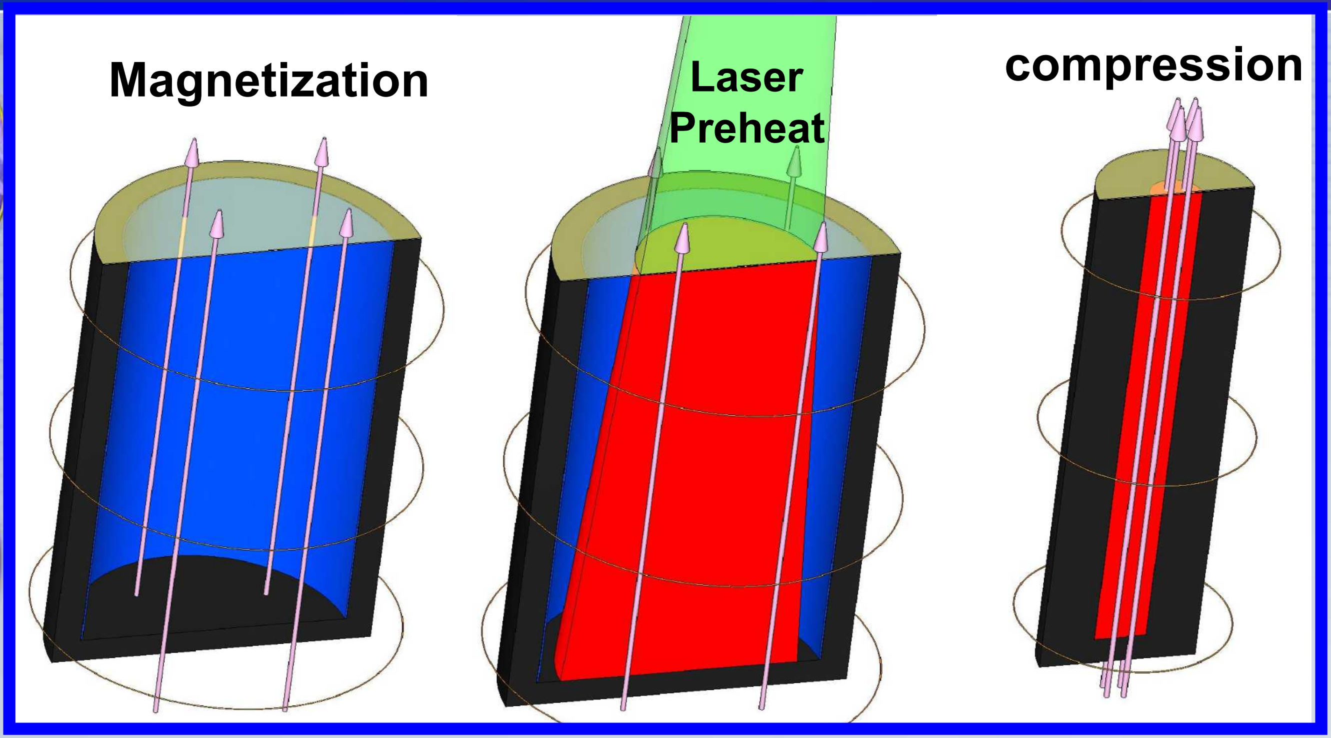
Blast Deflection of High-Yield Magnetized Liner Fusion Explosions

SAND2011-6420C



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NNSA National Nuclear Security Administration

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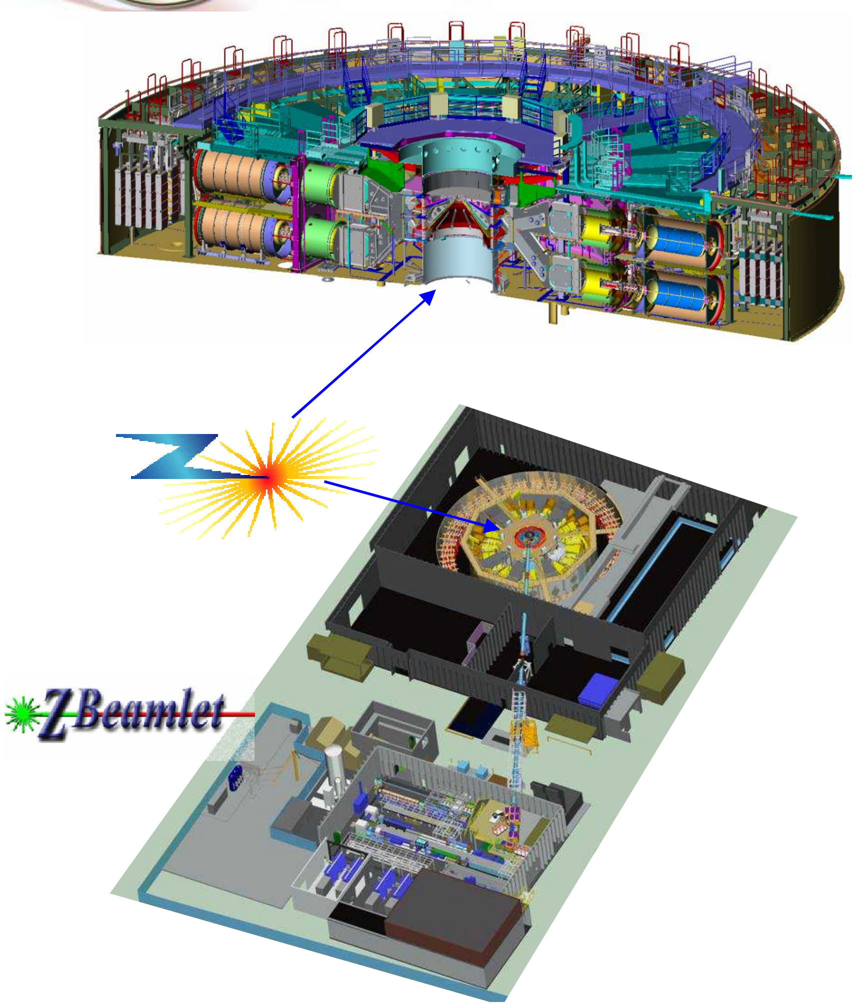
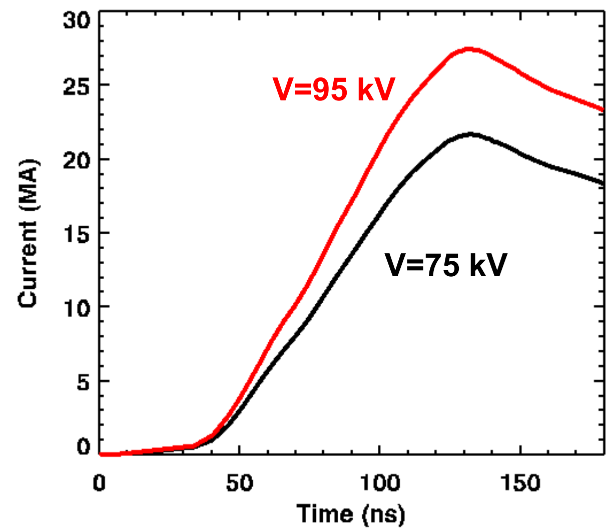
The Z facility contains the worlds largest pulsed power machine and the Z-Beamlet and Z-Petawatt lasers





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

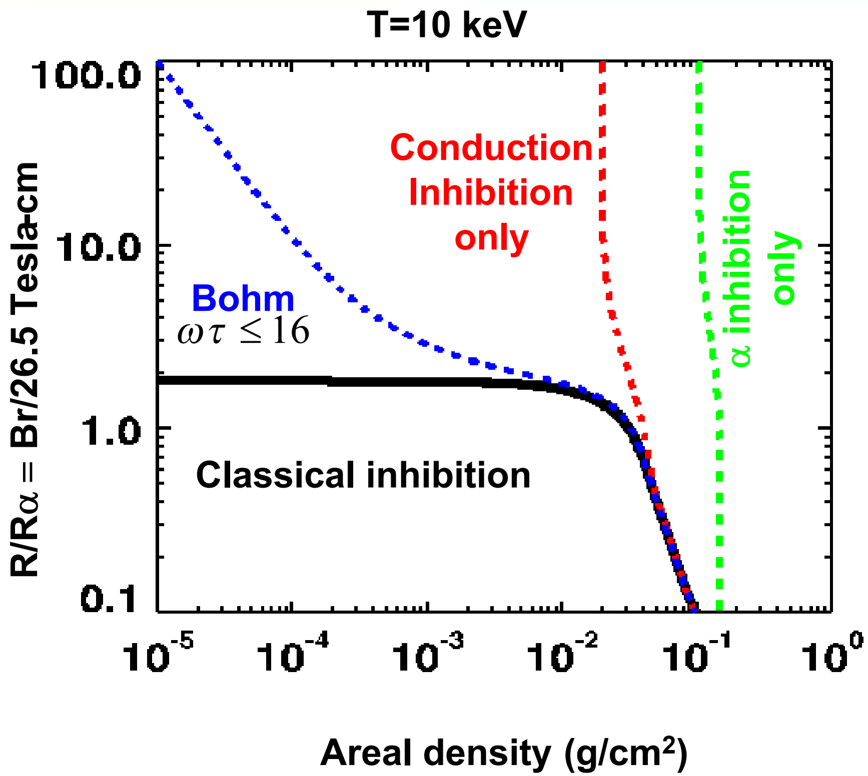
Direct magnetically driven implosion ~ 50 times more efficient than radiation drive

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

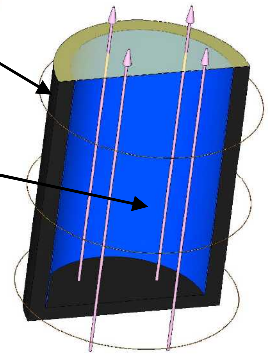


Axial α-trapping requires closed field lines or moderately high fuel density so that

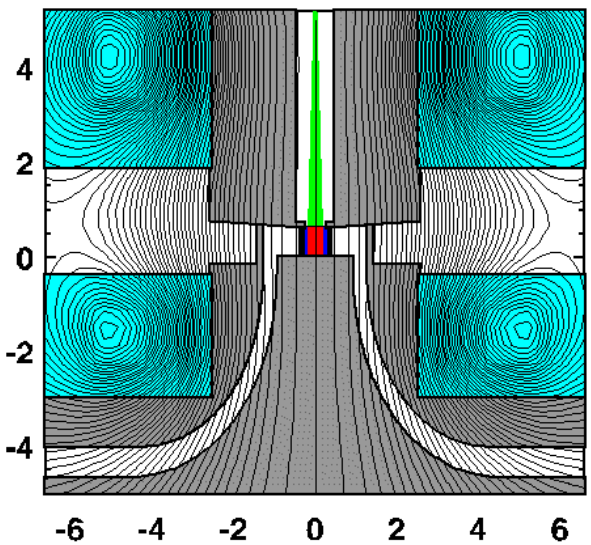
$$\rho\Delta z > 0.5 g/cm^2$$

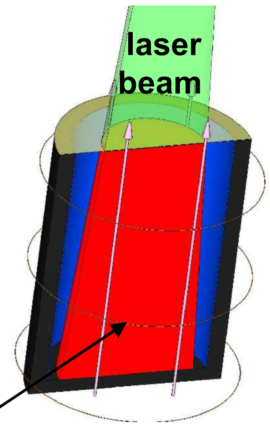
The Z facility provides a unique opportunity to test the benefits of fuel magnetization and preheat*

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

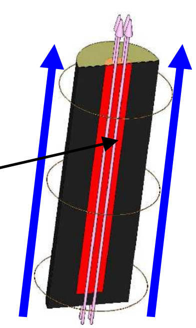


1. An axial magnetic field is applied to inhibit thermal conduction and enhance alpha particle deposition



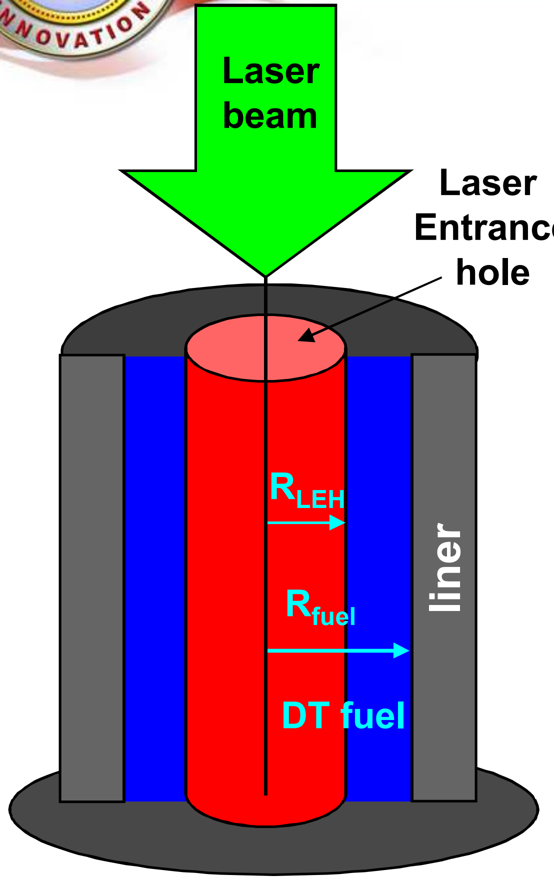


2. Z Beamlet preheats the fuel

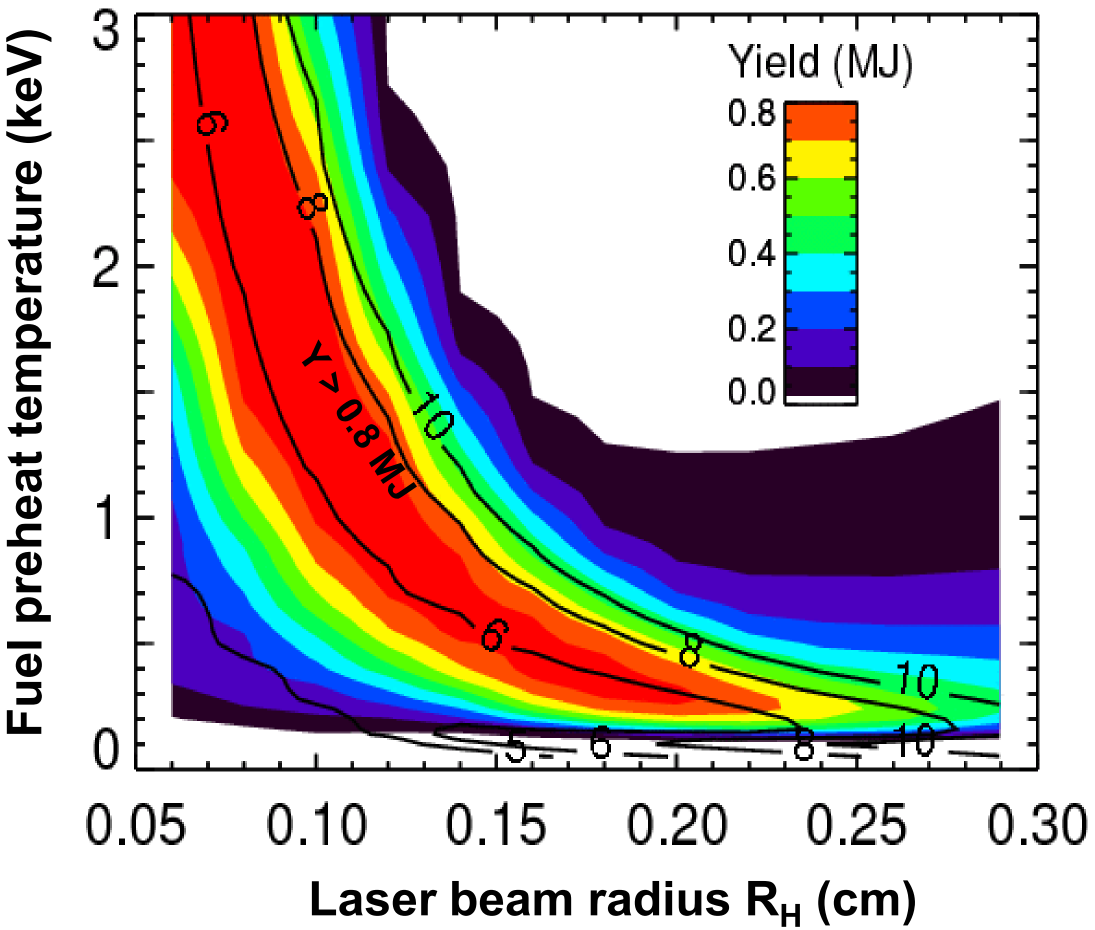


3. The Z accelerator efficiently drives a z-pinch implosion

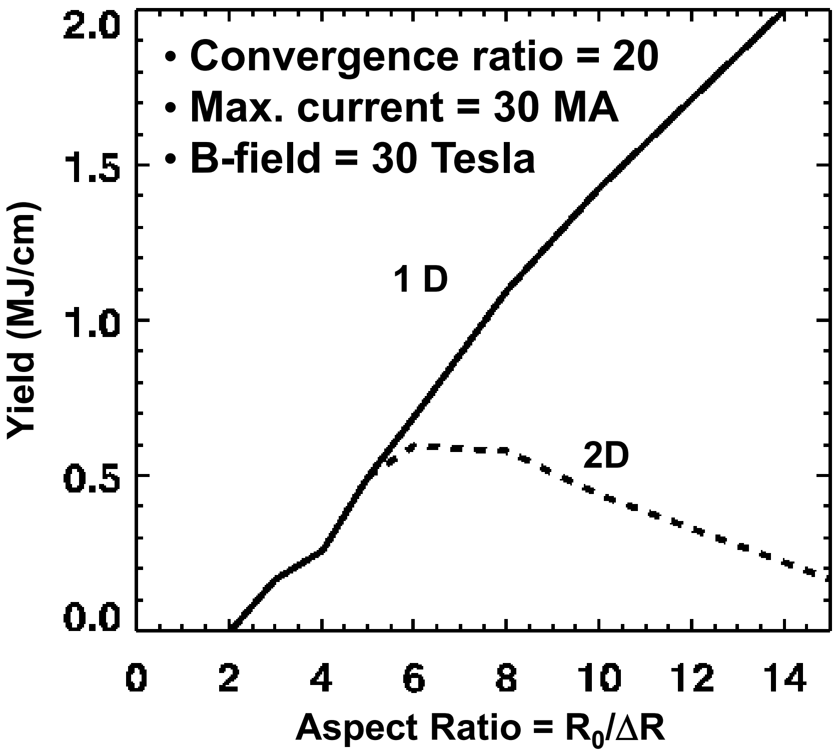
A small laser entrance hole (LEH) increases the yield



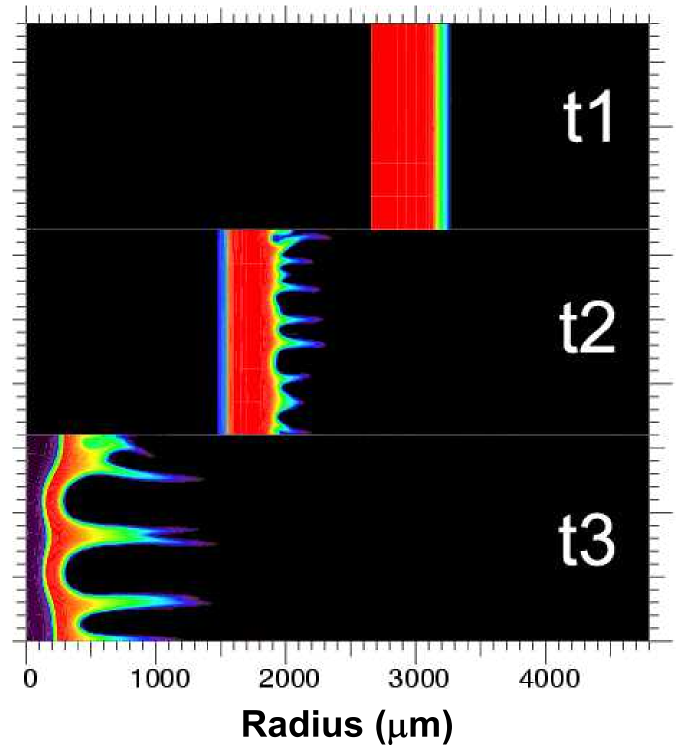
Yield contours (color) from a series of 1D Lasnex simulations



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

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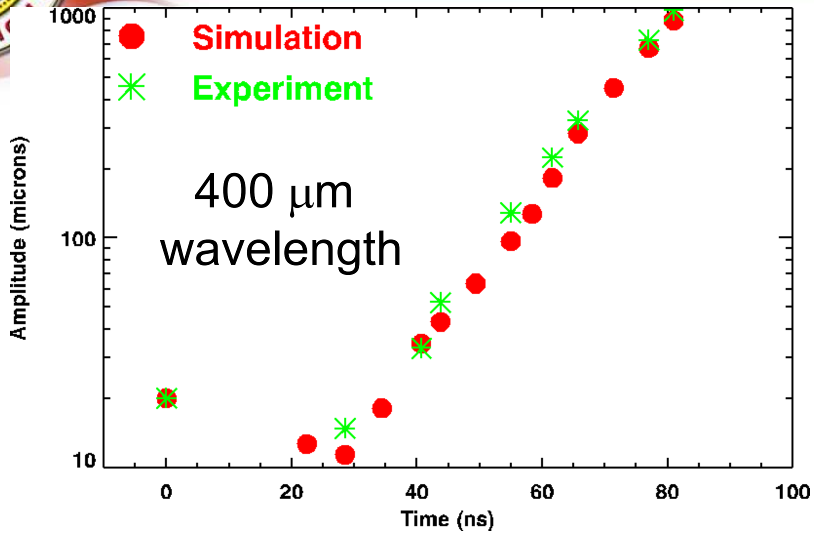
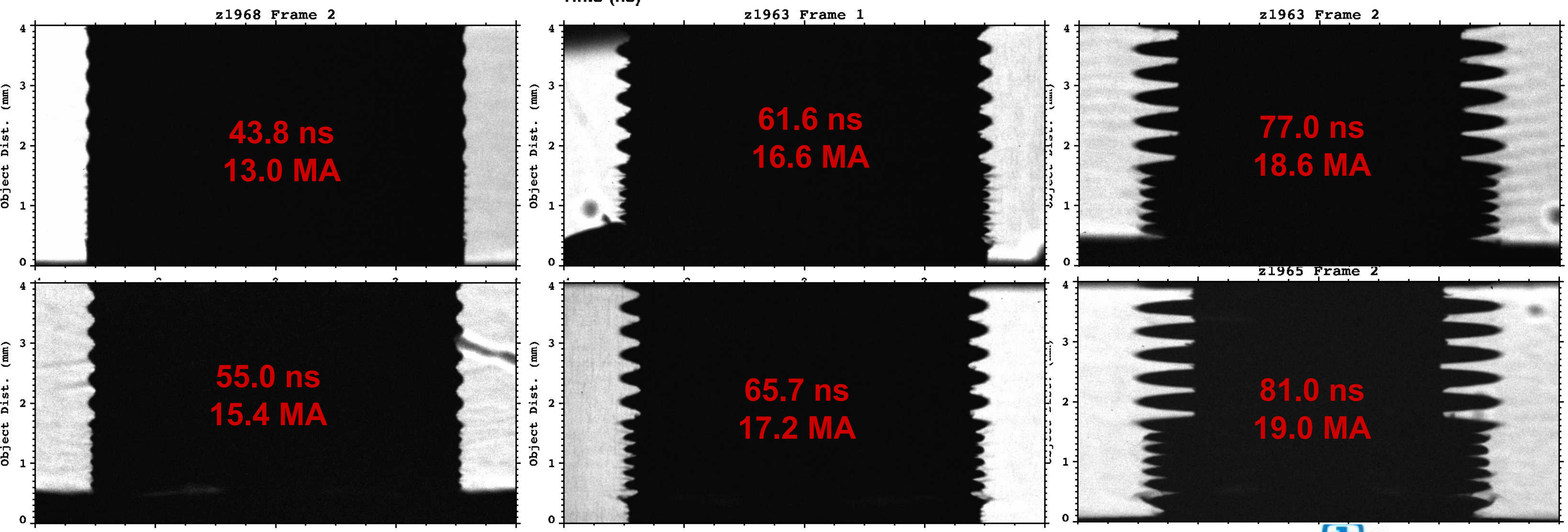
We have initiated studies of liner implosion stability, e.g. D. Sinars et al. PRL 105, 185001 (2010)

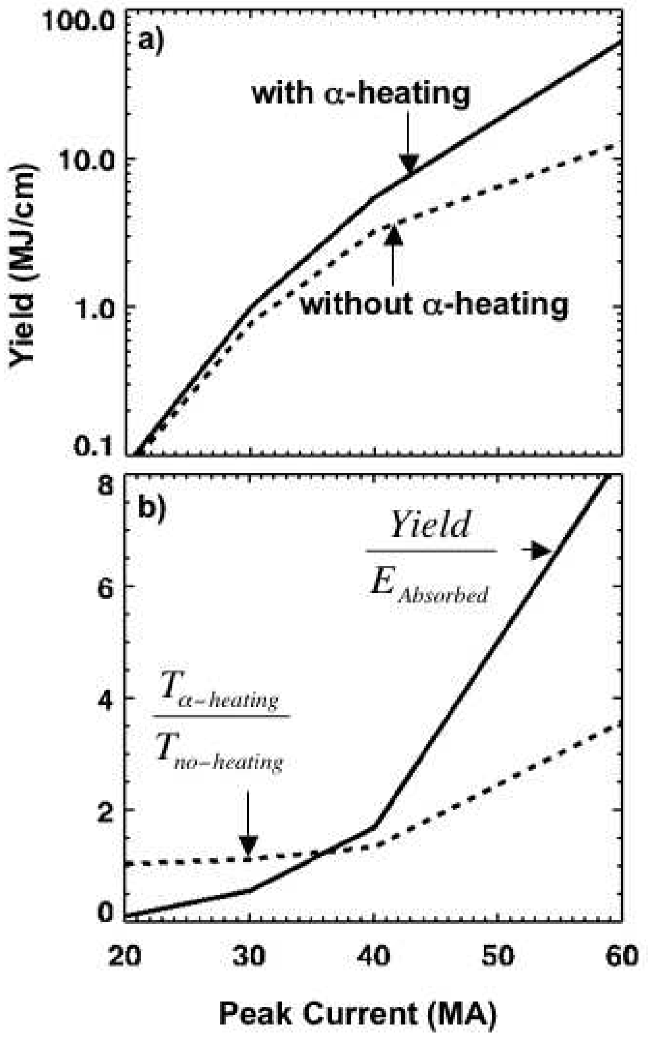


Experiments are progressing with beryllium liners

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



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



Liner parameters:

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

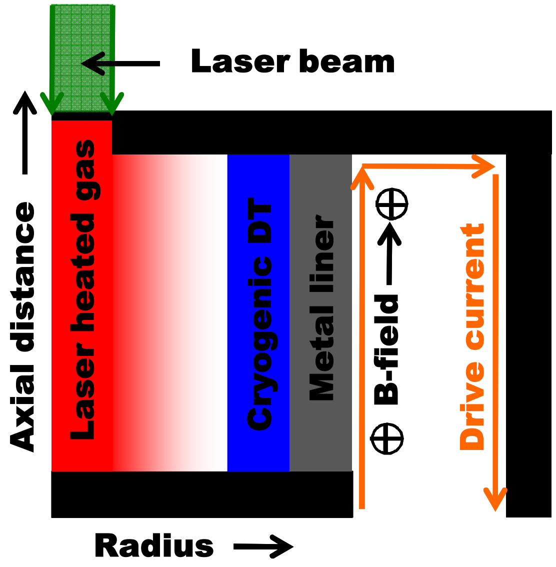
A large amount of energy is needed to raise DT to the ignition temperature

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)

Potential High-Gain MagLIF



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

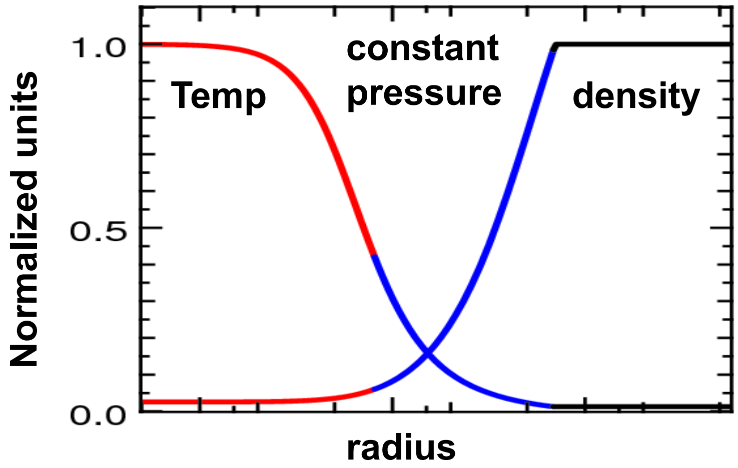
High Gain is obtained by only heating a small central portion of the fuel during compression
- minimizes compressive heating
- burn wave propagates into cold fuel as a deflagration

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

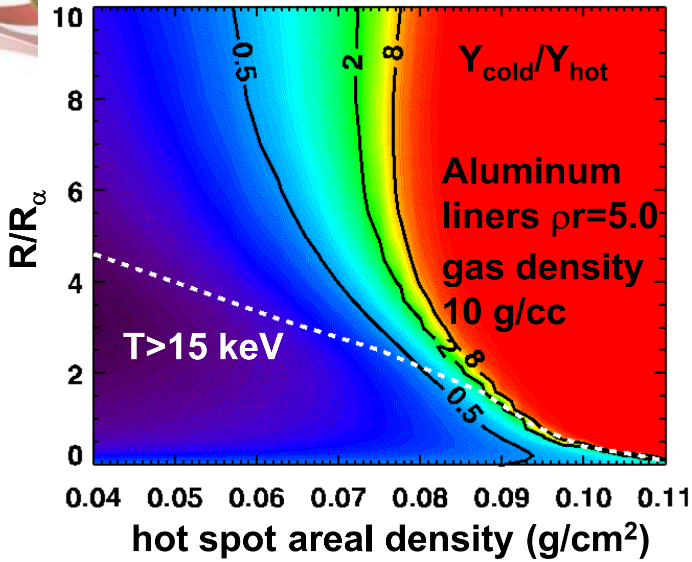


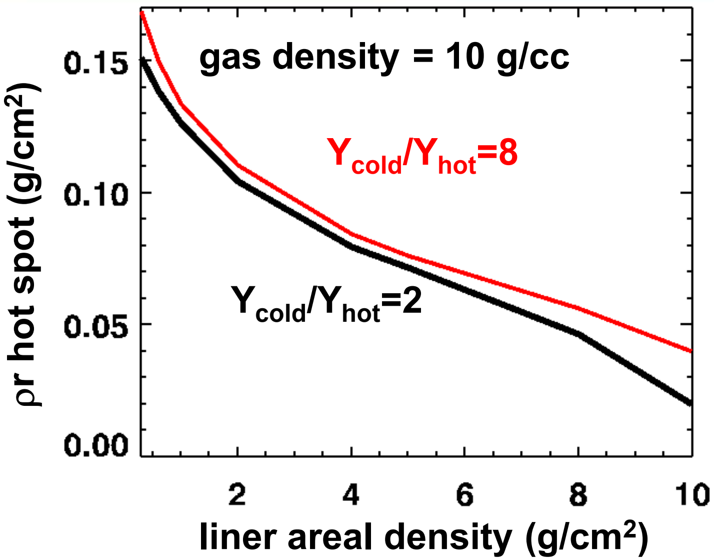
1D Lasnex simulations were performed starting at an idealized stagnated state with the following attributes:

- **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}

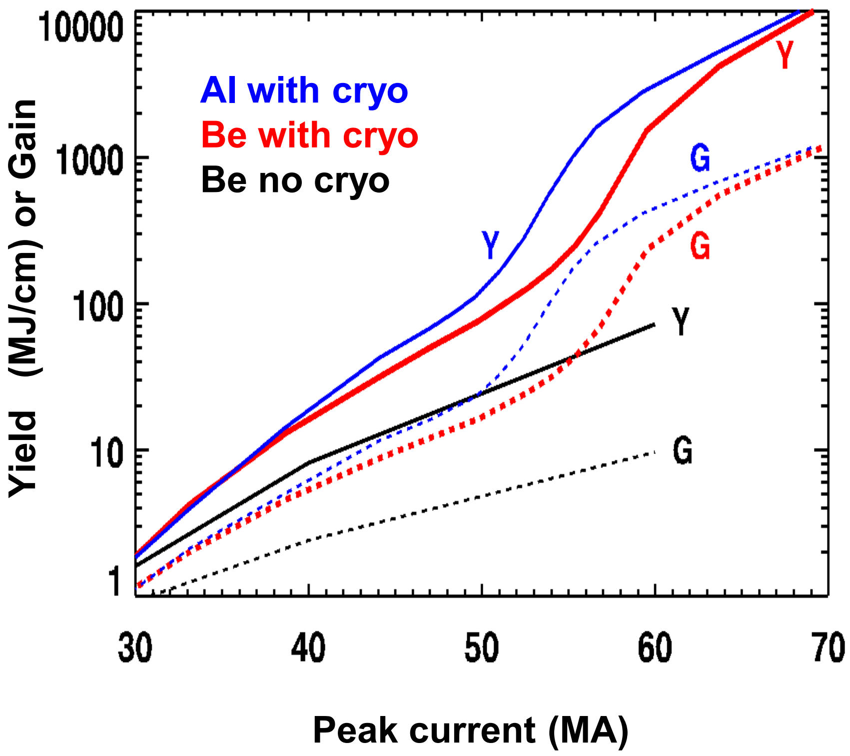
There is an optimal magnetic field strength for radial propagation





- 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!

Gains >1000 are possible with MagLIF!



Further optimization is possible

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

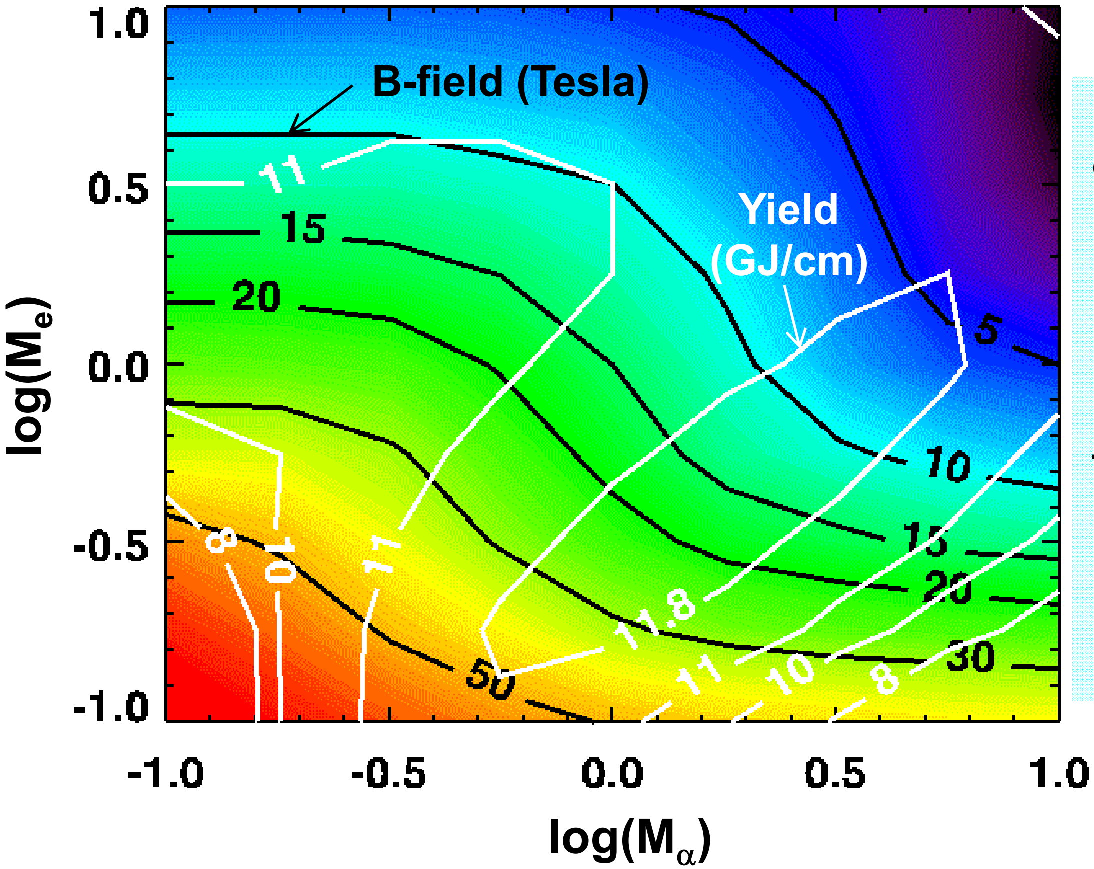
Margin increases with current

>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 $\omega_e \tau_e$

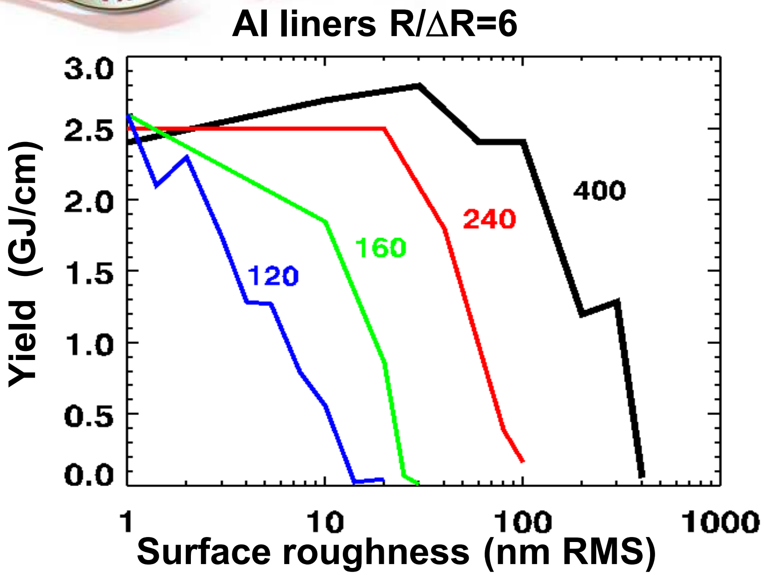
$$K_{cond} = K_0 F(M_e \omega_e \tau_e)$$

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



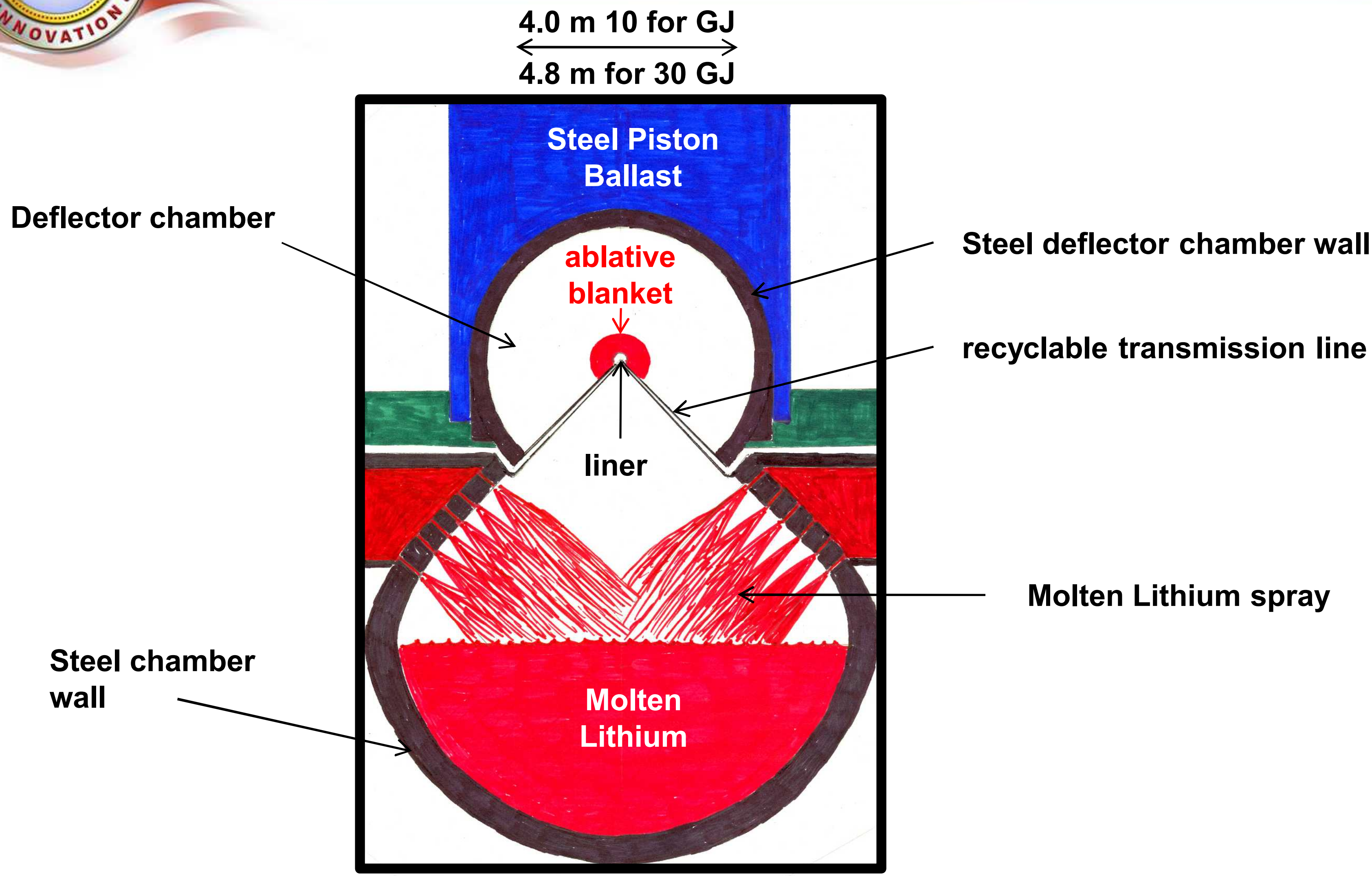
The simulated yields are not robust to short wavelengths

- 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

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



Blast containment in a spherical vessel

Tritium breeding and neutron protection can be provided by an ablative blanket (AB) surrounding the capsule, 40 cm of LiH is sufficient

Lasnex simulations indicate that nearly 100% of the capsule yield is converted to kinetic energy of the AB, which delivers a momentum pulse to the containment vessel

$$\Pi \approx 2\left(2YM_{AB}\right)^{1/2}$$

The vibration of the steel shell with aspect ratio, A_R, Young's modulus, E, density, ρ radius, r_0, shell is given by the equation

$$\ddot{S} + \frac{2E}{\rho r_0^2} S = \frac{PA_R}{\rho r_0^2} \qquad S = \frac{\Delta r}{r}$$

The maximum amplitude for a tensile strength, T is $S_x = \frac{T}{E}$

The deflector geometry allows energy to escape from the AB reducing the momentum by a factor of 3-4. The deflector chamber radius is then

$$R_{def} > 2.2\left(\frac{Y}{10GJ}\right)^{1/6}\left(\frac{A_R}{6}\right)^{1/3} m$$

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

We have presented the concept of the deflector, which enables the containment of large yields (10-30 GJ) with relatively short recyclable transmission lines (2-3 m).