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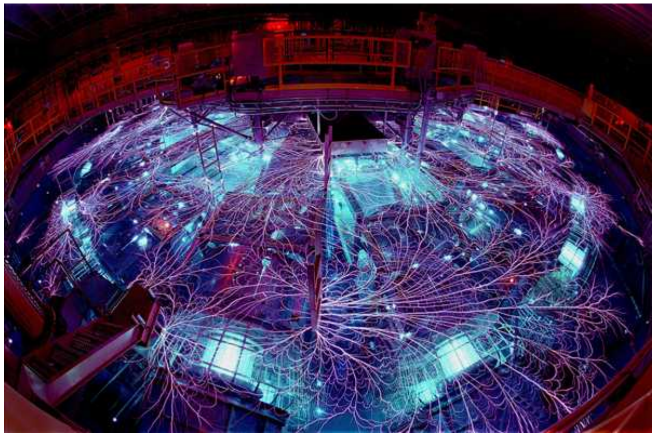

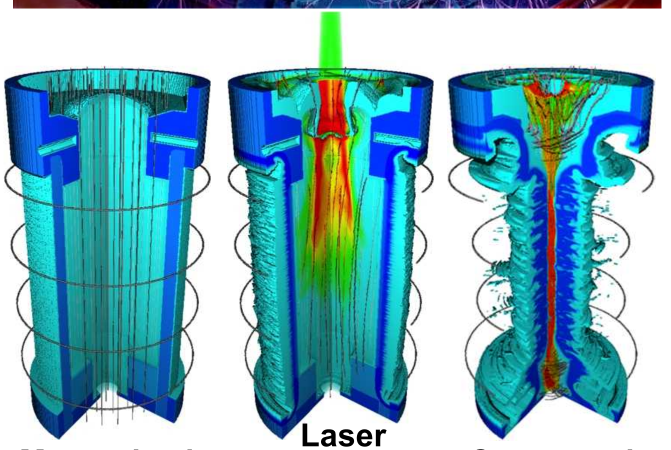

Overview of the Magnetized Liner Inertial Fusion Research Program in the United States

Daniel B. Sinars

Sandia National Laboratories,

Albuquerque, NM, USA

IFSA 2015 Conference

Sept. 20-25, 2015

Seattle, WA, USA

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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I am representing the work of many scientists and engineers working on the MagLIF project

T.J. Awe, C.J. Bourdon, E.M. Campbell, G.A. Chandler, P.J. Christenson, M.E. Cuneo, M. Geissel, M.R. Gomez, K.D. Hahn, S.B. Hansen, E.C. Harding, A.J. Harvey-Thompson, M.C. Herrmann, M.H. Hess, C.A. Jennings, B. Jones, M. Jones, R.J. Kaye, P.F. Knapp, D.C. Lamppa, J.S. Lash, M.R. Lopez, M.R. Martin, R.D. McBride, L.A. McPherson, T.N. Nagayama, K.J. Peterson, J.L. Porter, G.A. Rochau, D.C. Rovang, C.L. Ruiz, S.E. Rosenthal, M.E. Savage, P.F. Schmit, A.B. Sefkow, D.B. Sinars, S.A. Slutz, I.C. Smith, W.A. Stygar, R.A. Vesey, E.P. Yu

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B.E. Blue*, D.G. Schroen, K. Tomlinson, M.S. Wei

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Laboratory for Laser Energetics, University of Rochester, Rochester, NY, USA

* Now at LLNL; ** Now at U. Michigan

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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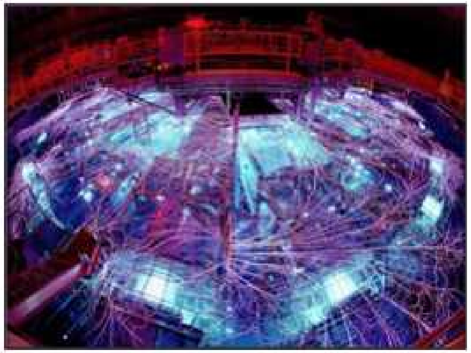
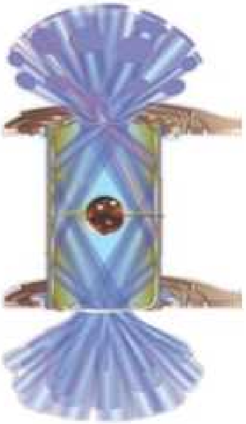
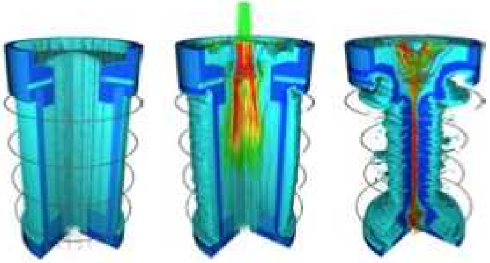
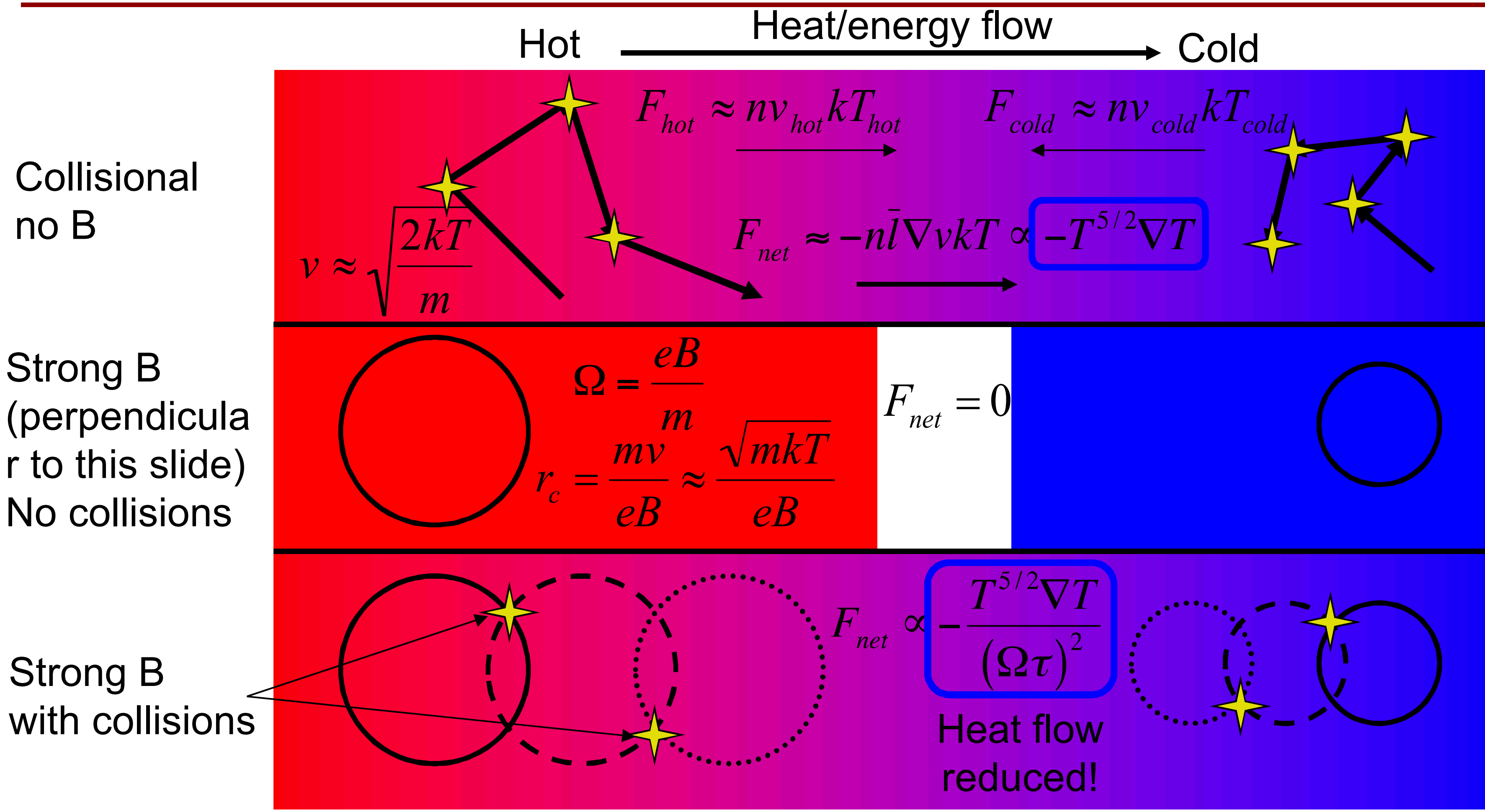
- The initial MagLIF experiments demonstrated that there is merit to the idea of magneto-inertial fusion
- Laser heating of a magnetized initial plasma with minimal high-Z mix is critical
  - Initial experiments used "unconditioned" beams and thick (>3 μm) foils and deposition into the gas was lower 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

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

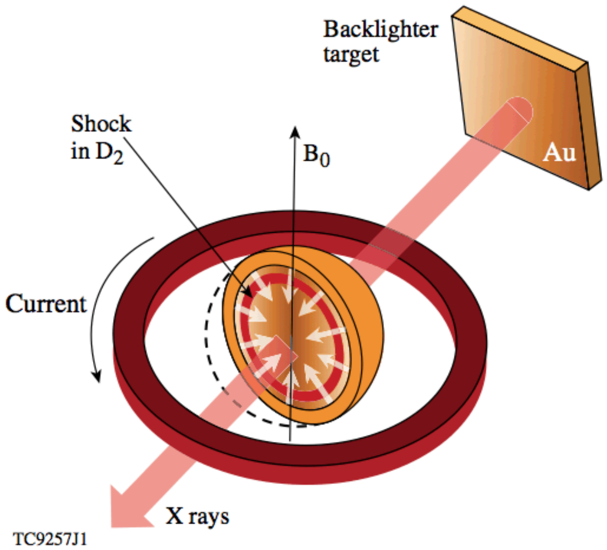
Laser x-ray drive	Laser direct drive	Magnetic direct drive
		
192 beams, 1.8 MJ, 400 TW	60 beams, 30 kJ, 20 TW	26 MA, 80 TW
		 Magnetization / Laser heating / Compression

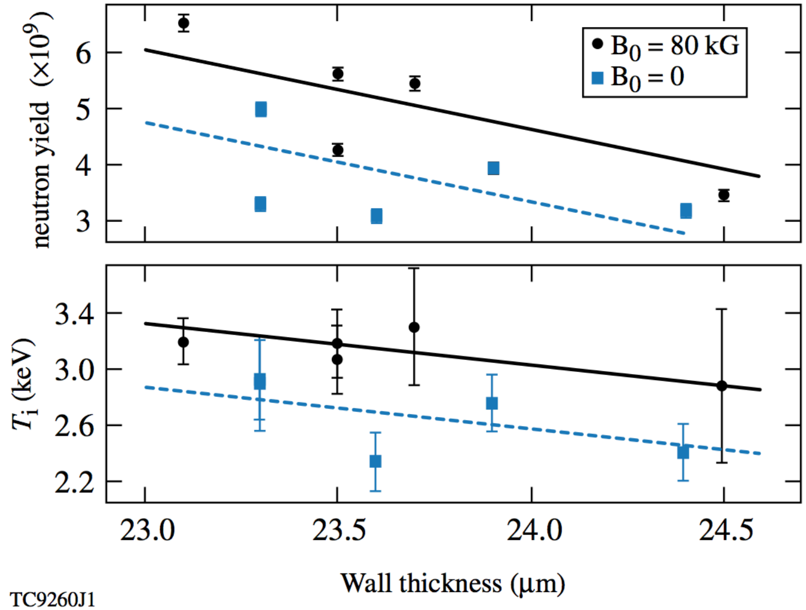
Magneto-inertial fusion is based on the idea that energy and particle transport can be reduced by strong magnetic fields, even in collisional plasmas



"Anomalous" heat transport can reduce the benefit of magnetic fields (e.g., in tokamaks) but there remains a significant benefit

Laser-driven spherical capsule implosions* showed higher temperatures (and yields) due to fuel magnetization



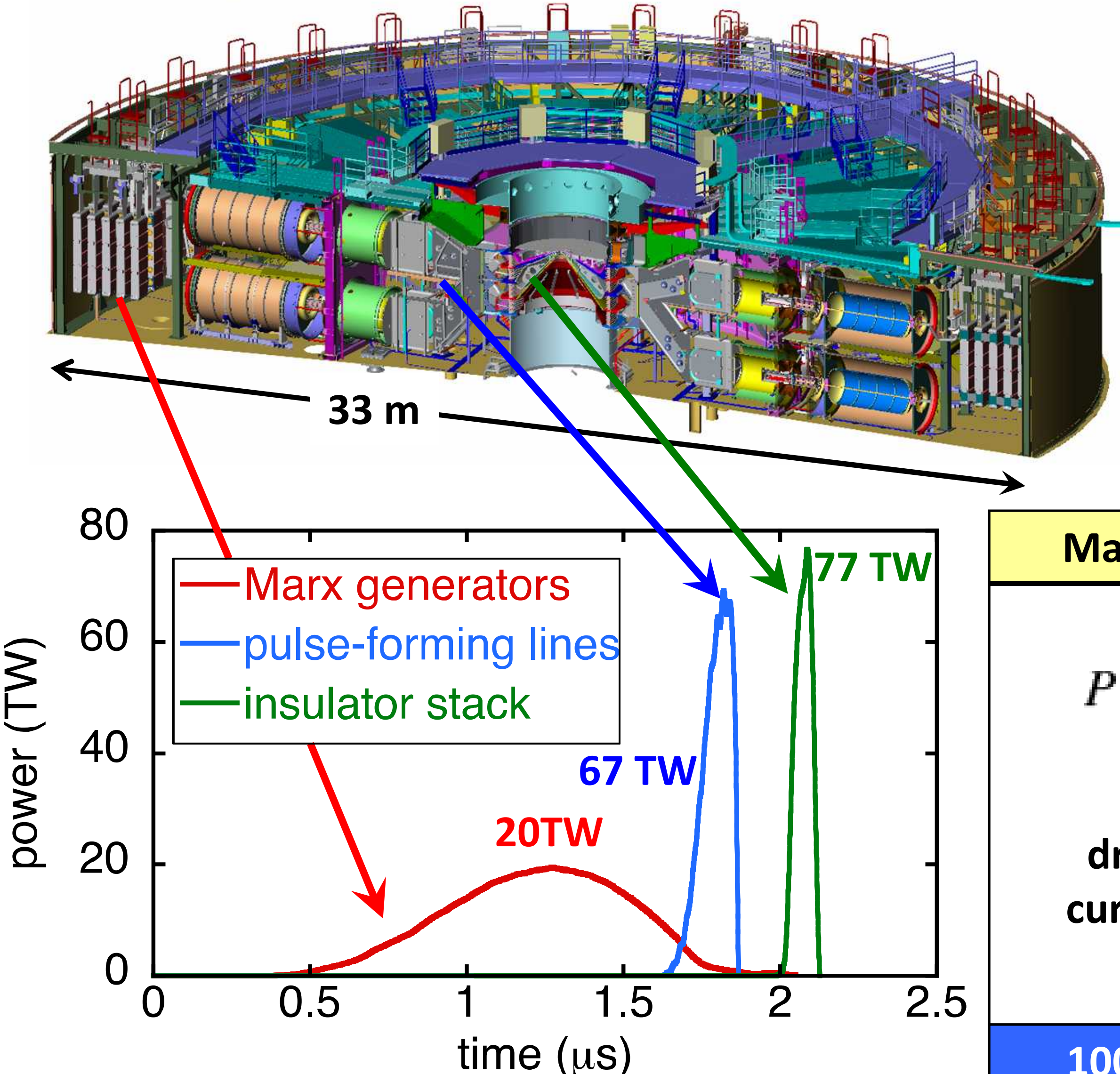


- Simple axial field used in a spherical implosion geometry
- Field suppressed electron heat conduction losses along one direction
- The resulting 30% increase in temperature and 15% increase in yield is consistent with rough estimates for heat loss suppression
- This is an example of success with a target that produced fusion yield without magnetization—can we produce yield in targets that wouldn't produce significant yield otherwise? (and gain benefit from doing so?)

* P.Y. Chang *et al.*, Phys. Rev. Lett. 107, 035006 (2011).

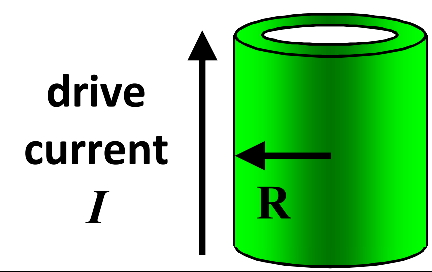
Magnetic direct drive is based on efficient use of large currents to create high pressures

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

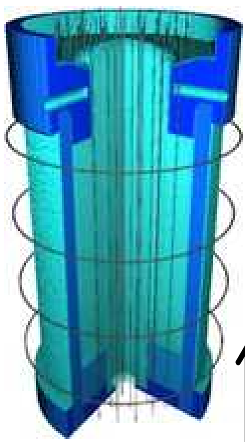
$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$



100 MBar at 26 MA and 1 mm

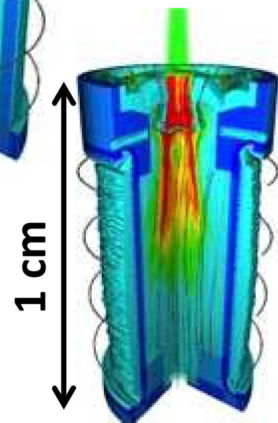
See talk by Joel Lash this afternoon (We.S.2) for more details on Z

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



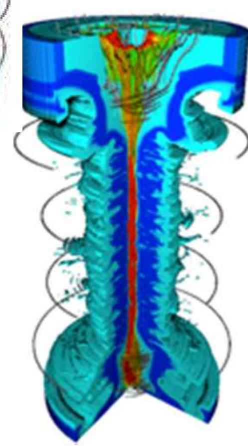
Axial Magnetic Field (10 T initially; 30 T available)

- 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 ~ 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).

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

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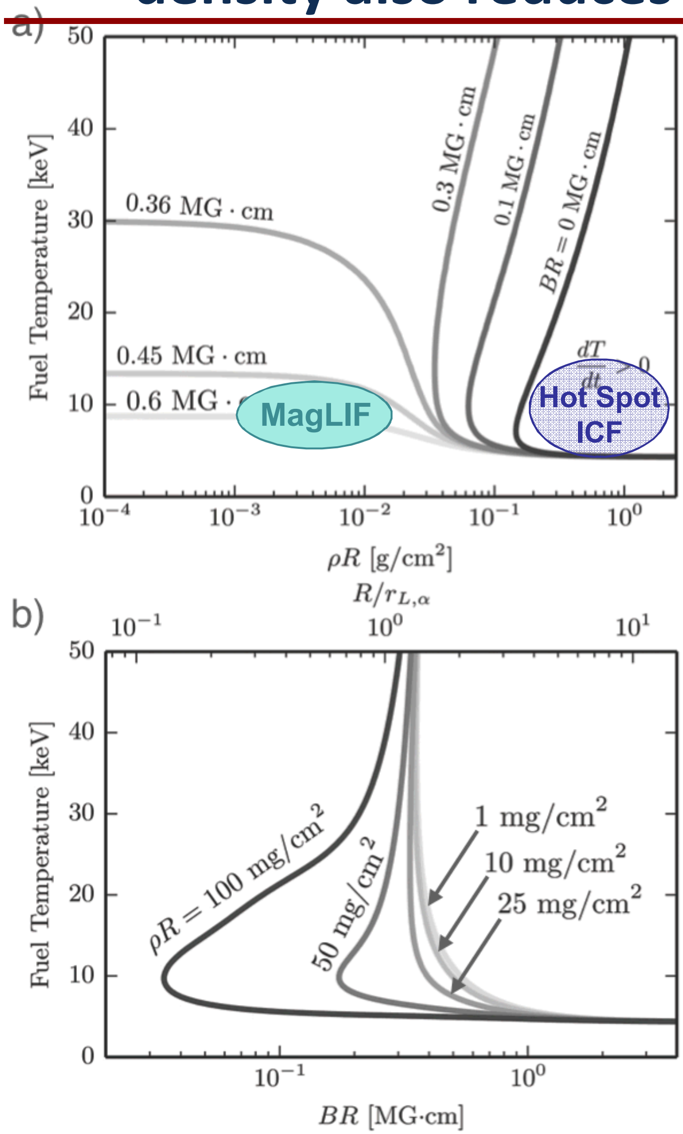
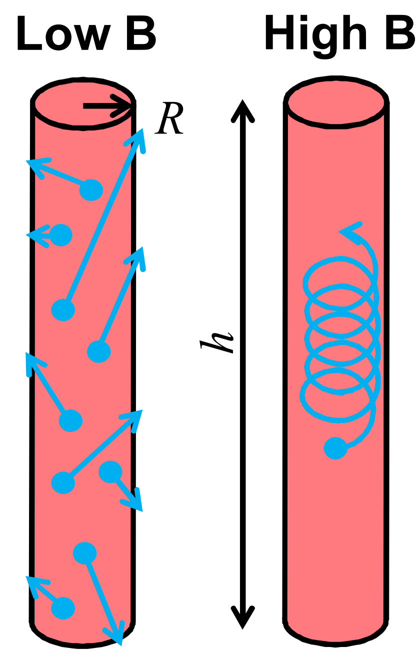


- **Initial 10-30 T field greatly amplified during the implosion through flux compression**
- **Too much field is inefficient—want to stagnate on plasma pressure, not magnetic pressure**



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

- **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**

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

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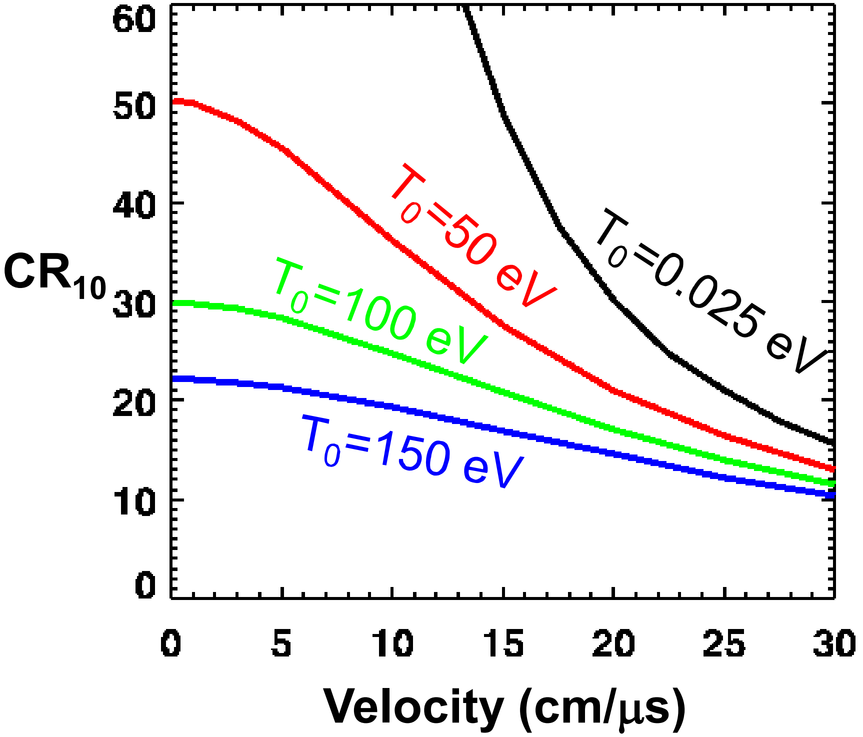
Simulation with:
- Constant velocity
- No radiation loss
- No conductivity loss



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

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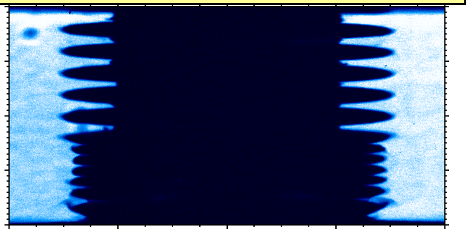
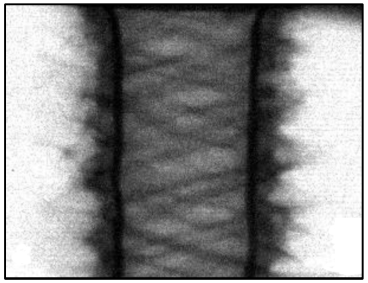
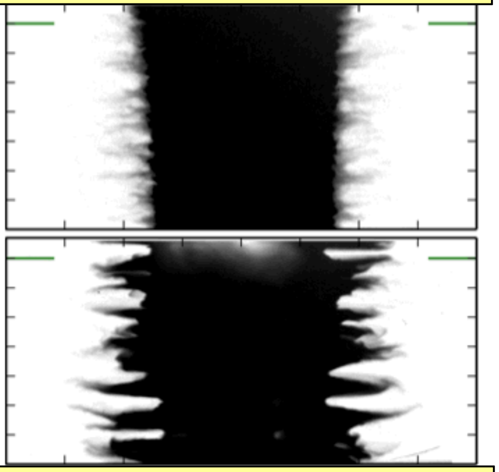
Single-mode magneto-Rayleigh-Taylor growth



Magnetized MRT growth

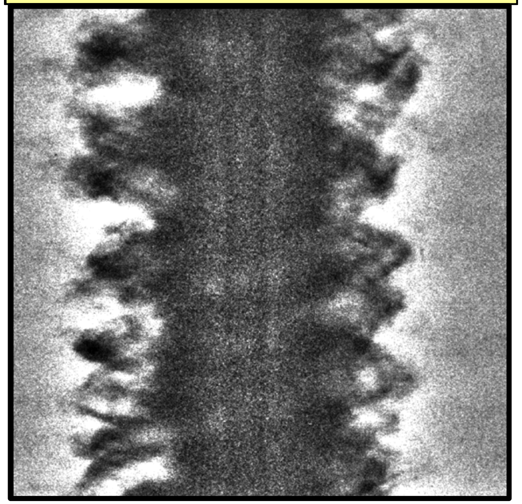


Dielectric-coated Al liner implosion

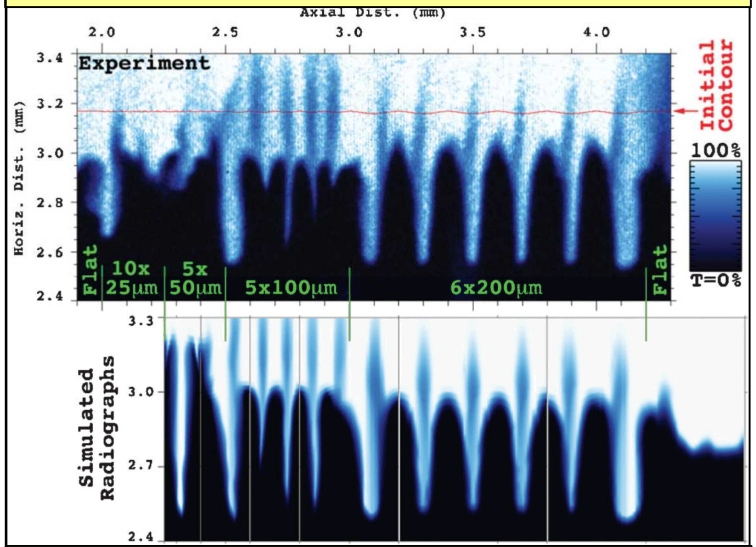


Uncoated

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



Experimental Data

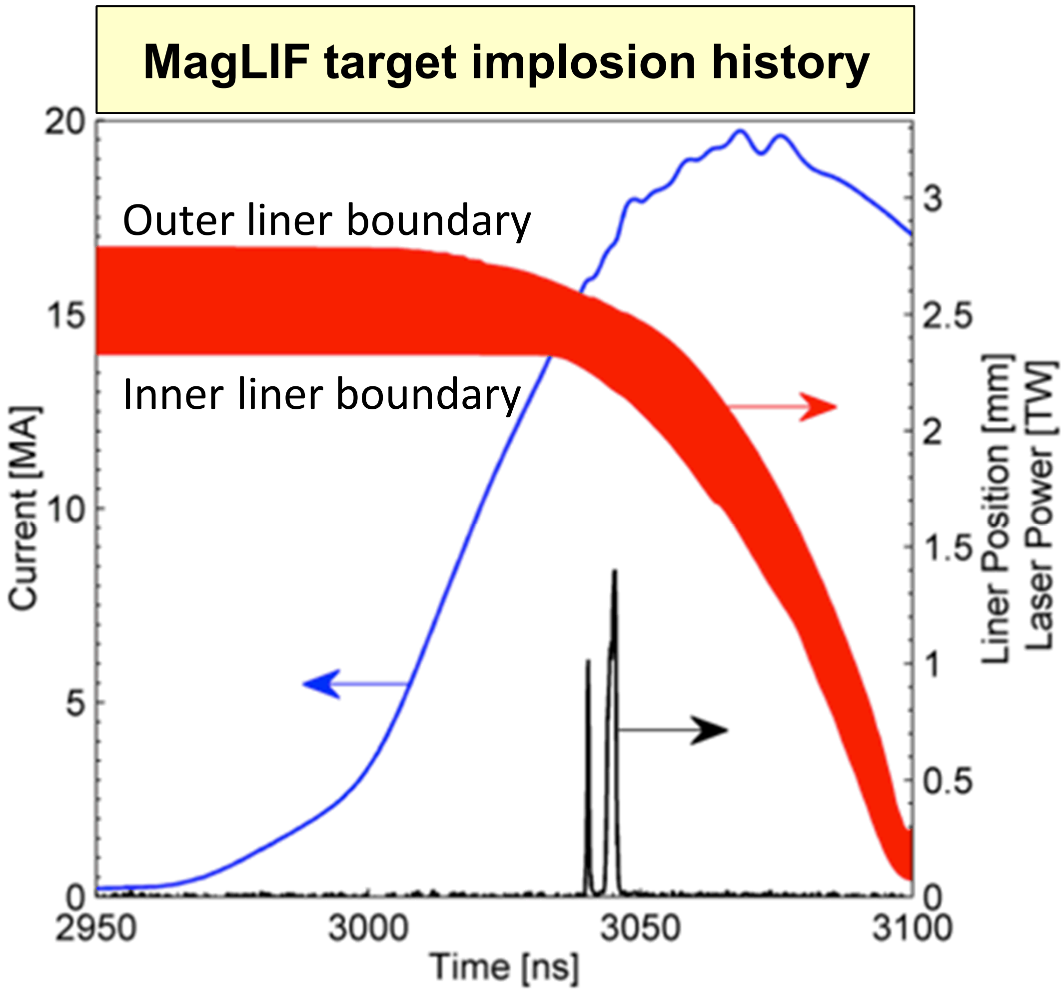


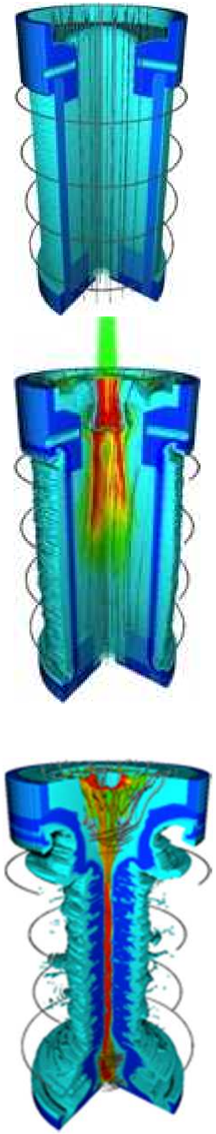
Simulated Data

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.*, submitted (2015).

We seek to understand the MagLIF plasma stages by studying the relevant physics on multiple facilities



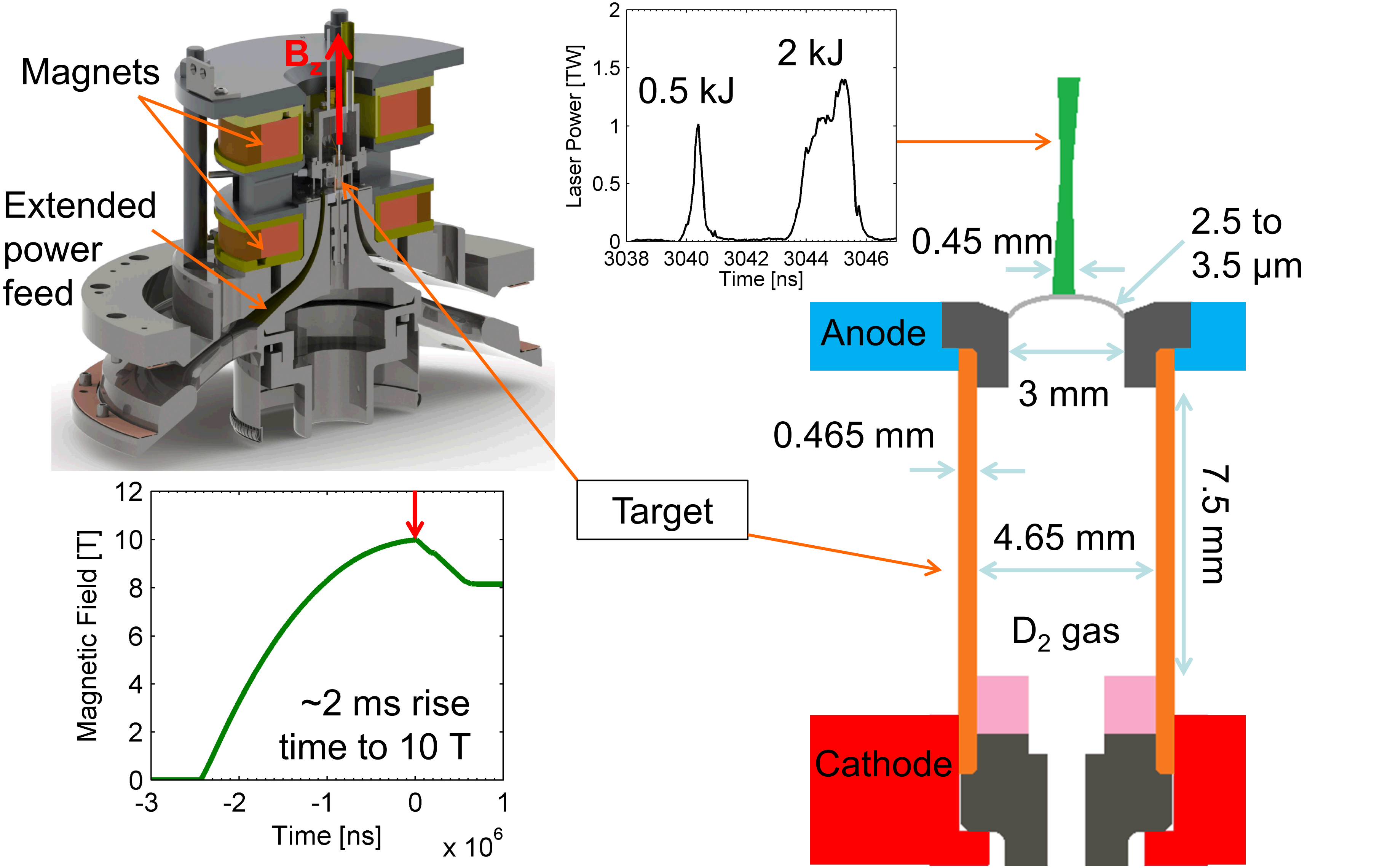


Initial Conditions
- Be liner
- ρ_{DT}~1-4 mg/cc
- B_{z0}~10-30 T (~0.1 MG)

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

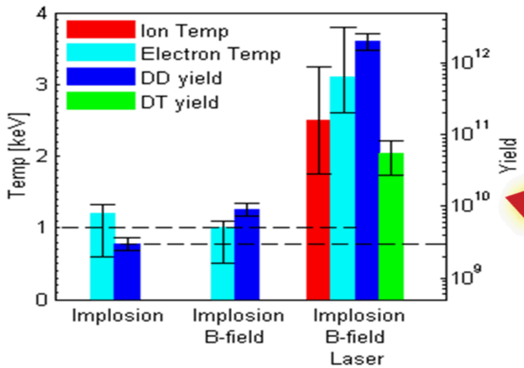
Implosion/stagnation
- V_{imp}~70-100 km/sec
- P_{DT} ~5 Gbar
- T_{ion} > 5 keV
- ωτ ~ 200 (B~100 MG)
- Research on Z, Omega, NIF (2016+)

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

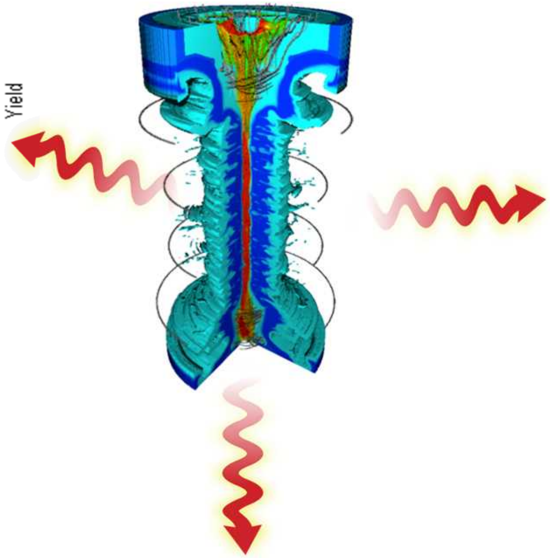


An ensemble of measurements from our first MagLIF experiments are consistent with a magnetized, thermonuclear plasma!

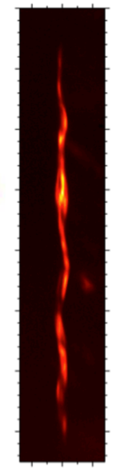
Nuclear Activation (yield)



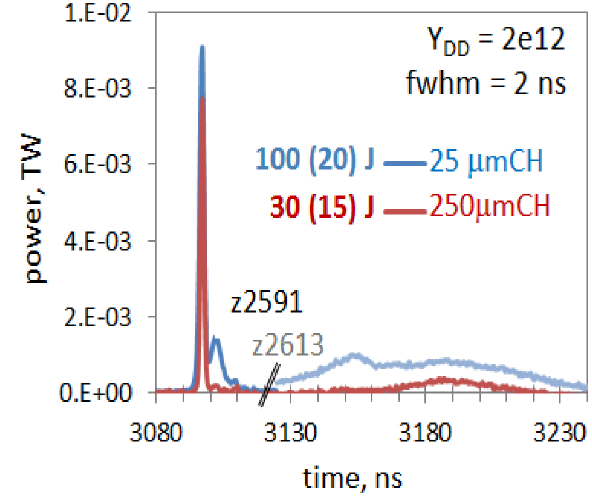
MagLIF Z pinch



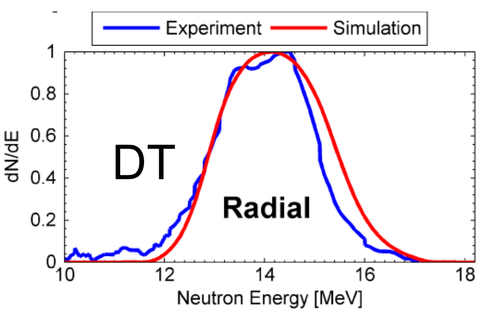
X-ray Imaging (hot plasma shape)

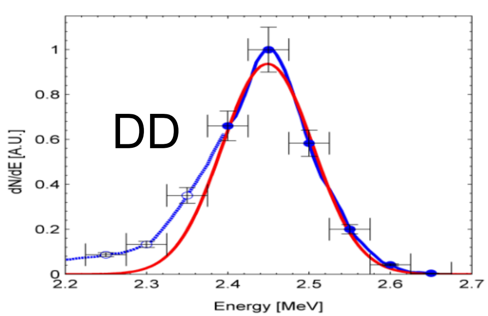


X-ray Power (duration)

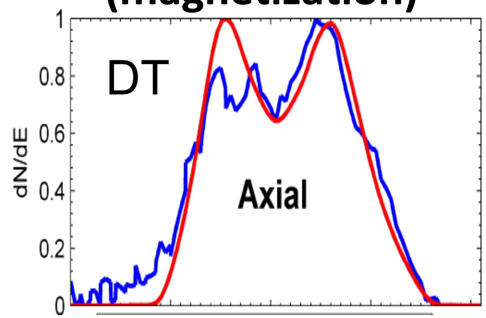


Neutron spectra (Tion)

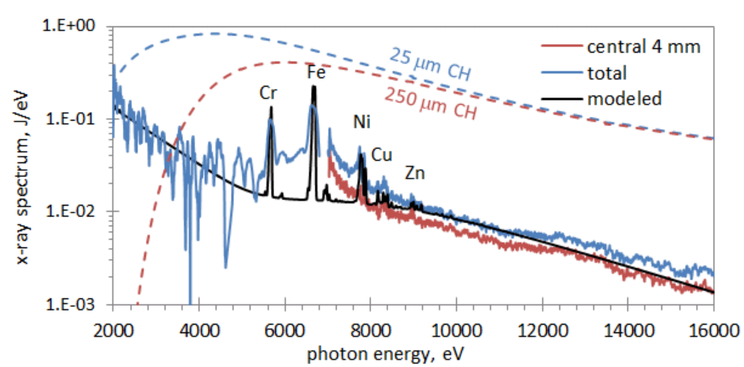




DT Neutron spectra (magnetization)



X-ray Spectra (Te, mix)



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Nuclear Activation (yield)

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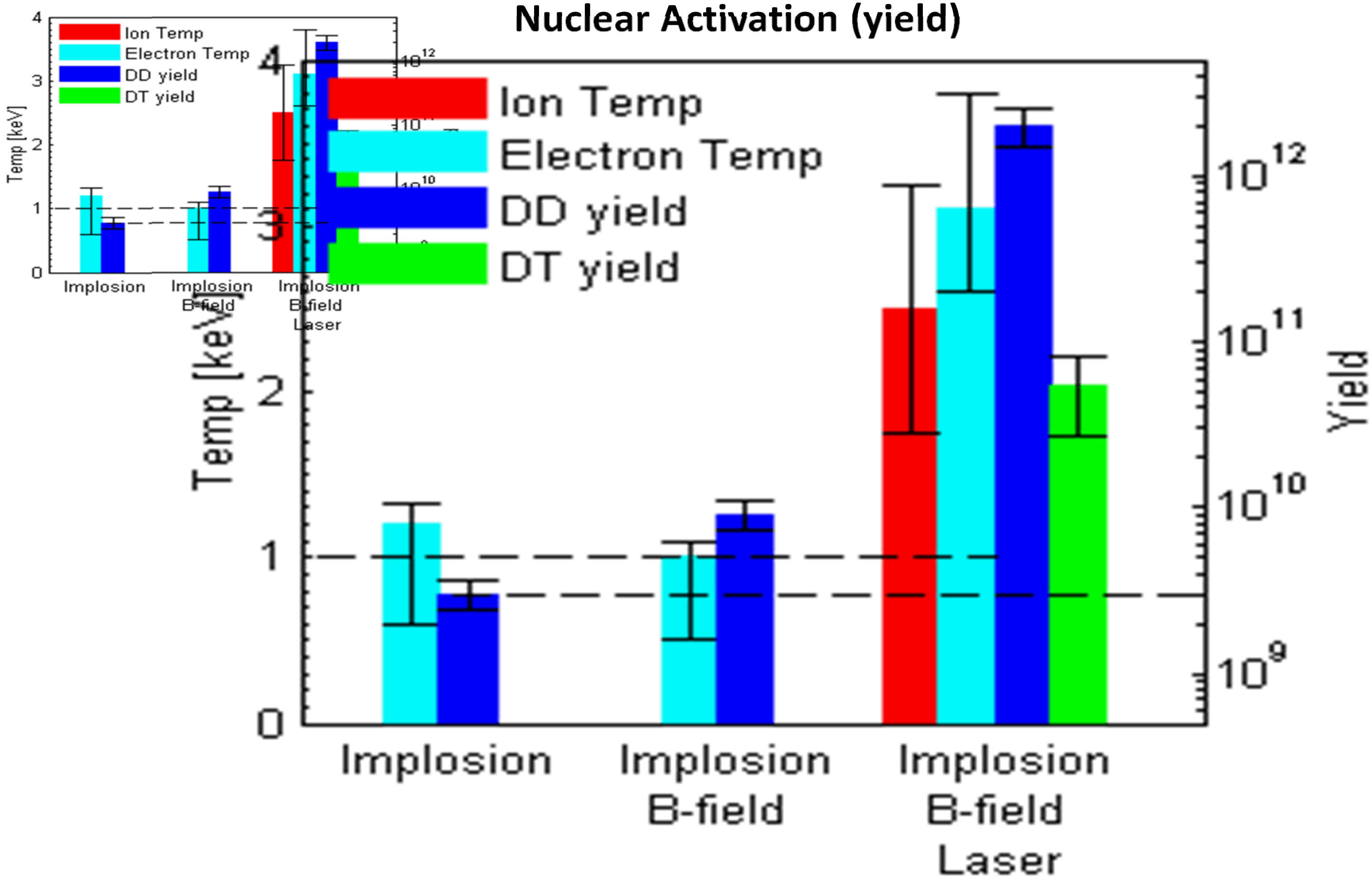

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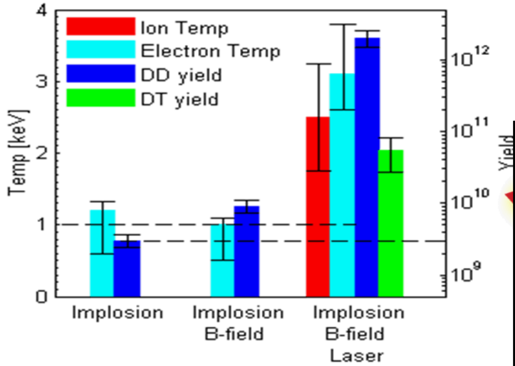
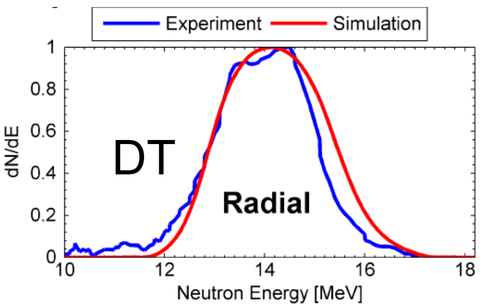
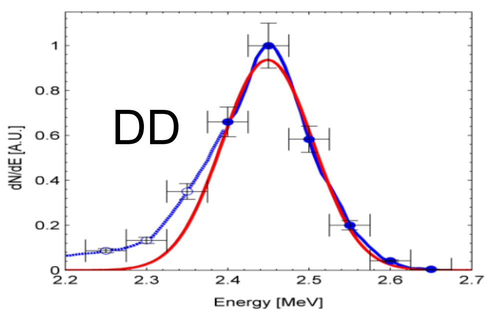
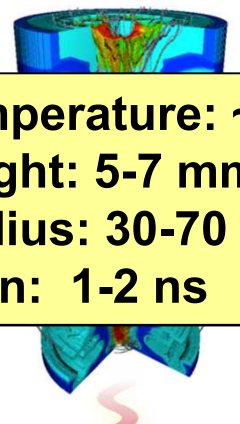


Neutron spectra (Tion)



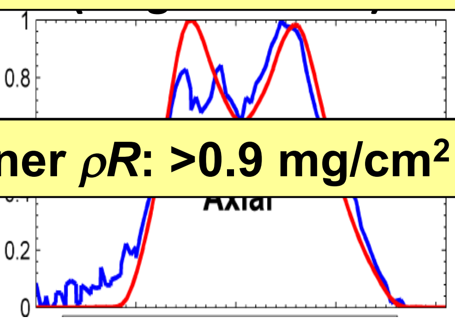


MagLIF Z pinch



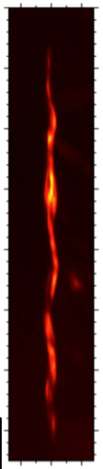
Temperature: ~3 keV
Height: 5-7 mm
Radius: 30-70 μm
Burn: 1-2 ns

Fuel ρ: 0.2-0.4 g/cm^3
Fuel ρR: ~1.5 mg/cm^2
Fuel ρz: ~150 mg/cm^2
Pressure: ~1 Gbar

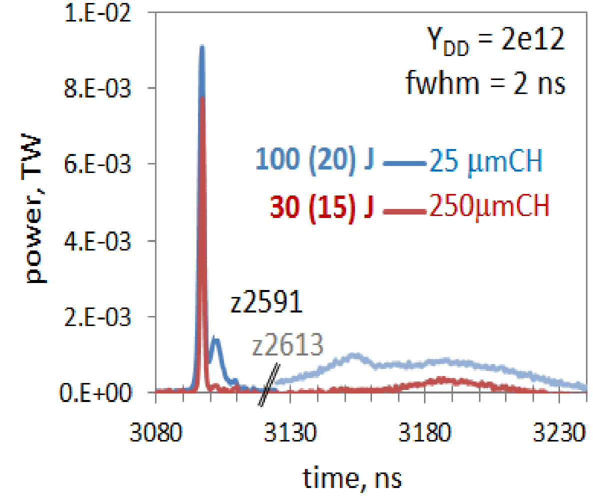


Liner ρR: >0.9 mg/cm^2

X-ray Imaging (hot plasma shape)



X-ray Power (duration)



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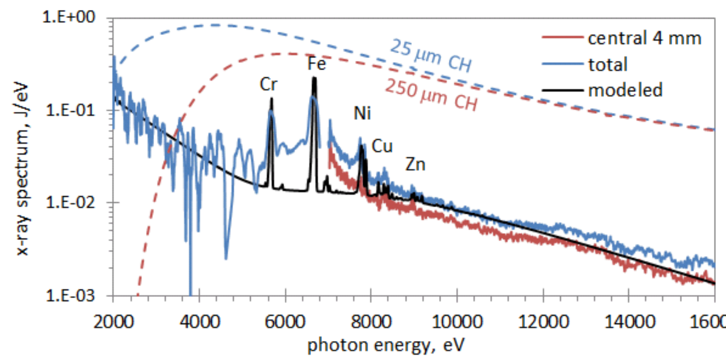

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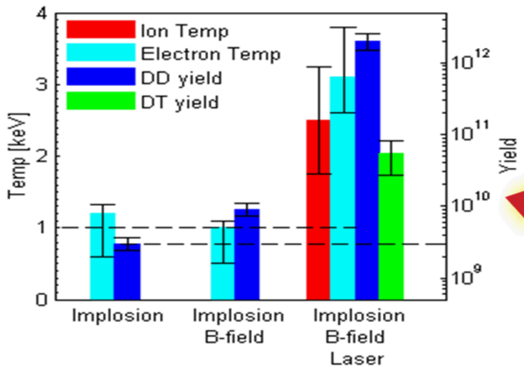
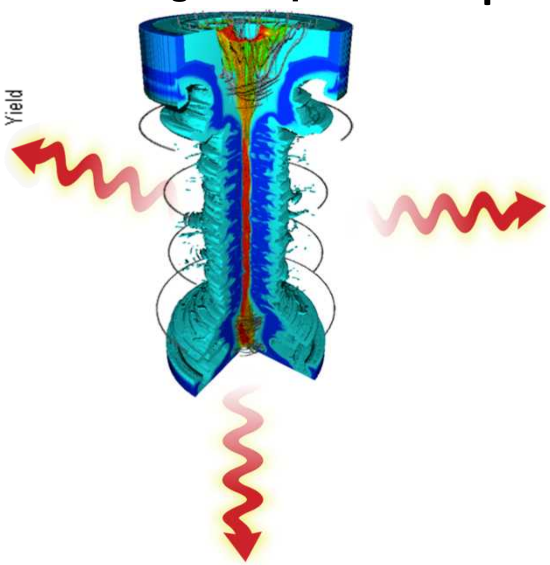


MagLIF Z pinch



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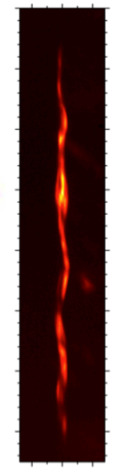
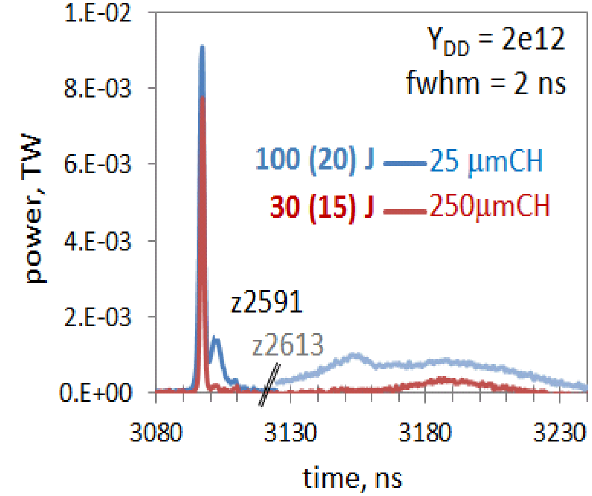


X-ray Power (duration)



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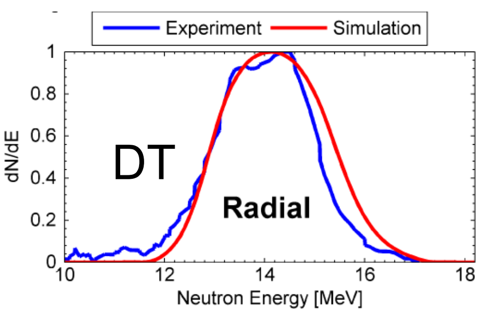

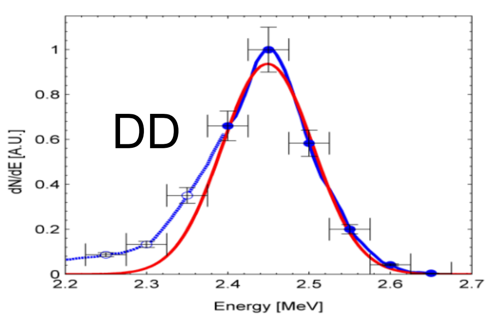

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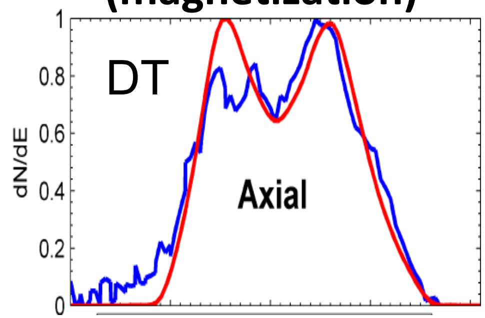

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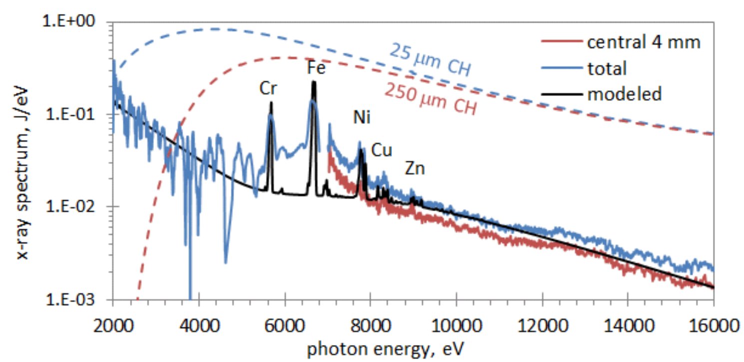

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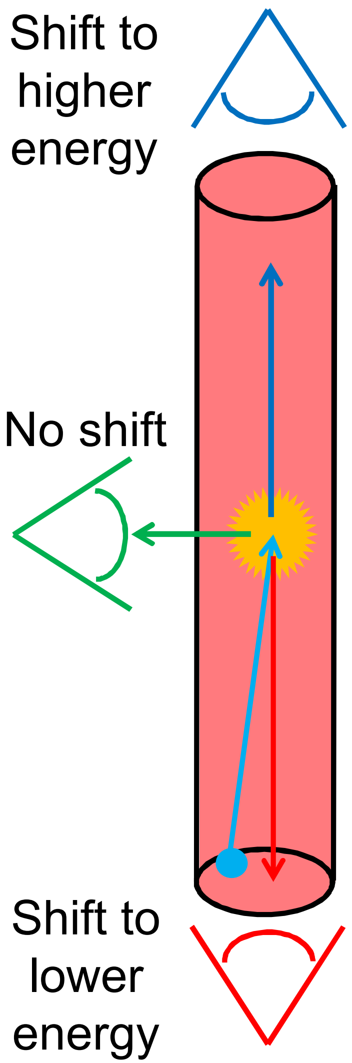
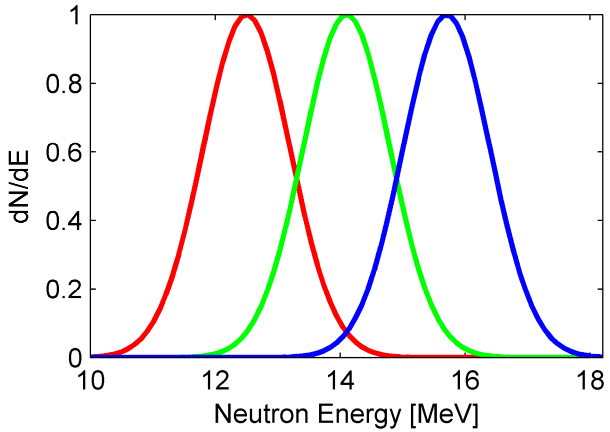
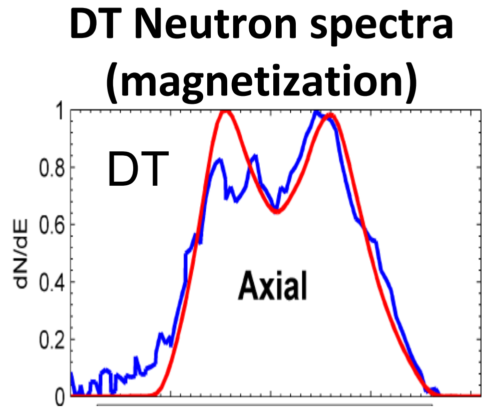
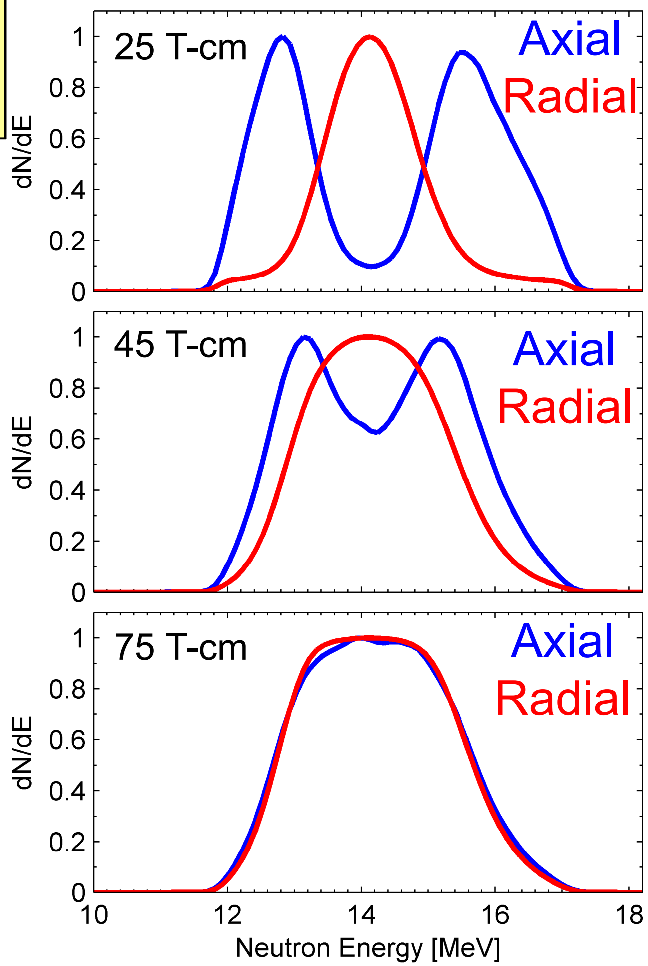


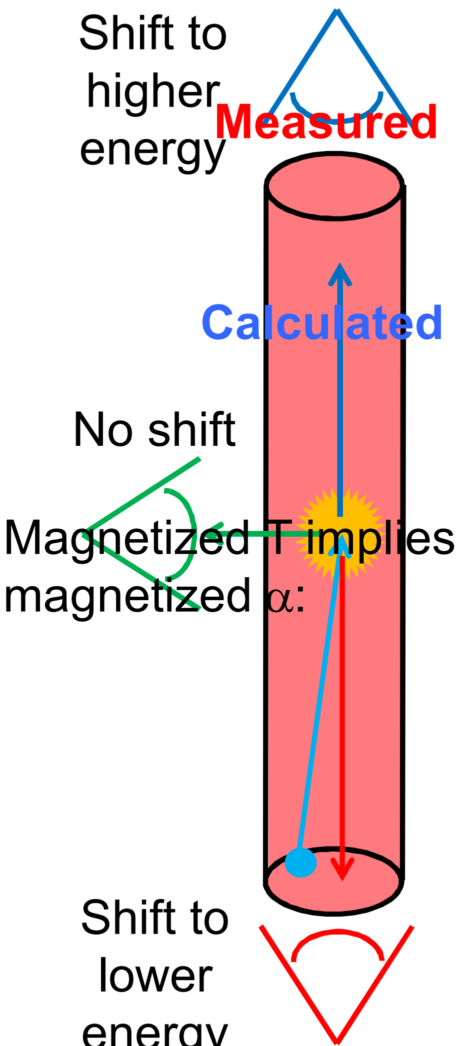
DT reactions primarily occur for tritons traveling along the Z axis



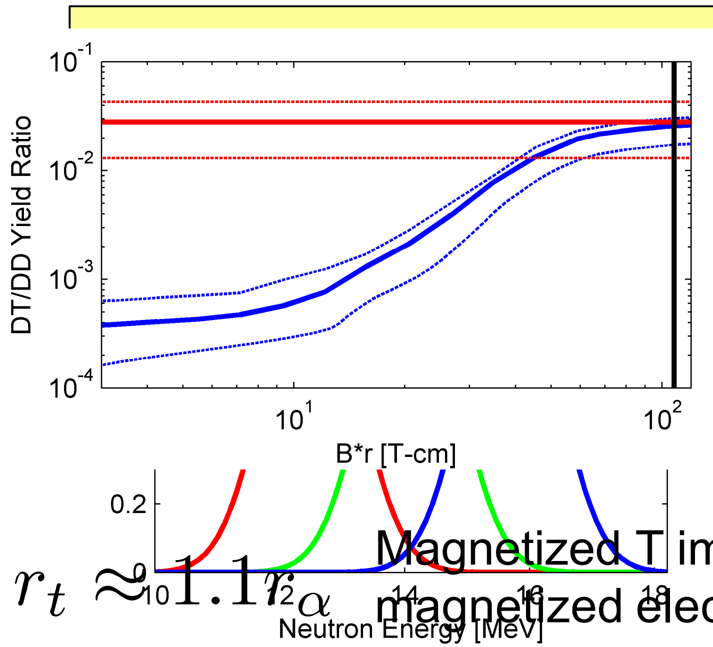




An ensemble of measurements from our first MagLIF experiments are consistent with a magnetized, thermonuclear plasma!

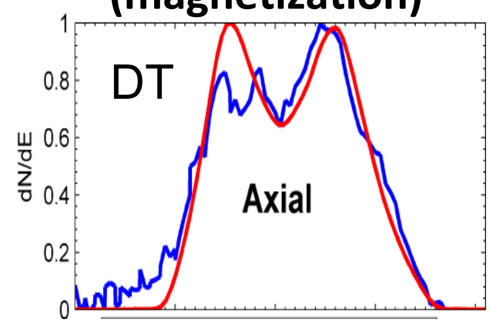


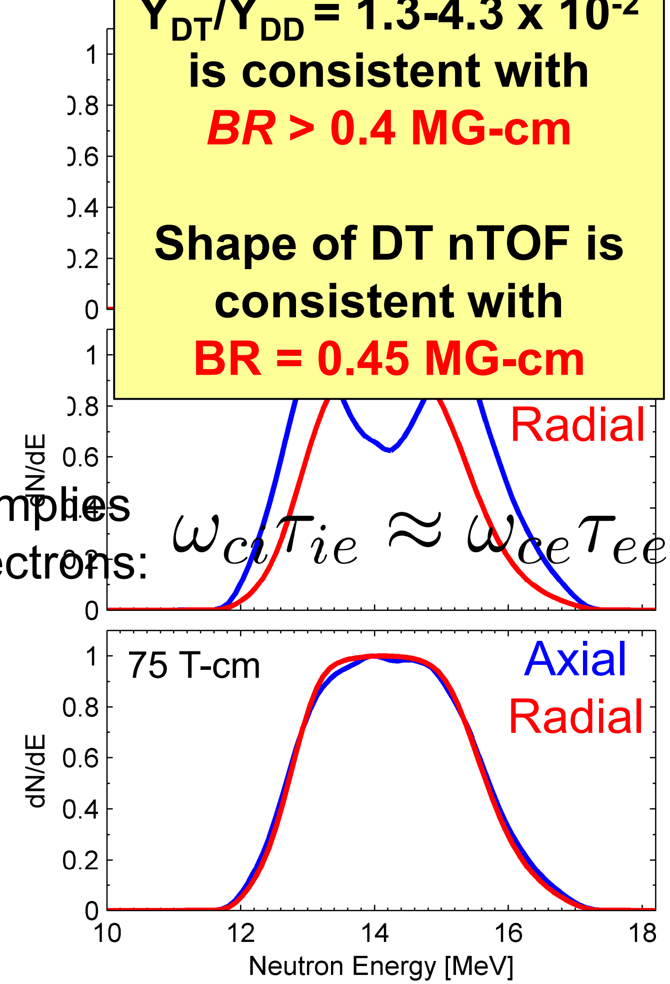
Magnetized T implies magnetized α: $r_t \approx 1.1 r_\alpha$



Magnetized T implies magnetized electrons: $\omega_{ci}\tau_{ie} \approx \omega_{ce}\tau_{ee}$

DT Neutron spectra (magnetization)



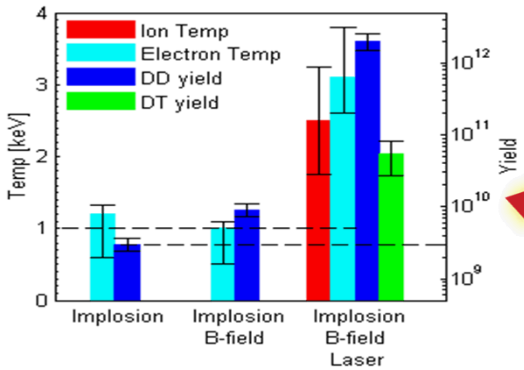


$Y_{DT}/Y_{DD} = 1.3\text{-}4.3 \times 10^{-2}$ is consistent with ***BR* > 0.4 MG-cm**

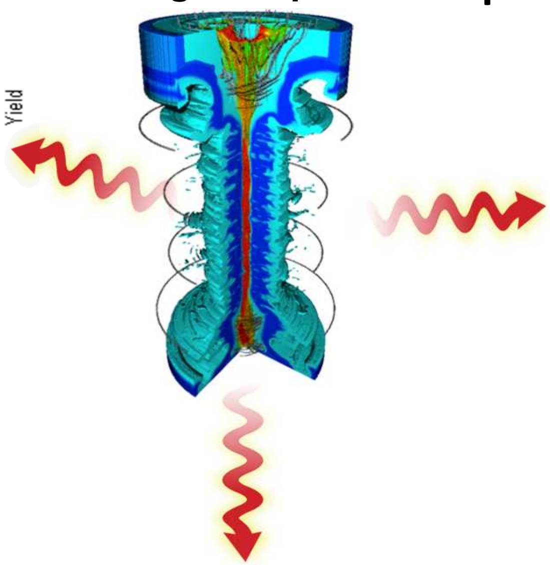
Shape of DT nTOF is consistent with BR = 0.45 MG-cm

Measurements from the first MagLIF experiments are consistent with a magnetized, thermonuclear plasma!

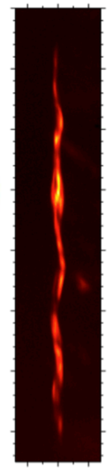
Nuclear Activation (yield)



MagLIF Z pinch

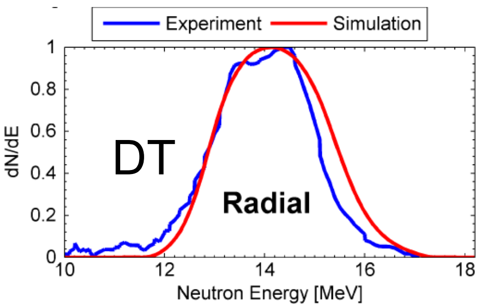


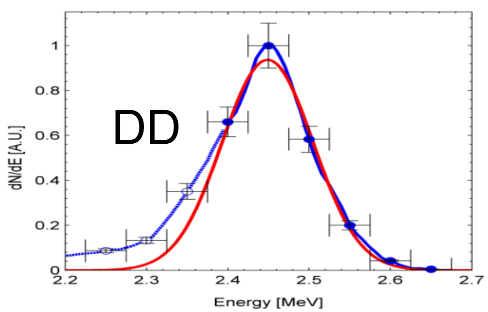
X-ray Imaging (hot plasma shape)



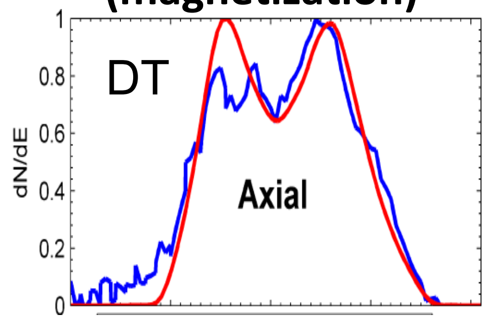
M.R. Gomez *et al.* PRL (2014).
P.F. Schmit *et al.*, PRL (2014).
P.F. Knapp *et al.*, PoP (2015).
M.R. Gomez *et al.*, PoP (2015).
S.B. Hansen *et al.*, PoP (2015).

Neutron spectra (Tion)

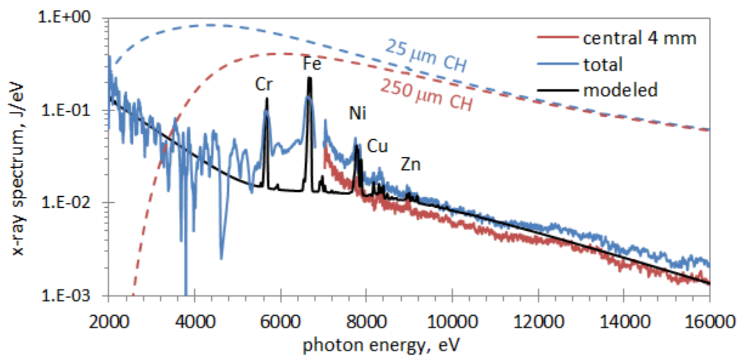




DT Neutron spectra (magnetization)



X-ray Spectra (Te, mix)



Lower than predicted coupling of laser energy to the fusion fuel was a leading hypothesis: Original MagLIF data can be modeled by assuming no mix and 200-300 J in fuel

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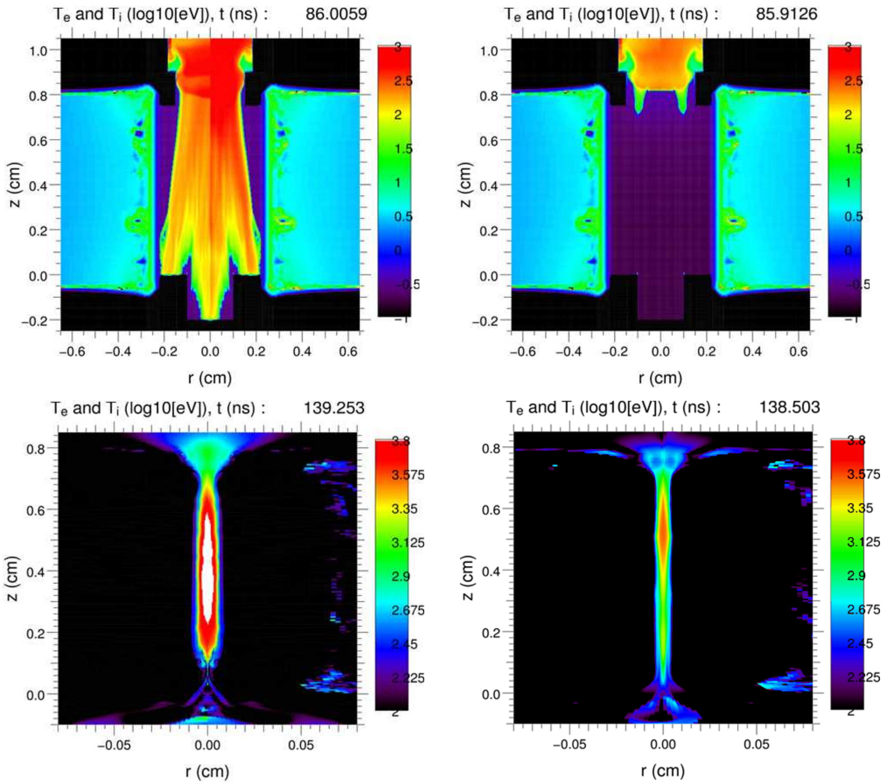
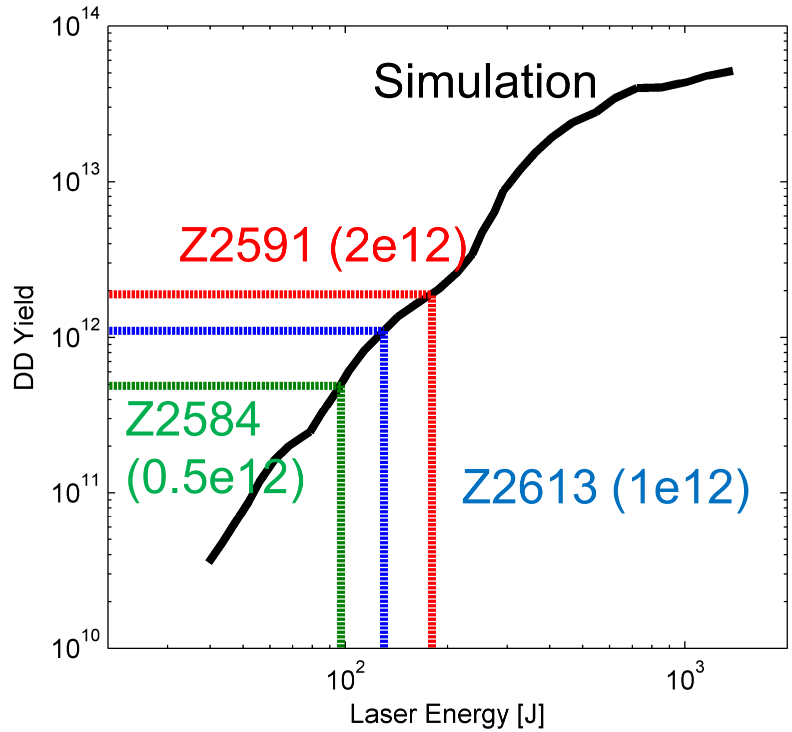
HYDRA Simulations

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.)

Laser-only experiments appear to confirm that laser-fuel coupling is a concern: Multiple measurements are consistent with low energy coupling (~10-20%)

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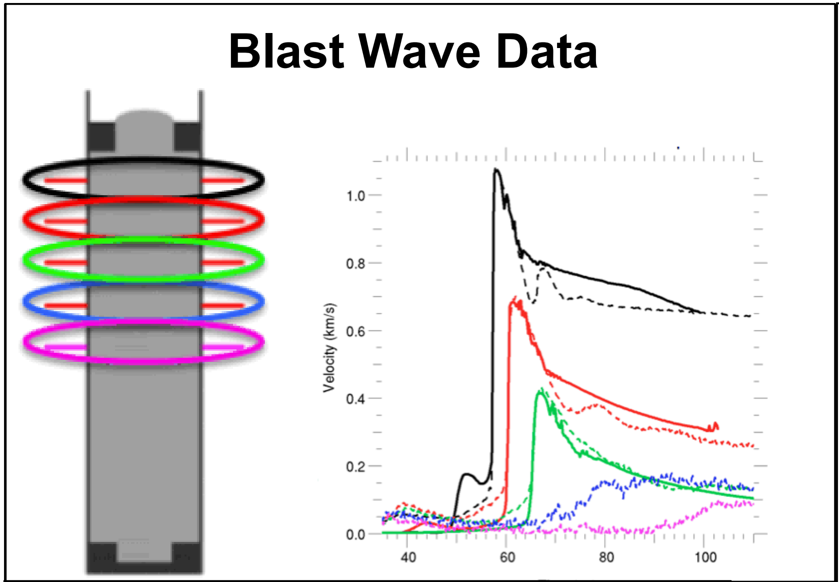
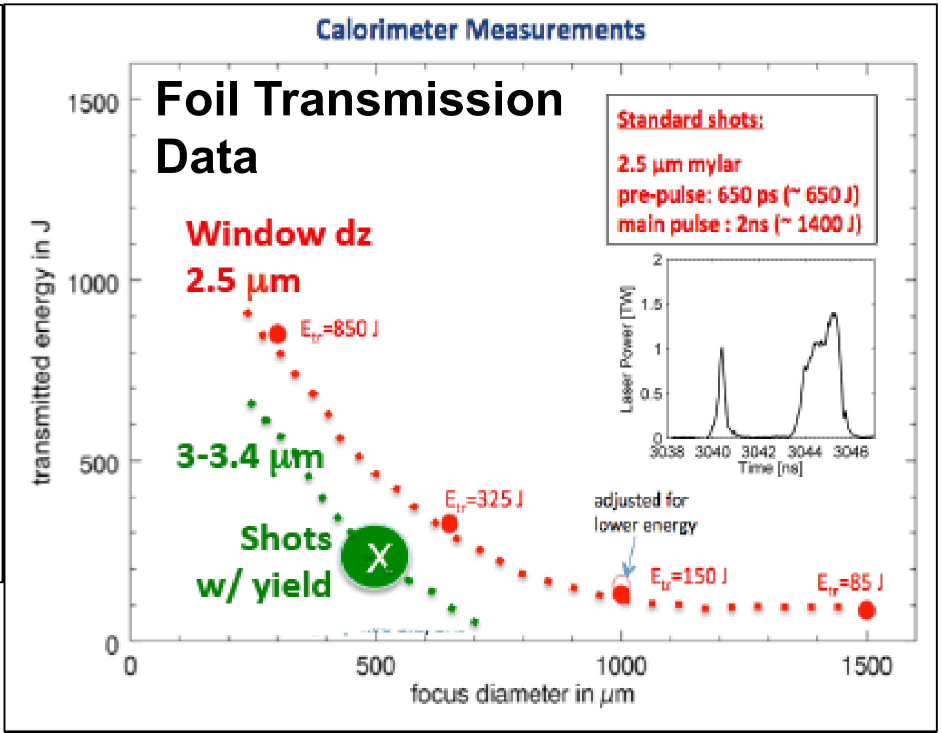
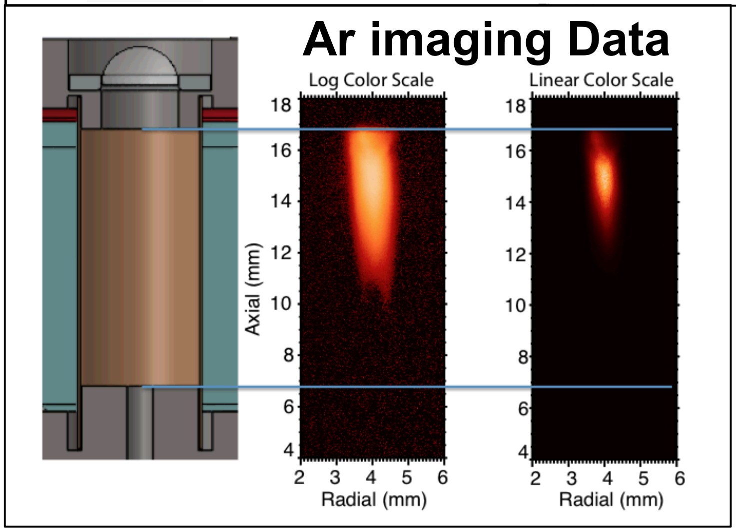
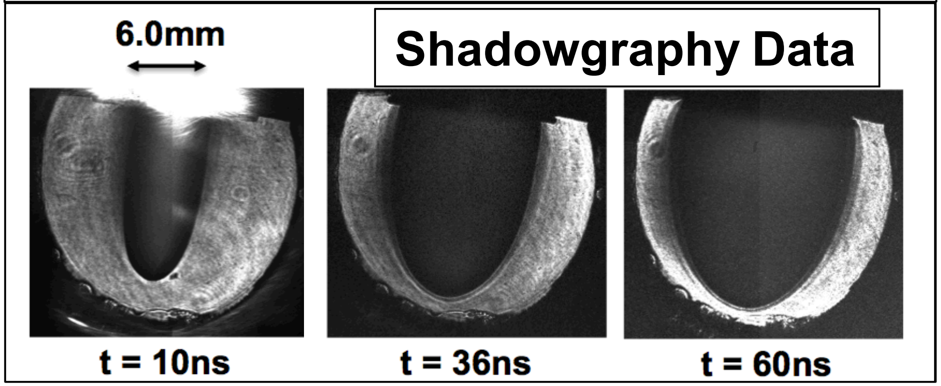


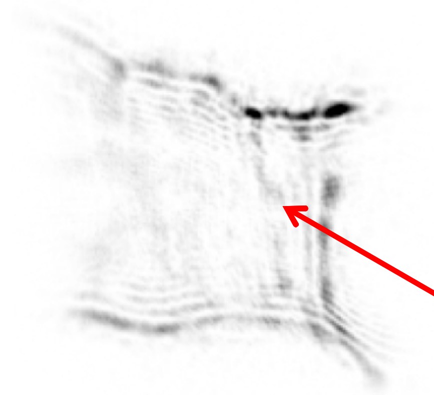






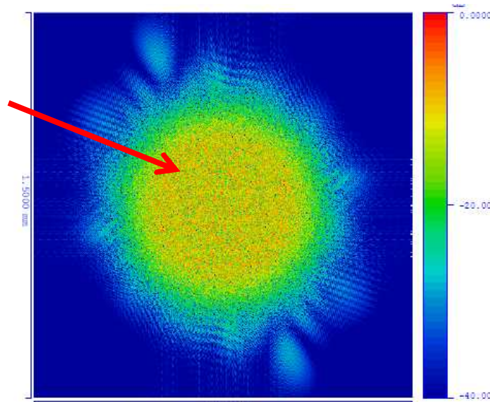
The Z-Beamlet beam spot quality is thought to be why we are not coupling as well to the fusion fuel as predicted

Z-Beamlet currently does not use any beam smoothing techniques adopted by the laser community

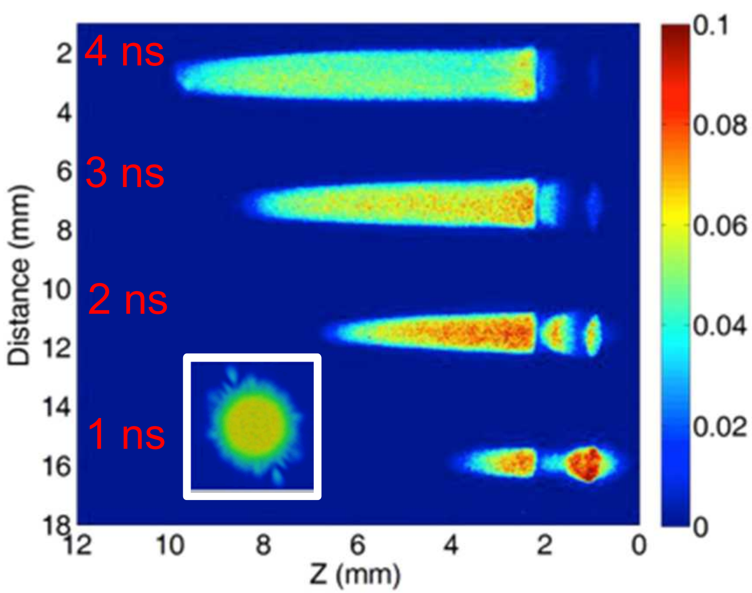


ZBL: No DPP (representative)

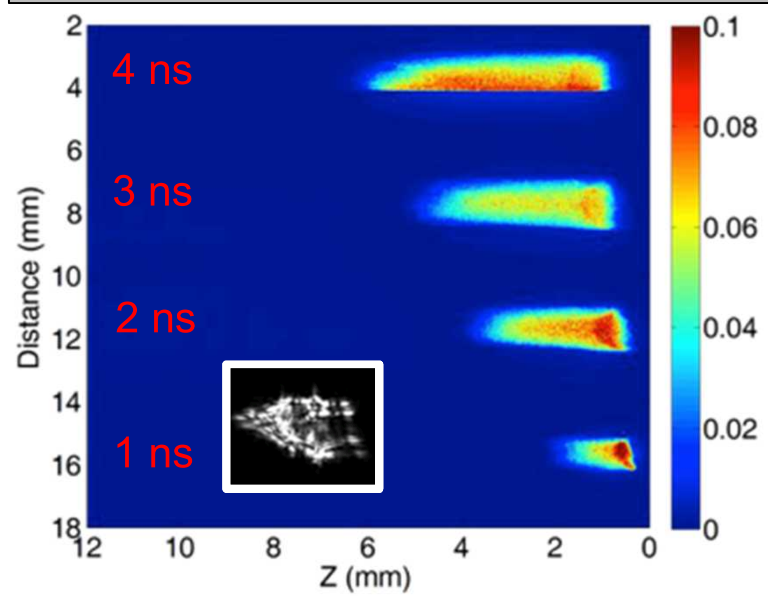
OMEGA-EP 750um DPP



4 ns/3.1 kJ, 2 μm LEH, no prepulse with DPP (SNL Omega-EP data)



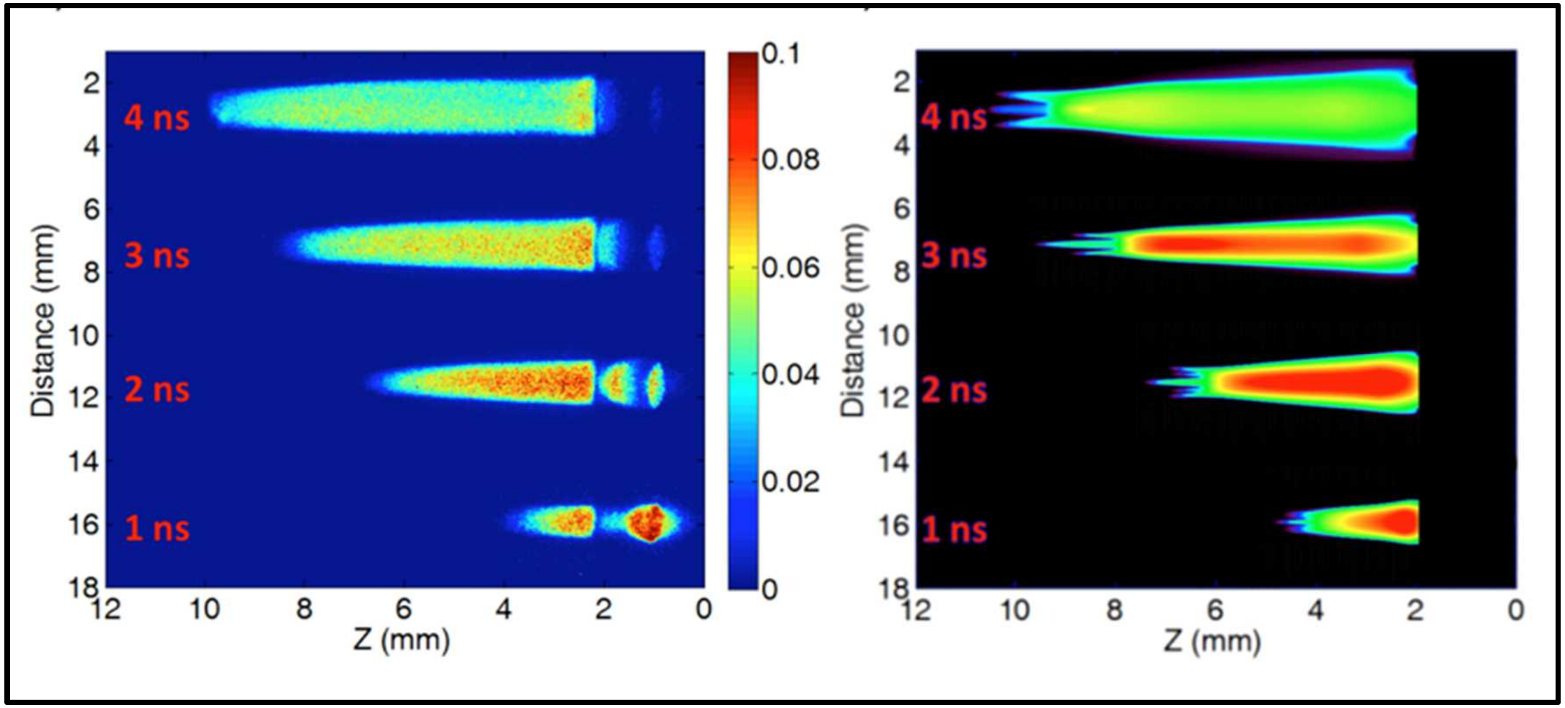
4 ns/2.93 kJ, 2 μm LEH, no prepulse without DPP (SNL Omega-EP data)



Our HYDRA simulations appear to be able to match the OMEGA-EP laser heating propagation when beam conditioning is used—testing at Z-Beamlet underway

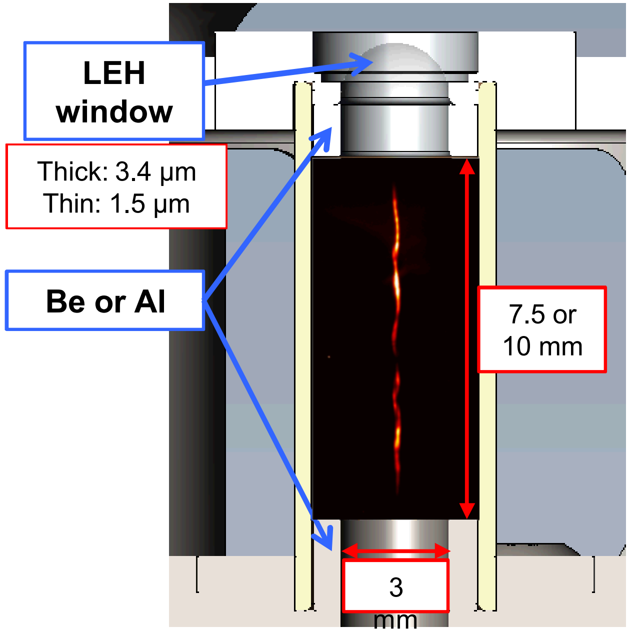
Pinhole Imaging Data

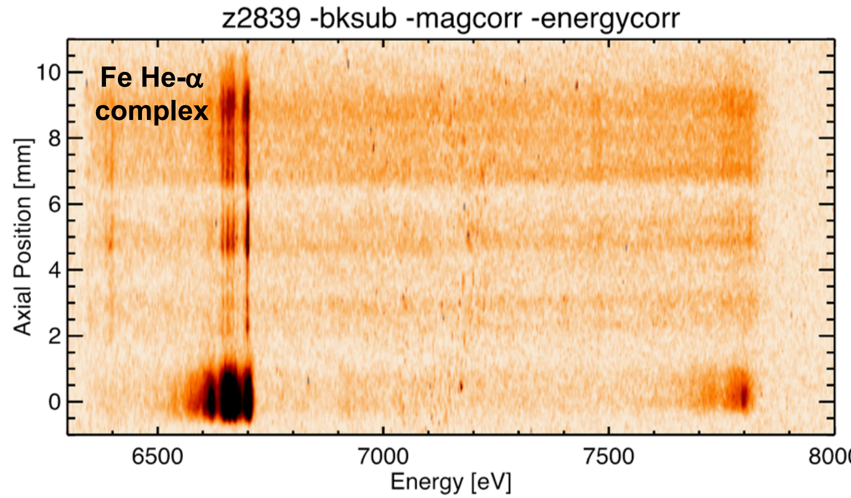
Simulated data from HYDRA



Data and analysis by A.J. Harvey-Thompson, A.B. Sefkow *et al.*
Submitted for publication in Physics of Plasmas

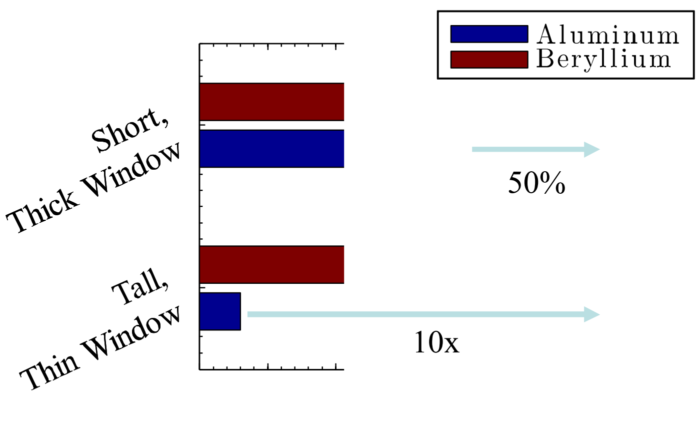
Recent experiments have isolated laser-induced mix as a key factor limiting performance with unconditioned beams





- Switching from Al to Be end caps improved the
 and thin window cases
natic in thin-window case
sibly due to increased laser

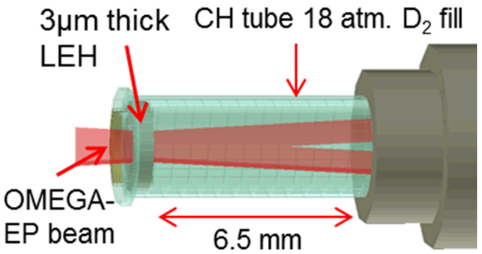
neter that allows us to
on which comes from Al
lso capture Ni, which is
only located in Be and not Al.

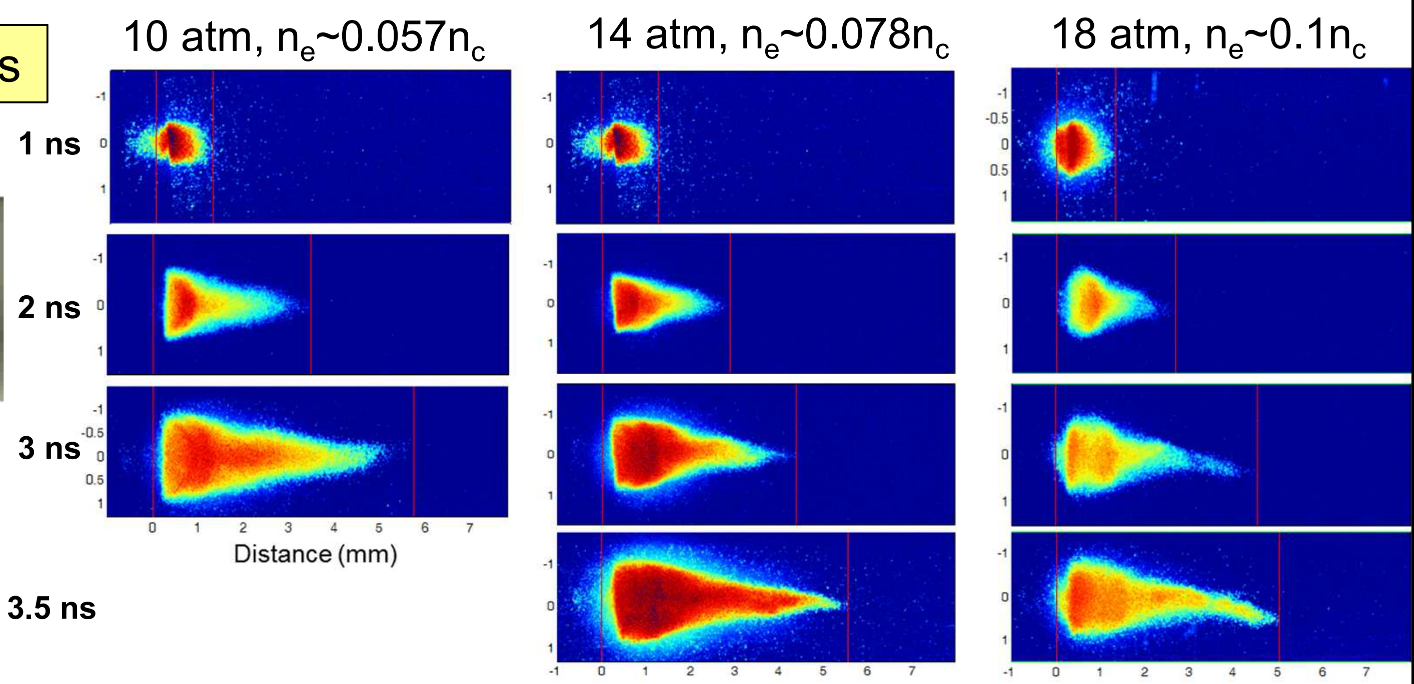


We are using OMEGA-EP experiments to systematically test laser heating of underdense plasmas

July 2015 experiments tested effect of D_2 gas fill density on beam propagation in magnetized (5T) targets

View for XRFC images

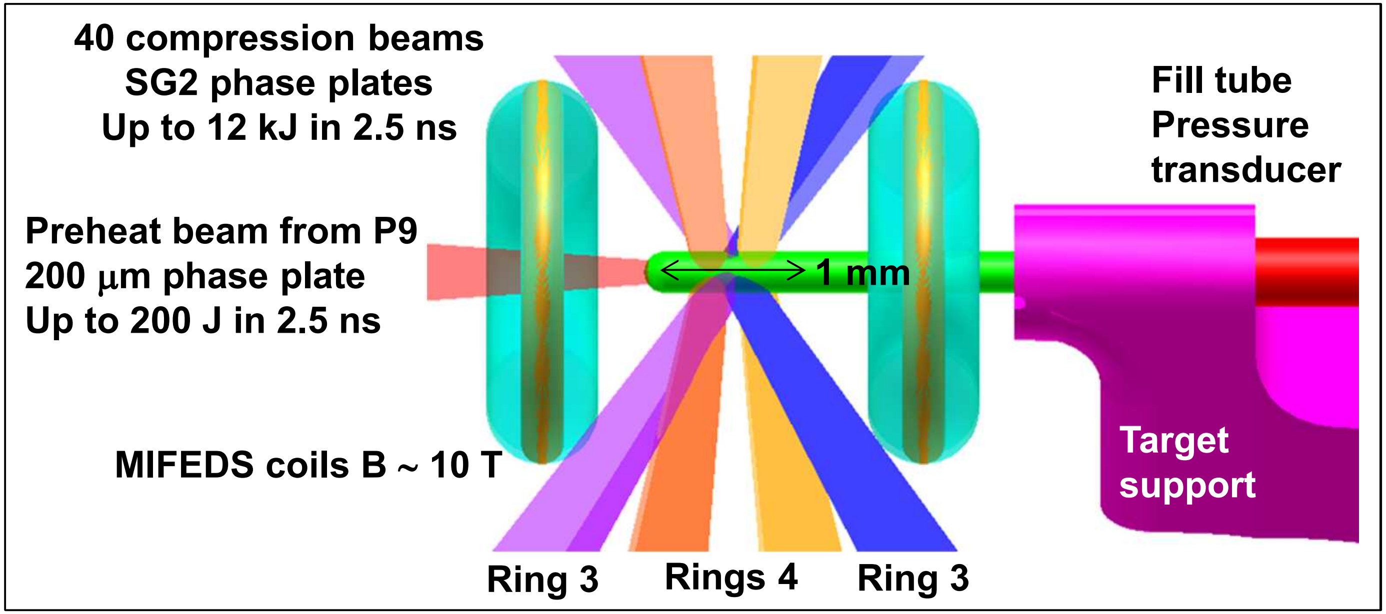




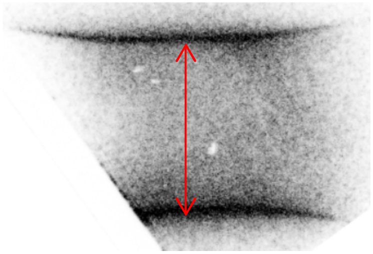
- Beam propagation appears to bend for higher densities (n_e=0.1n_c)
- Multiple shots per day possible – dataset gives a robust test for codes, identifies where models are no longer valid

A. Harvey-Thompson, Mo.0.5.3; T. Nagayama, Mo.Po.48

A point design for laser-driven MagLIF on OMEGA has been developed and will be refined in the next two years



X-ray image of compression

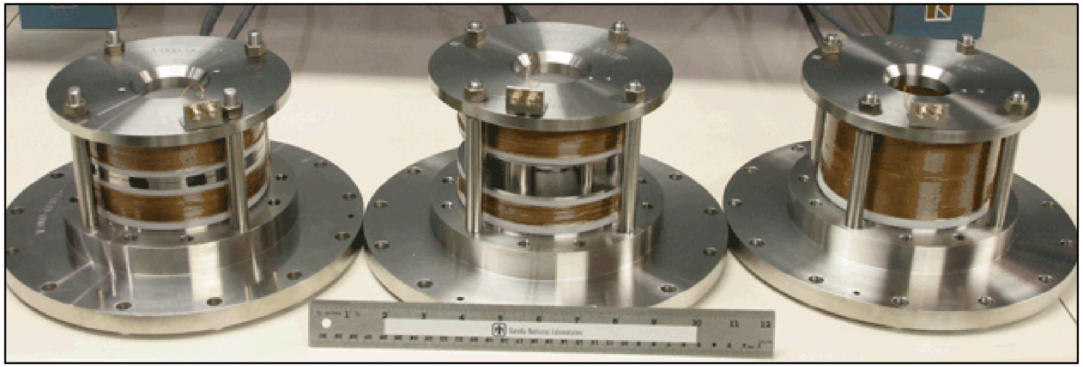


Parylene-N Target

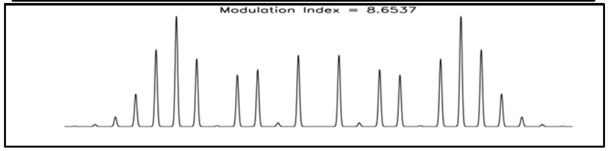
Outer diameter:	600 μm	D_2 fill density:	1 – 2.1 mg/cc
Shell thickness:	30 μm	Preheat temperature:	≥ 100 eV
Compressed length:	600 – 700 μm		

- 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 are now optimizing the axial uniformity and compressed length

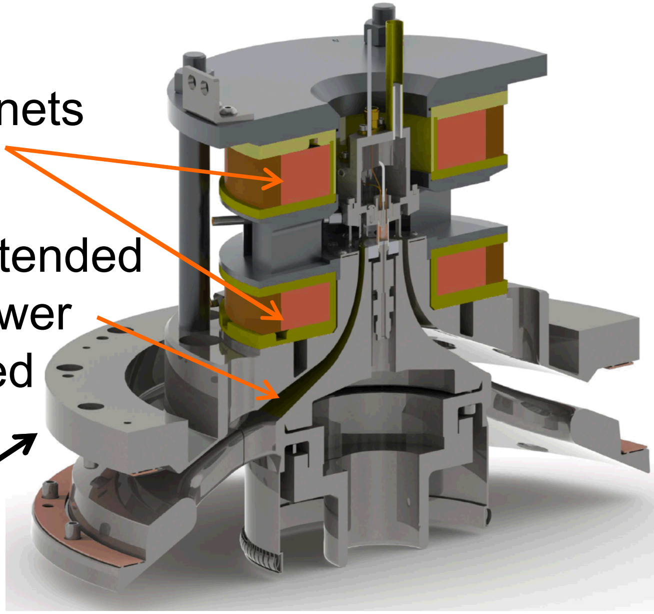
To meet our 5-year goal of demonstrating P-tau>5 Gbar-ns and BR>0.5 MG-cm in a continuous cylindrical plasma, we are working to increase the available drive conditions.



Increase B-field from 10 T to 30 T



Increase laser energy from 2 kJ to 6-10 kJ; Install phase plates



Increase current from 19 MA to ~25 MA (Z facility upgrades; load hardware optimization)

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.

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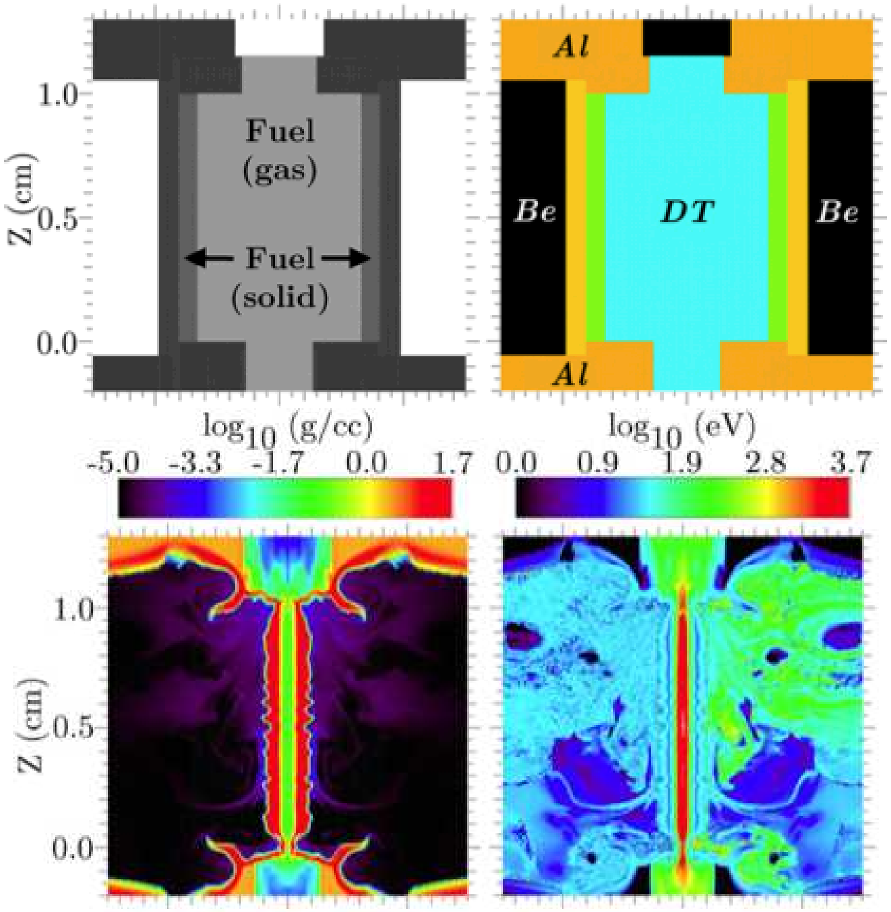
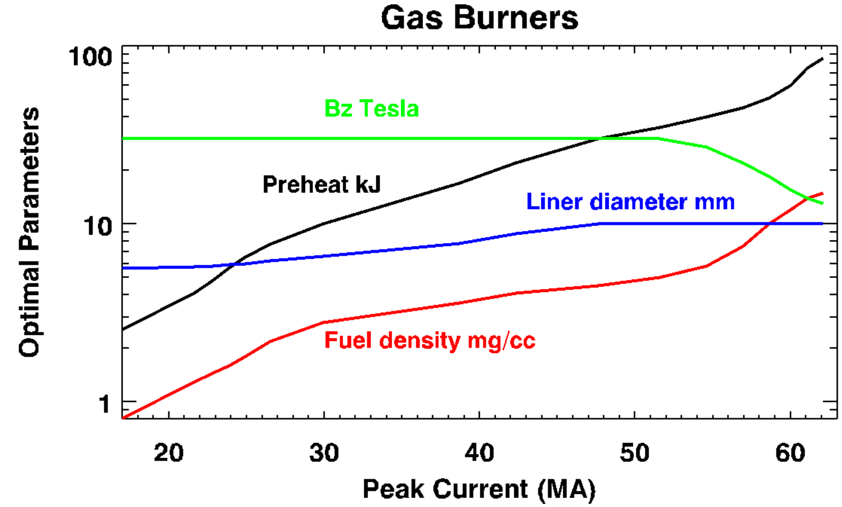
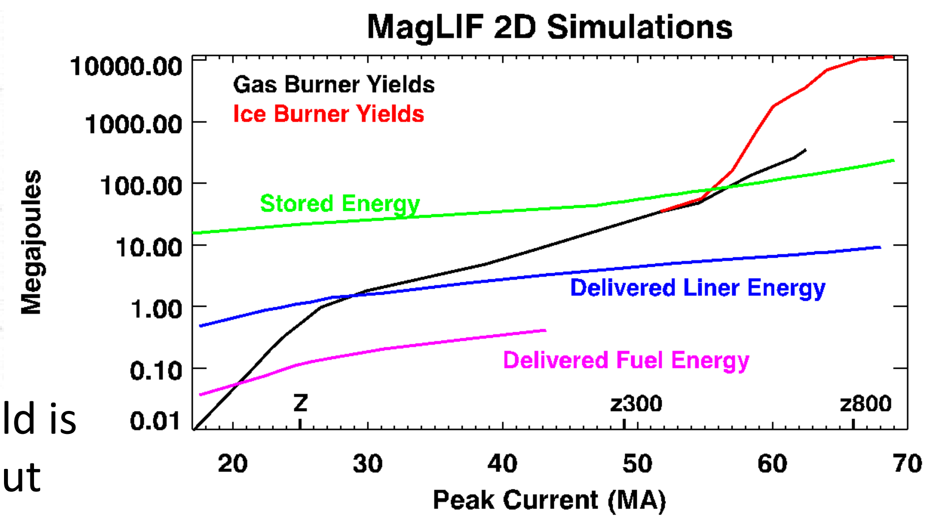






An intermediate regime exists wherein the B_z field is

- *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

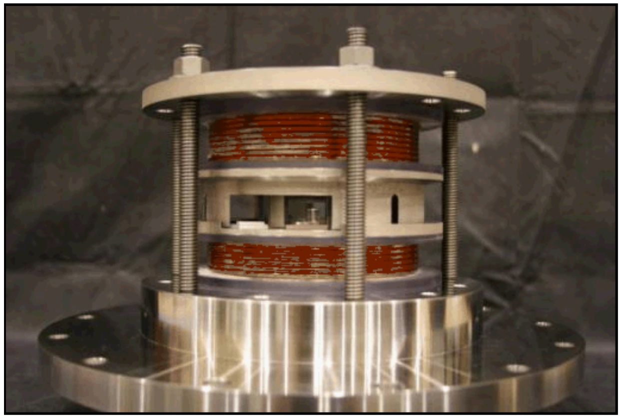
- The initial MagLIF experiments demonstrated that there is merit to the idea of magneto-inertial fusion
- Laser heating of a magnetized initial plasma with minimal high-Z mix is critical
  - Initial experiments used “unconditioned” beams and thick (>3 μm) foils and deposition into the gas was lower 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

Questions?

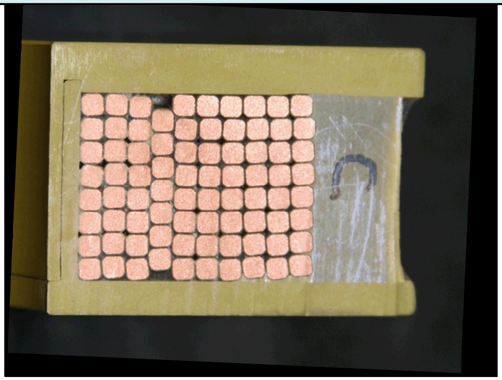
We have successfully implemented 10-30 T axial fields over a several cm³ volume and several ms for MagLIF

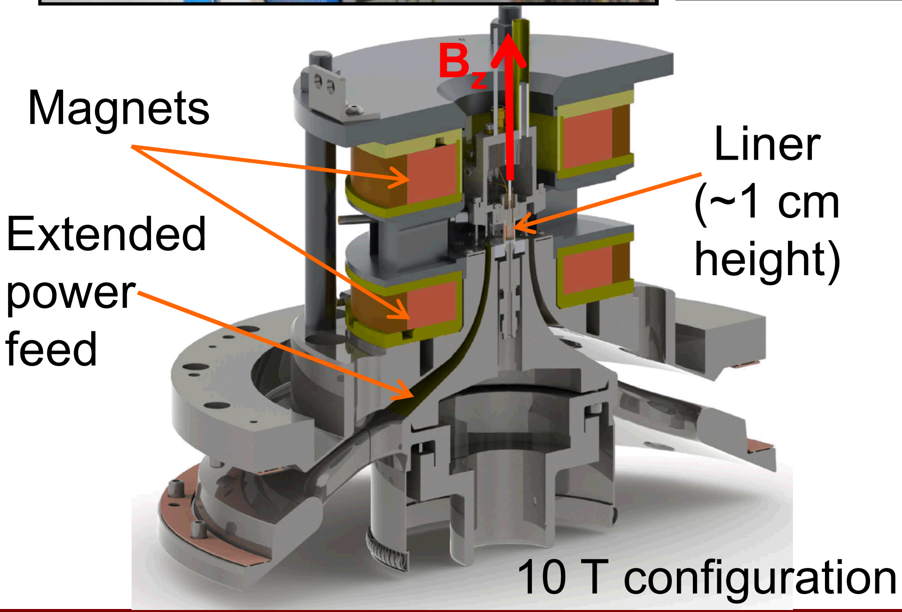
Capacitor bank system on Z
900 kJ, 8 mF, 15 kV (Feb. 2013)

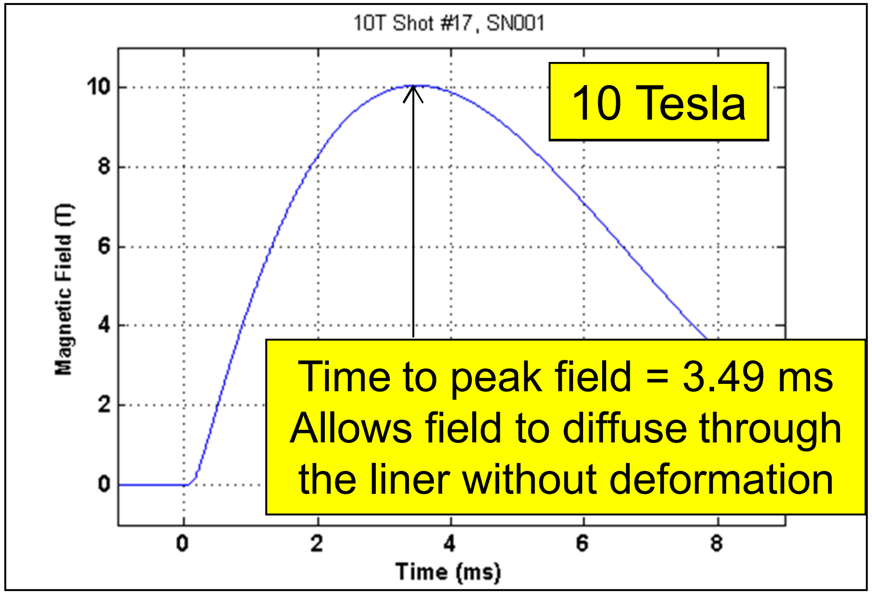
Example MagLIF coil assembly with copper windings visible



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







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

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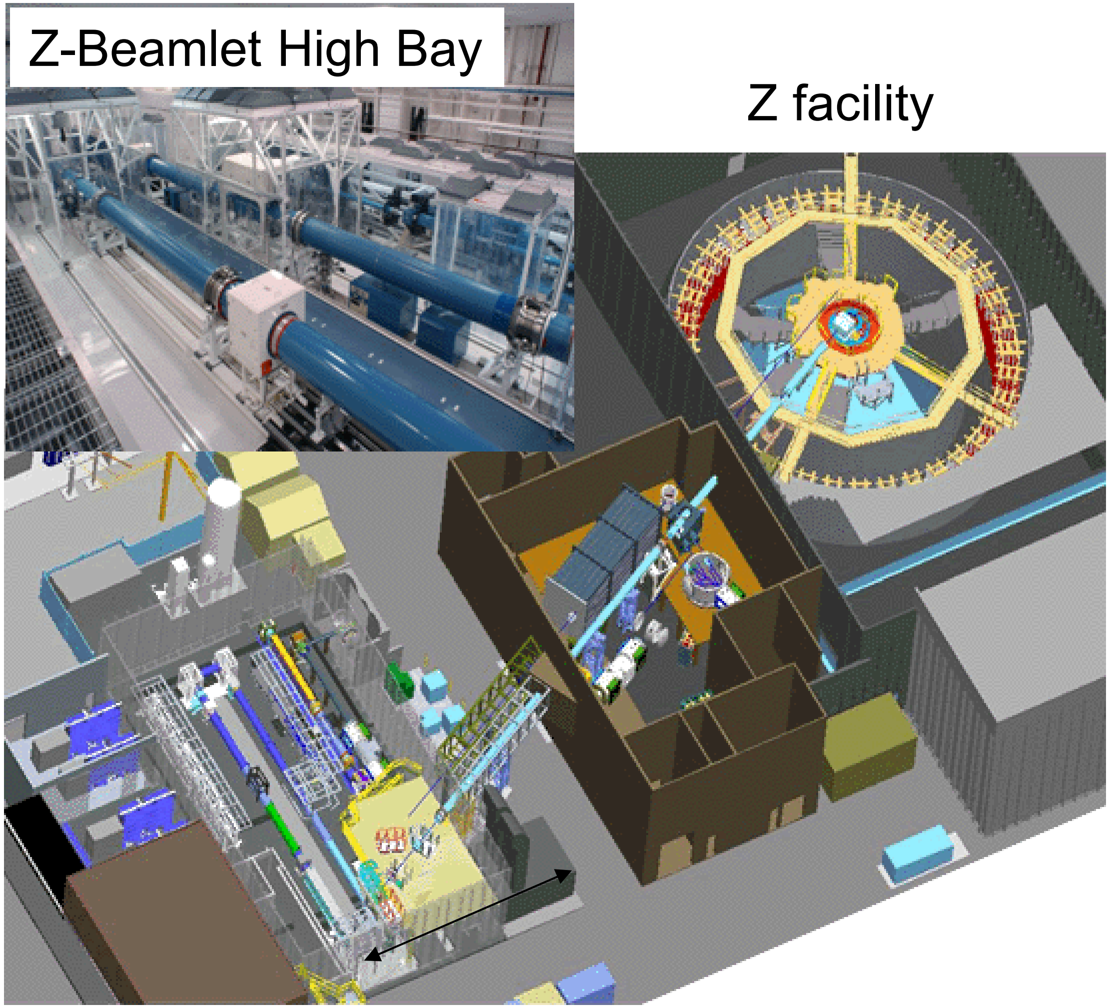

Z-Beamlet and Z-Petawatt lasers

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).

In August 2013 we commissioned a new vacuum final optics assembly to safely enable 2 kJ of on-axis laser heating of fuel

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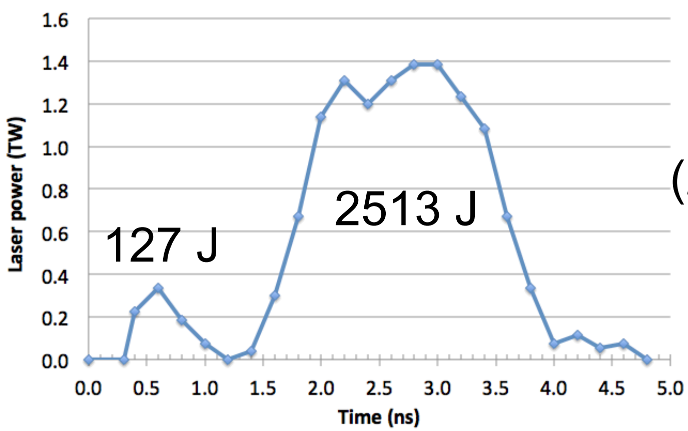
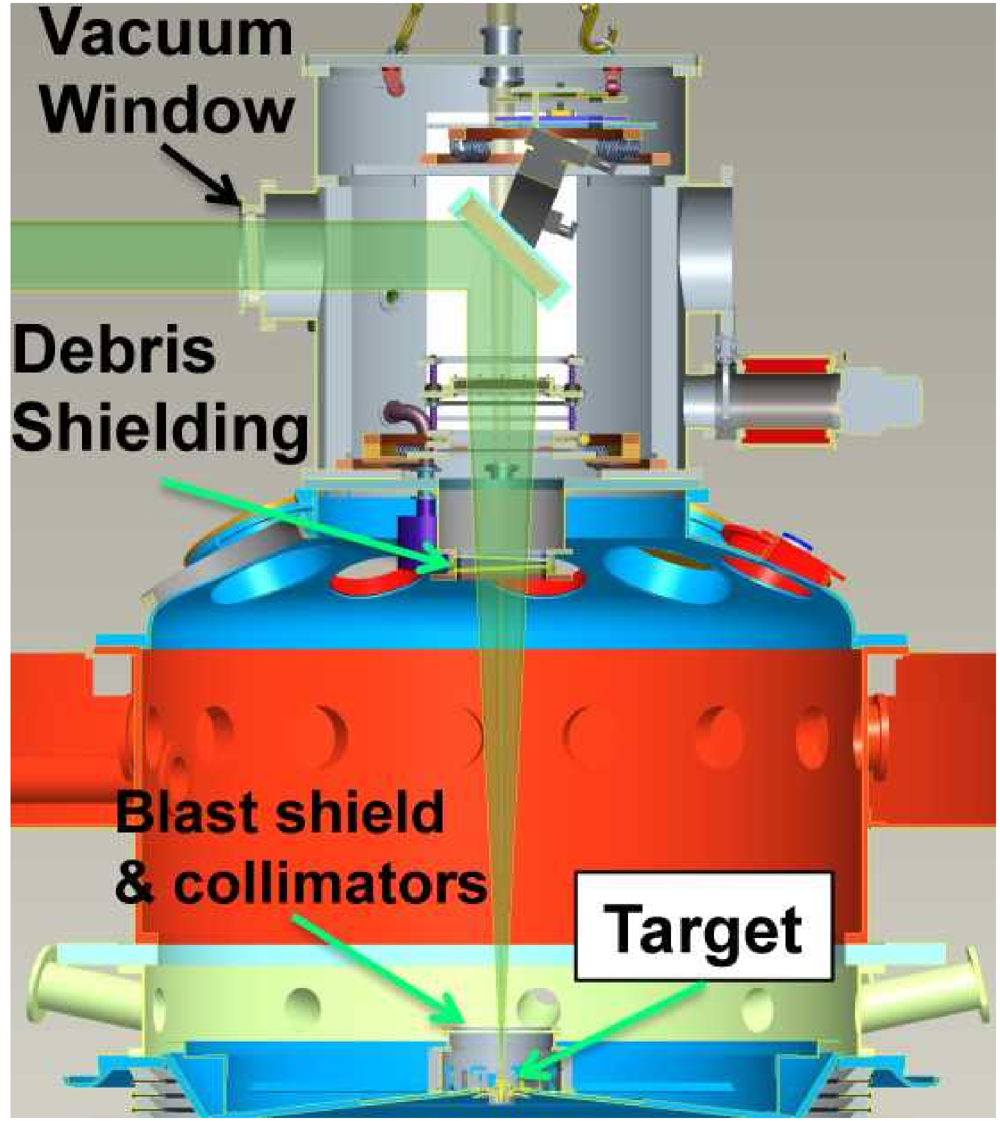
Example pulse measurement



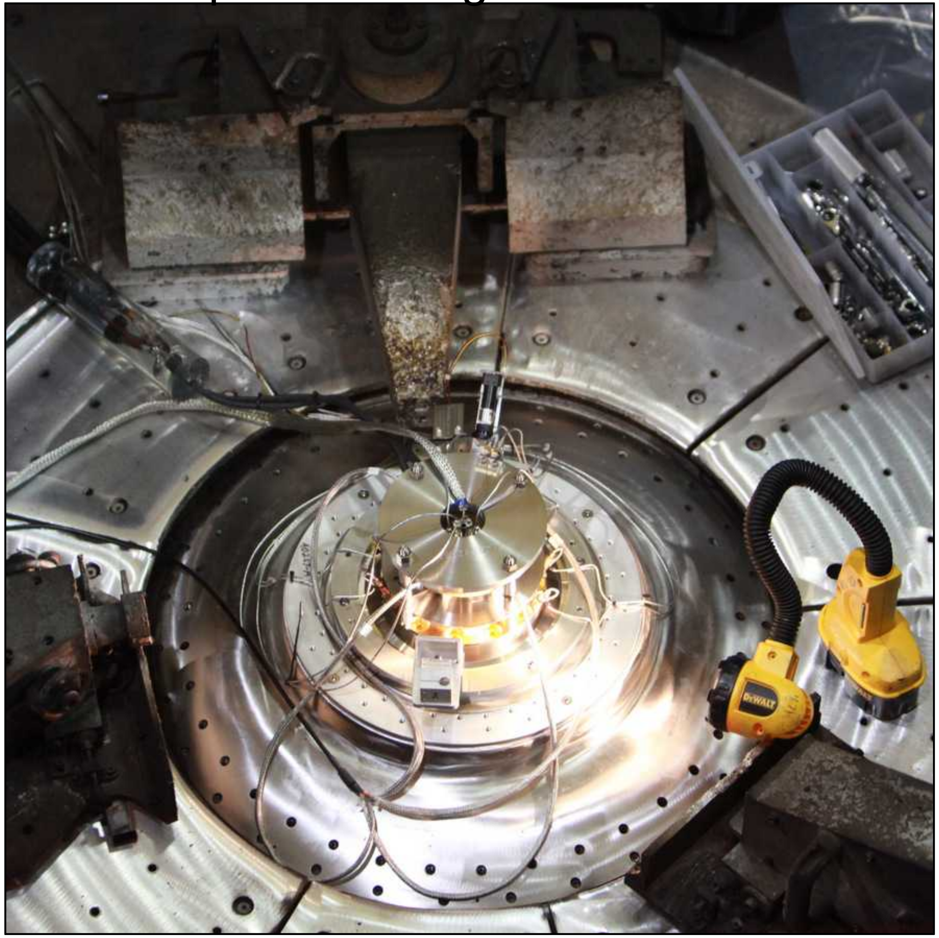
ZBL
2ω light
(2.64 kJ)

Prepulse vaporizes gas-containing foil; main pulse couples to DD fuel



Z couples several MJ of energy to the load hardware, ~equivalent to a stick of dynamite, making diagnostic measurements and laser coupling challenging

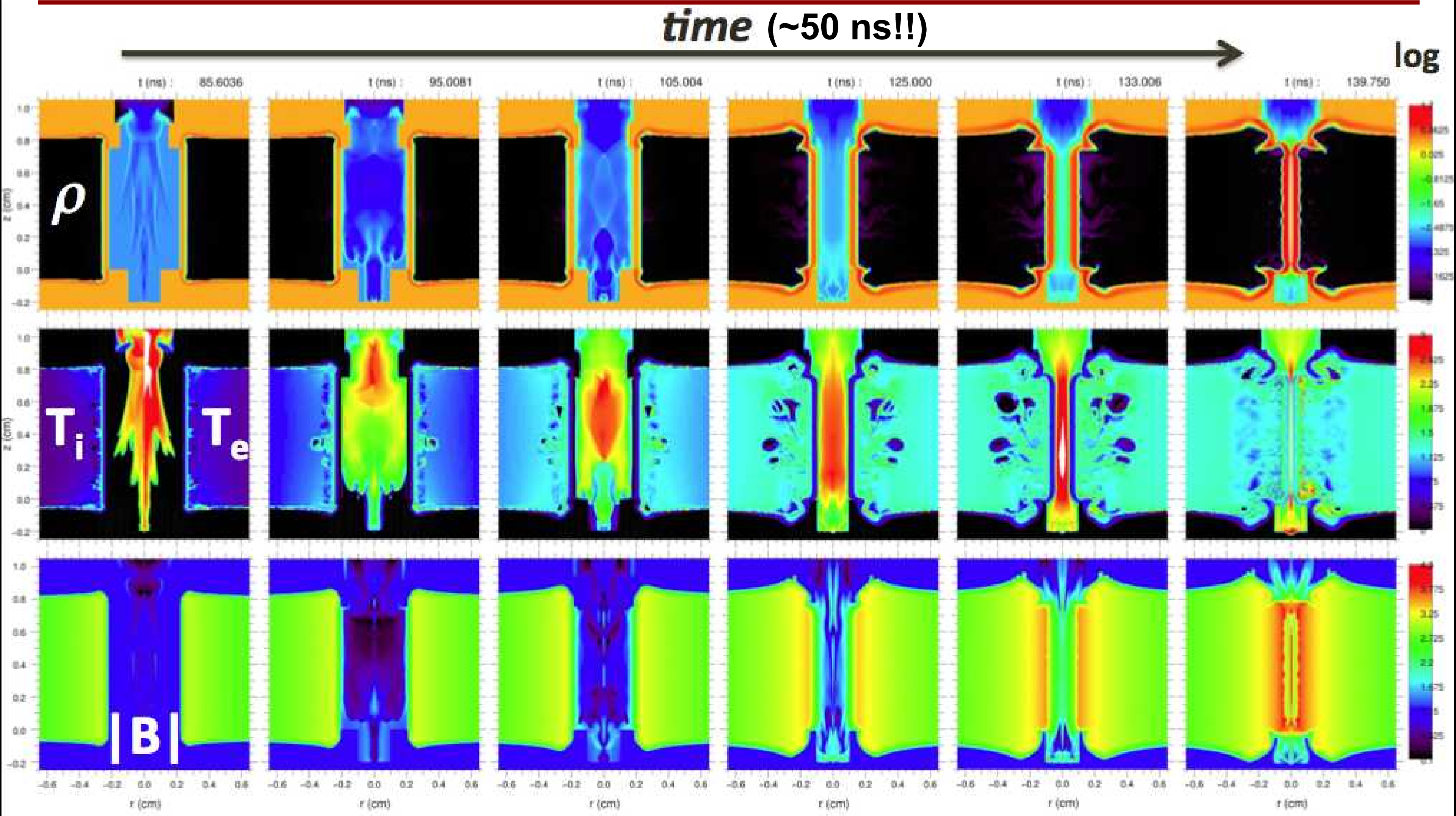
Pre-shot photo of MagLIF load hardware



Damage to FOA debris shielding

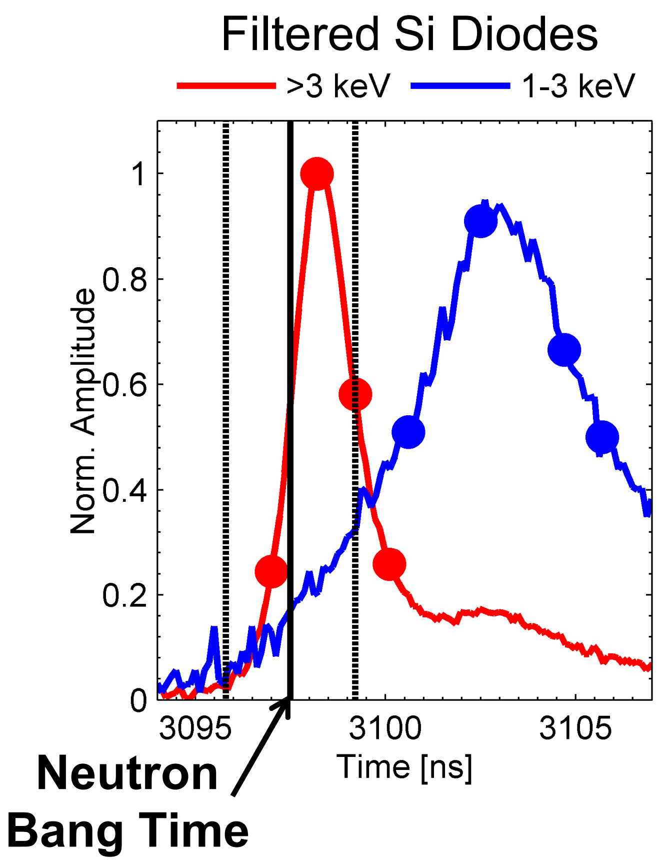
Post-shot photo

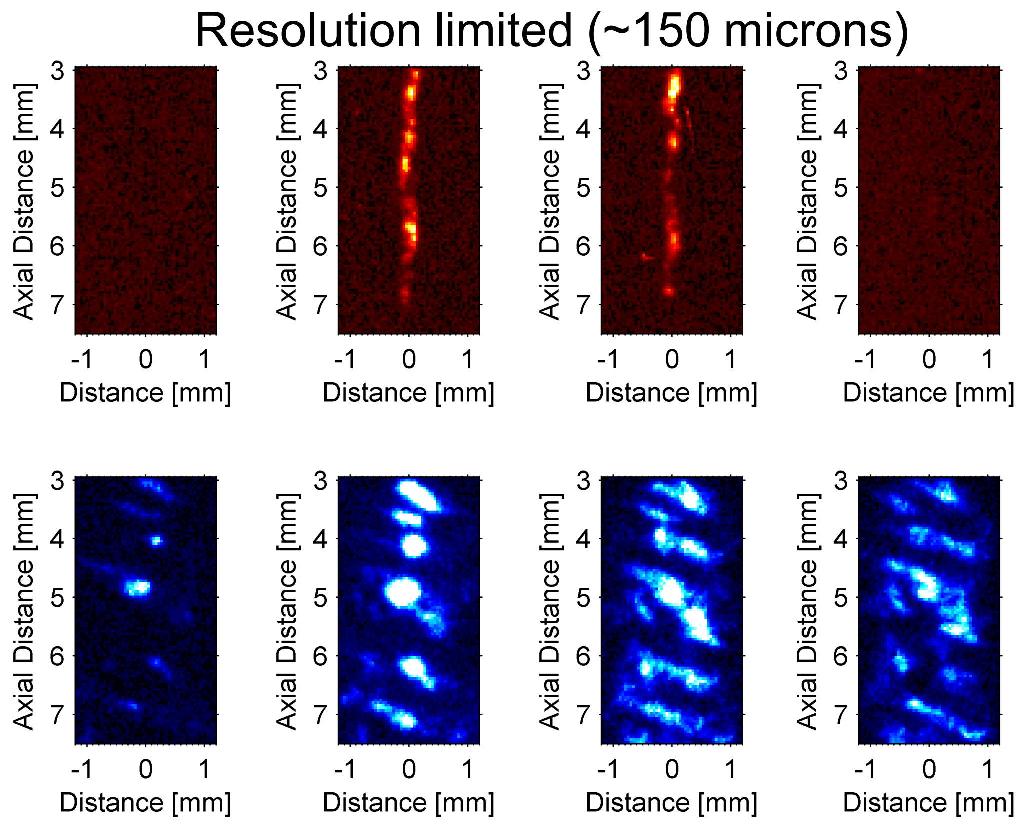
Example fully-integrated HYDRA calculations of near-term Z experiments (19 MA, 10 T, 2 kJ) illustrate the stages of a MagLIF implosion



A.B. Sefkow, S.A. Slutz *et al.*, Phys. Plasmas 21, 072711 (2014).

High energy x-ray emission is only present in magnetized and laser-heated experiments, and its timing is consistent with neutron bang time estimates from nTOF





High energy emission from fuel is only observed in experiments with laser and B-field

Emission from exterior of liner is observed with and without laser and B-field

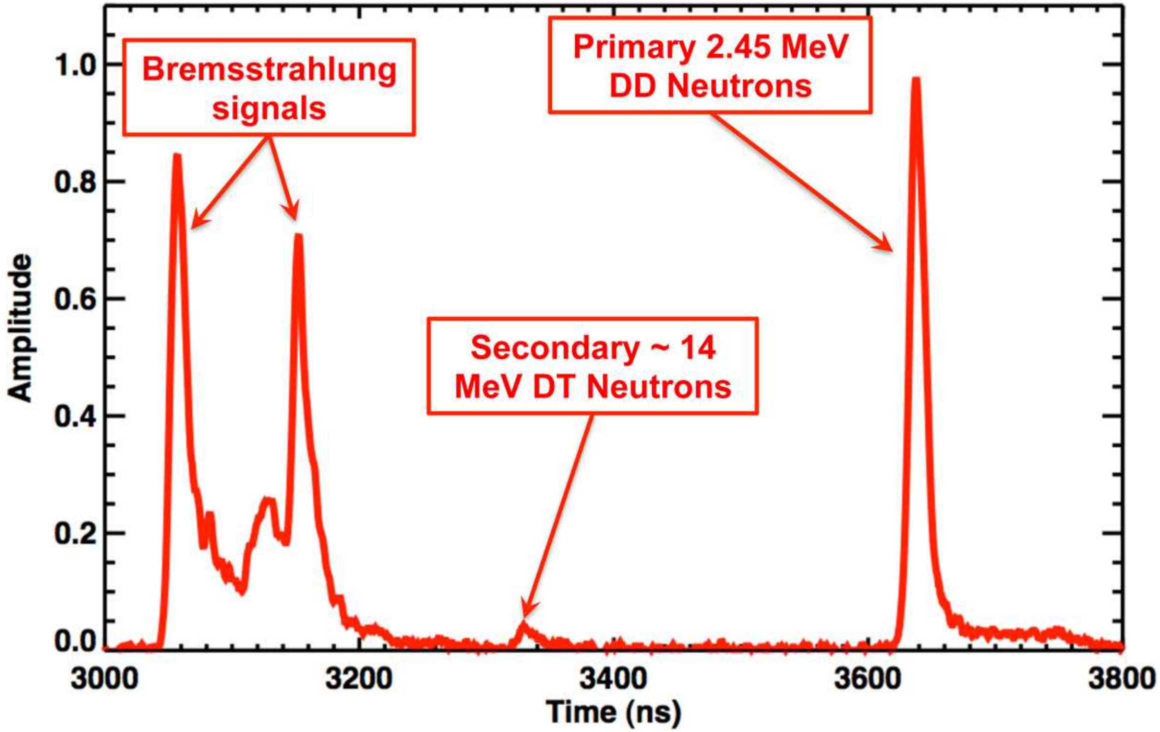
M.R. Gomez *et al.*, Phys. Rev. Lett. (2014).

These experiments produced both primary (2.45 MeV) and secondary (14 MeV) neutrons recorded by neutron time-of-flight and activation sample diagnostics (D2 fill only!!!)

"Secondary" 14 MeV neutrons can be produced by 1 MeV tritons interacting with D fuel

$$D + D \xrightarrow{50\%} 0.8\ \text{MeV He}^3 + 2.5\ \text{MeV n}$$
$$\xrightarrow{50\%} 1.0\ \text{MeV T} + 3.0\ \text{MeV p}$$

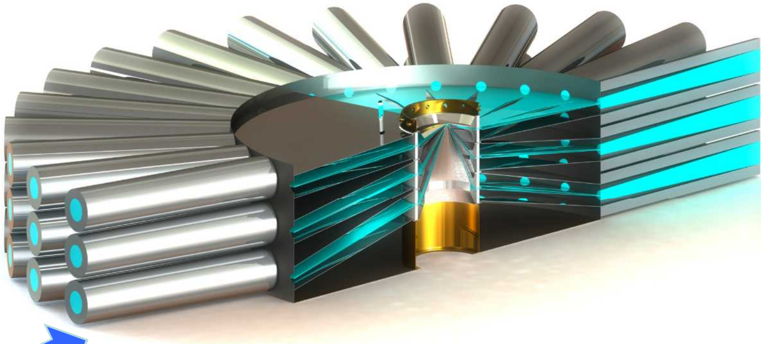
So one triton is produced for every 2.45 MeV neutron that is produced



Note: Significant ~0.1-10 MeV bremsstrahlung produced by facility induces a background activation "yield"—e.g., shots with no fusion fuel produce ~5e9 "DD yield"

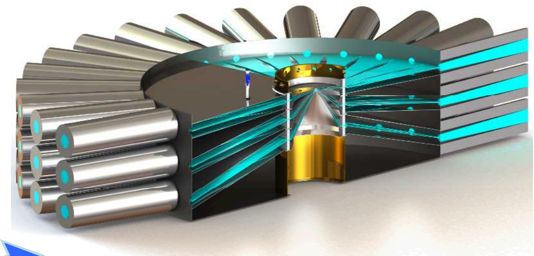
We are currently exploring target designs and pulsed power architectures that may be on the path to 0.5-1 GJ yields and that also meet the needs of the science campaigns

Fusion Yield 0.5-1 GJ?
Burning plasmas



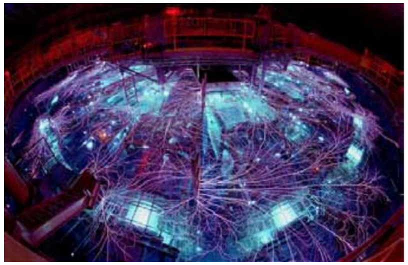
"Z800"
- 800 TW
- 52 Meter diameter
- 61 MA
- 130 MJ Stored Energy

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