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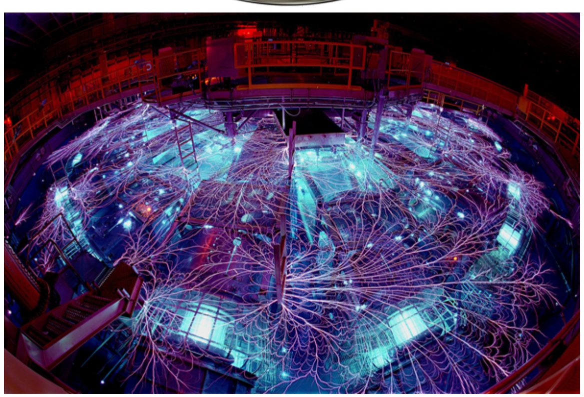
Sandia National Laboratories

Pulsed Power Sciences
Harnessing Extreme Environments

Semi-analytic modeling & simulation of magnetized liner inertial fusion

Ryan D. McBride and Stephen A. Slutz

Dense Z-Pinch Conference
Napa, California, August 5, 2014



With special thanks to: K. Cochrane, R.A. Vesey, D.B. Sinars, M.E. Cuneo, M.C. Herrmann, S.B. Hansen, P.F. Schmit, C.W. Nakhleh, K.J. Peterson, M.R. Martin, A.B. Sefkow, C.A. Jennings, P.F. Knapp, and T.J. Awe

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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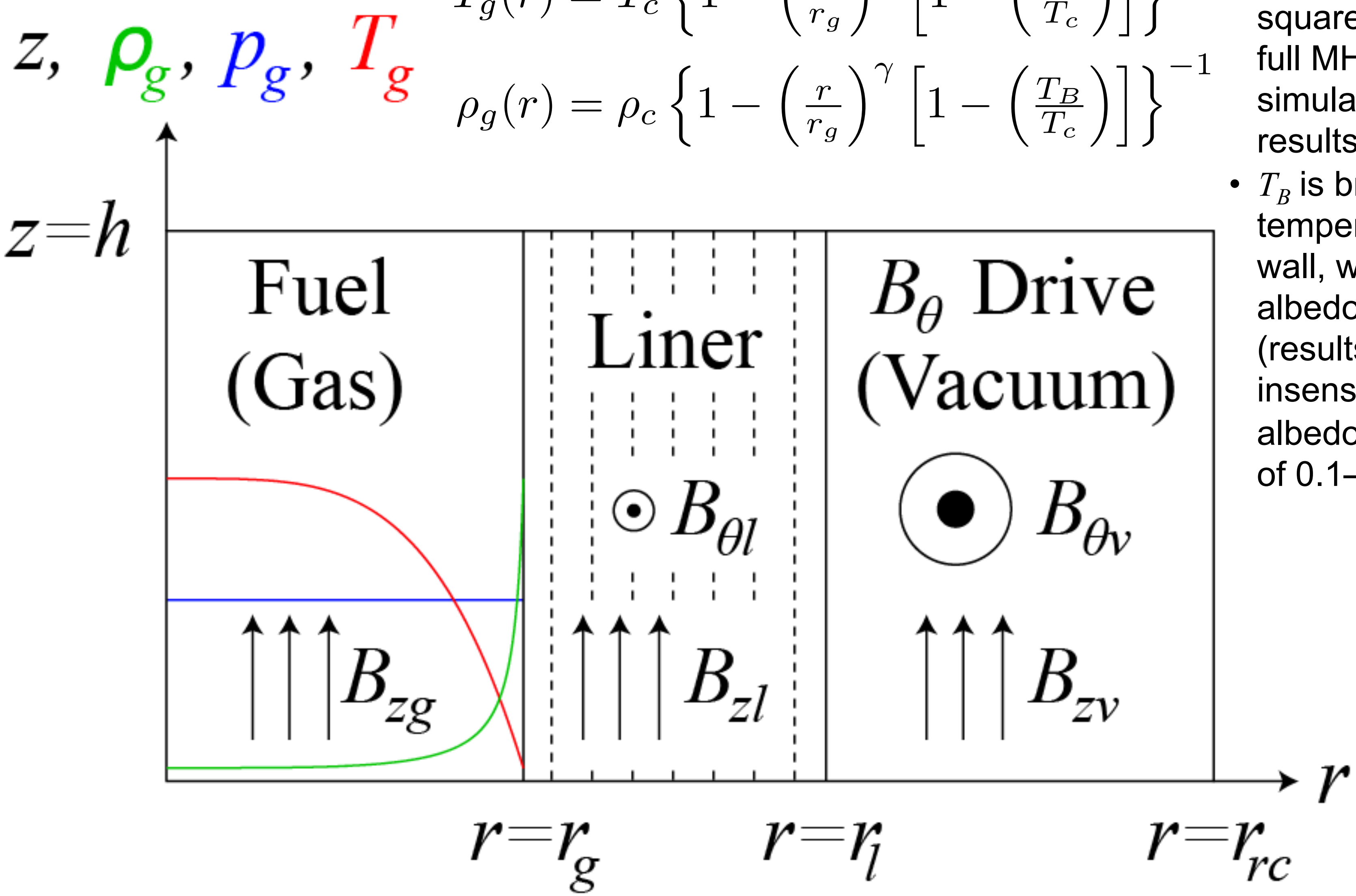
Overview of semi-analytic MagLIF model (SAMM):

$$T_g(r) = T_c\left\{1 - \left(\frac{r}{r_g}\right)^{\gamma}\left[1 - \left(\frac{T_B}{T_c}\right)\right]\right\}$$

$$\rho_g(r) = \rho_c\left\{1 - \left(\frac{r}{r_g}\right)^{\gamma}\left[1 - \left(\frac{T_B}{T_c}\right)\right]\right\}^{-1}$$



- γ~4 from least-squares fits to full MHD simulation results
- T_B is brightness temperature at wall, with albedo of ~0.5 (results are insensitive to albedo in range of 0.1–0.9)

Overview of semi-analytic MagLIF model (SAMM):

- System of ordinary differential equations that are straight forward to solve with MATLAB, IDL, Mathematica, etc.
- ~20 seconds/simulation on my laptop
- Parameter scans of ~3000 simulations in ~5 minutes using Sandia cluster

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

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

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

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

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

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

$$\dot{E}_l = -\left(\frac{2}{3}\frac{E_l}{V_l} + q_l\right)\dot{V}_l + P_r + P_{ce} + P_{ci} + I_l^2 R_l$$

$$\dot{\Phi}_{B_z} = -2\pi r_g f(\omega\tau) \left.\frac{dT_g}{dr}\right|_{r=r_g,\, T_g=T_B}$$

$$\dot{N}_{dj} = n_d n_j \langle\sigma v\rangle_{dj} \cdot (1 - \delta_{dj}/2) \cdot V_g \quad (j = d, t)$$

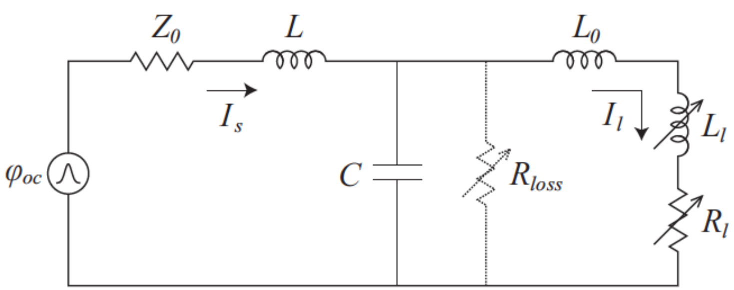
Overview of semi-analytic MagLIF model (SAMM):

Drive (circuit model driven by open-circuit voltage φ_{oc})

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

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

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



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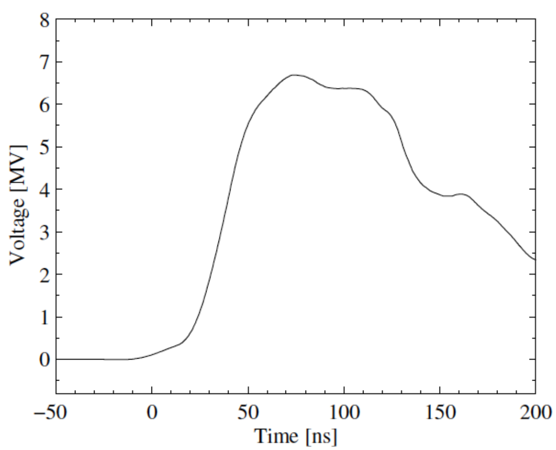

Overview of semi-analytic MagLIF model (SAMM):

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

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

Dynamics (fuel and liner) →

- p_l = ideal gas + Birch-Murnaghan cold curve (used for analytic fits to SESAME tables)
- q_l ~ simple v^2 dependence

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

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

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

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$$\dot{\Phi}_{B_z} = -2\pi r_g f(\omega\tau) \left.\frac{dT_g}{dr}\right|_{r=r_g, T_g=T_B}$$

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Energetics (fuel and liner) →

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

$$\dot{E}_l = -\left(\frac{2}{3}\frac{E_l}{V_l} + q_l\right)\dot{V}_l + P_r + P_{ce} + P_{ci} + I_l^2 R_l$$

- P_α = Basko
- P_r = Grey model with emissivity & opacity integral over T & ρ profiles
- P_{ce} = Epperlein-Haines
- P_{ci} = Braginskii
- $I_l^2 R_l$ = From assumed distribution:

$$B_\theta(r) \sim r^{\beta(\delta skin)}$$

and Maxwell's equations

(results somewhat sensitive to β)

$$\dot{\Phi}_{B_z} = -2\pi r_g f(\omega\tau) \left.\frac{dT_g}{dr}\right|_{r=r_g,\, T_g=T_B}$$

$$\dot{N}_{dj} = n_d n_j \langle \sigma v \rangle_{dj} \cdot (1 - \delta_{dj}/2) \cdot V_g \quad (j = d, t)$$

Overview of semi-analytic MagLIF model (SAMM):

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B_z flux loss due to the Nernst thermoelectric effect (Braginskii) →

$$\dot{\Phi}_{B_z} = -2\pi r_g f(\omega\tau) \left.\frac{dT_g}{dr}\right|_{r=r_g,\, T_g=T_B}$$

$$\dot{N}_{dj} = n_d n_j \langle\sigma v\rangle_{dj} \cdot (1 - \delta_{dj}/2) \cdot V_g \quad (j = d, t)$$

Overview of semi-analytic MagLIF model (SAMM):

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$$\dot{\Phi}_{B_z} = -2\pi r_g f(\omega\tau) \left.\frac{dT_g}{dr}\right|_{r=r_g, T_g=T_B}$$

DD & DT Fusion Burn →

- Analytic <σv> (Bosch & Hale)

$$\dot{N}_{dj} = n_d n_j \langle \sigma v \rangle_{dj} \cdot (1 - \delta_{dj}/2) \cdot V_g \quad (j = d, t)$$

Overview of semi-analytic MagLIF model (SAMM):

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

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

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

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

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

\+ $$\ddot{r}_{l,i} = \frac{p_{in,i} + q_{in,i} - p_{out,i} - q_{out,i}}{m_l/n} \cdot 2\pi r_{l,i} \cdot h \qquad (i = 2, 3, \ldots, n)$$

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

~~$\dot{E}_l = -\left(\frac{2}{3}\frac{E_l}{V_l} + q_l\right)\dot{V}_l + P_r + P_{ce} + P_{ci} + I_l^2 R_l$~~ →

$$\dot{E}_{l,i} = -\left(\frac{2}{3}\frac{E_{l,i}}{V_{l,i}} + q_{l,i}\right)\dot{V}_{l,i} + \left(P_r + P_{ce} + P_{ci} + I_l^2 R_l\right)/n \qquad (i = 1, 2, \ldots, n)$$

$$\dot{\Phi}_{B_z} = -2\pi r_g f(\omega\tau) \left.\frac{dT_g}{dr}\right|_{r=r_g,\, T_g=T_B}$$

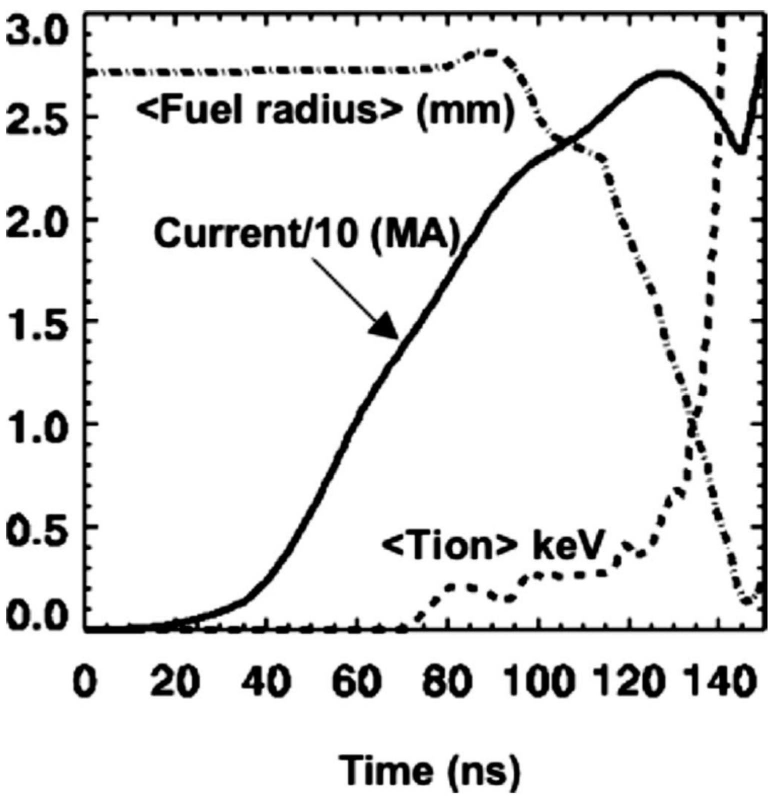
$$\dot{N}_{dj} = n_d n_j \langle\sigma v\rangle_{dj} \cdot (1 - \delta_{dj}/2) \cdot V_g \qquad (j = d, t)$$

We found that we needed to discretize the liner to obtain more reasonable convergence ratios

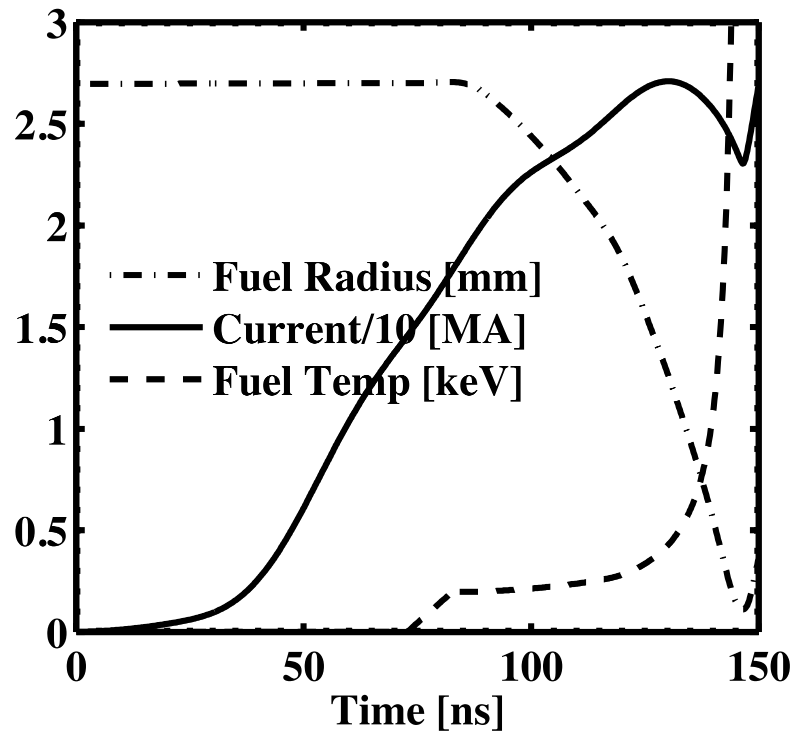
- This is particularly important for near term, low preheat energy solutions

SAMM captures the general 1D behavior presented in the original 2010 MagLIF paper*

Dynamics, Energetics, and Circuit Response



S. A. Slutz *et al*., PoP (2010).

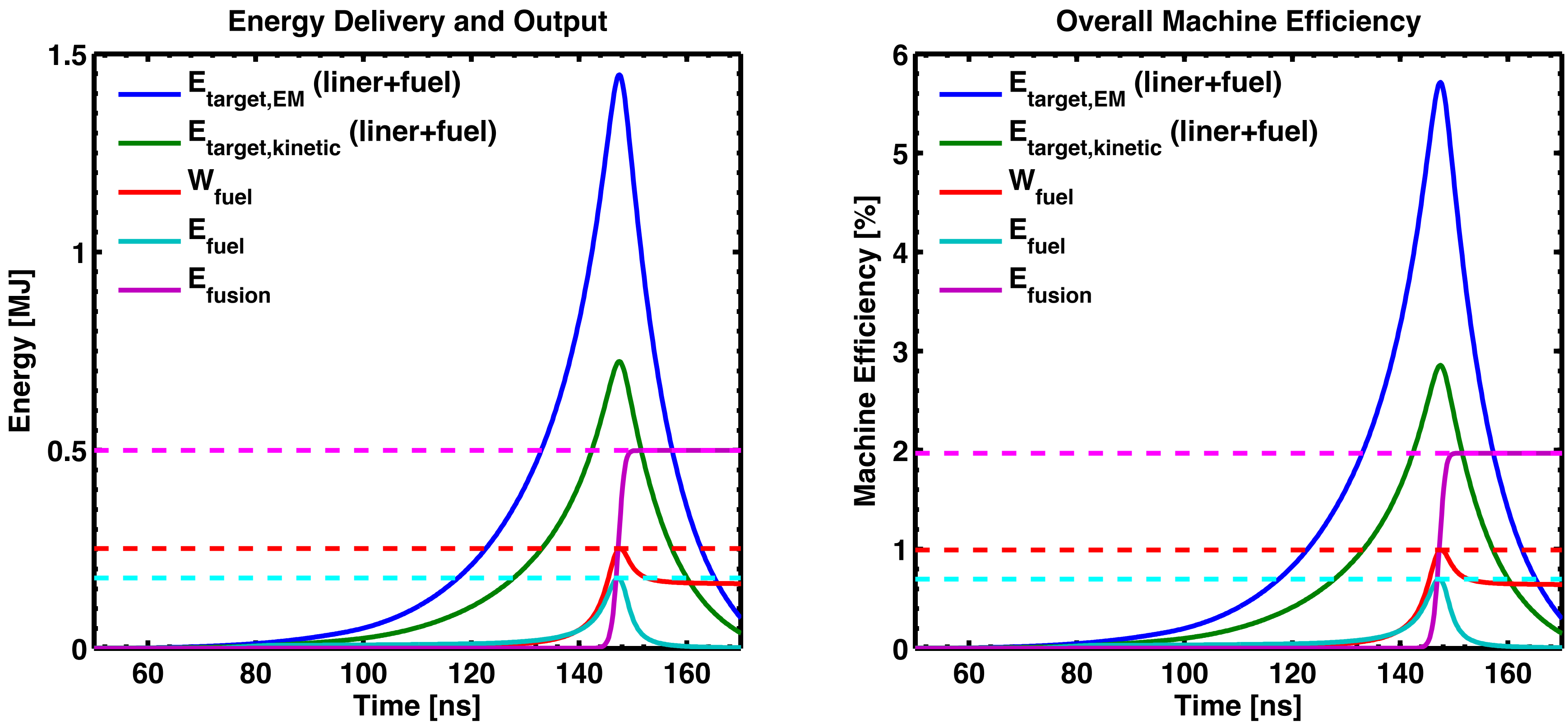


SAMM

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

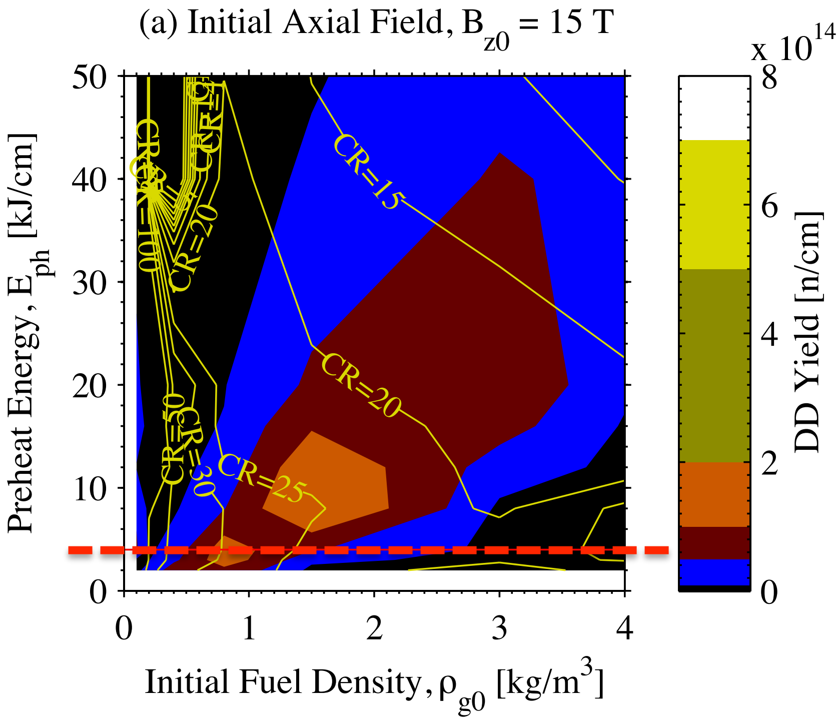
SAMM can be used to illustrate the overall efficiencies of MagLIF:

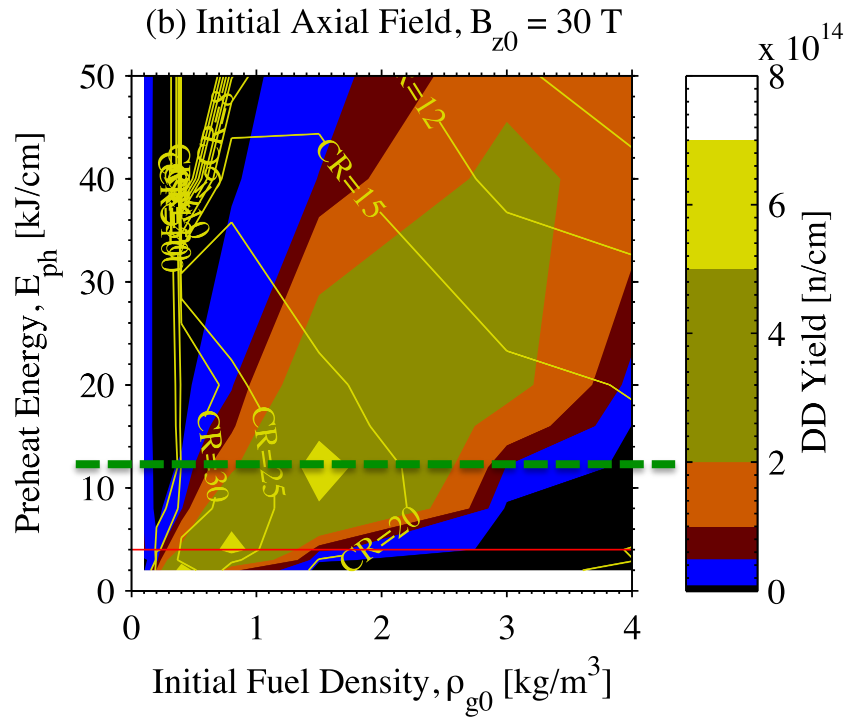
"Point Design" with DT fuel, 6–8 kJ preheat, 30 T and 95-kV Marx Charge (~25 MJ stored)*



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

SAMM can be used to rapidly explore the MagLIF parameter space:



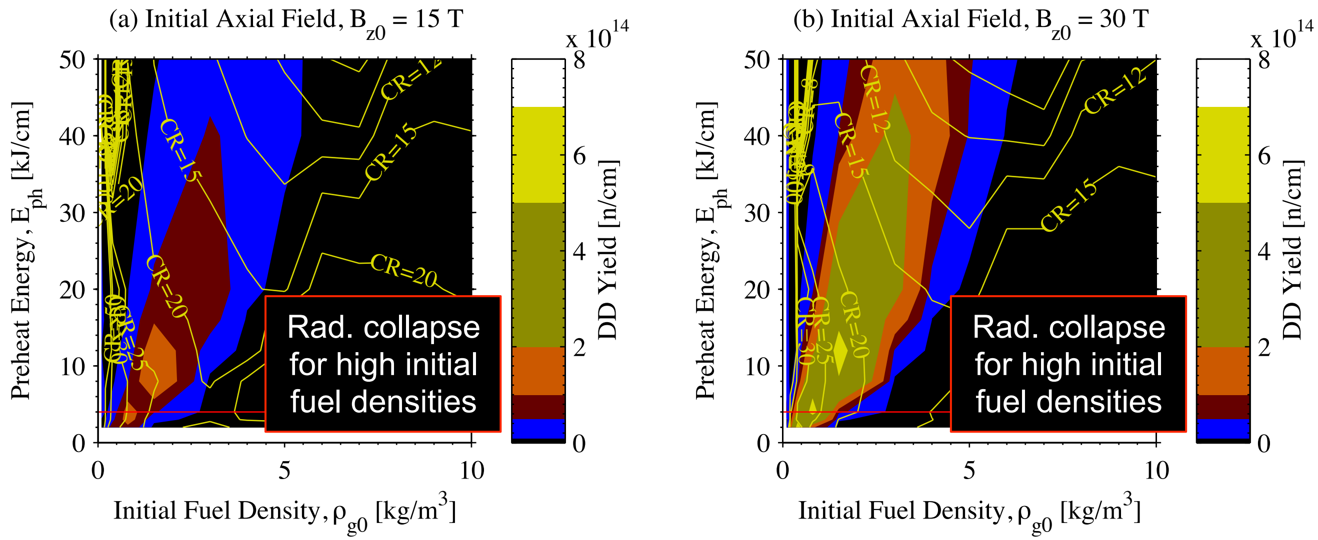


First Integrated experiments: ---
~2 kJ laser
80–85 kV Marx charge,
10–15 T, DD fuel

~2015: ---
~6 kJ laser, 30 T
(also 90–95 kV Marx charge
and *maybe* DT fuel)

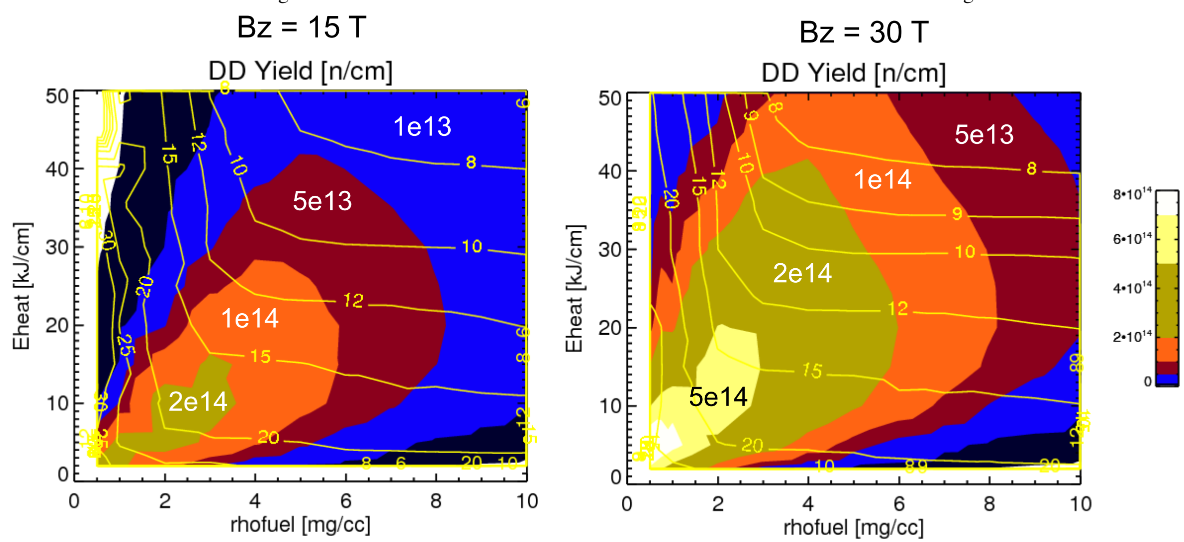
SAMM can be used to rapidly explore the MagLIF parameter space, however:

Semi-analytic model where all fuel is uniformly preheated



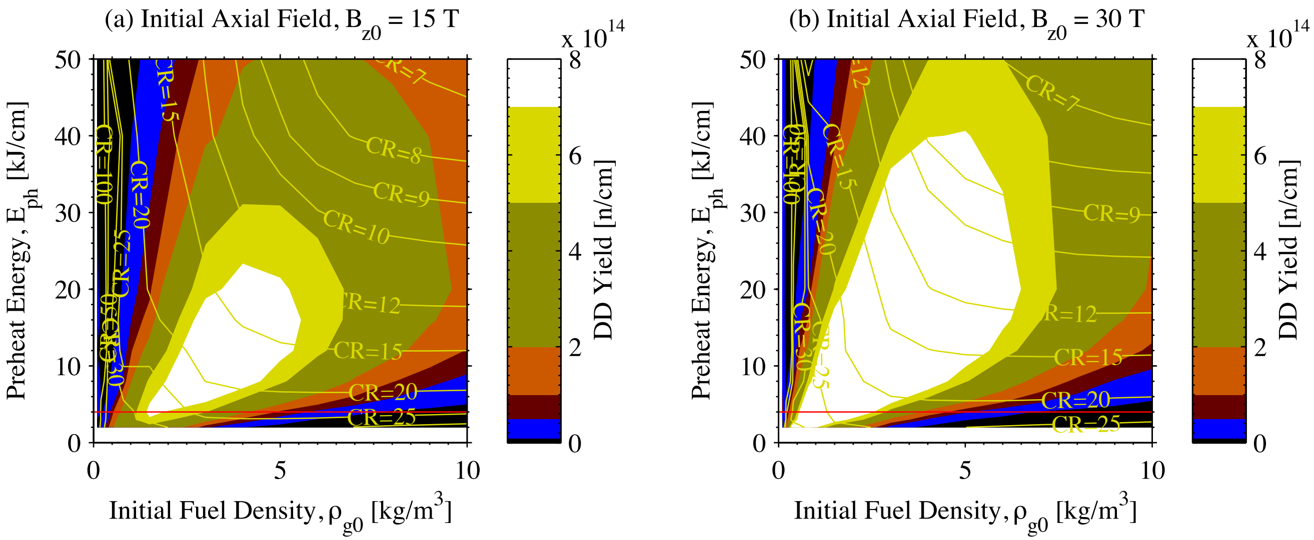
LASNEX simulations with uniformly preheated fuel from $r = 0$ to $r = 0.5\ r_g$

(LASNEX contour plots courtesy of R. A. Vesey)



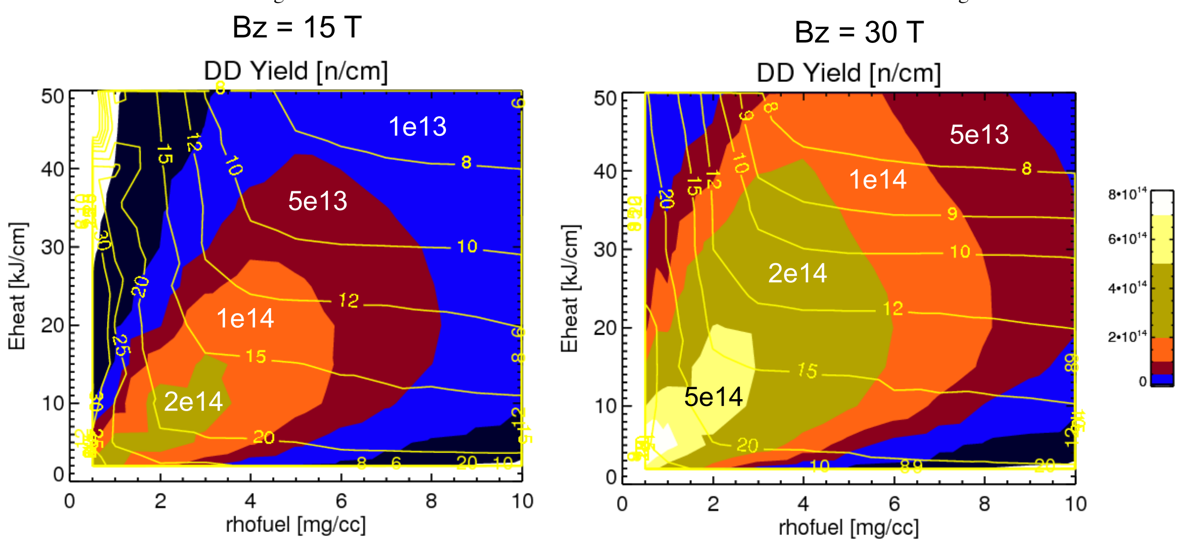
SAMM can be used to rapidly explore the MagLIF parameter space, however:

Semi-analytic model with uniformly preheated fuel and brems turned off to recover solutions for high initial fuel densities



LASNEX simulations with uniformly preheated fuel from $r = 0$ to $r = 0.5\, r_g$

(LASNEX contour plots courtesy of R. A. Vesey)



Radial fraction of fuel preheated dramatically affects high initial fuel density solutions via bremsstrahlung

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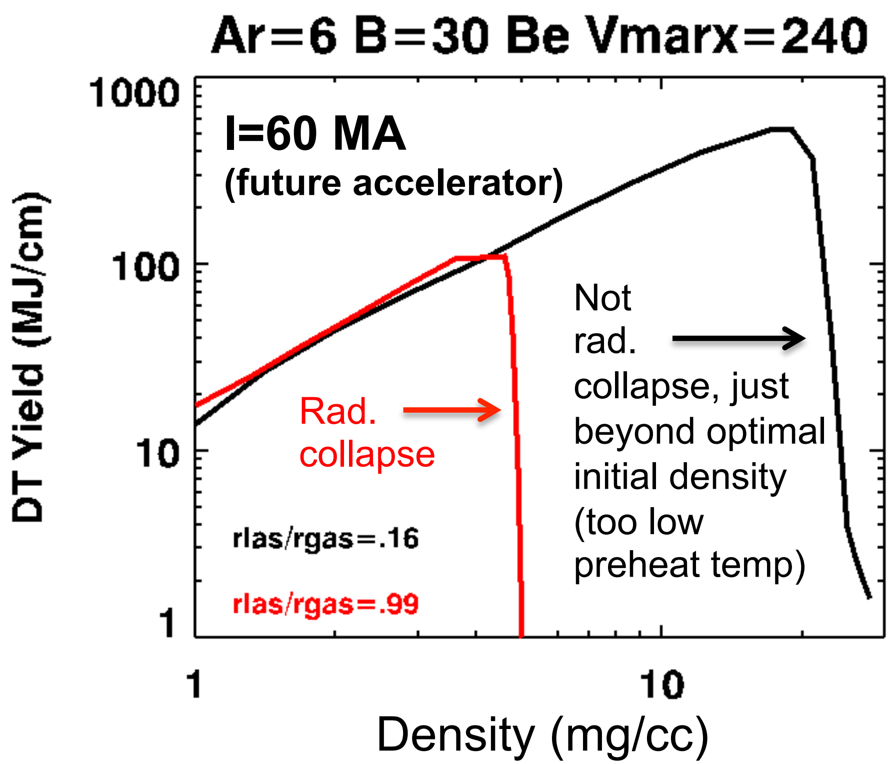
- Uniformly heating all of the fuel leads to radiative collapse for high initial fuel densities
- Uniformly heating only the fuel from $r = 0$ to $r \sim 0.5\, r_g$ leads to a blast wave and bores out a low density hot spot that dramatically reduces bremsstrahlung losses
- Most significant for high currents (future accelerators), where optimum yields are affected, though could affect near term experiments as well



"Blast wave" solution implemented to handle radial fractions of fuel preheated

- Fuel split into two parts that evolve:
  - Hot spot region
  - Cold, dense shelf region
- Entire fuel is still at constant pressure radially
- Shelf temperature is brightness/radiation temperature, T_B
- Shelf provides a buffer region between the hotspot and the liner wall
- Shelf mass ablation model given by:

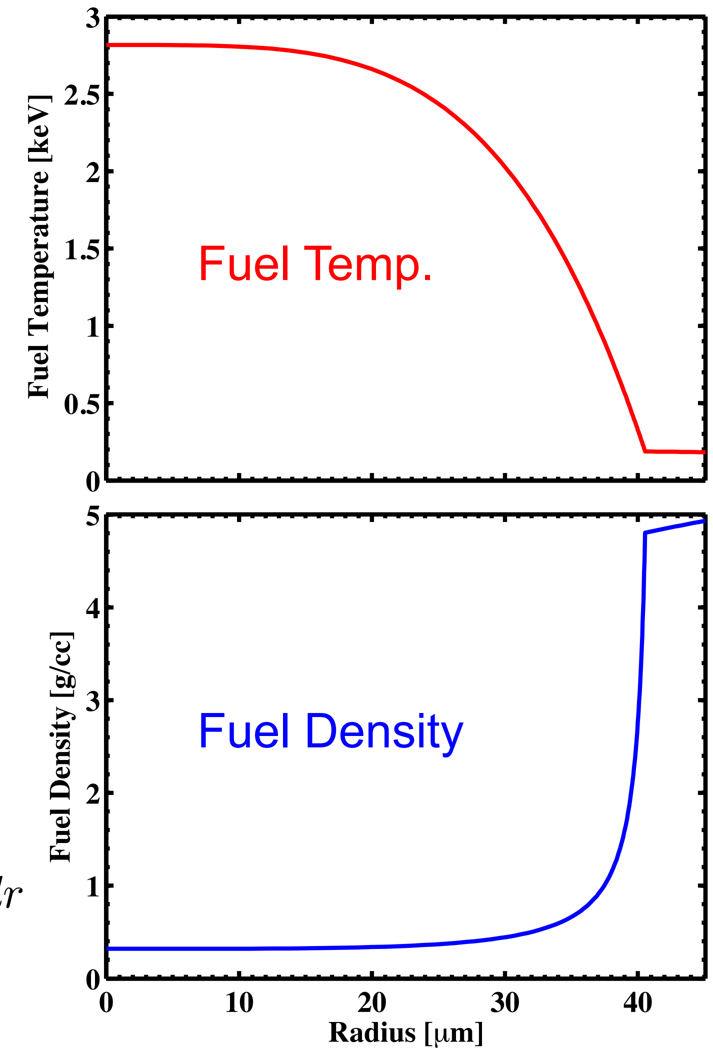
$$E = \frac{3}{2} NkT$$

$$\rightarrow \dot{m} = \frac{2}{3} \frac{\bar{m}_i}{(\bar{T}_{hot} - \bar{T}_{shelf})} \cdot P_{therm}$$

- Shelf reduces brems losses since radiation model is given by:

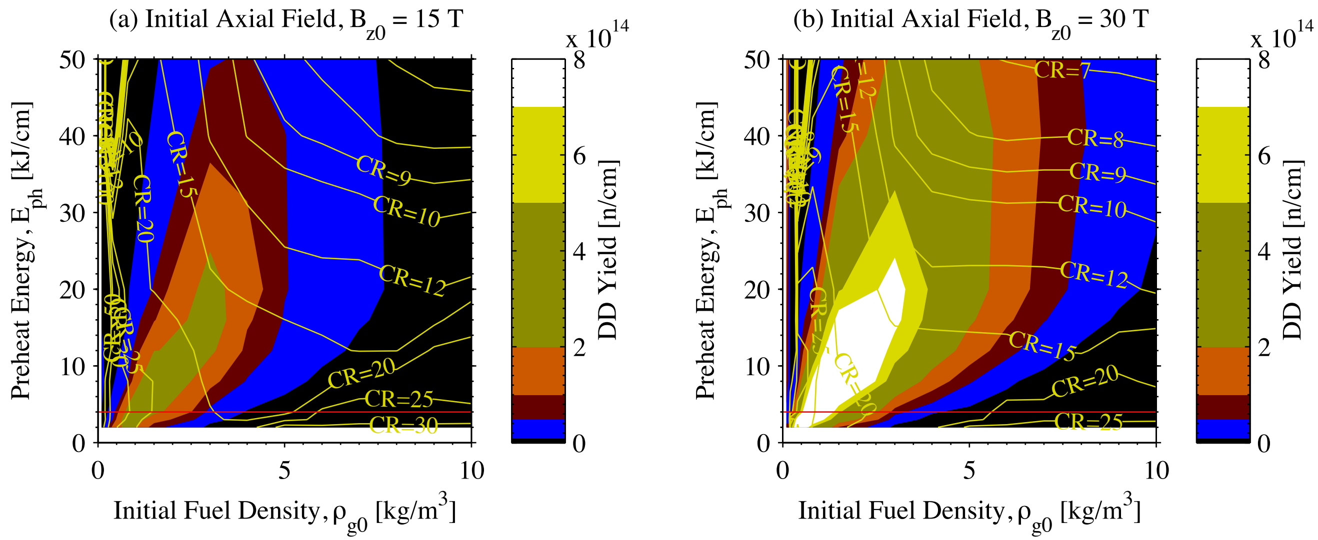
$$P_{rad} = A_{br} \int_0^{r_g} n_i(r) n_e(r) \bar{Z}^2 \sqrt{T_g(r)} \left[1 - \left(\frac{T_B}{T_g(r)} \right)^4 \right] r dr$$

$$P_{rad} = (1 - \alpha) \sigma T_B^4 \cdot A_w$$



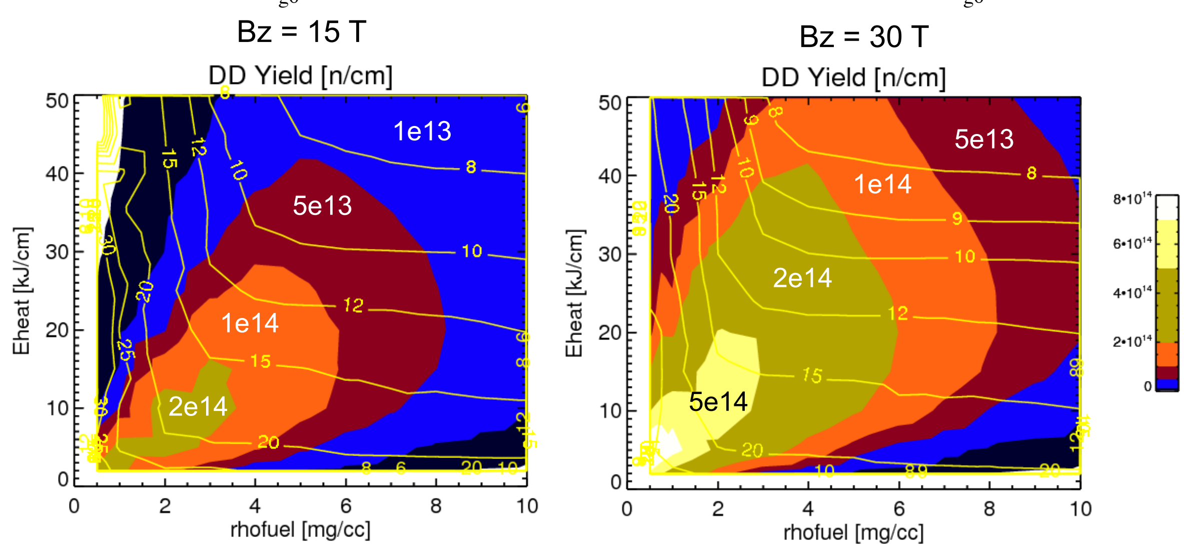
SAMM with new fuel shelf ablation model, brems, and only a fraction of the fuel uniformly preheated:

Semi-analytic model with uniformly preheated fuel from $r = 0$ to $r = 0.5\ r_g$



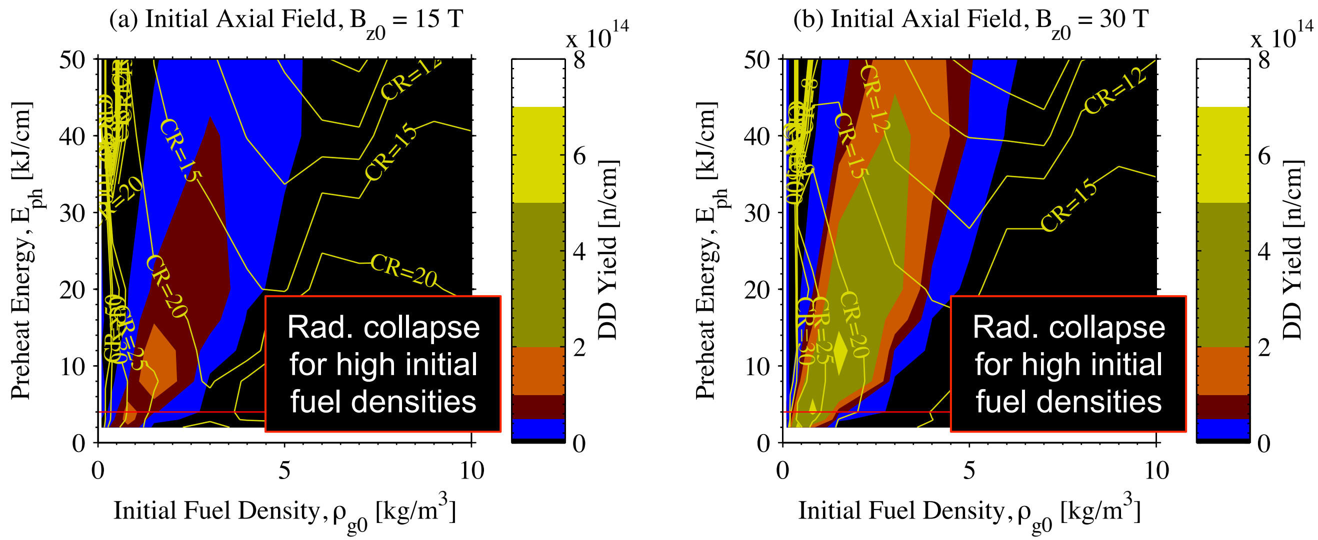
LASNEX simulations with uniformly preheated fuel from $r = 0$ to $r = 0.5\ r_g$

(LASNEX contour plots courtesy of R. A. Vesey)

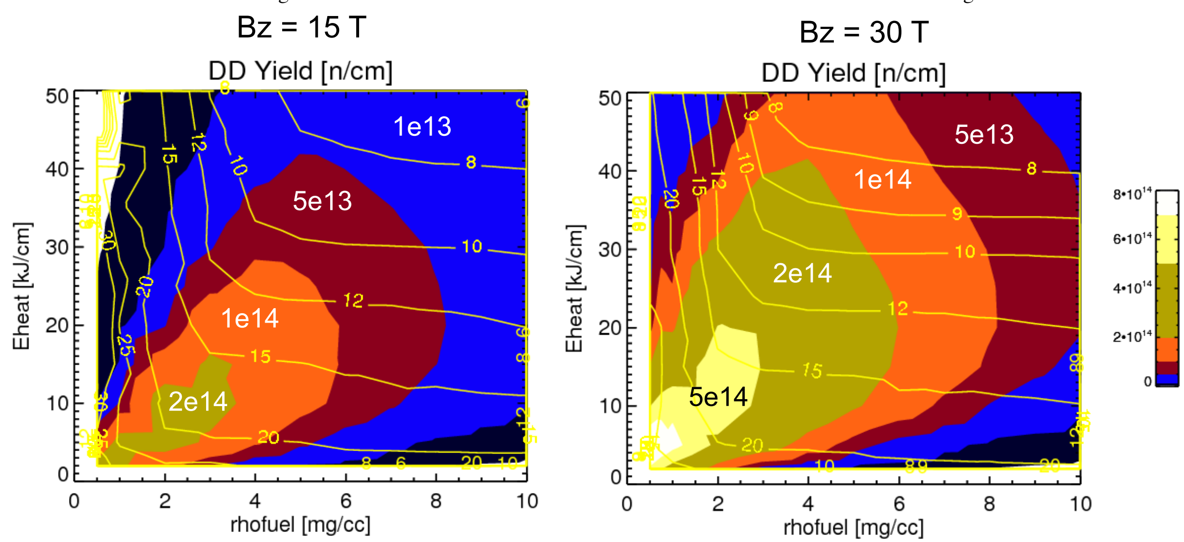


SAMM with all fuel uniformly preheated and brems:

Semi-analytic model where all fuel is uniformly preheated



LASNEX simulations with uniformly preheated fuel from $r = 0$ to $r = 0.5\ r_g$



(LASNEX contour plots courtesy of R. A. Vesey)

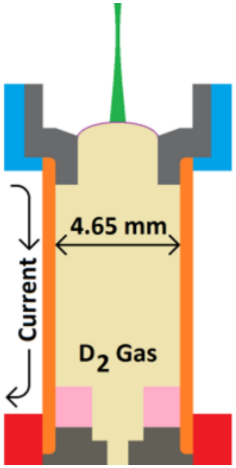
Some other recent additions into SAMM include:

- Effects of prescribed mix and/or dopants on radiation and thermal conduction losses and ionization energy:

$$E_{ion,s}(\bar{Z}_s) = \mathrm{Ry} \cdot \frac{Z_{nuc,s}^{2.407}}{(Z_{nuc,s}-\bar{Z}_s+1)^{1/2.407}}$$

$$\bar{Z}_s = \min(20\sqrt{T_{g,keV}},\ Z_{nuc,s})$$

- Laser deposition with simple inverse bremsstrahlung analytics:



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

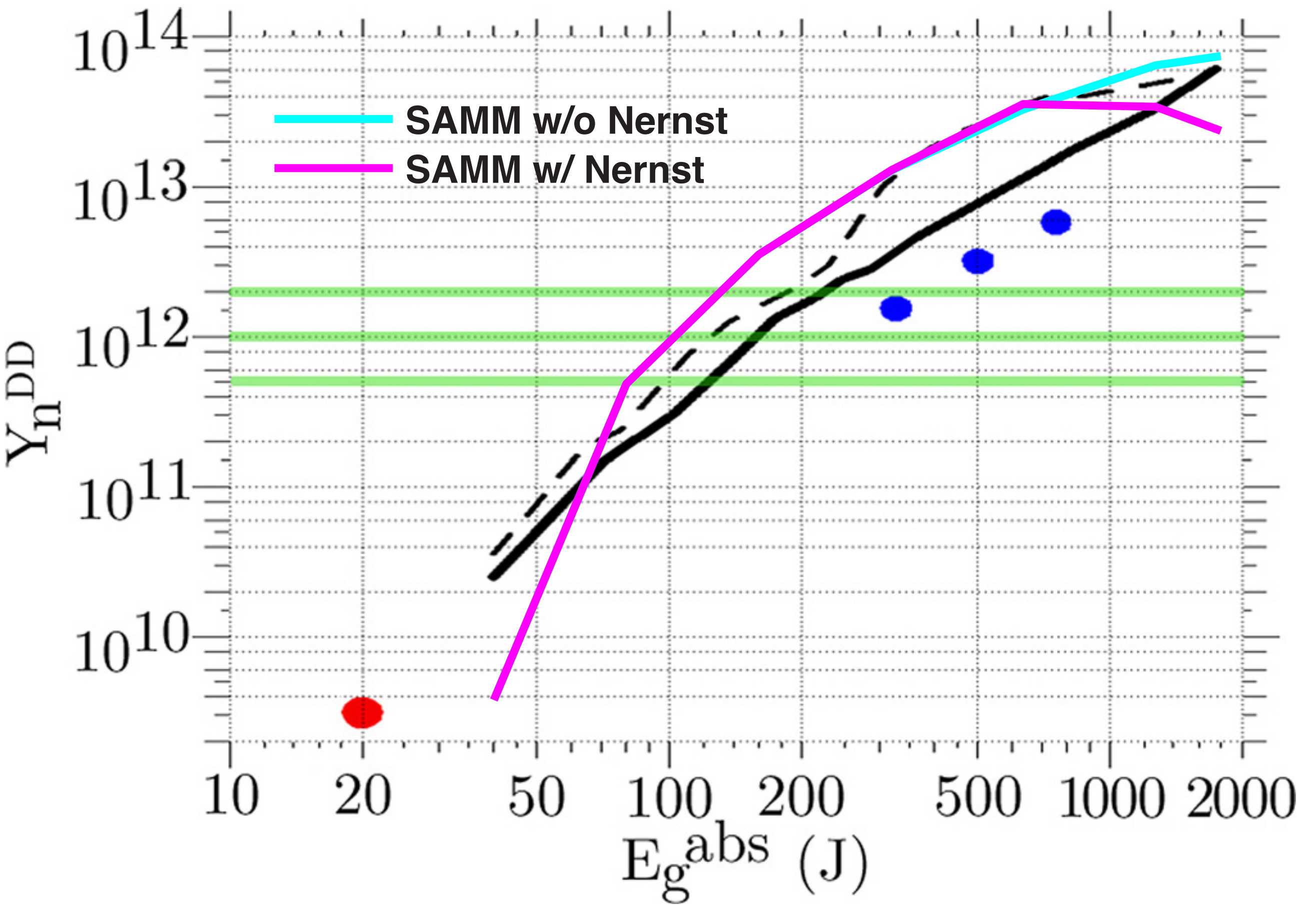
$$z_f(t) = \frac{5}{3}\frac{I_0(t-t_{laser})}{\varepsilon_0(t)}$$

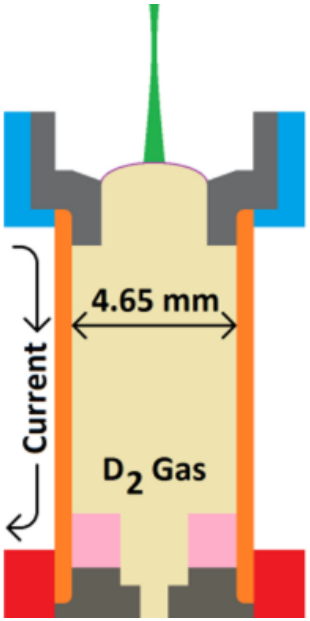
- Mass and energy end losses using simple sound speed arguments:

$$\dot{Q} = (3/4)^4 \int_0^{r_H} \rho_Q(r) \cdot c_s(r) \cdot 2\pi r \cdot dr$$

$$r_H = \min(r_{LEH}, r_g)$$

SAMM provides some reasonable guidance for present MagLIF experiments:



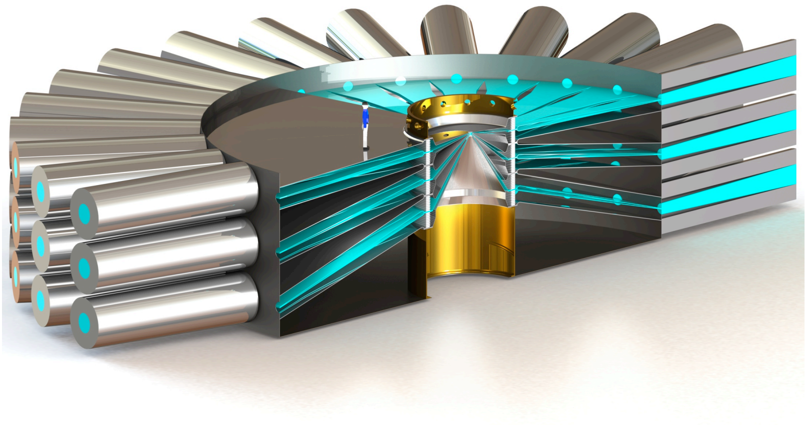


<u>HYDRA Simulations by A. B. Sefkow – For more details, see:</u>

- A. B. Sefkow *et al.*, Phys. Plasmas **21**, 072711 (2014).
- M. R. Gomez *et al.*, Phys. Rev. Lett. (submitted).
- Talk by M. R. Gomez, Session 4, at 8:30 AM

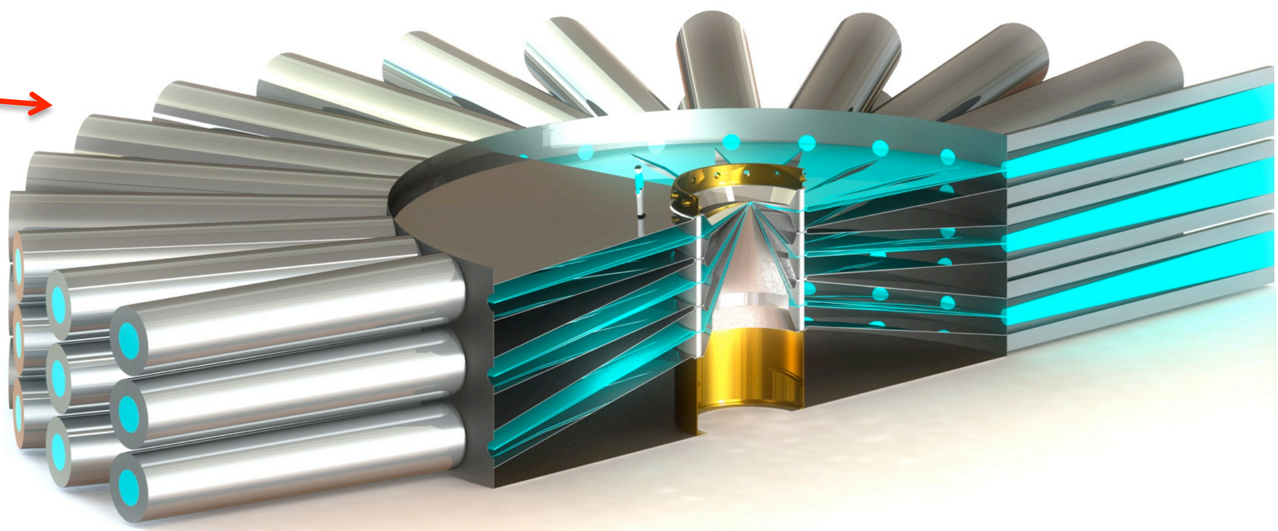
MagLIF Scans for Z300 & Z800:

See talk by W. A. Stygar, Session 6, at 2:30 PM

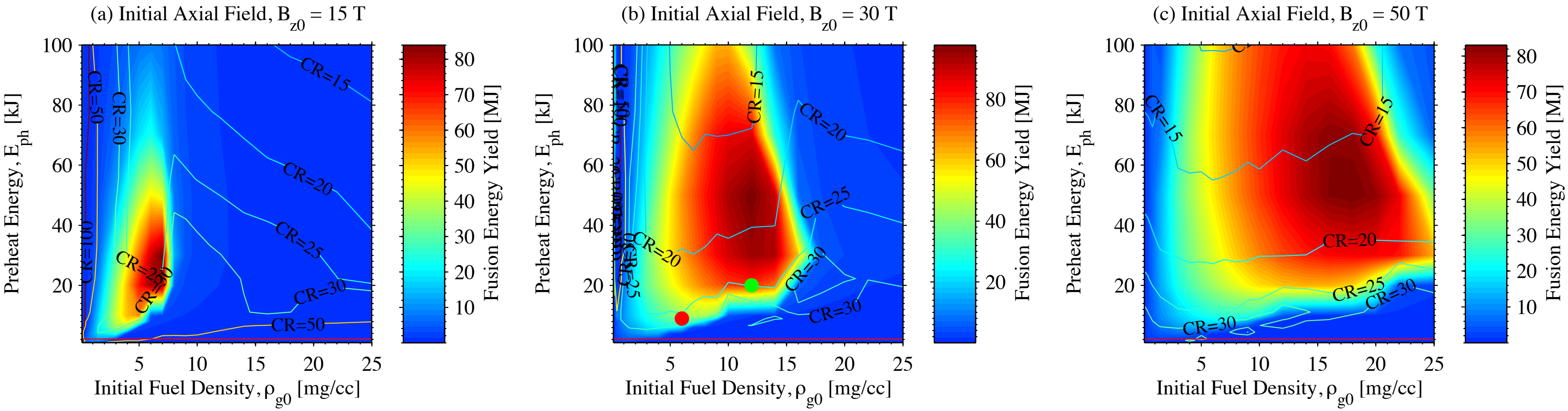


Z300:
- 300 TW delivered
- 47 MJ stored
- 49 MA
- 130 ns rise
- 35 m in diameter (size of Z today)

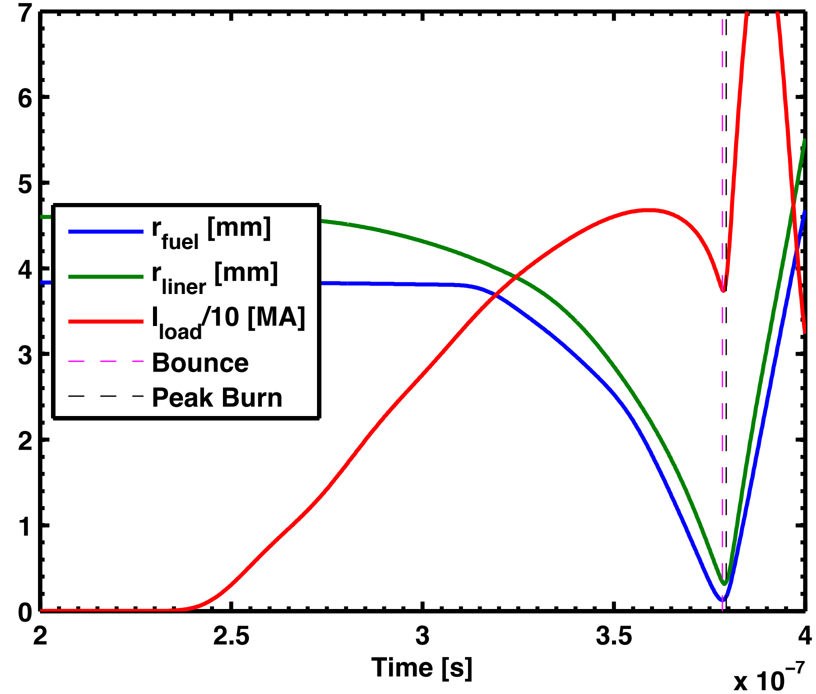
Z800:
- 870 TW delivered
- 130 MJ stored
- 64 MA
- 120 ns rise
- 55 m in diameter



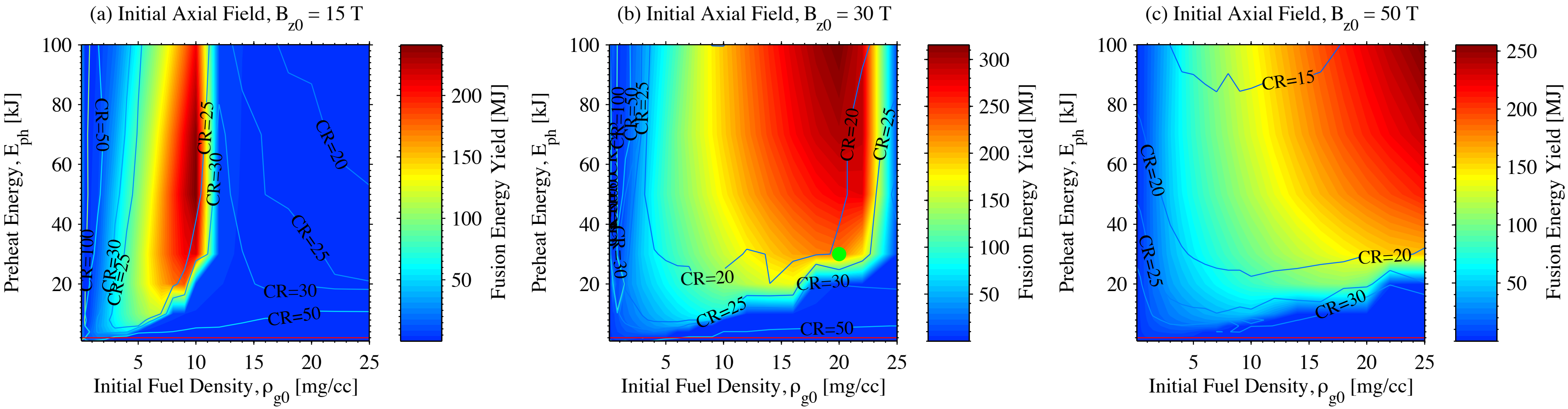
MagLIF Scans for Z300:



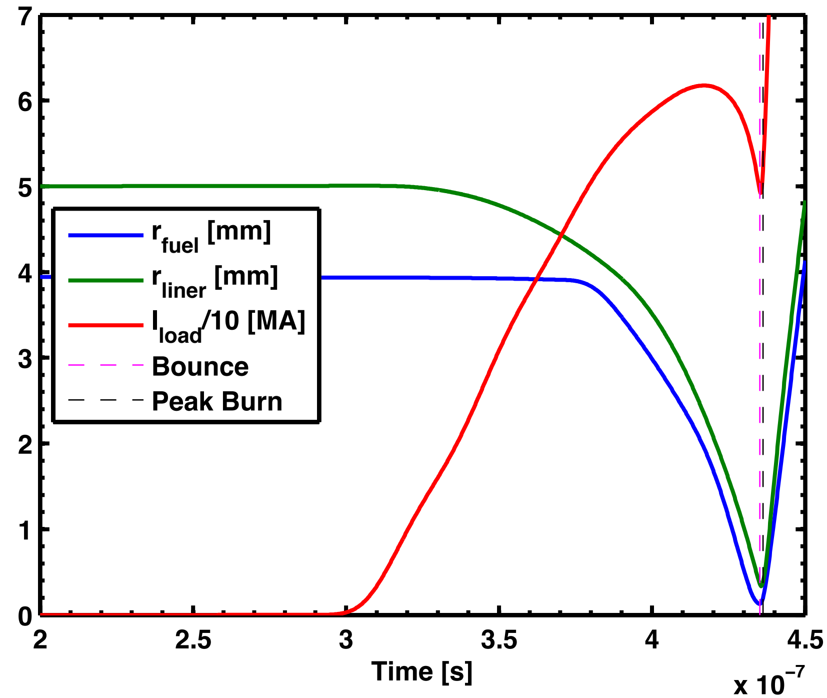
- 47 MJ stored in Z300
- 5.1 MJ absorbed by target
- 38.2 MJ fusion energy (w/ 9 kJ preheat)
- 77.7 MJ fusion energy (w/ 20 kJ preheat)
- CR~23–32
- B_{z0} = 30 T



MagLIF Scans for Z800:



- 130 MJ stored in Z800
- 9.8 MJ absorbed by target
- 221.9 MJ fusion energy (w/ 30 kJ preheat)
- CR~20–31
- B_{z0} = 30 T



Summary & Conclusions

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- The development of this semi-analytic model has been a fun, 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., uniformly from r=0 to $r=r_g/2$) 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 (we have now developed an analytic solution to this problem in the model)
  - 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
  - Discretized liners are required to obtain reasonable convergence ratios
  - 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~~ ~4 kJ to ~6 kJ and beyond, assuming that we can couple the laser energy to the fuel!
- This model's accessible physics and fast run times (~20 seconds/simulation unoptimized) 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

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

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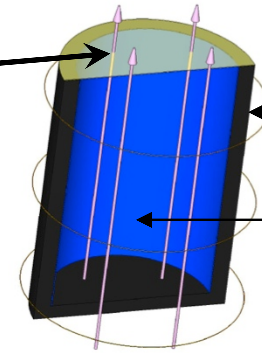
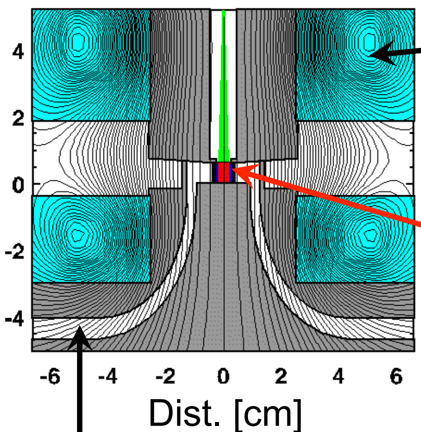
1. A 10–50 T axial magnetic field (B_z) is applied to inhibit thermal conduction losses and to enhance alpha particle deposition

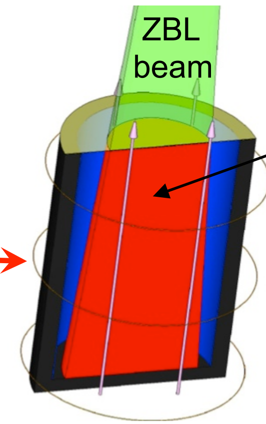




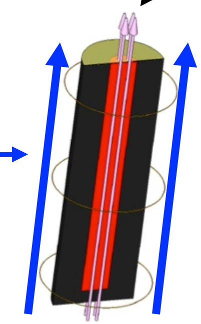
B_z coils

Z power flow (A-K gap)

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



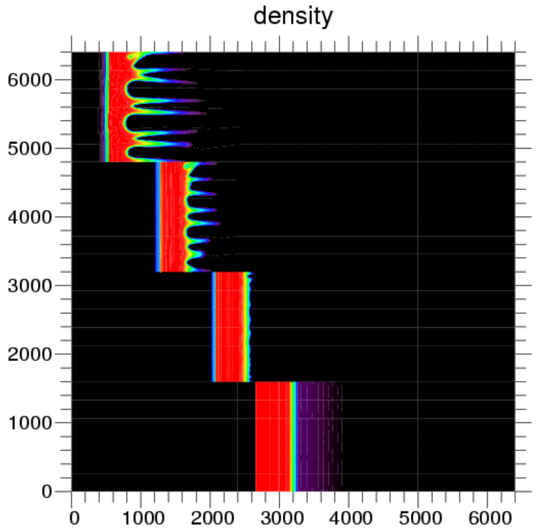
3. Z drive current and B_θ field implode the liner (via z-pinch) at 50–100 km/s, compressing the fuel and B_z field by factors of 1000

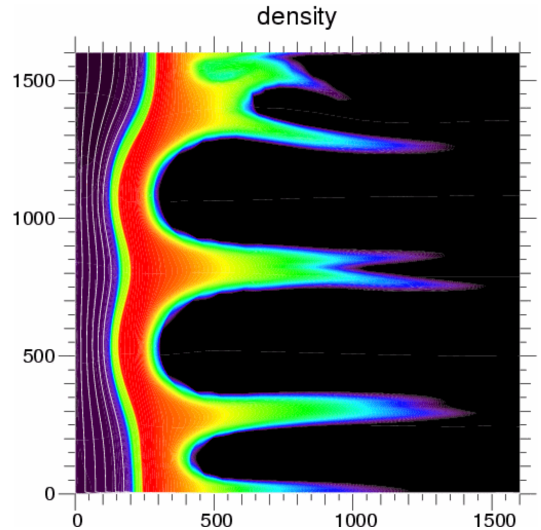


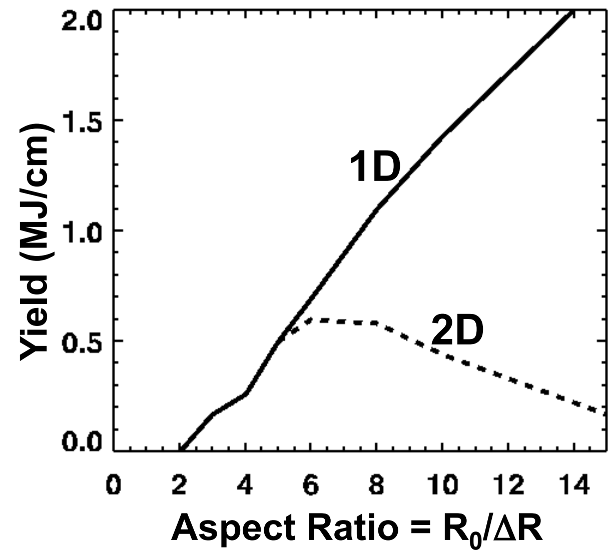
With DT fuel, simulations indicate scientific breakeven may be possible on Z (fusion energy out = energy deposited in fusion fuel)

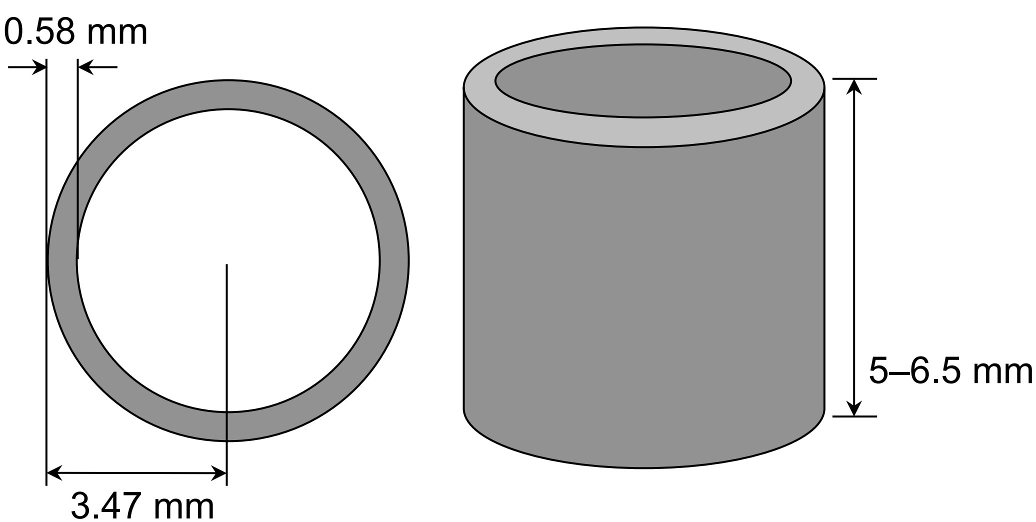
* S. A. Slutz *et al.*, PoP 17, 056303 (2010). S. A. Slutz and R. A. Vesey, PRL 108, 025003 (2012).

1D & 2D simulations of MagLIF suggest 1D-like behavior up to an aspect ratio of 6*









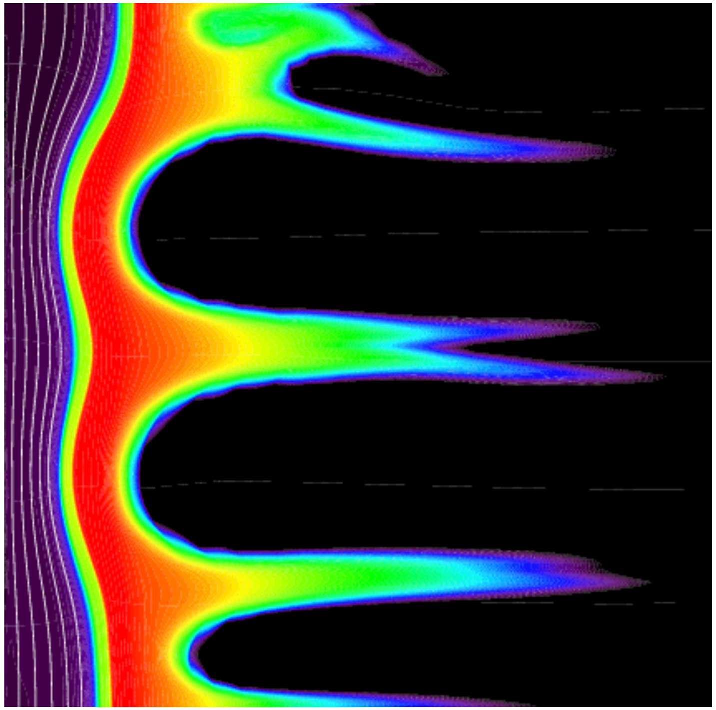
$$\mathrm{AR} \equiv \frac{R_{outer,0}}{\Delta R_0}$$

Thus, we restrict the range of validity of our 1D semi-analytic model to liners with AR ≤ 6

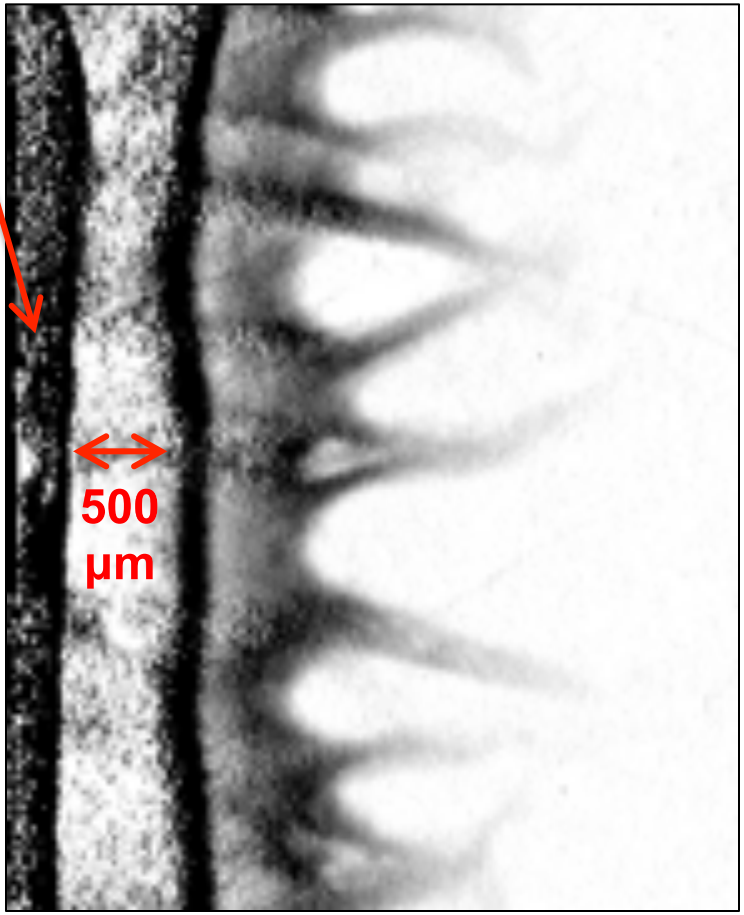
* S. A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).

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

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).

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

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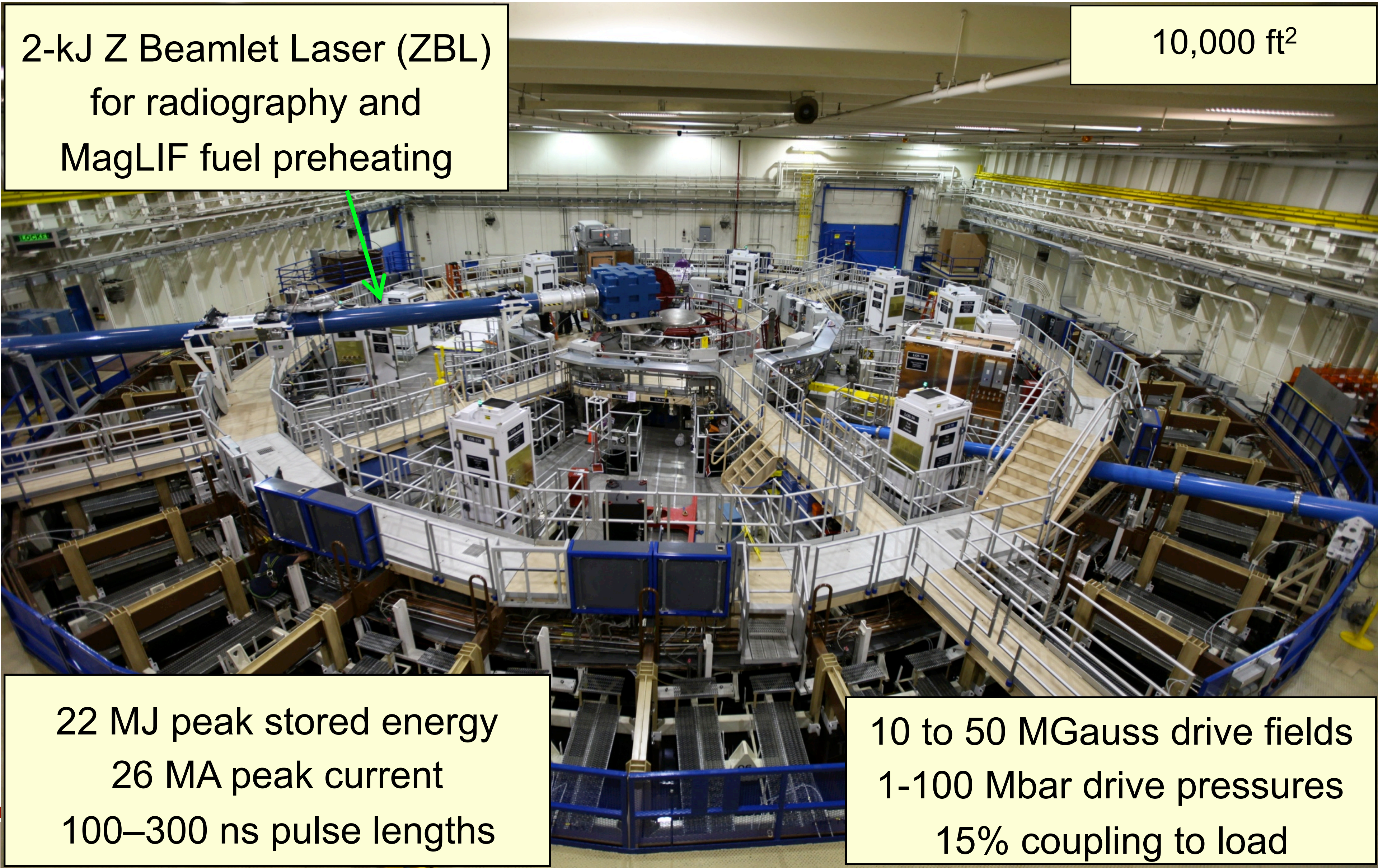
2-kJ Z Beamlet Laser (ZBL) for radiography and MagLIF fuel preheating

10,000 ft^2

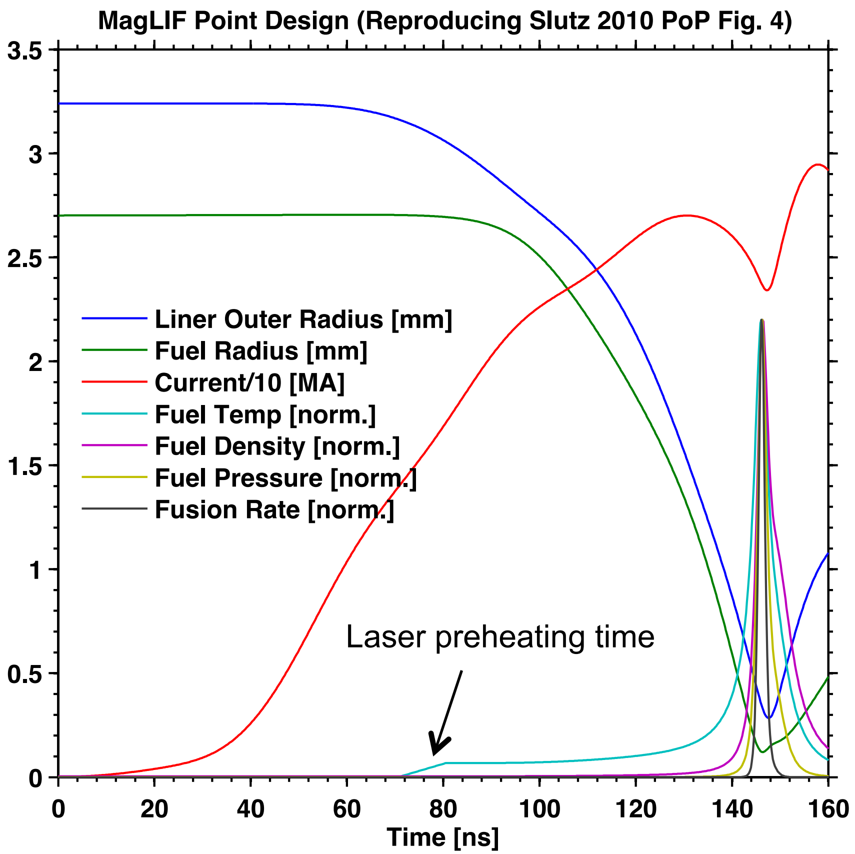


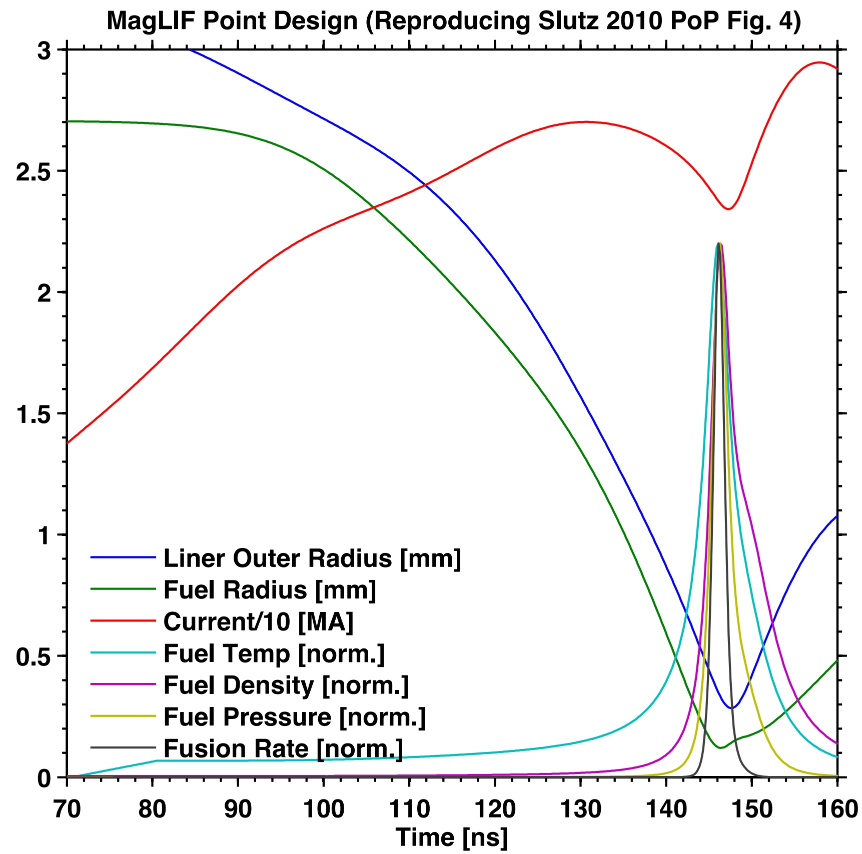
22 MJ peak stored energy
26 MA peak current
100–300 ns pulse lengths

10 to 50 MGauss drive fields
1-100 Mbar drive pressures
15% coupling to load

MagLIF Timing Overview

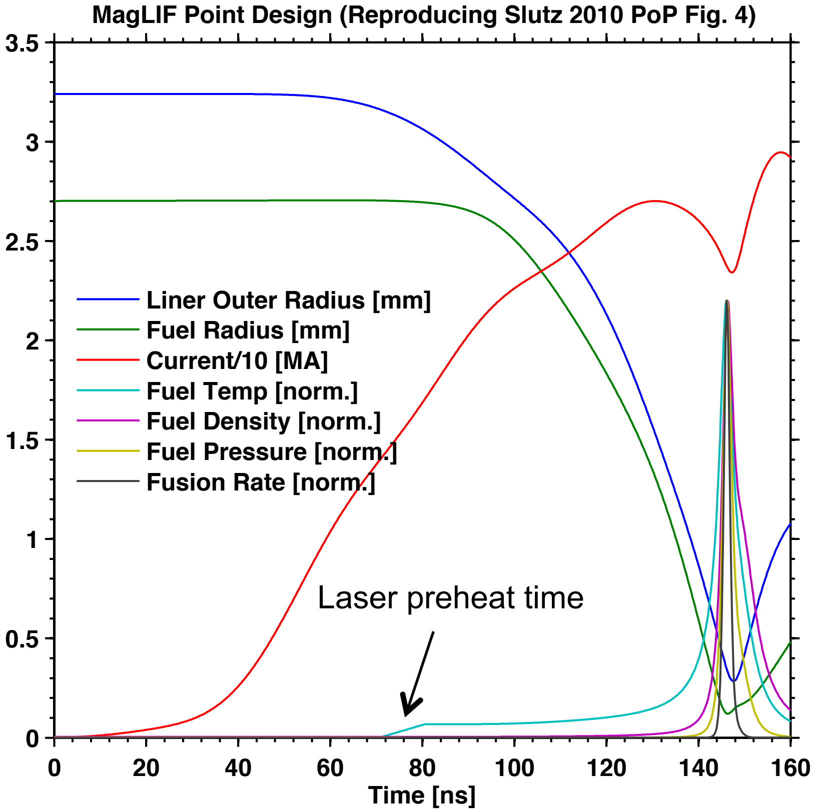
~ 100-ns implosion times
~ adiabatic fuel compression (thus preheating the fuel is necessary)
~ 5-keV fuel stagnation temperatures
~ 1-g/cc fuel stagnation densities
~ 5-Gbar fuel stagnation pressures

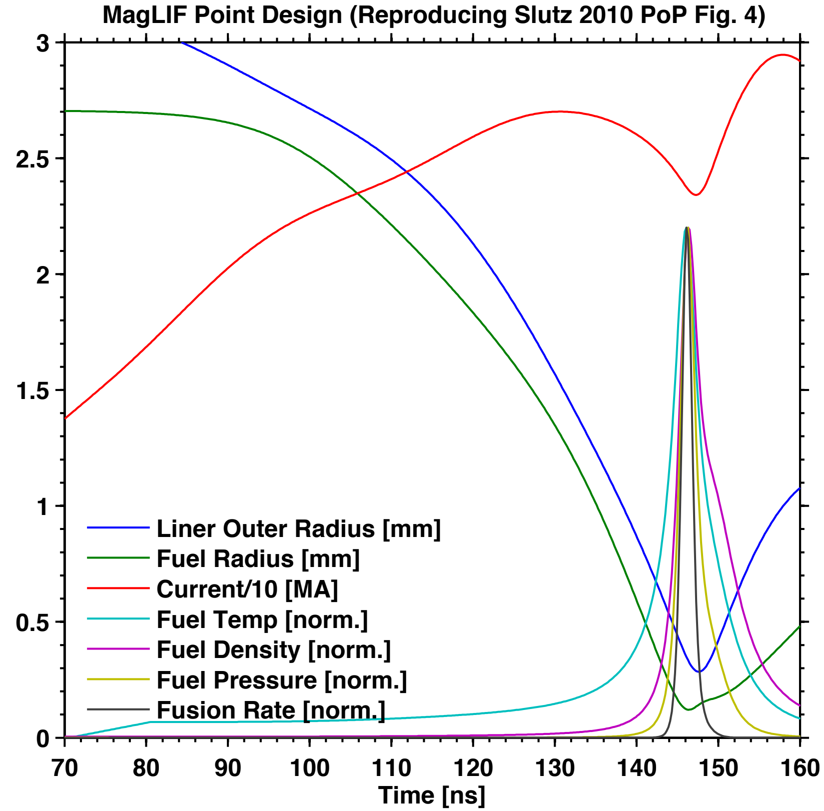




Preheat is necessary for the adiabatic compression and heating of MagLIF fuel

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





- 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