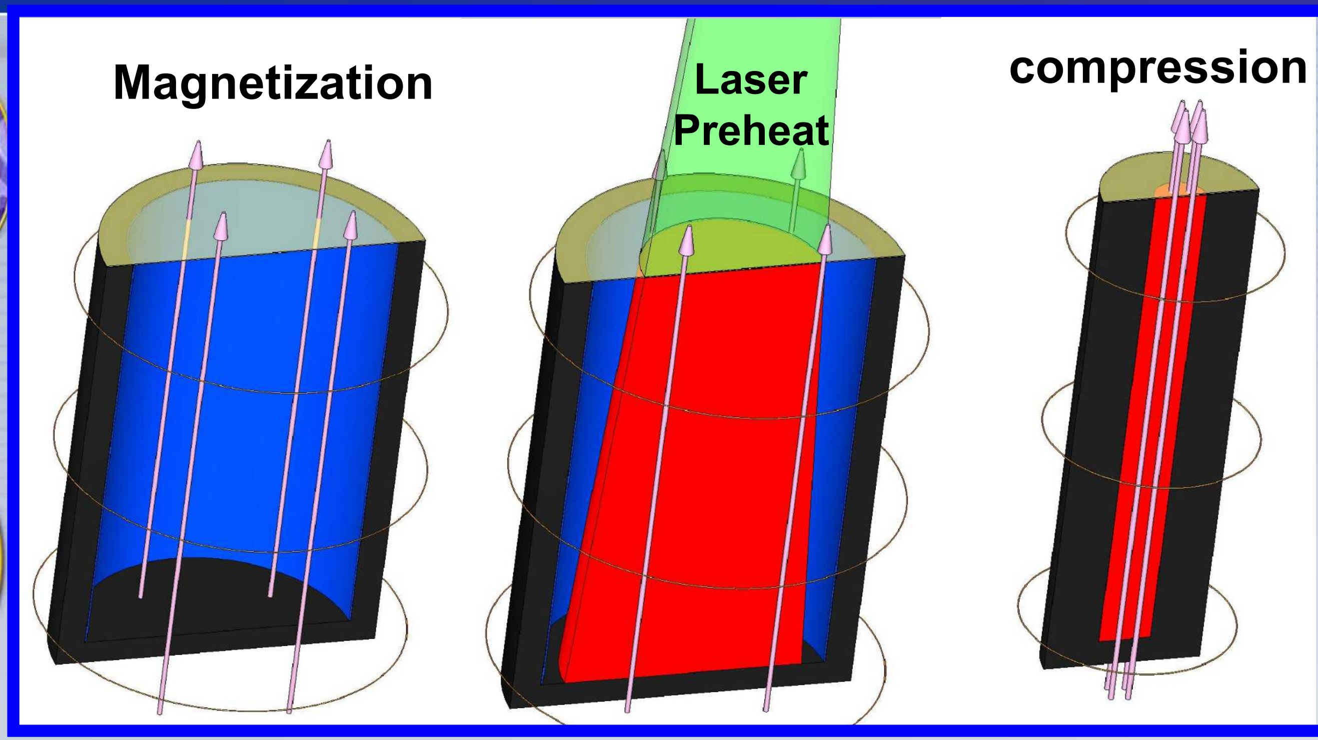
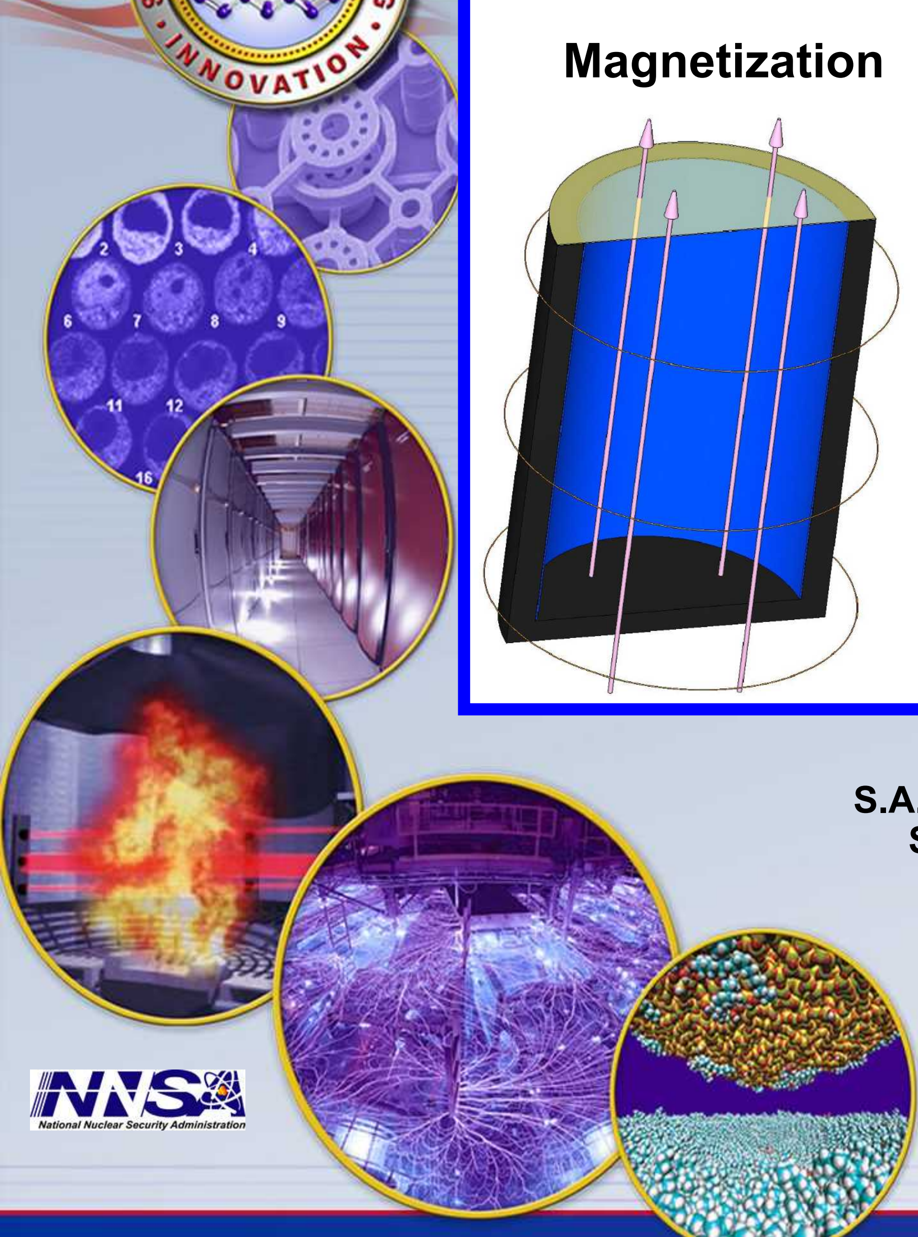
High-Gain Magnetized Liner Inertial Fusion (High-Gain MagLIF)

SAND2011-5344C



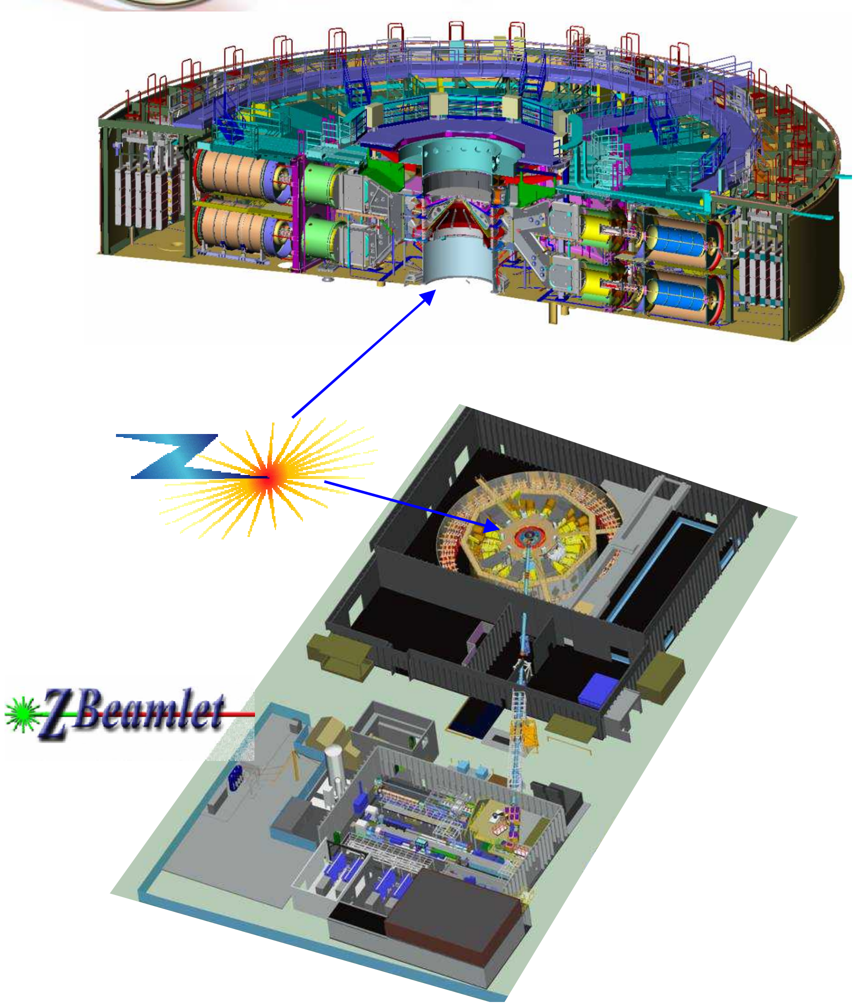


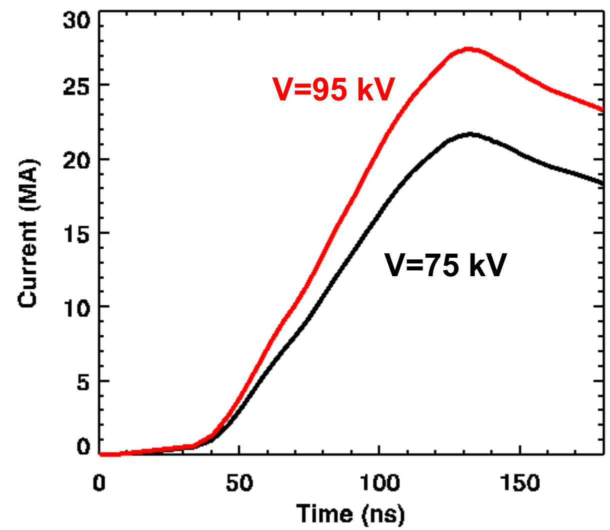
DZP Biarritz, June 5-9, 2011

S.A. Slutz, R.A. Vesey, M.C. Herrmann, A.B. Sefkow, D.B Sinars, D.C. Rovang, K. Peterson, and M.E. Cuneo

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

The Z facility contains the worlds largest pulsed power machine and the Z-Beamlet and Z-Petawatt lasers





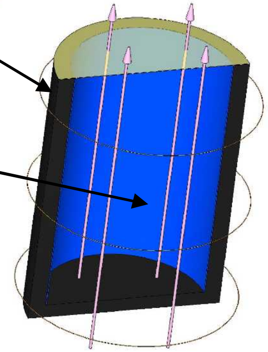
Magnetically-Driven Cylindrical Implosion

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

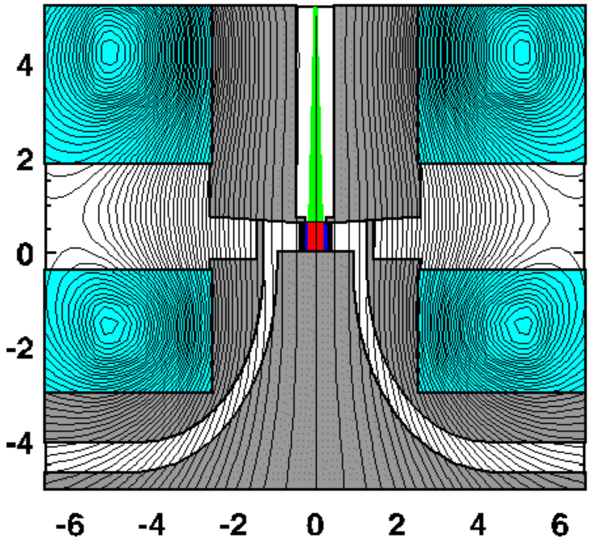
140 MBar is generated by 300 eV radiation drive

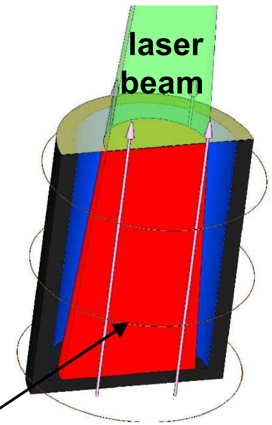
The Z facility provides a unique opportunity to test the benefits of fuel magnetization and preheat*

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

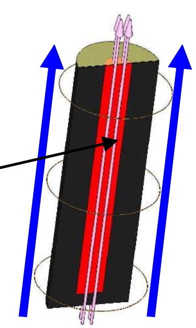


1. An axial magnetic field is applied to inhibit thermal conduction and enhance alpha particle deposition





2. Z Beamlet preheats the fuel



3. The Z accelerator efficiently drives a z-pinch implosion

Magnetically driven implosions are a unique capability for pulsed power accelerators

Direct magnetically driven implosions could be about 50 times more efficient than indirect radiation driven implosions

Natural geometry is cylindrical

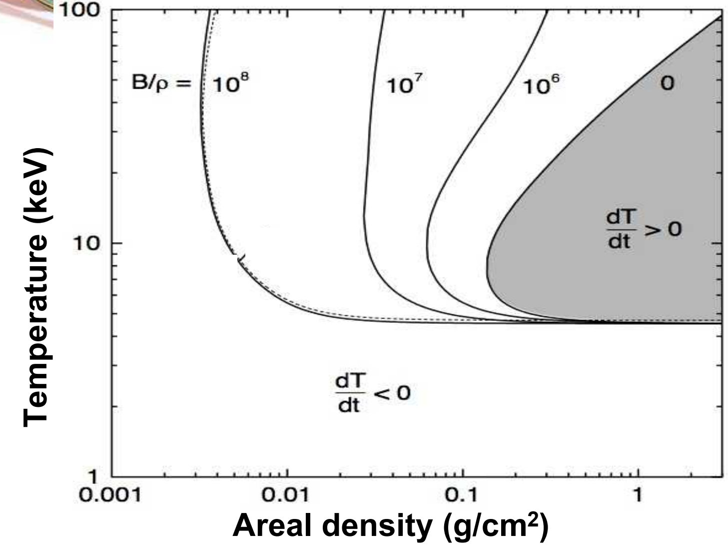
- **reduced volume compression (ρr and T_{ig} difficult)**
- **implosion velocity is slow V_{imp} ~ 12 cm/μs for instability-robust liners**

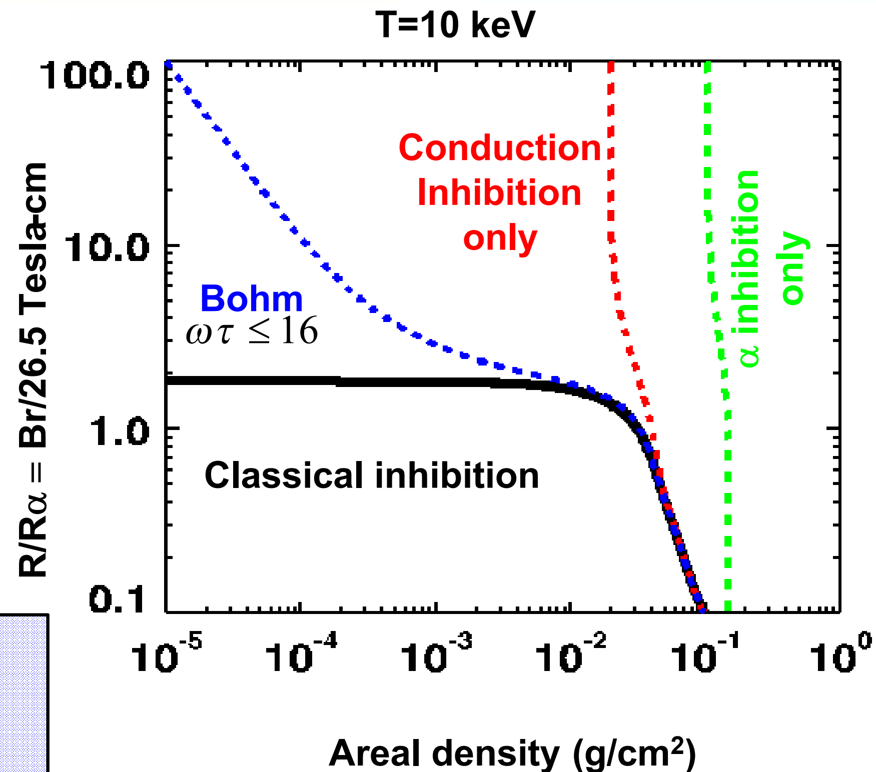
Fuel magnetizing and preheating is a potential solution

- **the attainment of ignition conditions with slow implosions and modest radial convergence**

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

*Basko et al. Nuc. Fusion (2000)





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

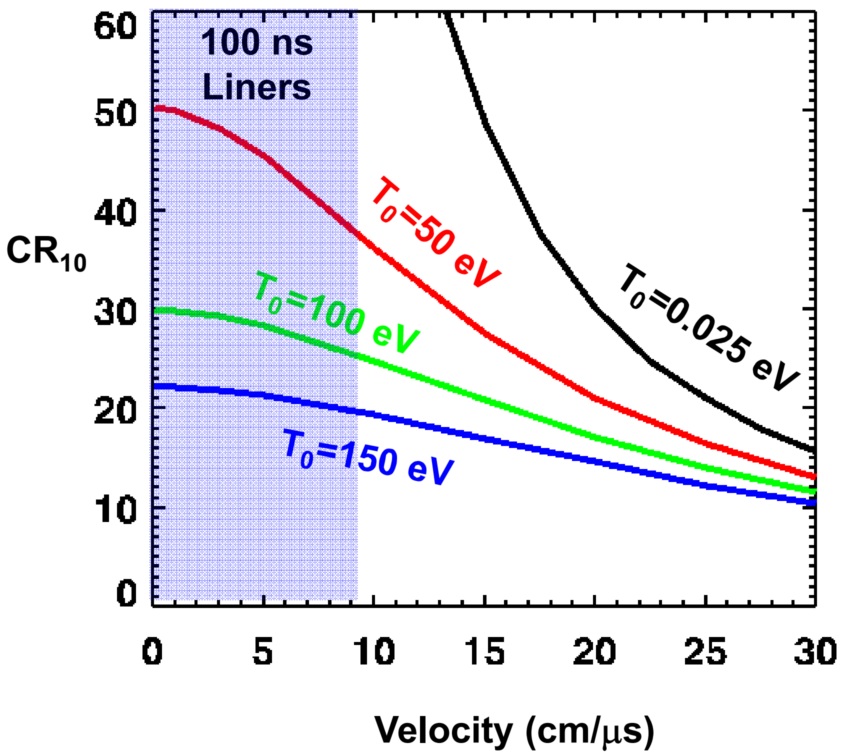
Axial α-trapping requires closed field lines or moderately high fuel density so that

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

Preheat is necessary for slow implosions

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



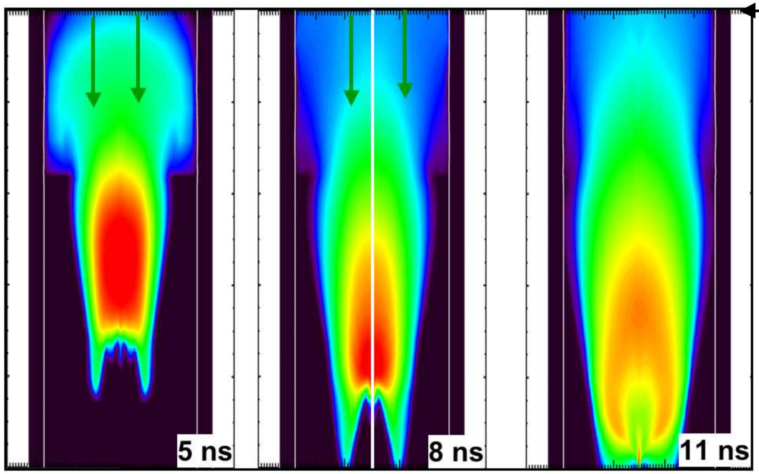
Fuel can be heated to ignition temperature with modest Convergence Ratio when the initial adiabat is large

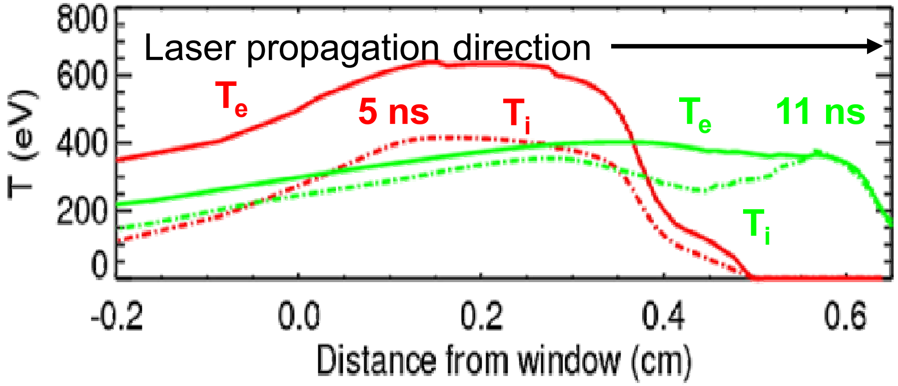
- **adiabat set by implosion velocity (shock) or**
- **alternatively by fuel preheat**

Simulations indicate the Z-Backlighter Laser could preheat fuel for experiments on Z

0.8 TW, 10 ns pulse, 1 mm spot radius, 2.5x10^{13} W/cm^2

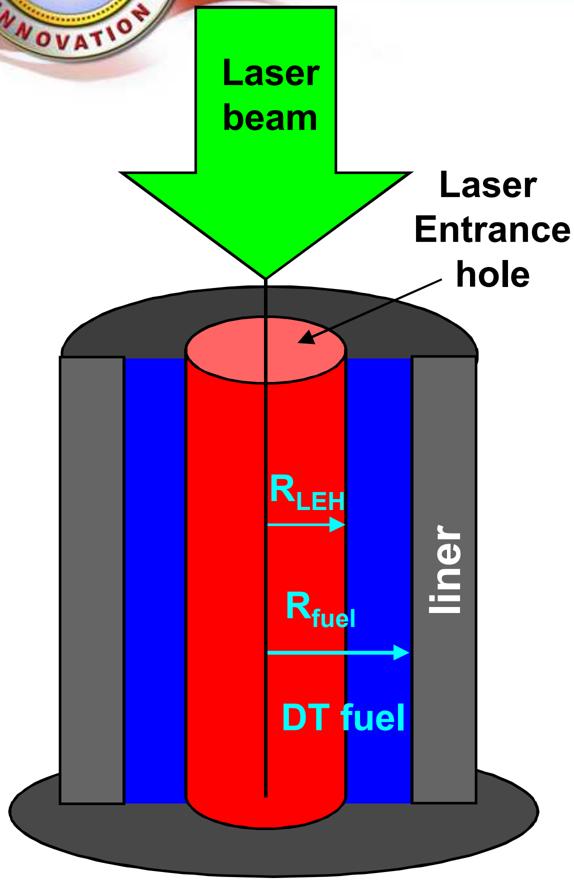
Electron Temperature contours (r,z)



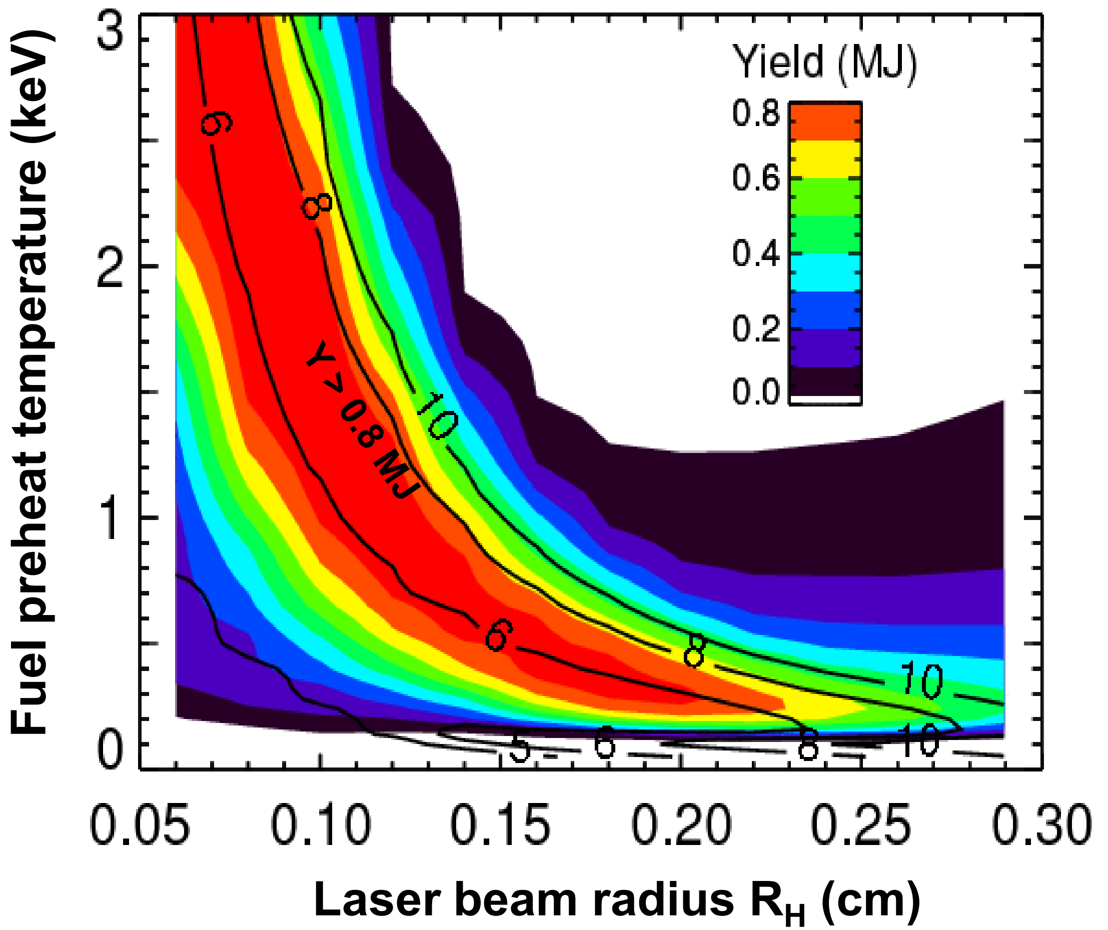


- The gas can be held in place by a 1 μ plastic foil
- The critical density for green light is 4-7 x initial fuel density absorption by inverse bremsstrahlung
- The total laser energy needed <10 kJ
- analytic solution shows that the laser must bleach through the fuel

A small laser entrance hole (LEH) increases the yield

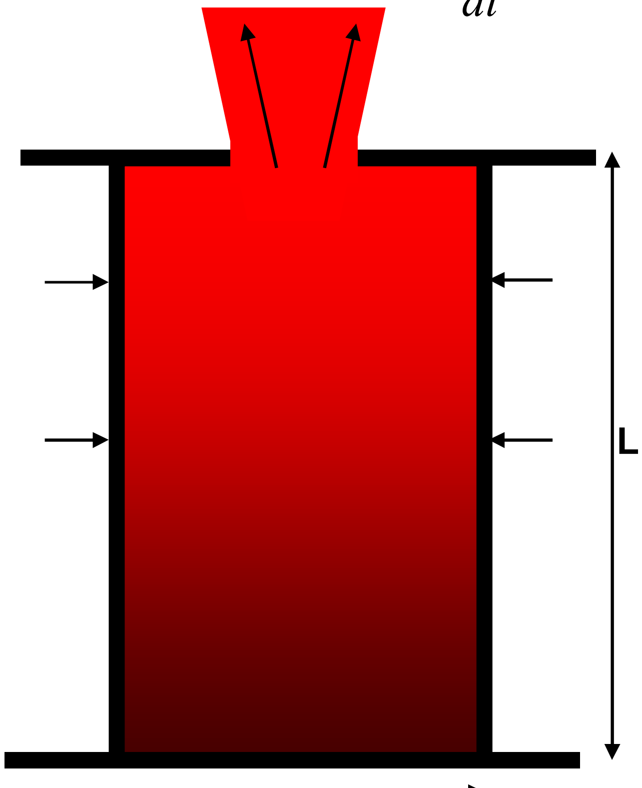


Yield contours (color) from a series of 1D Lasnex simulations

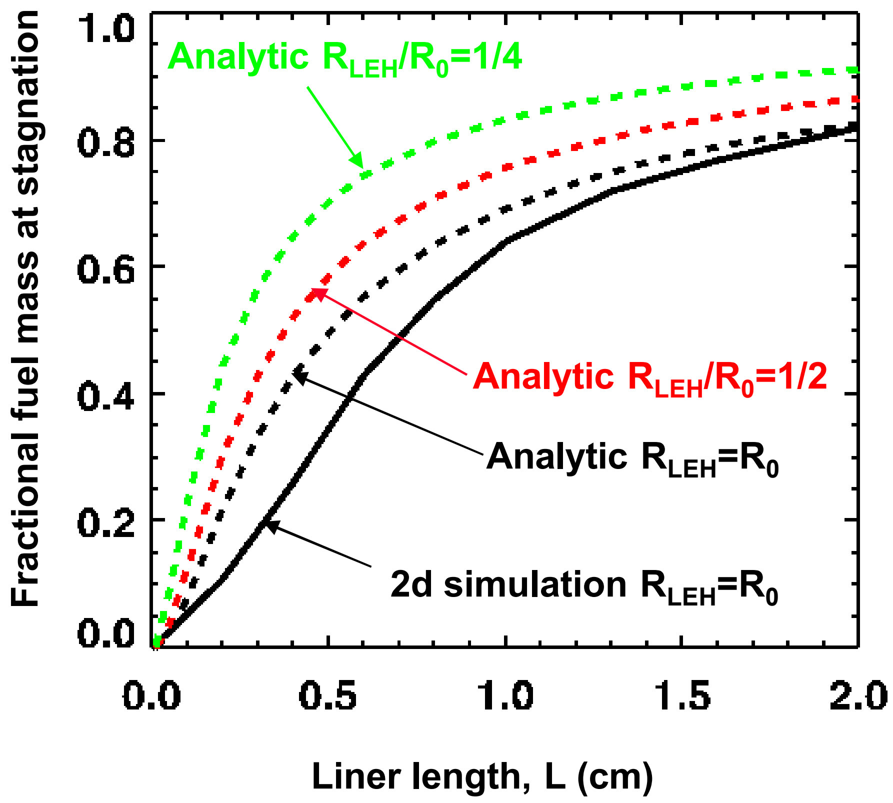


End losses should be manageable

Gas escaping $\frac{dM}{dt} \approx 0.31 c_{s0} \rho_0 \pi r_{LEH}^2$



$$r(t) \sim r_0 \left[1 - (t/t_P)^{5/3}\right]$$



MagLIF benefits from short implosion times and is robust to mix

The optimal fuel density is determined by the balance between PdV heating and Bremstrahlung radiation losses

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

•**purely axial fields can be used on Z, since**

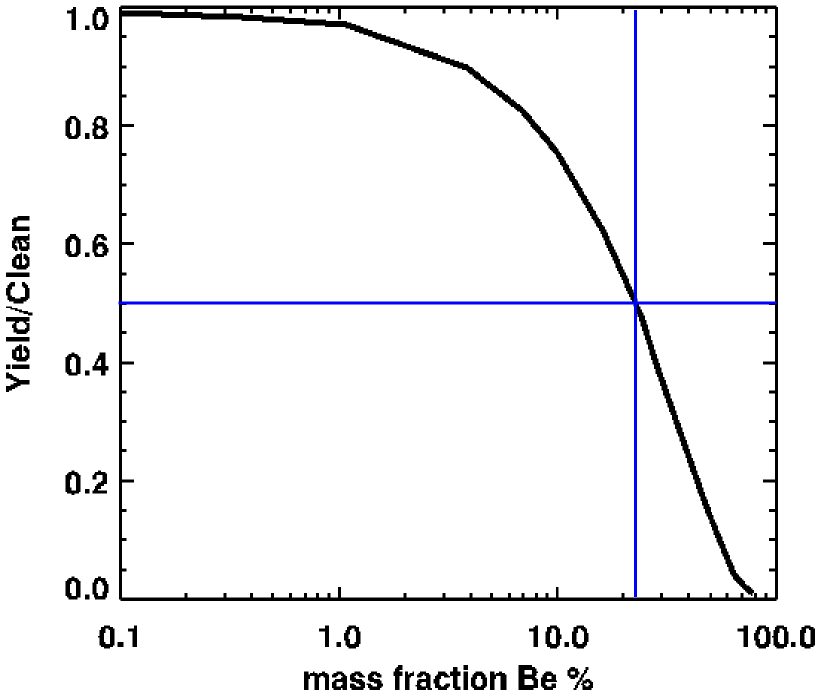
$\rho\Delta z > 0.5$ **for small Δz**

The preheat energy is roughly proportional to the implosion time

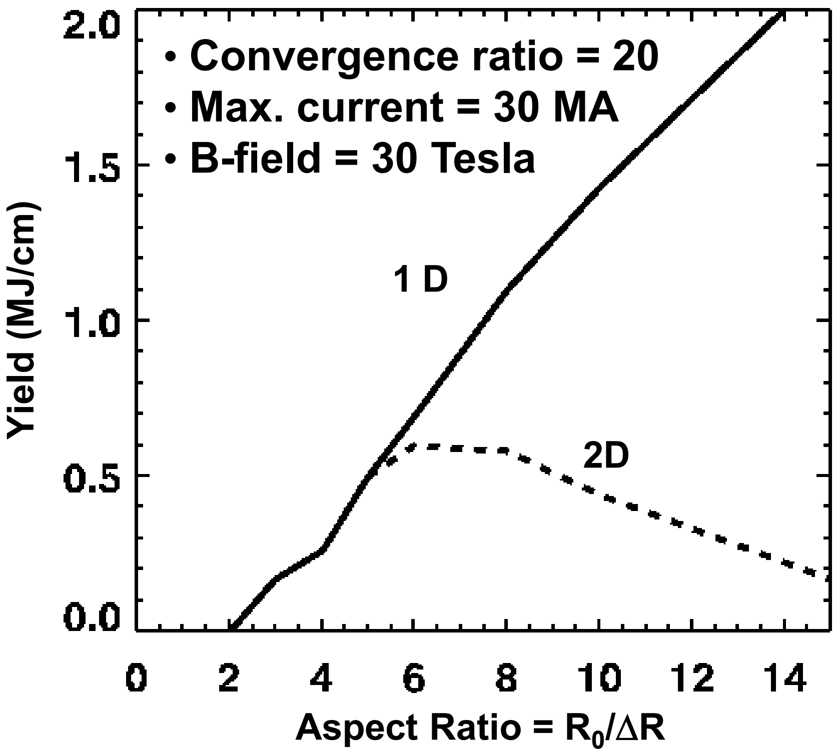
•**Fuel preheat requires < 10 kJ for Z (τ_{imp} = 100 ns)**

•**Preheat feasible with a laser**

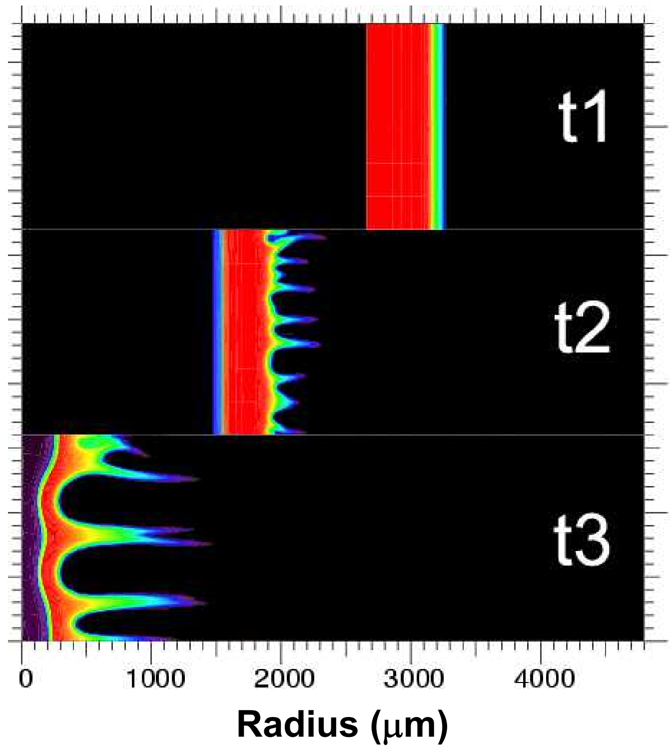
20% mix degrades the yield by only 50%



The MRT instability determines performance of MagLIF and other implosion systems



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



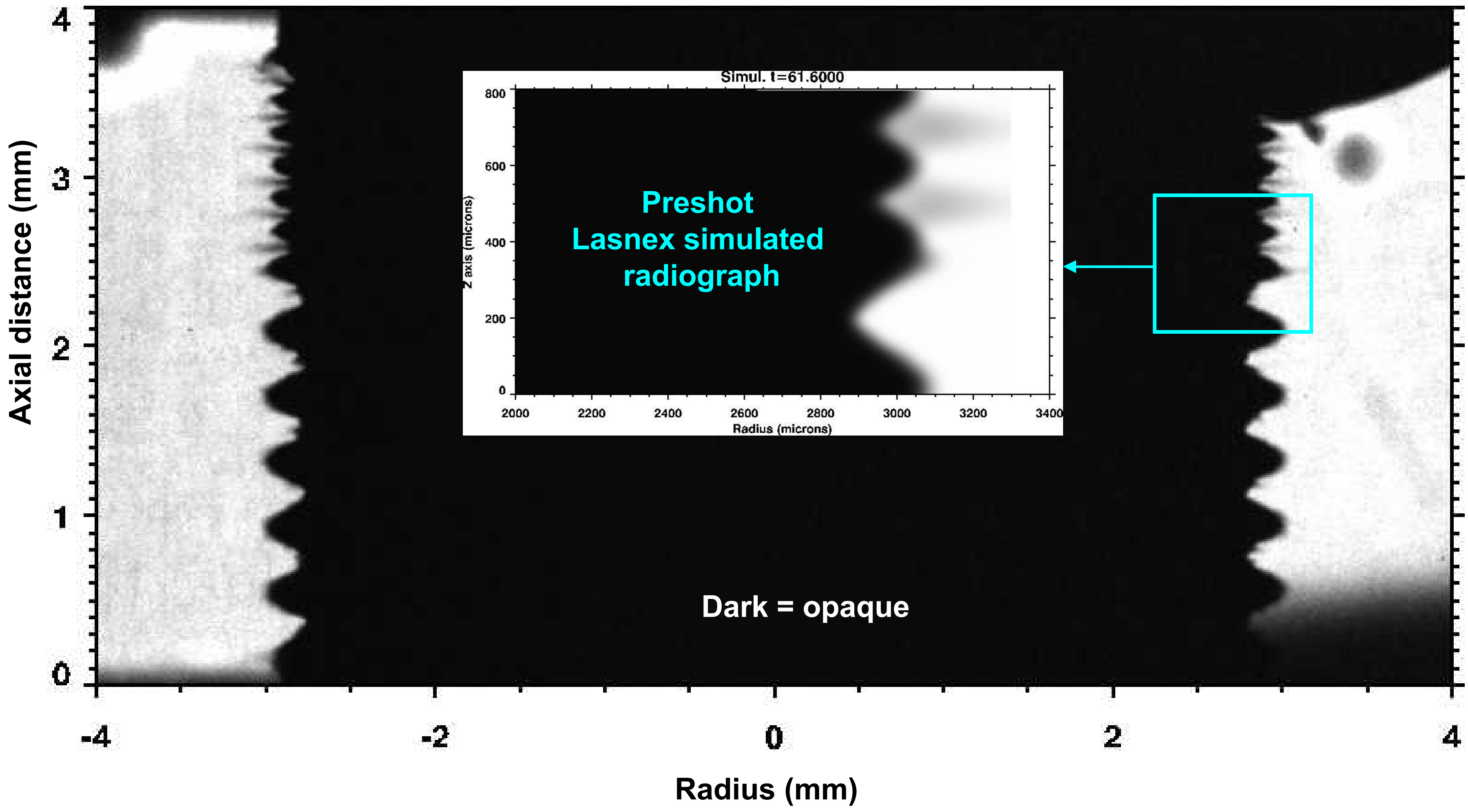
2D Lasnex Be liner simulations AR=6

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

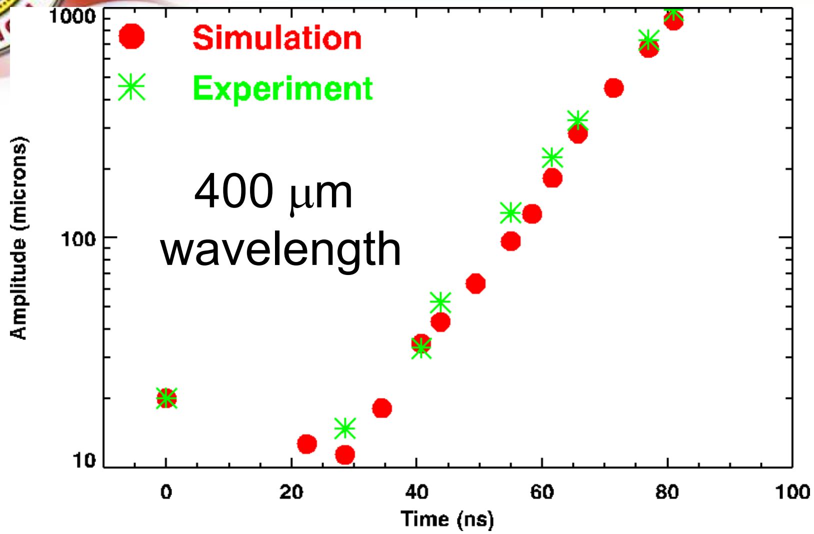
Sandia National Laboratories

We are benchmarking Lasnex with Magneto-Rayleigh-Taylor instability experiments

Aluminum liner with machined perturbations 200 and 400 micron

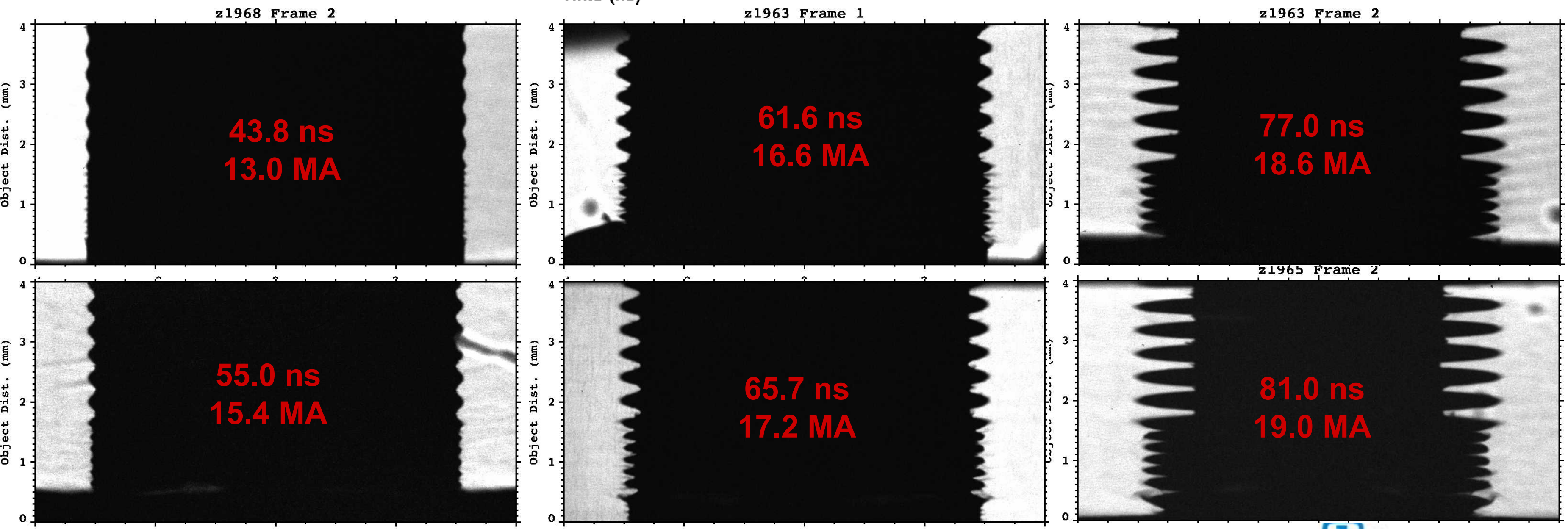


We have initiated studies of liner implosion stability, e.g. D. Sinars et al. PRL 105, 185001 (2010)

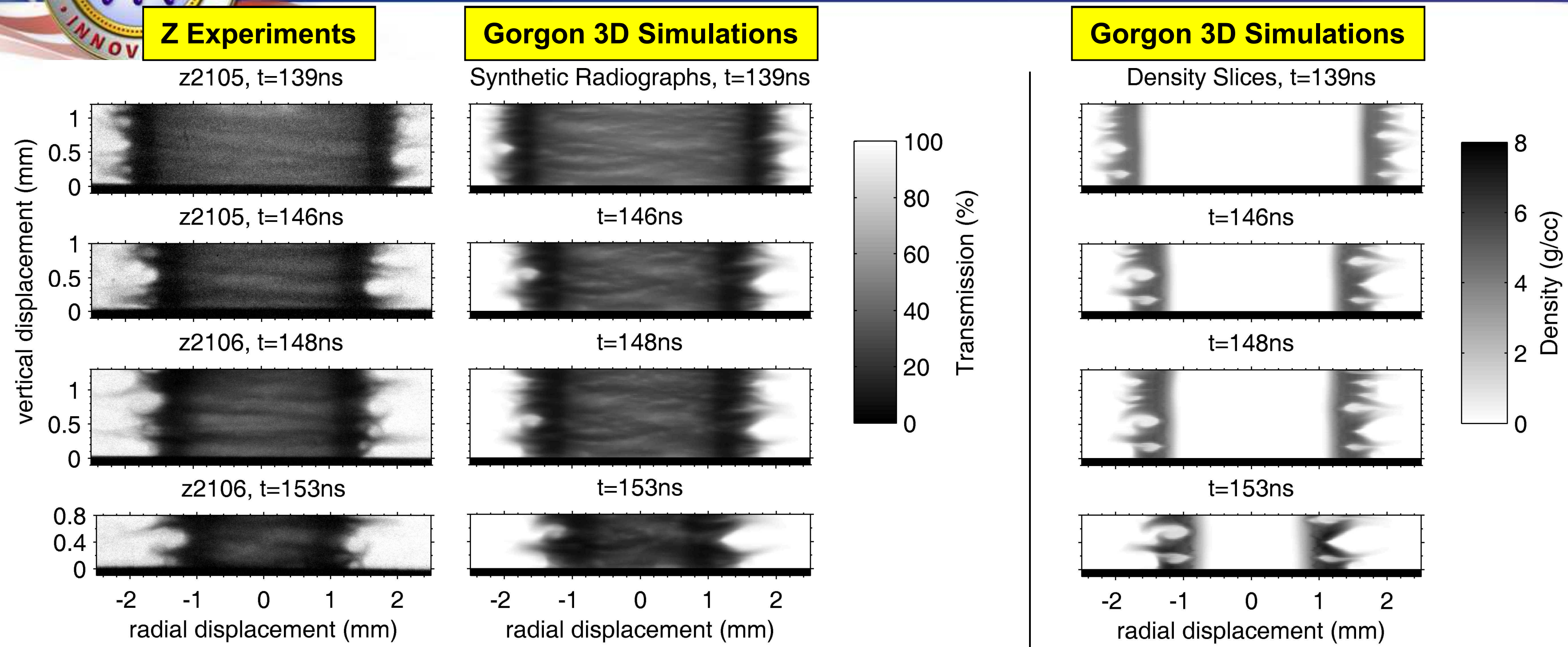


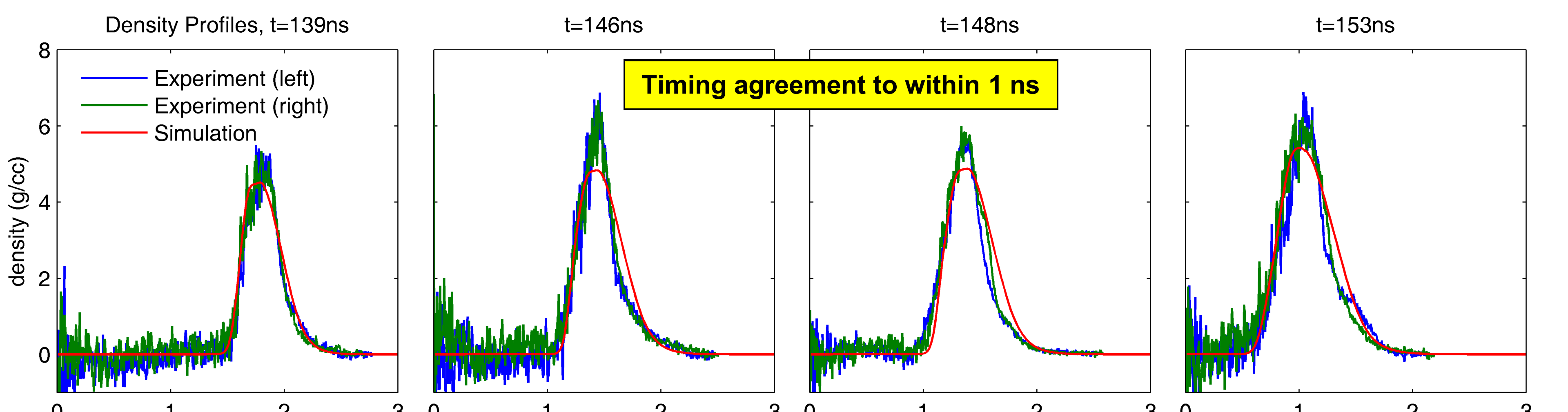
Experiments are progressing with beryllium liners

- Some information about the inner surface can be obtained due to the lower opacity
- Higher energy back lighters are under development

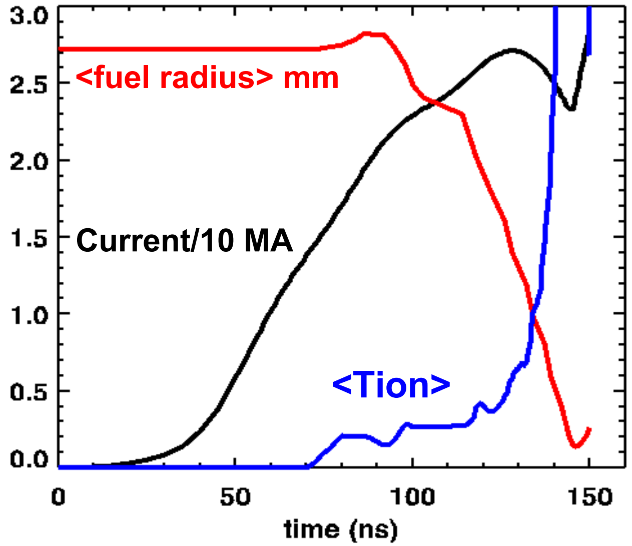


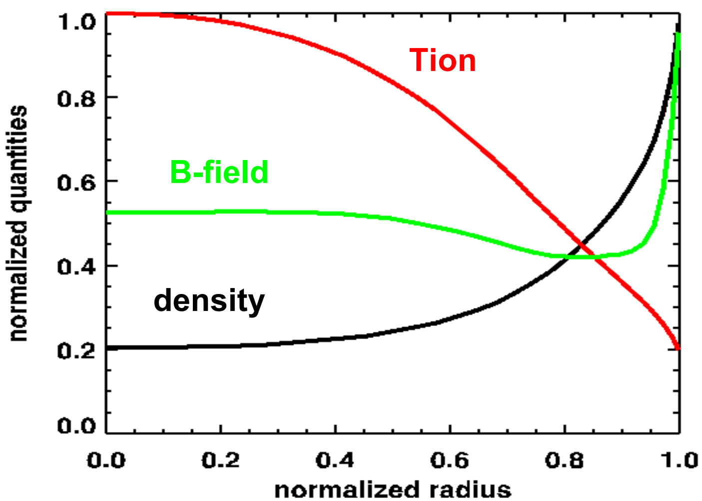
3D simulations capture features of multi-mode MRT growth





We are working toward a MagLIF point design for Z





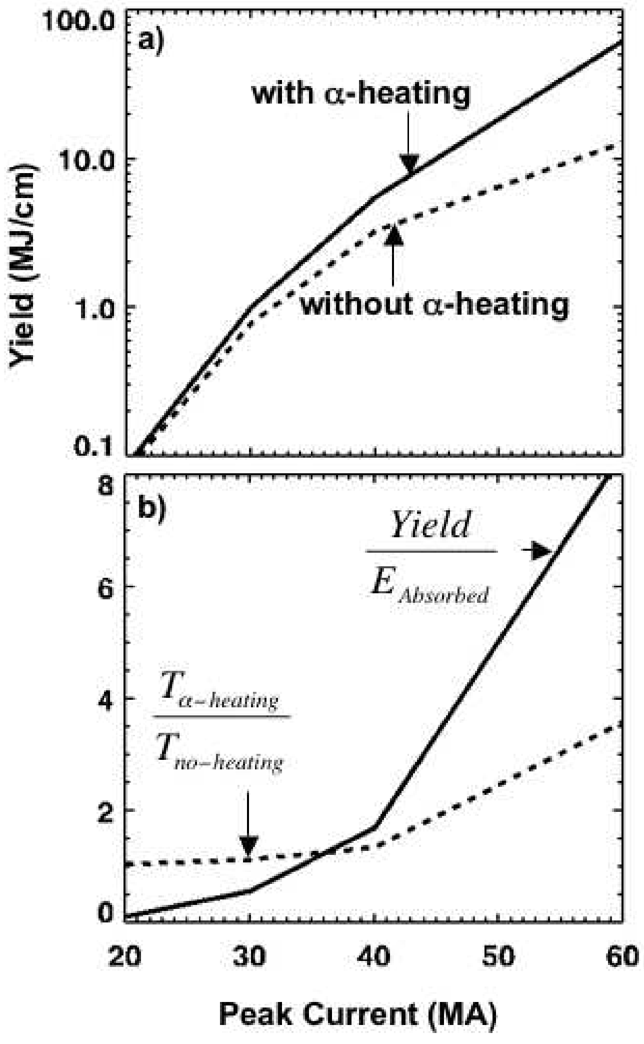
We are using Lasnex to simulate MagLIF

- Well benchmarked
- Radiation hydrodynamics
- Includes the effect of B on alphas

Preliminary point design parameters

•Beryllium liner R_0	2.7	mm
•Liner length	5.0	mm
•Aspect Ratio $R_0/\Delta R$	6	
•Initial fuel density	0.003	g/cc
•Final fuel density <on axis>	0.5	g/cc
•Preheat temperature	250	eV
•Peak central averaged Tion	8	keV
•Initial B-field	30	Tesla
•Final peak B-field	13500	Tesla
•Peak current	27	MA
•1D Yield	500	kJ
•Convergence Ratio	23	
•Peak Pressure	3	Gbars
•Fuel Energy	120	KJ
•Total absorbed energy	600	KJ

The yield is a moderate function of drive current ($Y \propto I^7$)



Liner parameters:

$R_0/\Delta R = 6$, CR = 20, B=30, Preheat temp~250 eV, Initial fuel density 2 - 5 mg/cc

A large amount of energy is needed to raise DT to the ignition temperature

Heating all of the fuel to ignition temperature "*Batch burn*" doesn't lead to high gain!

We need to determine if the burn can be propagated radially into a cold dense fuel layer.

High Gain is required for Inertial Fusion Energy (IFE)

Fusion energy requires $G\eta_E f_{RP}\eta_D = 1$

$$G > 50$$

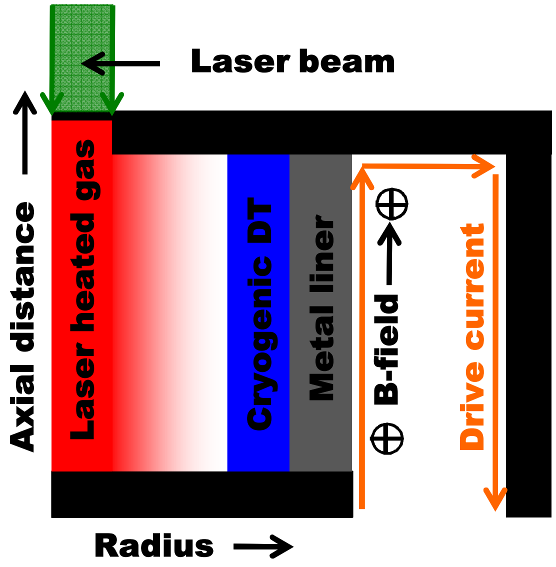
G = Gain=Yield/liner absorbed energy

η_E = electricity production efficiency~0.4

f_{RP} = fraction of power recirculated~0.25

η_D = driver efficiency ~ 0.2 for magnetic implosions

Potential High-Gain MagLIF



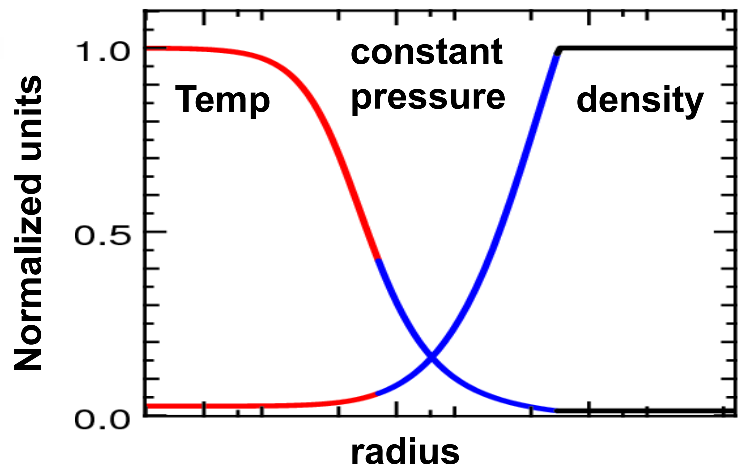
High Gain is obtained by only heating a small central portion of the fuel during compression
- minimizes compressive heating
- burn wave propagates into cold fuel as a deflagration

B_Z decreases radial heat transport
- increases self-heating in the hot spot
- decreases burn wave propagation into cold fuel

Jones and Mead, Nuclear Fusion 1986 suggested magnetized fuel is not compatible with propagating burn!

Is there a regime that allows both enhancement of hot spot ignition and burn wave propagation?

Radial propagation in magnetized fuel was studied with a simple stagnation model

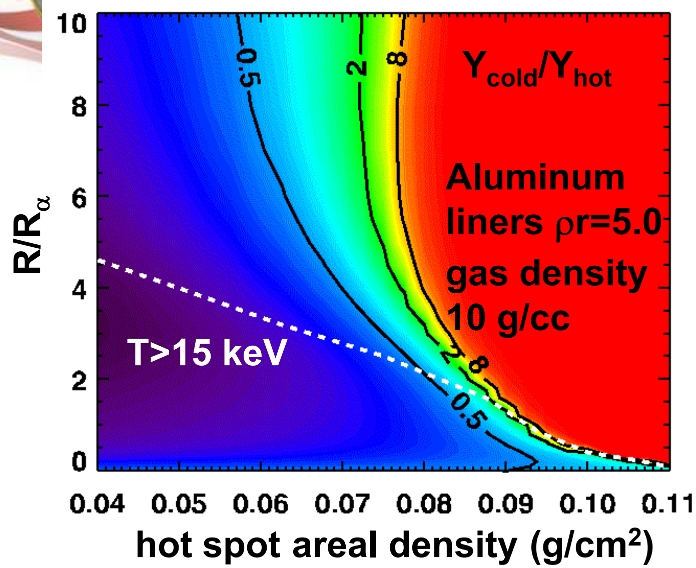


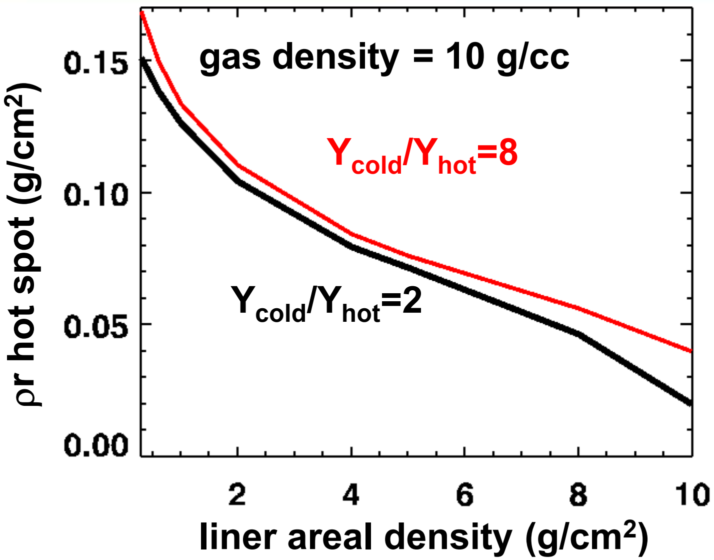
1D Lasnex simulations were performed starting at an idealized stagnated state with the following attributes:

- **pressure equilibrium**
- **central hot spot Tion=10 keV @ center**
- **specific areal density of the hot spot and the surrounding metal liner were varied**

The ratio of the yield from the cold ice layer to the yield from the hot spot is a measure of the propagation, i.e. Y_{cold}/Y_{hot}

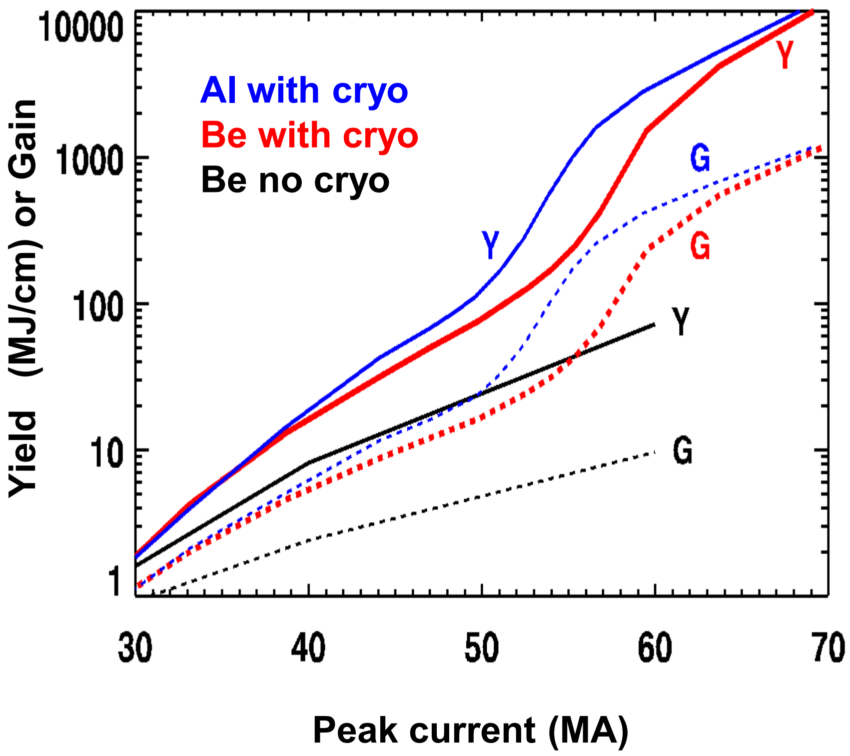
There is an optimal magnetic field strength for radial propagation





- The inhibition of thermal conduction and alpha transport lowers the hot spot areal density required for for ignition
- Too large a B-field inhibits propagation into the cold fuel
- Minimum hot spot areal density is a weak function of gas density, but is significantly affected by the areal density of the liner
- More confinement time allows slower burn propagation!

Very high gains (1000) are possible with MagLIF!



These liners were not highly optimized

- fuel is not on a low isentrope
- no current pulse shaping

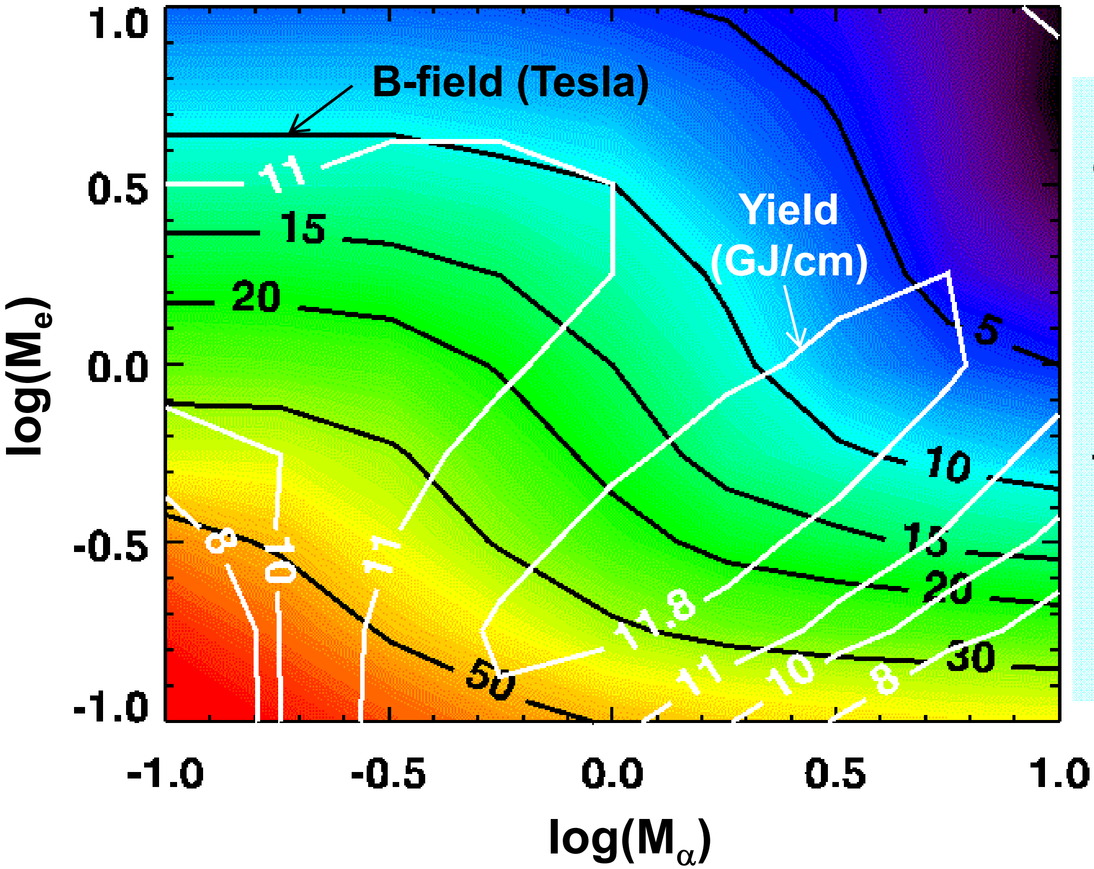
Margin increases with current

>50% as I => 70 MA

Initial gas density increases with current

- not at vapor pressure
- laser energy =>22 KJ
- pulse length => 30 ns

High Gain MagLIF is robust to errors in magnetic inhibition modeling



Magnetic inhibition of thermal conduction depends on $\omega_e \tau_e$

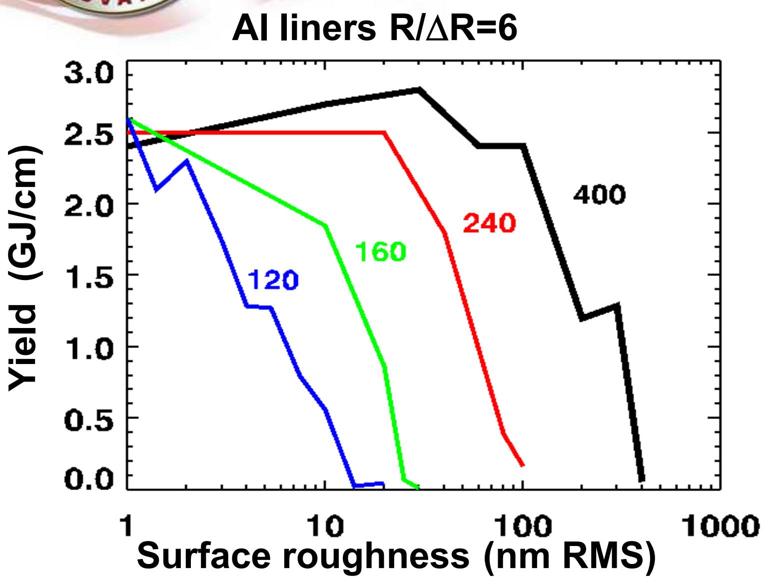
$$K_{cond} = K_0 F(M_e \omega_e \tau_e)$$

Magnetic inhibition of α-particle transport depends on $\omega_\alpha \tau_{\alpha e}$

$$D_\alpha = D_{\alpha 0} G(M_\alpha \omega_\alpha \tau_{\alpha e})$$

Initial B-field is varied to obtain maximum yield for (M_e, M_α)

The Magneto-Rayleigh-Taylor instability is always a concern



The simulated yields are not robust to short wavelengths

- •2D simulations had stronger growth than experiments at short wavelengths (Sinars et al. PRL 105, 185001)
- •2D may be pessimistic at short wave lengths
- •3D simulations and experiments needed for clarification
- •RMS amplitudes less than 20 nm may be required and achieved with polishing

There are several possible ways to mitigate the effect of the MRT

- •The axial B-field reduces the growth rate on the fuel/liner interface (Ryutov)
- •An initially low density liner would have a large B-field when compressed which could suppress the instability
- •Nested wire arrays mitigate the MRT. Multi-shell liners may also be effective
- •Pulse shaping can avoid shocks and retain material strength

Summary

- We have presented detailed simulations indicating that High-Gain Magnetized Inertial Fusion is possible.

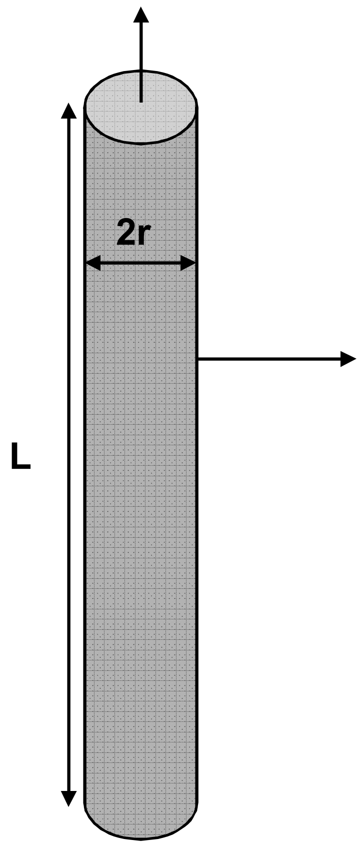
- This may lead to a low cost means to generate electricity with fusion

- High-Gain MagLIF is obtained by adding a cryogenic layer of DT to the inside of the liner
    - laser preheat energy is modestly increased to about 22 kJ
    - Optimum initial Bz is decreased from 30 to about 10 Tesla
    - 2D simulations indicate that surface perturbations with short wavelengths may be the most damaging
    - 3D simulations and further experimentation are needed to determine the effect of the MRT and the allowed surface roughness
    - MRT mitigation needs to be explored

- High-Gain MagLIF with yields of 10 GJ/cm could allow the low rep-rates required by recyclable transmission lines

Axial Thermal losses should not be important

Axial loss $L_{axial} = C\theta^{7/2}\left(A = 2\pi r^2\right)\left(\nabla\theta \sim \theta / L\right)$



Radial loss $L_{rad} = C\theta^{7/2}\left(A = 2\pi r L\right)\left(\nabla\theta \sim \theta / r\right)$

$$L_{rad} / L_{axial} = \left(L / r\right)^2 \sim \left(0.5 / .01\right)^2 = 2500$$

The Nernst term has a significant effect on profiles and the yield