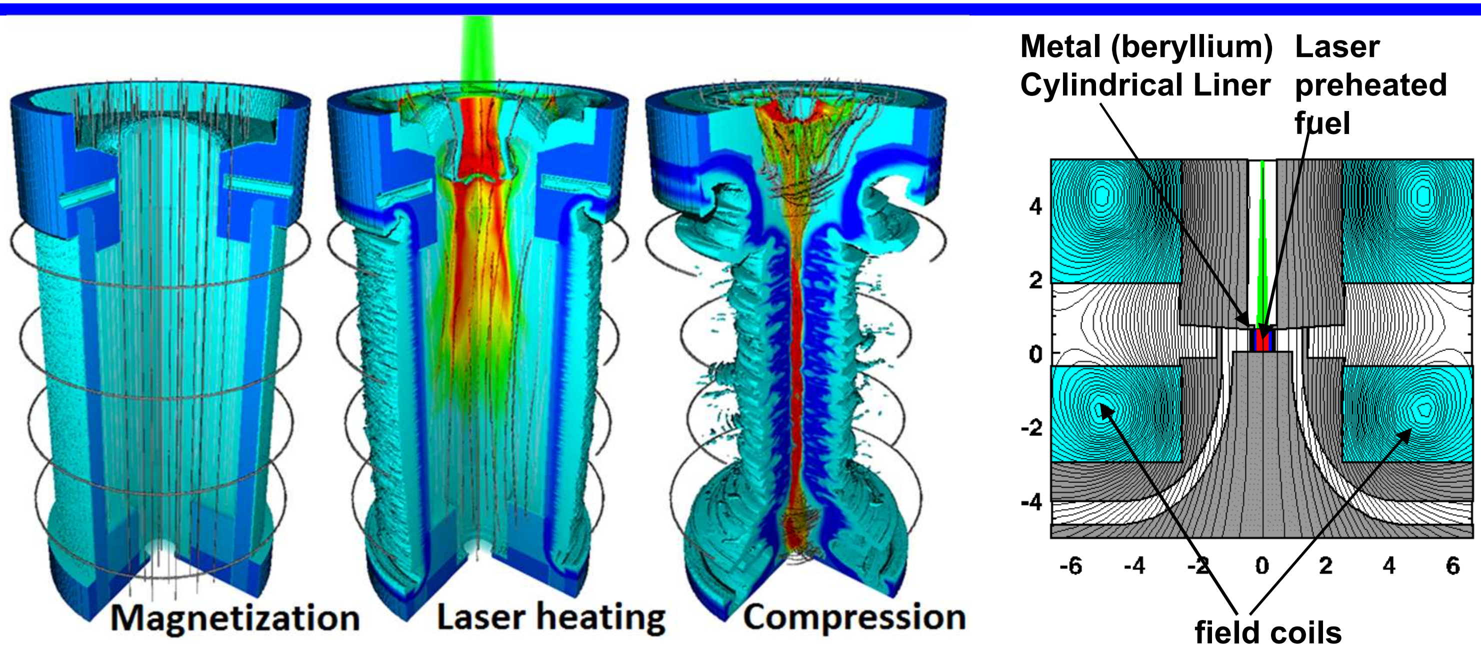
Magnetized Liner Inertial Fusion, MagLIF[1]

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



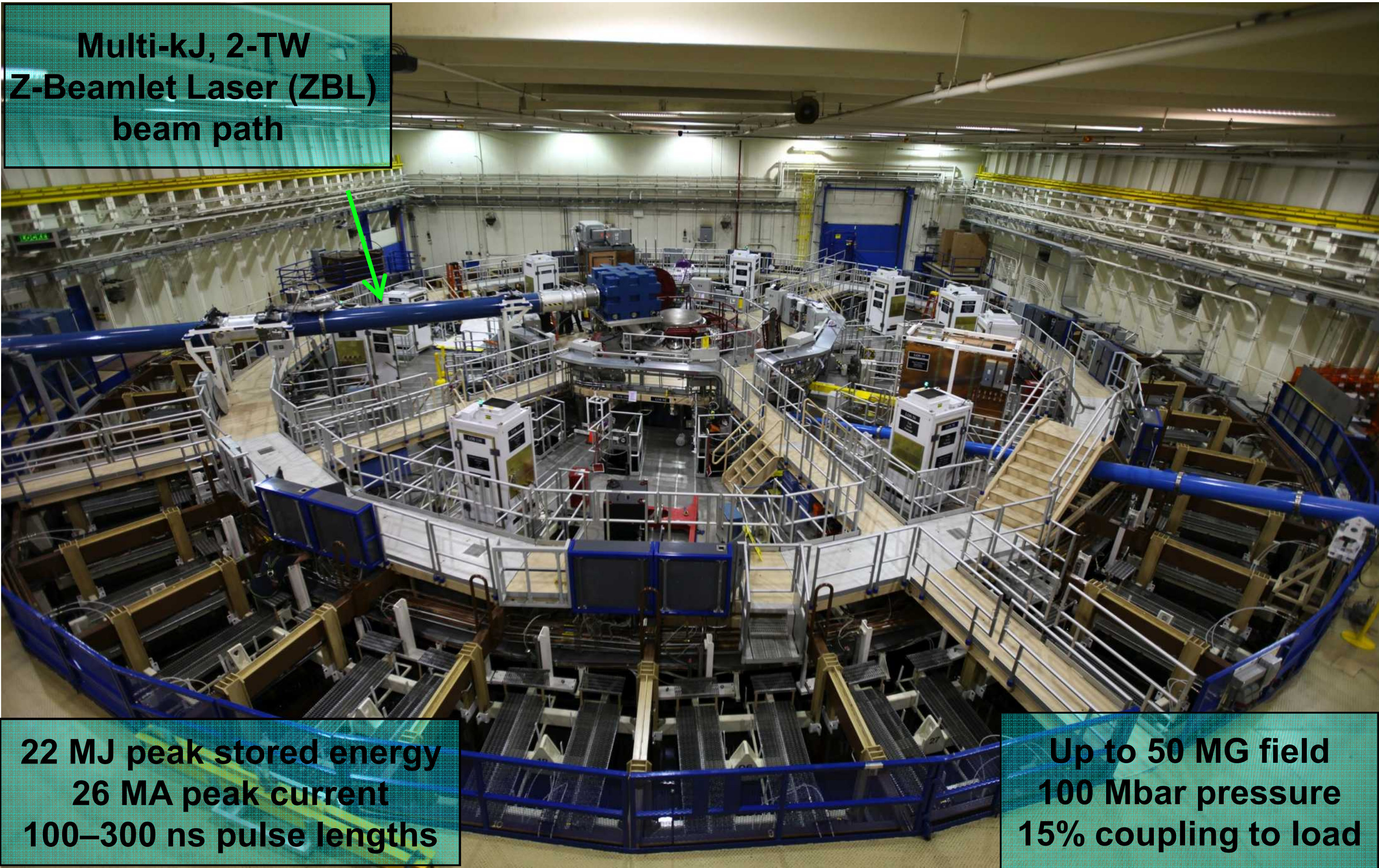
University of New Mexico

Albuquerque, NM, May 6, 2016

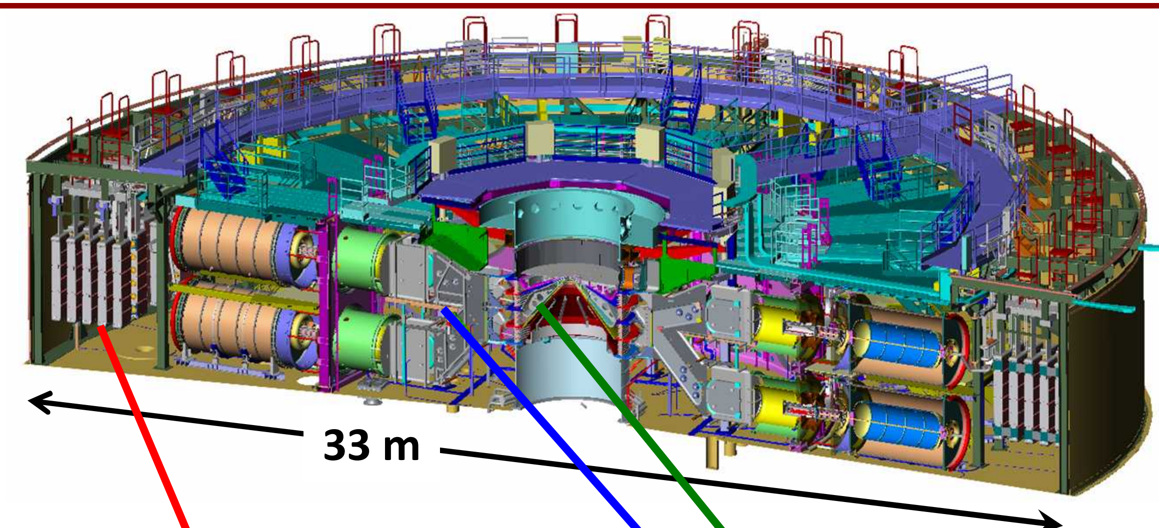
Stephen A. Slutz, *Sandia National Laboratories*

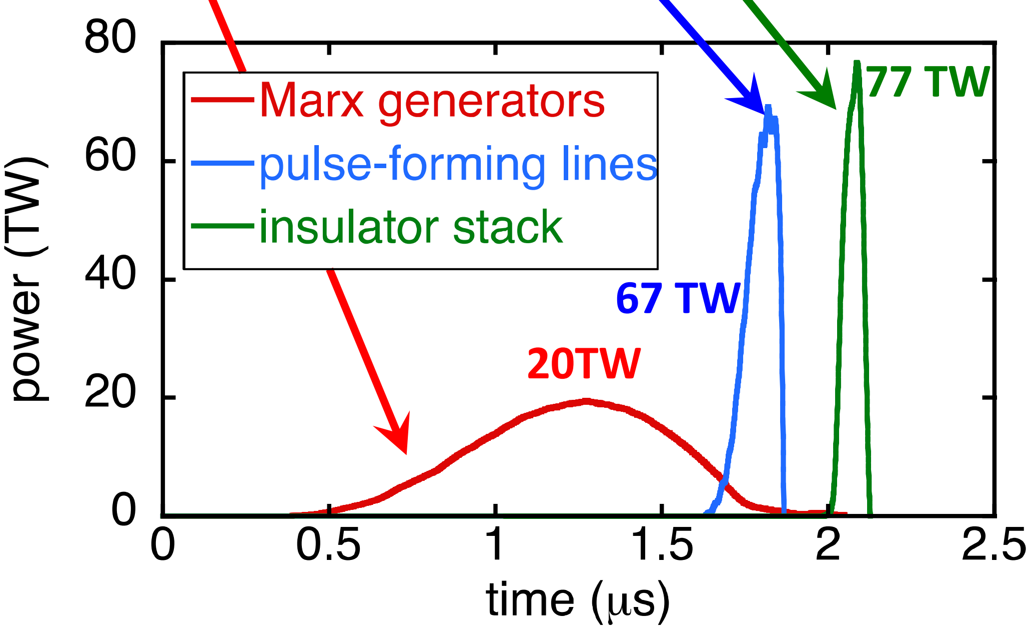
This work in collaboration with M. R. Gomez, A. B Sefkow, R. A. Vesey, D. B. Sinars, D. C. Rovang, E. M. Campbell, M. C. Herrmann, K. J. Peterson, W. A. Stygar, T. J. Awe, R. McBride, M. Geissel, K. D. Hahn, D. C. Rovang, G. W. Cooper and M. E. Cuneo.

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



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

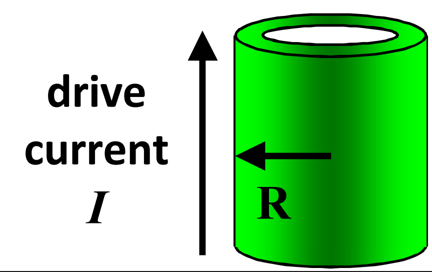




Z today couples ~0.5 MJ out of 20 MJ stored to magnetized liner inertial fusion (MagLIF) target (0.1 MJ in DD fuel).

Magnetically Driven Implosion

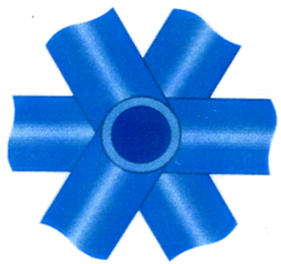
$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$



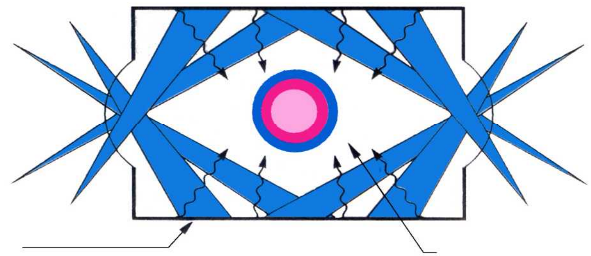
100 MBar at 26 MA and 1 mm

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)

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

$$T \approx 5\,\mathrm{keV}$$

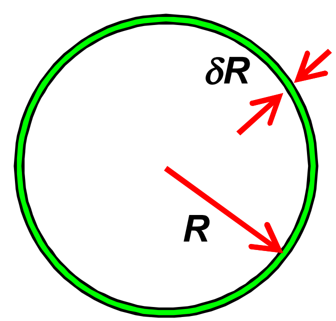
In either direct or indirect drive, ablation pressures are of order ~ 50-150 Mbar, but ~500,000 Mbar for ignition!

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

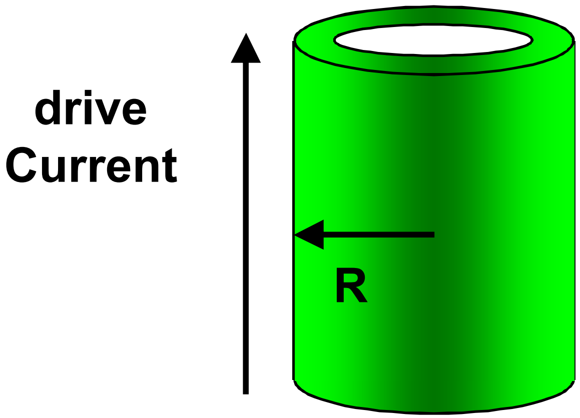
Thin shell implosions can reach the 200-400 km/s needed for ICF

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

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



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

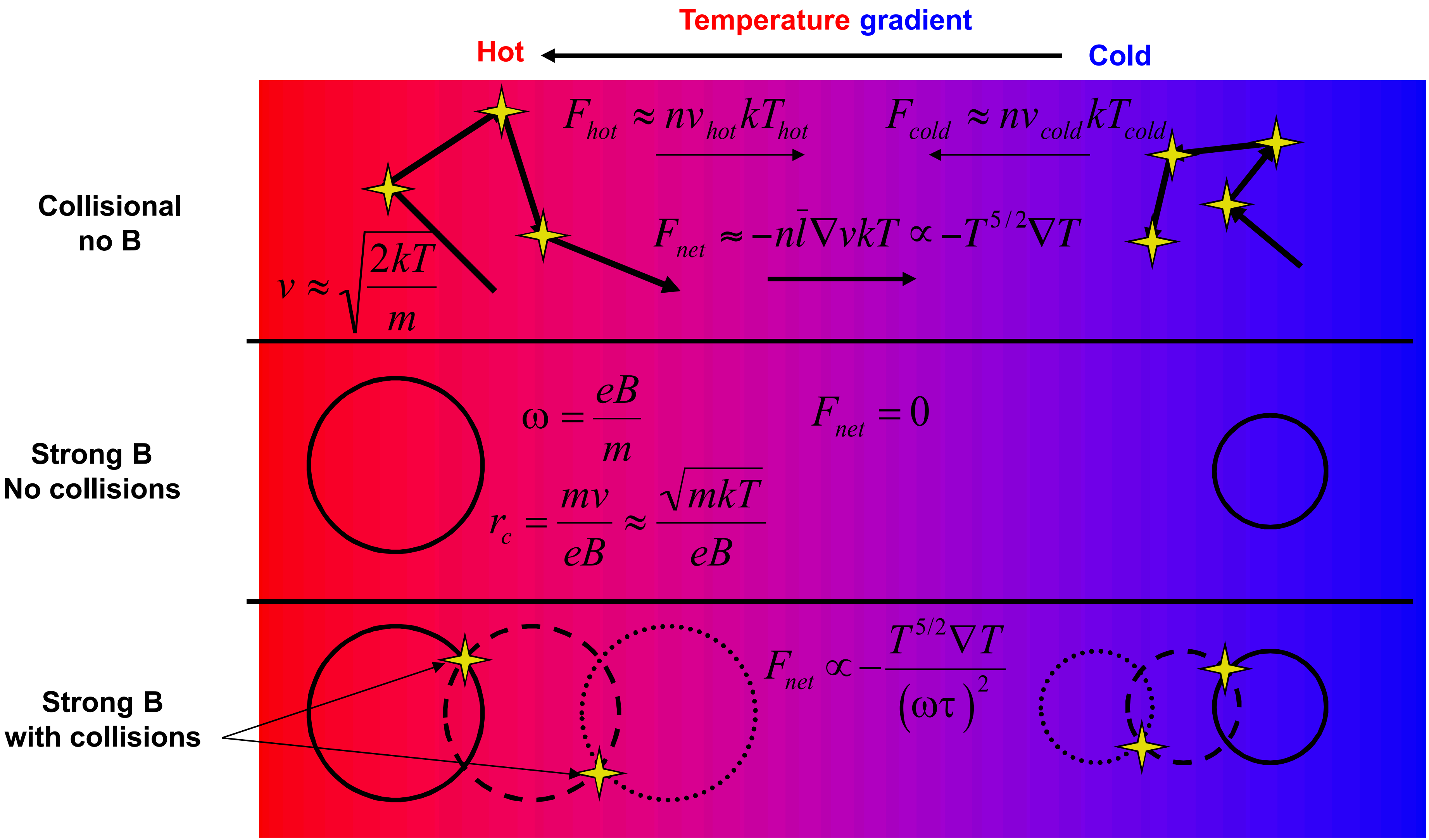


$$R\frac{d^2R}{dt^2} = -\frac{\mu_0}{4\pi}\frac{I^2}{m_l}$$

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

- **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**

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

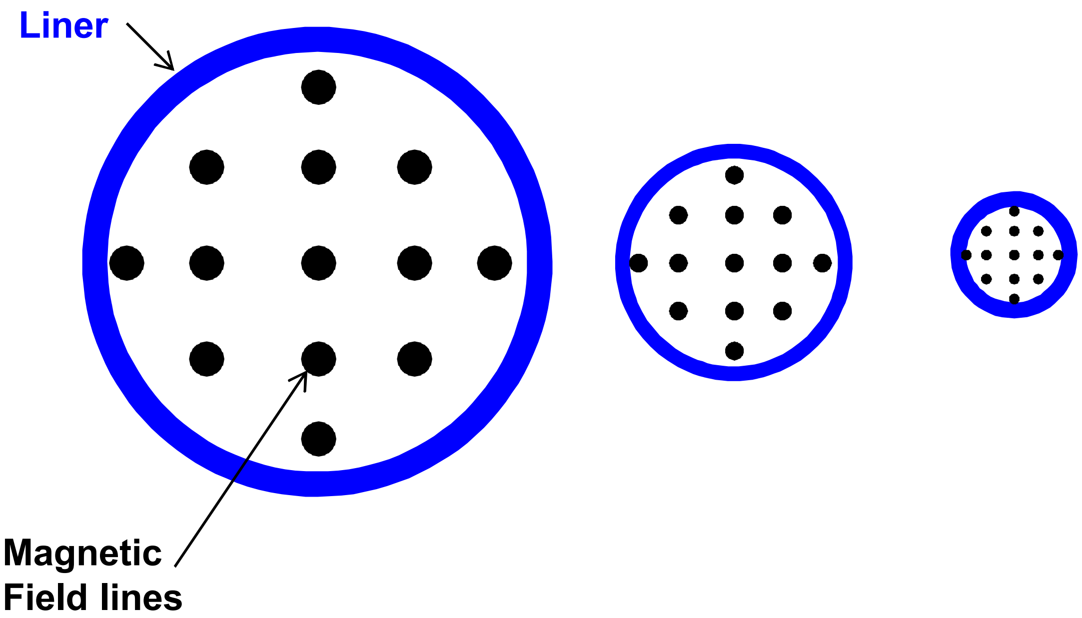


Energetic particles are also strongly affected by magnetic fields

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

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



Magnetization reduces the minimum implosion velocity for ICF

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Compressive heating during the implosion must significantly exceed losses

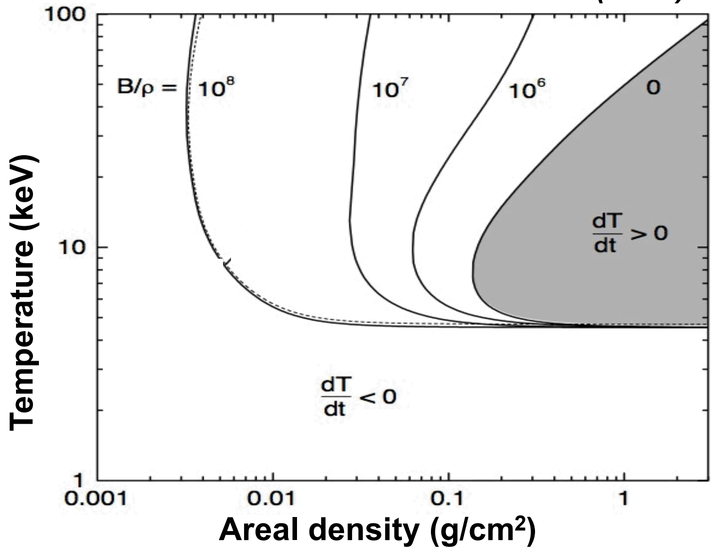
- **The heating rate is proportional to the implosion velocity** $P\frac{dV}{dt} \approx 5.0x10^{8}\rho r T\frac{dr}{dt} W/cm$
- **The dominant cooling rate is electron thermal conduction** $L_{ce} \approx \frac{8.7x10^{12}T^{7/2}}{(\omega\tau)^{2}} W/cm$

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

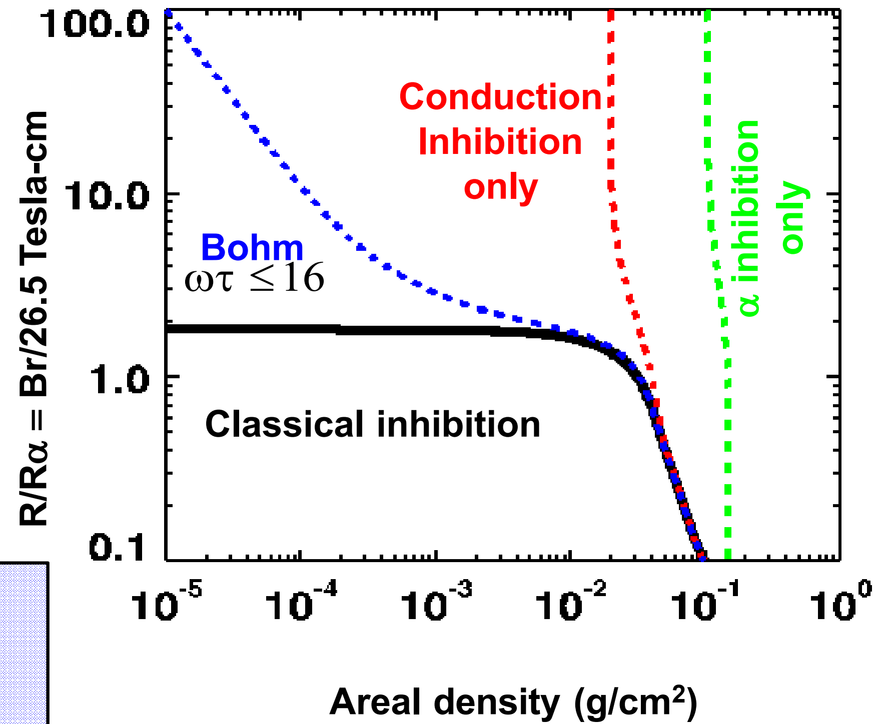
- **The bremsstrahlung losses** $L_{rad} \approx 9.6x10^{16}\left(\rho r\right)^{2} T^{1/2} W/cm$
- **The implosion time then determines the maximum fuel density** $\rho_{final} \approx \left(\frac{100ns}{\tau_{imp}}\right) g/cc$

Magnetization increases the ignition space replacing the minimum fuel ρr with minimum Br

**Basko et al. Nuc. Fusion (2000)*



T=10 keV



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 $\quad F_e(\theta, B/\rho) \propto \theta^{-3} (B/\rho)^{-2}$

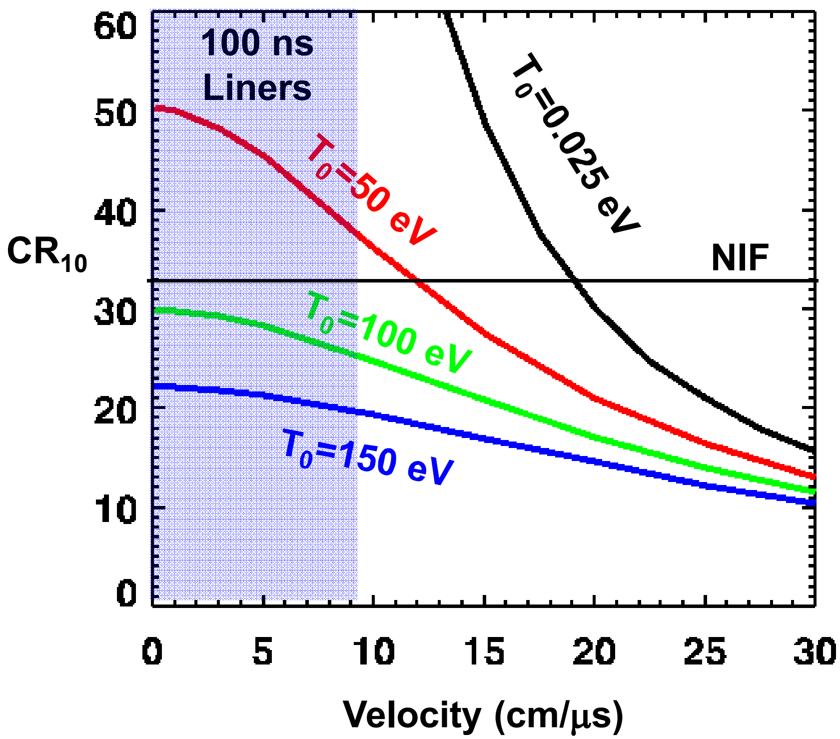
Axial α-trapping requires closed field lines or moderately high fuel density so that

$$\rho \Delta z > 0.5\, g/cm^2$$

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

Lasnex simulation with constant velocity



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

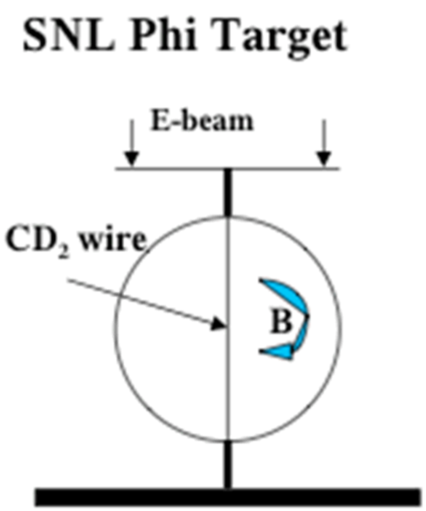
- **adiabat set by implosion velocity (shock) or**
- **alternatively by fuel preheat**

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

Preheating can be used to control the required convergence ratio

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

The benefit of magnetized fuel for ICF capsules was first demonstrated and Sandia



Electron beam driven ICF capsules imploded too slowly

...fuel temperature was limited by electron thermal conduction to the capsule wall

…no neutrons could be measured without magnetization

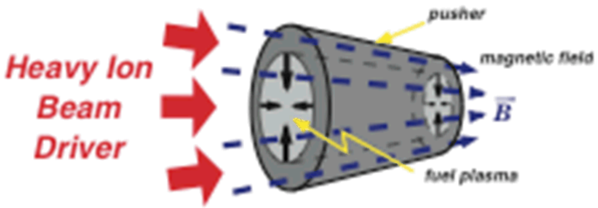
A portion of the beam was used to create a magnetic field and preheated fuel

…the “Phi” targets produced ~ 10^6 neutrons

M.M. Widner, Bull. Am. Phys. Soc. 22, 1139 (1977)   M.A. Sweeney and A.V. Farnsworth, Nucl. Fusion, 21, 41 (1981)

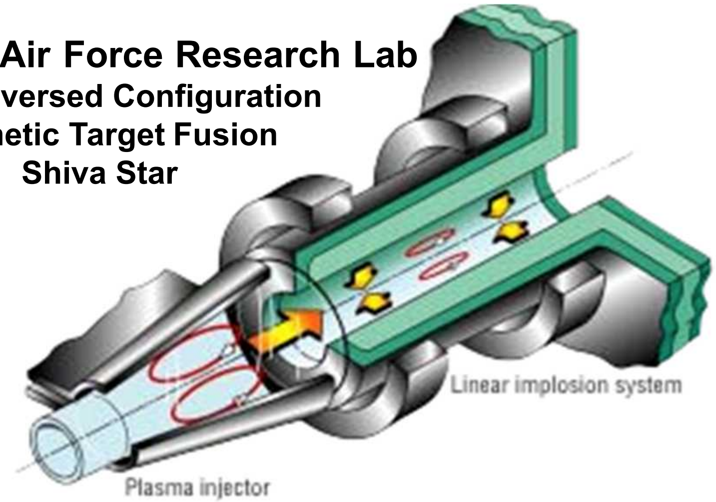
A number of scenarios using magnetized fuel have since been proposed

Max Planck/ITEP

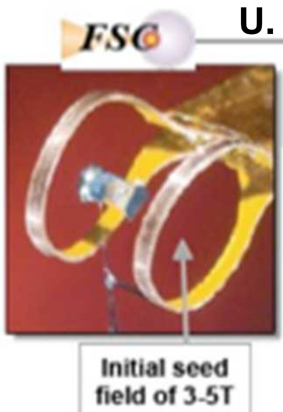


Los Alamos/Air Force Research Lab

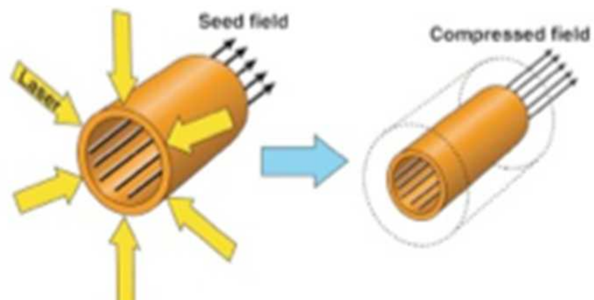
Field Reversed Configuration
Magnetic Target Fusion
Shiva Star



U. Rochester LLE



A magnetized ICF implosion yields higher fuel temperatures



Direct drive laser implosion of cylinders
…preheat not necessary due to high implosion velocity

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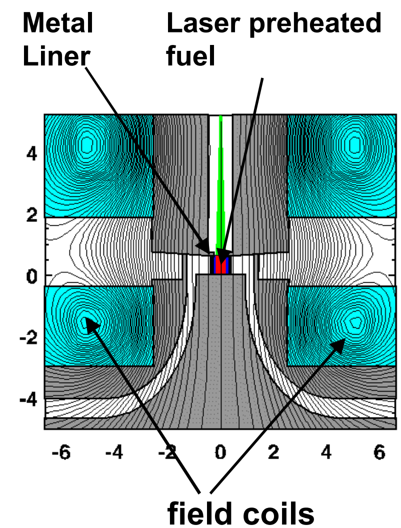
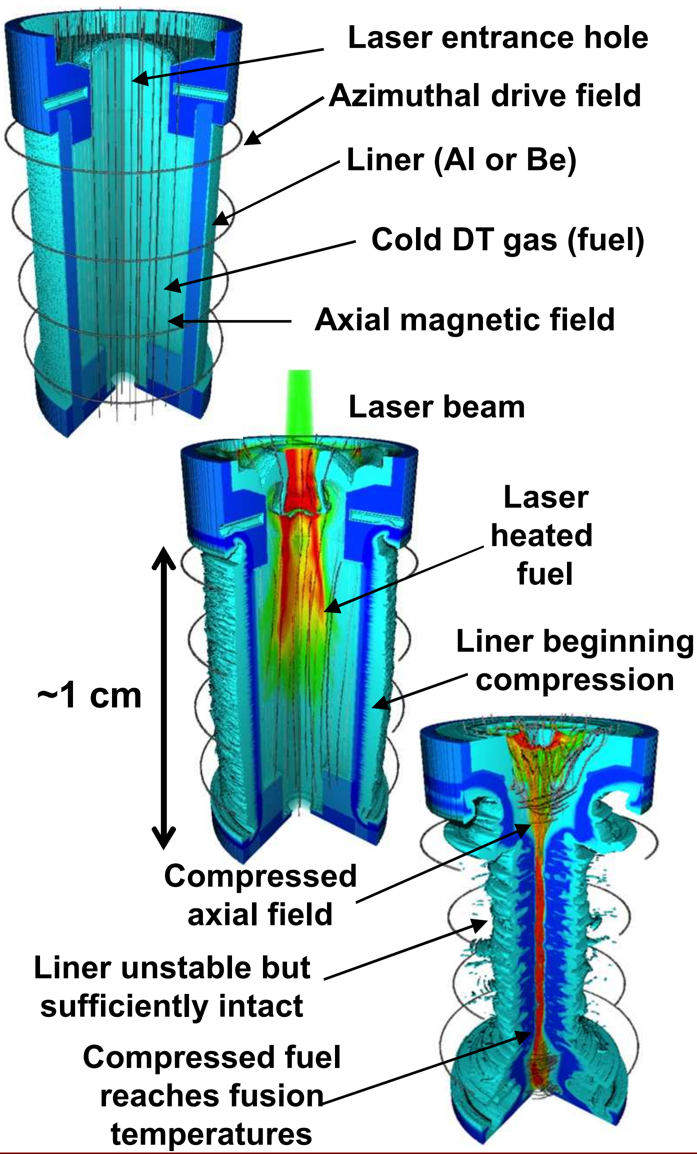
MagLIF: Magetized Liner Inertial Fusion



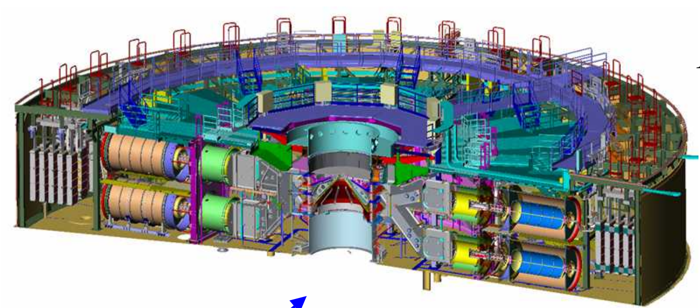
Magnetized Liner Inertial Fusion (MagLIF)* concept has three steps



- An initial 30 T axial magnetic field is applied
  - Inhibits thermal conduction losses
  - Appears to stabilize implosion at late times
- At the beginning of the ~100 ns implosion, the fuel is heated using the Z-Beamlet laser (2-6 kJ)
  - Preheating to ~300 eV reduces the compression needed to obtain fusion temperatures to 23 on Z
  - Preheating reduces the implosion velocity needed to ~100 km/s, allowing us to use thick liners that are more robust against instabilities
- The Z machine supplies current to drive the implosion

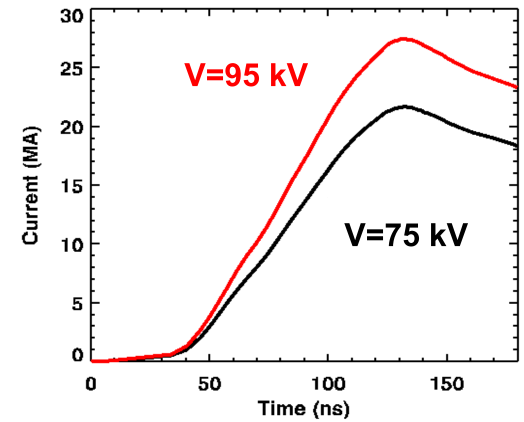
The Z facility combines the worlds largest pulsed power machine with a high power laser, which enables MagLIF

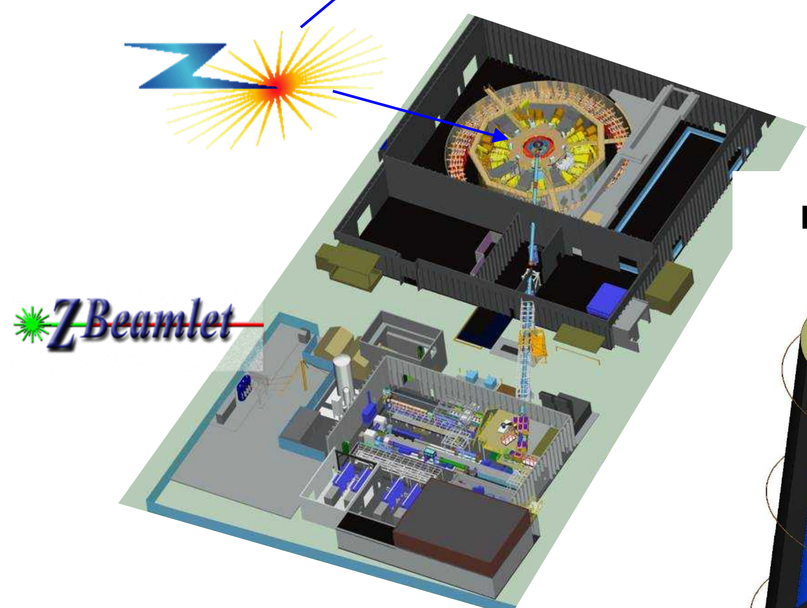
Z can generate high magnetic pressures to drive cylindrical implosions



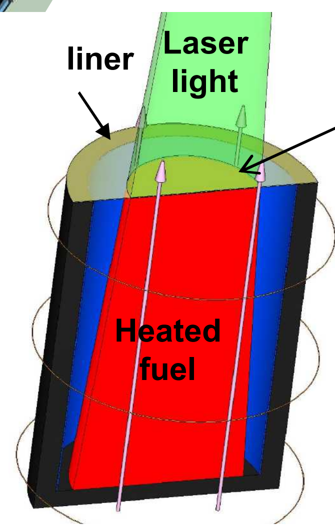
$$P = \frac{B^2}{2\mu_o} = 140\left(\frac{I_{MA}/30}{R_{mm}}\right)^2 MBar$$

140 MBar is generated by 300 eV radiation drive





The Z-Beamlet* laser can preheat the fuel

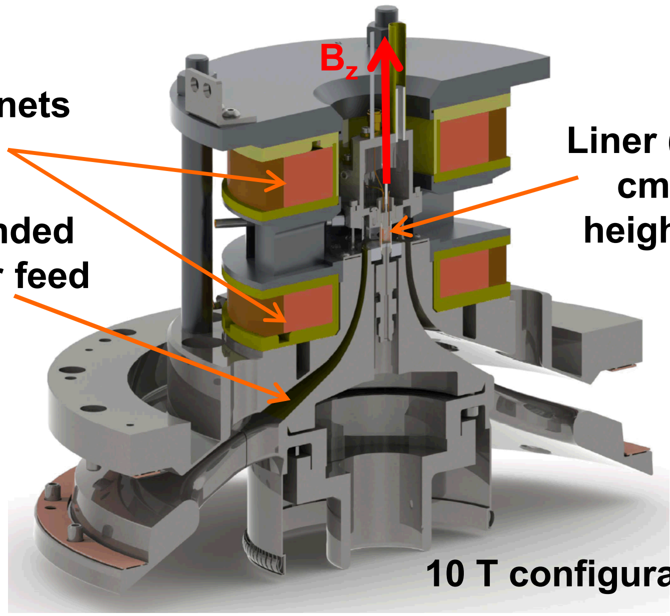


The gas is held by a thin plastic foil ~ 1um

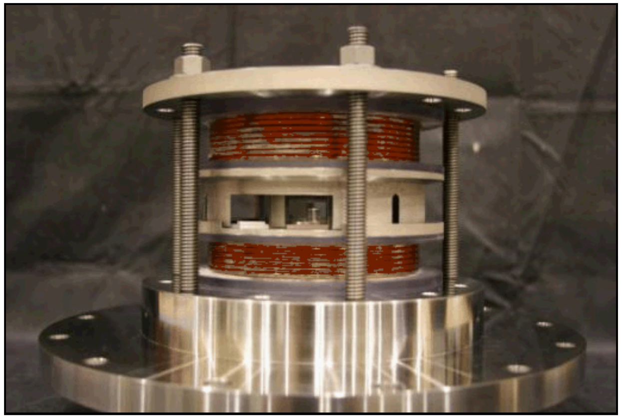
The required energy is modest (2-6 kJ)

* Z-Beamlet was construct from the prototype of the NIF Laser

10-30 T axial fields[1] can be supplied for MagLIF experiments on Z



Copper windings of MagLIF coil



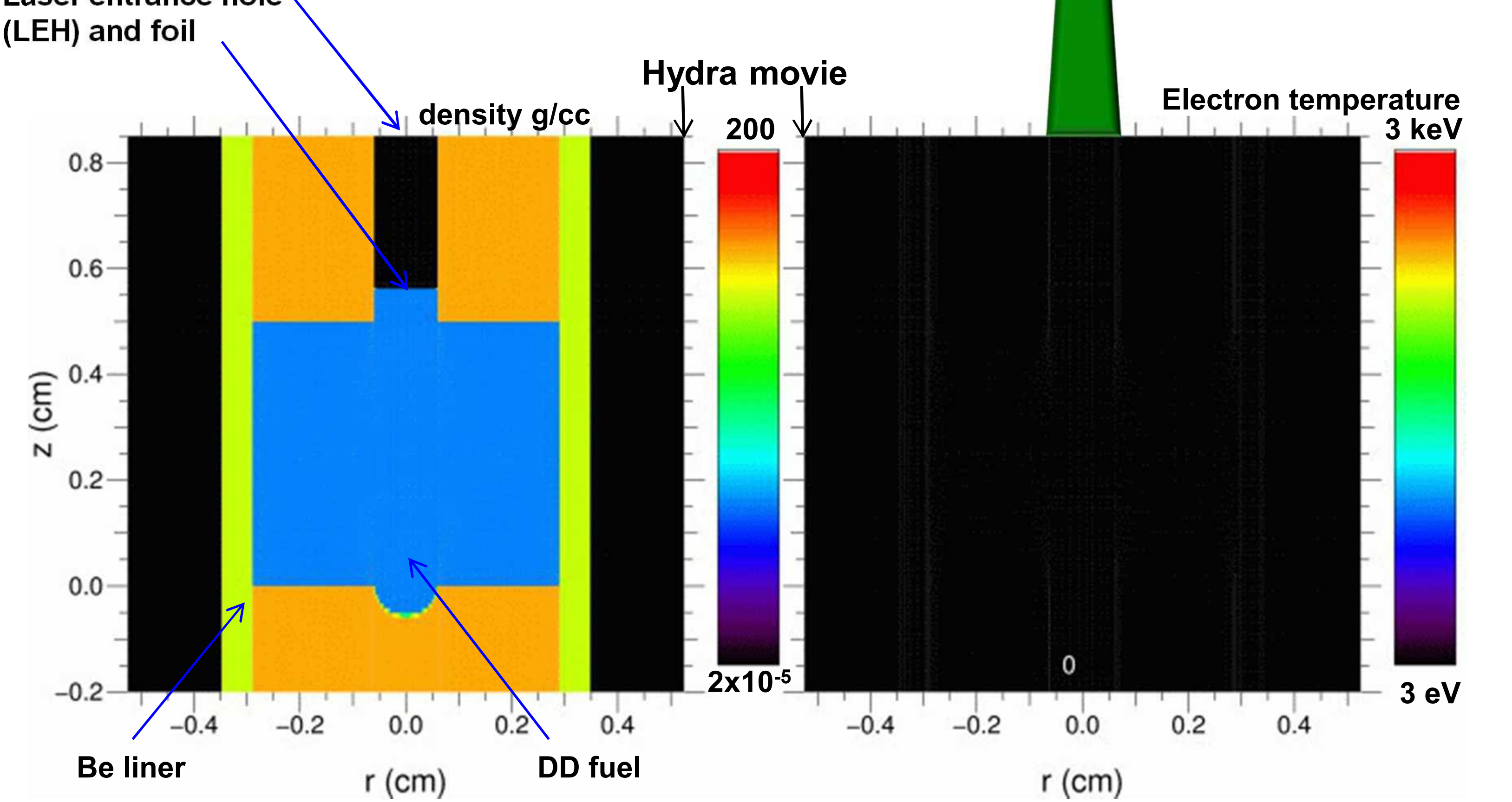
The power feed was modified to center MagLIF within the coils
Axial coil separation determines the maximum field

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

Fully integrated 2D simulations[1] 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



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

MagLIF has advantages over other Magnetized Inertial Fusion approaches

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The fuel density of magnetically confined approaches (e.g. FRC) is limited by the initial magnetic field strength (low yields and gains)

- **for MagLIF the optimal fuel density is only determined by the balance between PdV heating and Bremsstrahlung radiation losses**

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

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

- **Axial stopping of alpha particles requires** $\rho \Delta z > 0.5$
- **Axial lengths of ~ 1 cm are adequate due to relatively high fuel density**

Preheat feasible with a laser

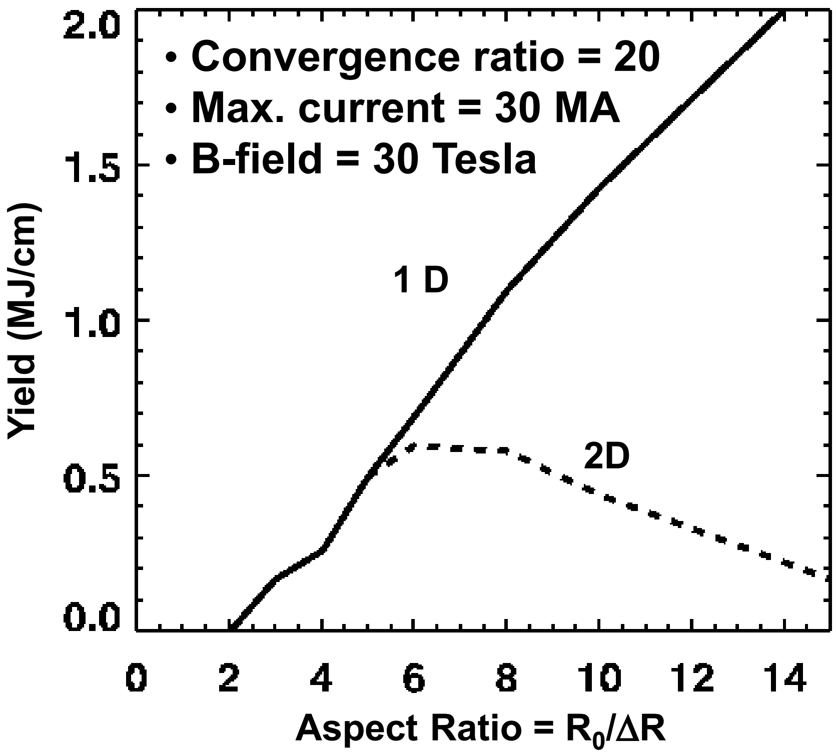
•The preheat energy increases quickly with implosion time

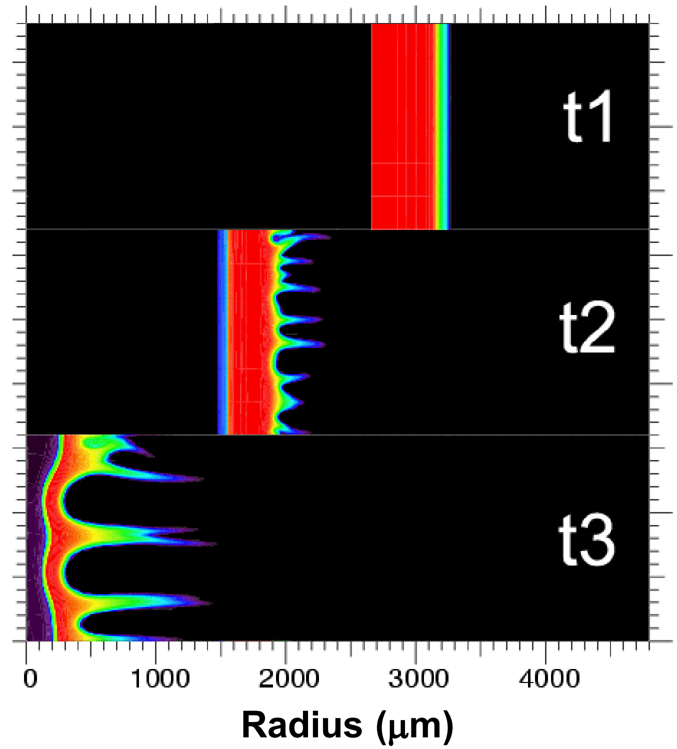
$$E_{pre} \approx C_V T \pi \left(r \propto \tau_{imp} \right)^2 \left(\rho \Delta z \approx 0.5 \right)$$

•Fuel preheat requires < 10 kJ for Z (τ_{imp} = 100 ns)

The Magneto-Rayleigh-Taylor (MRT) instability determines performance of MagLIF and other implosion systems[1]

LASNEX 2D MHD simulations





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

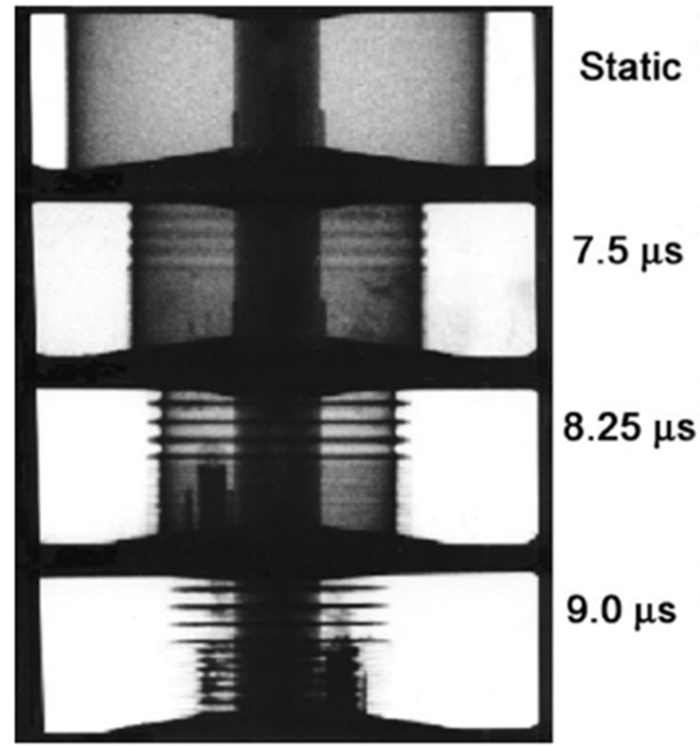
2D Lasnex Be liner simulations AR=6

- 60 nm surface roughness
- resolve waves down to ~80 μm
- wavelengths of 200-400 μm near stagnation

[1]S. A. Slutz, M. C. Herrmann, R. A. Vesey, A. B. Sefkow et al., Phys. Plasmas 17, 056303 (2010)

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 ~7μs 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

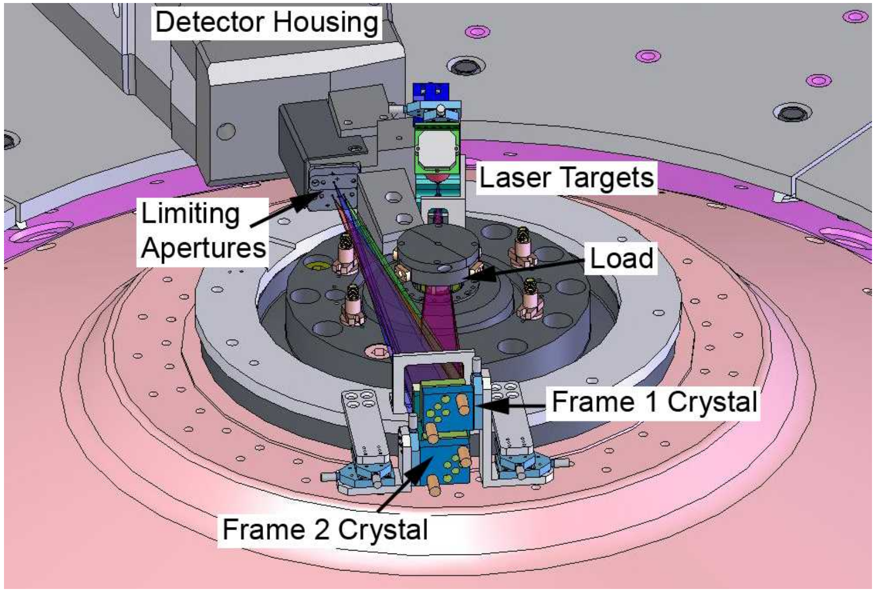


Radiographic Data

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

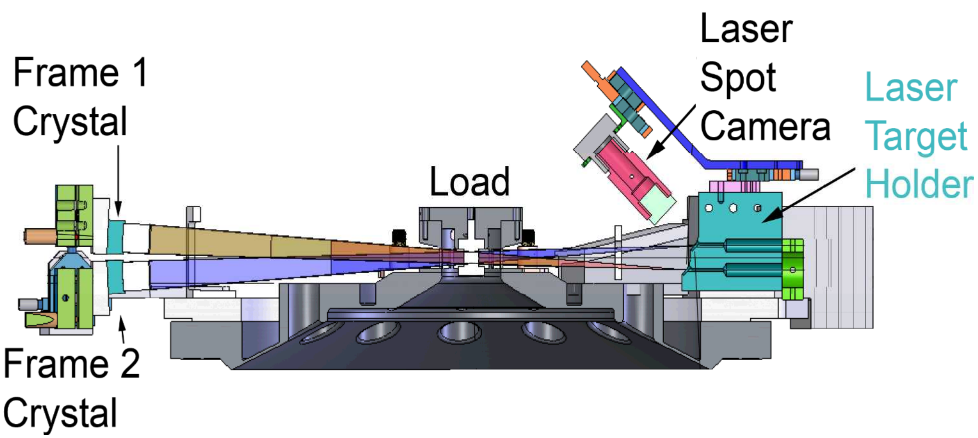
* R.E. Reinovsky *et al.*, IEEE Trans. Plasma Sci. (2002).

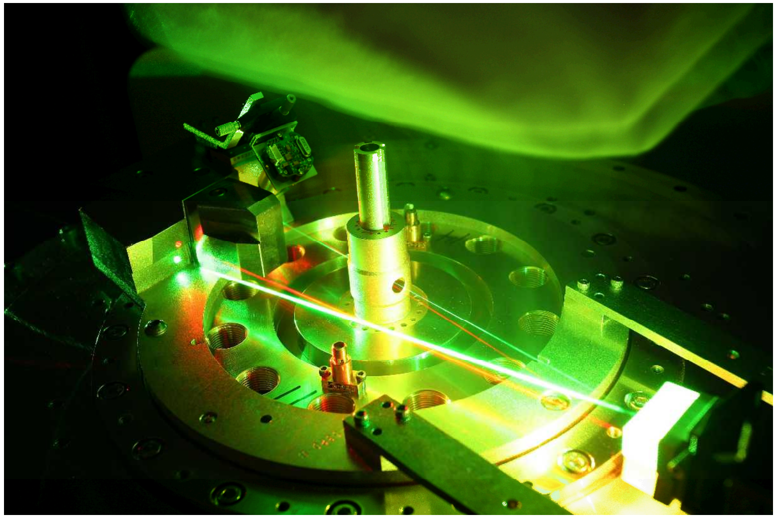
In preparation for MagLIF the MRT was studied on Z with 2-frame monochromatic crystal backlighting diagnostic[1,2]



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



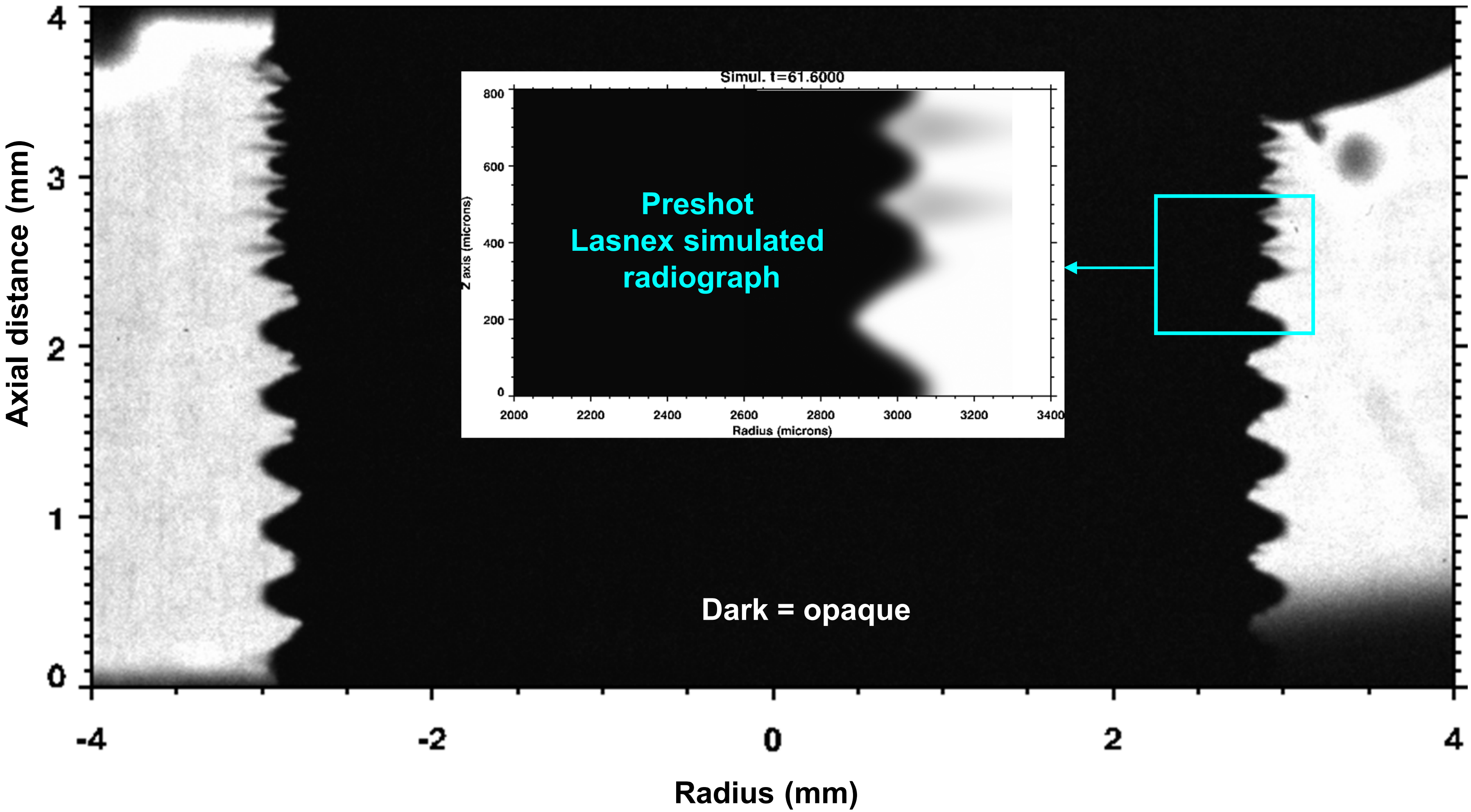


Radiograph lines of sight ±3° from horizontal

[1] S.A. Pikuz *et al.*, RSI (1997) [2] D.B. Sinars *et al.*, RSI (2004)

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

Aluminum liner with machined perturbations 200 and 400 micron



[1]D. B. Sinars, S. A. Slutz, M. C. Herrmann et al., Phys. Rev. Lett. 105, 185001 (2010)

Simulations of MRT growth from machined perturbations in aluminum liners agree well with experiments[1]

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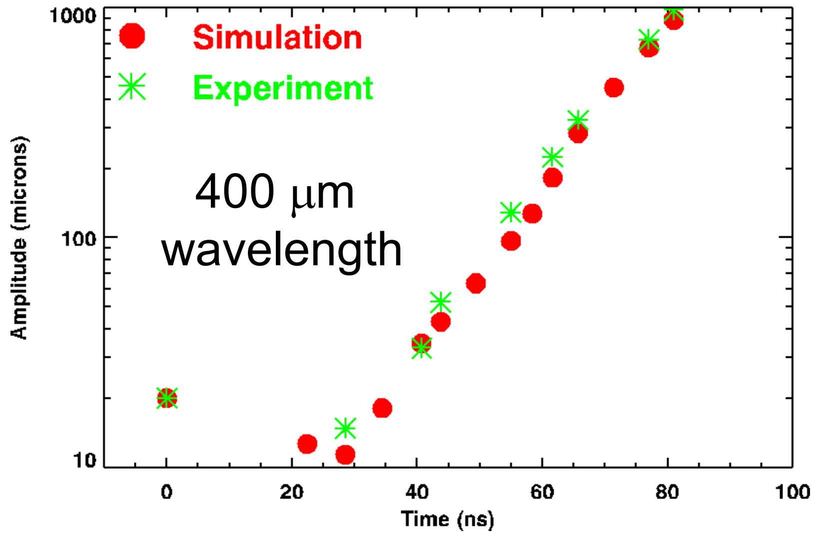
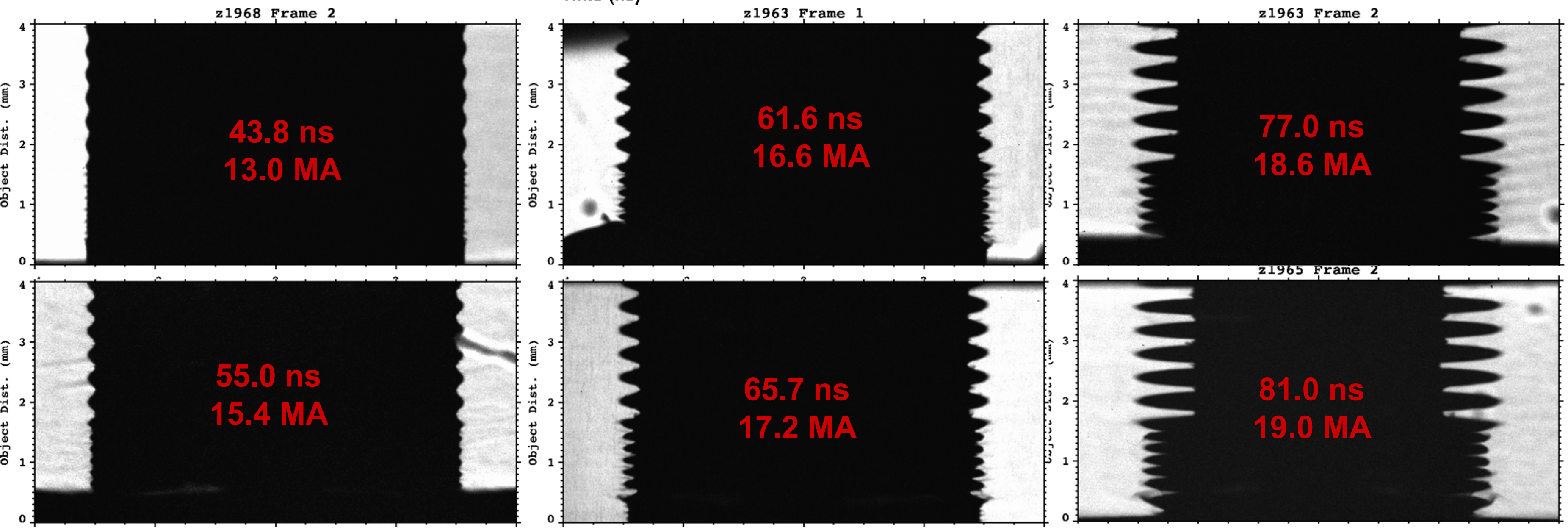


Aluminum liners are too opaque to probe the interior

- **6 keV x-rays could penetrate a Beryllium liner**



[1]D. B. Sinars, S. A. Slutz, M. C. Herrmann et al., Phys. Rev. Lett. 105, 185001

Smooth beryllium liners show surprisingly correlated instability growth at late times[1]

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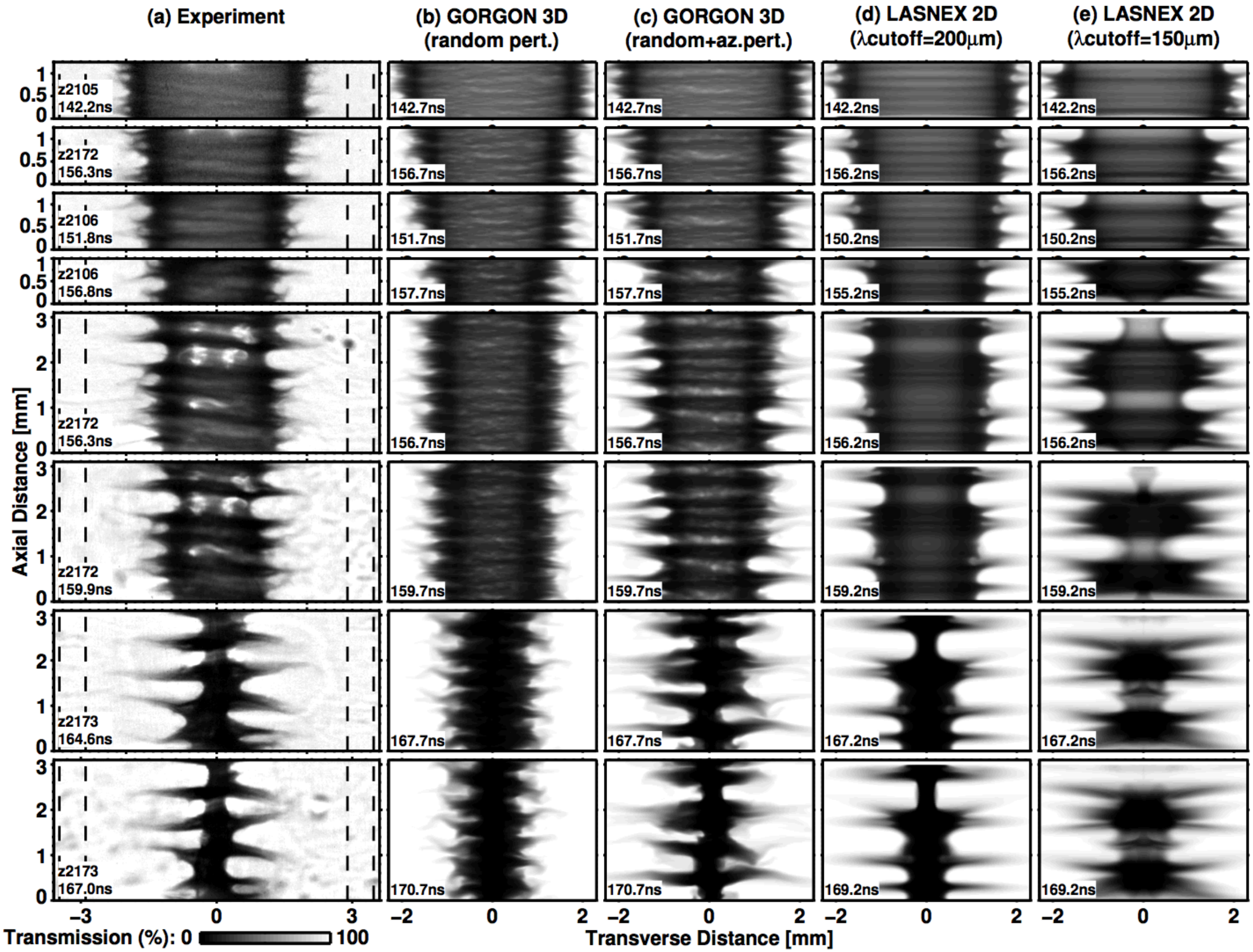

[1]R.D. McBride *et al.*, Phys. Rev. Lett. 109, 135004 (2012).

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

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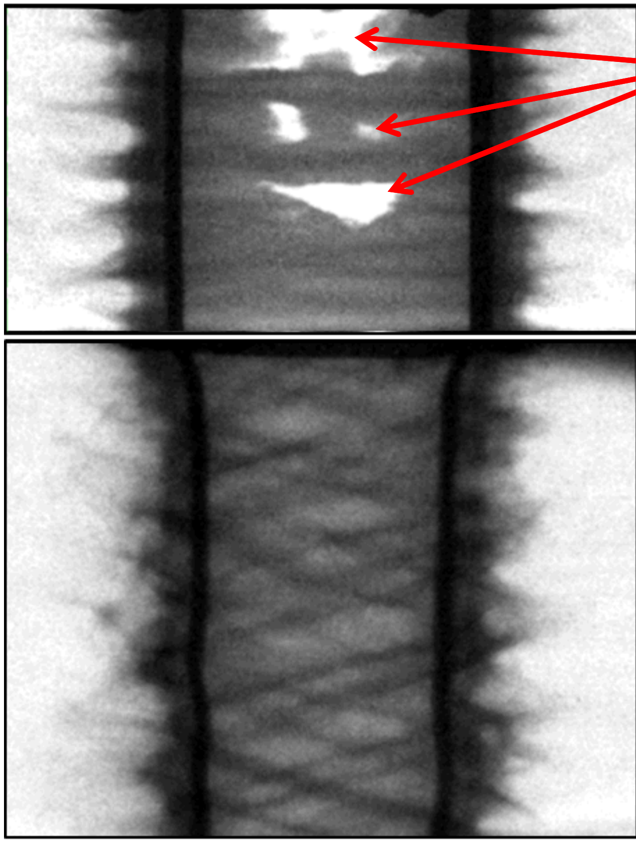
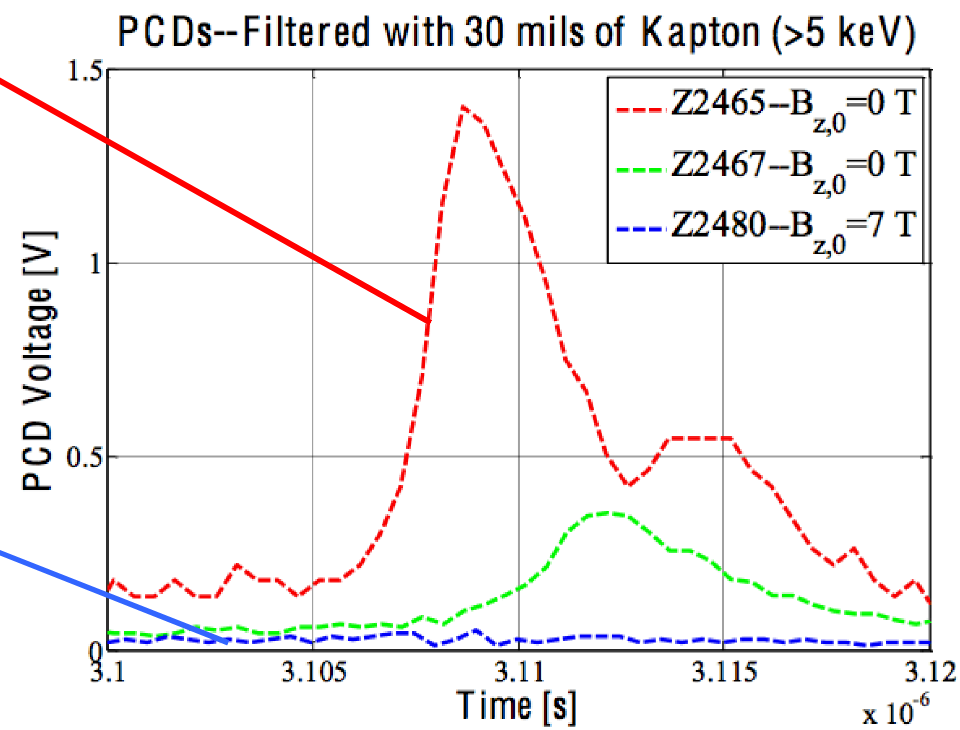
Without Magnetic Field



With Magnetic Field

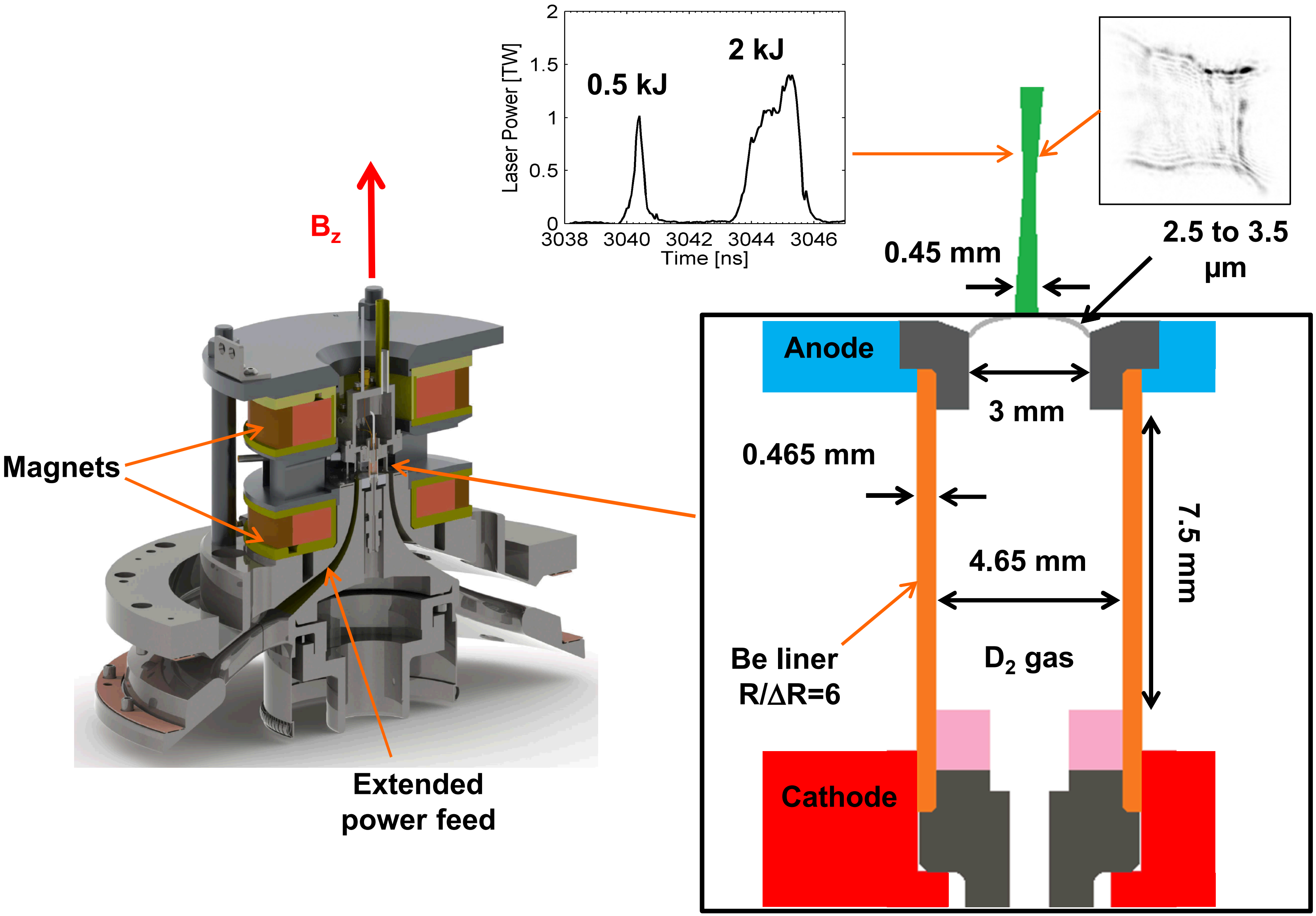
Time-integrated self-emission from liner implosion at 6151 eV; missing in shots with axial field



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

T.J. Awe *et al.*, Phys. Rev. Lett. (2013); *ibid.*, Phys. Plasmas (2014).

Initial MagLIF experiments[1] used 10 T, 2.5 kJ laser energy, and 18 MA of current to drive a D_2 filled (0.7 mg/cm^3) Be liner



[1]M.R. Gomez S.A. Slutz, A.B. Sefkow *et al.*, Phys. Rev. Lett. 113, 155003 (2014).

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

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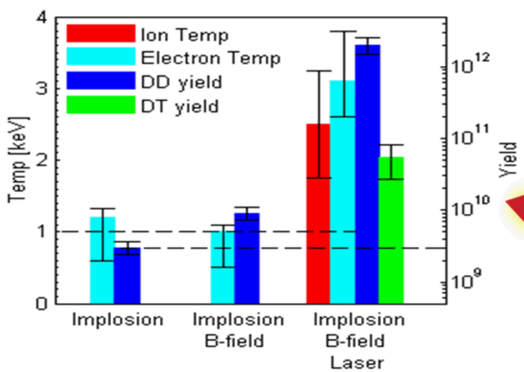
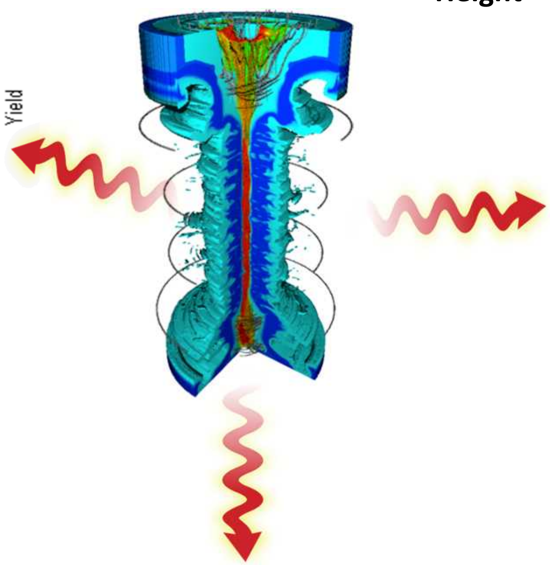
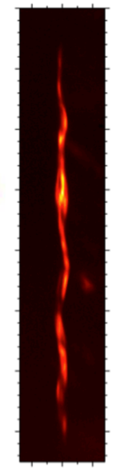
Nuclear Activation > 10^{12} DD neutrons



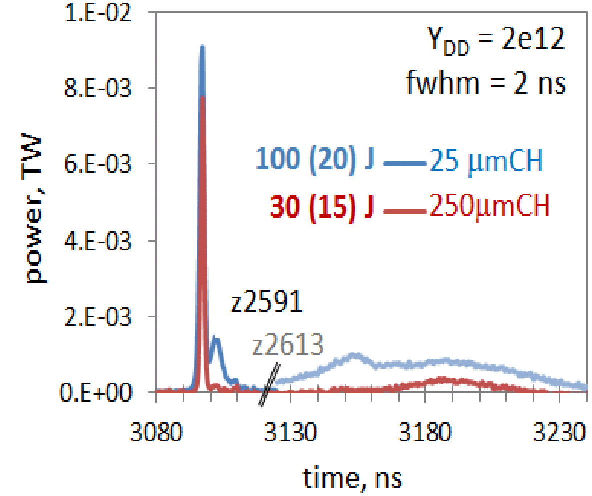
MagLIF Z pinch



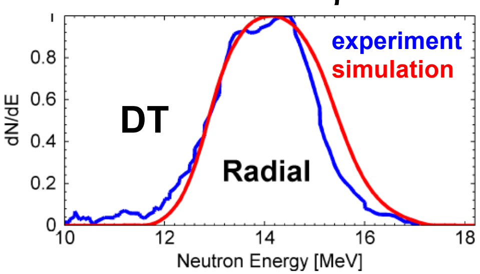
X-ray Imaging
hot plasma shape
Height ~ 6mm radius~ 30-70

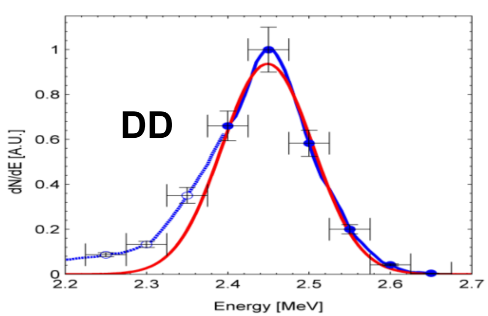


X-ray Power
burn time 1-2 ns

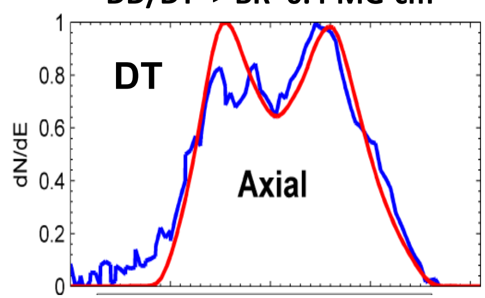


Neutron spectra
Tion~3 keV liner ρR~0.9

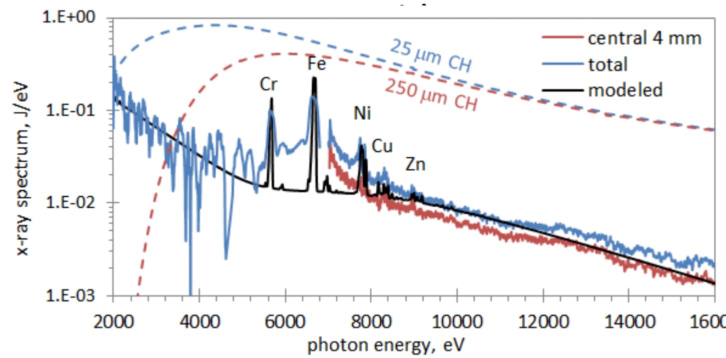




DT Neutron spectra
DD/DT=> BR~0.4 MG-cm



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



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)

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

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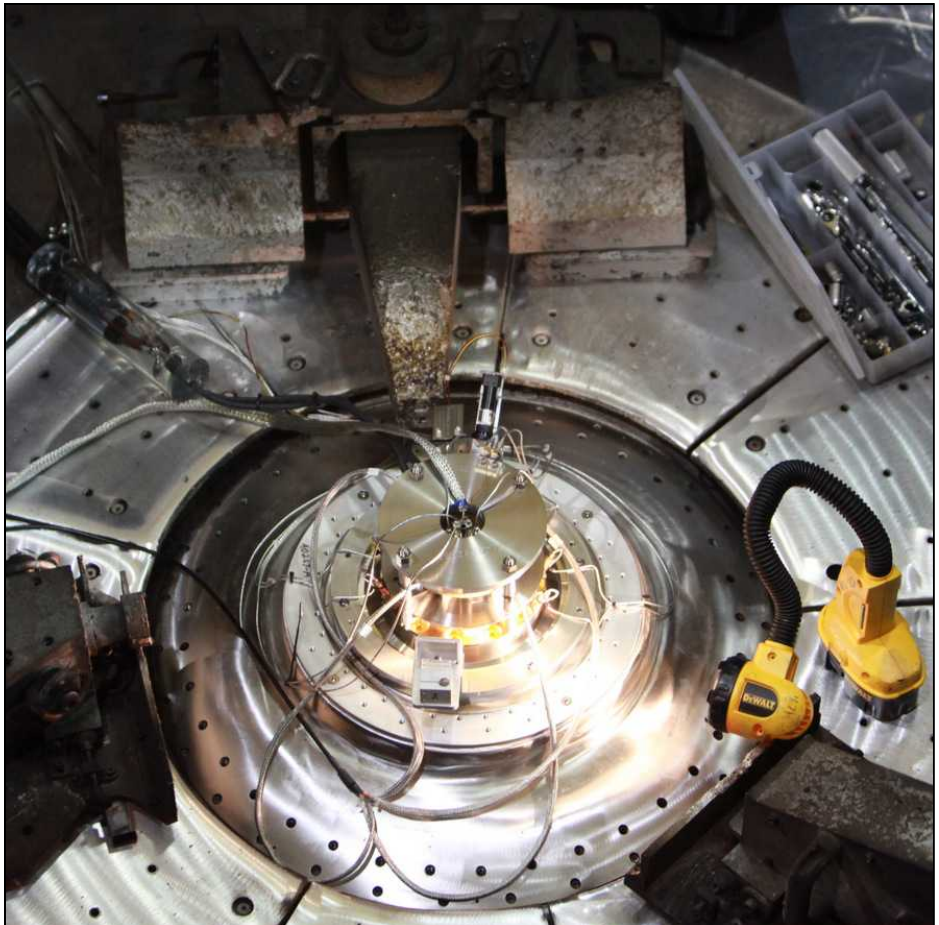
Pre-shot photo of MagLIF load hardware



Damage to FOA debris shielding

Post-shot photo

The MagLIF concept[1] is being tested[2] on the Z facility. Higher drive currents could be provided by future machines[3]

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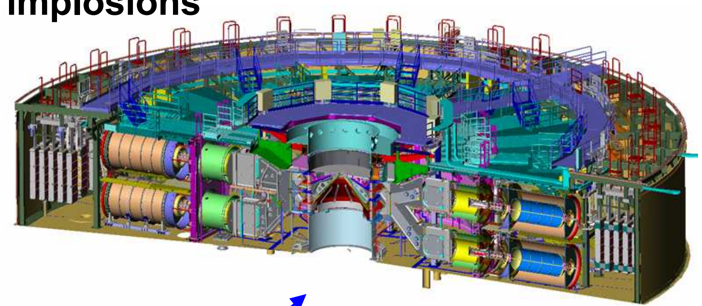
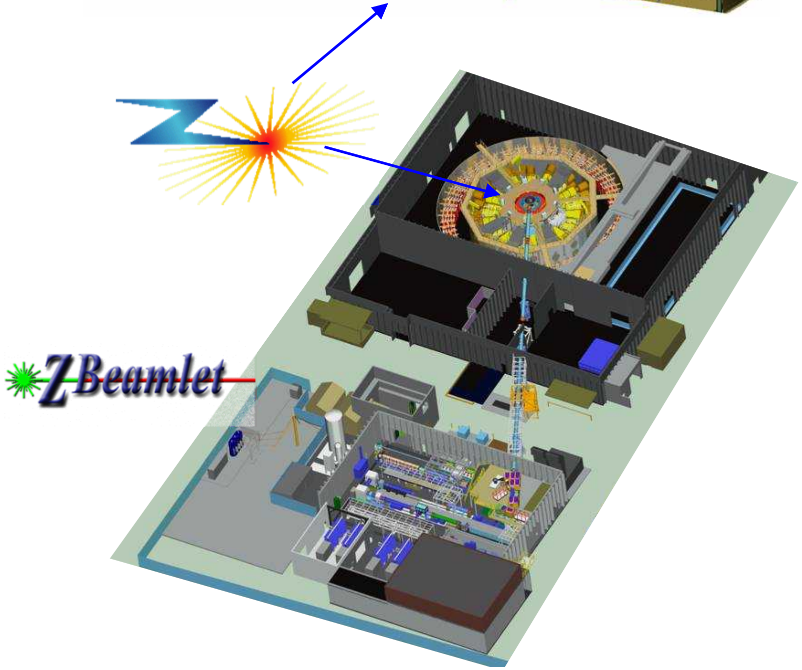
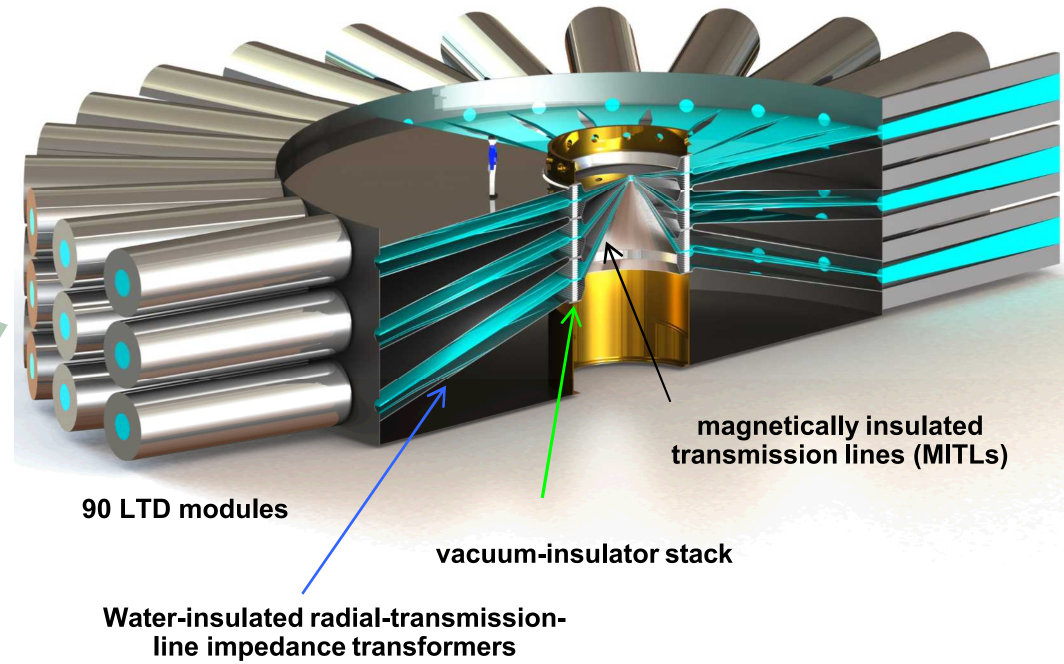
Z can generate high magnetic pressures to drive cylindrical implosions





Z-Beamlet provides fuel preheat

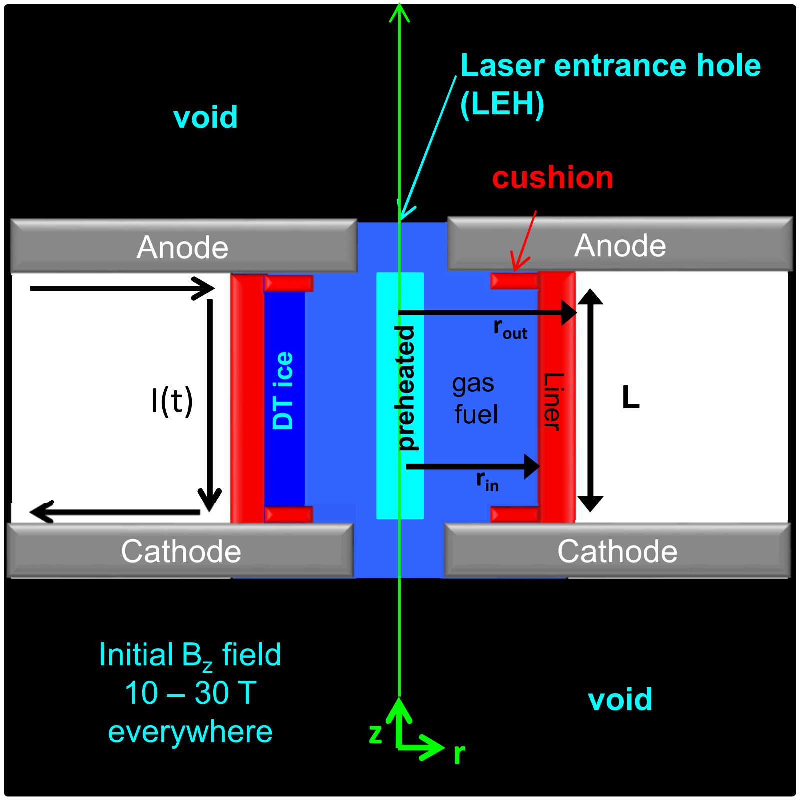
Z 300 employs Linear Transformer Driver (LTD) technology to deliver 48 MA to a MagLIF load, and would fit within the existing Z building.

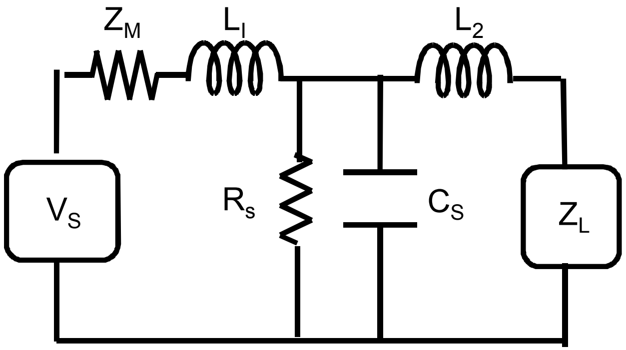


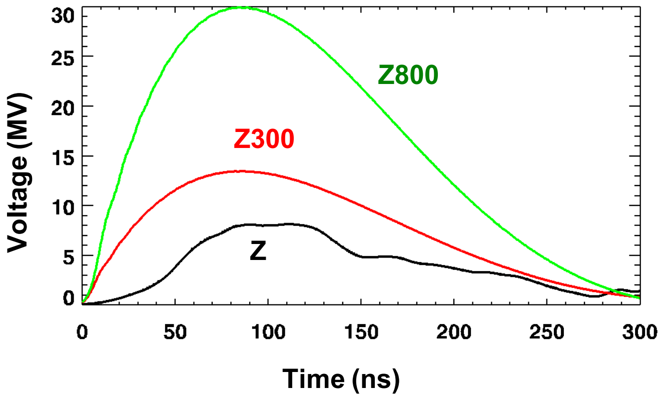
Z800 would deliver 65 MA with the same technology

[1] *Slutz et al. PoP 2010* [2] *Gomez et al. PoP 2014* [3] *Stygar et al Phys. Rev. ST Accel. Beams 2015*

2D Lasnex simulations based on simplified geometry and circuit model

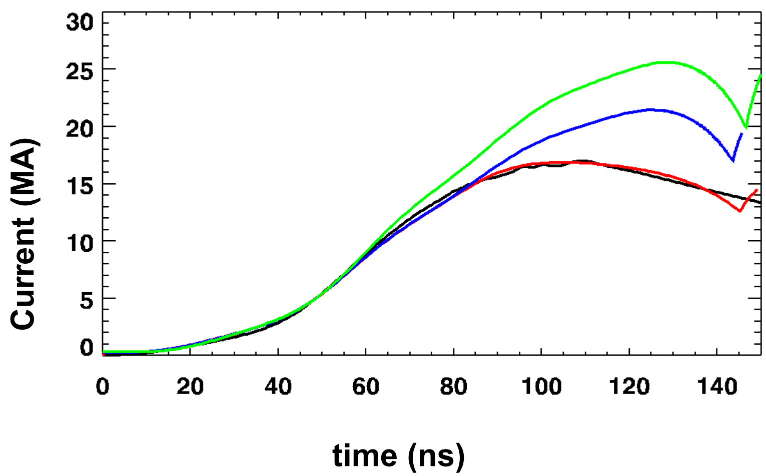




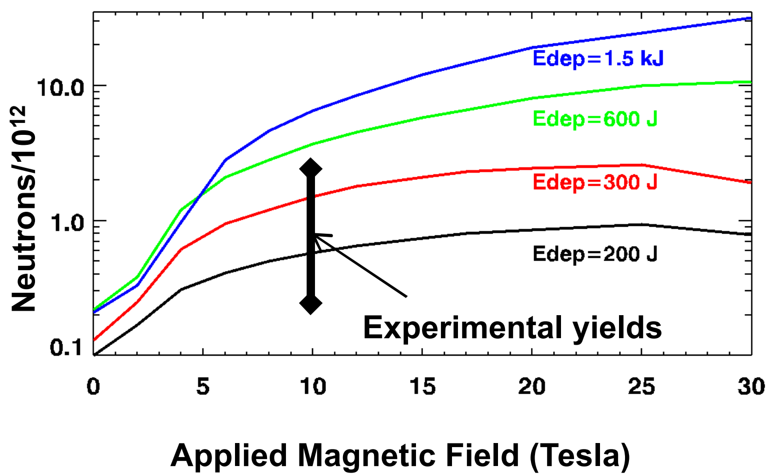


Simulated yields are comparable to experiments results

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



2D MagLIF simulations



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

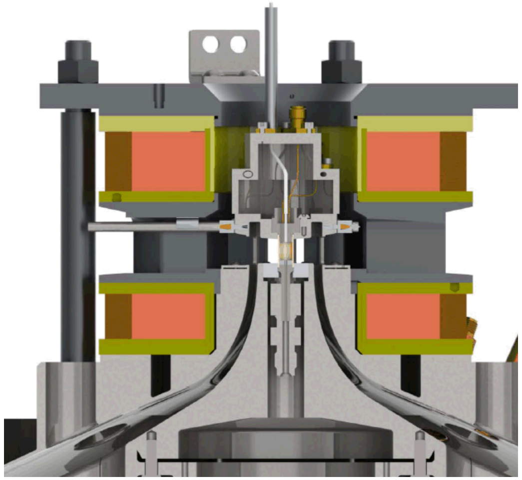
Only 200 J penetrates the foil from a 2 kJ unsmoothed Z Beamlet pulse with 0.53 μm light[1]

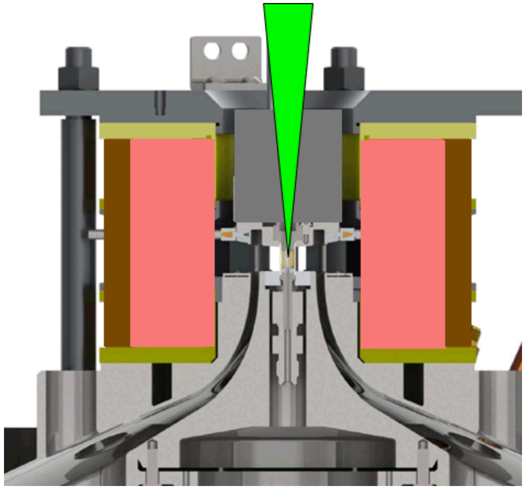
[1]M. Geissel et al. 41st EPS Conference on Plasma Physics 26 June 2014, Berlin, Germany

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**

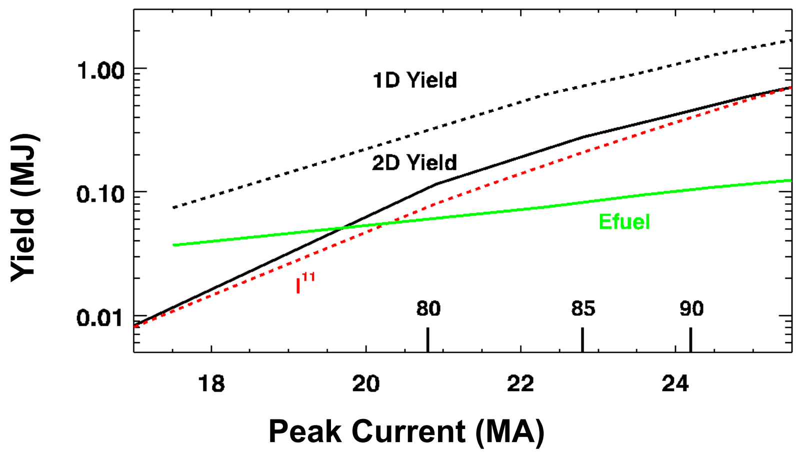
Full-Access Coils (15 T max)





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.

There is presently a significant current loss

- Convolute loses current into high inductance loads (improve convolute)
- The present MagLIF design has a high inductance feed (design low inductance feeds for MagLIF

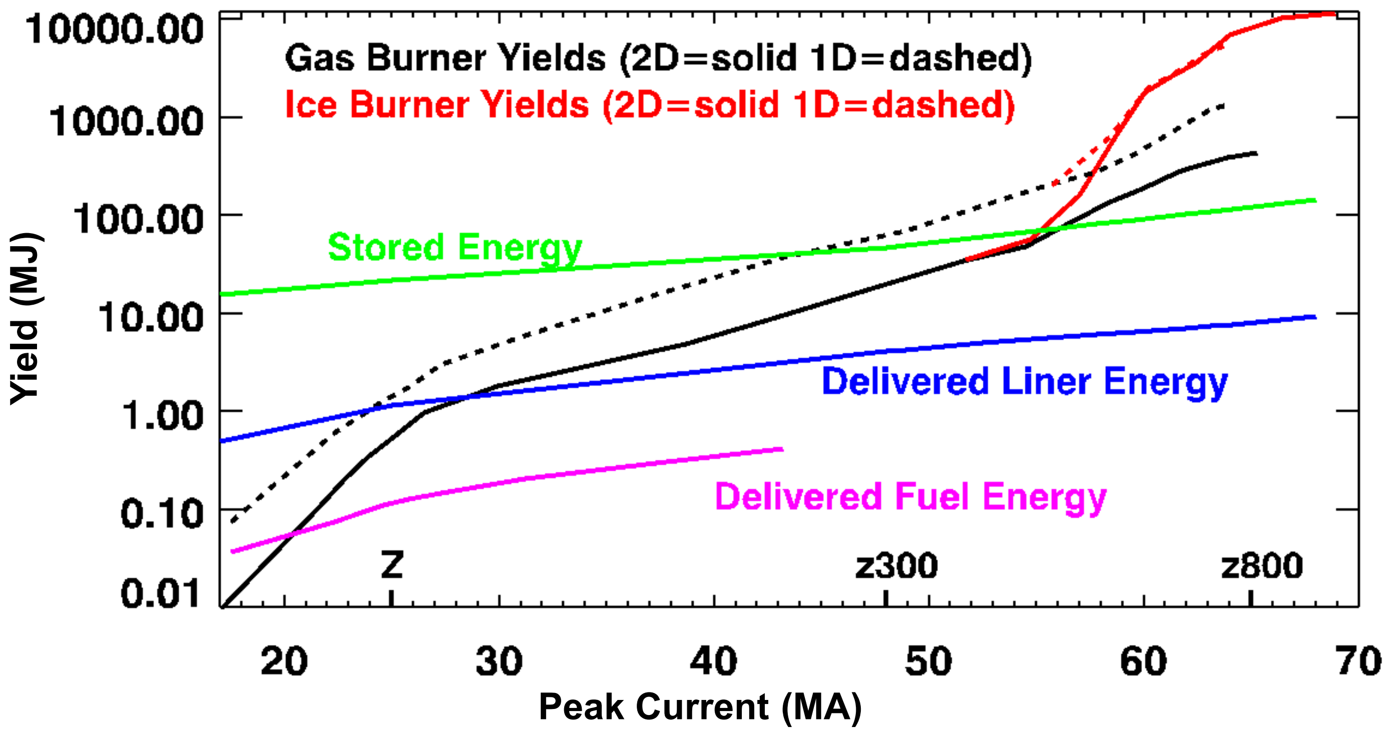
Optimum preheat increases with current (2-8 kJ)

- Z Beamlet is being upgraded
- Beam smoothing is being developed

Experimental demonstration of current scaling on Z will build confidence

- in the MagLIF concept
- In our simulation codes
- scaling to a new larger machine

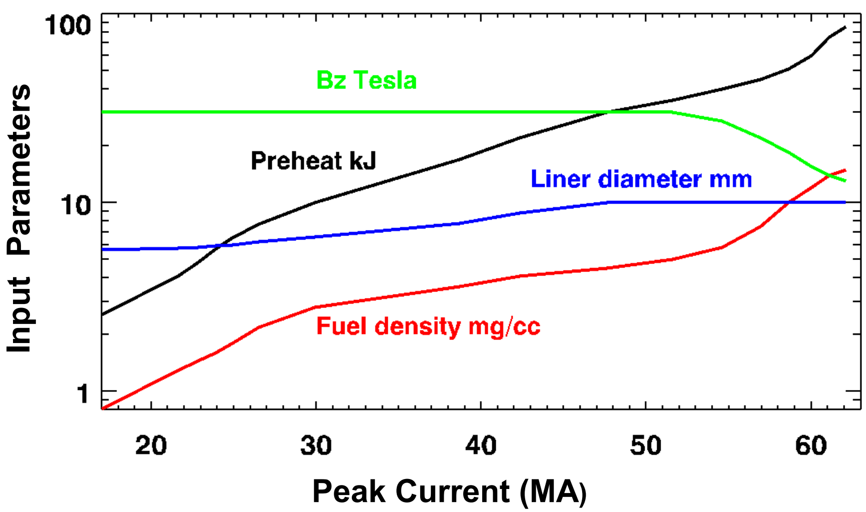
2D simulations indicate that Z300 could drive a MagLIF with a gain greater than unity

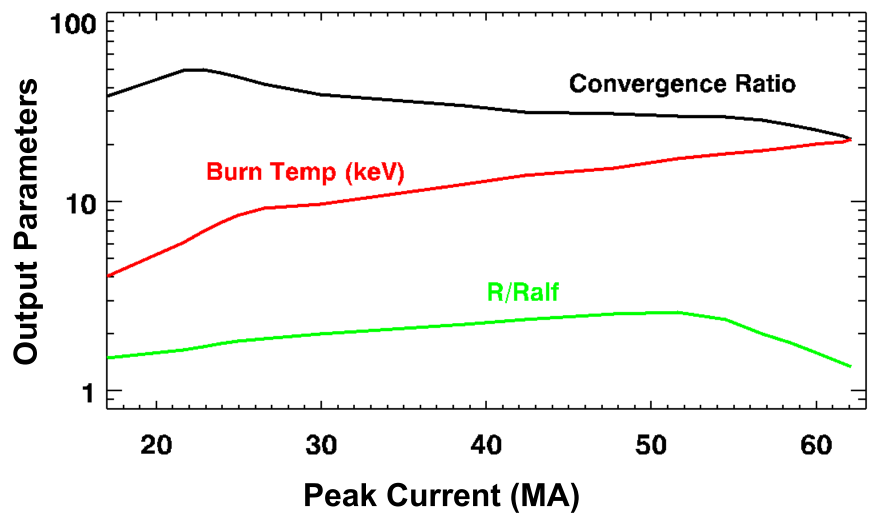


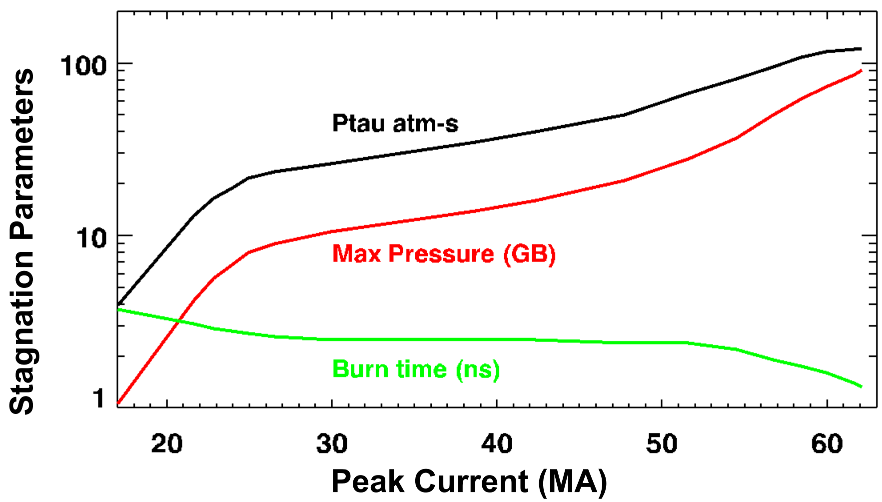
DT ice layers significantly enhance yields for drive currents > 60 MA

Engineering gains of 70 might be possible with Z800 ice burners

2D simulations indicate optimal design parameters and output quantities







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

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Laser absorption coefficient dominated by inverse Bremsstrahlung

$$C_V \frac{d\theta}{dt} = \frac{dI}{dz} = -kI \qquad k = \frac{\nu_{ei}\omega_p^2}{c\omega_L^2}\left(1-\frac{\omega_p^2}{\omega_L^2}\right)^{-1/2} = \frac{k_0}{\theta^{3/2}} \qquad k_0 \approx 1.23x10^6\left(\rho\lambda_L Z_b\right)^2\left(1-227\rho Z_b\lambda_L^2\right)^{-1/2}$$

$$I = I_0\left(1-\frac{z}{z_f}\right)^{2/3} \qquad z_f = \frac{5}{3}\left(\frac{2}{5k_0}\right)^{2/5}\left(\frac{I_0 t}{2C_V\rho}\right)^{3/5} \qquad R_{laser} = 5.4x10^{-7} E_{laser}^{1/2}\lambda_L^{-.67}\rho^{-1.17}z_f^{-.83}\left(1-227\rho\lambda_L^2\right)^{.17}$$

Hydrodynamics and refraction make this process more complicated

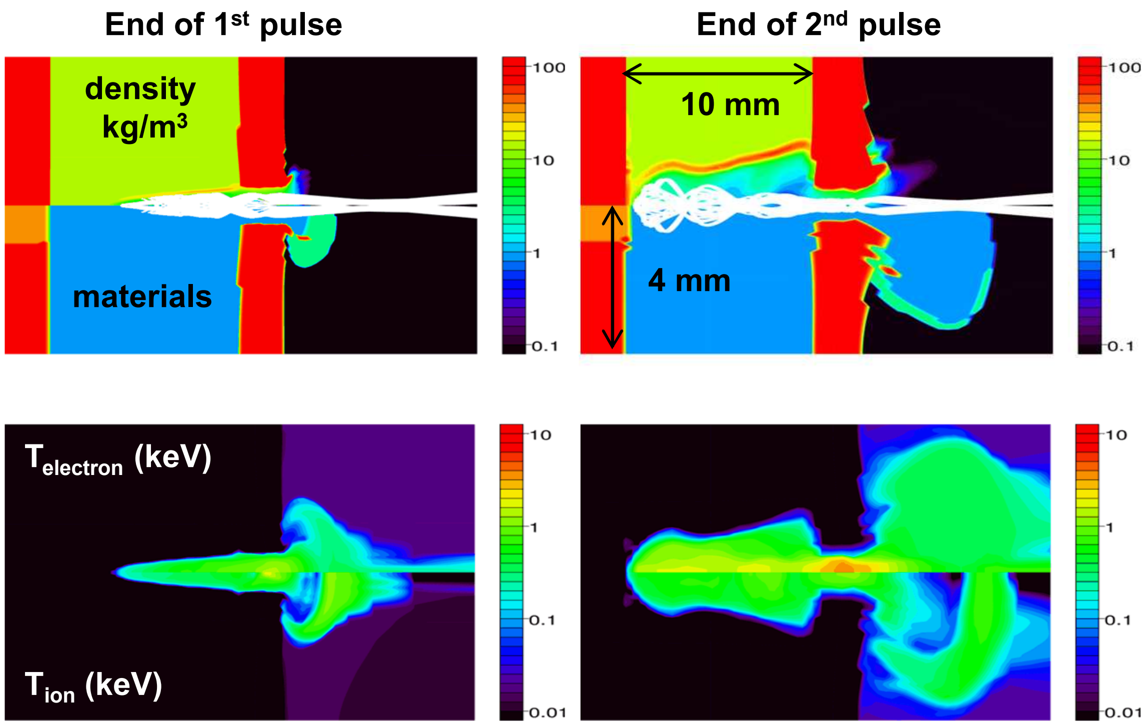
A short wavelength laser (λ ~ 0.25-0.33 μ) could be used to penetrate the initially high density DT forming a low density channel

A second pulse of longer wavelength light (λ = 0.5-1 μ) 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



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

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LPI is unimportant if:

- the plasma density is much lower than the critical density ($n/n_{crit}<<1$)
- The laser intensity is low ($I_{Laser}<10^{14}$ watts/cm^2)

Optimum fuel densities are larger on future accelerators

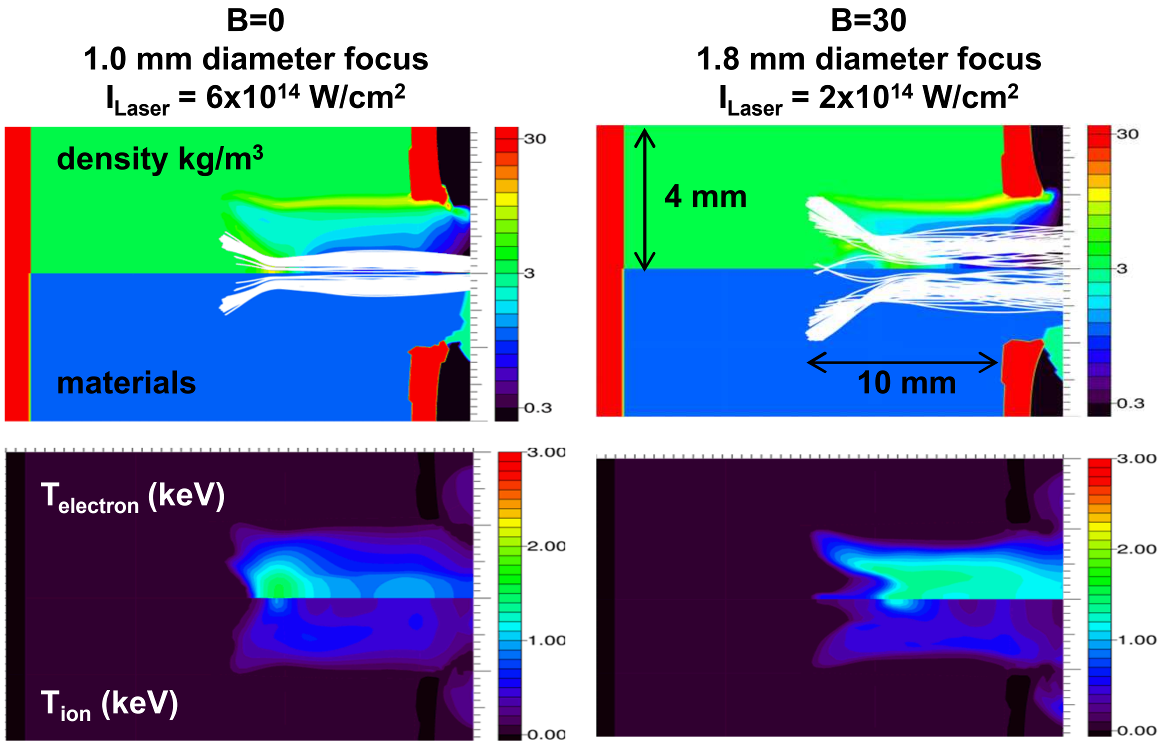
- Optimal fuel density ~ 5 mg/cc on Z300 (n/n_{crit}~0.13) for 3ω

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/cm^2

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 perform 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

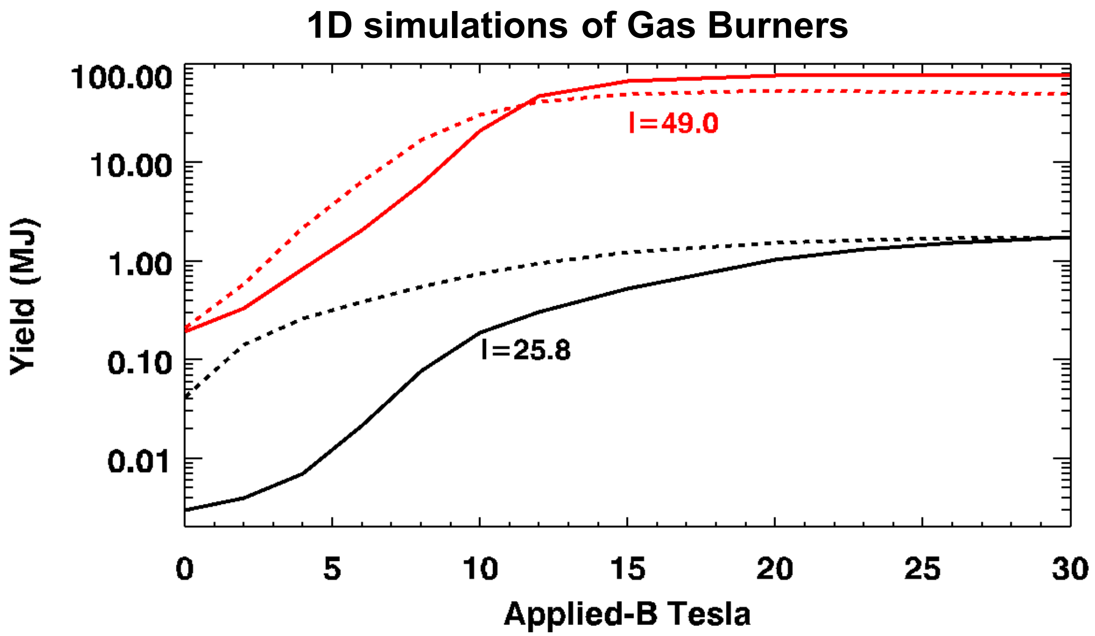
Agreement between the simulation scaling presented here and the results of experimental scaling will greatly increase our confidence to predict MagLIF performance on future machines

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 x 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**



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

Lasnex simulations of Gas Burners