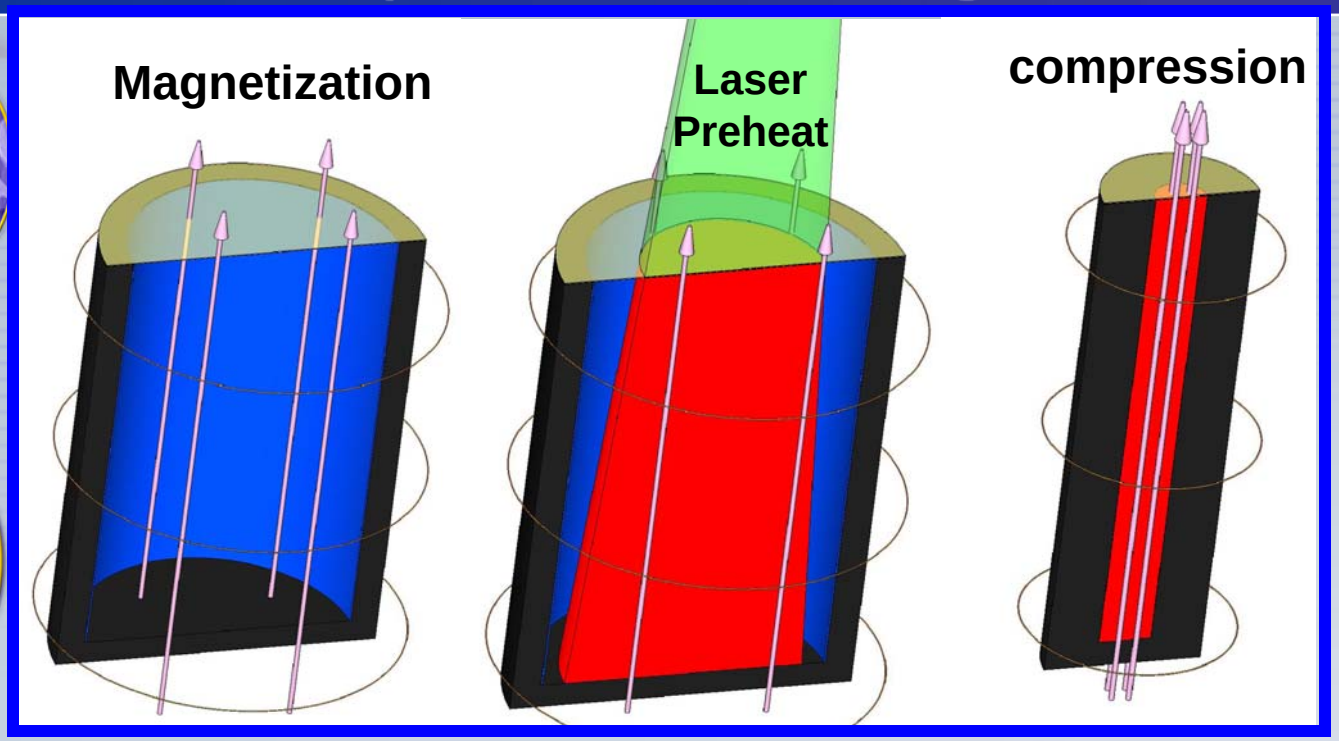
Magnetized Liner Inertial Fusion (MagLIF): the promise and challenges



MagLIF Workshop, Albuquerque February 6, 2012

Stephen A. Slutz

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.

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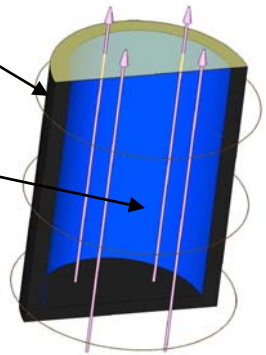
The MagLIF concept is a 3 step process*

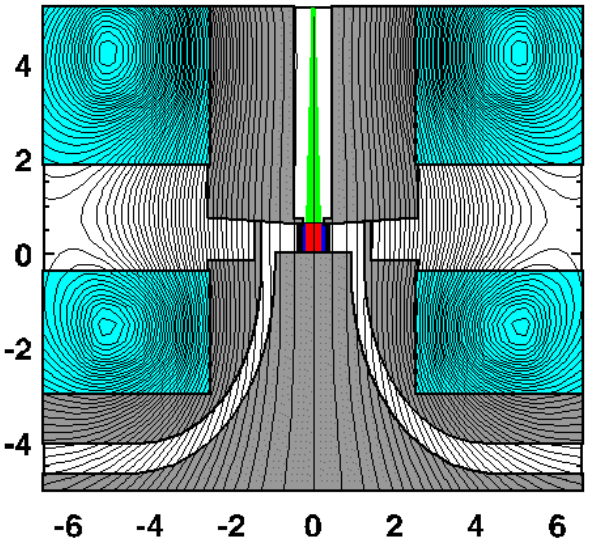
Metal (beryllium) Cylindrical Liner

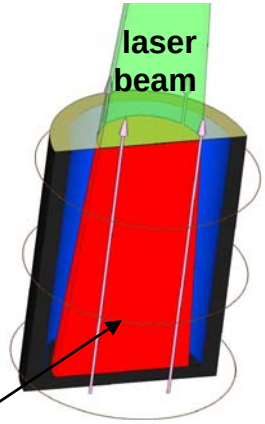
cold deuterium/tritium gas (fuel)



** 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

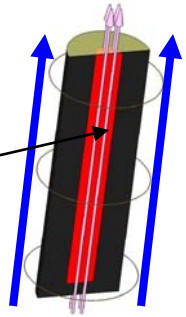




Laser preheated fuel

2. Z Beamlet preheats the fuel

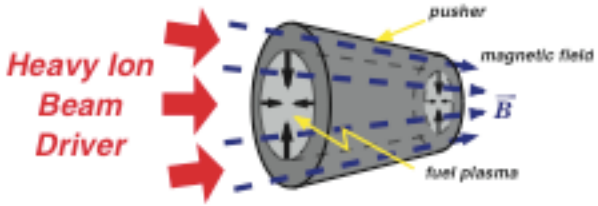
compressed axial field



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

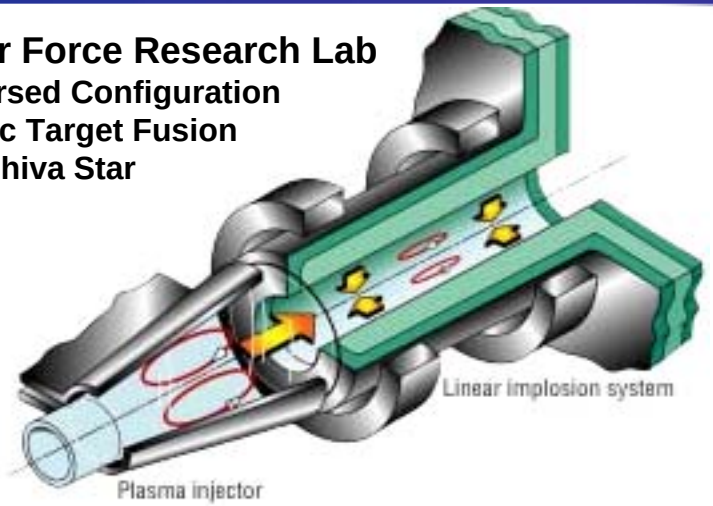
A number of scenarios using magnetized fuel have been proposed

Max Planck/ITEP

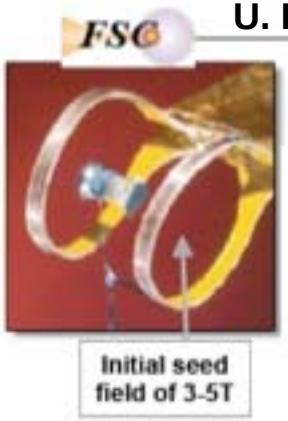


Los Alamos/Air Force Research Lab

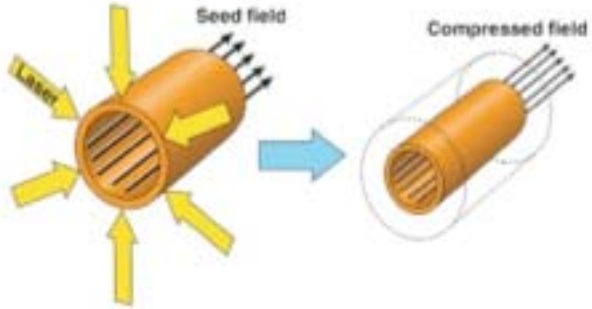
Field Reversed Configuration
Magnetic Target Fusion
Shiva Star



U. Rochester LLE

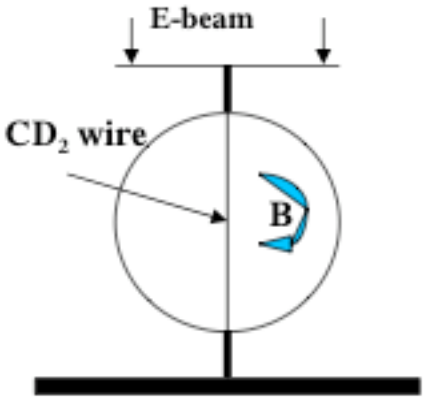


A magnetized ICF implosion yields higher fuel temperatures



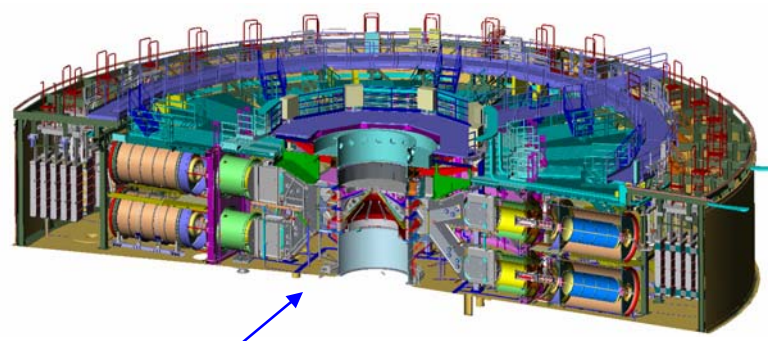
Direct drive laser implosion of cylinders
…preheat not necessary due to high implosion velocity

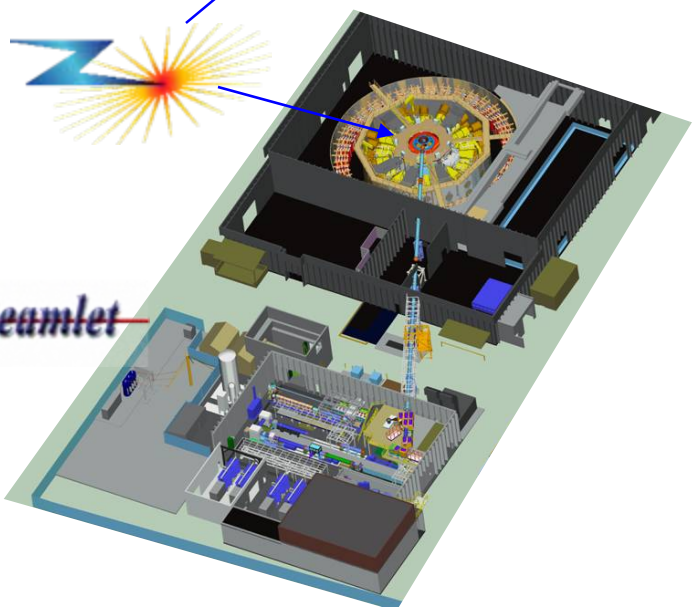
SNL Phi Target

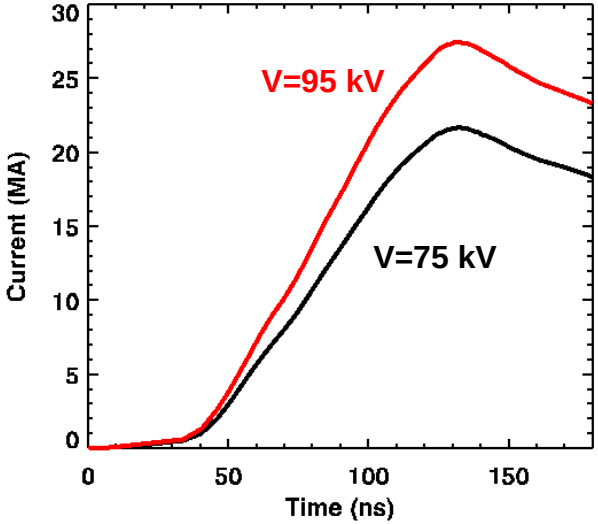


The Z facility provides a unique opportunity to test magnetized and preheated fuel

Z is the worlds largest pulsed power machine





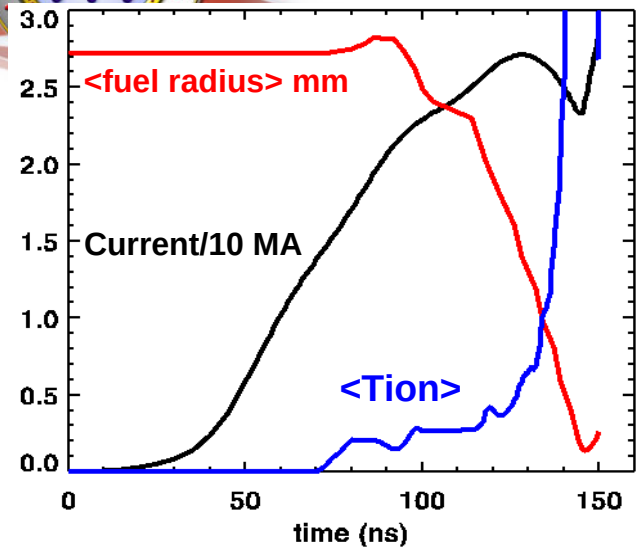


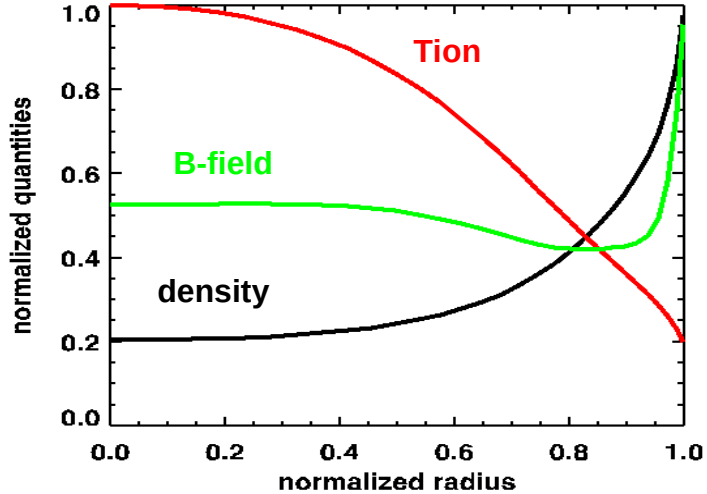
Magnetically-Driven Cylindrical Implosion

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

140 MBar is generated by 300 eV radiation drive

A MagLIF point design for Z is being developed





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
•Preheat temperature	250	eV
•Initial B-field	30	Tesla
•Peak current	27	MA
•Convergence Ratio	23	
•Peak Pressure	3	Gbars
•Fuel Energy	120	KJ
•Total absorbed energy	600	KJ
•Final fuel density <on axis>	0.5	g/cc
•Peak central averaged Tion	8	keV
•Final peak B-field	13500	Tesla
•1D Yield	500	kJ

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

However, the natural geometry is cylindrical

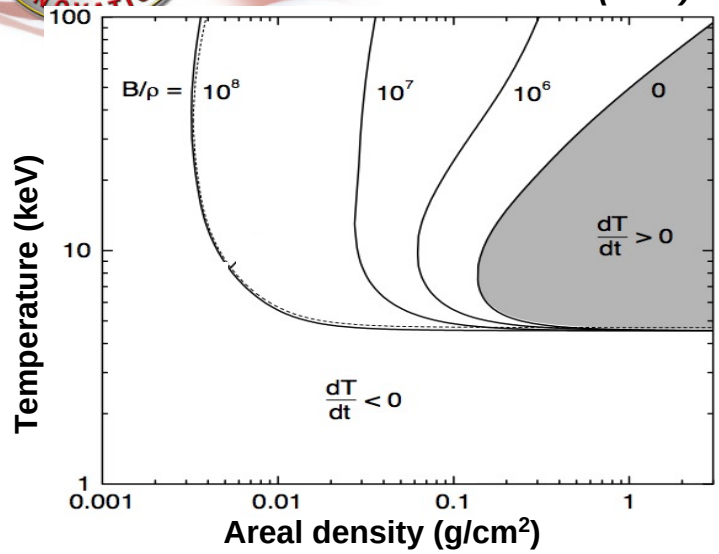
- **reduced volume compression (ρr and T_{ig} difficult)**
- **implosion velocity is slow V_{imp} ~ 12 cm/μs for instability-robust liners**

Fuel magnetizing and preheating is a potential solution

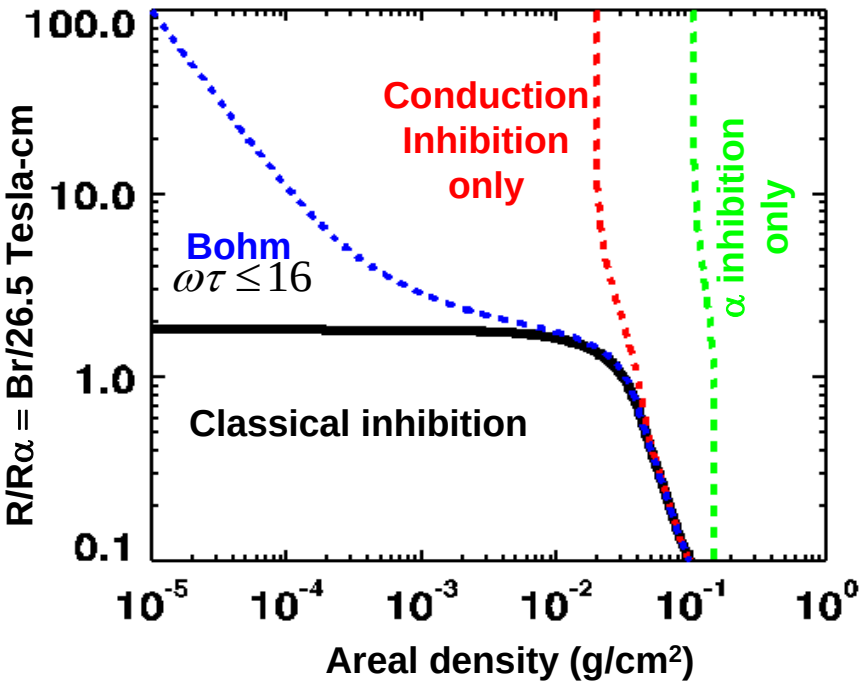
- **the attainment of ignition conditions with slow implosions and modest radial convergence**

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

*Basko et al. Nuc. Fusion (2000)



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

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

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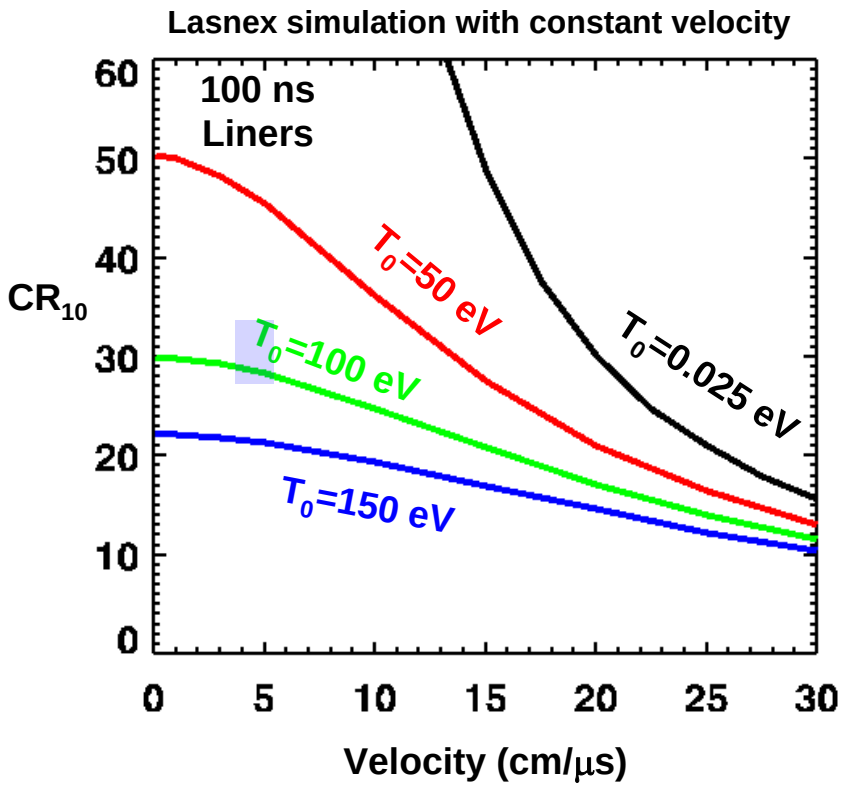
Preheat is necessary for slow implosions

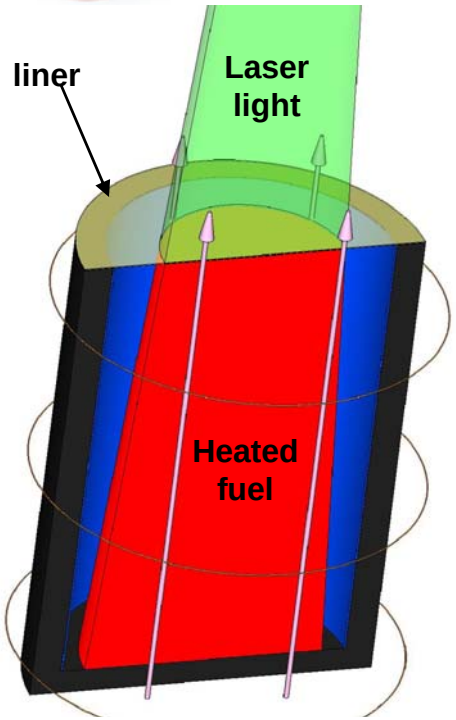
CR_{10} = Convergence Ratio (R_0/R_f) needed to obtain 10 keV (ignition) with no radiation or conductivity losses



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**

The Z-Beamlet laser could preheat the fuel for experiments on Z



Conditions for heating of DT gas

The critical density for green light is 17 mg/cc in DT

…initial gas density is 2-3 mg/cc implies absorption by inverse bremsstrahlung

The gas can be held in place by a thin plastic foil

…a 1 μ window will have less areal density than the gas

The total laser energy is modest

$$E_{laser} = \pi r^2 L \rho C_V \theta \qquad C_V \approx 1.2x10^8 J/g/keV$$

$$E_{laser} \approx 3.4\left(\frac{r}{0.3cm}\right)^2\left(\frac{L}{1cm}\right)\left(\frac{\rho_0}{1mg/cc}\right)\left(\frac{\theta}{0.1keV}\right)kJ$$

Laser penetration of the gas has been modeled analytically (no hydro or conductivity)

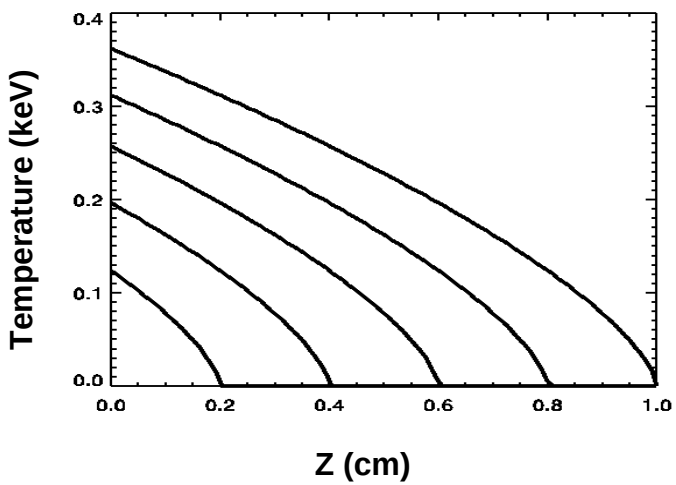
Laser absorption is dominated by inverse bremstrahlung

$$\frac{dI}{dz} = -kI \qquad k = \frac{\nu_{ei}\omega_e^2}{c\omega_L^2}\left(1-\frac{\omega_p^2}{\omega_L^2}\right)^{-1/2} = \frac{k_0}{\theta^{3/2}} \qquad k_0 \approx 1.37x10^5\left(\rho\lambda_L Z_b\right)^2\left(1-227\rho Z_b\lambda_L^2\right)^{-1/2}$$

The gas heating is described by the equation $C_V\frac{d\theta}{dt} = \frac{dI}{dz} - kI$ **which has solutions**

$$I = I_0\left(1-\frac{z}{z_f}\right)^{2/3} \qquad \theta = \theta_0\left(1-\frac{z}{z_f}\right)^{2/3}$$

where $\theta_0 = \left(\frac{5k_0 I_0 t}{2C_V}\right)^{2/5}$



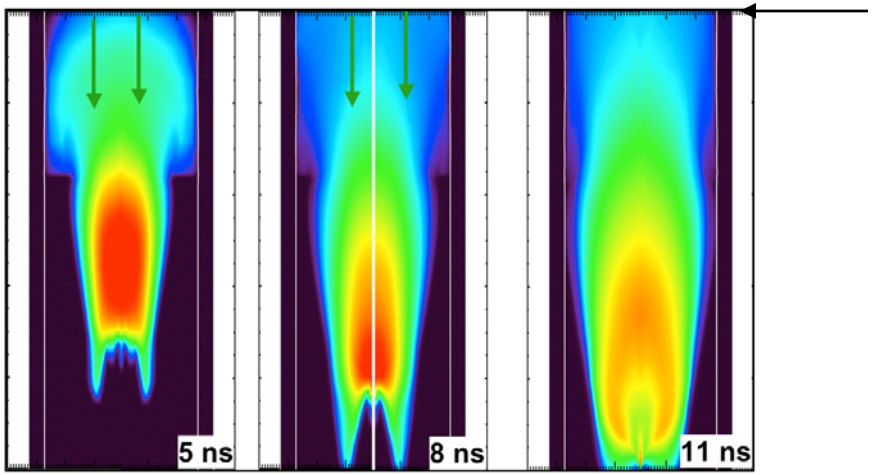
The laser light propagates further into the gas as it heats up due to a reduction in k. Thus a "bleaching wave" is developed

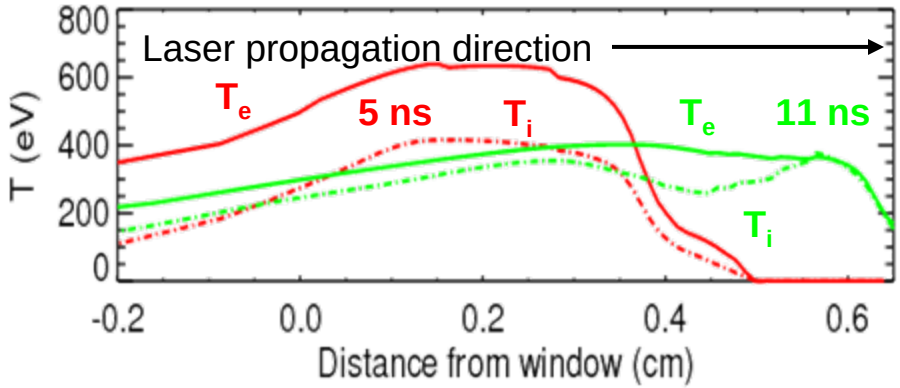
Temperature profiles are flatter when conduction is included!

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

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

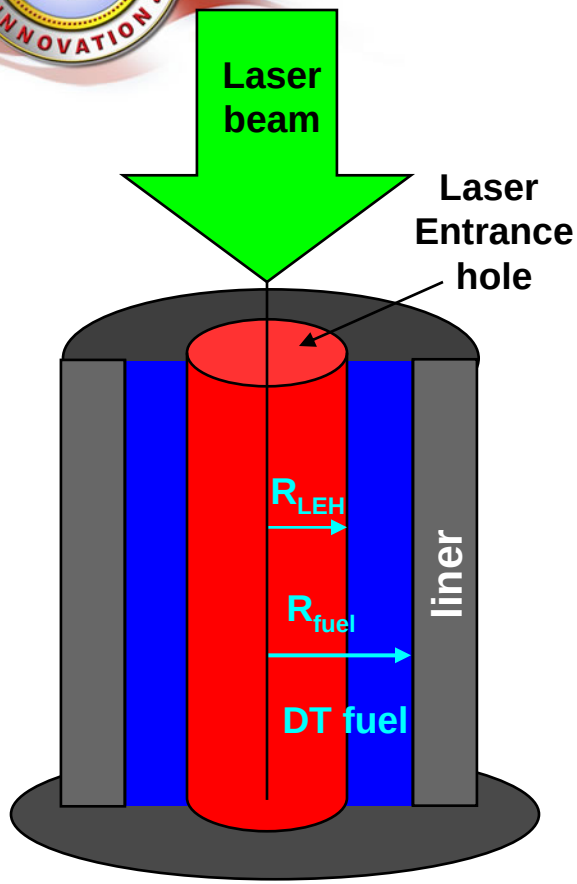
Electron Temperature contours (r,z)



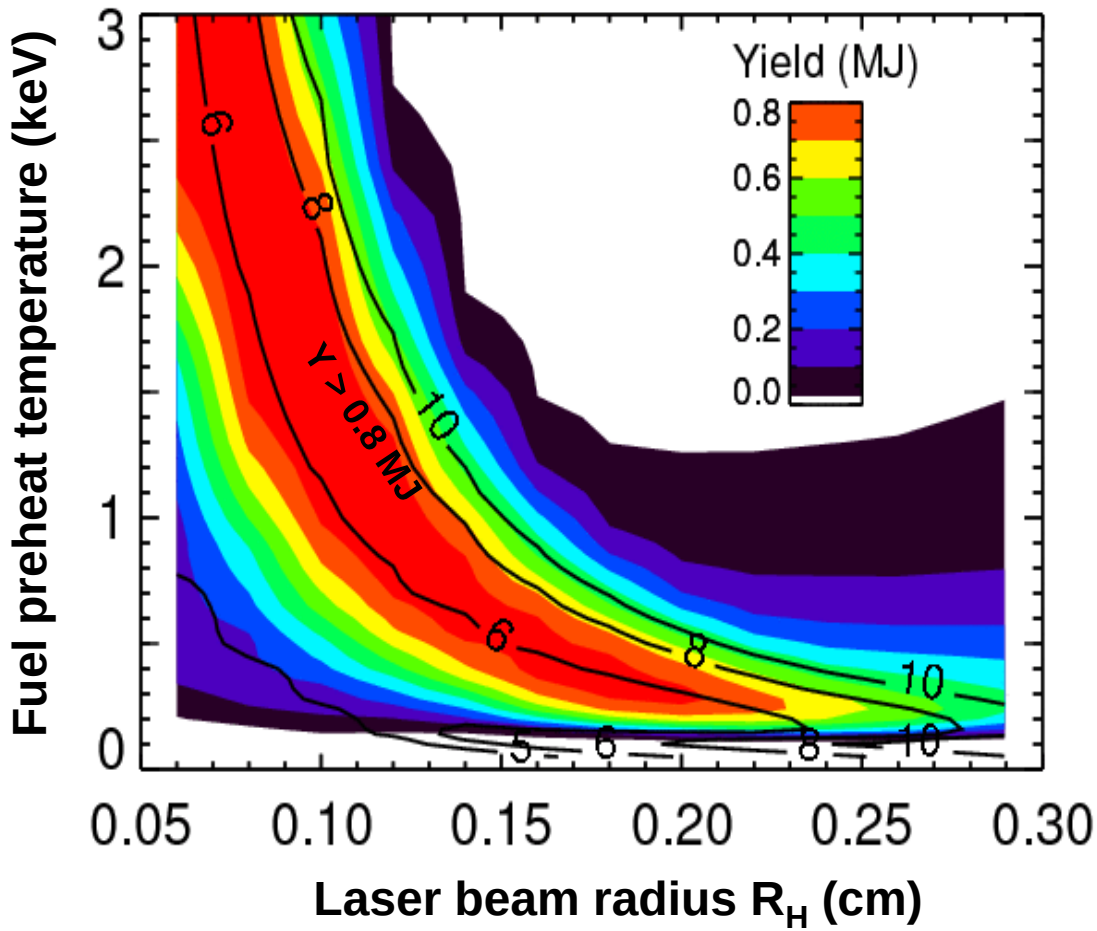


- **The gas can be held in place by a 1 μ plastic foil**
- **The critical density for green light is 4-7 x initial fuel density absorption by inverse bremsstrahlung**
- **The total laser energy needed <10 kJ**

A small laser entrance hole (LEH) actually increases the yield

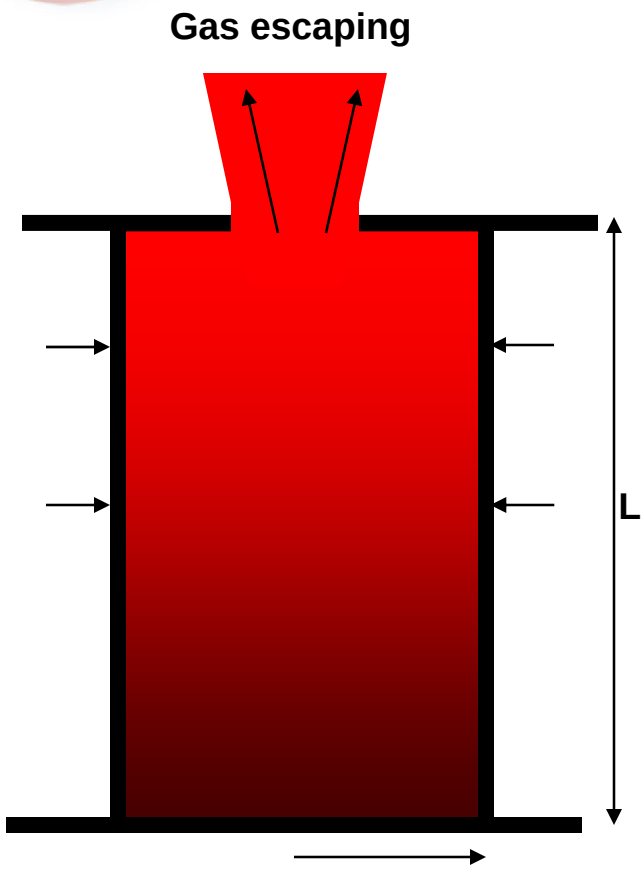


Yield contours (color) from a series of 1D Lasnex simulations

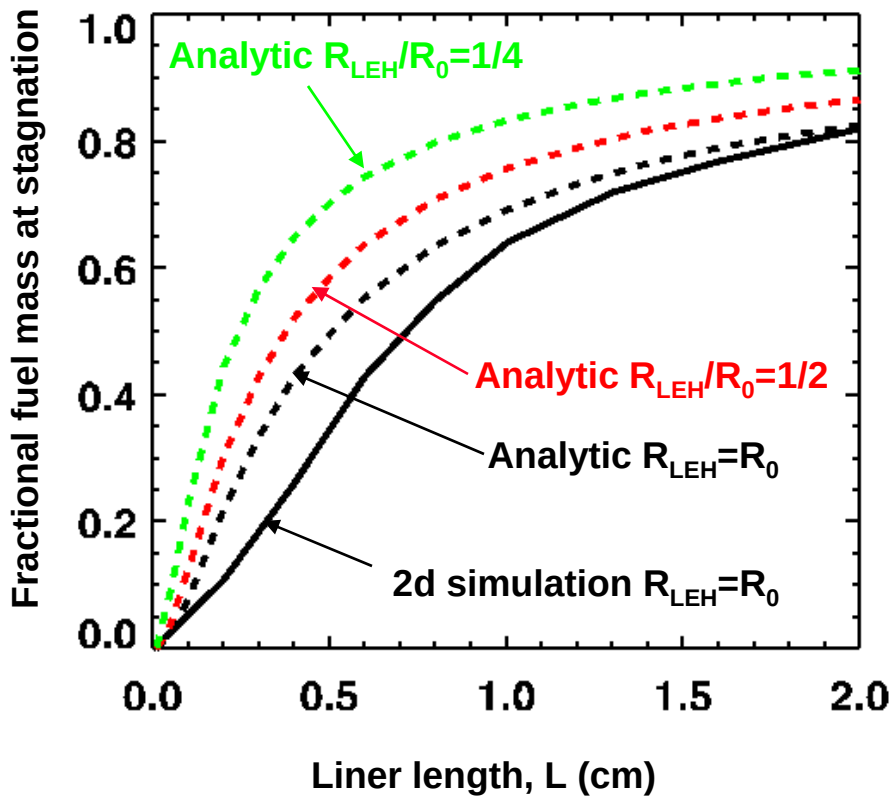


The loss of fuel through the laser entrance hole should be manageable

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

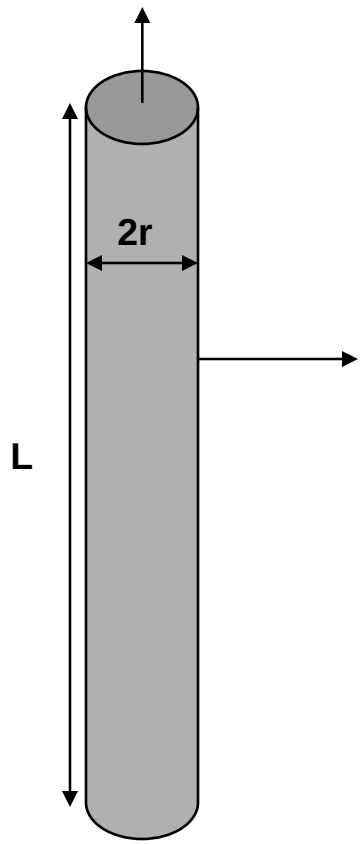


$$r(t) \sim r_0 \left[1 - \left(t / t_P \right)^{5/3} \right]$$



Axial Thermal losses should be acceptable

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



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

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

Axial losses are being addressed with fully integrated simulations, see Adam Sefkow's talk

MagLIF benefits from short implosion times and is robust to mix due to low Z liner

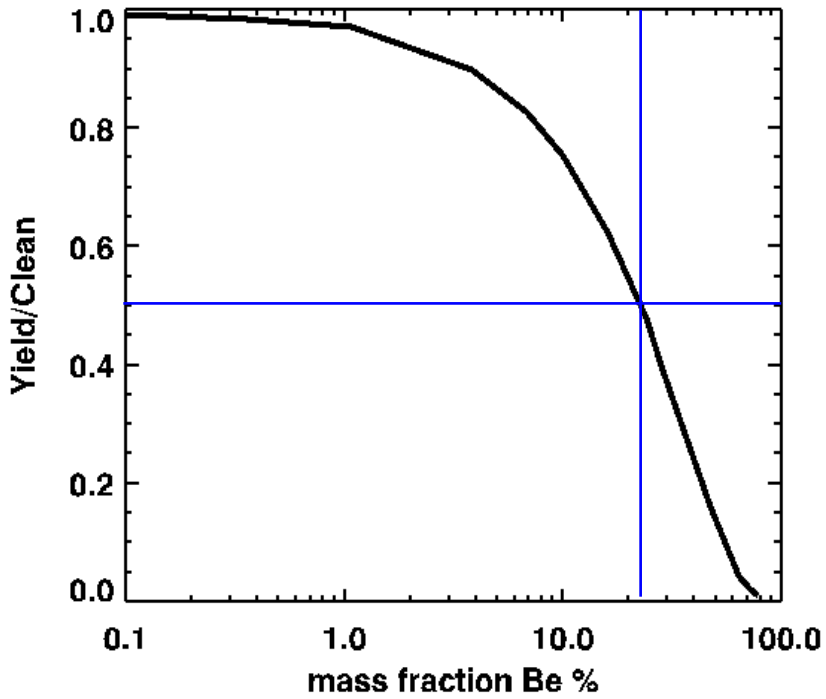
The optimal fuel density is determined by the balance between PdV heating and Bremstrahlung radiation losses

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

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

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

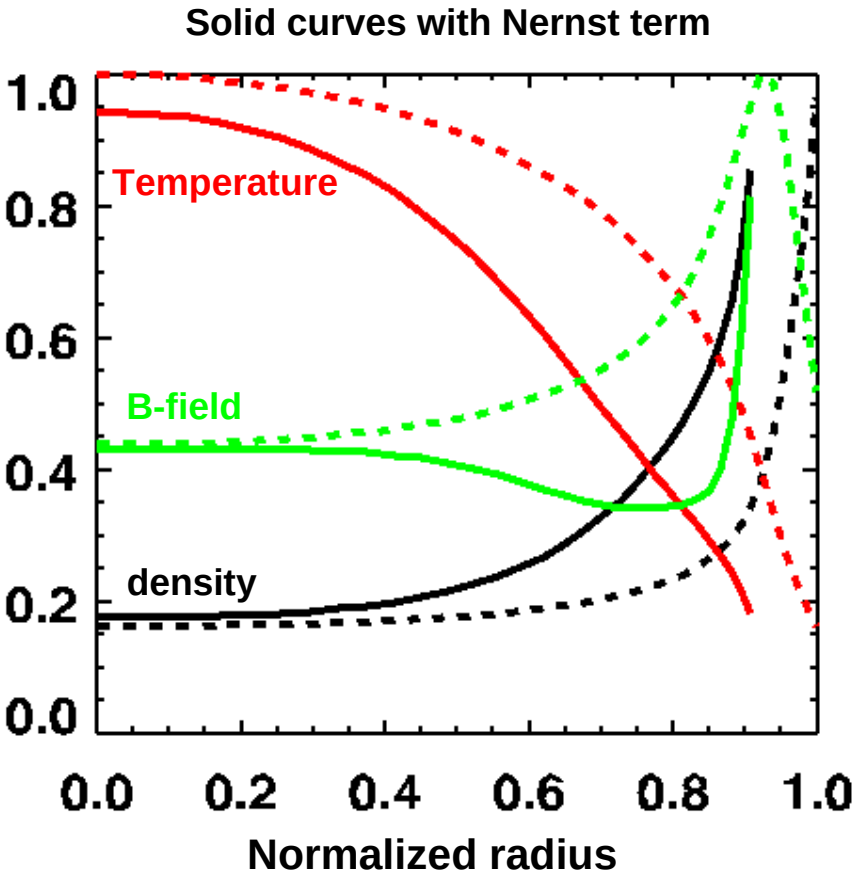
20% mix degrades the yield by only 50%



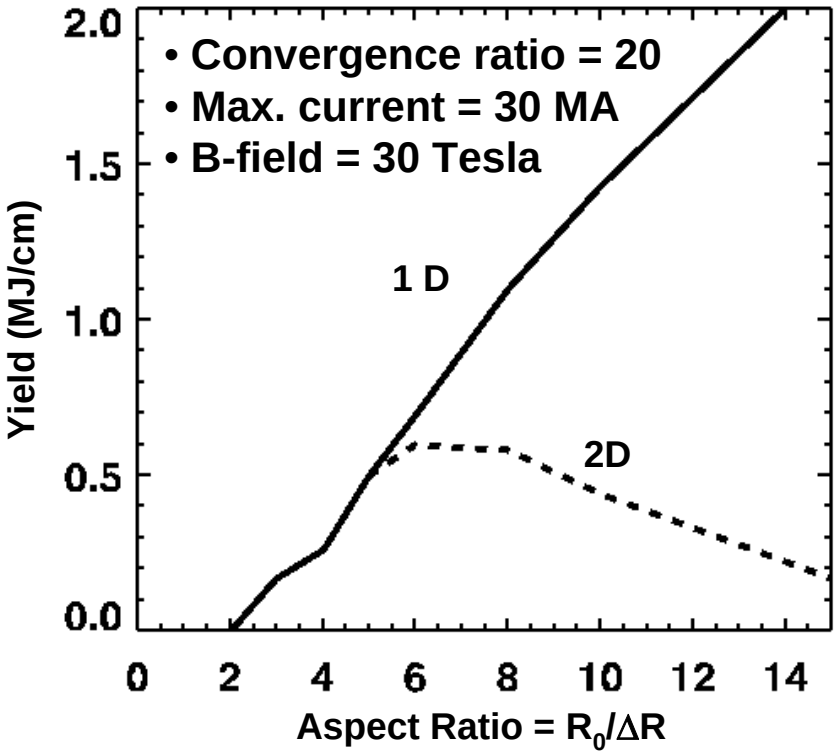
The preheat energy is roughly proportional to the implosion time

- **Fuel preheat requires < 10 kJ for Z (τ_{imp} = 100 ns)**
- **Preheat feasible with a laser**

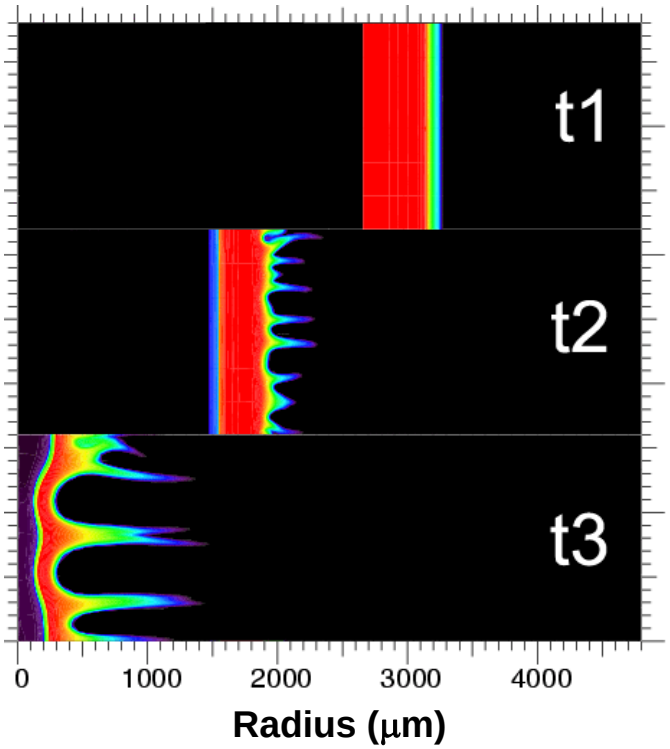
The Nernst term has a significant effect on profiles and the yield



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
- resolved wavelengths 200-1600 μm
- wavelengths of 300-600 μm near stagnation

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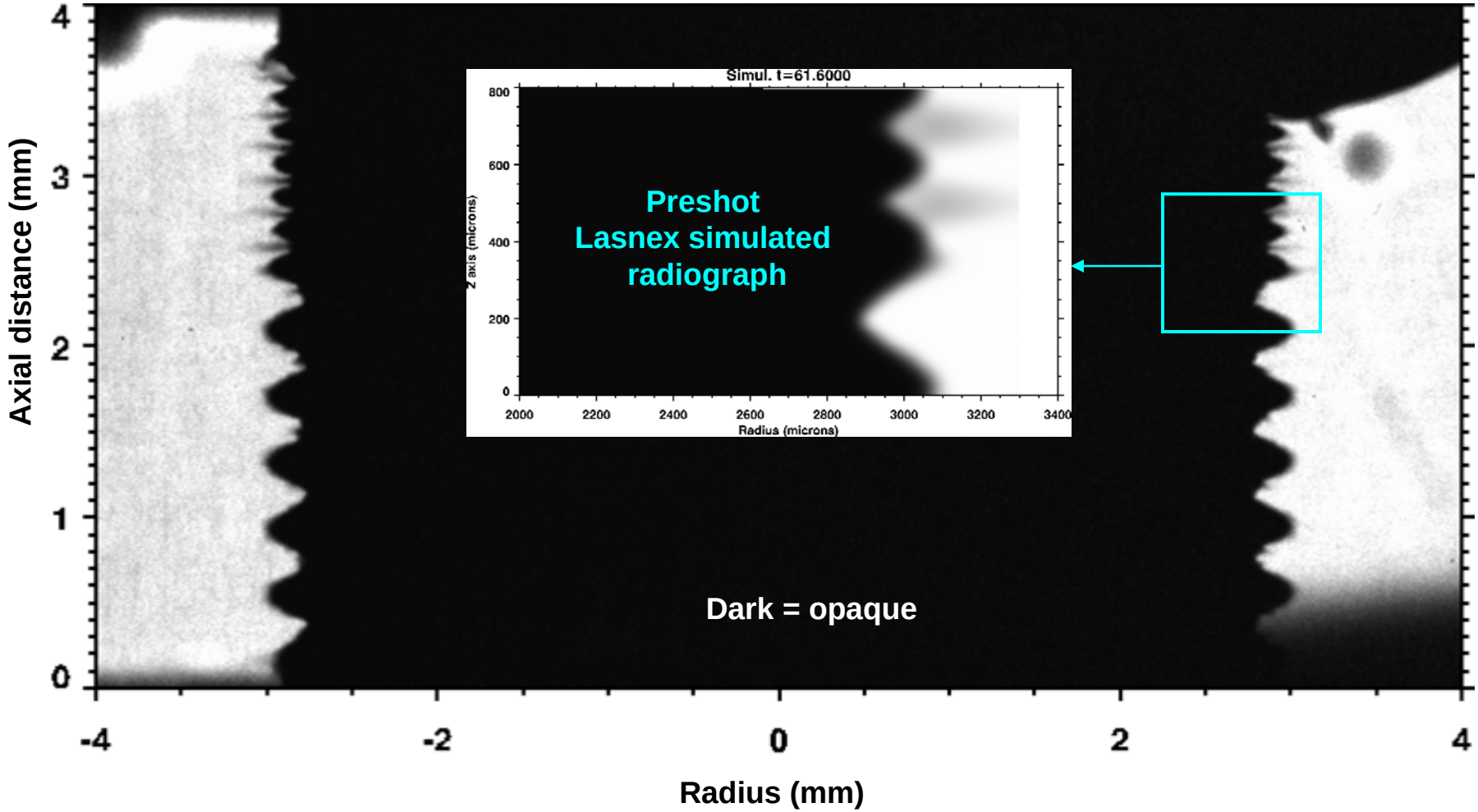
We are benchmarking Lasnex with Magneto-Rayleigh-Taylor instability experiments

Aluminum liner with machined perturbations 200 and 400 micron



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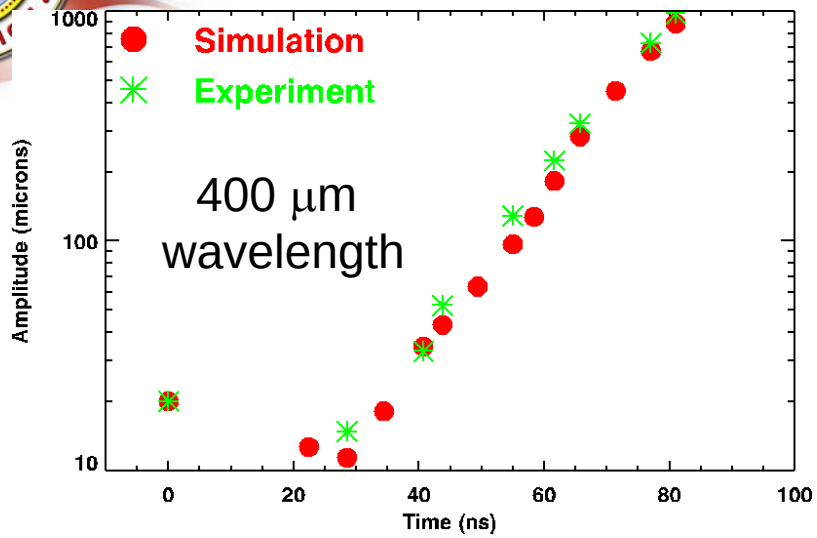
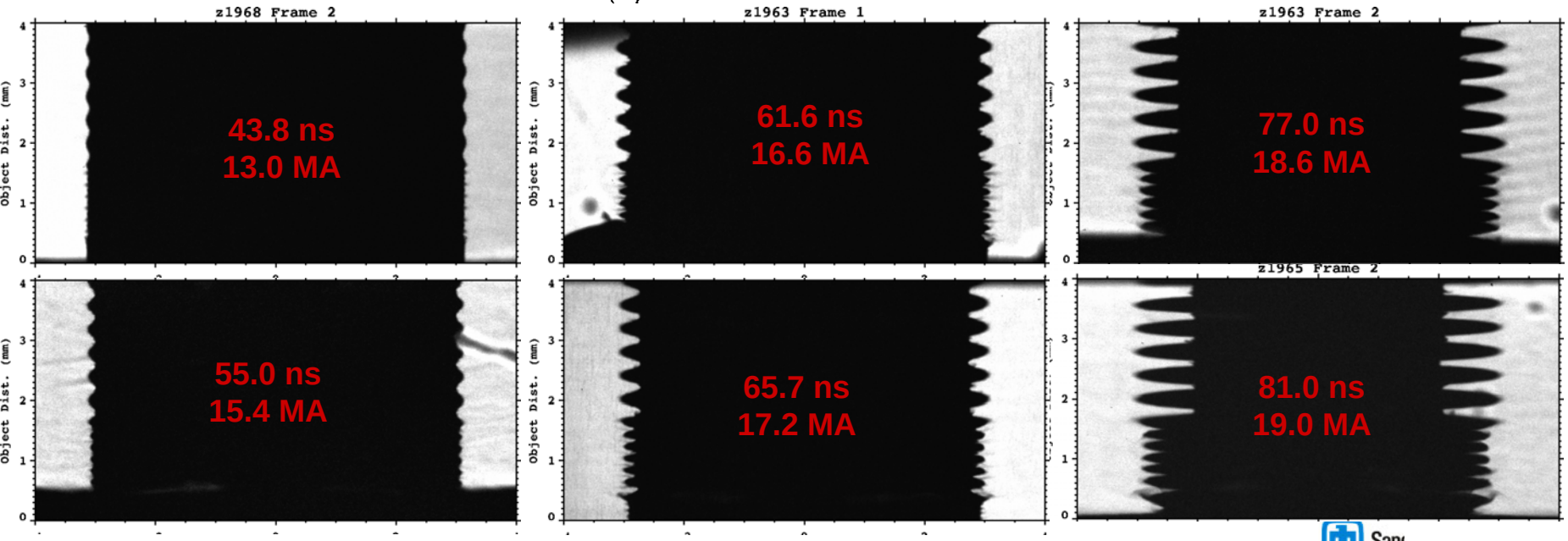
We have initiated studies of liner implosion stability, e.g. D. Sinars et al. PRL 105, 185001 (2010)

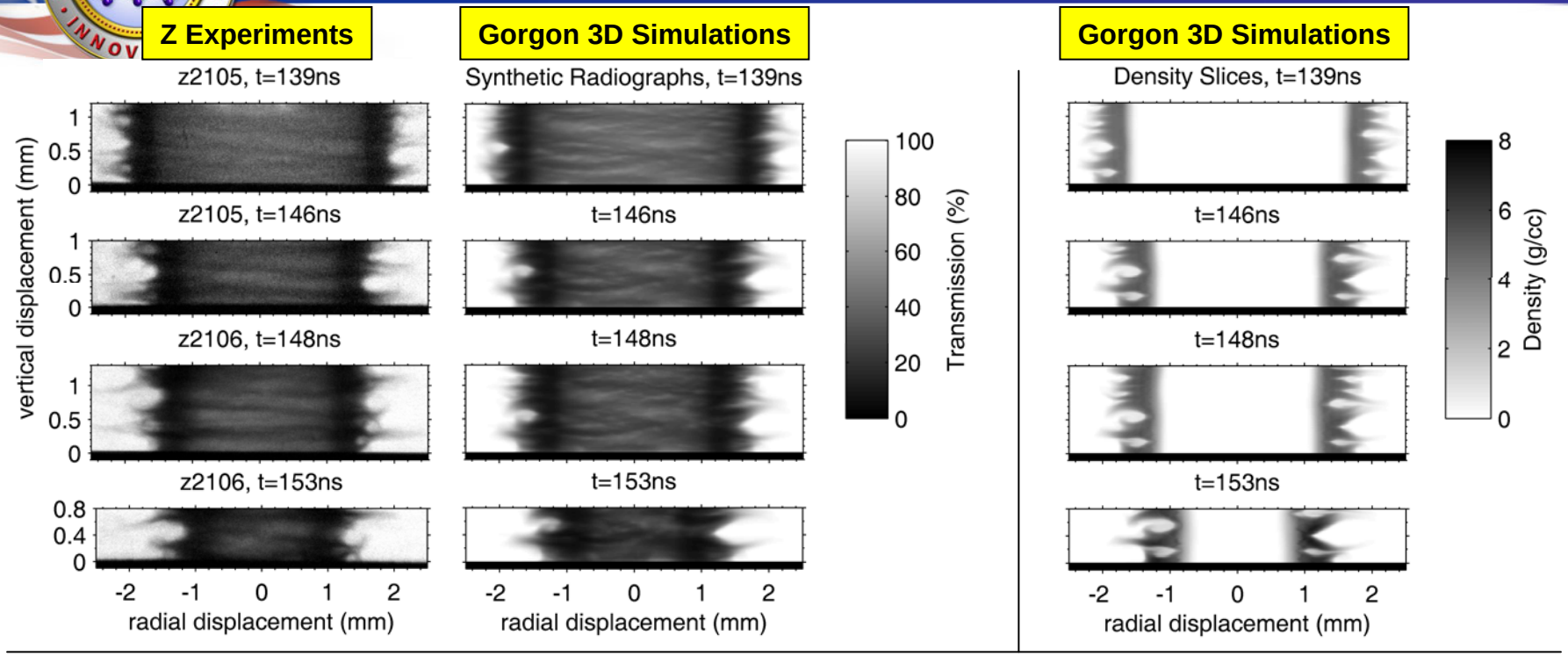


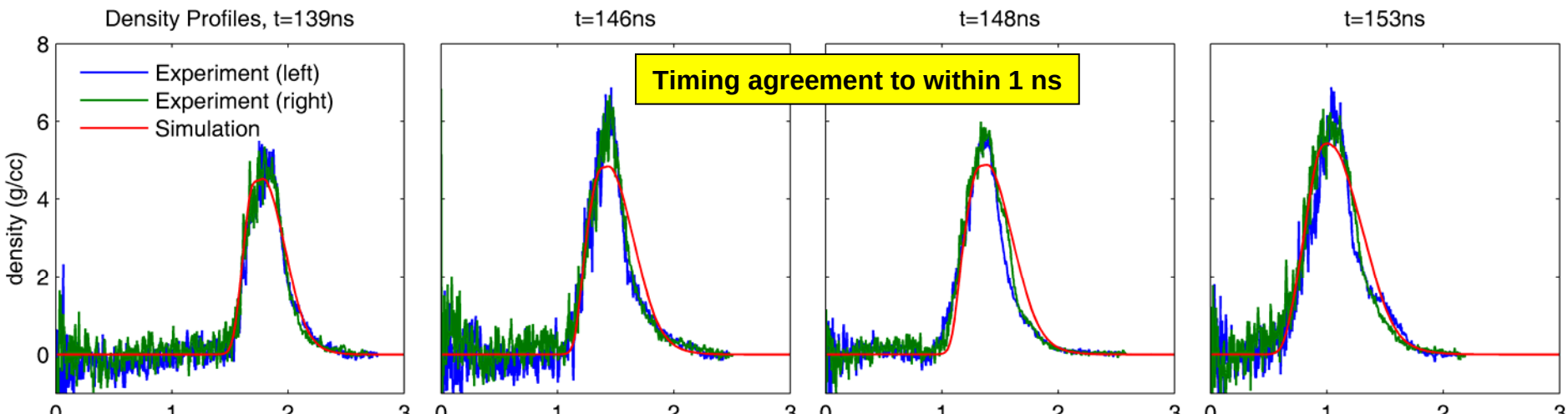
Experiments are progressing with beryllium liners

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

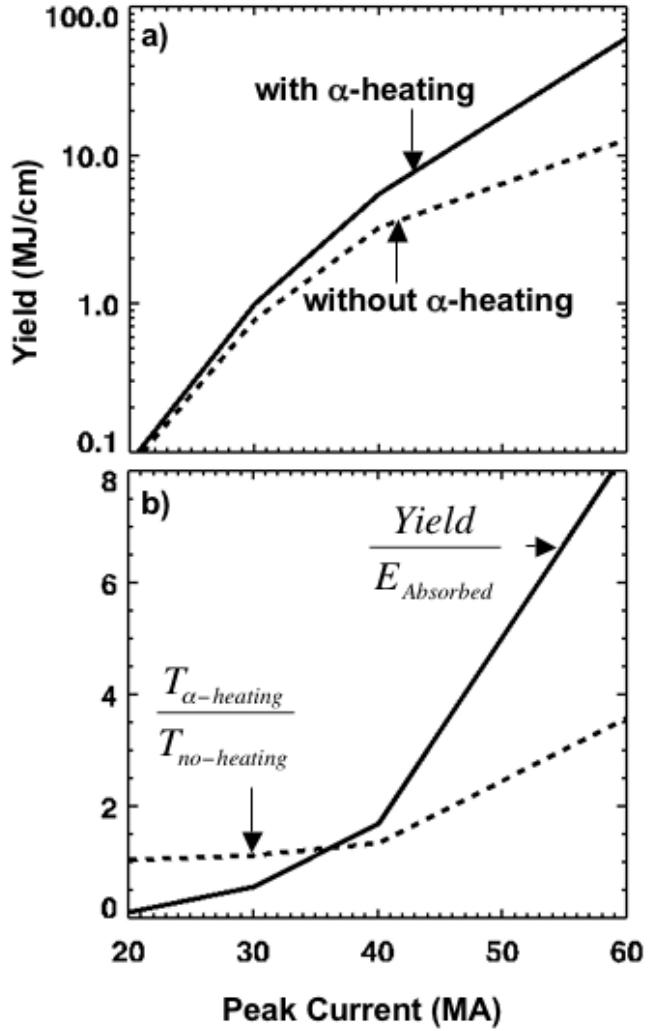


3D simulations capture features of multi-mode MRT growth (*see C. Jennings' and R. McBride's talks*)





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.

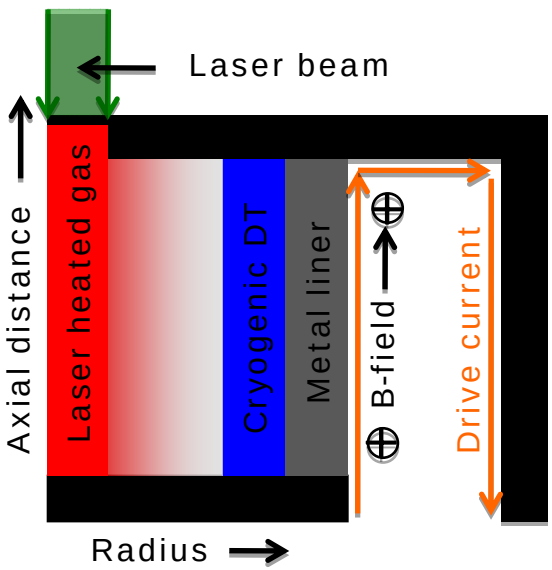
High Gain is required for Inertial Fusion Energy (IFE)

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



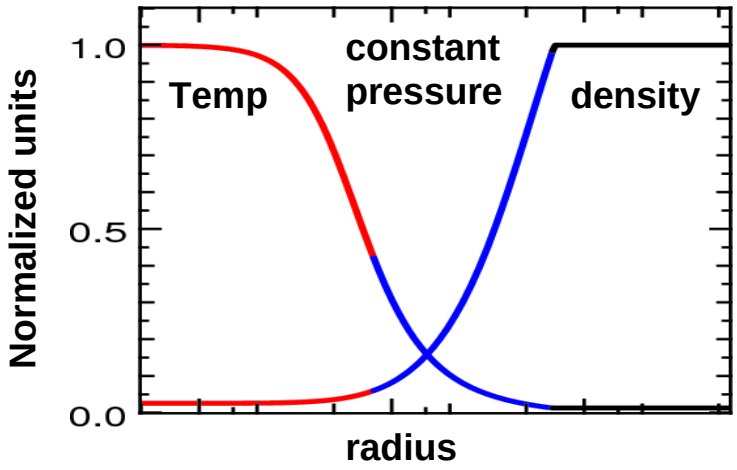
High Gain is obtained by only heating a small central portion of the fuel during compression
- minimizes compressive heating
- burn wave propagates into cold fuel as a deflagration

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

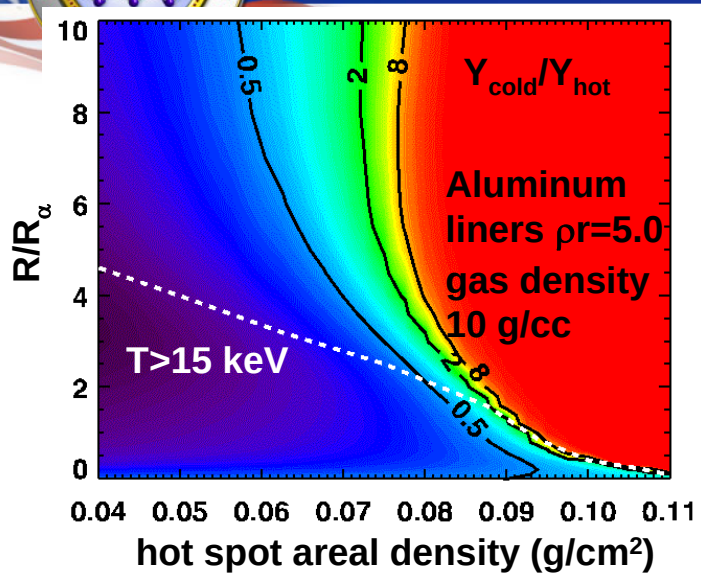


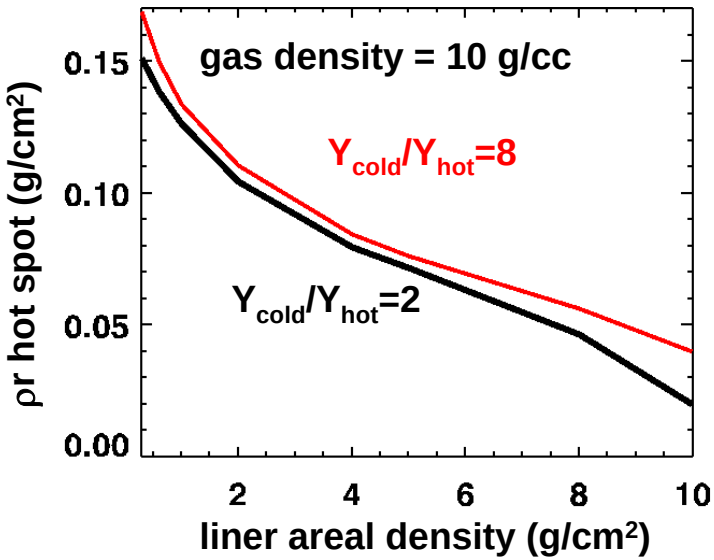
1D Lasnex simulations were performed starting at an idealized stagnated state with the following attributes:

- **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

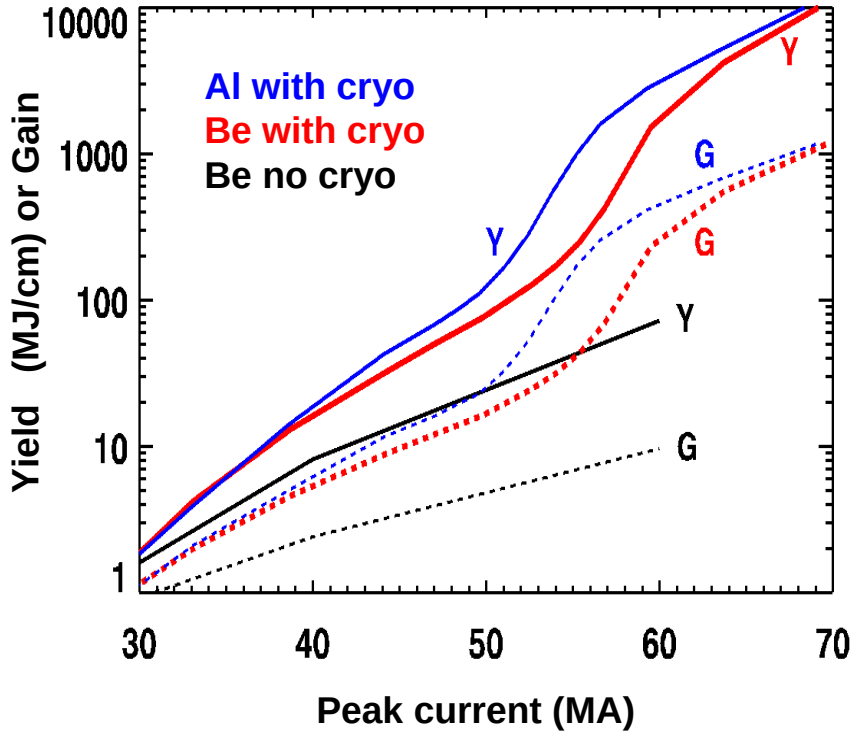




- The inhibition of thermal conduction and alpha transport lowers the hot spot areal density required for for ignition
- Too large a B-field inhibits propagation into the cold fuel
- Minimum hot spot areal density is a weak function of gas density, but is significantly affected by the areal density of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

Gains >1000 are possible with MagLIF*

**S.A. Slutz and R.A. Vesey Physical Review Letters 108, 025003 (2012)*



Further optimization is possible

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

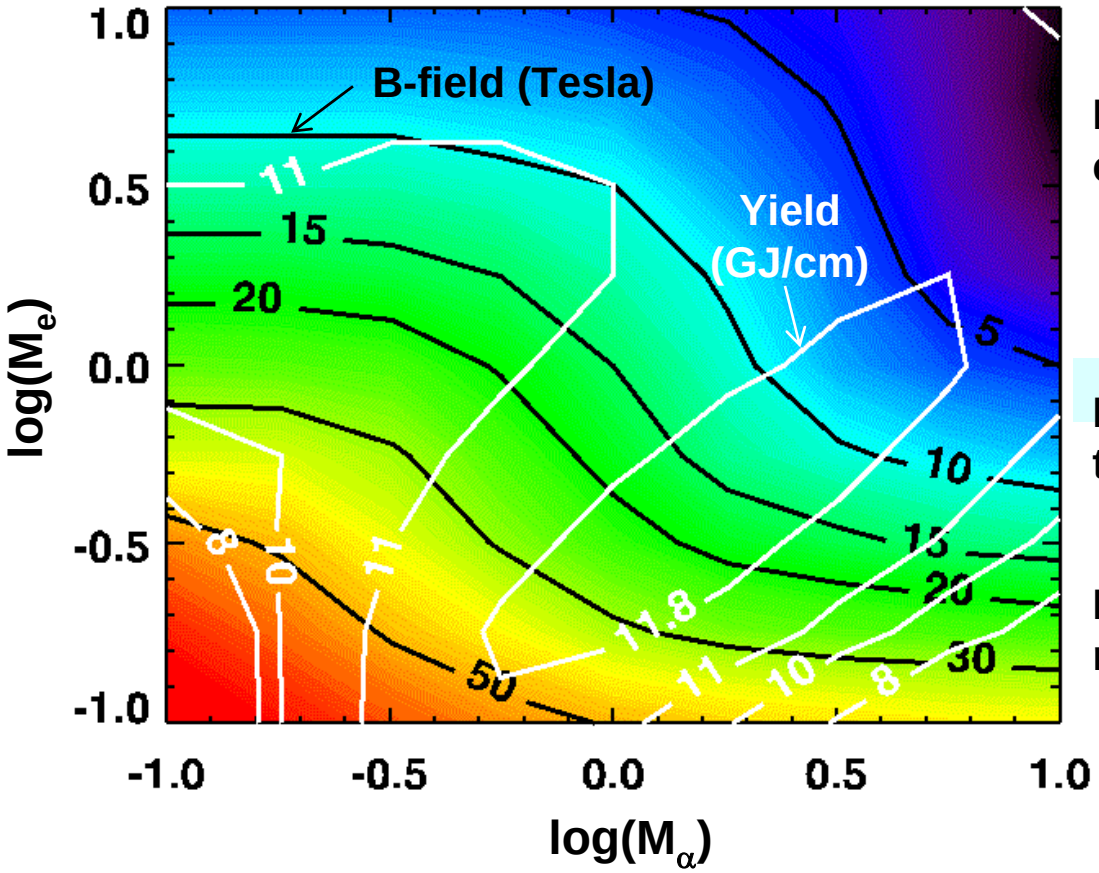
Margin increases with current

>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 $\omega_e \tau_e$

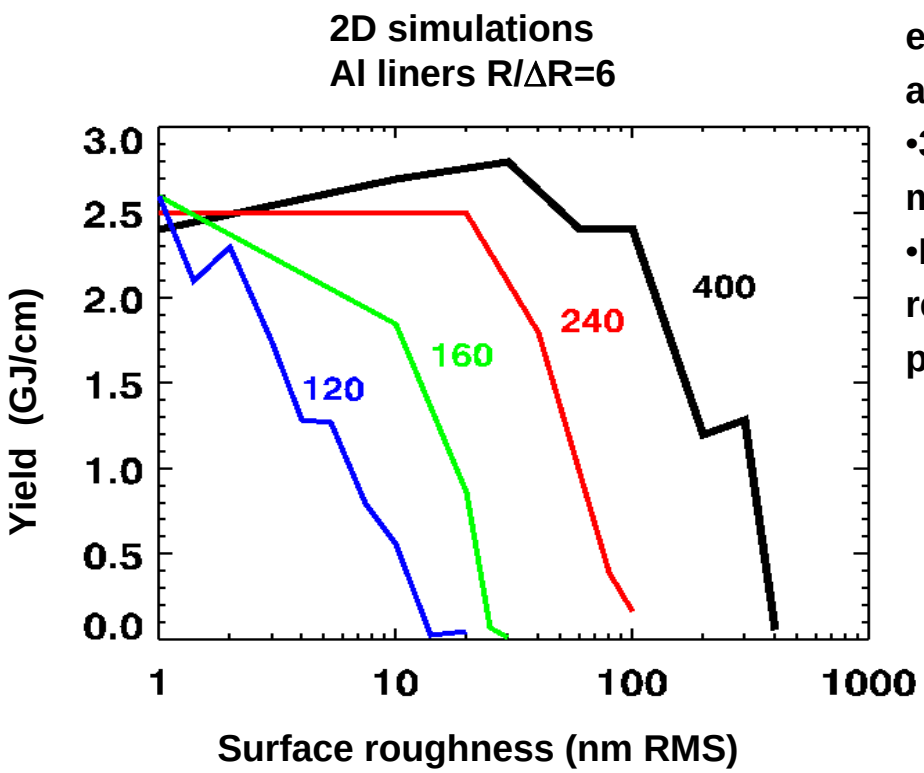
$$K_{cond} = K_0 F\left(M_e \omega_e \tau_e\right)$$

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

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

Initial B-field is varied to obtain maximum yield for $\left(M_e, M_\alpha\right)$

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)**
- **3D simulations indicate that 2D simulations may be pessimistic at short wave lengths**
- **RMS amplitudes less than 20 nm may be required, which could be achieved with polishing**

Summary: the promise

Simulations indicate that MagLIF could produce significant fusion yields on Z

- **Scientific breakeven may be possible (*yield > energy absorbed by the fuel*)**

Simulations further indicate that High-Gain Magnetized Inertial Fusion is possible on future accelerators delivering more current.

- **Gains of 1000**
- **Yields of 10 MJ/cm**

MagLIF has the potential to provide a means to generate electricity with fusion

- **Laser energy is a small fraction of energy delivered to the liner**

Summary: the challenges

Fully integrated 2D simulations are needed to determine

- the thermal end losses
- the loss of DT fuel through the laser entrance hole
- the effect of axially nonuniform laser preheating of the fuel

Non ideal MHD can affect the imbedded magnetic field. Magnetic field measurements will be required

- Bdot probes will probably breakdown before the peak field is reached
- Proton imaging will be difficult due to large azimuthal B-field of the drive
- Faraday rotation could be promising, but requires development
- Zeeman-splitting measurements will also require development

Non fluid phenomenon could affect heat loss from the DT plasma

- Hybrid PIC simulations could address this issue
- Diagnostics?

Summary: more challenges

The Magneto-Rayleigh-Taylor instability could seriously degrade yields

- **Need to determine a specification for surface roughness**
- **Simulations of the MRT are very challenging, both high resolution and 3D may be required**
- **Higher photon energy backlighting will be needed to radiograph liner implosions at stagnation**
- **Can solid liners be maintained using pulse shaping?**
- **Can the surface be engineered to be robust to MRT, e.g. helical perturbations**

Mix of liner material could degrade yield

- **Rayleigh-Taylor instability could be mitigated by the axial field (*Ryutov)***
- **Spall on the inner surface (can pulse shaping mitigate this effect)**

Can instabilities in the magnetized plasma enhance heat transport to exceed Bohm?

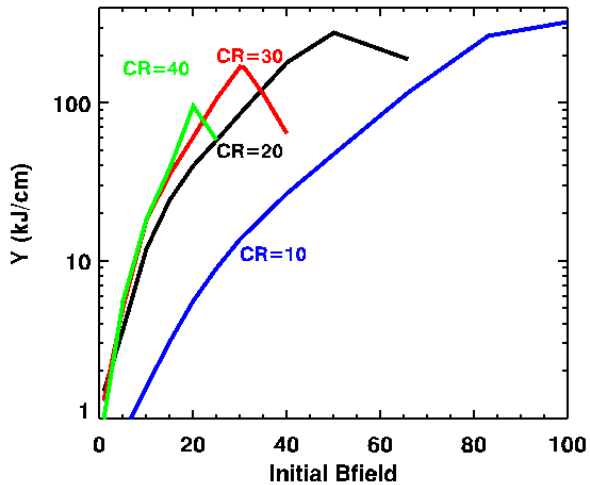
The nearly constant pressure fuel may be less unstable than magnetic confined plasmas

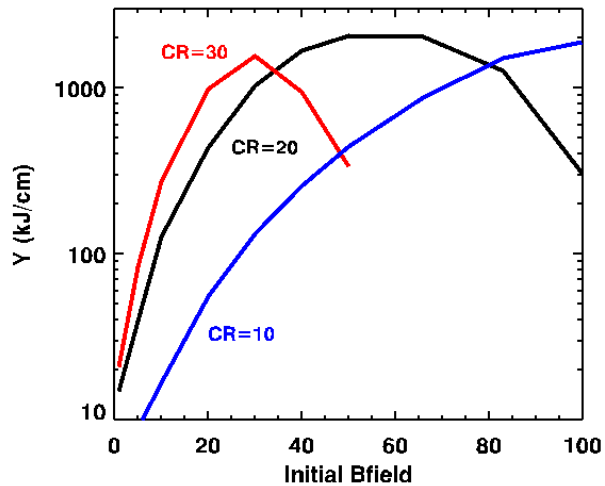
However, there is a large temperature gradient near the liner (drift instabilities)

There is an optimal initial B-field which depends on the convergence ratio and drive current

Aspect ratio = 6

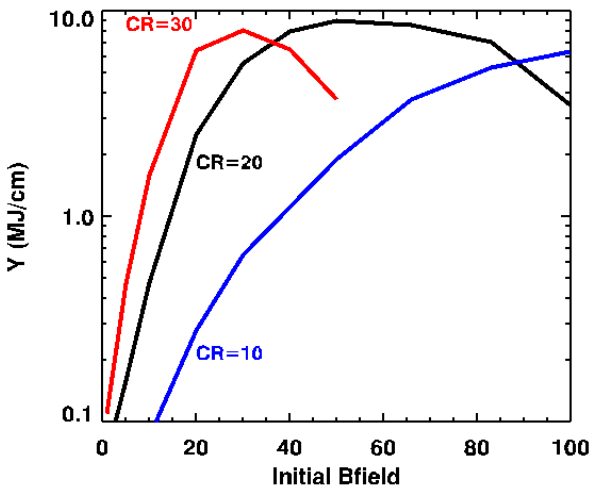
I=20

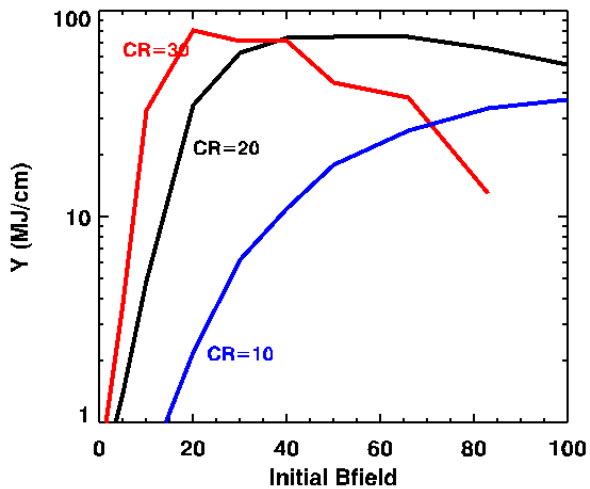




I=30

I=40





I=60