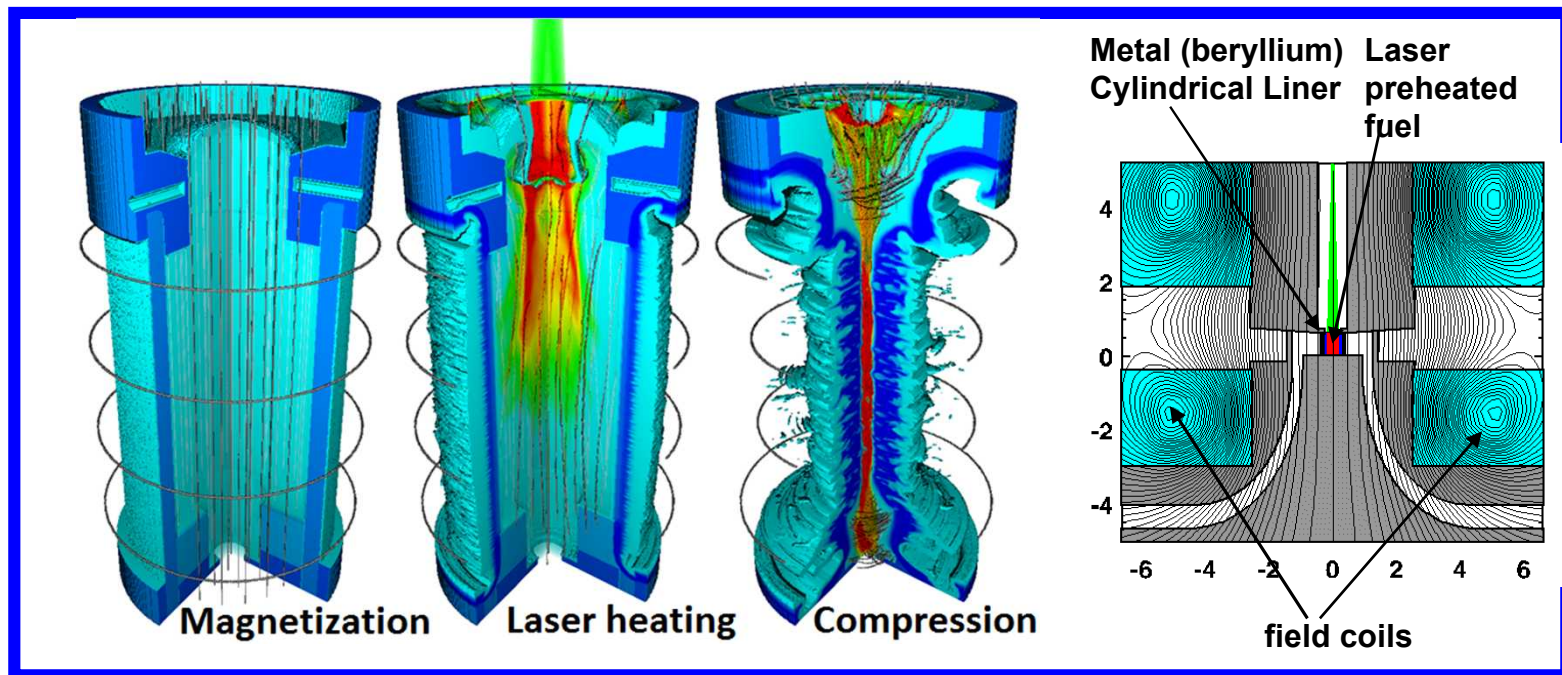


Magnetized Liner Inertial Fusion, MagLIF¹

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



University of New Mexico

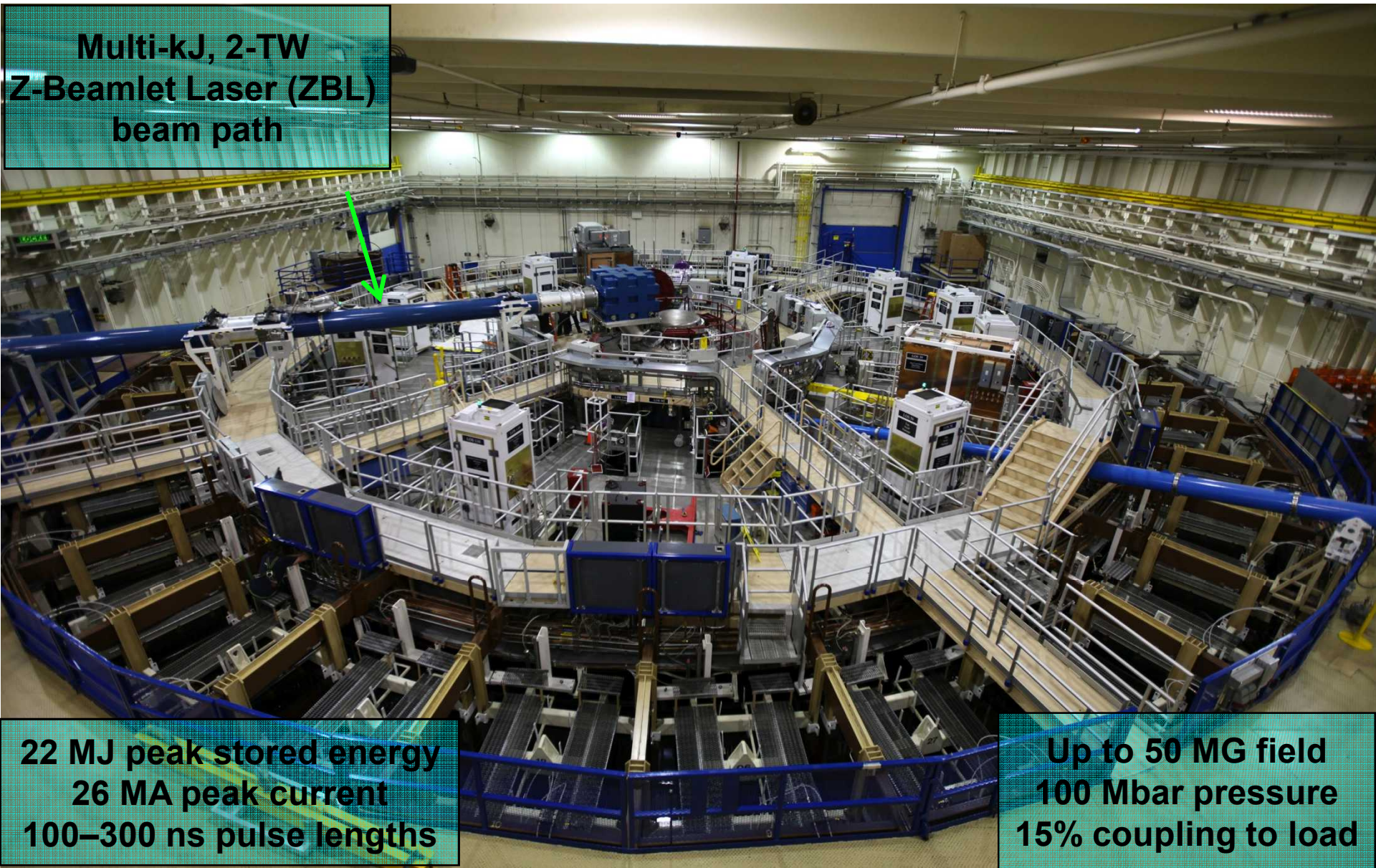
Albuquerque, NM, October 27, 2015

Stephen A. Slutz, Sandia National Laboratories

This work in collaboration with M. R. Gomez, A. B Sefkow, R. A. Vesey, D. B. Sinars, D. C. Rovang, E. M. Campbell, M. C. Herrmann, K. J. Peterson, W. A. Stygar, T. J. Awe, R. McBride, M. Geissel, K. D. Hahn, D. C. Rovang, G. W. Cooper and M. E. Cuneo.

The Sandia Z facility uses magnetic pressure to efficiently drive targets for a wide variety of applications

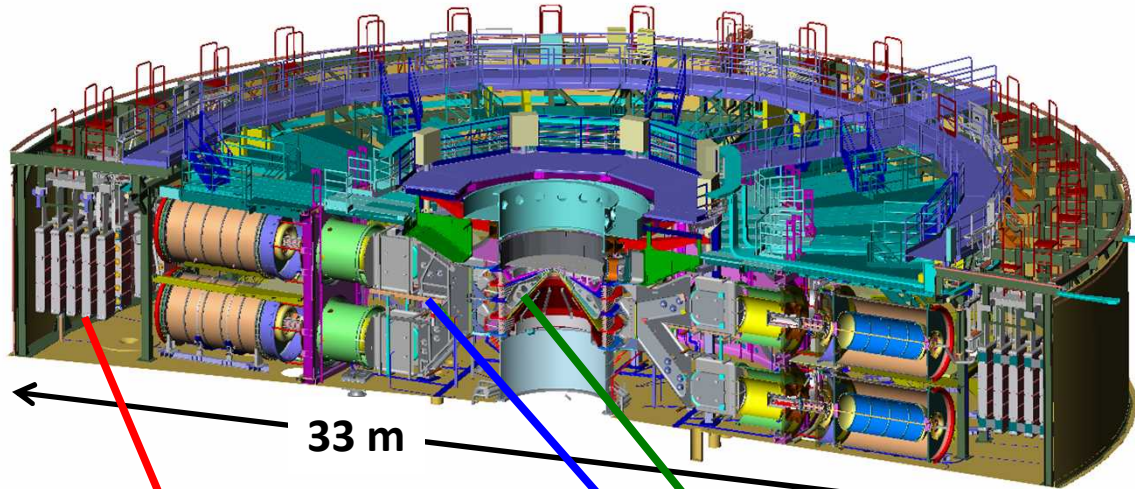
Multi-kJ, 2-TW
Z-Beamlet Laser (ZBL)
beam path



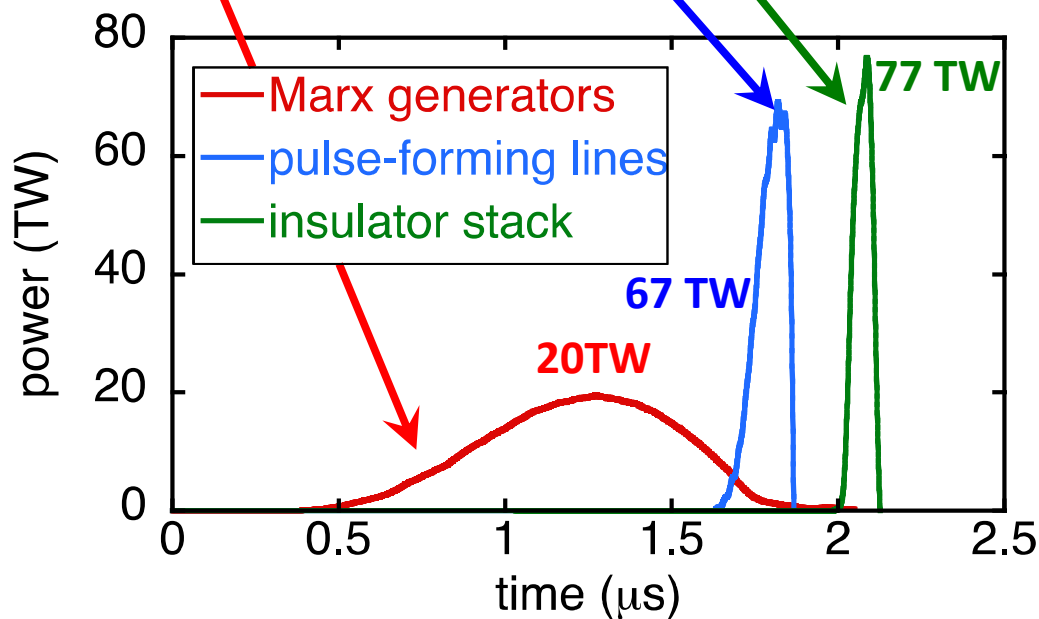
22 MJ peak stored energy
26 MA peak current
100–300 ns pulse lengths

Up to 50 MG field
100 Mbar pressure
15% coupling to load

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

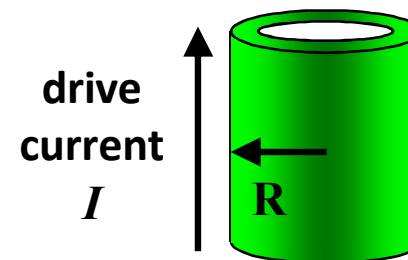


Z today couples ~0.5 MJ out of 20 MJ stored to magnetized liner inertial fusion (MagLIF) target (0.1 MJ in DD fuel).



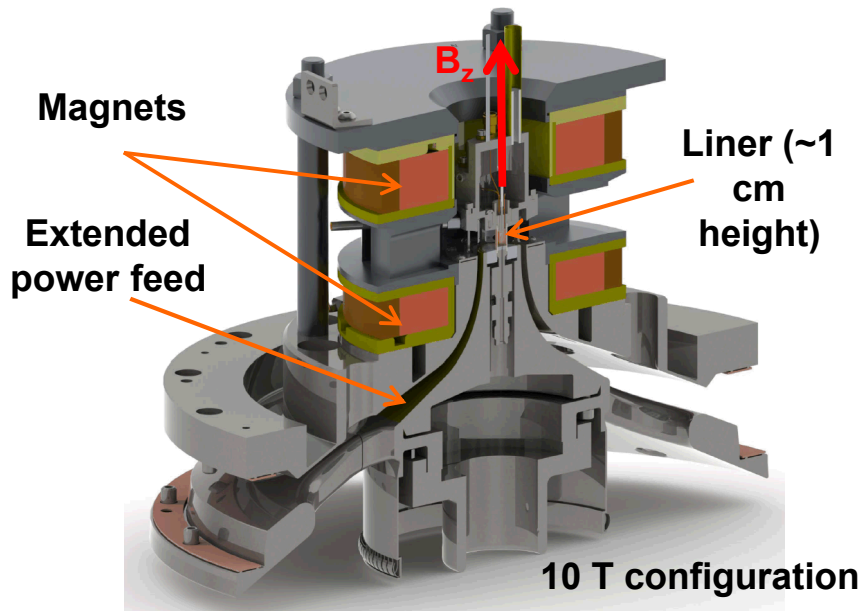
Magnetically Driven Implosion

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

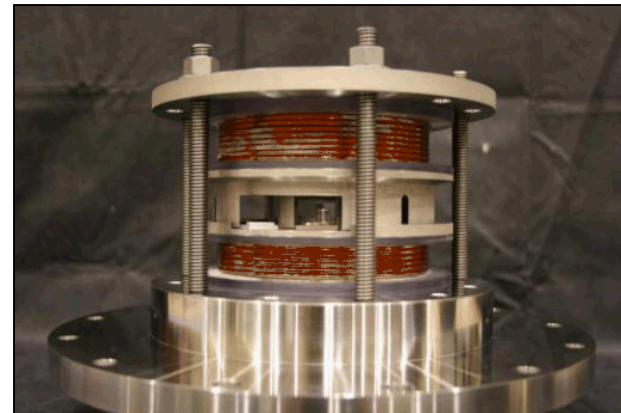


100 MBar at 26 MA and 1 mm

10-30 T axial fields¹ can be supplied for MagLIF experiments on Z



Copper windings of MagLIF coil



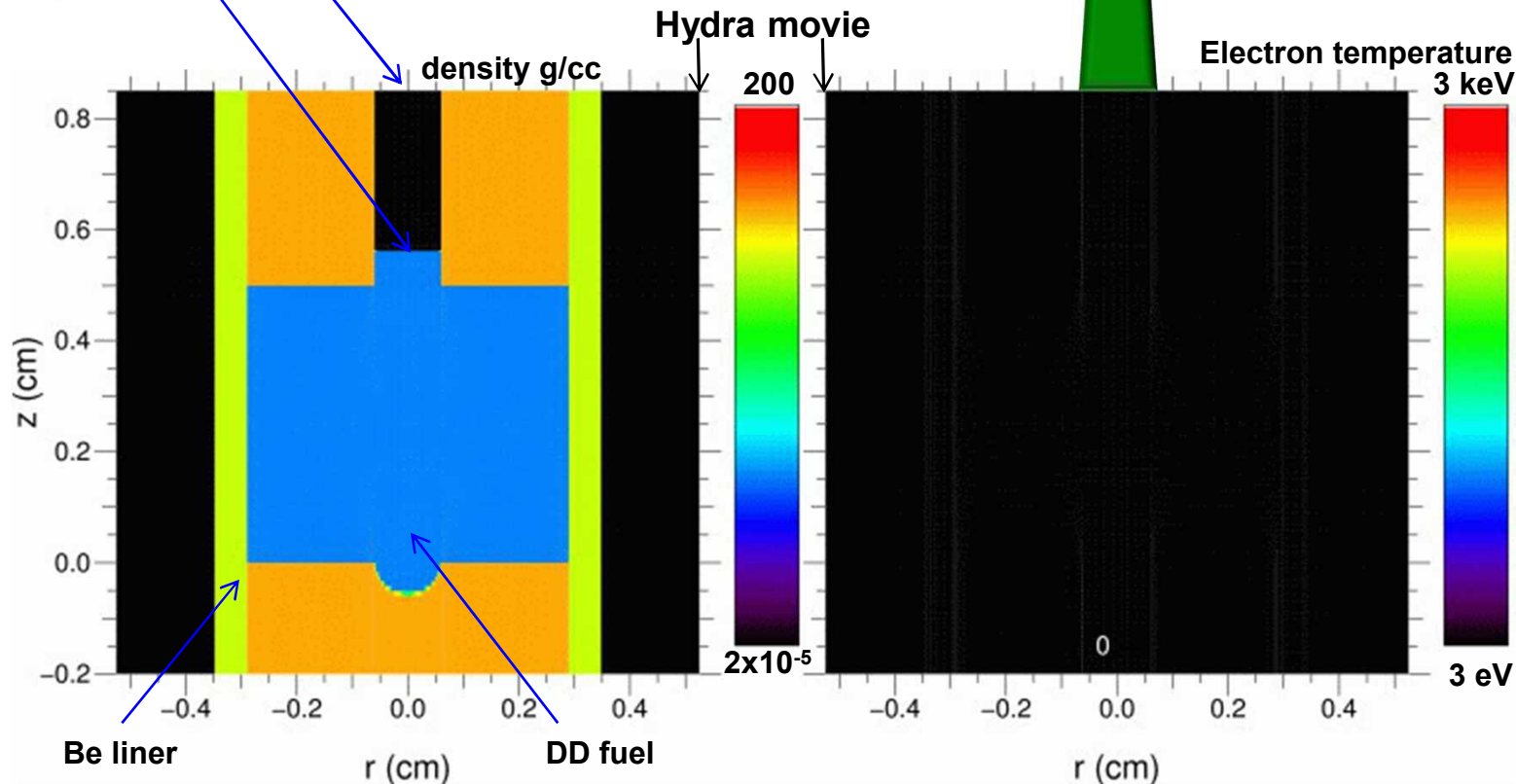
The power feed was modified to center MagLIF within the coils
Axial coil separation determines the maximum field

Fully integrated 2D simulations¹ have been performed using both Lasnex and Hydra

Integrated simulations include:

- Laser interaction with foil and gas
- Axial heat loss at electrodes
- Loss of DT or D2 gas through LEH
- Yields ~10%-30% of clean 1D

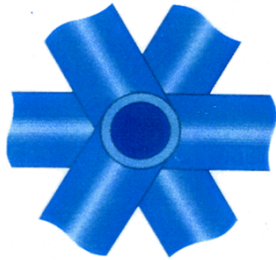
Laser entrance hole (LEH) and foil



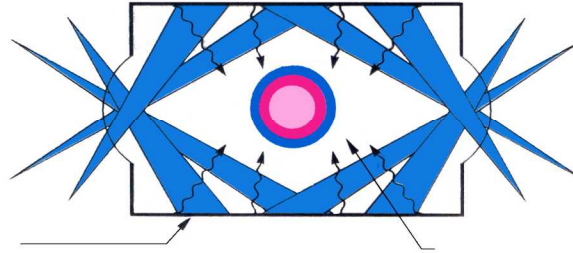
¹A.B. Sefkow, S.A. Slutz, J.M. Koning et al., Phys. Plasmas 21, 072711 (2014).

Thin high velocity shells are used to reach ICF conditions with laser drive

Direct Drive (Laser)



Indirect Drive (X-ray)



For ignition conditions:
(large alpha-heating)

$$\rho R \approx 0.4 \text{ g/cm}^2$$

$$T \approx 5 \text{ keV}$$

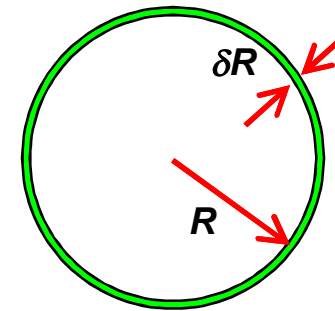
In either direct or indirect drive, ablation pressures are of order $\sim 50\text{-}150$ Mbar, but $\sim 500,000$ Mbar for ignition!

Kinetic energy is developed during the implosion, which is converted to pressure at stagnation. High velocity and high stagnation pressure can be obtained using thin shells. **This is possible due to ablative stabilization of the Rayleigh-Taylor instability**

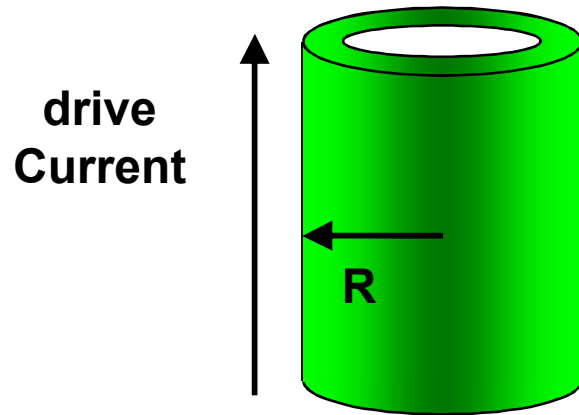
Thin shell implosions can reach the 200-400 km/s needed for ICF

$$\int P_{drive} dV = \frac{1}{2} m v^2$$

$$P_{drive} R^3 \sim R^2 \rho \delta R v^2 \Rightarrow v^2 \sim \frac{P_{drive}}{\rho} \frac{R}{\delta R}$$



Liners cannot be thin because there is no Rayleigh-Taylor stabilization mechanism for magnetic drive

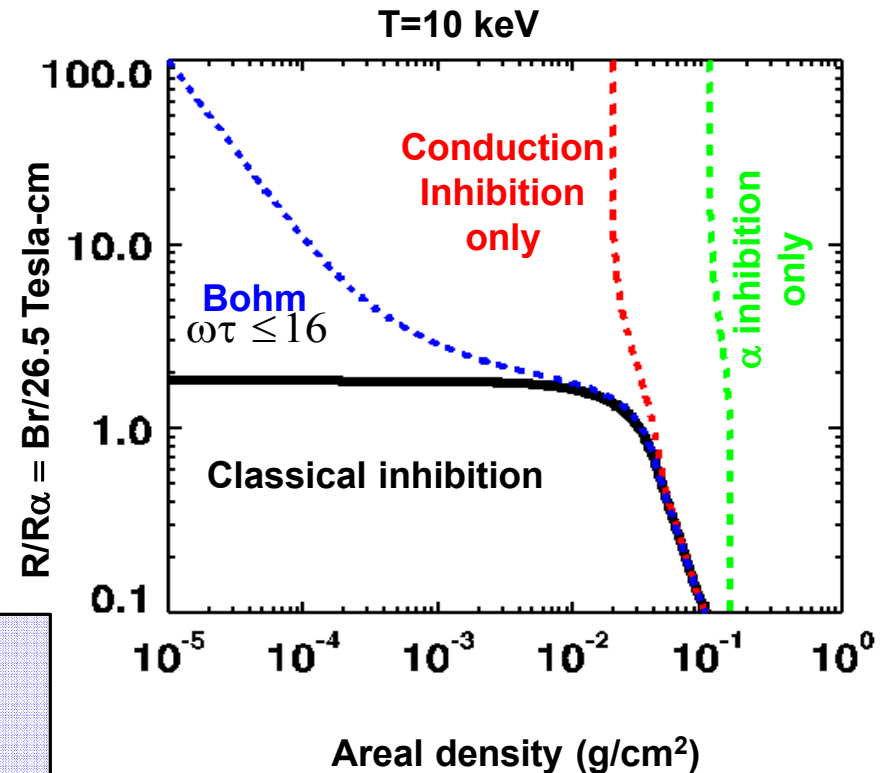
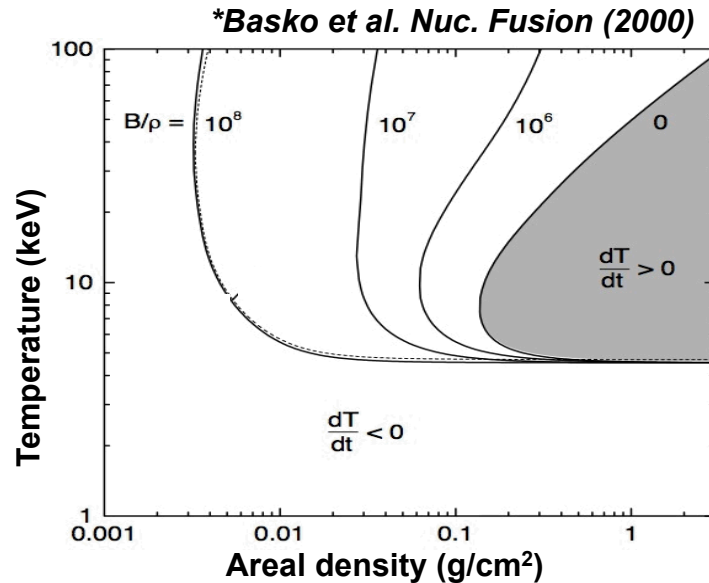


$$R \frac{d^2 R}{dt^2} = - \frac{\mu_0}{4\pi} \frac{I^2}{m_l}$$

$$Velocity \approx \sqrt{\frac{\mu_0}{4\pi} \frac{I^2}{m_l}}$$

- A liner implosion with a duration of 100 ns reaching an implosion velocity of 300 km/s needs to have an initial radius of about 0.75 cm.
- Assuming a drive of 25 MA, the liner thickness must be about 18 μm .
- Such a thin liner would be quickly shredded by instabilities and would not compress the fuel
- Thick liners will have relatively low implosion velocities ~ 100 km/s

Magnetization increases the ignition space replacing the minimum fuel ρr with minimum $B r$



Ignition: alpha particle deposition in excess of losses

$$P_\alpha \propto (\rho r)^2 \theta^{2.6} f_\alpha$$

f_α , the fraction of the α energy deposited in the fuel increases with either B or ρr

$$P_{Brem} \propto (\rho r)^2 \theta^{1/2}$$

Conduction losses are important for small ρr

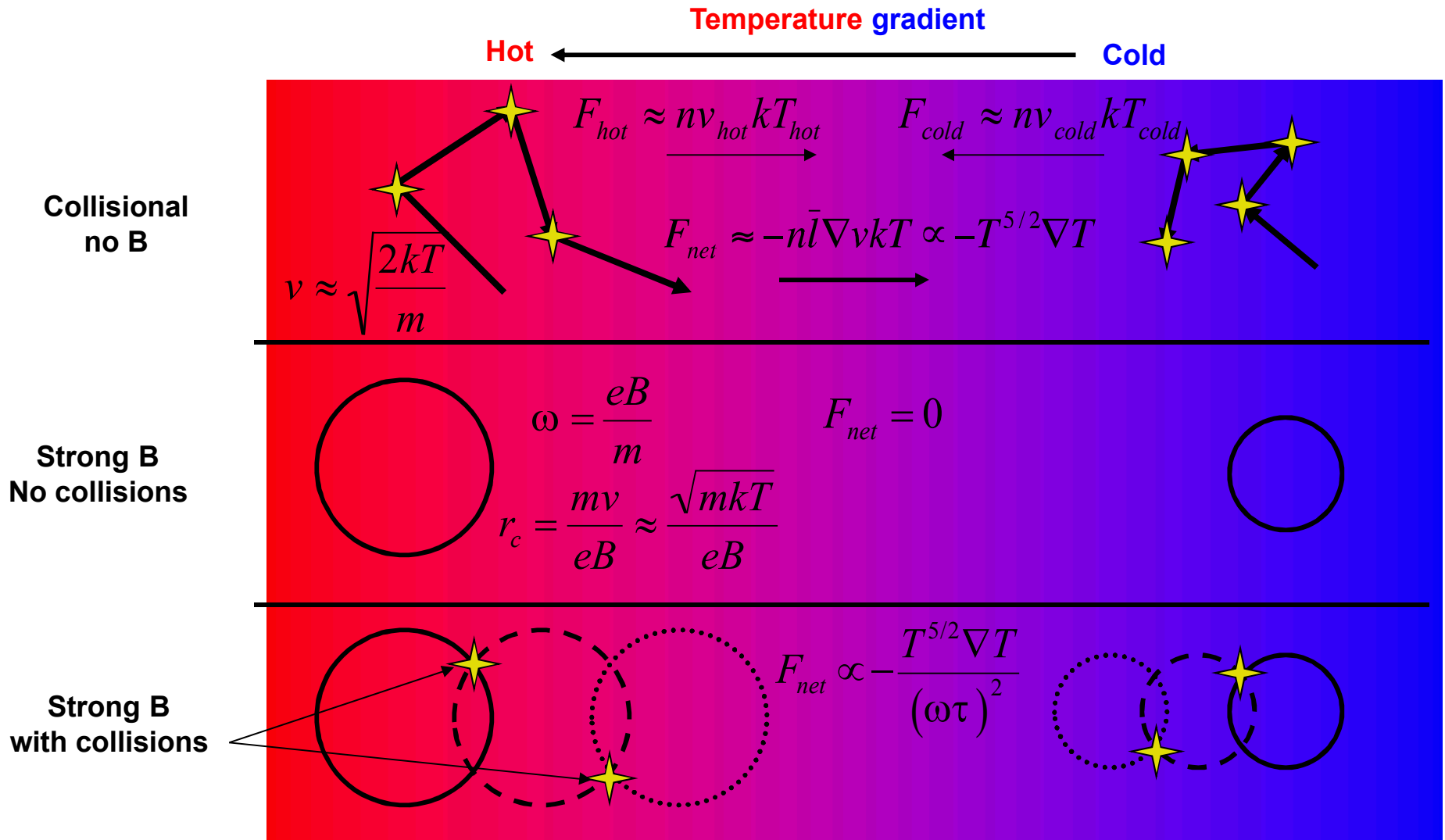
$$P_{ce} \propto \theta^{7/2} F_e(\theta, B/\rho)$$

In the limit of large B/ρ $F_e(\theta, B/\rho) \propto \theta^{-3} (B/\rho)^{-2}$

Axial α -trapping requires closed field lines or moderately high fuel density so that

$$\rho \Delta z > 0.5 \text{ g}/\text{cm}^2$$

The presence of a magnetic field strongly reduces transport, e.g. heat conduction



Energetic particles are also strongly affected by magnetic fields

High magnetic fields can be obtained by flux compression

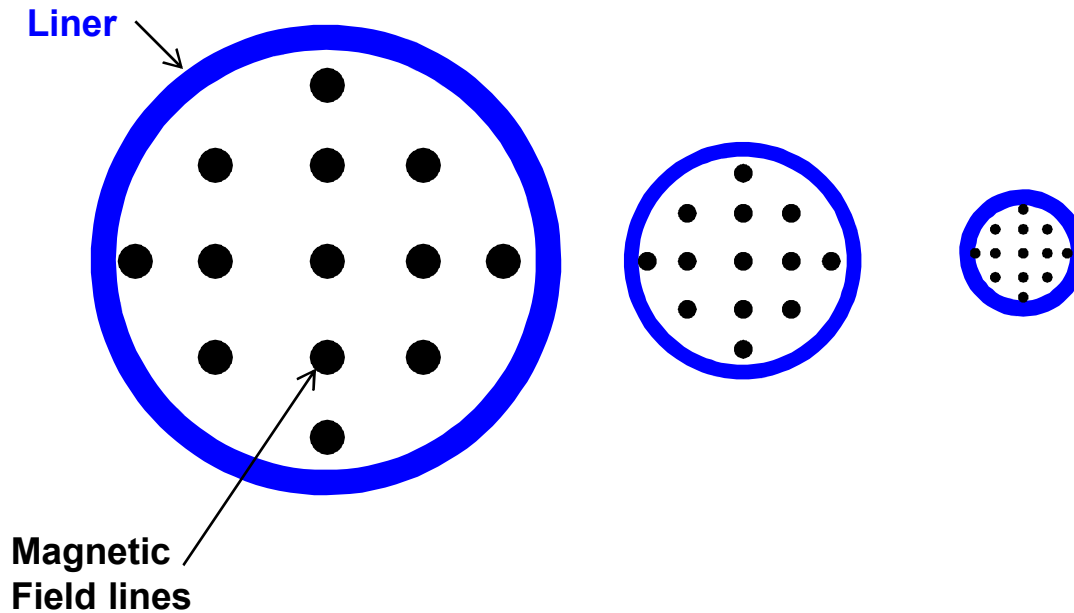
The Flux = # of field lines

Field strength = # of field lines/area

Field lines are “frozen in” for high conductivity

- Flux is conserved

$$\text{Since } Area = \pi r^2 \quad B \approx B_0 \left(\frac{r_0}{r} \right)^2$$



Magnetization reduces the minimum implosion velocity for ICF

Compressive heating during the implosion must significantly exceed losses

- The heating rate is proportional to the implosion velocity $P \frac{dV}{dt} \approx 5.0 \times 10^8 \rho r T \frac{dr}{dt} W / cm$
- The dominant cooling rate is electron thermal conduction $L_{ce} \approx \frac{8.7 \times 10^{12} T^{7/2}}{(\omega \tau)^2} W / cm$

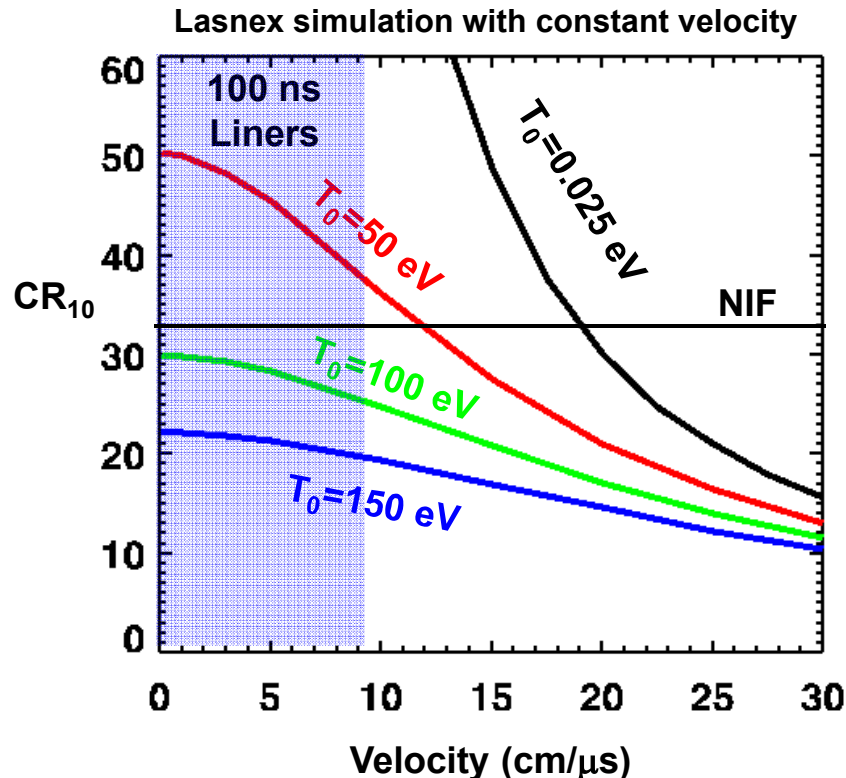
Bremsstrahlung radiation losses are dominant when the thermal conduction has been made negligible by a large magnetic field

- The bremsstrahlung losses $L_{rad} \approx 9.6 \times 10^{16} (\rho r)^2 T^{1/2} W / cm$
- The implosion time then determines the maximum fuel density $\rho_{final} \approx \left(\frac{100 ns}{\tau_{imp}} \right) g / cc$

Fuel preheat is necessary for slow implosions

preheat is good in this scenario!

CR_{10} = Convergence Ratio (R_0/R_f) needed to obtain 10 keV (ignition)
with no radiation or conductivity losses



Fuel can be heated to ignition temperature with modest convergence ratio when the initial temperature (adiabat) is large

- adiabat set by implosion velocity (shock) or
- alternatively by fuel preheat

$$T \sim T_0 C_R^{4/3}$$

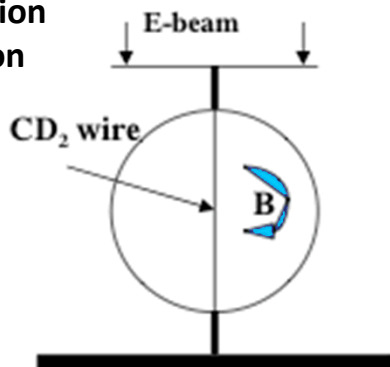
Preheating can be used to control the required convergence ratio

- High convergence ratio systems are more susceptible to asymmetry and instability

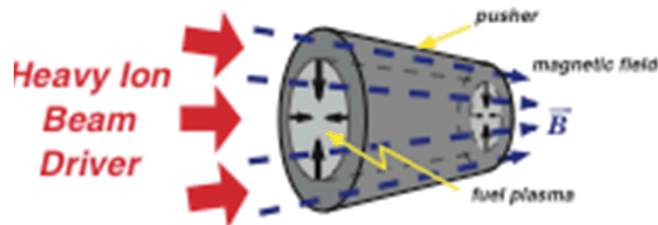
Many groups want to use magnetic fields to relax inertial fusion stagnation requirements

SNL Phi Target

1982 Demonstration of enhanced fusion yield with magnetization (~1e6 DD yield)



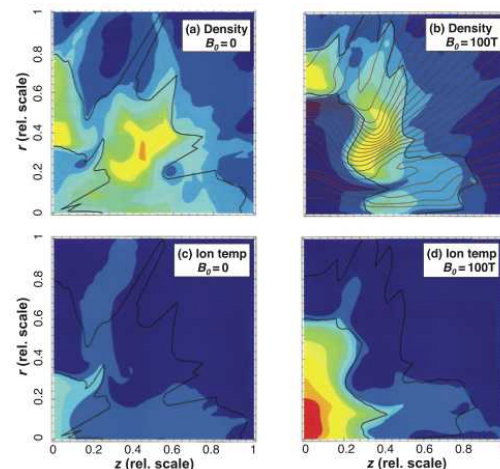
Max Planck/ITEP



Basko, Kemp, Meyer-ter-Vehn, *Nucl. Fusion* **40**, 59 (2000)
Kemp, Basko, Meyer-ter-Vehn, *Nucl. Fusion* **43**, 16 (2003)

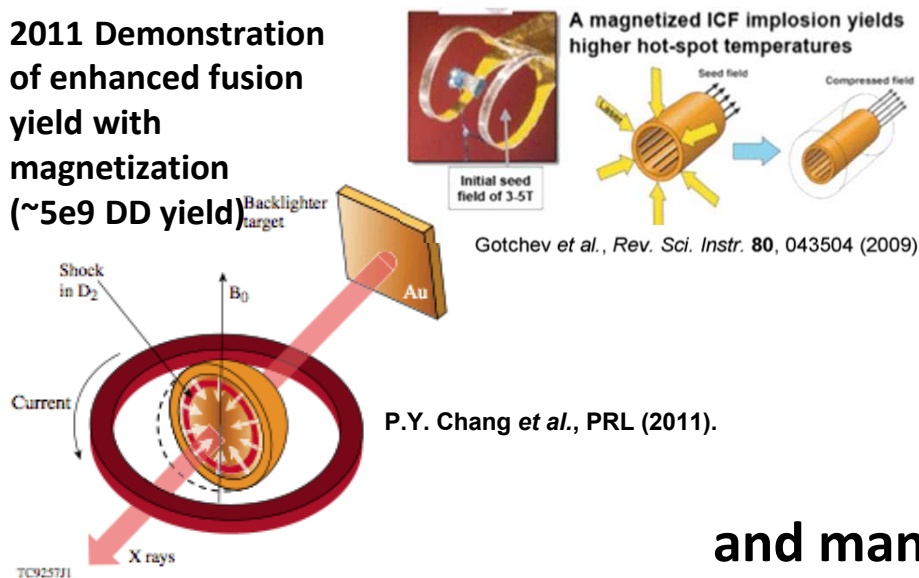
LLNL

(Perkins et al., *Phys Plasmas* 2013)



University of Rochester/LLE

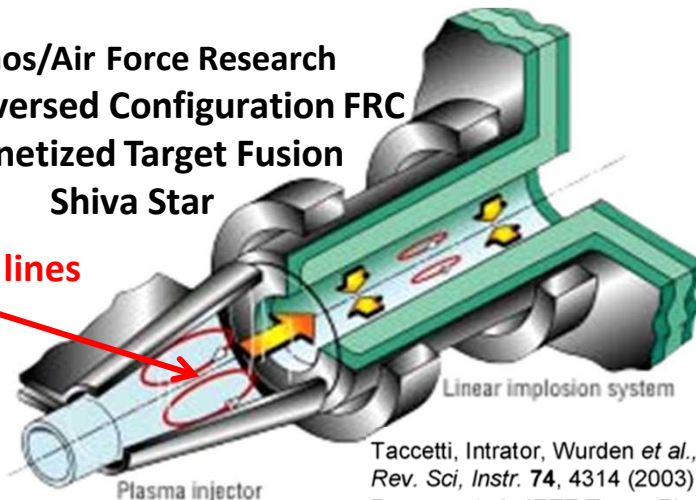
2011 Demonstration of enhanced fusion yield with magnetization (~5e9 DD yield)



P.Y. Chang et al., *PRL* (2011).

Los Alamos/Air Force Research Field Reversed Configuration FRC Magnetized Target Fusion Shiva Star

closed field lines
FRC



Taccetti, Intrator, Wurden et al., *Rev. Sci. Instr.* **74**, 4314 (2003)
Degnan et al., *IEEE Trans. Plas. Sci.* **36**, 80 (2008)

and many others...

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

Metric	X-ray Drive on NIF	100 kJ MagLIF on Z
Characteristic 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_o/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

Other ALPHA MIF concepts

Characterized by:

Lower velocities

Lower densities

Longer burn times

MagLIF has advantages

Axial fields can be generated by a simple coil pair: *much simpler than closed fields*

- Axial stopping of alpha particles requires $\rho\Delta z > 0.5$
- The optimal fuel density is determined by the balance between PdV heating and Bremsstrahlung radiation losses

$$\rho_{final} \approx \left(\frac{100 ns}{\tau_{imp}} \right) g/cc$$

- Axial lengths of 0.5-1.0 cm are adequate

Preheat feasible with a laser

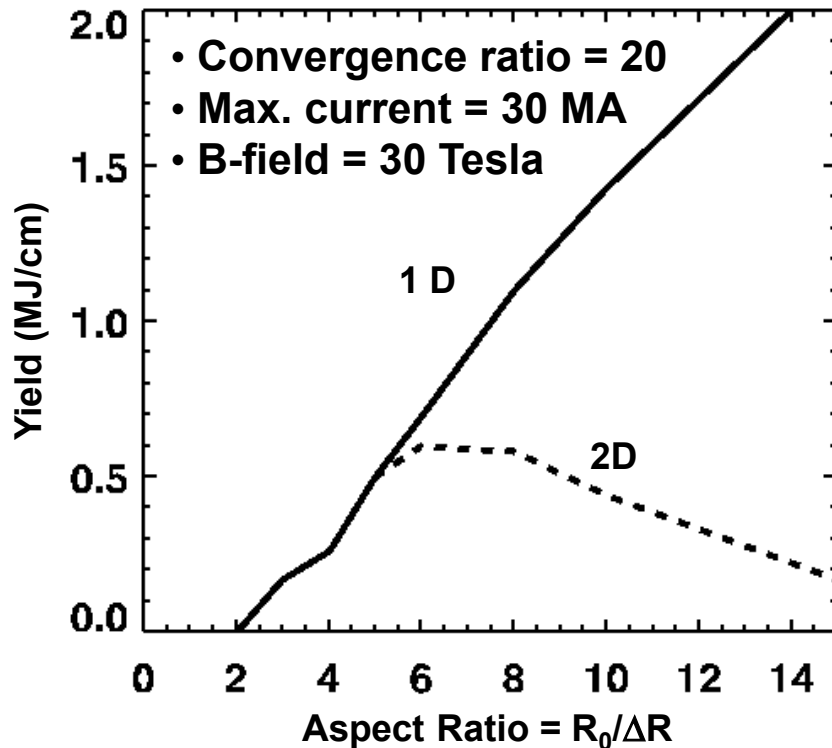
- The preheat energy increases quickly with implosion time

$$E_{pre} \approx C_V T \pi (r \propto \tau_{imp})^2 (\rho\Delta z \approx 0.5)$$

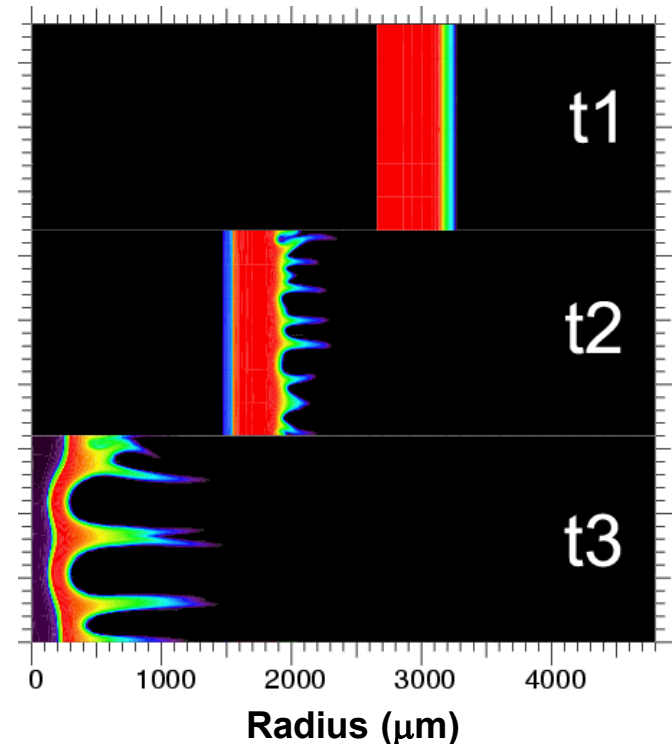
- Fuel preheat requires < 10 kJ for Z ($\tau_{imp} = 100$ ns)

The Magneto-Rayleigh-Taylor (MRT) instability determines performance of MagLIF and other implosion systems¹

LASNEX 2D MHD simulations



The Magneto-Rayleigh-Taylor instability degrades the yield as the aspect ratio is increased due to decreased liner ρr

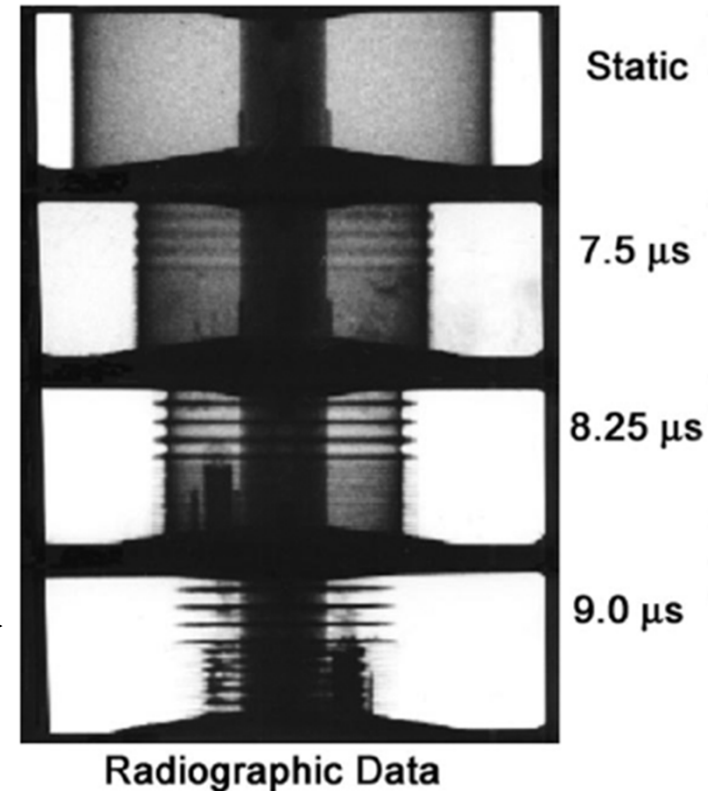



2D Lasnex Be liner simulations AR=6

- 60 nm surface roughness
- resolve waves down to $\sim 80 \mu\text{m}$
- wavelengths of 200-400 μm near stagnation

Almost no high-quality data on the MRT instability in solid liners had been published when MagLIF was proposed

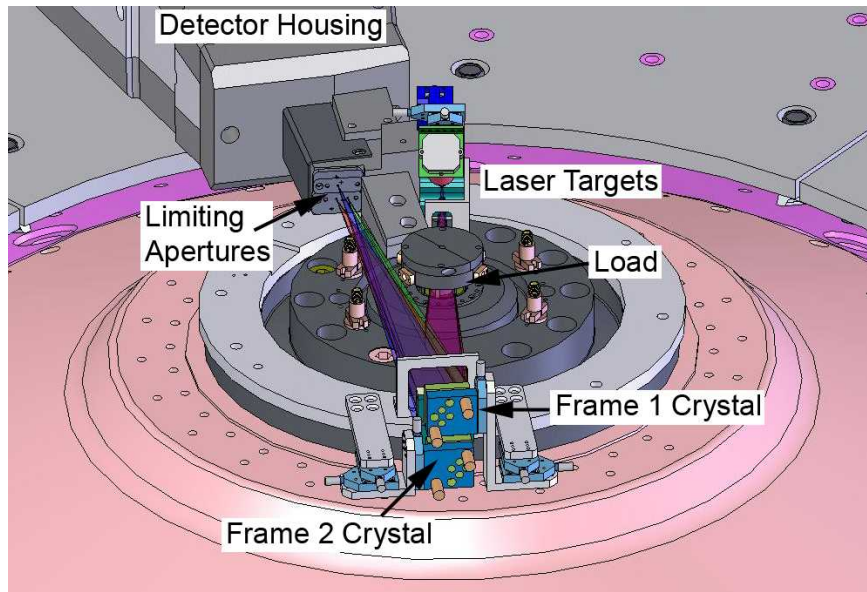
- ICF codes extensively benchmarked against decades of radiation-driven experiments, but magnetic field packages in these ICF codes are not as well validated
- Little data in relevant regime in literature
 - MRT instability growth studies that had been done with solid liners have $\sim 7\mu\text{s}$ time scales (e.g., PEGASUS*), where material strength plays a much larger role
 -
 - Most ~ 100 ns z-pinch experiments use low-mass, high-velocity wire arrays or gas-puffs
 - Some work with modulated-diameter wire arrays done (B. Jones, PRL 2005) but plasma ablation physics dominates




24 mm radius, 20 mm tall, 0.4 mm
thick Al 1100

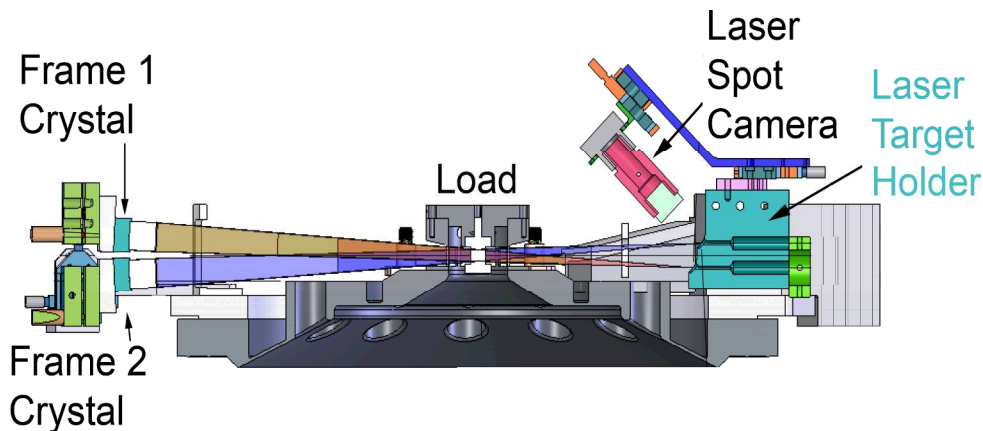
* R.E. Reinovsky *et al.*, IEEE Trans. Plasma Sci. (2002).

In preparation for MagLIF the MRT was studied on Z with 2-frame monochromatic crystal backlighting diagnostic^{1,2}

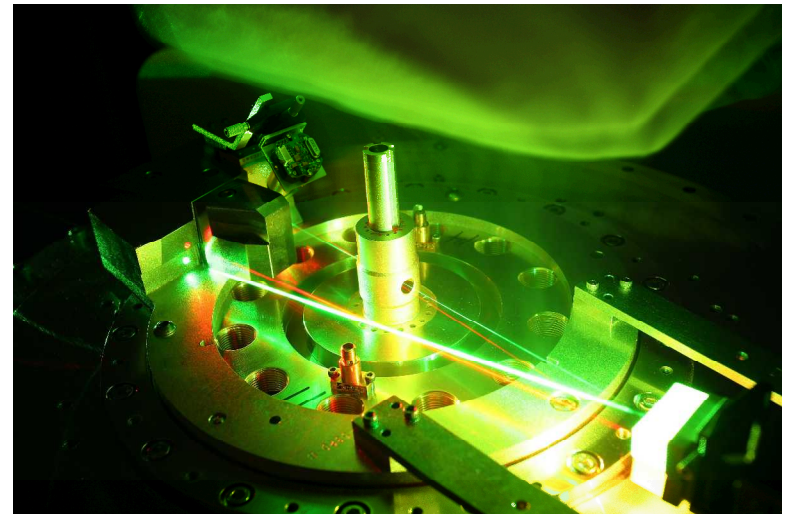


2-frame 6.151 keV Crystal Imaging

- Monochromatic (~ 0.5 eV bandpass)
- 15 micron resolution (edge-spread)
- Large field of view (10 mm x 4 mm)
 - Debris mitigation

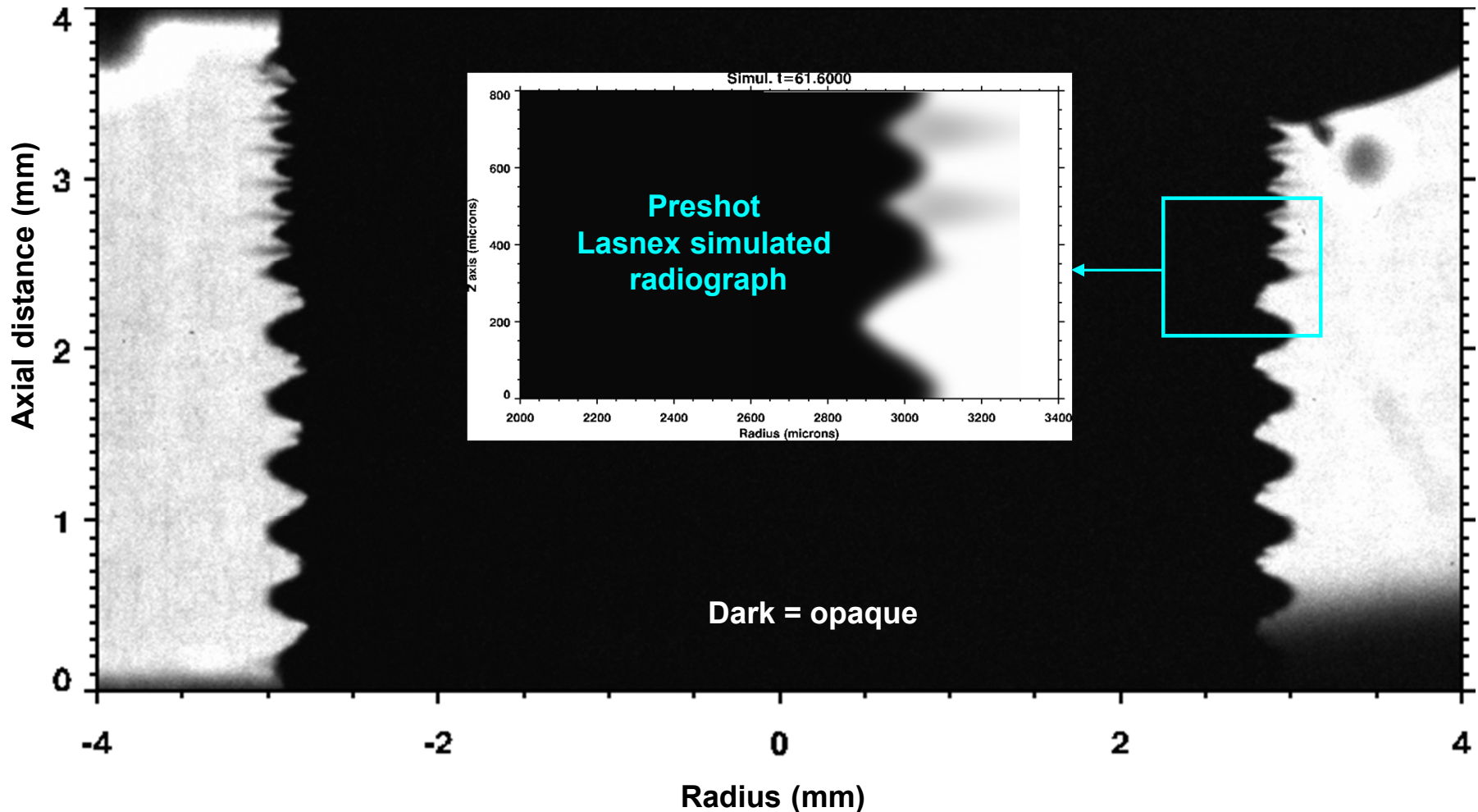


Radiograph lines of sight $\pm 3^\circ$ from horizontal

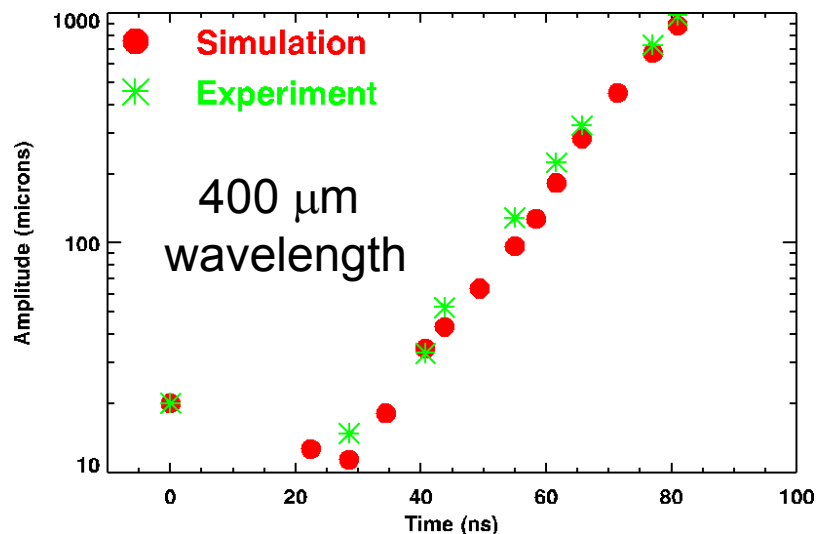


We benchmarked our MHD codes with Magneto-Rayleigh-Taylor instability experiments

Aluminum liner with machined perturbations 200 and 400 micron

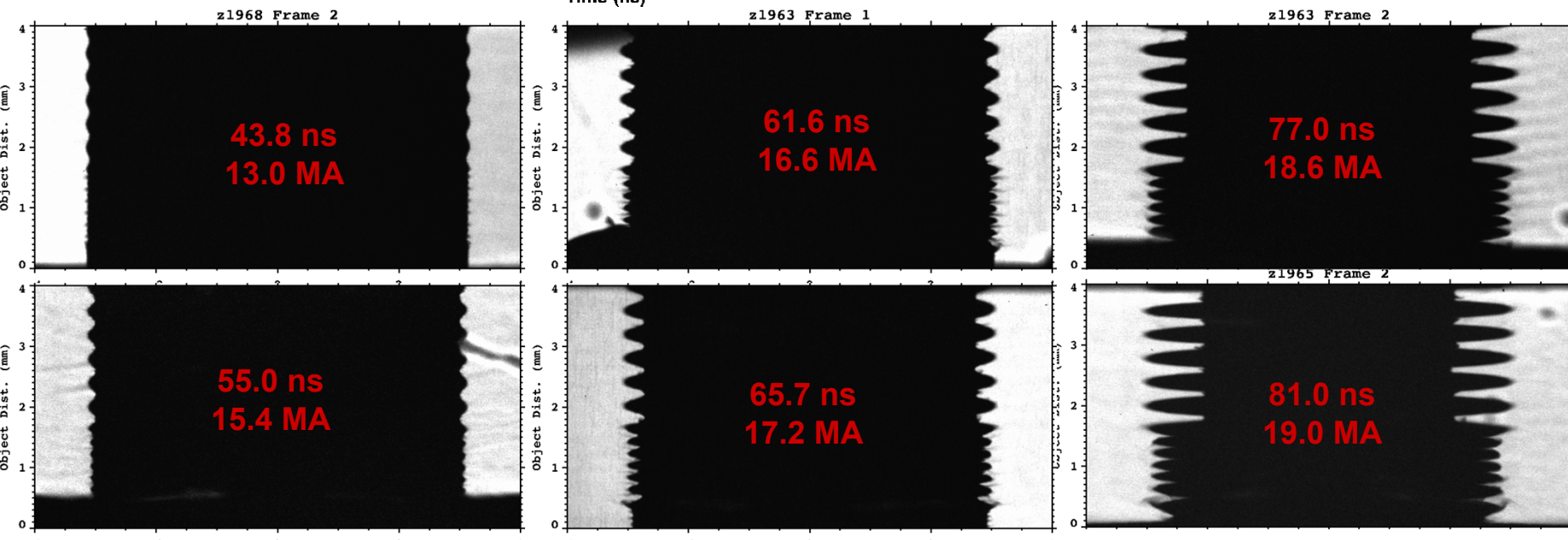


Simulations of MRT growth from machined perturbations in aluminum liners agree well with experiments¹

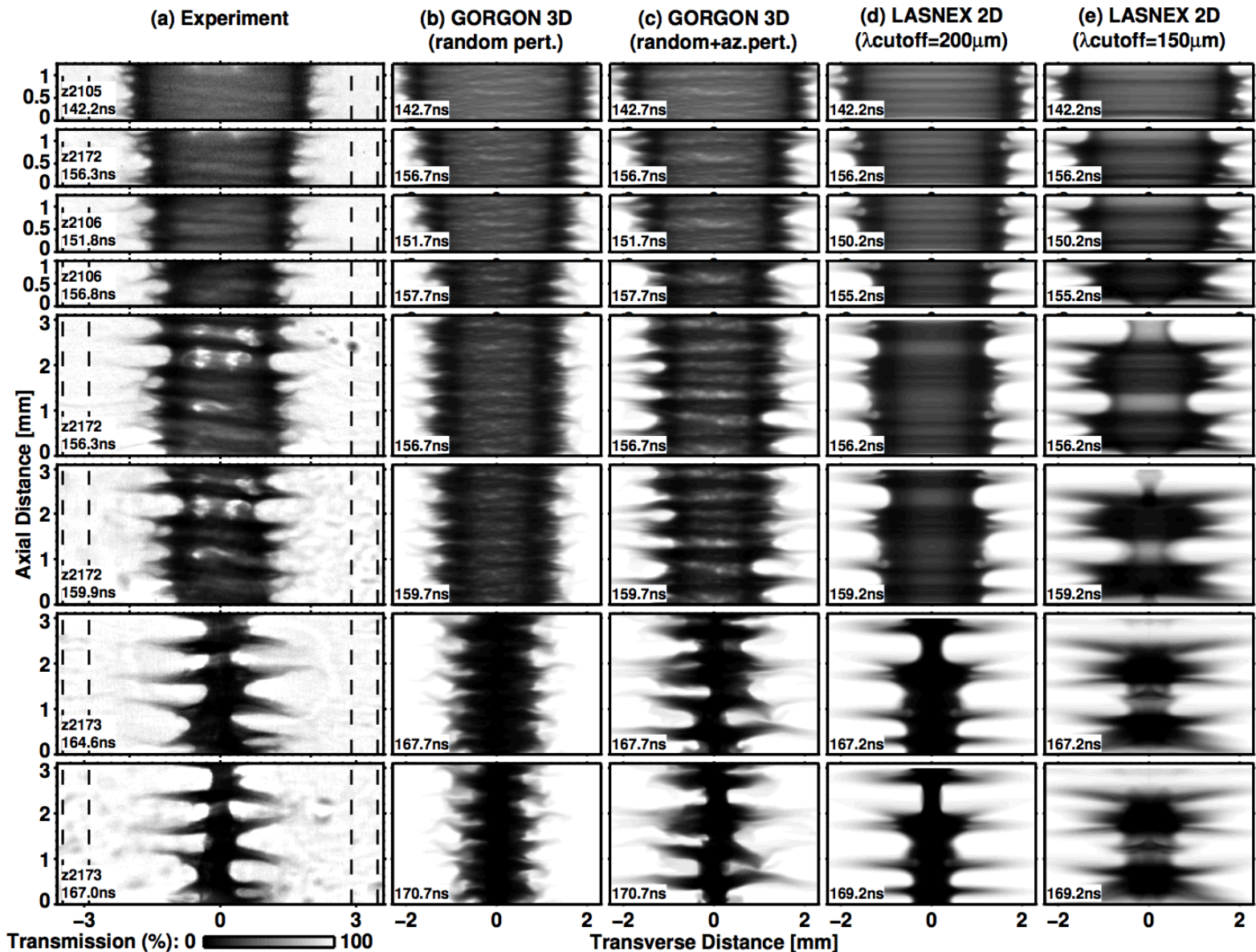


Aluminum liners are too opaque to probe the interior

- 6 keV x-rays could penetrate a Beryllium liner



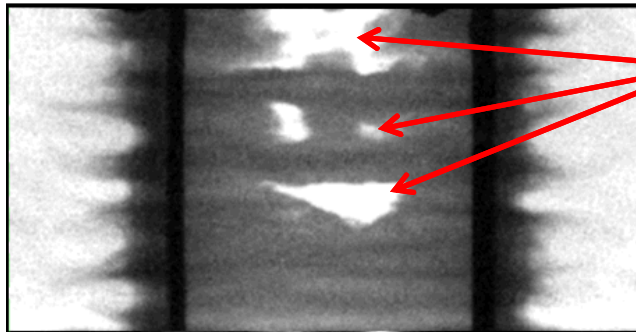
Smooth beryllium liners show surprisingly correlated instability growth at late times¹



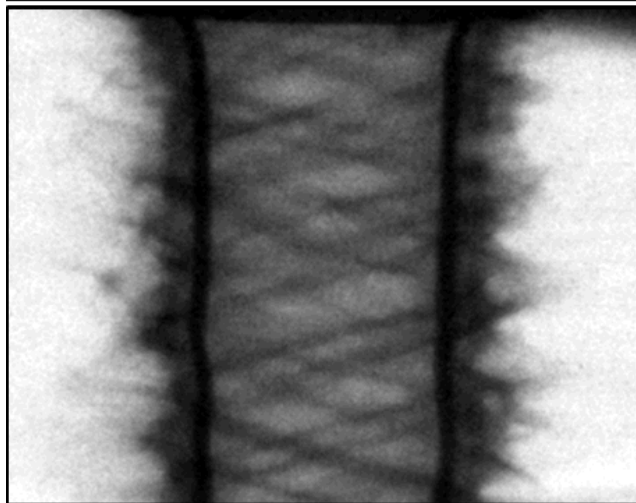
¹R.D. McBride *et al.*, Phys. Rev. Lett. 109, 135004 (2012).

An axial magnetic field reduces hard x-rays and changes the liner instability structure from cylindrical to helical

Without Magnetic Field

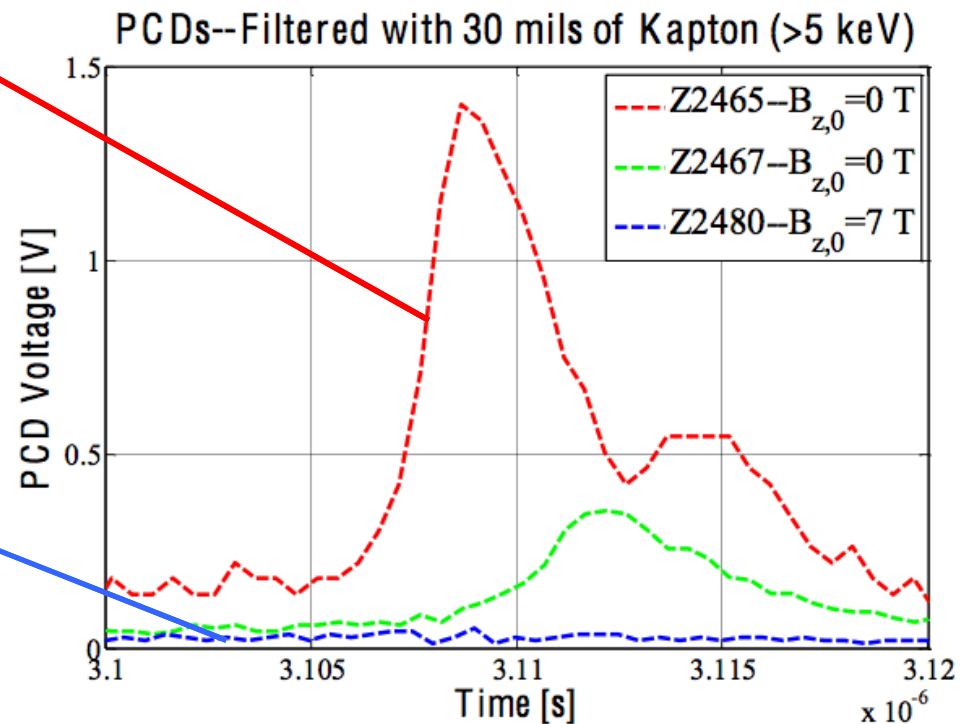


Time-integrated self-emission from liner implosion at 6151 eV; missing in shots with axial field

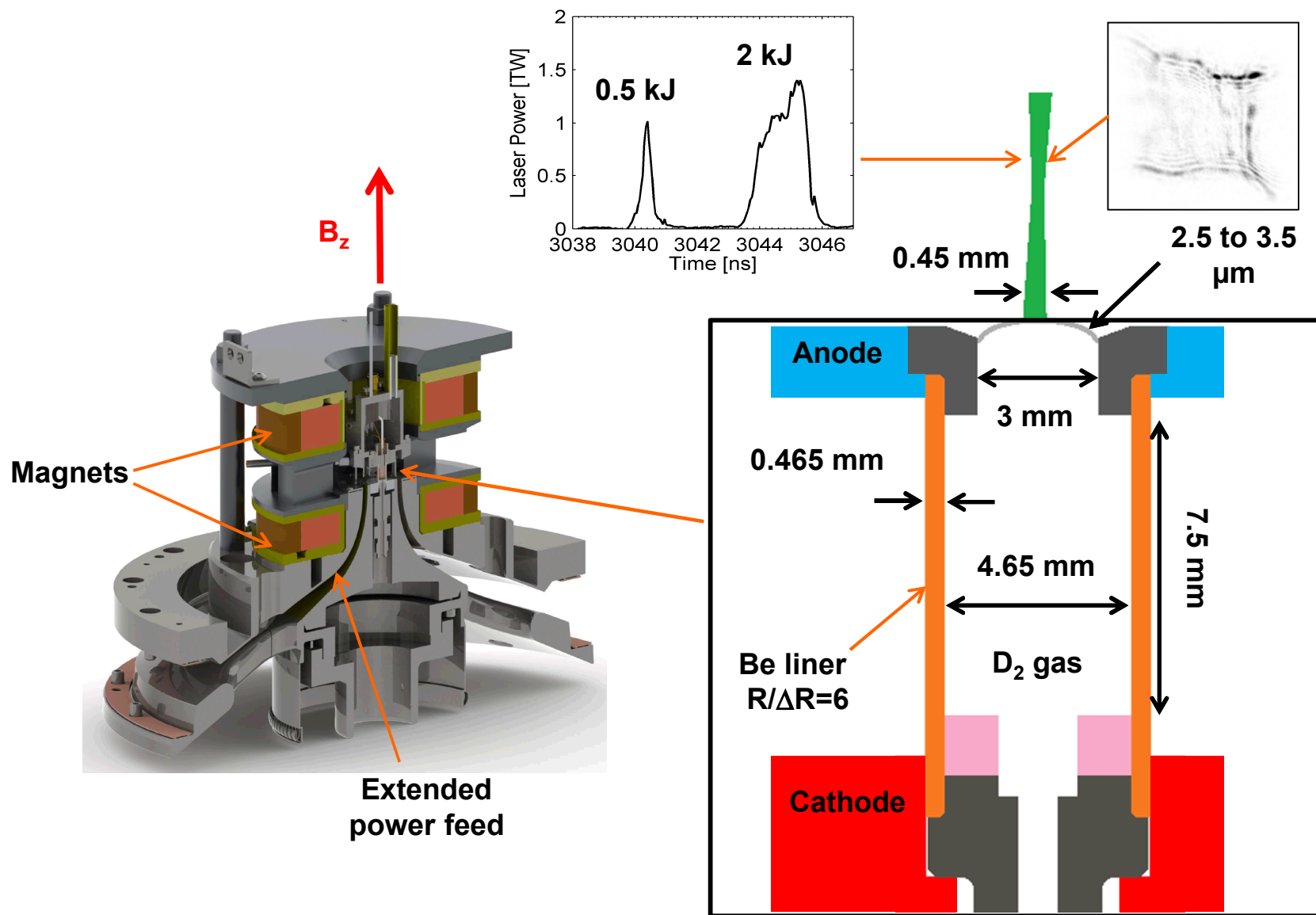


With Magnetic Field

If magnetic flux roughly conserved the additional magnetic pressure from the axial field will suppress micro-pinching—this is indirect evidence for flux compression

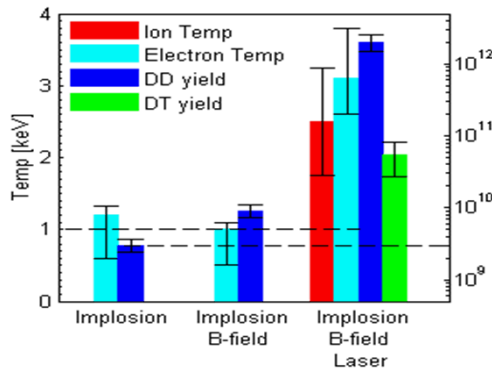


Initial MagLIF experiments¹ used 10 T, 2.5 kJ laser energy, and 18 MA of current to drive a D₂ filled (0.7 mg/cm³) Be liner

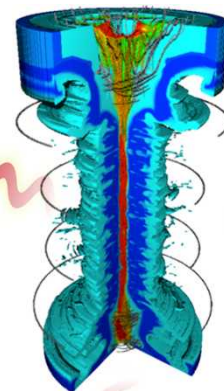


An ensemble of measurements from our first MagLIF experiments are consistent with a magnetized, thermonuclear plasma!

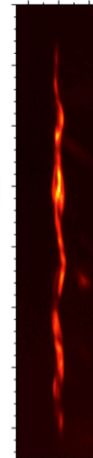
Nuclear Activation > 10^{12} DD neutrons



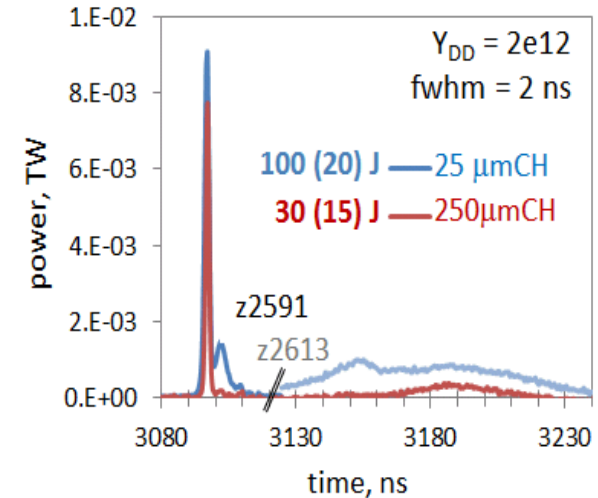
MagLIF Z pinch



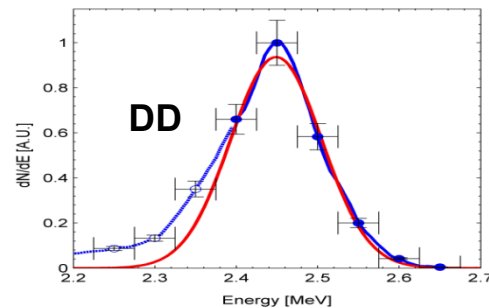
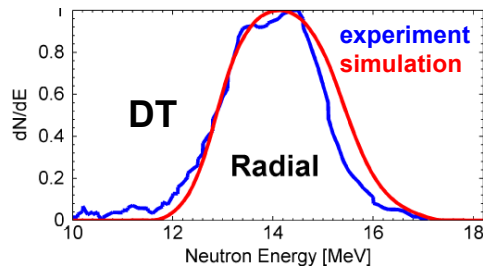
X-ray Imaging
hot plasma shape
Height ~ 6mm radius ~ 30-70



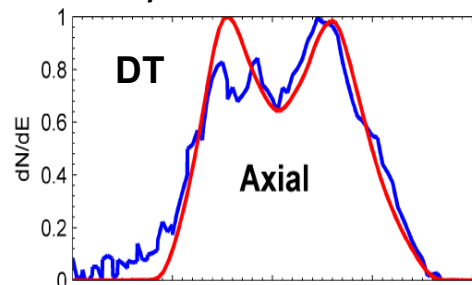
X-ray Power
burn time 1-2 ns



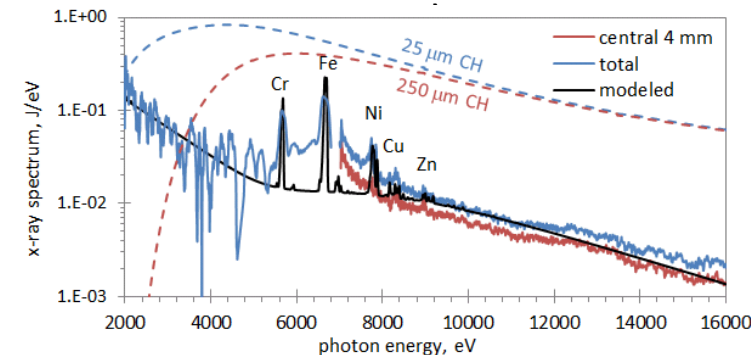
Neutron spectra
Tion ~ 3 keV liner pR ~ 0.9



DT Neutron spectra
DD/DT => BR ~ 0.4 MG-cm



X-ray Spectra (mix)
Te ~ 3 keV rfuel ~ 0.3 g/cc fuel pR ~ 1.5 mg/cm



**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



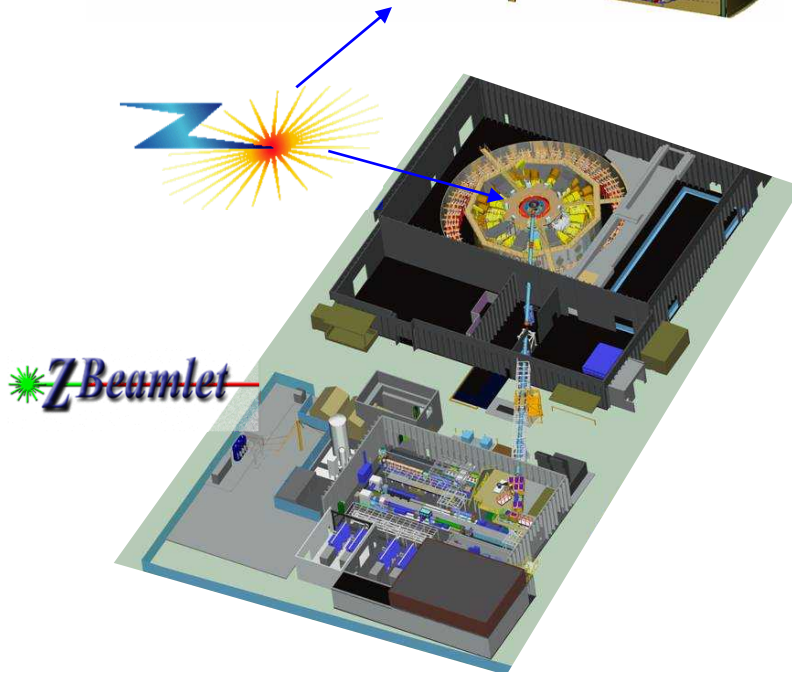
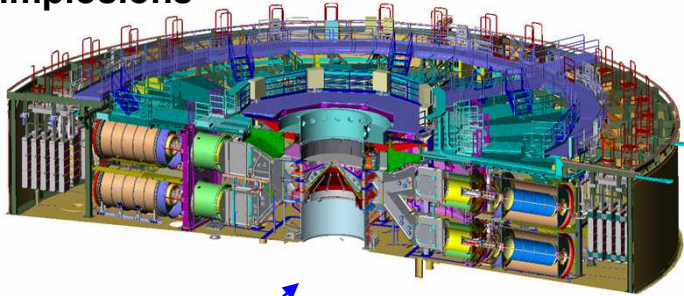
**Damage to FOA
debris shielding**



**Post-shot
photo**

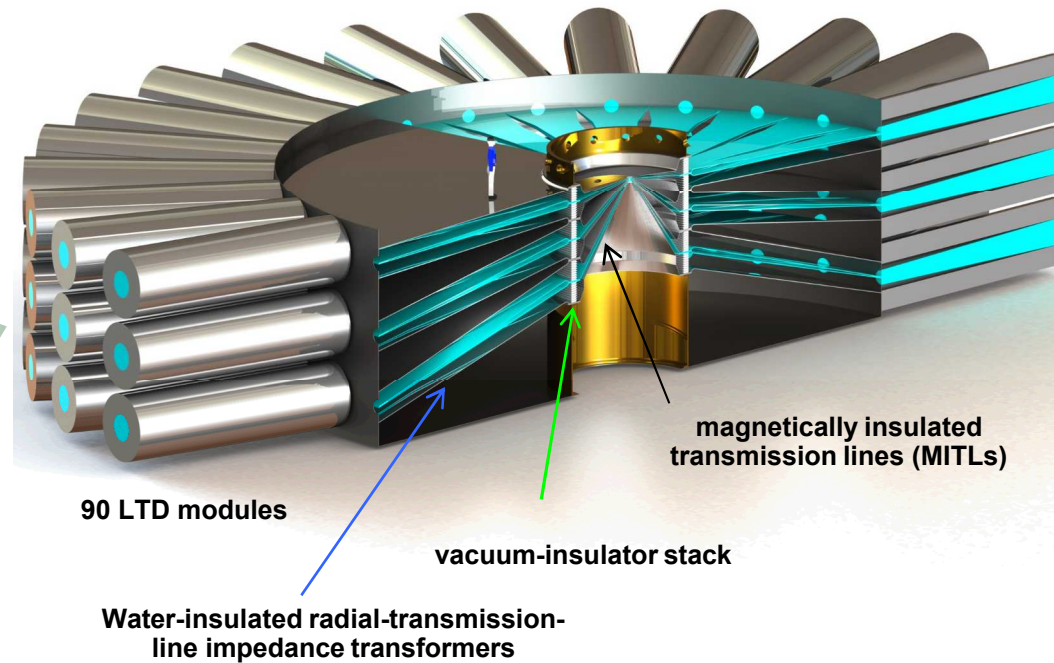
The MagLIF concept¹ is being tested² on the Z facility. Higher drive currents could be provided by future machines³

Z can generate high magnetic pressures to drive cylindrical implosions



Z-Beamlet provides fuel preheat

Z 300 employs Linear Transformer Driver (LTD) technology to deliver 48 MA to a MagLIF load, and would fit within the existing Z building.



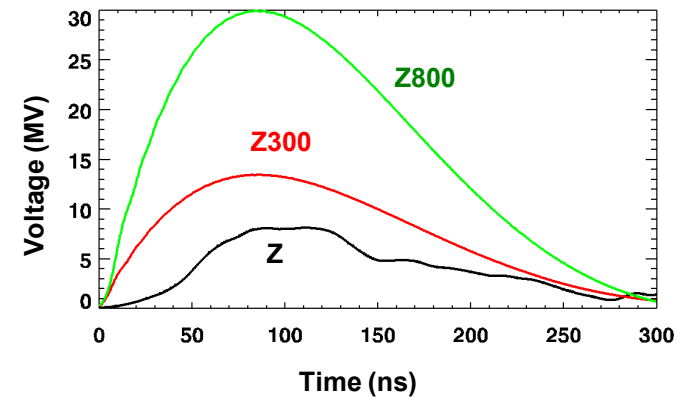
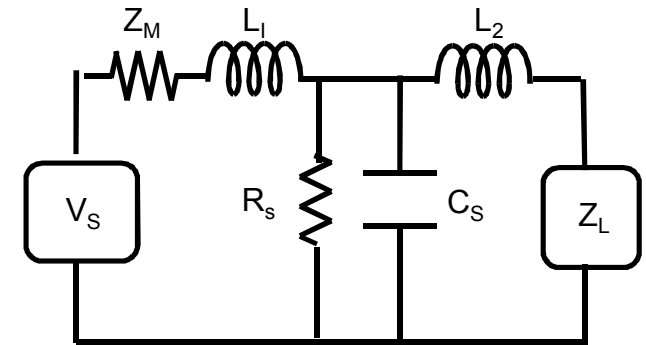
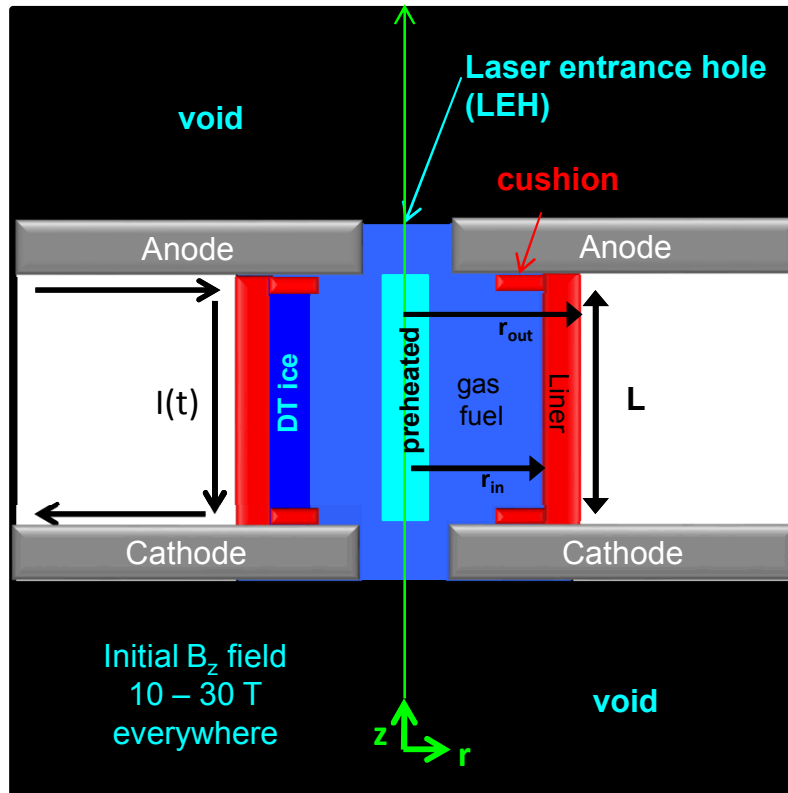
Z800 would deliver 65 MA with the same technology

¹Slutz et al. PoP 2010

²Gomez et al. PoP 2014

³Stygar et al Phys. Rev. ST Accel. Beams 2015

2D Lasnex simulations based on simplified geometry and circuit model



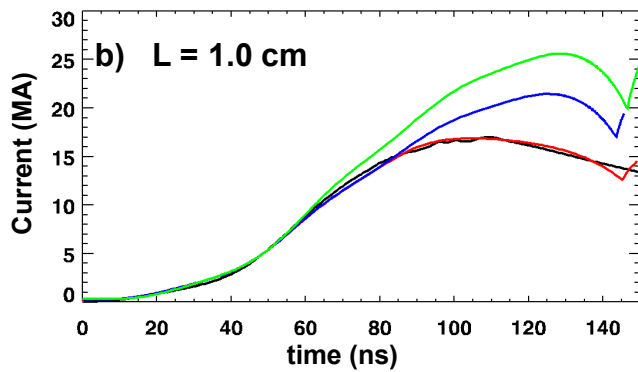
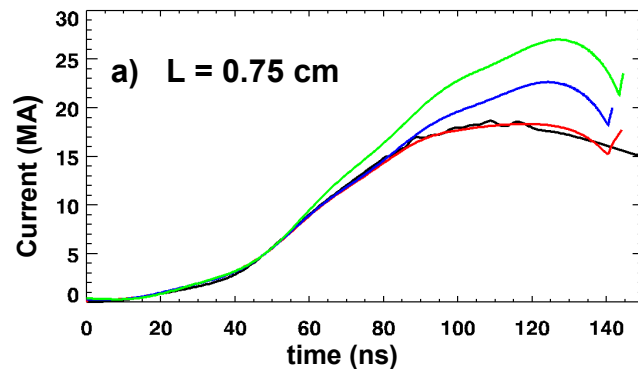
Simulated yields are comparable to experiments results

Black: 80 kV MagLIF experiments results

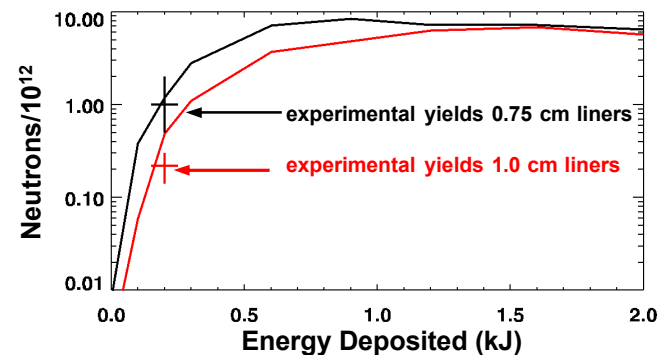
Red: 80 kV simulated with feed loss

Blue: 80 kV simulated without feed loss

Green: 95 kV simulated without feed loss



2D MagLIF simulations

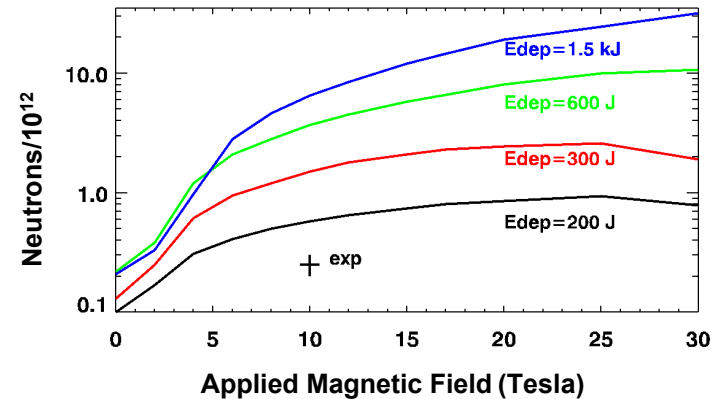
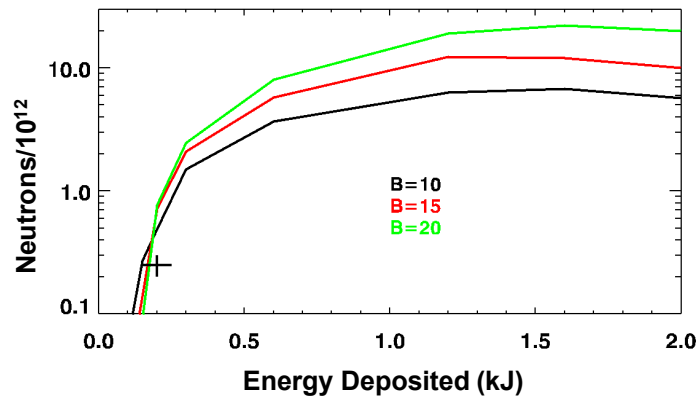


Z Beamlet produces 2 kJ of unsmoothed 0.53 mm light

- Only ~ 200 Joules penetrates foil¹

Present experiments on Z at 18 MA do not have optimal values of preheat or applied field according to simulation

2D Lasnex simulations of 1 cm long liners

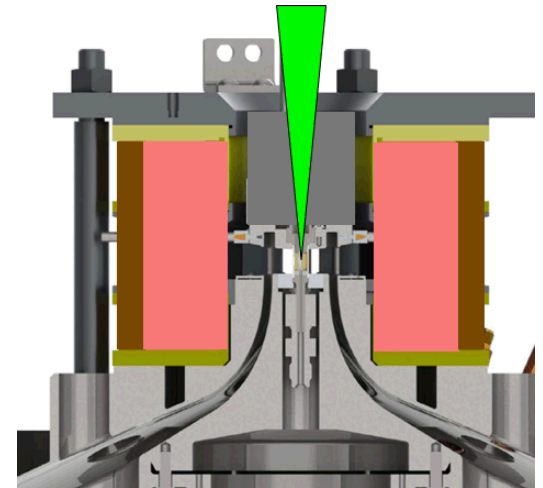
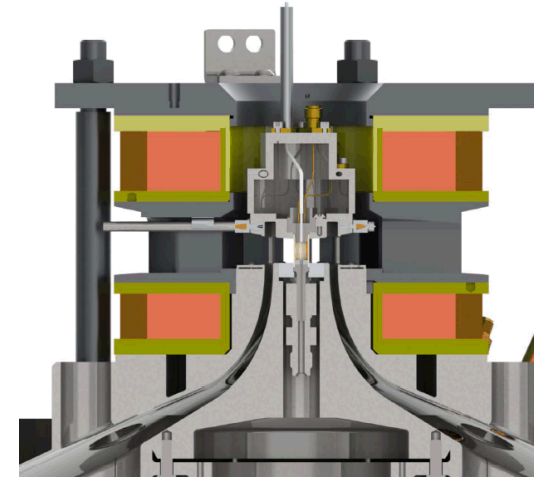


2D simulations predict yield increases with fuel preheat and applied B
Experiments will be performed to test these predictions

We are pursuing two parallel technology development paths to achieve 30 T fields on Z

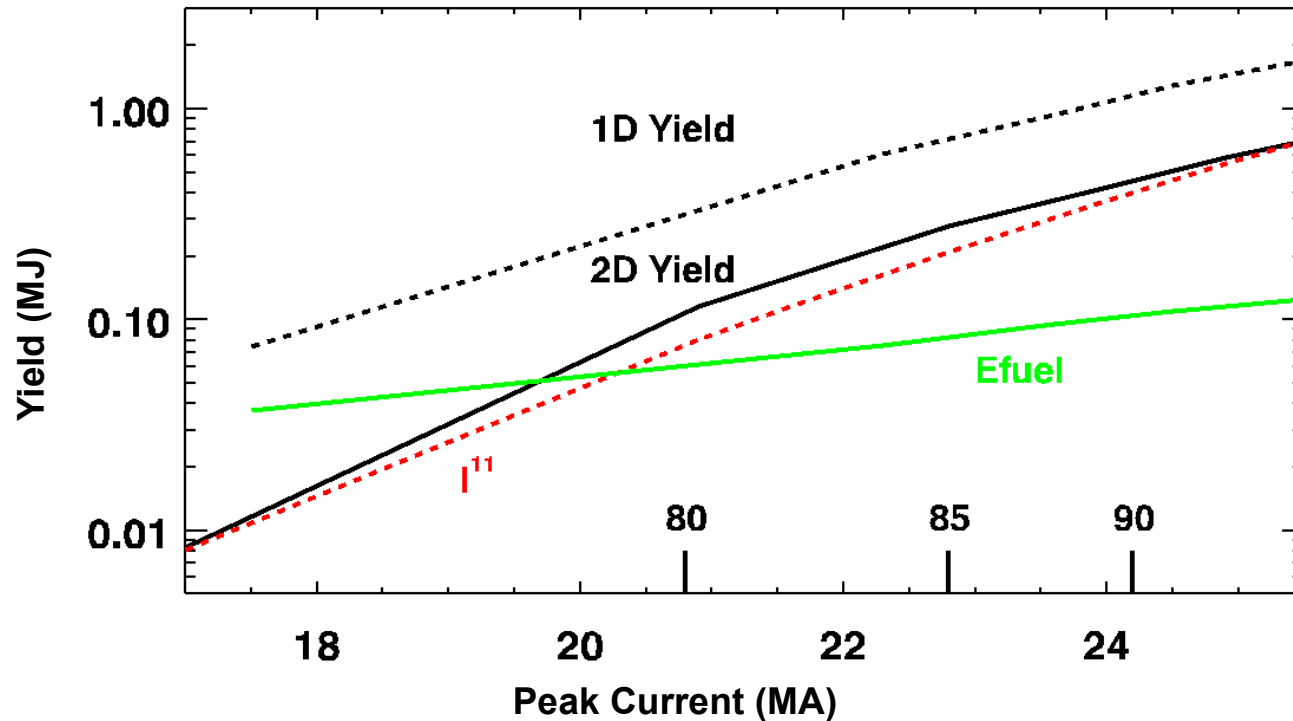
- **Most direct path to 30 T is to trade off radial diagnostic access for increased coil volume**
- **Have successfully tested the full-access coil configuration to 15 T in laboratory—peak stresses on those coils exceed those in our 30 T no-access coil designs**
- **Currently incorporating additional state-of-the-art high-field coil technologies (e.g., internally reinforced magnets, high strength conductors)**
- **Working in parallel with National High Magnetic Field Laboratory at Los Alamos to build an independent 30 T prototype by end of FY14—they have also reviewed our designs**

Full-Access Coils (15 T max)



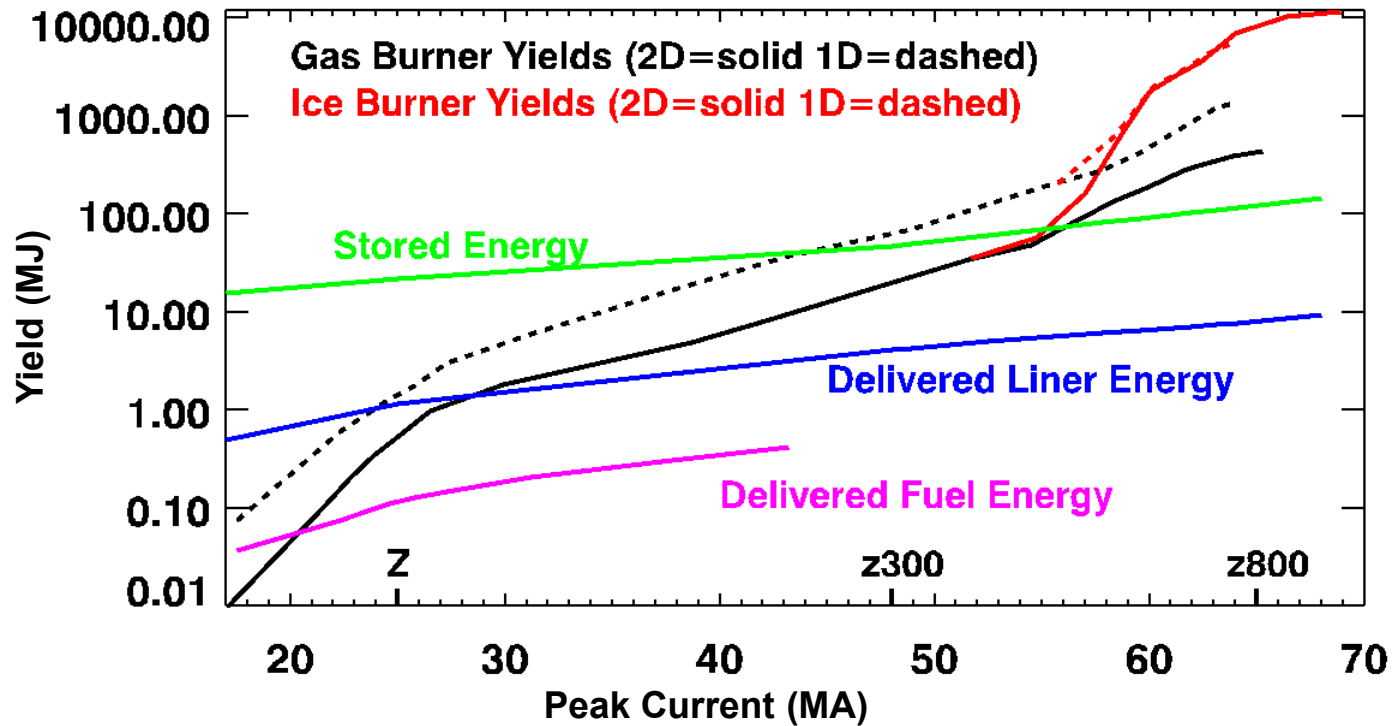
No-Access Coils (30-40 T max)

Simulations indicate that optimized yields are a strong function of current over the range accessible to Z



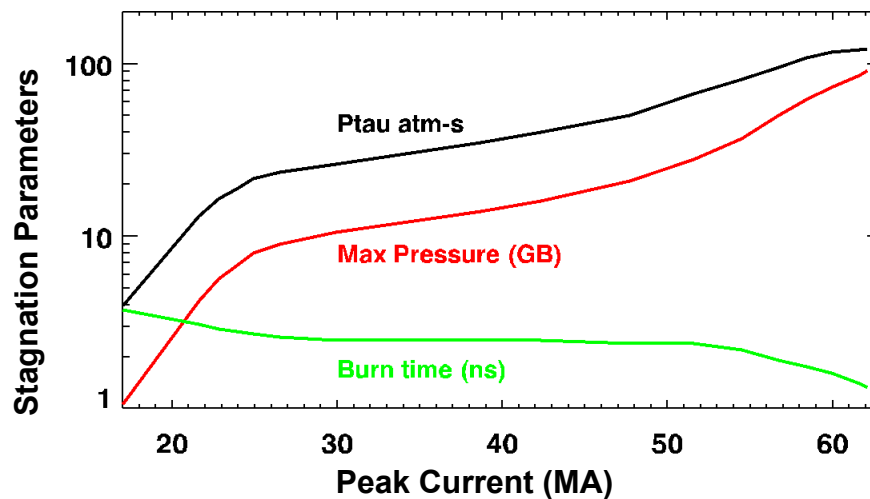
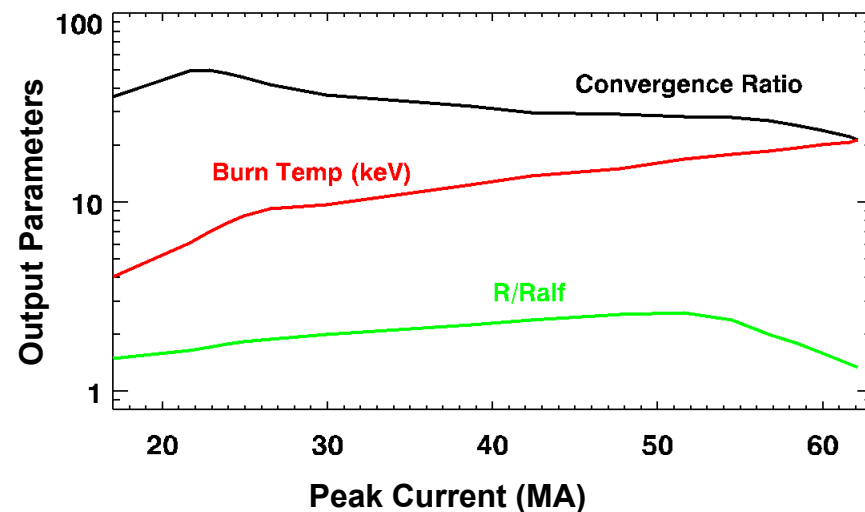
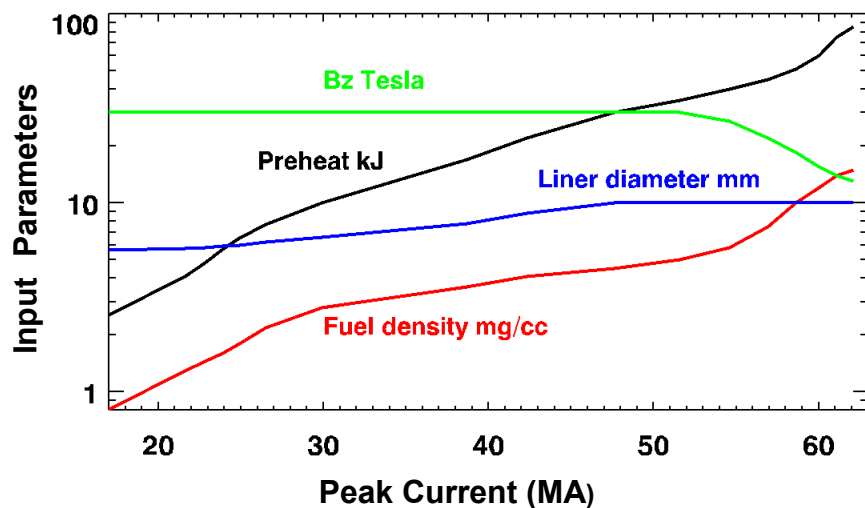
Capsule parameters (radius, fuel density, fuel preheat, and B_z) are optimized at each value of the drive current.

2D simulations indicate that Z300 could drive a MagLIF with a gain greater than unity

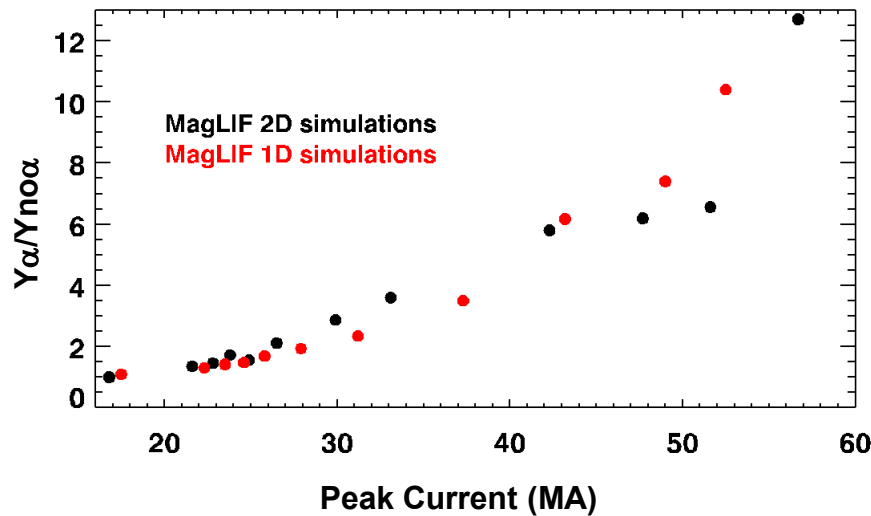


DT ice layers significantly enhance yields for drive currents > 60 MA
Engineering gains of 70 might be possible with Z800 ice burners

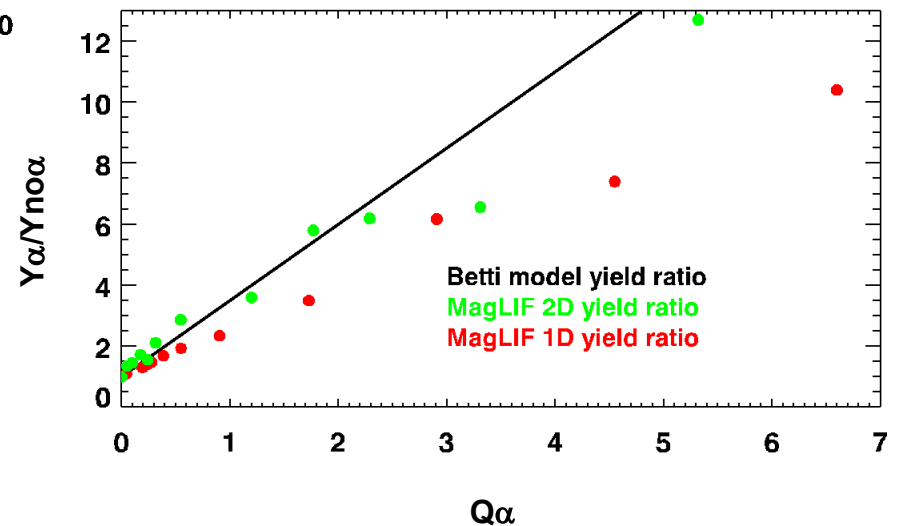
2D simulations indicate optimal design parameters and output quantities



The ratio of the yield with and without alpha particle heating can be used as an ignition metric¹



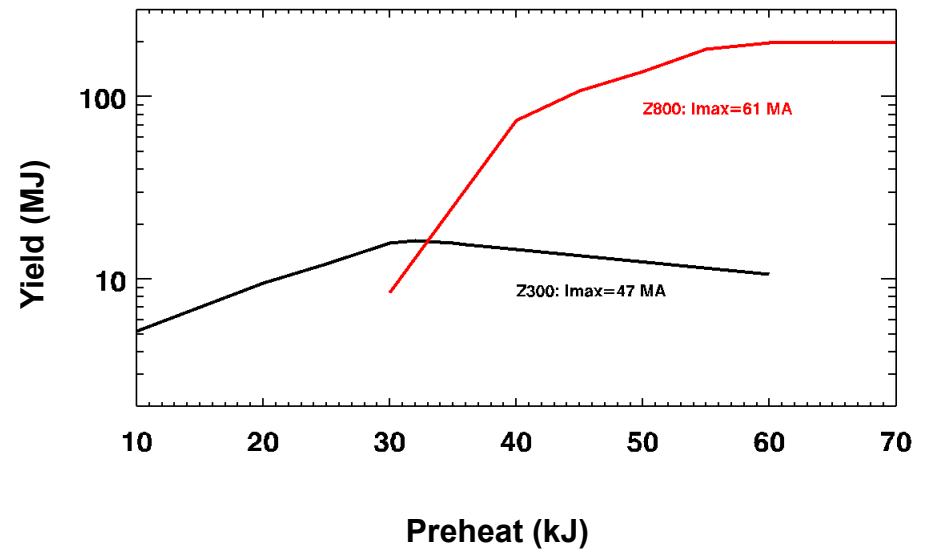
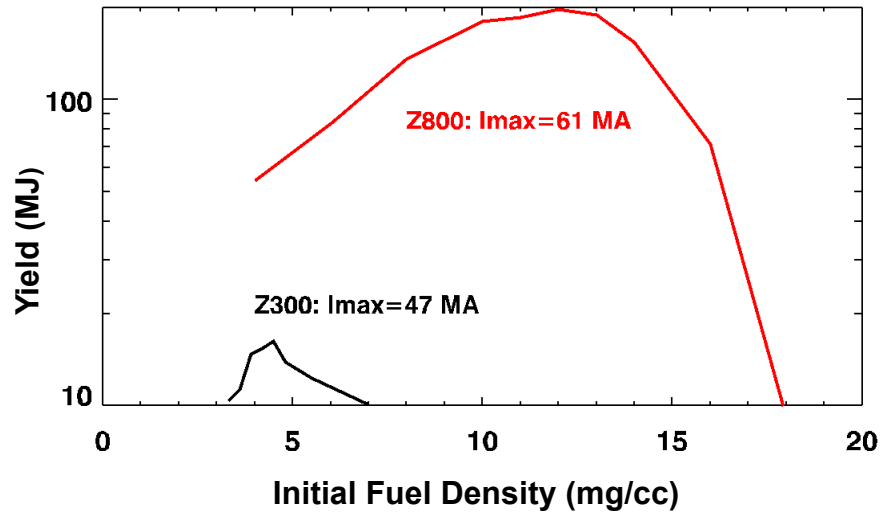
Defined Q_{α} : as the ratio of the fuel energy at peak burn with and without alpha deposition



¹Betti et al Phys. Rev. Lett. 114, 255003 2015

2D simulations indicate initial fuel density and preheat energies have broad optima

Lasnex simulations of Gas Burners

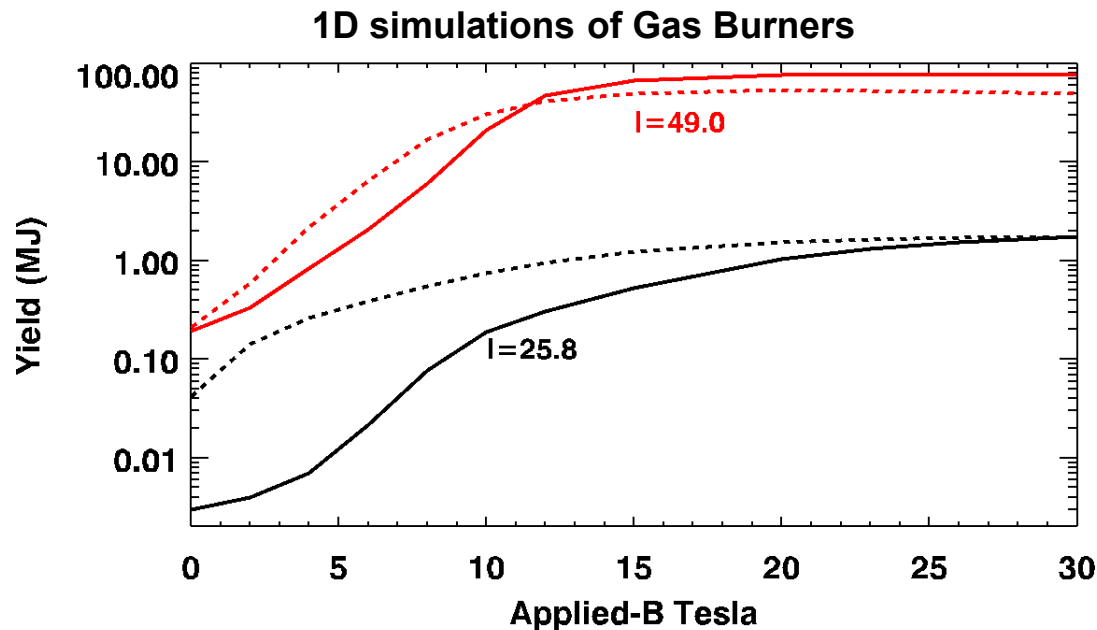


The Nernst effect can be significant

All of the preceding Lasnex simulations have included the Nernst (Ettingshausen) effect

Nernst produces an electric field E_{Nernst} proportional to $B \times \text{grad}(T)$

- The magnetic field is advected with a velocity proportional to E_{Nernst}/B
- The magnetic field is reduced in the hot core and increased near the fuel liner interface
- The effect is decreased when $\omega\tau$ is large and is not large for optimal B
- Experiments determining the yield as a function of B will determine the importance of this effect



Simple analytic theory predicts the laser penetration can be controlled by the beam radius

Laser absorption coefficient dominated by inverse Bremsstrahlung

$$C_V \frac{d\theta}{dt} = \frac{dI}{dz} = -kI \quad k = \frac{v_{ei} \omega_p^2}{c \omega_L^2} \left(1 - \frac{\omega_p^2}{\omega_L^2} \right)^{-1/2} = \frac{k_0}{\theta^{3/2}} \quad k_0 \approx 1.23 \times 10^6 (\rho \lambda_L Z_b)^2 (1 - 227 \rho Z_b \lambda_L^2)^{-1/2}$$
$$I = I_0 \left(1 - \frac{z}{z_f} \right)^{2/3} \quad z_f = \frac{5}{3} \left(\frac{2}{5k_0} \right)^{2/5} \left(\frac{I_0 t}{2C_V \rho} \right)^{3/5} \quad R_{laser} = 5.4 \times 10^{-7} E_{laser}^{1/2} \lambda_L^{-.67} \rho^{-1.17} z_f^{-.83} (1 - 227 \rho \lambda_L^2)^{.17}$$

Hydrodynamics and refraction make this process more complicated

A short wavelength laser ($\lambda \sim 0.25\text{-}0.33 \mu$) could be used to penetrate the initially high density DT forming a low density channel

A second pulse of longer wavelength light ($\lambda = 0.5\text{-}1 \mu$) could then propagate down this channel and efficiently deposit its energy

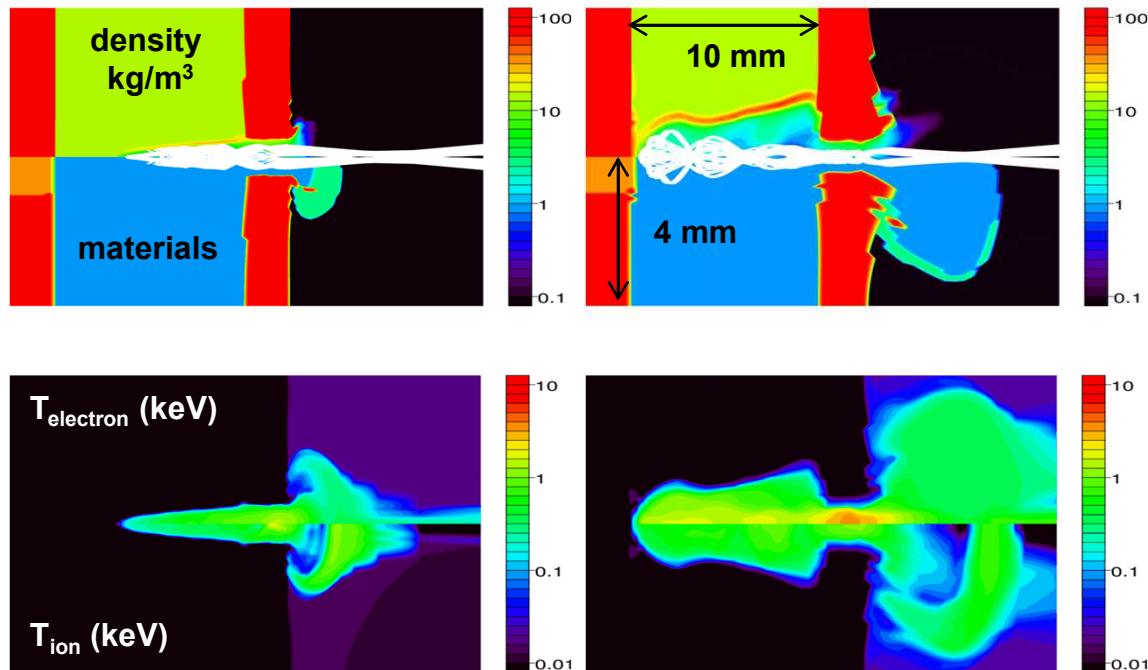
2D Lasnex simulation of laser deposition indicates that 30 kJ can be absorbed in 1 cm of 12 mg/cc DT fuel

3 kJ of 4ω to
bore a hole

30 kJ of 1ω to
deposit energy

End of 1st pulse

End of 2nd pulse



Laser plasma instabilities (LPI) could pose a problem for MagLIF preheat on future accelerators

LPI is unimportant if:

- the plasma density is much lower than the critical density ($n/n_{\text{crit}} \ll 1$)
- The laser intensity is low ($I_{\text{Laser}} < 10^{14}$ watts/cm²)

Optimum fuel densities are larger on future accelerators

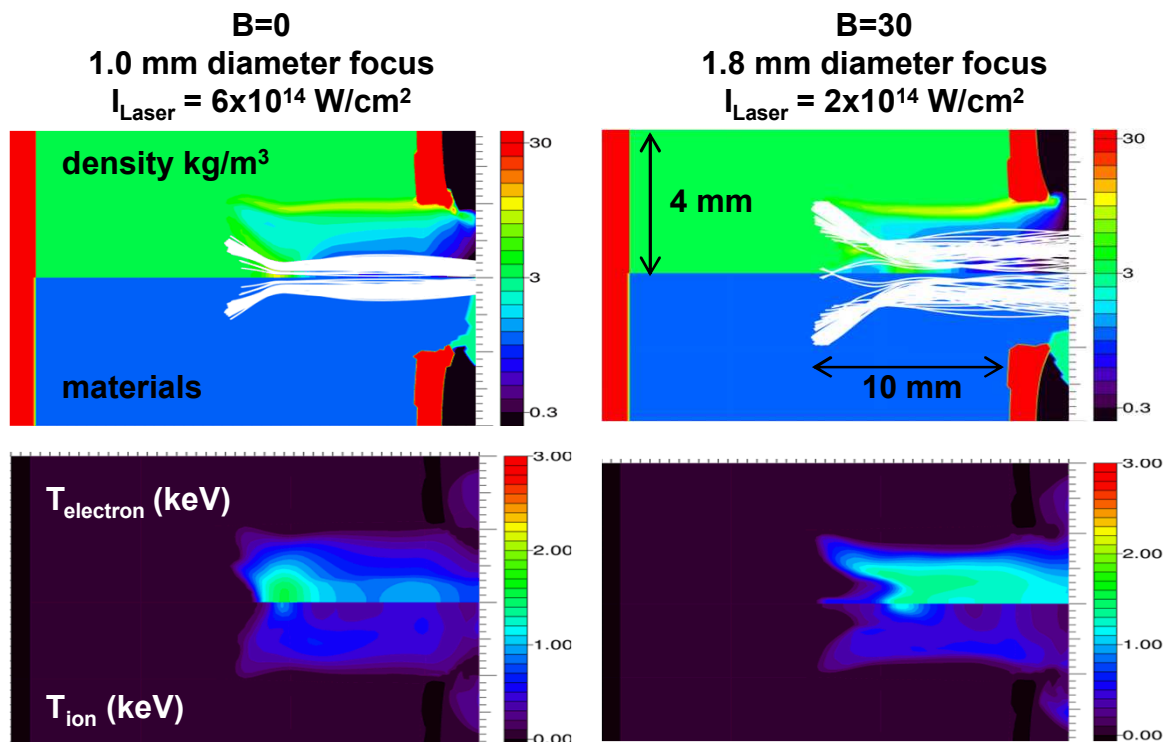
- Optimal fuel density ~ 5 mg/cc on Z300 ($n/n_{\text{crit}} \sim 0.13$) for 3ω

Optimum preheat energies are larger on future accelerators

- Optimum preheat ~ 30 kJ on Z300
- Laser pulse can not be too long or gas moves out of the way. Beam intensity may need to be $> 10^{14}$ watt/cm²

Laser preheating at Z300 levels could be tested using a quad of NIF

30 kJ 3ω at 5 TW stopped in 1 cm of DT at 4.5 mg/cc



Simulations and experiments indicate that MagLIF may be a viable alternative approach to fusion

Present experiments have been performed at 18 MA with B=10 Tesla and low preheat ~ 200 joules

- **Phase plates have been designed for Z Beamlet to enable larger preheat energies**
- **30 Tesla fields are possible with the existing field coil system**
- **An improved convolute design will be tested with MagLIF to obtain higher drive currents on Z**

1D and 2D simulations indicate that large yields and gains may be possible on a future machine such as Z300

Simulation predictive capability is greatest when the extrapolation is not large

Full scale laser deposition experiments could be performed using one quad of the NIF to remove uncertainties about laser preheating

Agreement between the simulation scaling presented here and the results of experimental scaling will greatly increase our confidence to predict MagLIF performance on future machines

Large yields (10-30 GJ) might be contained in compact chambers using the concept of a deflector

