

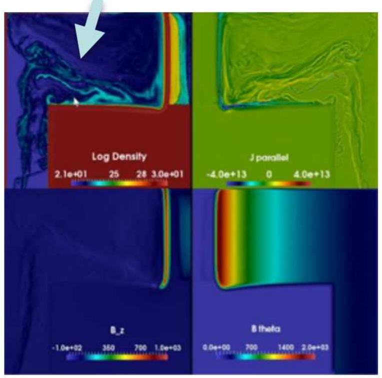
J. Davies (LLE), B. Barnak (LLE), R. Betti (LLE)

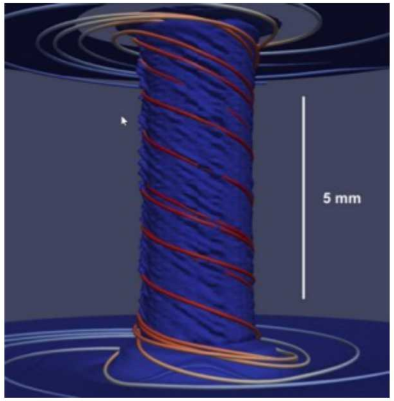
We are developing new tools to address identified shortcomings in simulation models

- **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

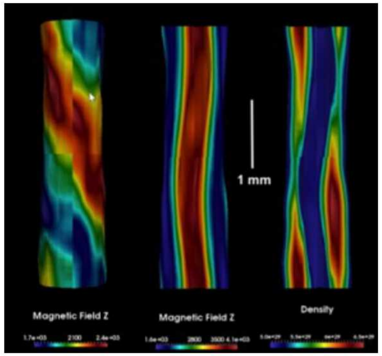
- **FLEXO** – new C++ XMHD code (Flux Limited EXtended Ohm’s law) based on PERSEUS, developed under SNL LDRD with new capabilities: multi-material equation of state(EOS), adaptive mesh refinement(AMR), and scalable DG radiation transport, all compatible with advanced architectures (GPU) to enable a predictive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

1) Feed plasma transport requires XMHD due to low densities





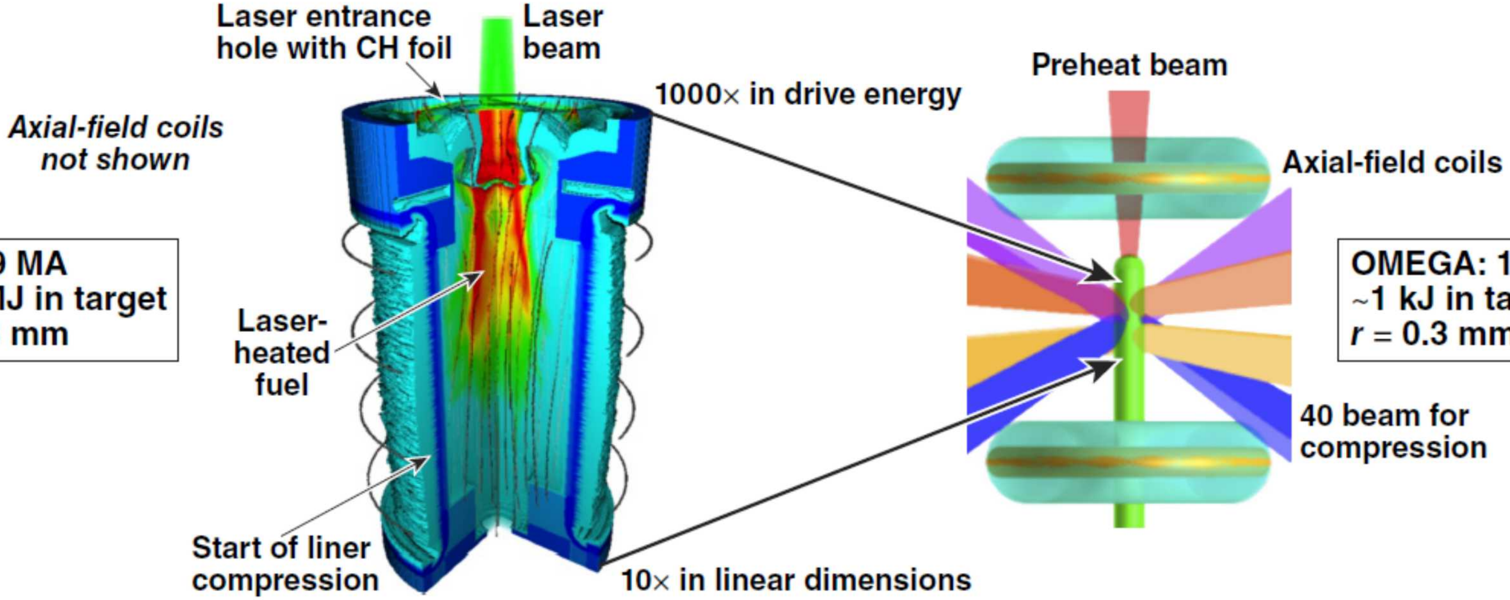
2) XMHD predicts helical instability in 3D calculations due to feed plasma driving flux compression in MagLIF



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

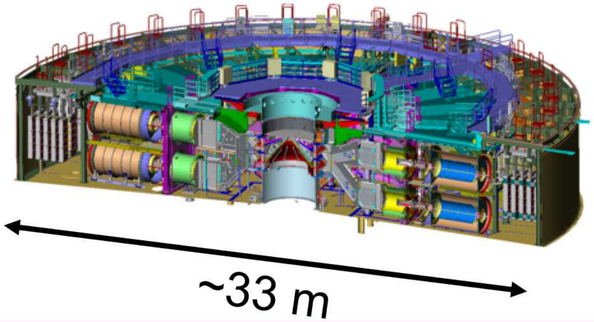
We developed a scaled-down laser driven MagLIF platform on OMEGA that enables key scaling keys and rapid assessment of physics

Z: 19 MA
~1 MJ in target
$r = 3$ mm

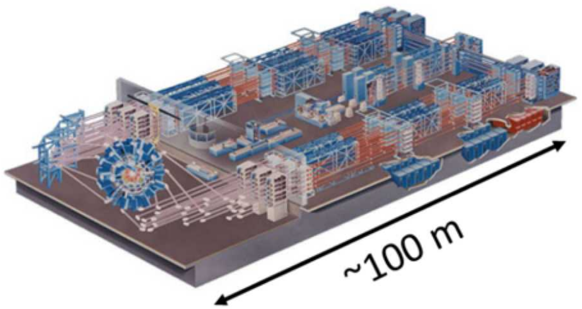


OMEGA: 14.5 kJ
~1 kJ in target
$r = 0.3$ mm

Z Facility



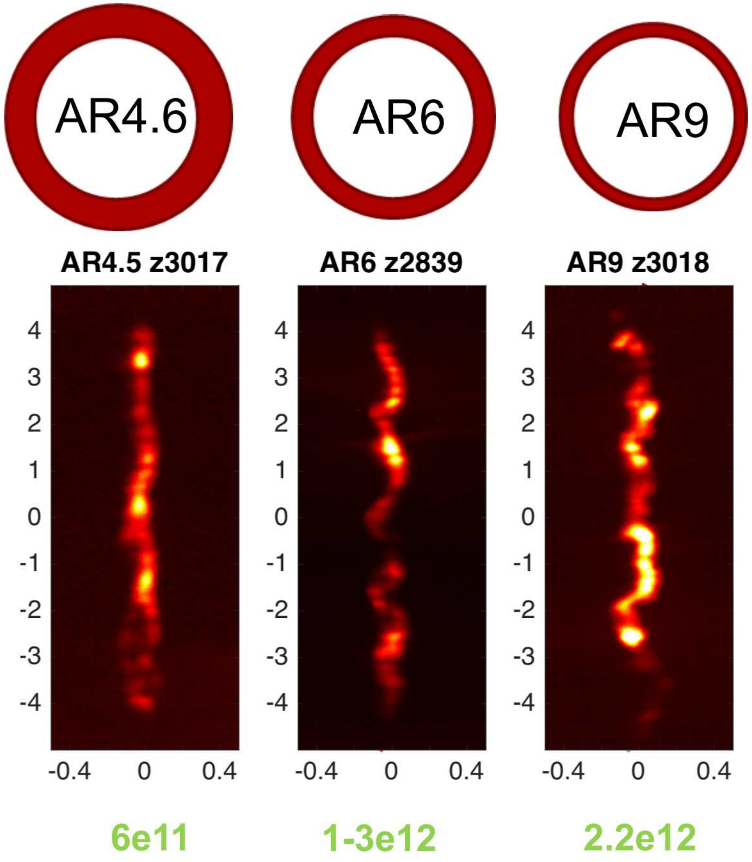
Omega Facility

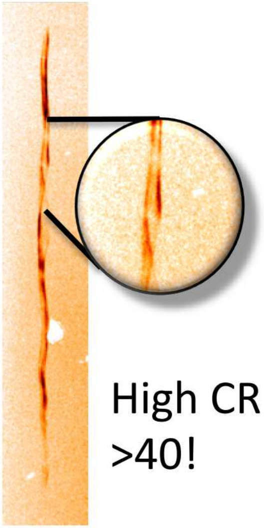


We are still working to understand the full impact of 3D instabilities on performance

我们仍在努力理解3D不稳定性对性能的全面影响

- Spectroscopic measurements suggest relatively high levels of mix
- Experiments with higher convergence generally have poorer performance
- Disruption due to instabilities?
- 3D simulations have matched experimental observables with quasi-2D pressure profiles
- Thicker liners (less feedthrough) have **decreased** performance





>6keV, time time integrated high resolution X-ray self-emission stagnation image

High CR >40!

AR = Liner Radius/Liner Thickness

C. Jennings, D. Ampleford