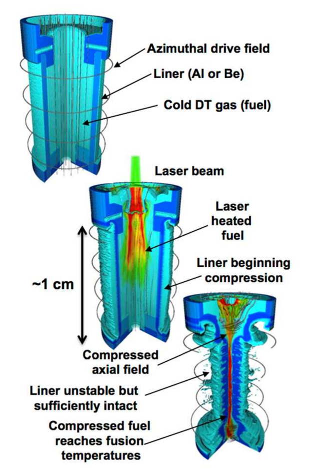
Exceptional service in the national interest

Sandia National Laboratories

MagLIF scaling on Z and Future Machines

S. A. Slutz, W.A. Stygar, M.R. Gomez, K.J. Peterson, A. B. Sefkow, D.B. Sinars, R. A. Vesey *Sandia National Laboratories*
E. M. Campbell and R. Betti *Laboratory for Laser Energetics, University of Rochester*

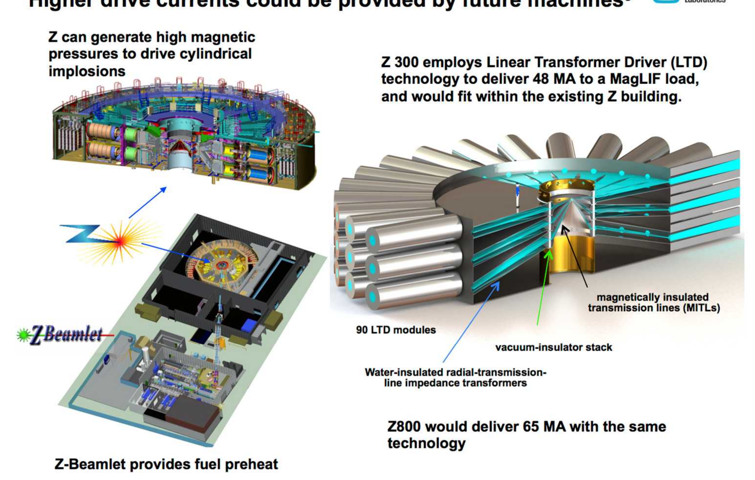
Magnetized Liner Inertial Fusion (MagLIF)* concept has three steps



- 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

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

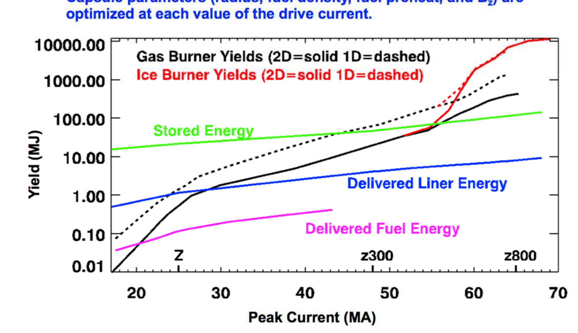
The MagLIF concept[1] is being tested[2] on the Z facility. Higher drive currents could be provided by future machines[3]



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

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

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



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

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_{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

Magnetization reduces the minimum implosion velocity for ICF

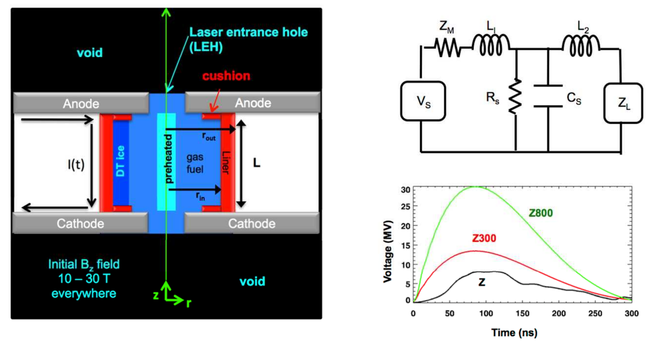
Compressive heating during the implosion must significantly exceed losses

- The heating rate is proportional to the implosion velocity $P\frac{dV}{dt} \approx 5.0x10^{8} \rho r T \frac{dr}{dt} W/cm$
- The dominant cooling rate is electron thermal conduction $L_{ce} \approx \frac{8.7x10^{13} T^{7/2}}{(\omega\tau)^2} W/cm$

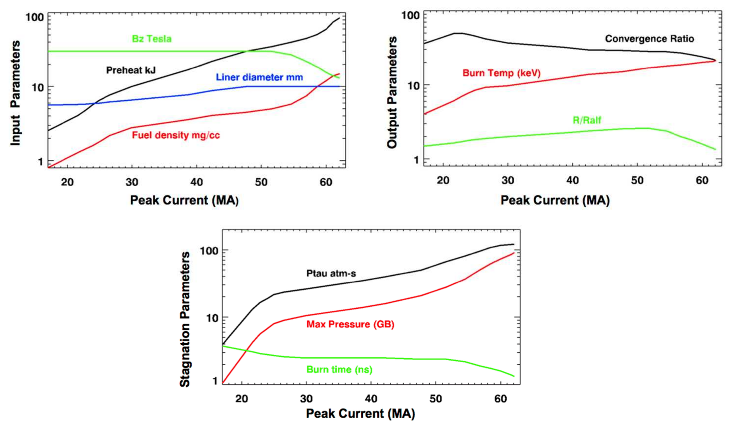
Bremsstrahlung radiation losses are dominant when the thermal conduction has been made negligible by a large magnetic field

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

2D Lasnex simulations based on simplified geometry and circuit model

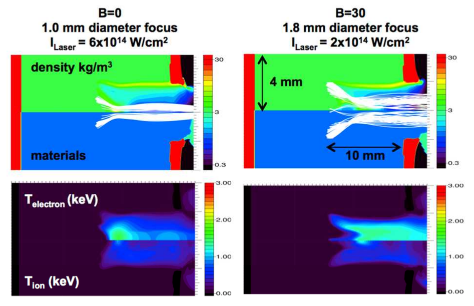


2D simulations indicate optimal design parameters and output quantities

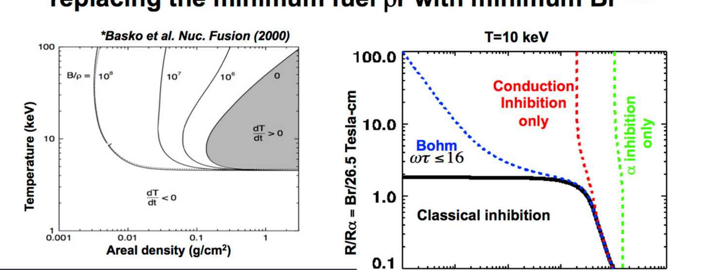


Laser preheating at Z300 levels could be tested using a quad of NIF

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



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



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

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

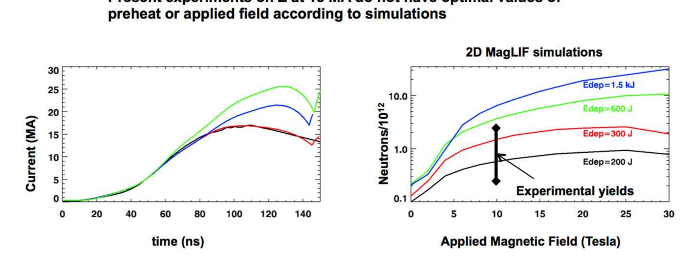
In the limit of large B/ρ $F_e(\theta,B/\rho) \propto \theta^{-3}(B/\rho)^{-2}$

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

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

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



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

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

Laser absorption coefficient dominated by inverse Bremsstrahlung

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

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

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

We have presented 1D and 2D simulations of MagLIF on upgraded Z and future machines

Simulations indicate that large yields and gains may be possible on future machines such as Z300

Simulation predictive capability is greatest when the extrapolation is not large

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

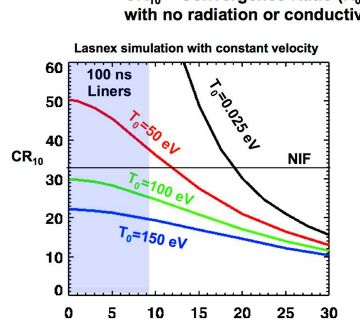
Full scale laser deposition experiments could be performed using one quad of the NIF to remove uncertainties about laser preheating

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

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

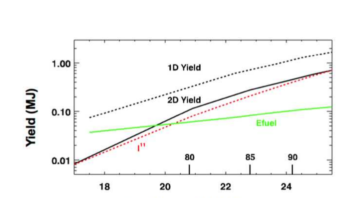
- adiabat set by implosion velocity (shock) or
- alternatively by fuel preheat

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

Preheating can be used to control the required convergence ratio

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

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

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