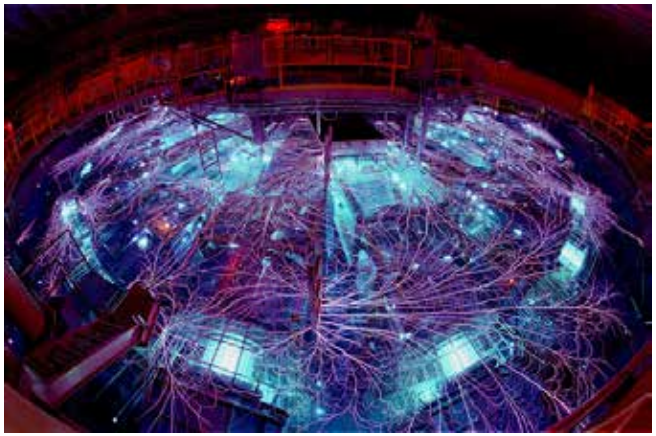
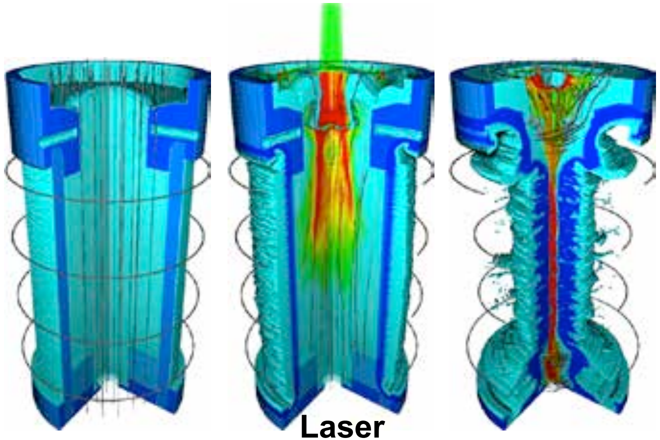
Exceptional service in the national interest





Status of the Magnetized Liner Inertial Fusion Research Program in the United States

Daniel Sinars

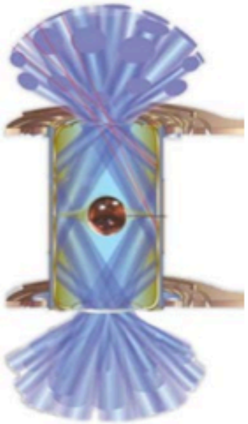
Senior Manager, Radiation and Fusion Physics Group
Sandia National Laboratories

Fusion Power Associates Meeting
Washington, D.C.
December 16-17, 2015

The U.S. ICF Program is pursuing three main approaches to fusion ignition to manage the scientific risk

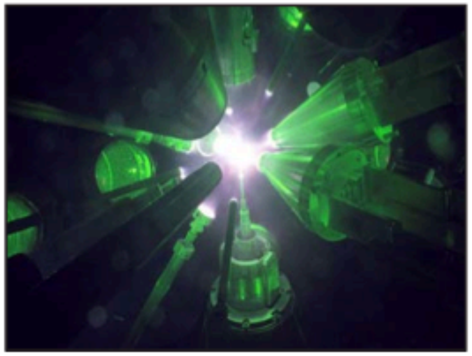
Laser x-ray drive

192 beams, 1.8 MJ, 400 TW

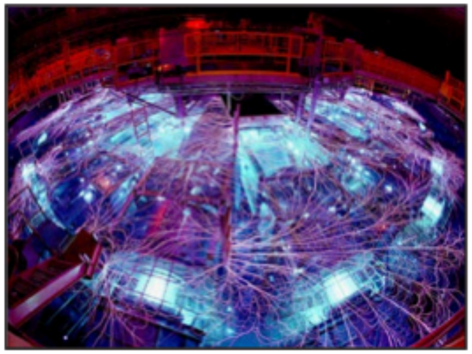


Laser direct drive

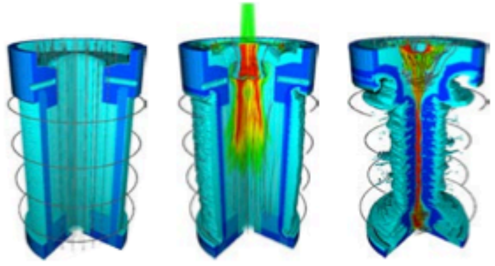
60 beams, 30 kJ, 20 TW



Magnetic direct drive

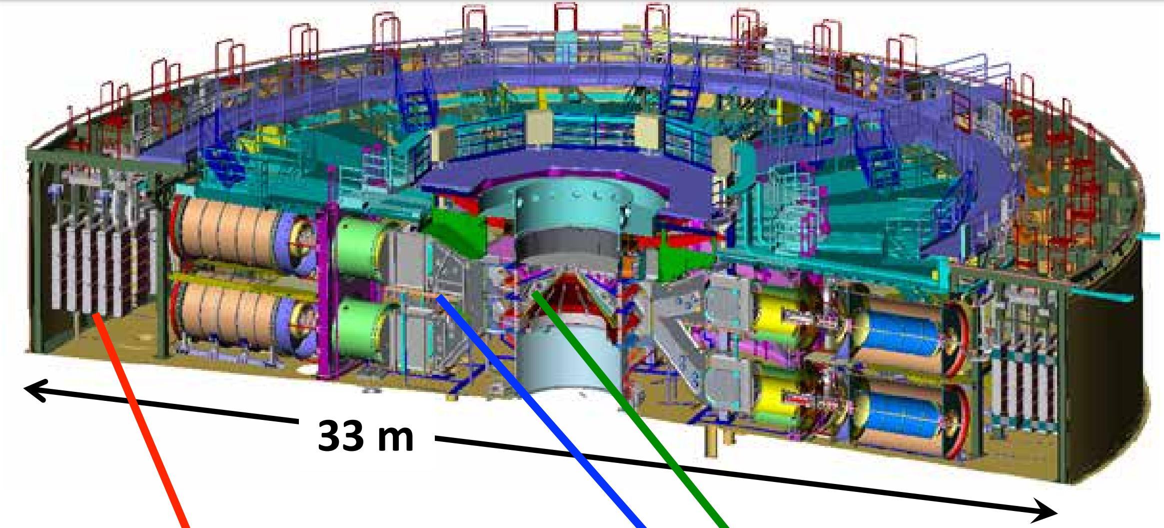


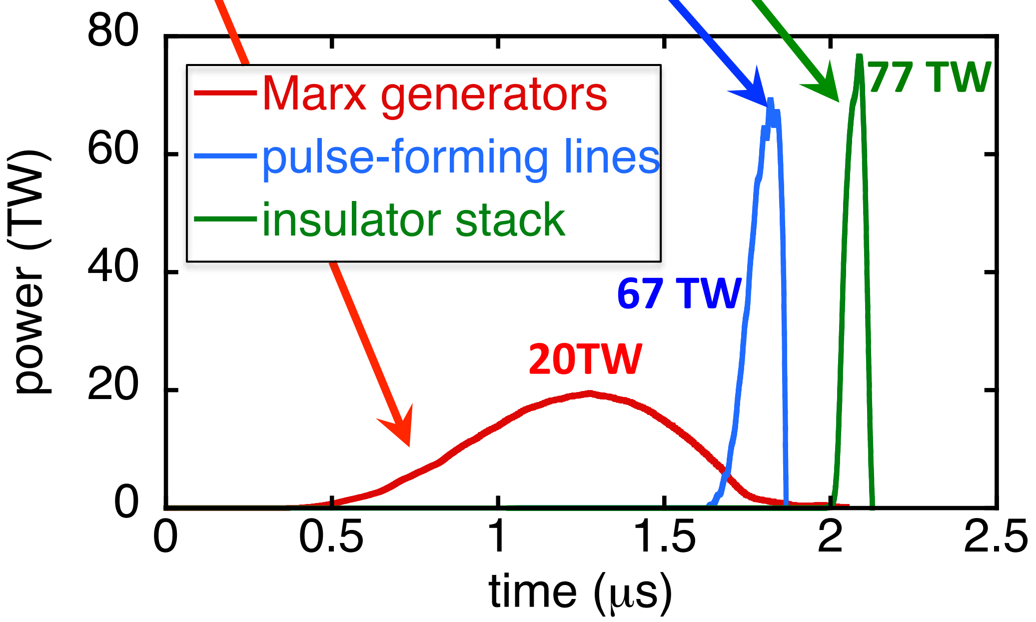
26 MA, 80 TW



Magnetization Laser heating Compression

Magnetic direct drive is based on efficient use of large currents to create high pressures

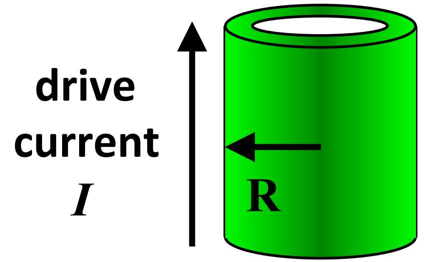




Z today couples ~0.5 MJ out of 20 MJ stored to magnetized liner inertial fusion (MagLIF) target (0.1 MJ in DD fuel).

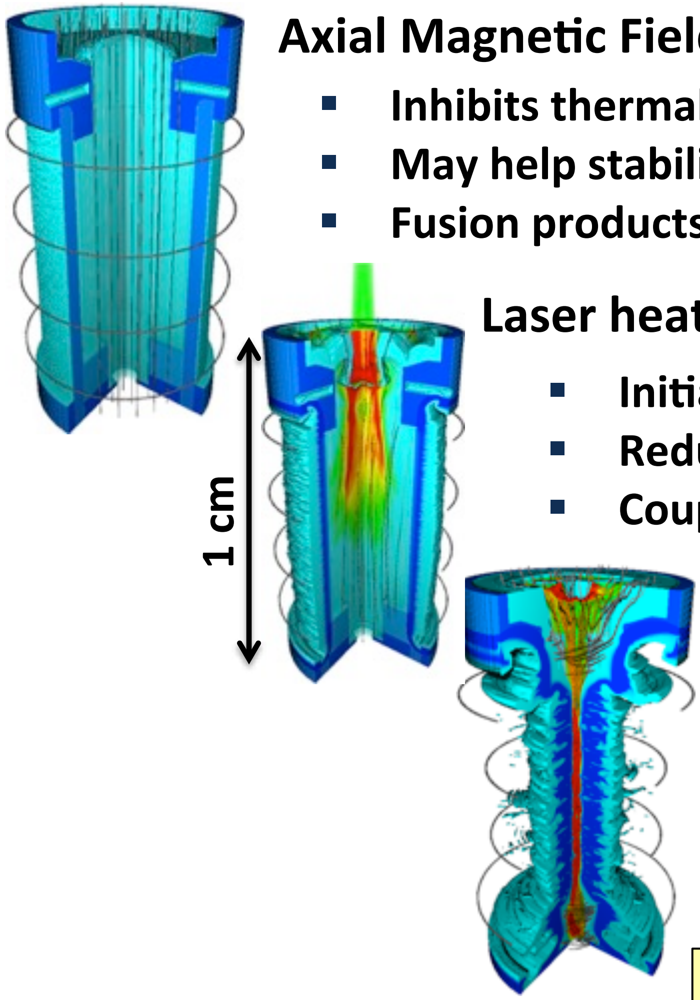
Magnetically Driven Implosion

$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$



100 MBar at 26 MA and 1 mm

Magnetized Liner Inertial Fusion (MagLIF) relies on fuel preheat and magnetization to achieve fusion



Axial Magnetic Field (10 T initially; 30 T available)

- Inhibits thermal losses from fuel to liner
- May help stabilize liner during compression
- Fusion products magnetized

Laser heated fuel (2 kJ initially; 6-10 kJ planned)

- Initial average fuel temperature 150-200 eV
- Reduces compression requirements ($R_0/R_f \sim 25$)
- Coupling of laser to plasma in an important science issue

Magnetic compression of fuel (~100 kJ into fuel)

- ~70-100 km/s, quasi-adiabatic fuel compression
- Low Aspect liners ($R/\Delta R$~6) are robust to hydrodynamic (MRT) instabilities
- Significantly lower pressure/density

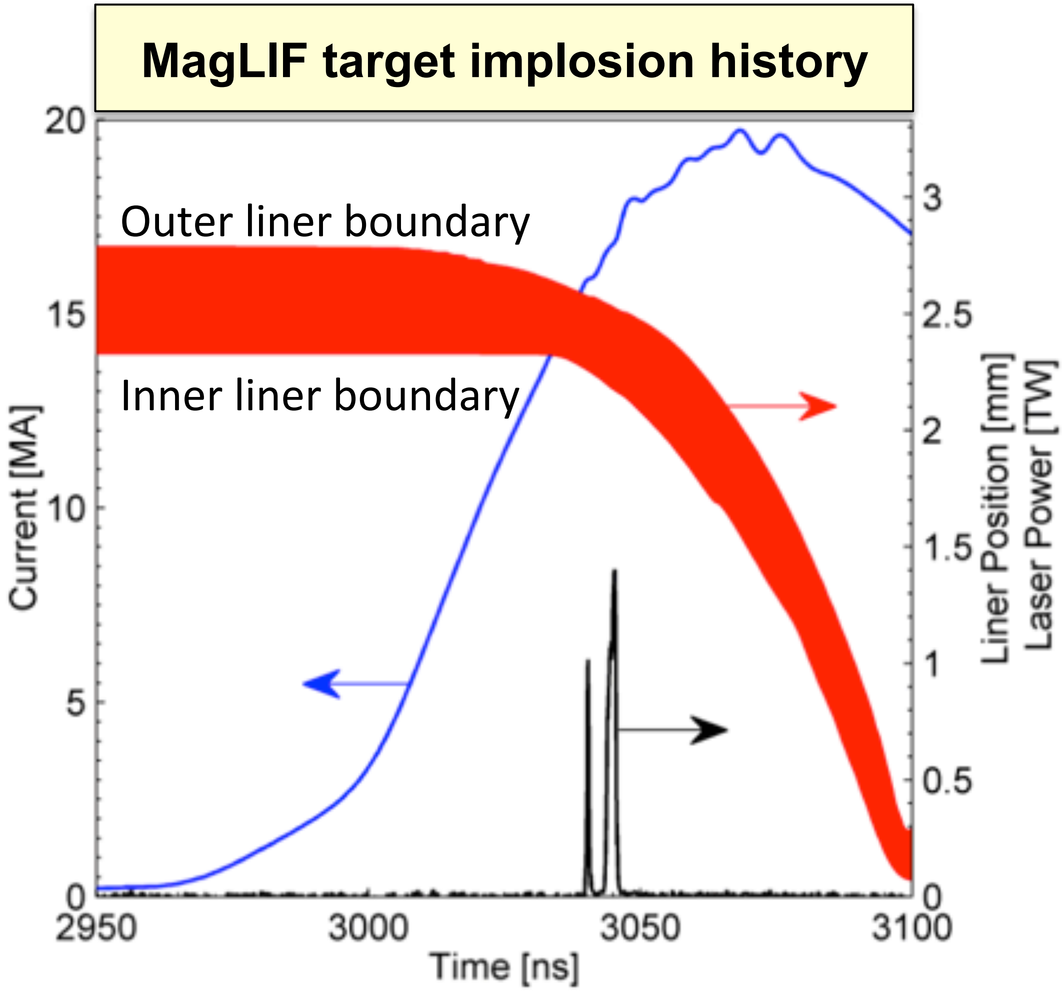
Goal is to demonstrate scaling: $Y\,(B_{z0}, E_{laser}, I)$
DD equivalent of 100 kJ DT yield possible on Z

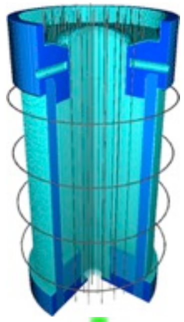
S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz & R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

Experiments have demonstrated thermal fusion with >10^{12} 2.45 MeV neutrons from a ~70 km/s, 1.5 mg/cm^2 implosion

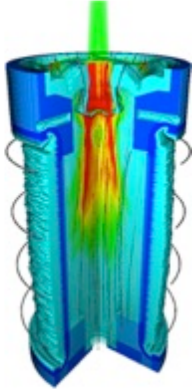
- The initial MagLIF experiments demonstrated that there is merit to the idea of magneto-inertial fusion
- Laser heating of a magnetized initial plasma with minimal high-Z mix is critical
  - Initial experiments used "unconditioned" beams and thick (>3 μm) foils and deposition into the gas was lower than expected
  - Low energy deposition and mix is borne out by several different experiments on multiple facilities
- Research over the next five years at Z, Omega, Omega-EP, and the NIF will address:
  - The physics of laser preheat
  - Implosion and stagnated fuel performance
  - Exploring fusion performance and scaling as a function of laser preheat, initial B field, and drive
- Present modeling predicts fusion yields of ~100 kJ (DT) are possible on Z

We are taking a careful look at all stages of the target using multiple facilities and diagnostics

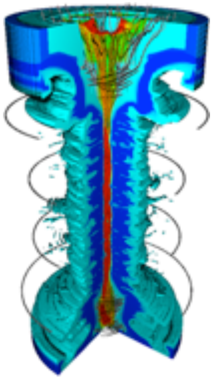




Initial Conditions
- **Be liner**
- **ρ_{DT}~ 1-4 mg/cc**
- **B_{z0}~ 10-30 T (~0.1 MG)**

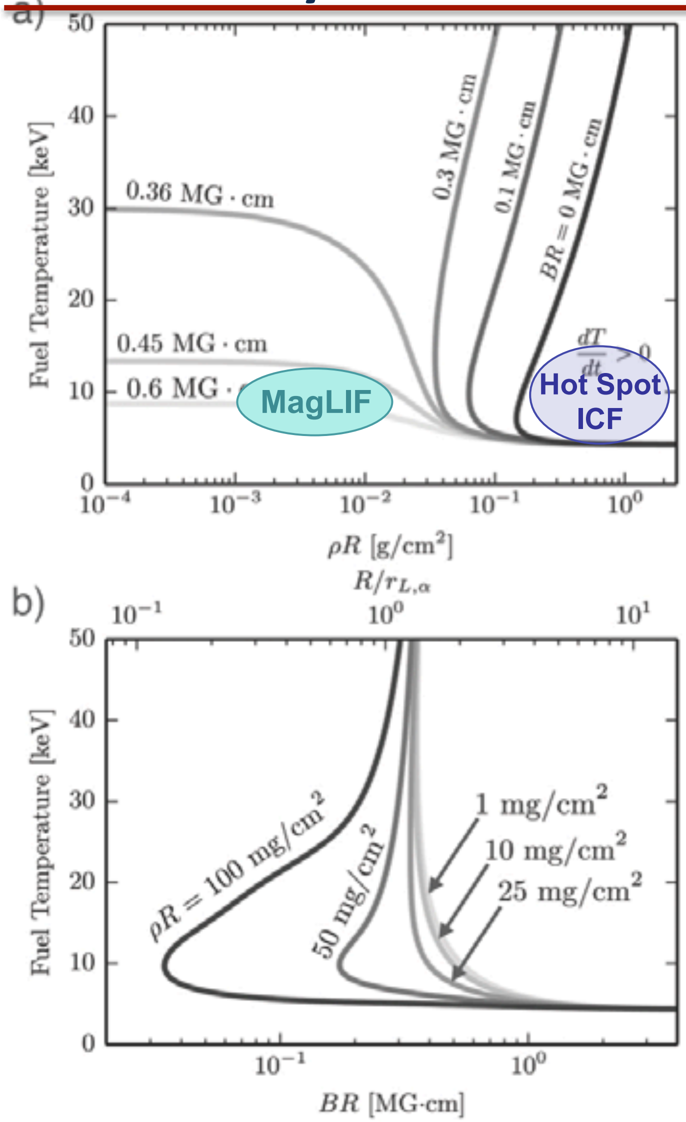


Laser Heating
- **E_{laser} ~ 2-6 kJ @.53µm**
- **T_{DT} ~ 0.2 KeV**
- **ωτ ~ 2-5**
- **Research on Z, ZBL, Omega, Omega-EP**

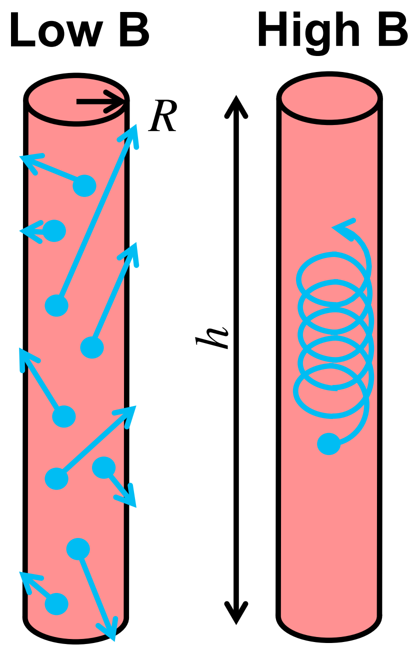


Implosion/stagnation
- **V_{imp}~ 70-100 km/sec**
- **P_{DT} ~ 5 Gbar**
- **T_{ion} > 5 keV**
- **ωτ ~ 200 (B~100 MG)**
- **Research on Z, Omega**

Magnetization (*BR*) can be used to reduce ρR requirements and reduce electron heat losses, lower density also reduces bremsstrahlung radiation losses



- **Initial 10-30 T field greatly amplified during the implosion through flux compression**
- **Too much field is inefficient—want to stagnate on plasma pressure, not magnetic pressure**



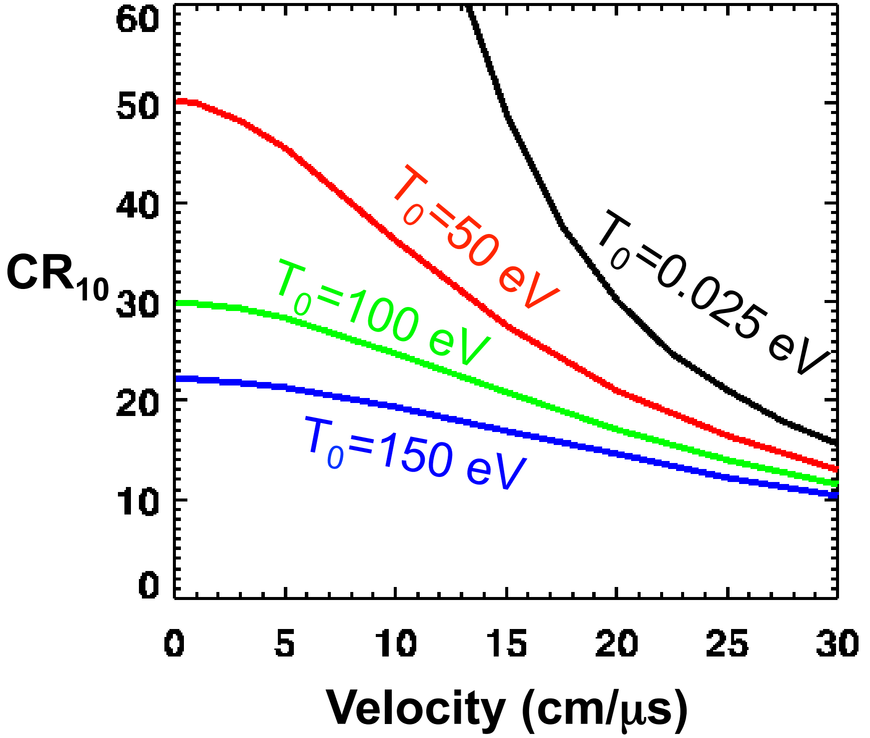
$$\frac{R}{r_\alpha} \approx 4BR\ [MG \cdot \mathrm{cm}]$$

- **Fraction of trapped tritons (or α's) a function of *BR***
- **Effects saturate at *BR* > 0.6 MG-cm**
- **Measurements to date suggest *BR* of 0.4 MG-cm**
- **Focused experiments have demonstrated flux compression w/ B>1000 T**

Basko *et al*. Nuclear Fusion 40, 59 (2000); P.F. Knapp *et al*., Phys. Plasmas (2015).

Heating the fuel prior to compression can lower traditional ICF requirements on velocity and fuel convergence

Simulation with:
- **Constant velocity**
- **No radiation loss**
- **No conductivity loss**



CR_{10} = Convergence Ratio (R_0/R_f) needed to obtain 10 keV (ignition)

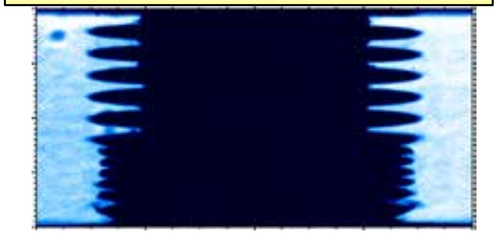
- **Laser heating of fuel (6-10 kJ) offers one way to reach pre-compression temperature of ~200 eV**
- **Detailed simulations suggest we can reach fusion temperatures at convergence R_0/R_f ~ 25**

MagLIF has a very different compression methodology and stagnation parameters than traditional ICF

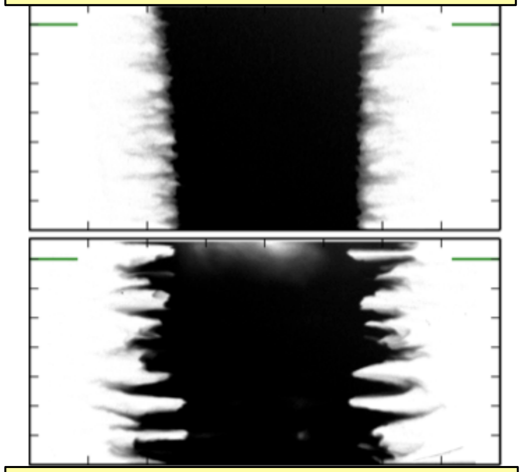
Metric	X-ray Drive on NIF	100 kJ MagLIF on Z
Drive Pressure	~140-160 Mbar	26 MA at 1 mm is 100 Mbar
Force vs. Radius	Goes as R^2 (decreasing)	Goes as 1/R (increasing)
Peak velocity	350-380 km/s	70-100 km/s
Peak IFAR	13-15 (high foot) to 17-20	8.5
Hot spot R_0/R_f	35 (high foot) to 45	25
Volume Change	43000x (high) to 91000x	625x
Fuel ρR	>0.3 g/cm^2	~0.003 g/cm^2
Liner ρR	n/a	>0.3 g/cm^2
BR	n/a	>0.5 MG-cm
Burn time	0.15 to 0.2 ns	1 to 2 ns
T_ion	>4 keV	>4 keV

We have spent many years testing our liner implosion modeling, and have made some interesting advances

Single-mode magneto-Rayleigh-Taylor growth

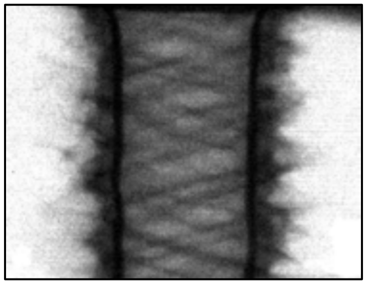


Dielectric-coated Al liner implosion

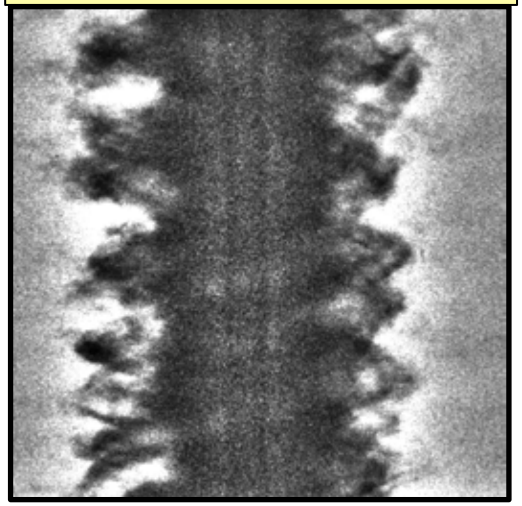


Uncoated

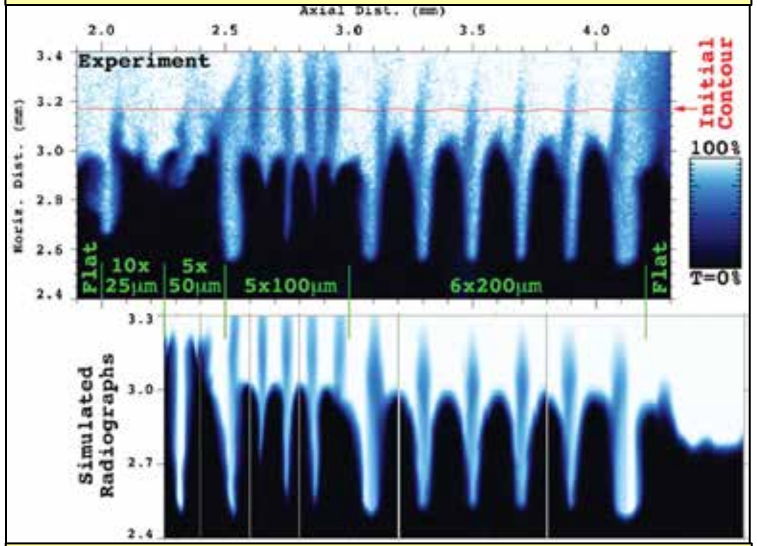
Magnetized MRT growth



Magnetized & dielectric-coated Be (R_0/R_f~17)



Experimental Data

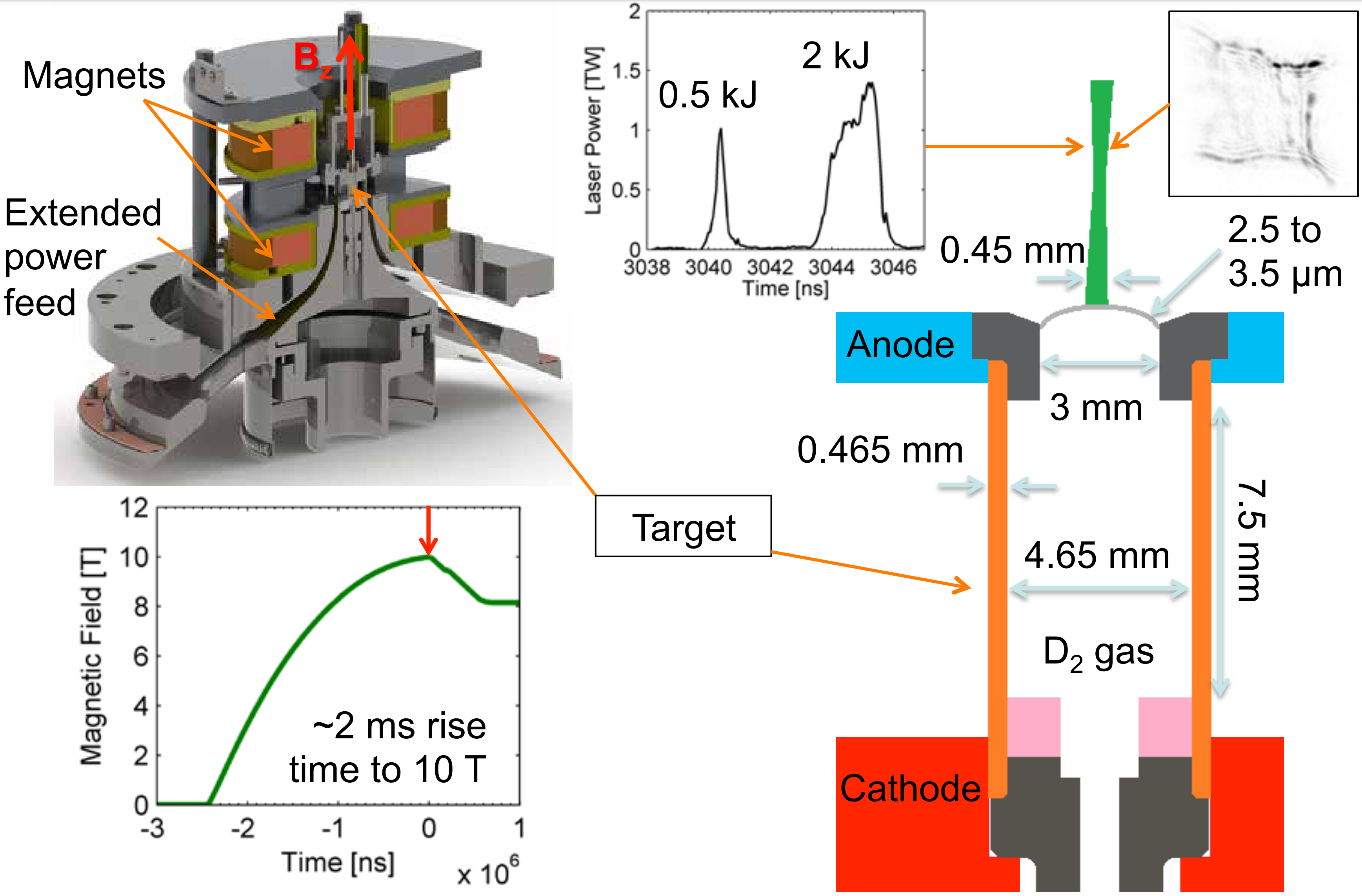


Simulated Data

High-resolution 2D modeling can capture early growth down to the ~50-micron scale

D.B. Sinars *et al.*, Phys. Rev. Lett. (2010).
R.D. McBride *et al.*, Phys. Rev. Lett. (2012).
T.J. Awe *et al.*, Phys. Rev. Lett. (2013).
K.J. Peterson *et al.*, Phys. Rev. Lett. (2014).
T.J. Awe *et al.*, accepted for PRL.

The initial experiments used 10 T, 2.5 kJ laser energy, and a ~19 MA current to drive a D_2 filled (0.7 mg/cm^3) Be liner

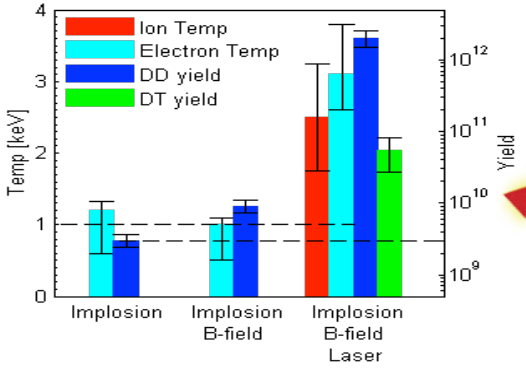


M.R. Gomez *et al.*, Phys. Rev. Lett. 113, 155003 (2014).

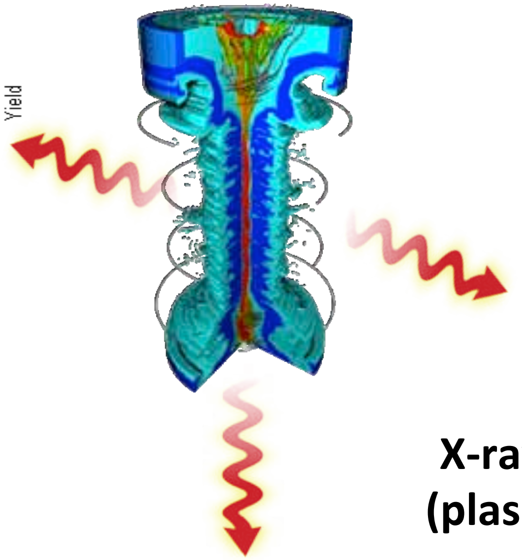
An ensemble of measurements from our first MagLIF experiments are consistent with a magnetized, thermonuclear plasma!

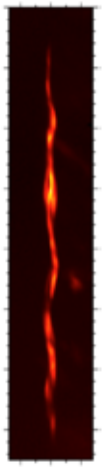
M.R. Gomez *et al.* PRL (2014).
P.F. Schmit *et al.*, PRL (2014).
P.F. Knapp *et al.*, PoP (2015).
M.R. Gomez *et al.*, PoP (2015).
S.B. Hansen *et al.*, PoP (2015).

Nuclear Activation (yield)



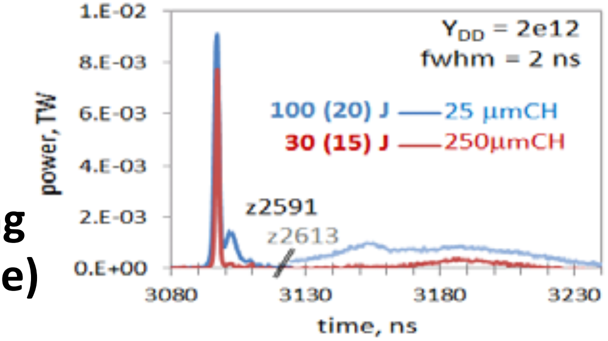
MagLIF Z pinch



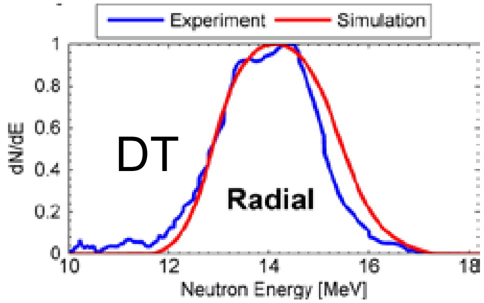


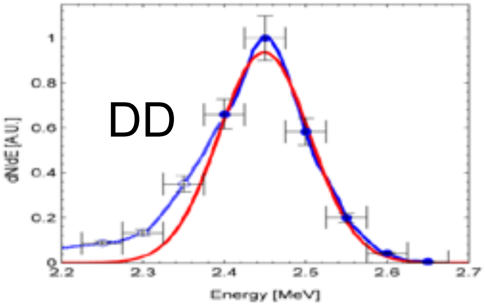
X-ray Imaging (plasma shape)

X-ray Power (duration)

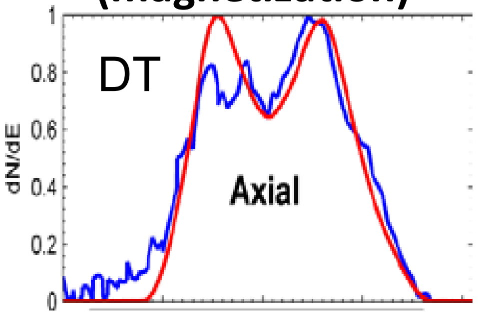


Neutron spectra (Tion)

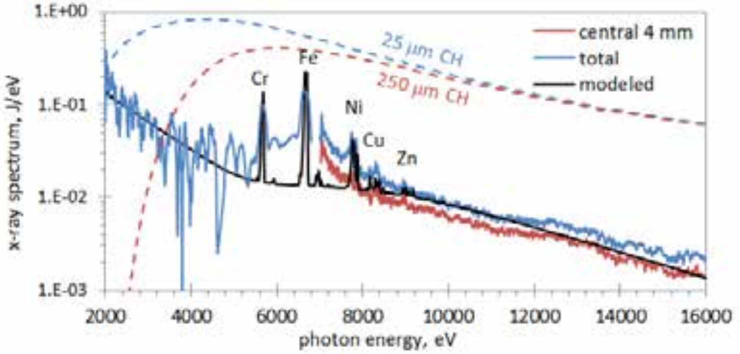




DT Neutron spectra (magnetization)



X-ray Spectra (Te, mix)

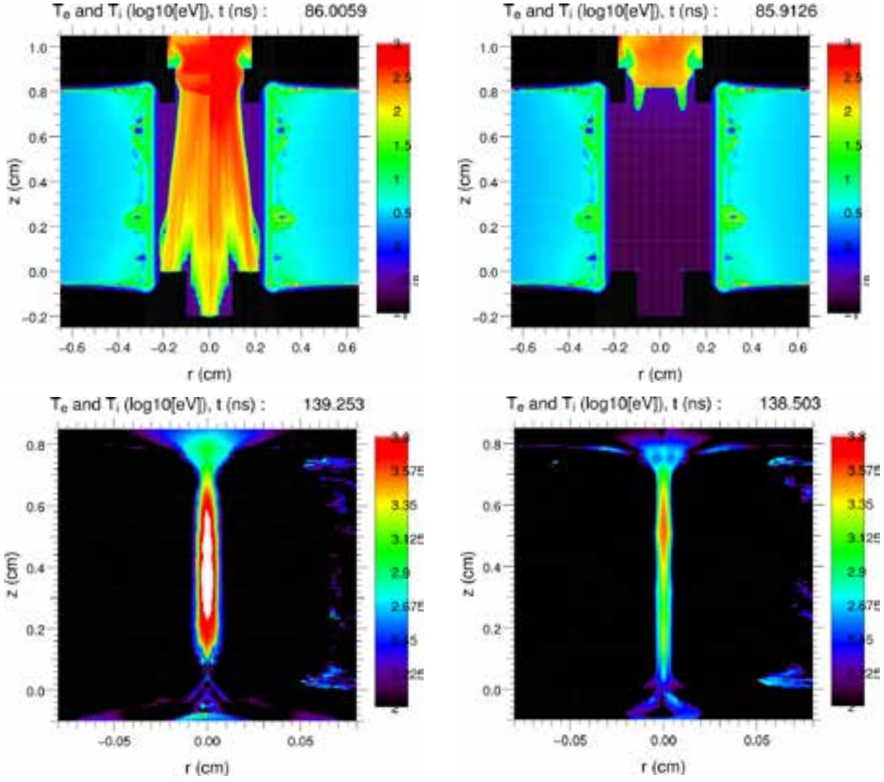


Lower than predicted coupling of laser energy due to un-conditoned beam (poor foil burn through)? Z data can be modeled by assuming no mix and 200-300 J in fuel

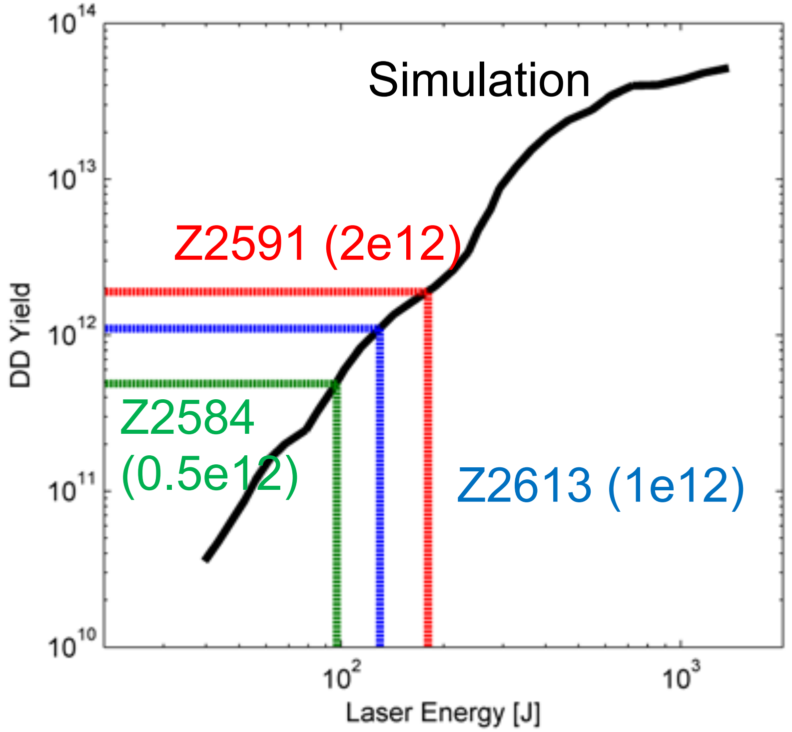
HYDRA Simulations

main pulse
2 ns, 2 kJ

main pulse
0.2 ns, 0.2 kJ

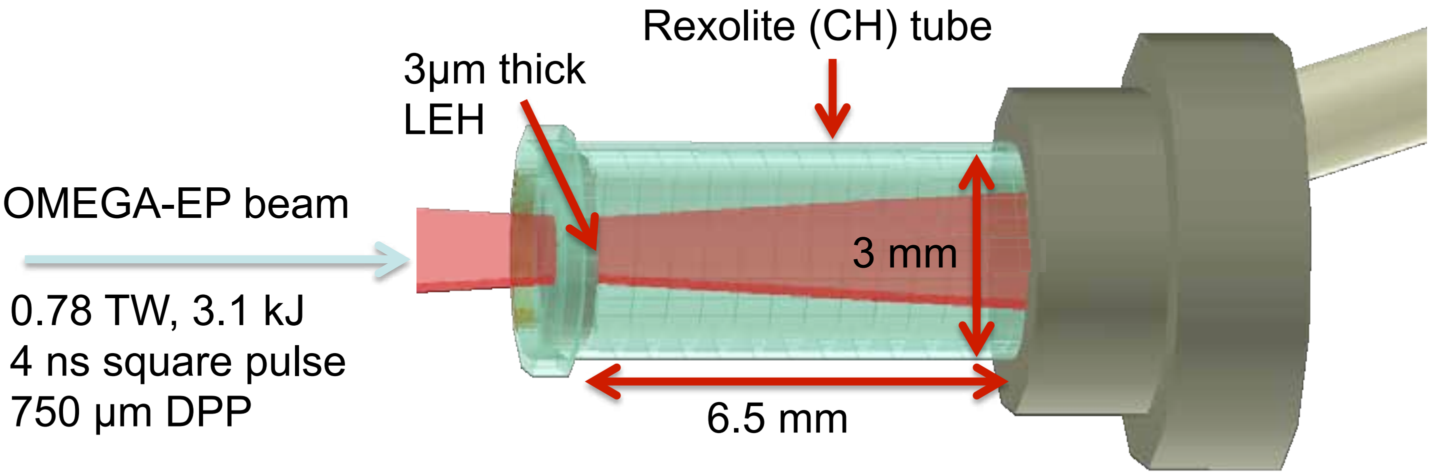


A.B. Sefkow *et al.*, Phys. Plasmas (2014).



Simulations with 200 J match not only the yield, but other parameters measured in the experiments (temperature, shape, BR, etc.)

We are using OMEGA-EP to investigate preheat at parameters relevant to MagLIF



OMEGA-EP beam

0.78 TW, 3.1 kJ
4 ns square pulse
750 μm DPP

3μm thick
LEH

Rexolite (CH) tube

3 mm

6.5 mm

Target and drive parameters kept consistent with MagLIF targets:

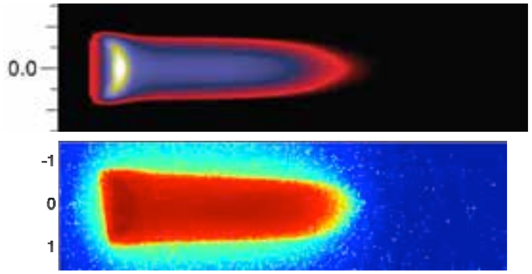
- **I~2.5x10^{14} W/cm^{2}** (similar to 850 μm DPP smoothed ZBL pulse) – square pulse
- **Total preheat energy: 3.1 kJ** (c.f. 2.5-4 kJ for ZBL)
- **Visible target length: 6.5 mm** (c.f. 7.5-10 mm in MagLIF)
- **Thick LEH window**

Propagation in 3 gas densities tested (1st MagLIF experiments n_e= 0.052-0.1 n_c)

- n_e = 0.055 n_c (10 atm pressure, 1.67 mg/cm^3)
- n_e = 0.077 n_c (14 atm pressure, 2.34 mg/cm^3)
- n_e = 0.10 n_c (18 atm pressure, 3.01 mg/cm^3)

OMEGA-EP experiments are helping us understand when and how much we can trust our modeling

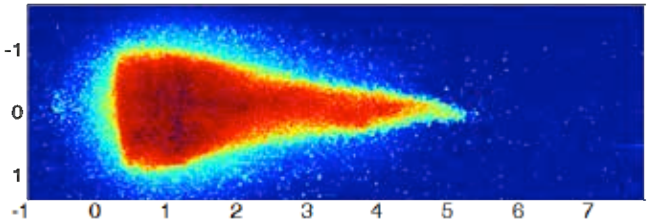
- Experiments in D_2 show the density (n_e=0.1n_c), increases LPI, affects energy deposition
- Increased LPI a result of thick LEH window disassembly – using a prepulse affects this
- For conditions where inverse Bremmstrahlung dominates, simulations can match experiments. Extrapolation to Z: multi-kJ heating possible

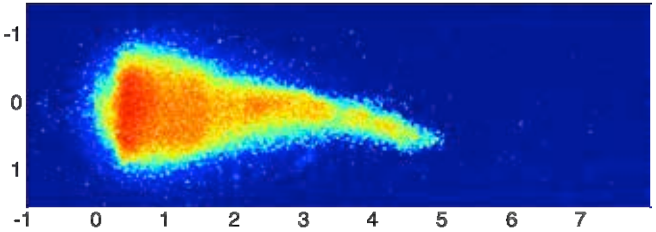


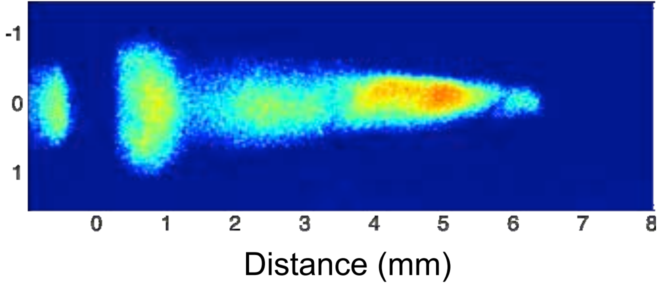
Experiments in pure Ar: n_e=0.047n_c, 1 μm thick LEH, I~2.5x10^{14} W/cm^2

- Developing thin-window cryo targets should improve target preheat, reduce LPI

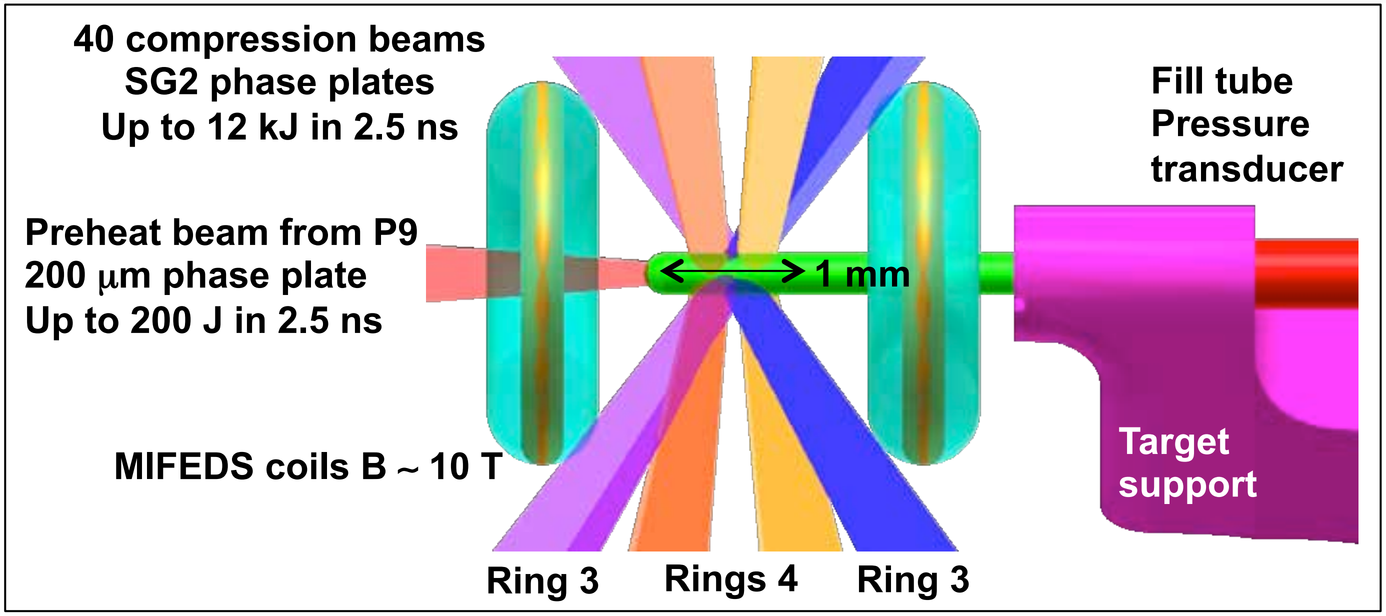
Time gated emission images
Propagation in doped D_2
3.1 kJ delivered to targets


n_e~0.077n_c


n_e~0.1n_c


n_e~0.1n_c, pulseshaped

A design for laser-driven MagLIF on OMEGA has been developed and will be demonstrated in the next 2 years



40 compression beams
SG2 phase plates
Up to 12 kJ in 2.5 ns

Preheat beam from P9
200 μm phase plate
Up to 200 J in 2.5 ns

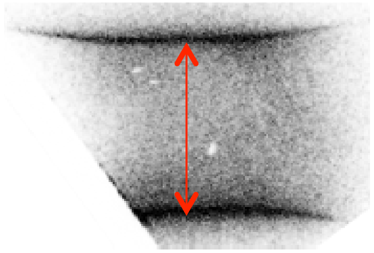
MIFEDS coils B ~ 10 T

Fill tube
Pressure
transducer

Target
support

X-ray image of compression

Ring 3 only



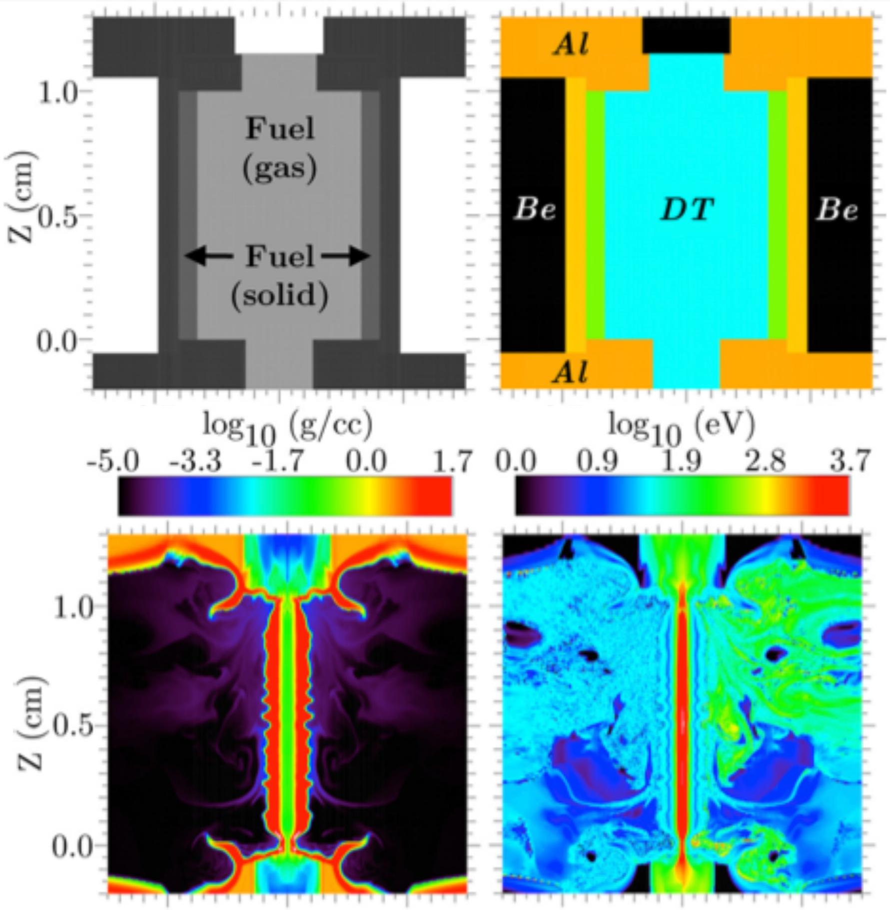
520±19 μm
~180 km/s (Ring 4)

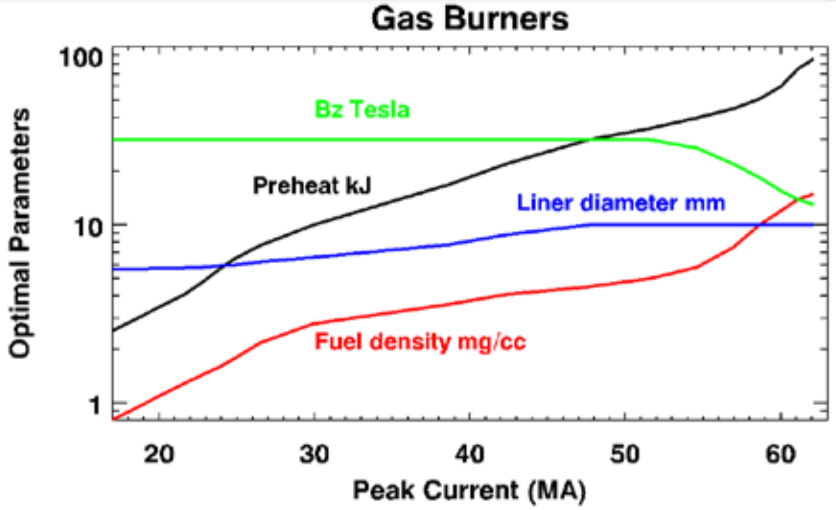
Parylene-N Target

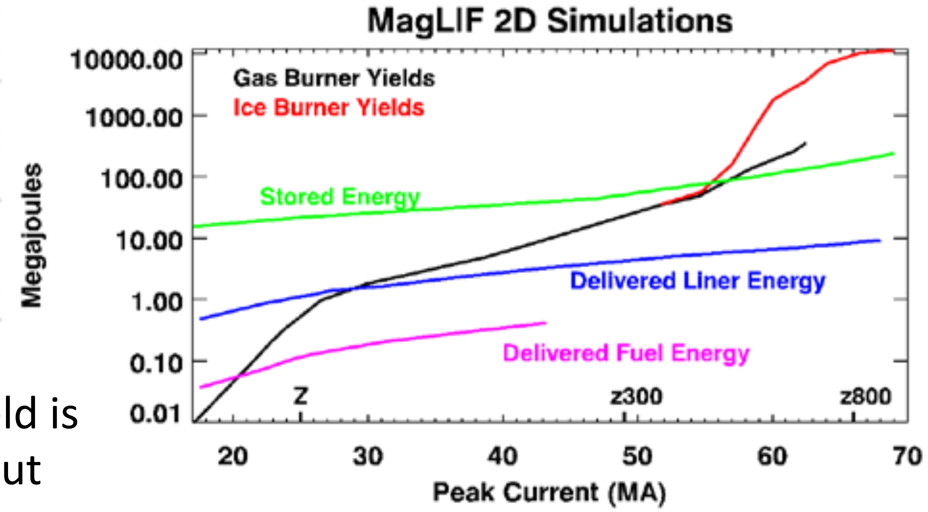
Outer diameter:	600 μm	D_2 fill density:	1 – 2.1 mg/cc
Shell thickness:	30 μm	Preheat temperature:	≥ 100 eV
Compressed length:	600 – 700 μm		

- Experiments in 2015 have established that we can couple the laser to the target and heat it all the way through to >100 eV
- We have achieved cylindrical compression at the desired implosion velocity, and recent experiments have optimized the compression length over >0.7 mm
- 1st integrated tests on OMEGA to start on June 1, 2016

It may be possible to achieve ~100 kJ yields on Z. 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).

Experiments have demonstrated thermal fusion with >10^{12} 2.45 MeV neutrons from a ~70 km/s, 1.5 mg/cm^2 implosion

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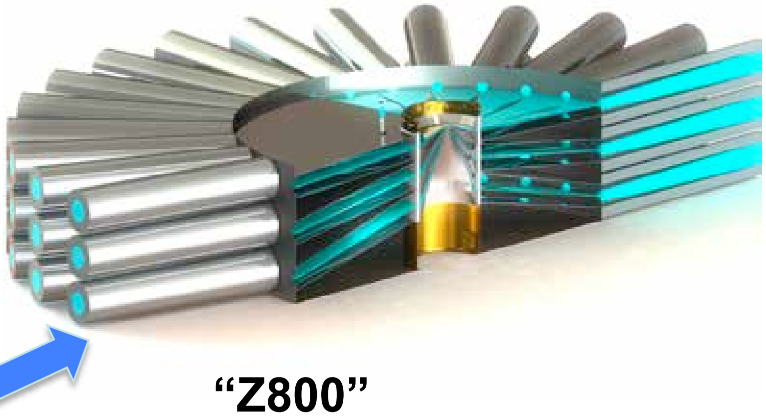
- Research over the next five years at Z, Omega, Omega-EP, and the NIF will address:
    - The physics of laser preheat
    - Implosion and stagnated fuel performance
    - Exploring fusion performance and scaling as a function of laser preheat, initial B field, and drive
- Present modeling predicts fusion yields of ~100 kJ (DT) are possible on Z

We are currently exploring target designs and pulsed power architectures that may be on the path to 0.5-1 GJ yields and that also meet the needs of the science campaigns

Fusion Yield 0.5-1 GJ?
Burning plasmas



"Z800"

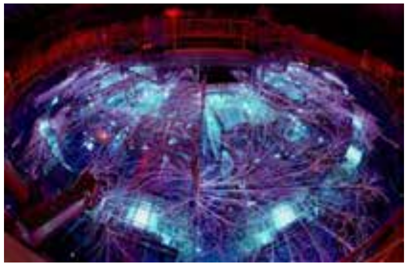
- 800 TW
- 52 Meter diameter
- 61 MA
- 130 MJ Stored Energy

Yield = Etarget?
(About 3-4 MJ)
α-dominated plasmas

"Z300"

- 300 TW
- 35 Meter diameter
- 47 MA
- 47 MJ Stored Energy

Yield = E_{fuel}?
(~100kJ$_{DT\ eq}$)
Physics Basis for Z300



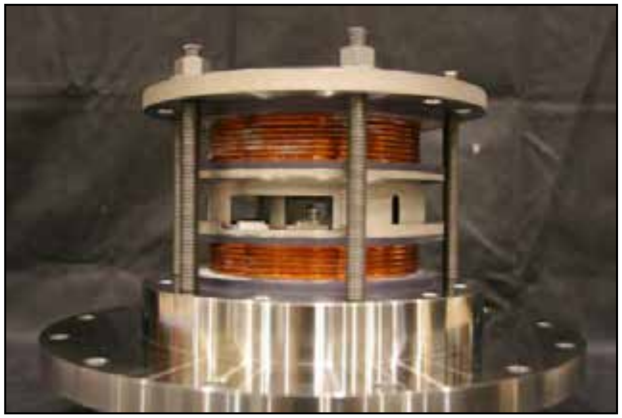
Z

- 80 TW
- 33 Meter diameter
- 26 MA
- 22 MJ Stored Energy

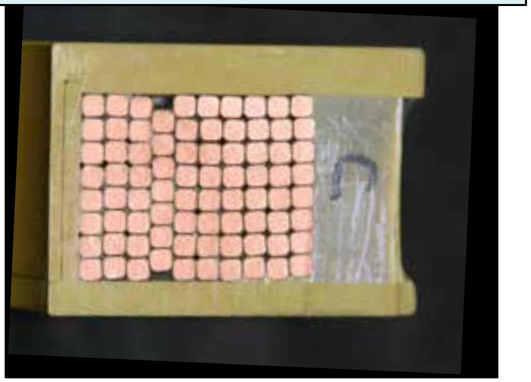
We have successfully implemented 10-30 T axial fields over a several cm^3 volume and several ms for MagLIF

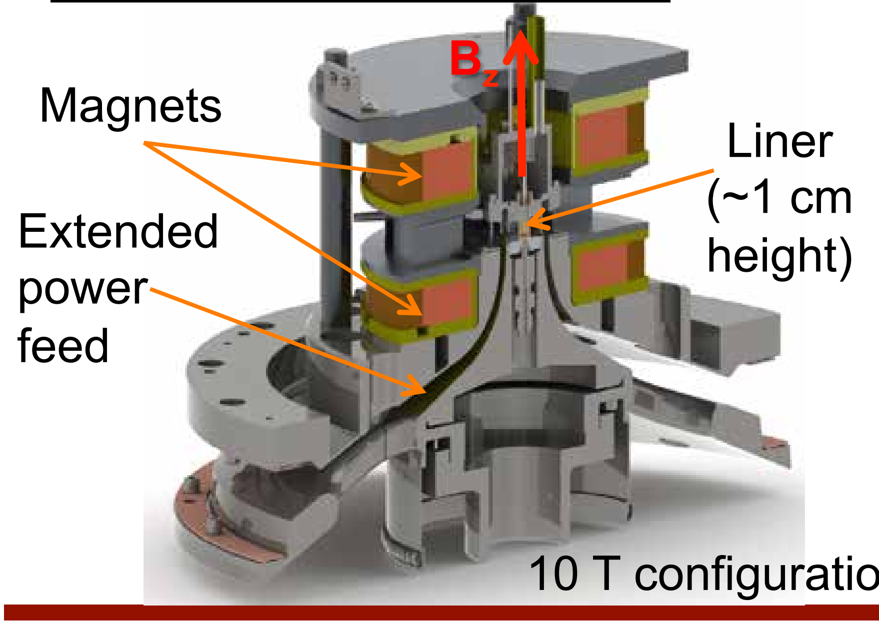
Capacitor bank system on Z
900 kJ, 8 mF, 15 kV (Feb. 2013)

Example MagLIF coil assembly with copper windings visible

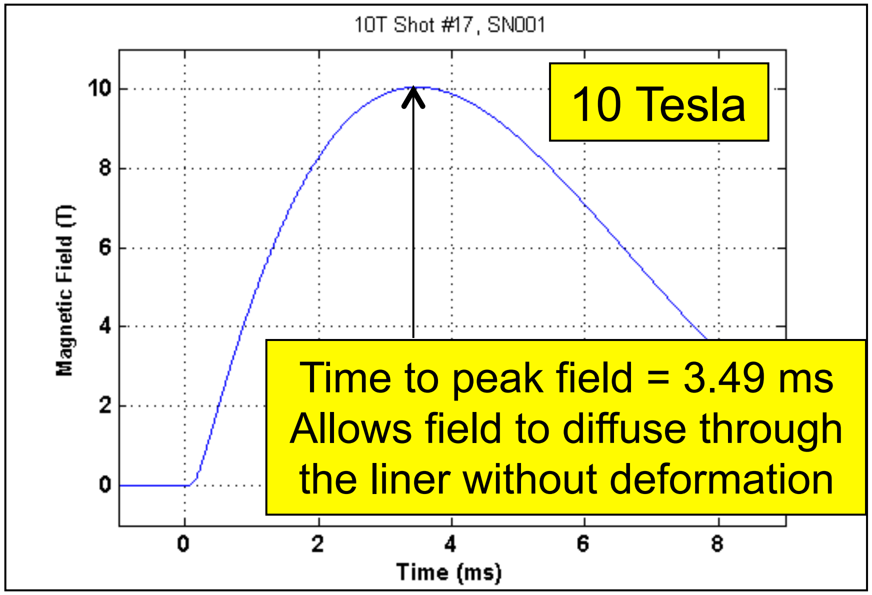


Cross section of coil showing Cu wire, Torlon housing, and Zylon/epoxy reinforcement





10 T configuration

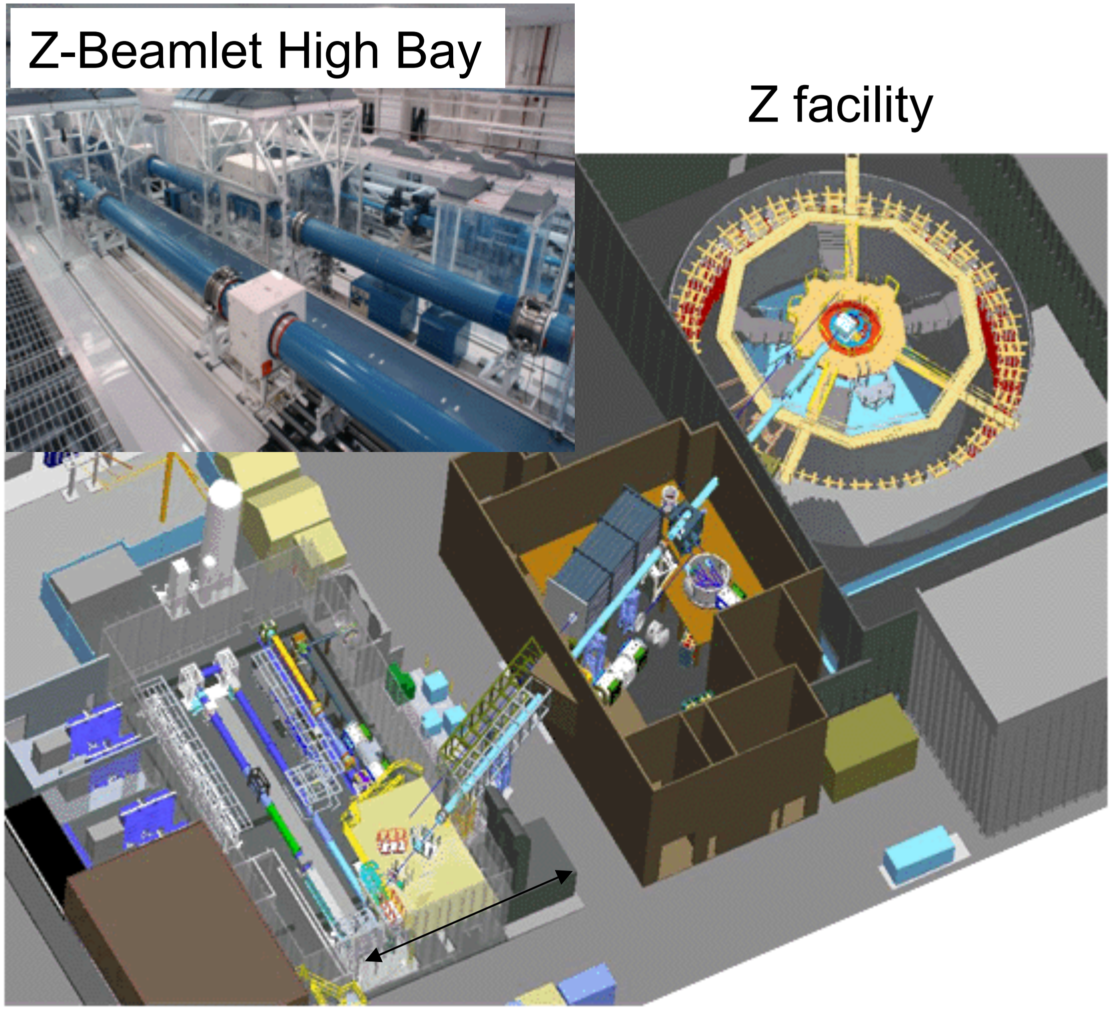


10 Tesla

Time to peak field = 3.49 ms
Allows field to diffuse through the liner without deformation

D.C. Rovang, D. Lamppa *et al.*, Rev. Sci. Instrum. (2014).

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

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