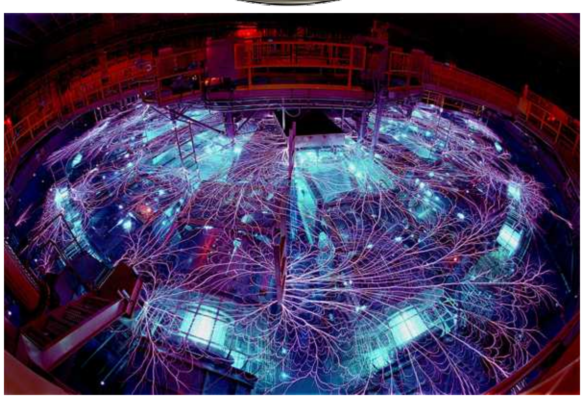
SAND2013-9655C

Semi-analytic modeling & simulation of magnetized liner inertial fusion

R.D. McBride, S.A. Slutz, and S.B. Hansen

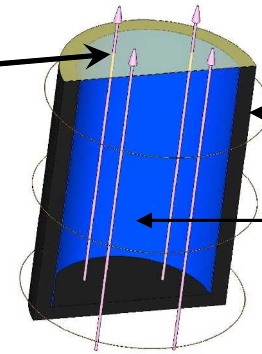


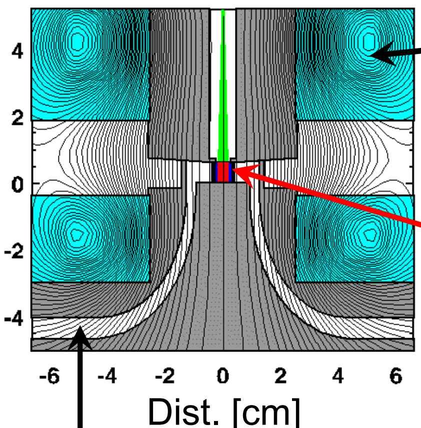
55th APS-DPP Meeting
Denver, Colorado, November 11, 2013

With thanks to: K. Cochrane, R.A. Vesey, D.B. Sinars, M.E. Cuneo, M.C. Herrmann, C.W. Nakhleh, K.J. Peterson, M.R. Martin, A.B. Sefkow, and C.A. Jennings

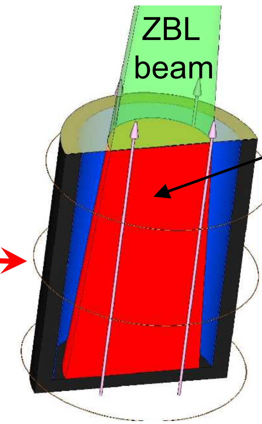
We are working toward the evaluation of a new Magnetized Liner Inertial Fusion (MagLIF)* concept

1. A 10–50 T axial magnetic field (B_z) is applied to inhibit thermal conduction losses and to enhance alpha particle deposition

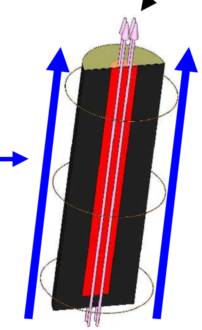




2. ZBL preheats the fuel to ~100–250 eV to reduce the required compression to CR≈20–30



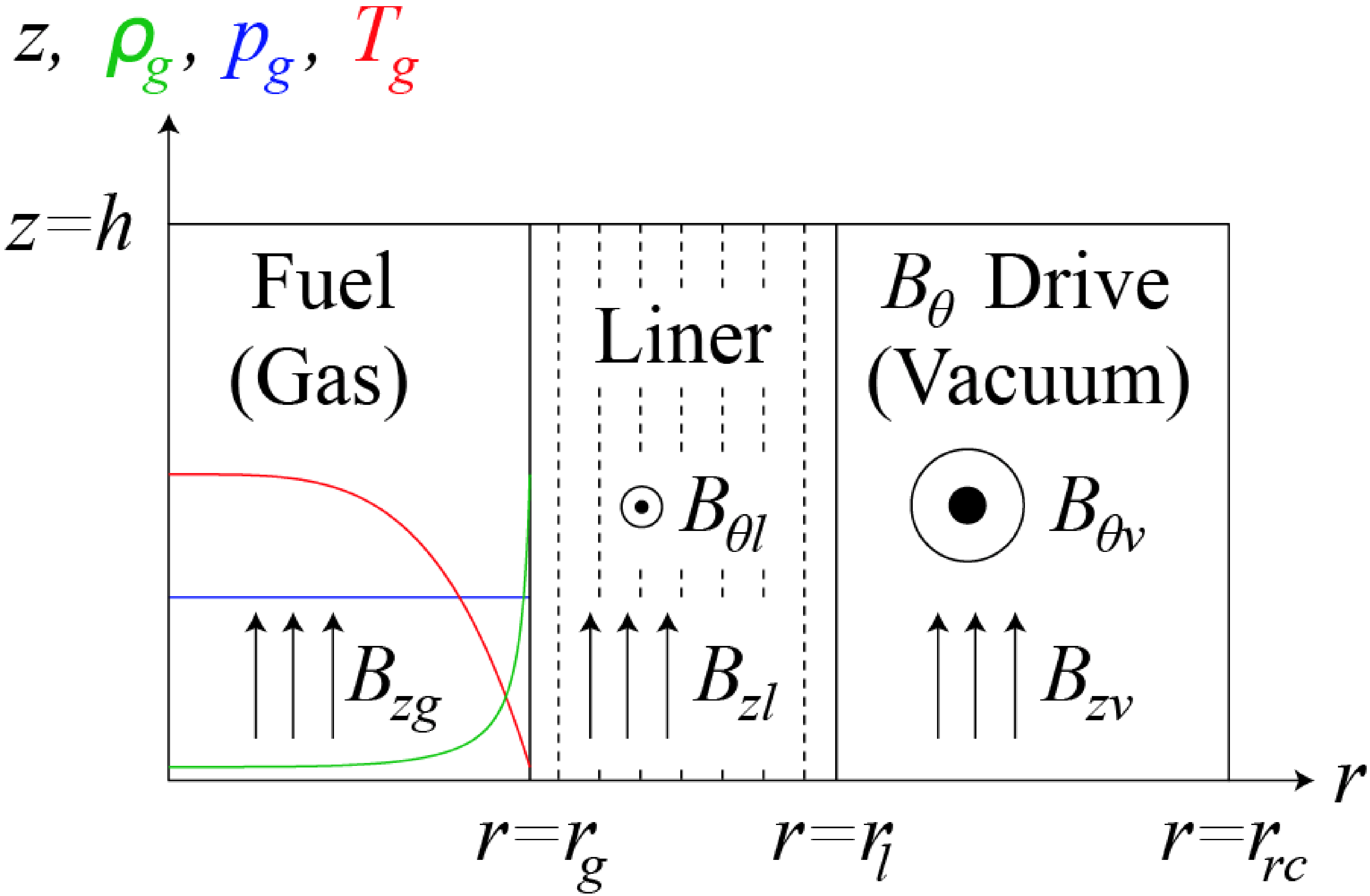
3. Z drive current and B_θ field implode the liner (via z-pinch) at 50–100 km/s, compressing the fuel and B_z field by factors of 1000



With DT fuel, simulations indicate scientific breakeven may be possible on Z (fusion energy out = energy deposited in fusion fuel)

* S. A. Slutz *et al.*, PoP 17, 056303 (2010). S. A. Slutz and R. A. Vesey, PRL 108, 025003 (2012).

Description of semi-analytic model:



Description of semi-analytic model:

$$\ddot{r}_g = \frac{p_g + p_{B_{zg}} - p_l - q_l}{m_l/2} \cdot 2\pi r_g \cdot h$$

$$\ddot{r}_l = \frac{p_l - p_{B_{\theta v}}}{m_l/2} \cdot 2\pi r_l \cdot h$$

$$\dot{I}_s = \frac{\varphi_{oc} - Z_0 I_s - \varphi_c}{L}$$

$$\dot{\varphi}_c = \frac{I_s - I_l - \varphi_c/R_{loss}}{C}$$

$$\dot{I}_l = \frac{\varphi_c - \dot{L}_l I_l}{L_0 + L_l}$$

$$\dot{E}_l = -\left(\frac{2}{3}\frac{E_l}{V_l} + q_l\right)\dot{V}_l$$

$$\dot{B}_z = \dot{B}_{zg,fc} + \dot{B}_{zg,N}$$

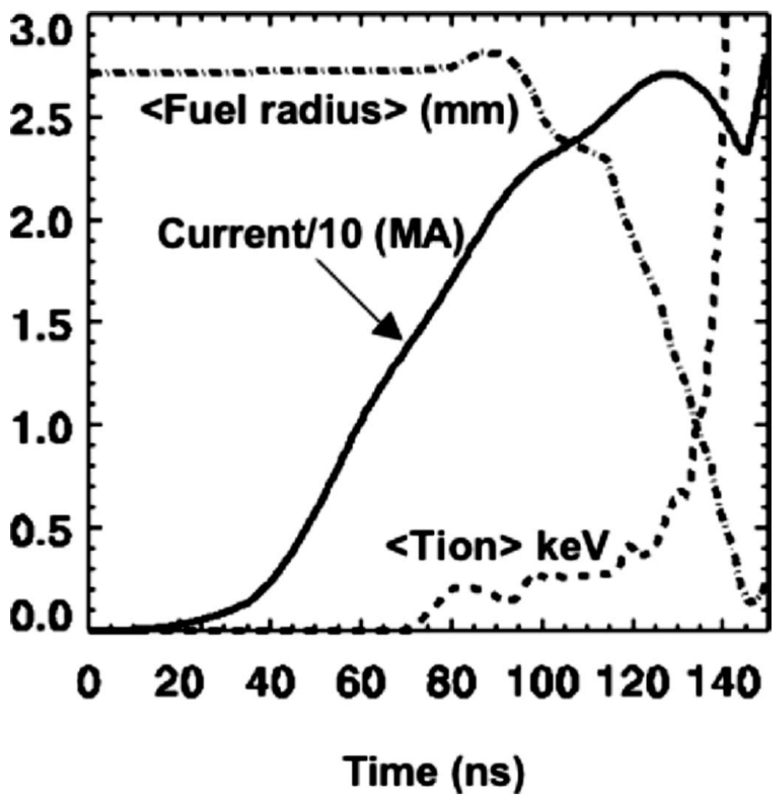
$$\dot{E}_g = P_{pdV} + P_{ph} + P_\alpha - P_r - P_{ce} - P_{ci}$$

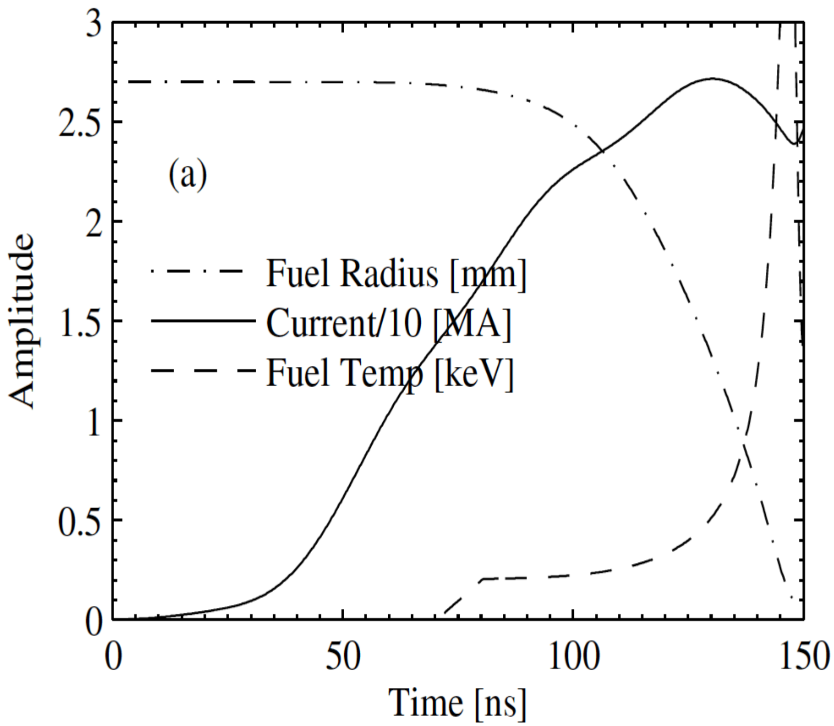
$$\dot{N}_{dt} = \frac{N_d}{V_g}\frac{N_t}{V_g}\langle\sigma v\rangle_{dt} \cdot V_g$$

$$\dot{N}_{dd,^3\mathrm{He}} = \frac{1}{2}\frac{N_d}{V_g}\frac{N_d}{V_g}\langle\sigma v\rangle_{dd,^3\mathrm{He}} \cdot V_g$$

$$\dot{N}_{dd,t} = \frac{1}{2}\frac{N_d}{V_g}\frac{N_d}{V_g}\langle\sigma v\rangle_{dd,t} \cdot V_g.$$

This semi-analytic model captures the general 1D behavior presented in the original 2010 MagLIF paper:





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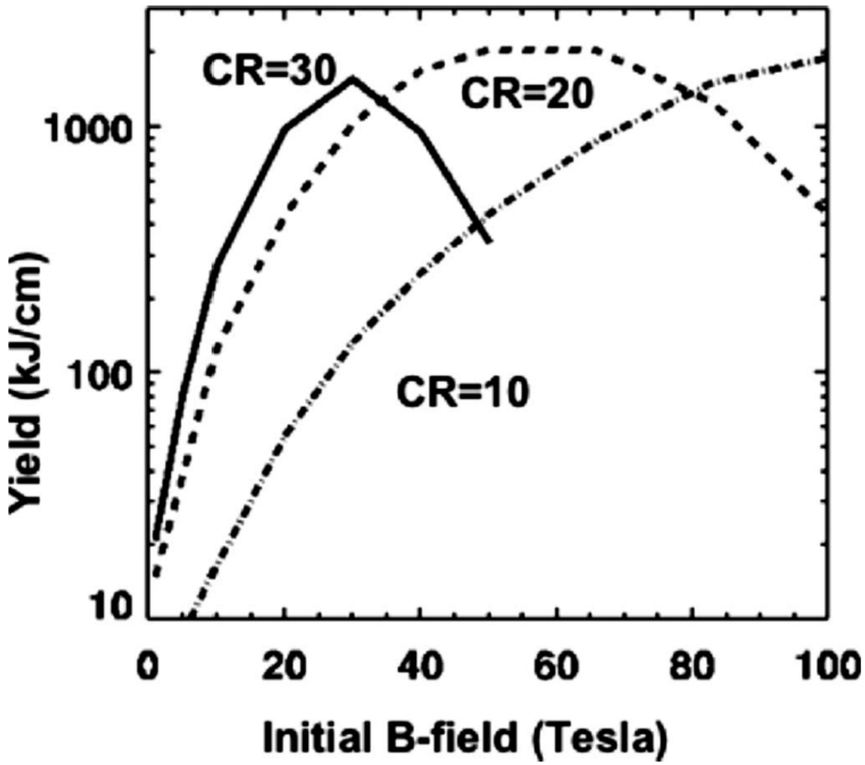
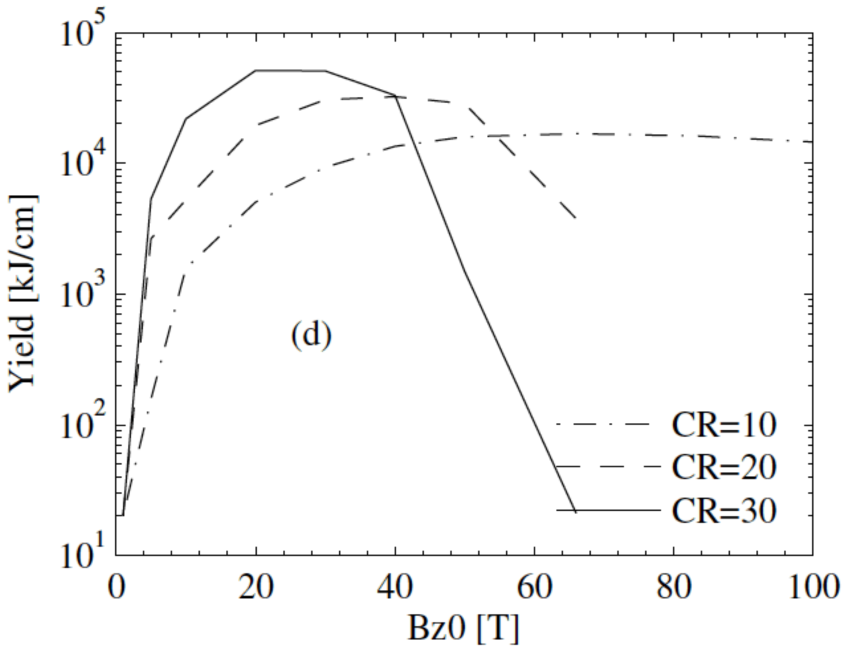
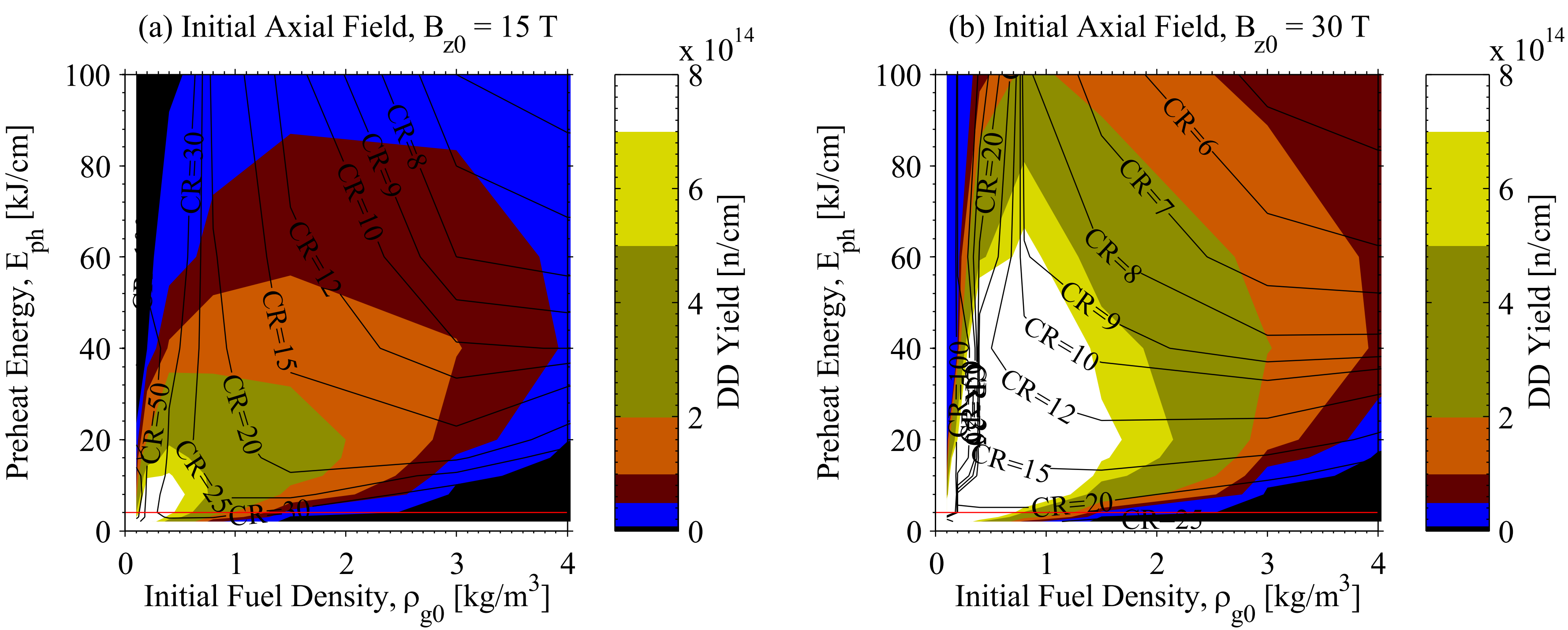
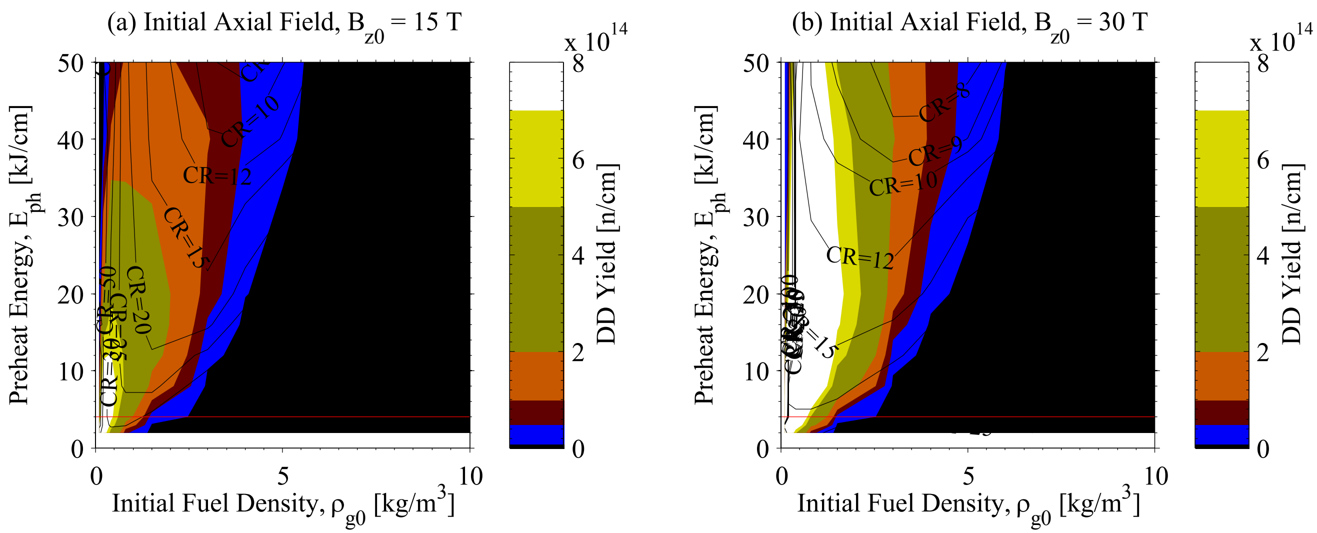




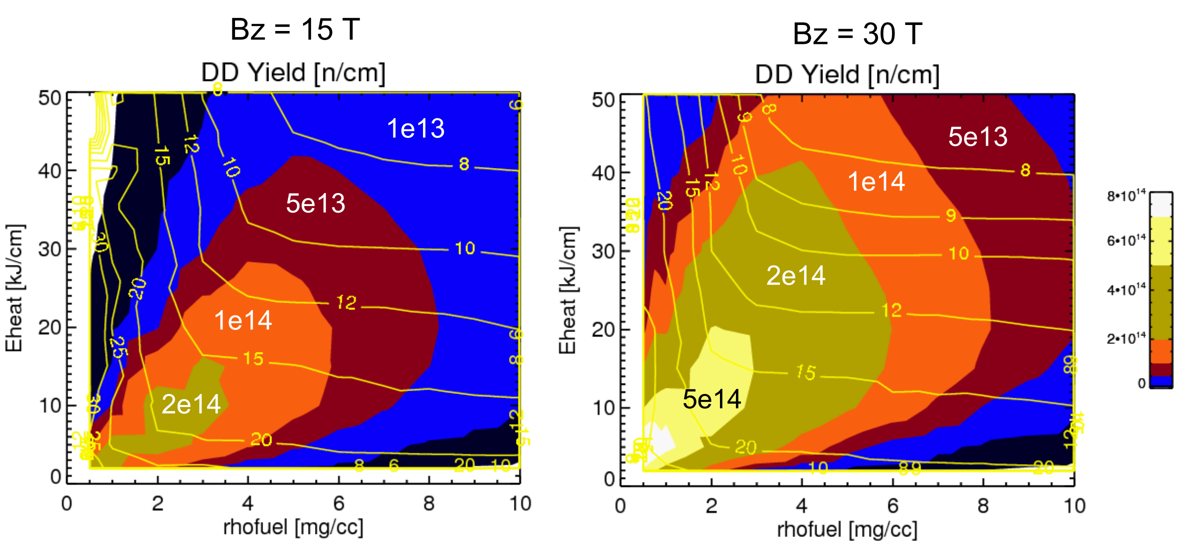
This semi-analytic model can be used to rapidly explore the parameter space of MagLIF:



This semi-analytic model can be used to rapidly explore the parameter space of MagLIF, however:



LASNEX contour plots courtesy of R. A. Vesey:



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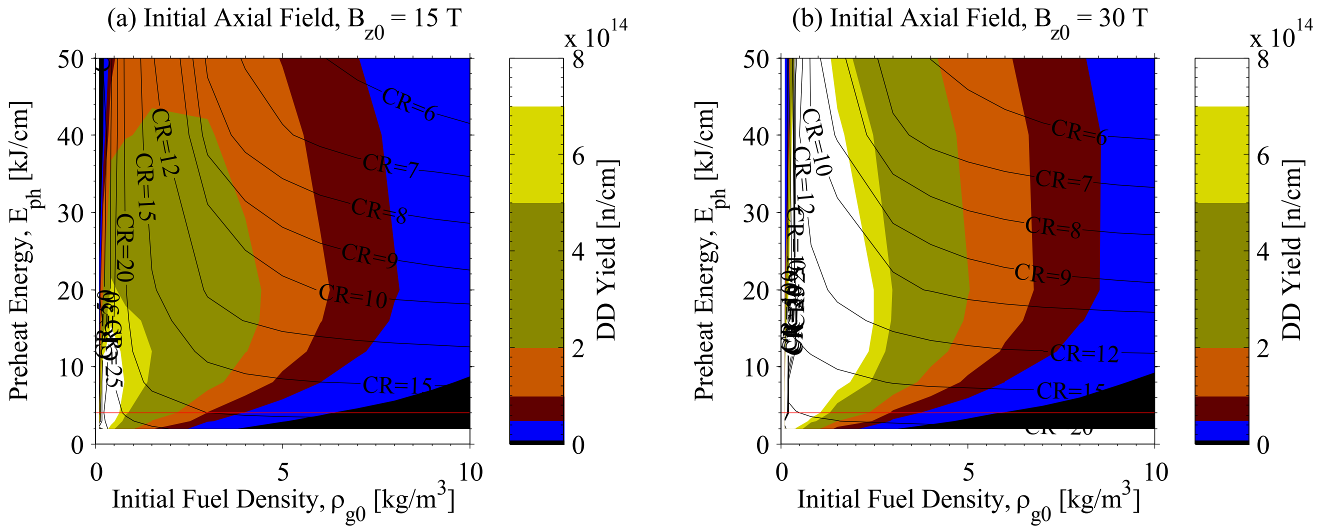

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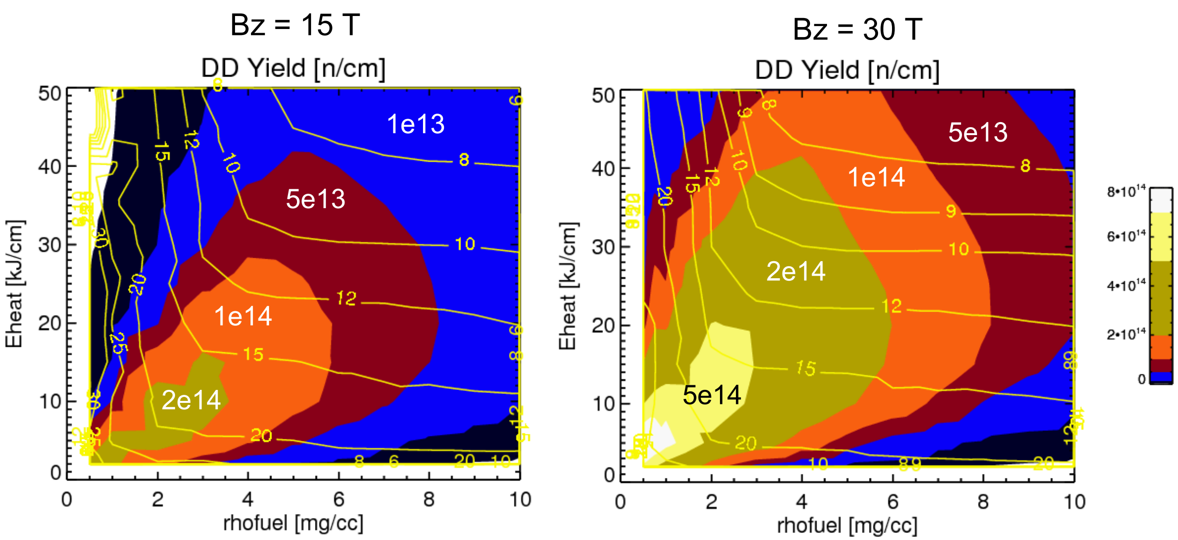

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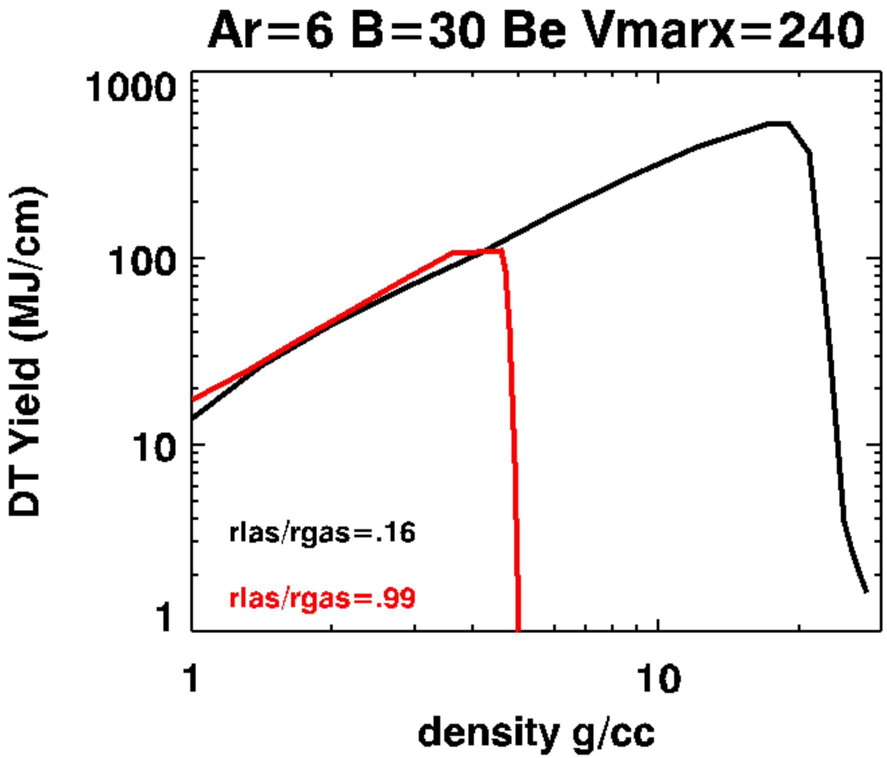

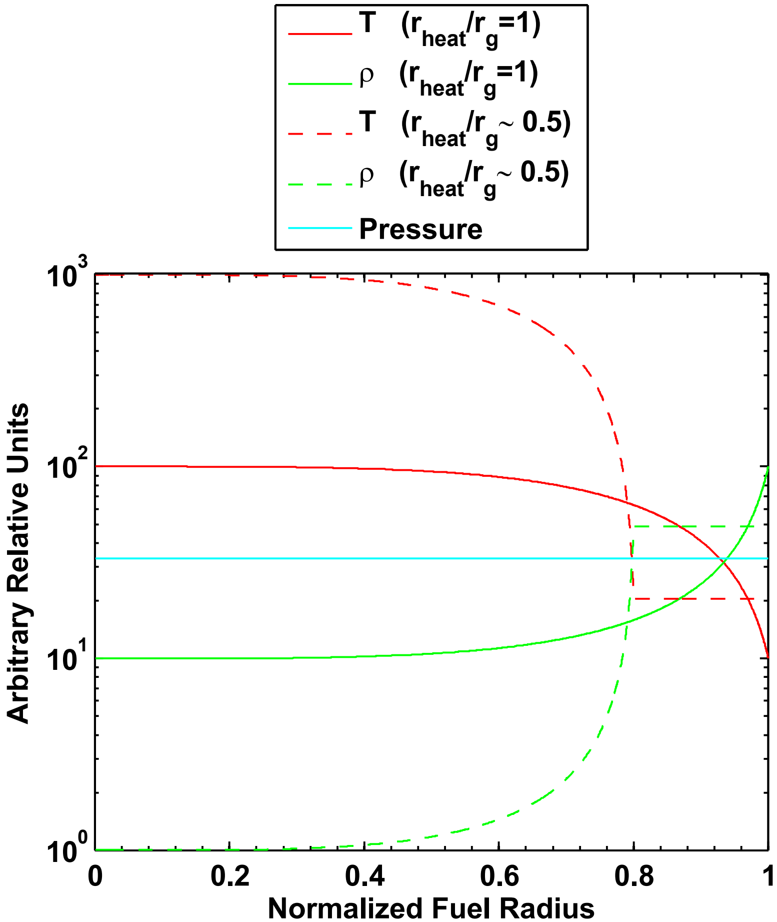

Summary & Conclusions

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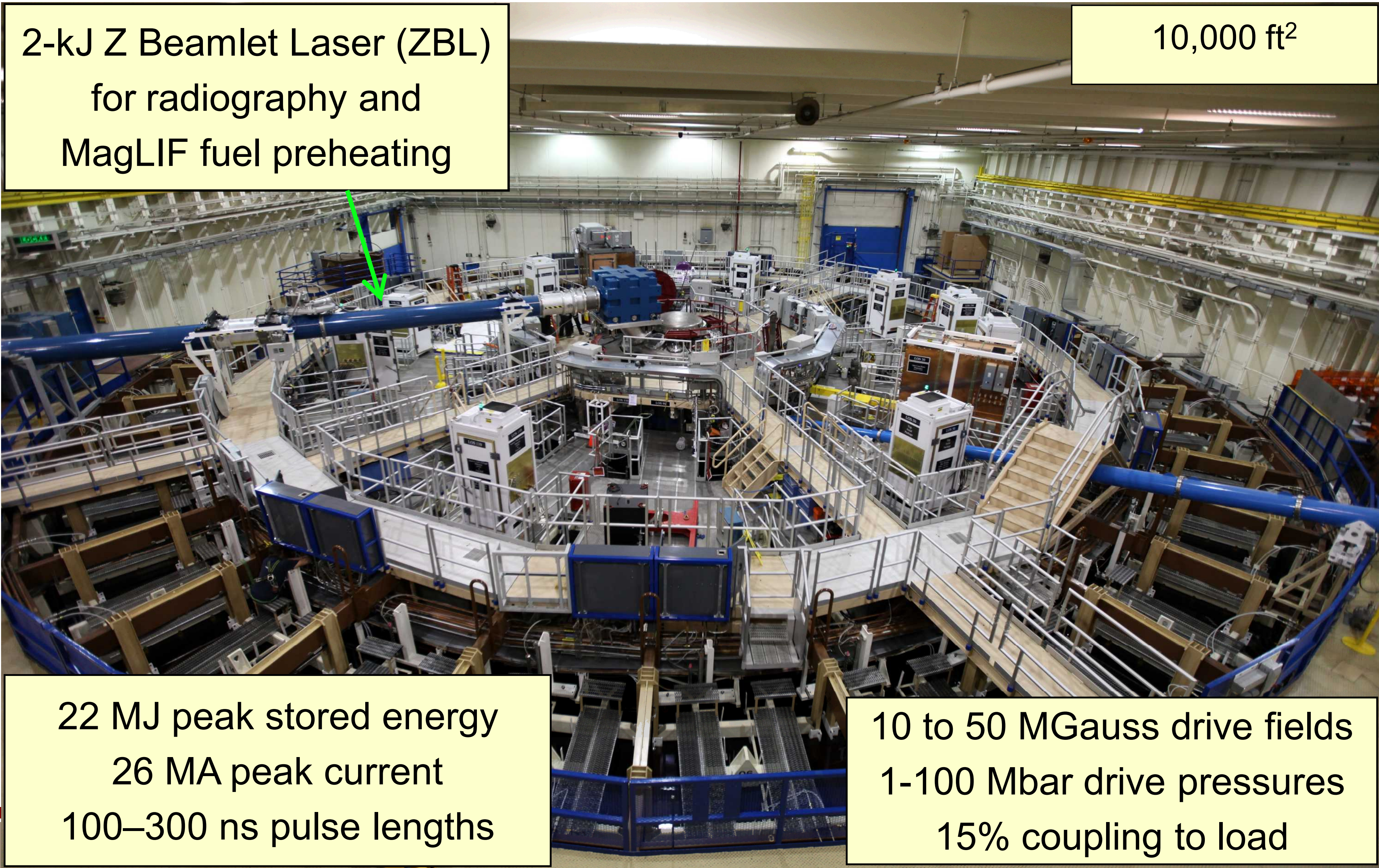
- The development of this semi-analytic model has been a useful and insightful exercise
  - Led to the realization that bremsstrahlung losses are significantly reduced when only a fraction of the fuel is preheated (e.g., from r=0 to $r=r_g/2$ uniformly) as opposed to heating all of the fuel uniformly; this is due to blast wave redistribution of fuel mass, which significantly affects the radial temperature and density profiles within the fuel
  - Led to a better understanding of electron and ion conductivity fluxes radially with the fuel, and the handoff from ion conductivity to electron conductivity near the liner wall
  - Multiple liner shells to obtain reasonable CRs
  - Parameter scans using this model illustrate that using the preheat energy presently available at the Z facility will be risky at first, but more robust solutions should be possible within the next three years, as the ZBL laser energy is increased from ~2 kJ to ~6 kJ
- This model's accessible physics and fast run times (~20 seconds/simulation) is a useful pedagogical tool, especially for students, experimentalists, and researchers interested in MagLIF
- We hope to publish and distribute this model to those who may be interested

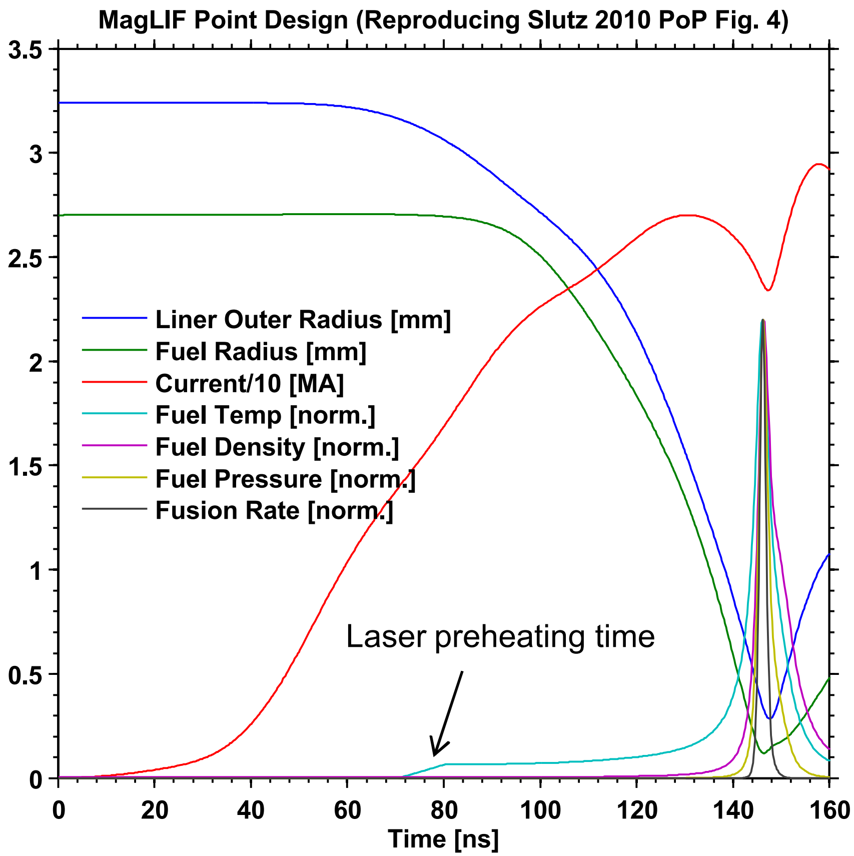
Backup Slides

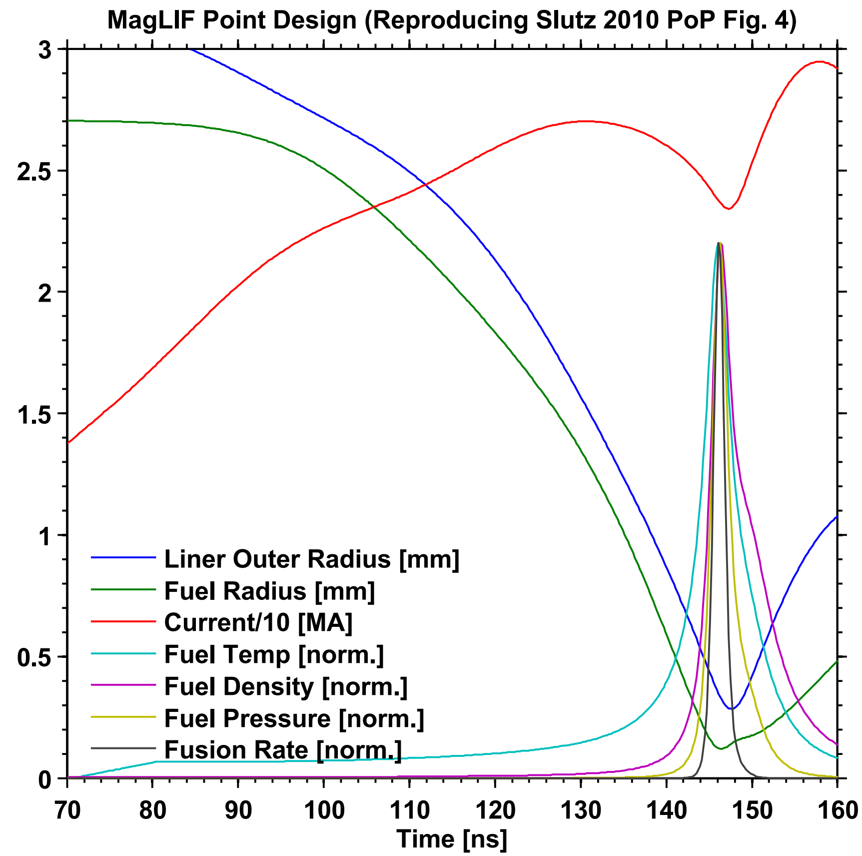
The Z pulsed-power facility combines a compact MJ-class target physics platform (the Z accelerator) with a TW-class laser (ZBL)



MagLIF Timing Overview

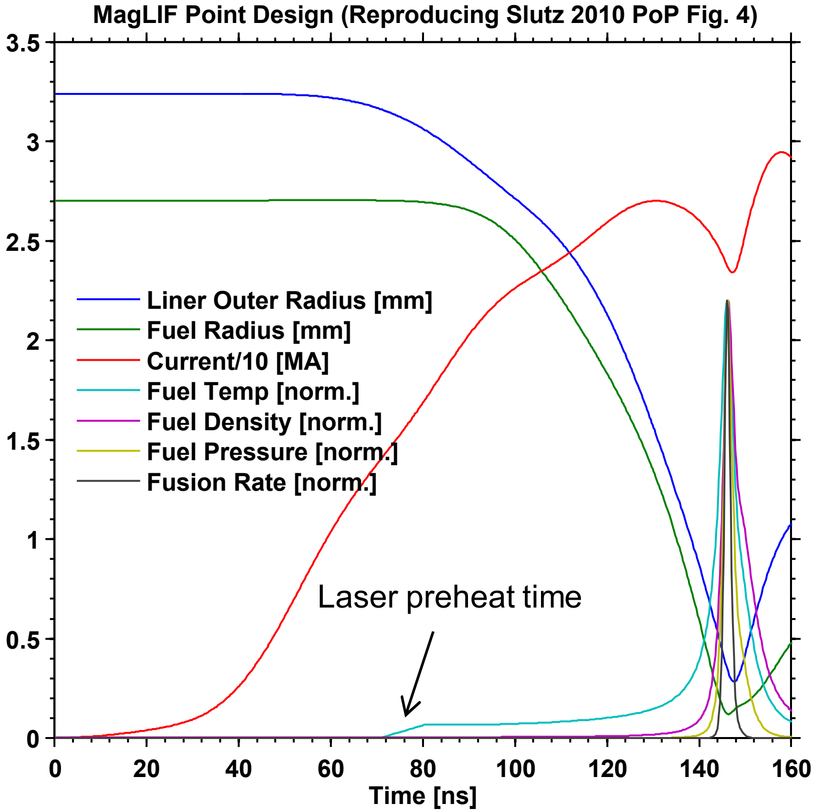
- ~ 100-ns implosion times
- ~ adiabatic fuel compression (thus preheating the fuel is necessary)
- ~ 5-keV fuel stagnation temperatures
- ~ 1-g/cc fuel stagnation densities
- ~ 5-Gbar fuel stagnation pressures

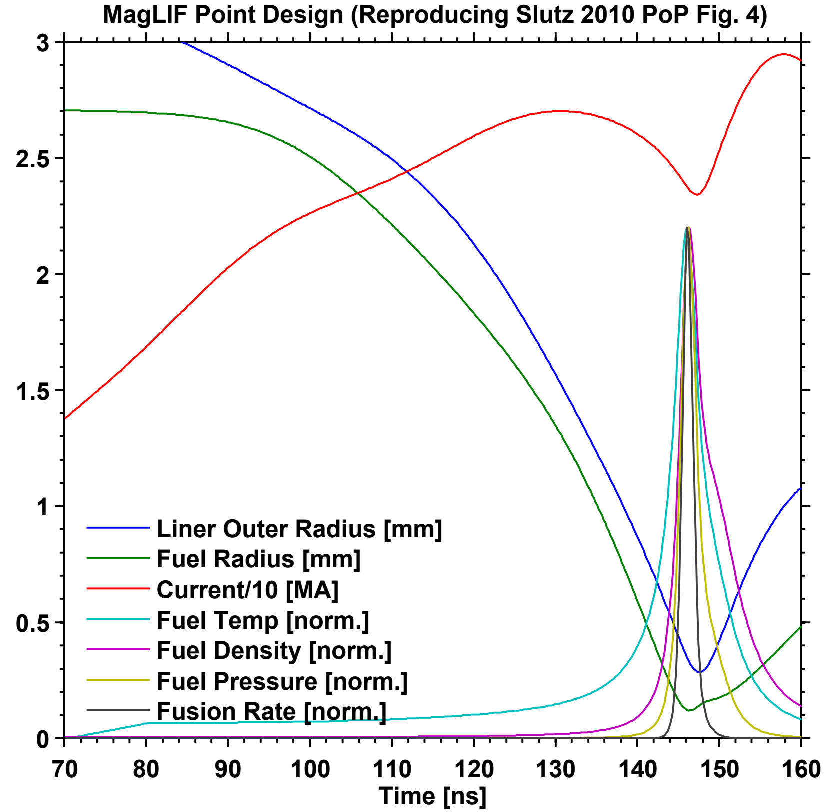




Preheat is necessary for the adiabatic compression and heating of MagLIF fuel

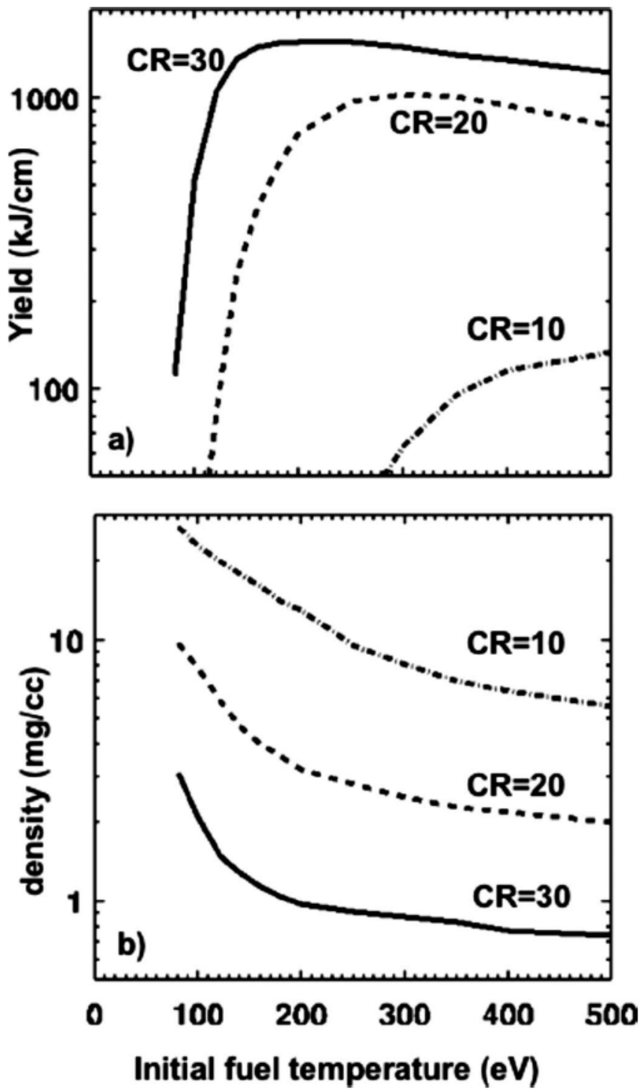
$$T \approx T_0 \left(\frac{\rho}{\rho_0} \right) \approx T_0 C_R^{4/3} \qquad (C_R = R_0 / R_{stagnation})$$

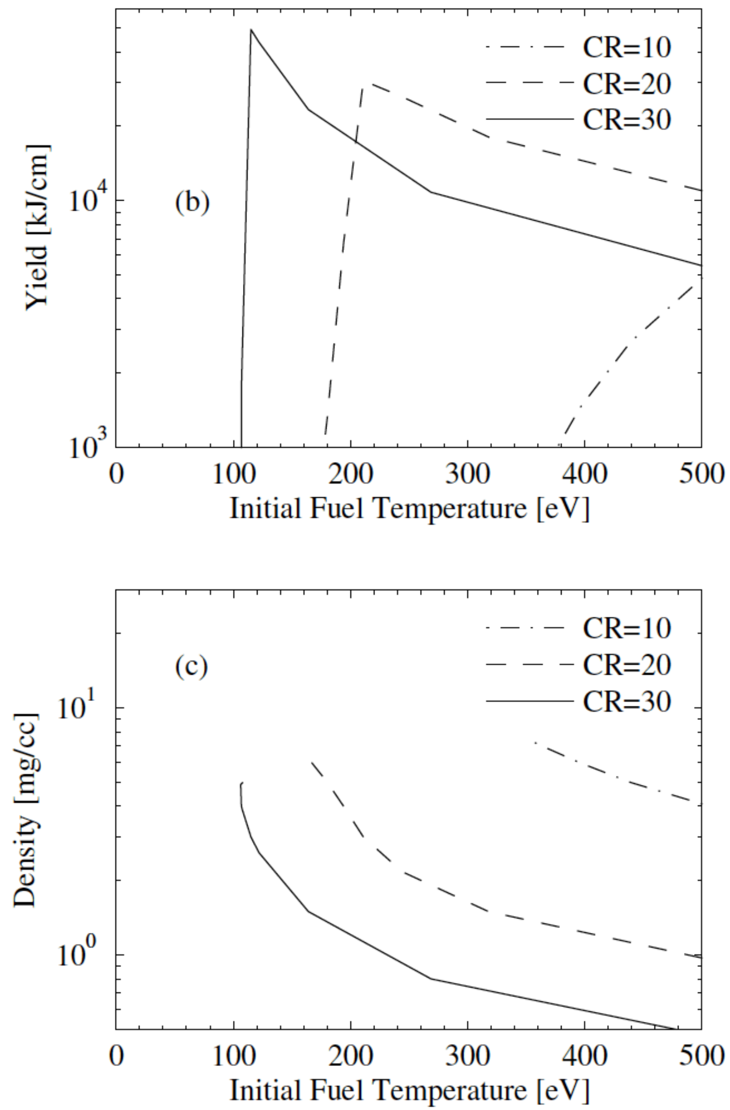




- Typically for ICF (e.g., NIF), faster implosions shock-heat the fuel, not so for MagLIF
- Magnetization is used to keep the preheated fuel from cooling off during the implosion

This semi-analytic model captures the general 1D behavior presented in the original 2010 MagLIF paper:





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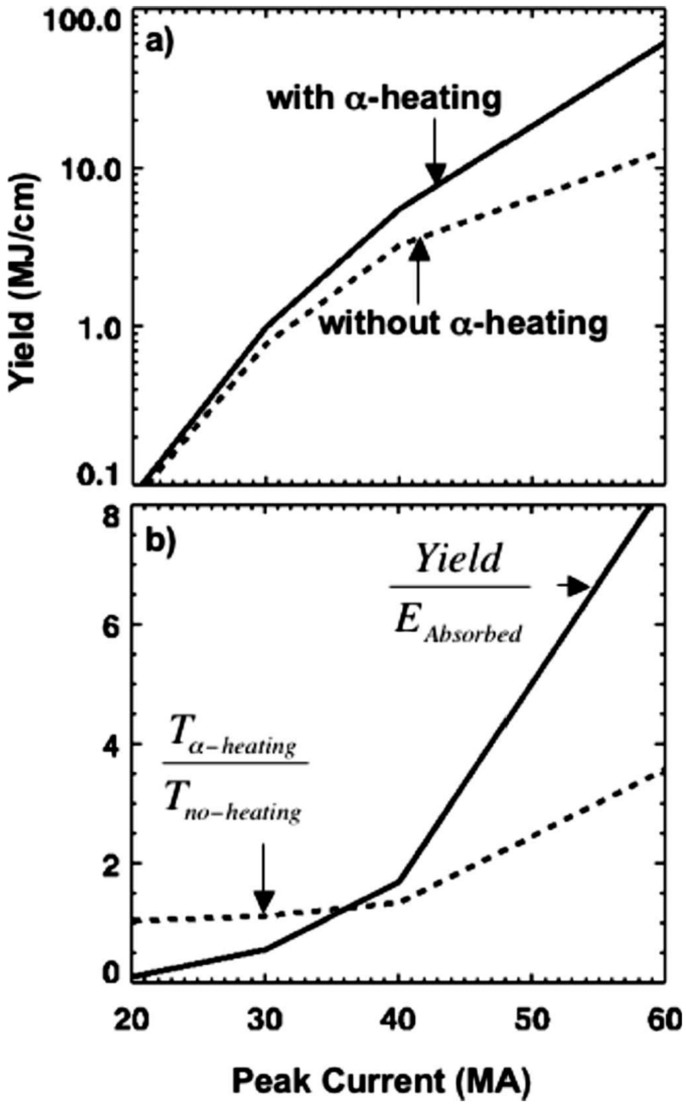

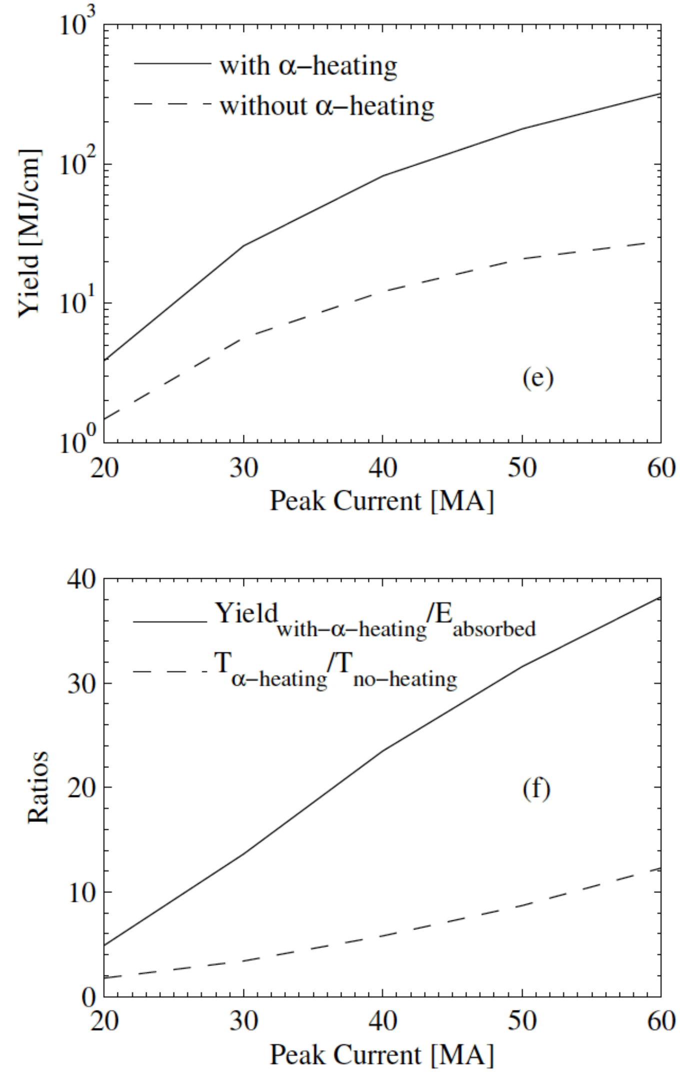

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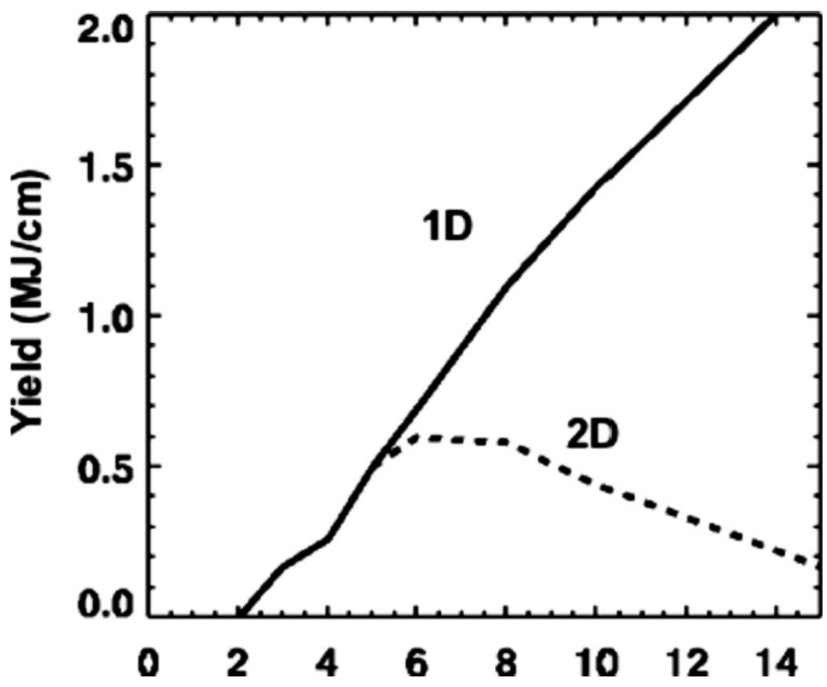
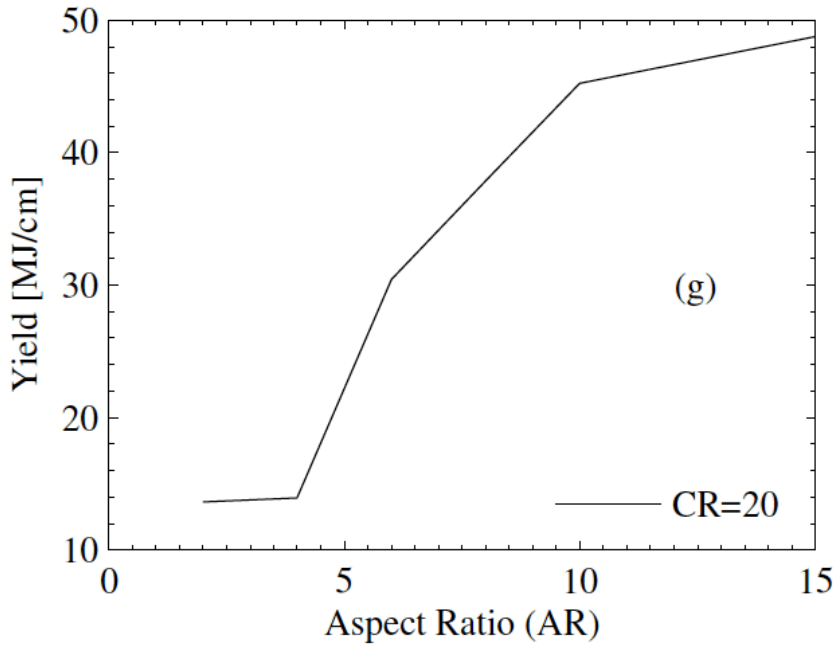
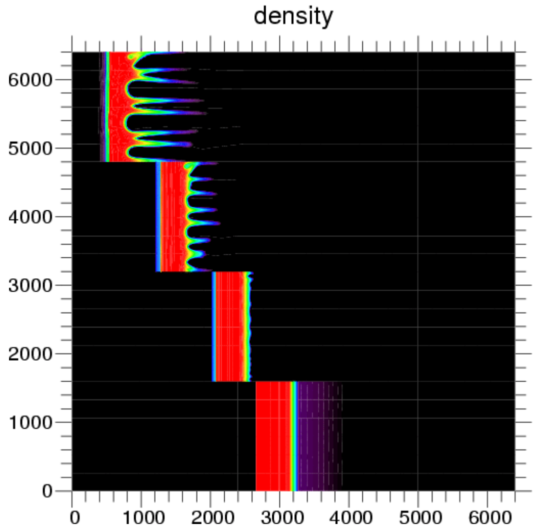
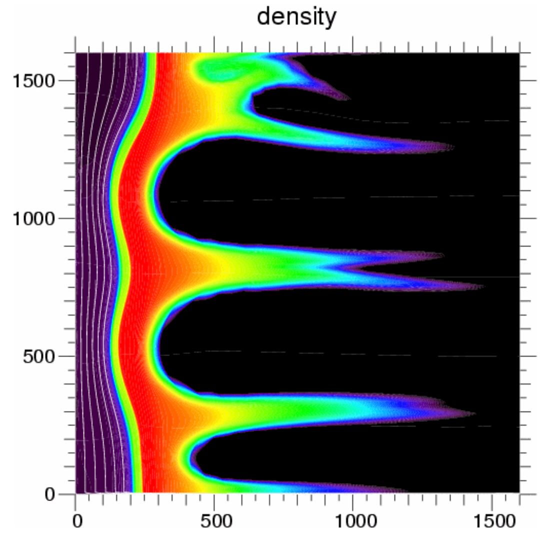
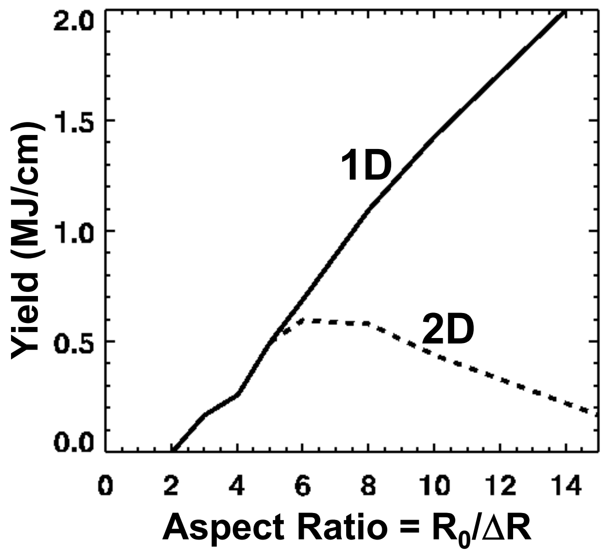


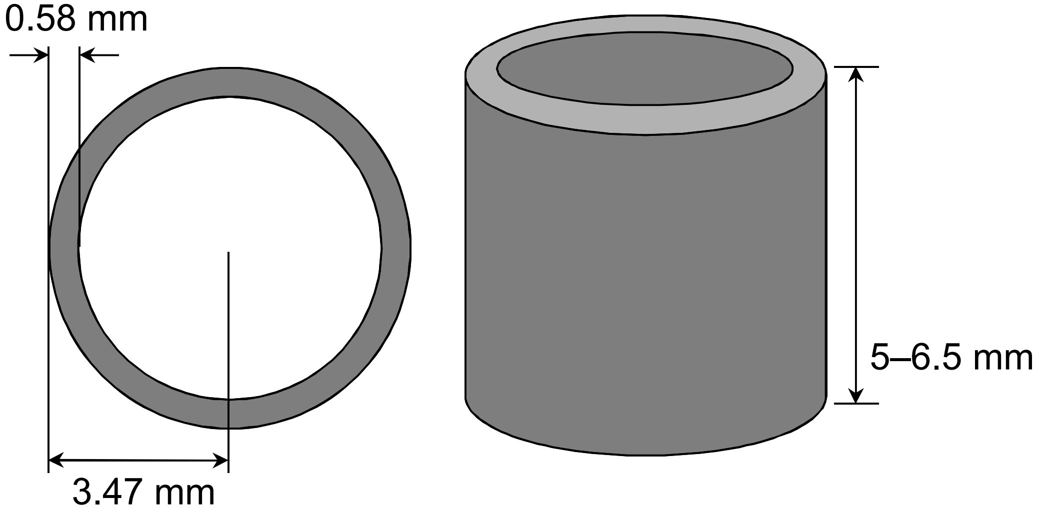


2D simulations of MagLIF suggest an optimum at an aspect ratio (AR) of 6*









$$AR \equiv \frac{R_{outer,0}}{\Delta R_0}$$

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

Radiographs at a convergence ratio of ~5 show remarkably good stability for inner liner surface

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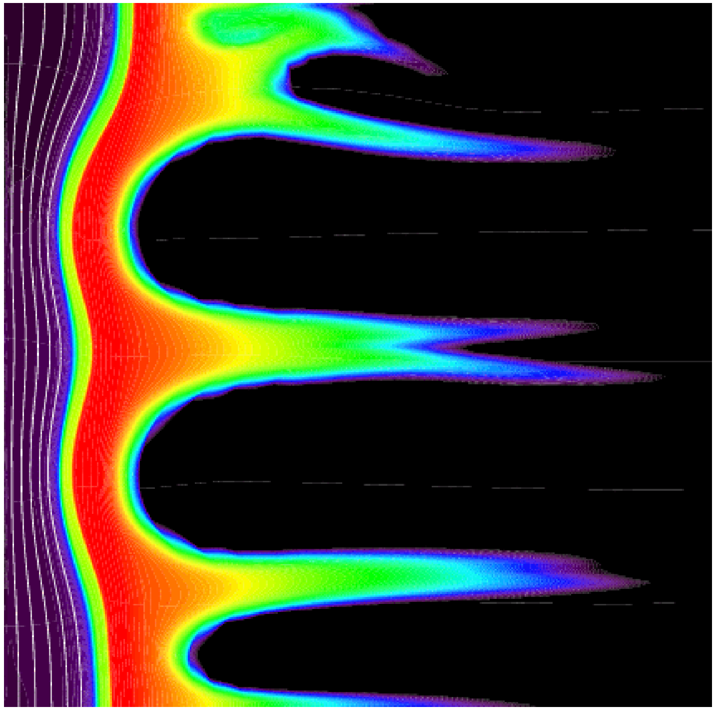
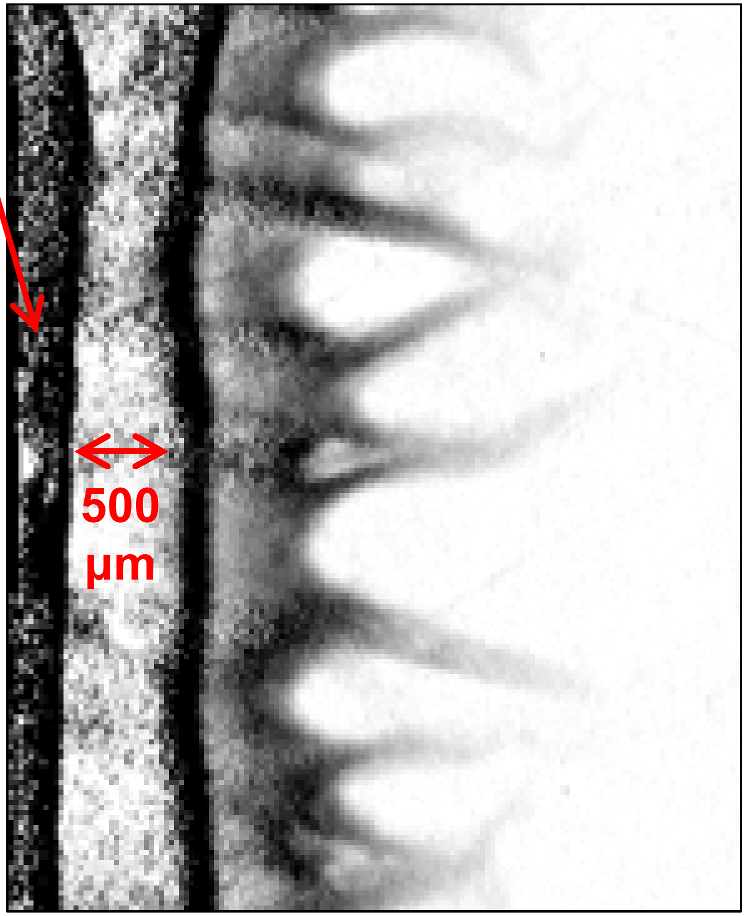
Note: MagLIF requires final compression to on-axis rod



2D Simulation from
S. A. Slutz, *et al*., PoP (2010)



Experiment*

* R. D. McBride et al., Phys. Plasmas **20**, 056309 (2013).