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Pulsed Power Sciences
Harnessing Extreme Environments

Exploring magnetized liner inertial fusion with a semi-analytic model*

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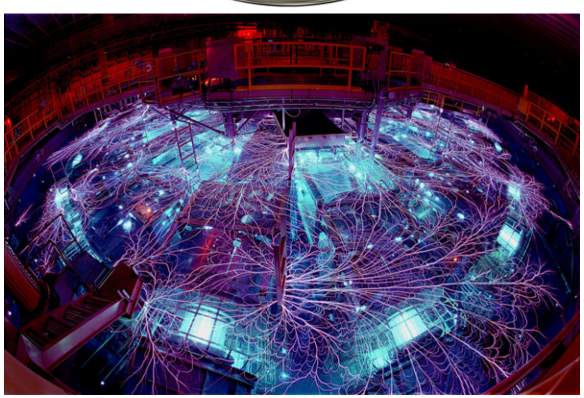

APS Division of Plasma Physics
Savannah, Georgia
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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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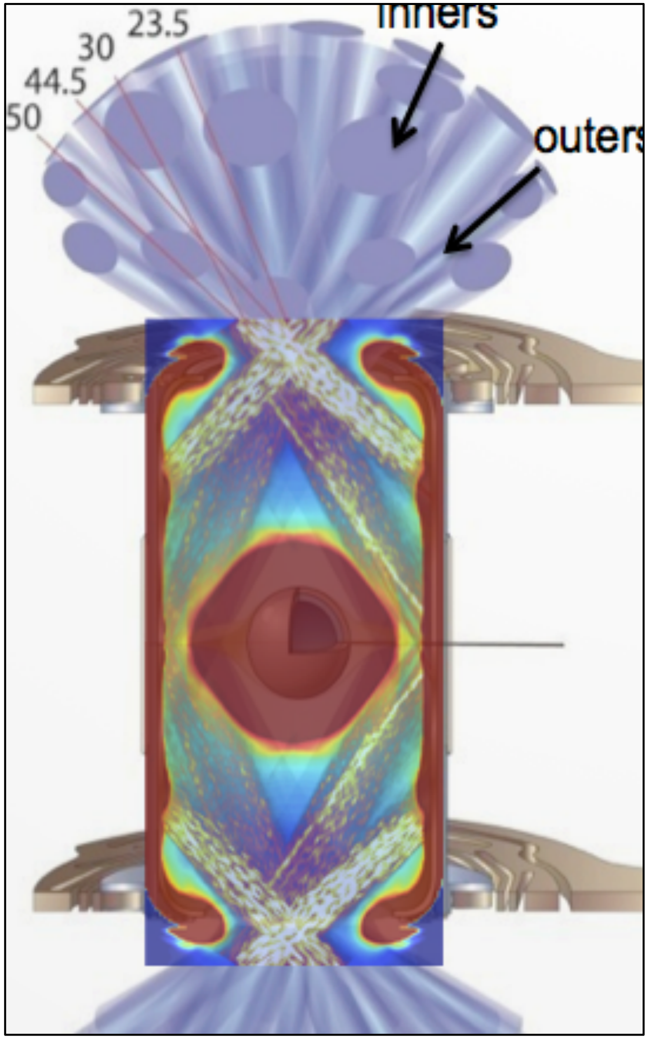
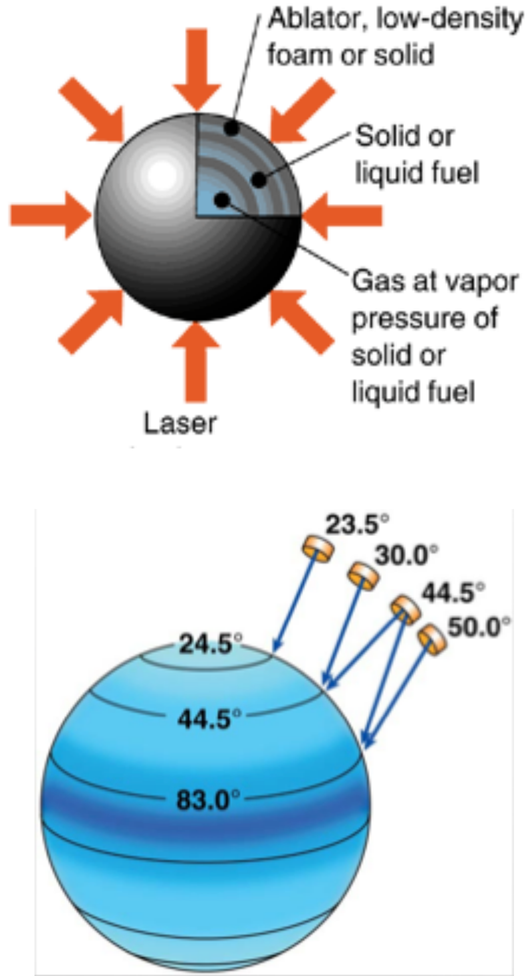
*Corresponding manuscript submitted to Physics of Plasmas (see pinup papers)

The United States ICF program is pursuing three main approaches to ignition

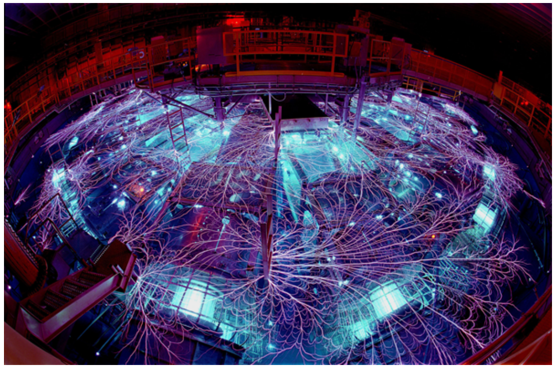
Radiation-driven implosions

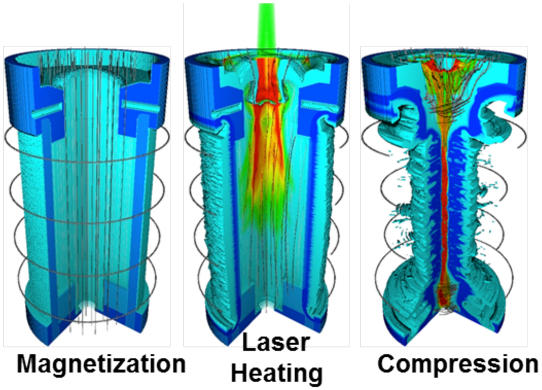


Laser-driven implosions



Magnetically-driven implosions





We are presently using the Z facility to study the Magnetized Liner Inertial Fusion (MagLIF) concept

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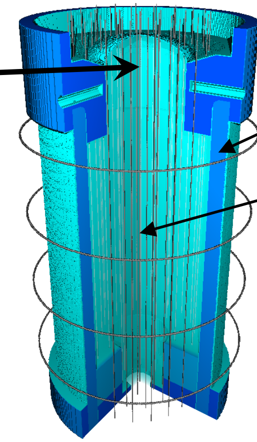
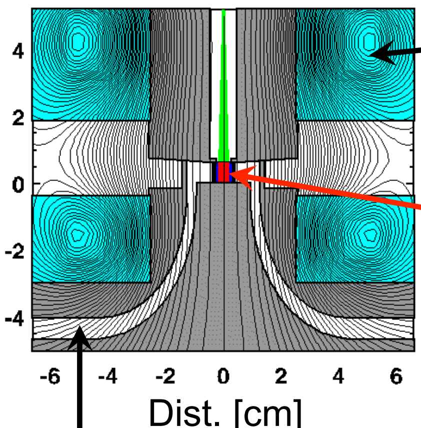
1. A 10–50 T axial magnetic field (B_z) is applied (~3-ms rise time) to inhibit thermal conduction losses and to enhance alpha particle deposition



Liner (Li, Be, or Al)

Cold DD or DT gas (fuel)

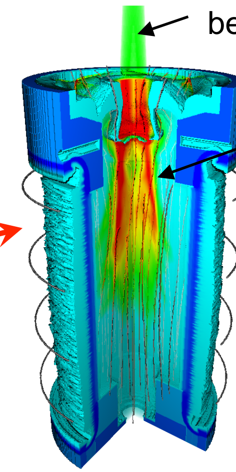


B_z coils

Z power flow (A-K gap)

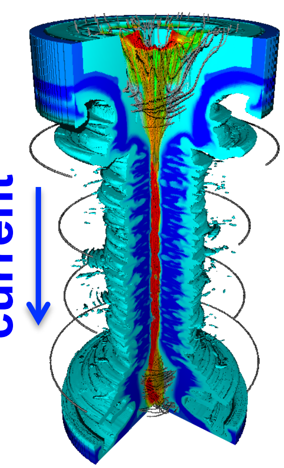
ZBL beam

ZBL preheated fuel



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

current



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).

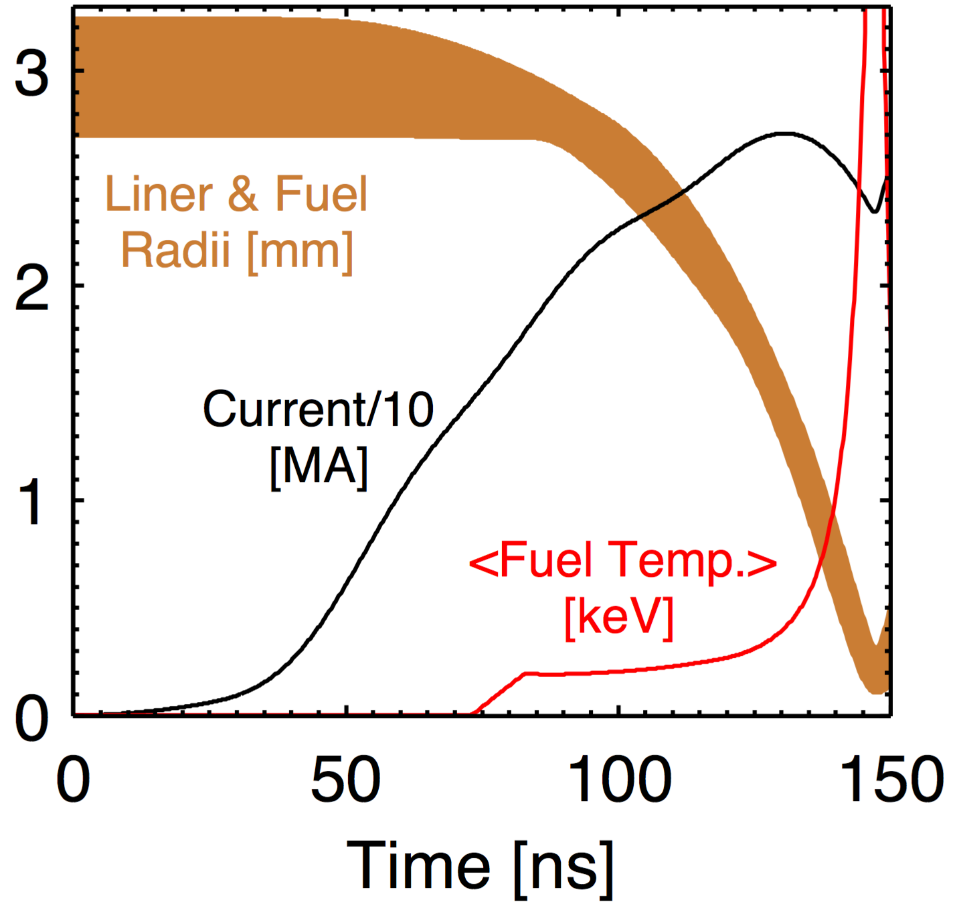
MagLIF Timing Overview

~ 60–100-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

$$T \approx T_0 \left(\frac{\rho}{\rho_0} \right) \approx T_0 C_R^{4/3}$$

$$(C_R = R_0 / R_{stagnation})$$

- 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



We have developed a semi-analytic model of MagLIF (SAMM)

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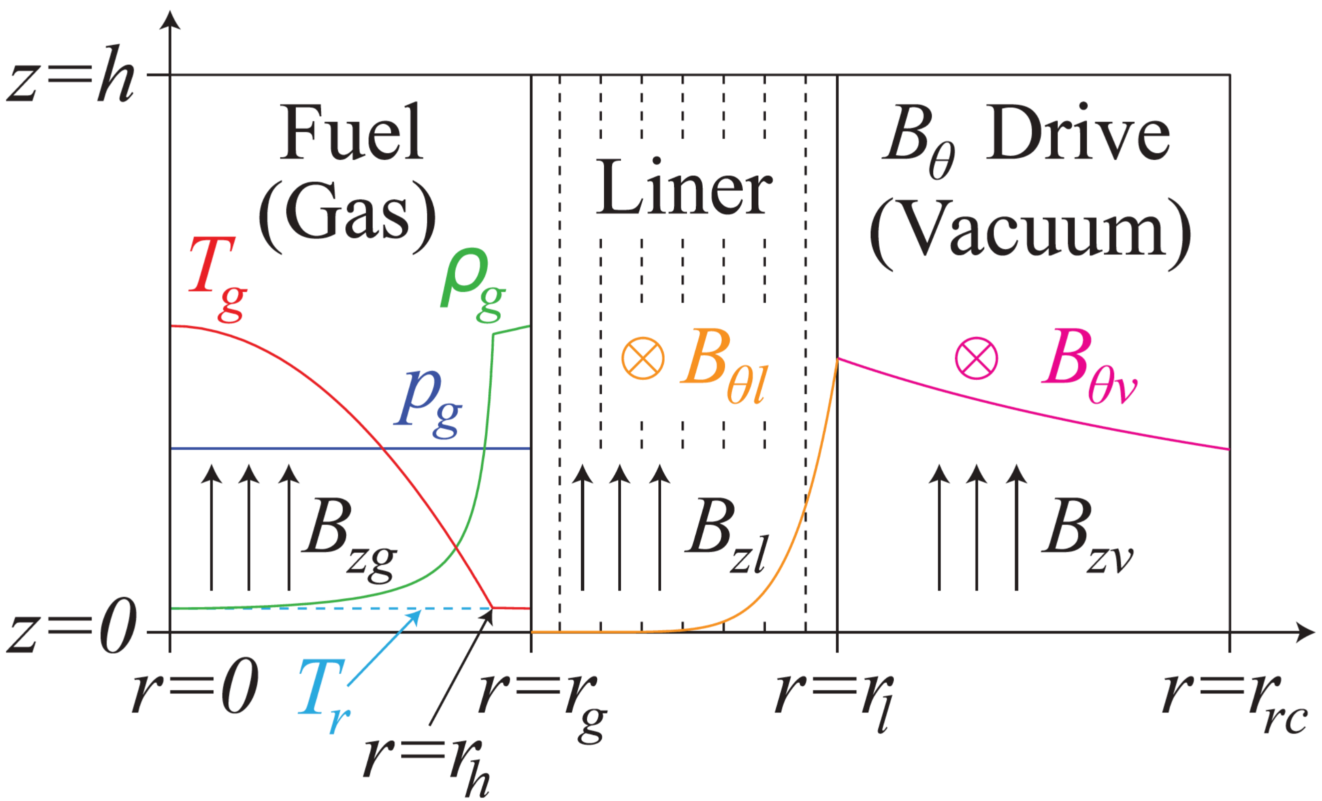
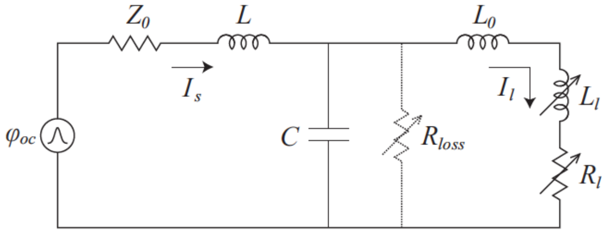
- Developed with the "interested student" in mind
- System of $2N_{ls}$+13 ordinary differential equations that are straight forward to solve with MATLAB, IDL, Mathematica, etc.
- ~30 seconds/simulation on a laptop
- ~3000 simulations in ~10 minutes using Sandia cluster (good for parameter scans)





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

$$\dot{I}_s = \frac{\varphi_{oc} - Z_0 I_s - \varphi_c}{L} \quad (1)$$

$$\dot{\varphi}_c = \frac{I_s - I_l - \varphi_c / R_{loss}}{C} \quad (2)$$

$$\dot{I}_l = \frac{\varphi_c - I_l(\dot{L}_v + \dot{L}_{lc})}{L_0 + L_v + L_{lc}} \quad (3)$$

SAMM ODEs:

Dynamics (fuel and liner)

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

$$\ddot{r}_{l,i} = \frac{p_{l,s=i-1} - p_{l,s=i}}{m_{ls}} \cdot 2\pi r_{l,i} \cdot h \quad (4)$$

$$(i = 2, 3, \ldots, N_{li} - 1)$$

$$\ddot{r}_g = \frac{p_g + p_{\bar{B}_{zg}} - p_{l,s=1}}{m_{ls}/2} \cdot 2\pi r_g \cdot h \quad (5)$$

$$\ddot{r}_l = \frac{p_{l,s=N_{ls}} - p_{B_{\theta l v}} - p_{\bar{B}_{zv}}}{m_{ls}/2} \cdot 2\pi r_l \cdot h \quad (6)$$

Energetics (fuel and liner)

- P_α = Basko
- P_r = Two-temperature grey model with emissivity & opacity integral over T & ρ profiles
- P_{ce} = Epperlein-Haines
- P_{ci} = Braginskii
- $I_l^2 R_l$ from assumed $B_\theta(r) \sim r^{\beta(\delta skin)}$ and Maxwell's equations

$$\dot{E}_{l,s} = -\left(\frac{2}{3}\frac{E_{l,s}}{V_{l,s}} + q_{l,s}\right)\dot{V}_{l,s} + \left(P_r + P_c + P_\Omega - P_{BB}\right)/N_{ls} \quad (7)$$

$$(s = 1, 2, \ldots, N_{ls})$$

$$\dot{E}_g = P_{pdV} + P_{ph} + P_\alpha - P_r - P_c - \dot{E}_{ends} \quad (8)$$

Loss of mix/dopant constituents due to end losses

$$\dot{N}_{mix} = -\sum_{s \neq d,t} \dot{N}_{s,ends} \quad (9)$$

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

$$\dot{\Phi}_{zg} = \left[-2\pi r \cdot \mathcal{F}(x_e) \cdot \frac{k}{q_e}\frac{\partial T_g}{\partial r}\right]_{r=r_g} \quad (10)$$

Ablative transfer rate for cold, dense shelf mass to hotspot mass

$$\dot{f}_{mh} = \dot{m}_{s \to h}/m_g \quad (11)$$

DT & DD fusion burn: analytic $\langle\sigma\upsilon\rangle$ (Bosch & Hale)

$$\dot{N}_{dt} = h \int_0^{r_g} n_d n_t \langle\sigma v\rangle_{dt} \cdot 2\pi r \cdot dr \quad (12)$$

$$\dot{N}_{dd,^3\mathrm{He}} = \frac{h}{2}\int_0^{r_g} n_d^2 \langle\sigma v\rangle_{dd,^3\mathrm{He}} \cdot 2\pi r \cdot dr \quad (13)$$

$$\dot{N}_{dd,t} = \frac{h}{2}\int_0^{r_g} n_d^2 \langle\sigma v\rangle_{dd,t} \cdot 2\pi r \cdot dr \quad (14)$$

Fuel loss due to fusion burn and end losses

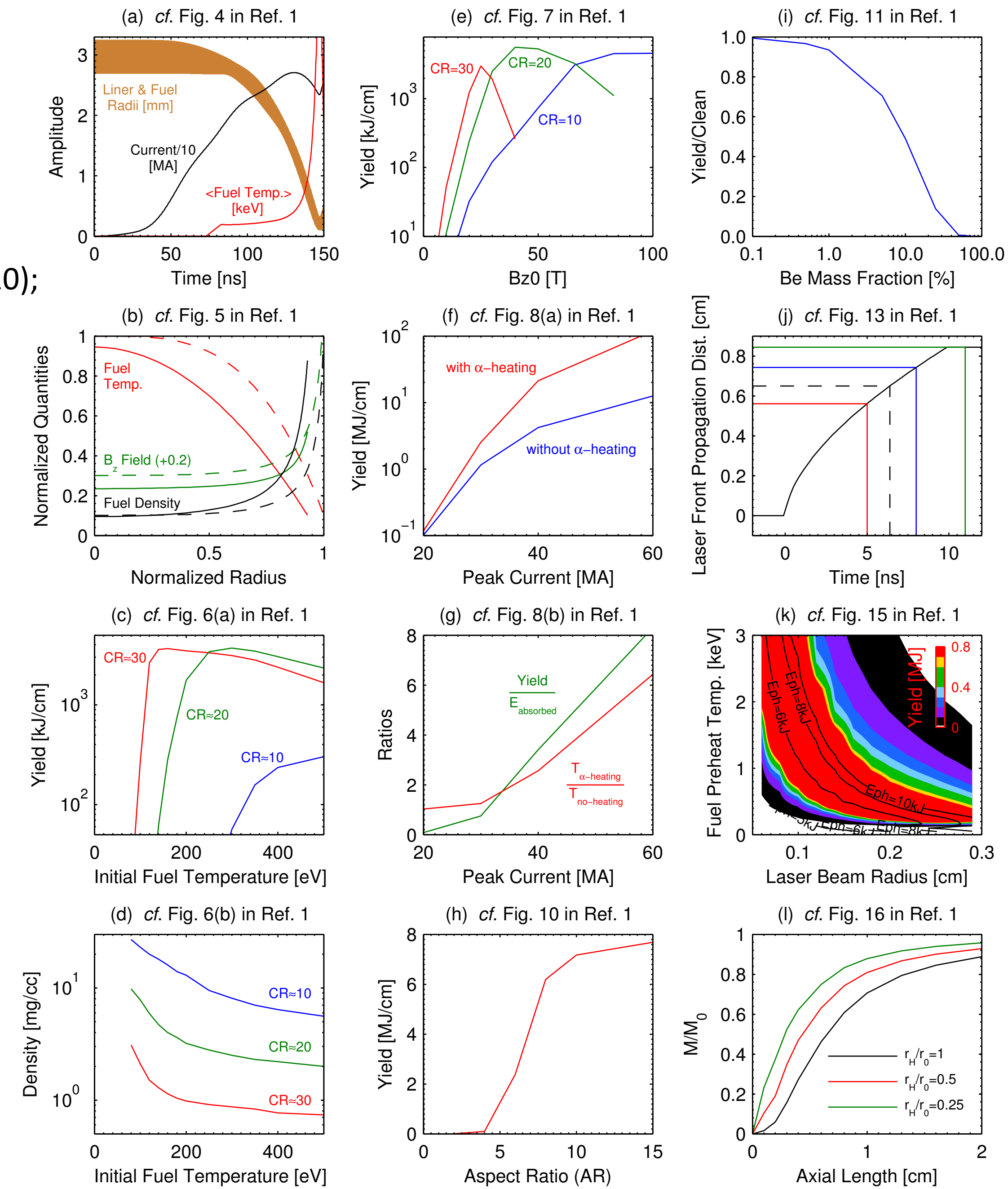
$$\dot{N}_d = -\dot{N}_{dt} - 2\dot{N}_{dd,^3He} - 2\dot{N}_{dd,t} - \dot{N}_{d,ends} \quad (15)$$

$$\dot{N}_t = -\dot{N}_{dt} - \dot{N}_{t,ends}. \quad (16)$$

R. D. McBride and S. A. Slutz, Phys. Plasmas **22**, 052708 (2015).

SAMM Verification:

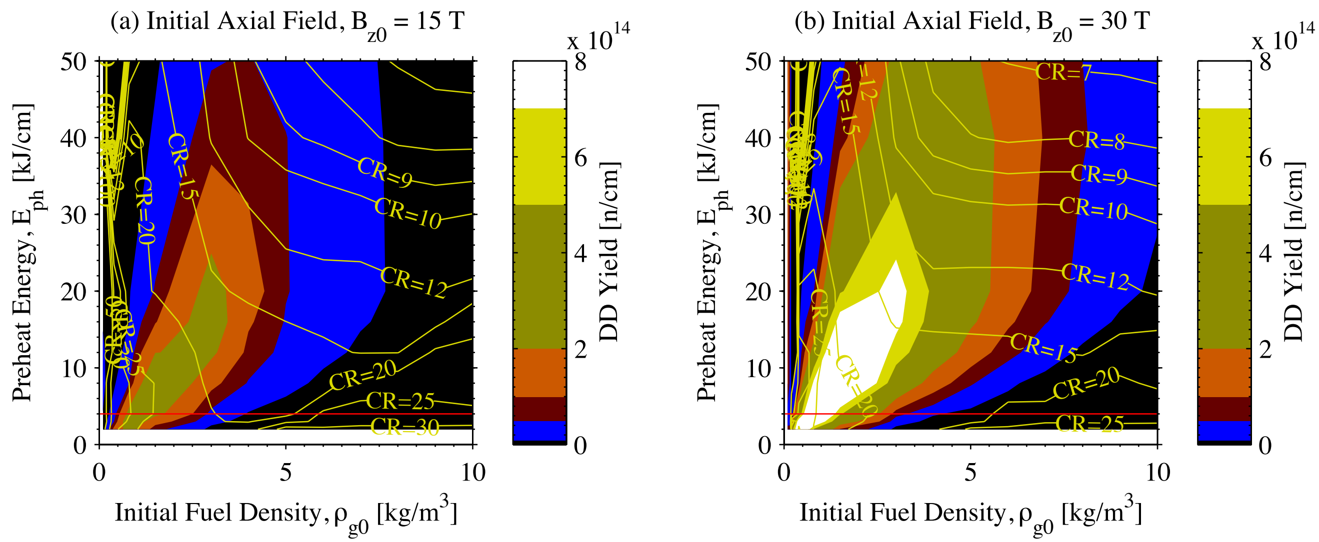
Ref. 1 in this figure is:
S. A. Slutz *et al.*, Phys. Plasmas **17**, 056303 (2010);
(see pinup papers).



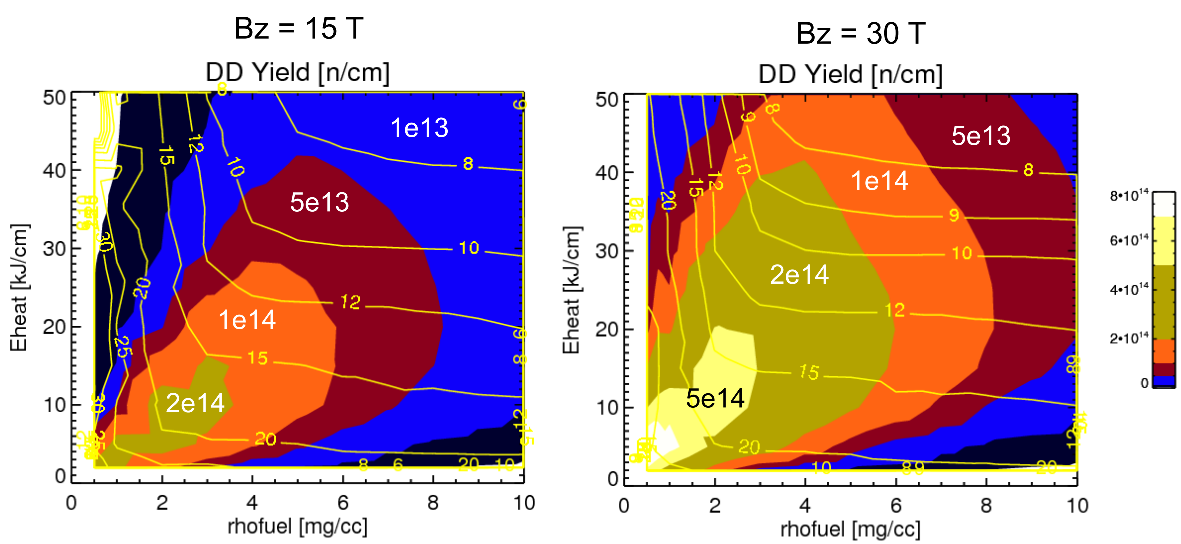
R. D. McBride and S. A. Slutz, Phys. Plasmas **22**, 052708 (2015).

SAMM Verification:

SAMM



Rad-MHD



(Rad-MHD contour plots courtesy of R. A. Vesey)

"2010 Point Design" Efficiencies:

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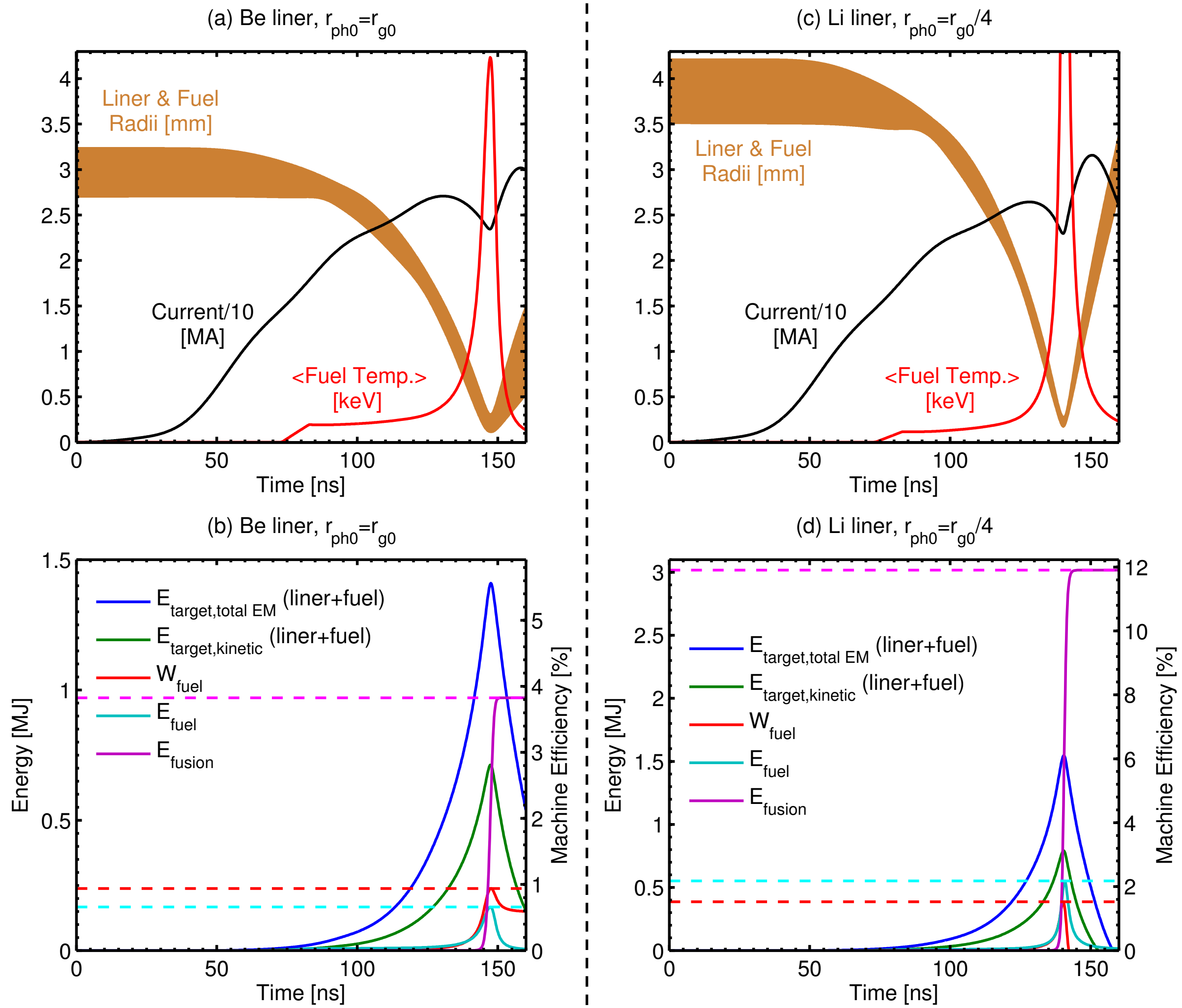
"2010 Point Design" is that described in S. A. Slutz *et al.*, Phys. Plasmas **17**, 056303 (2010).

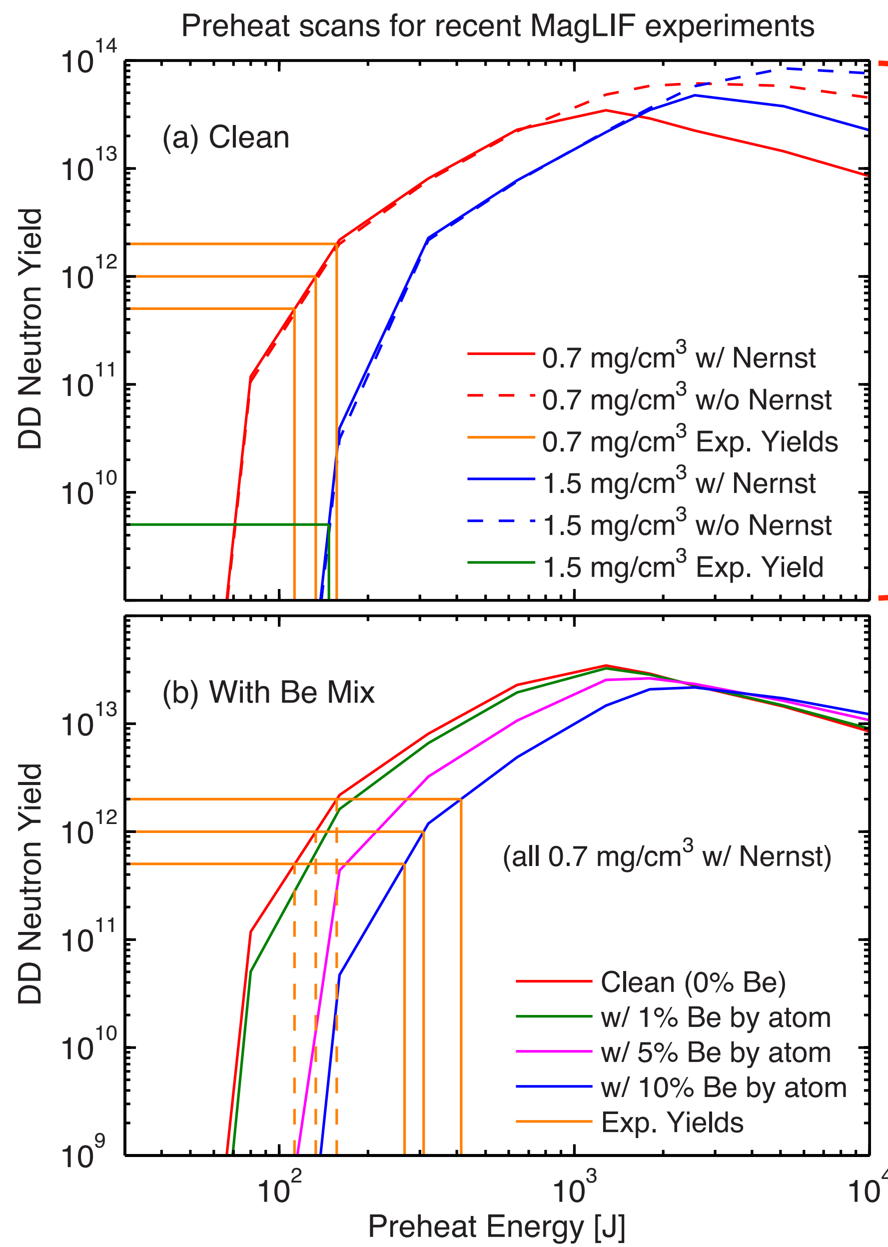
2010 Point Design:
DT fuel, 8 kJ preheat, 30 T, 27 MA, and 95-kV Marx Charge (~25 MJ stored)

Modified 2010 Point Design:
Li liner and $r_{ph0}=r_{g0}/4$



2014 Experiments:

- 2014 Experiments are those described in M. R. Gomez *et al.*, Phys. Rev. Lett., **113**, 155003 (2014).
- DD Fuel, 10 T, 2-kJ laser, 18 MA, and 80-kV Marx charge (~18 MJ stored)
- Inferred laser-coupled preheat energy is low (~150 J), but is dependent on assumed level of uniform contaminant mix
- With 10% Be mix by atom (consistent with that inferred spectroscopically), preheat energy could be ~400 J
  - Thus, with ~100 J absorbed in the laser entrance channel above the imploding region, ~500 J could have been transmitted past the laser entrance window, in agreement with laser-only foil-transmission experiments
- Nernst thermoelectric effect may not be relevant until we can increase the coupled preheat energy



Similar to A. B. Sefkow *et al.*, Phys. Plasmas **21**, 072711 (2014).

2014 Experiments:

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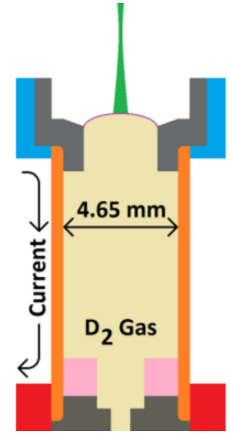
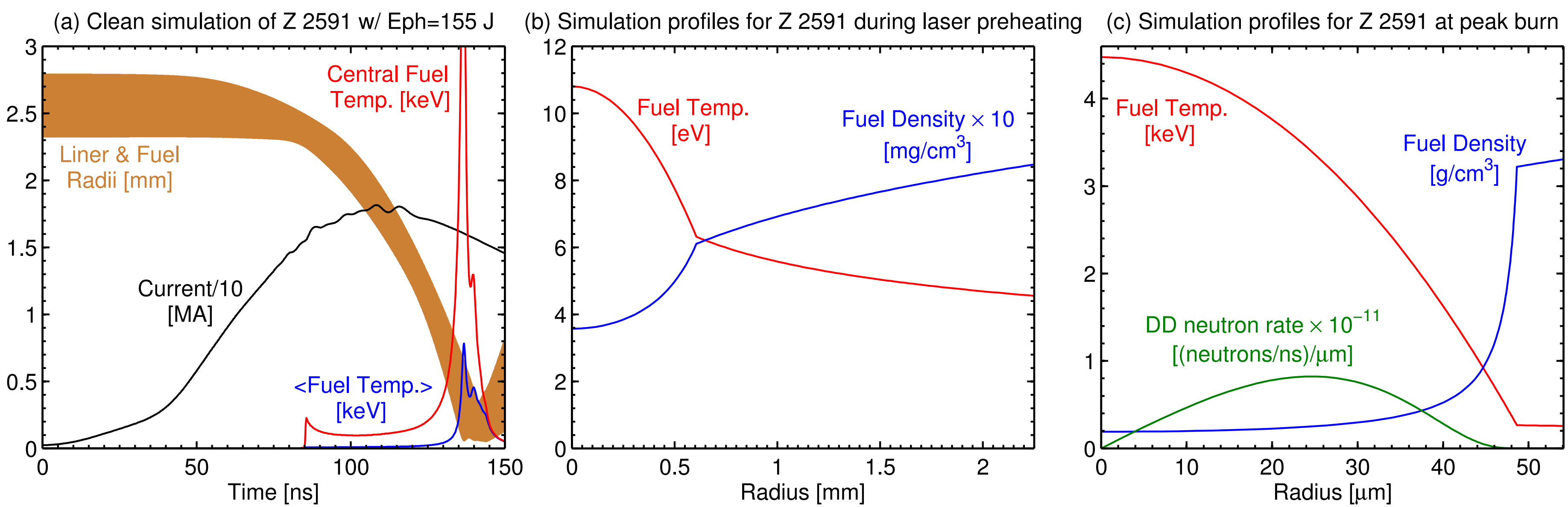
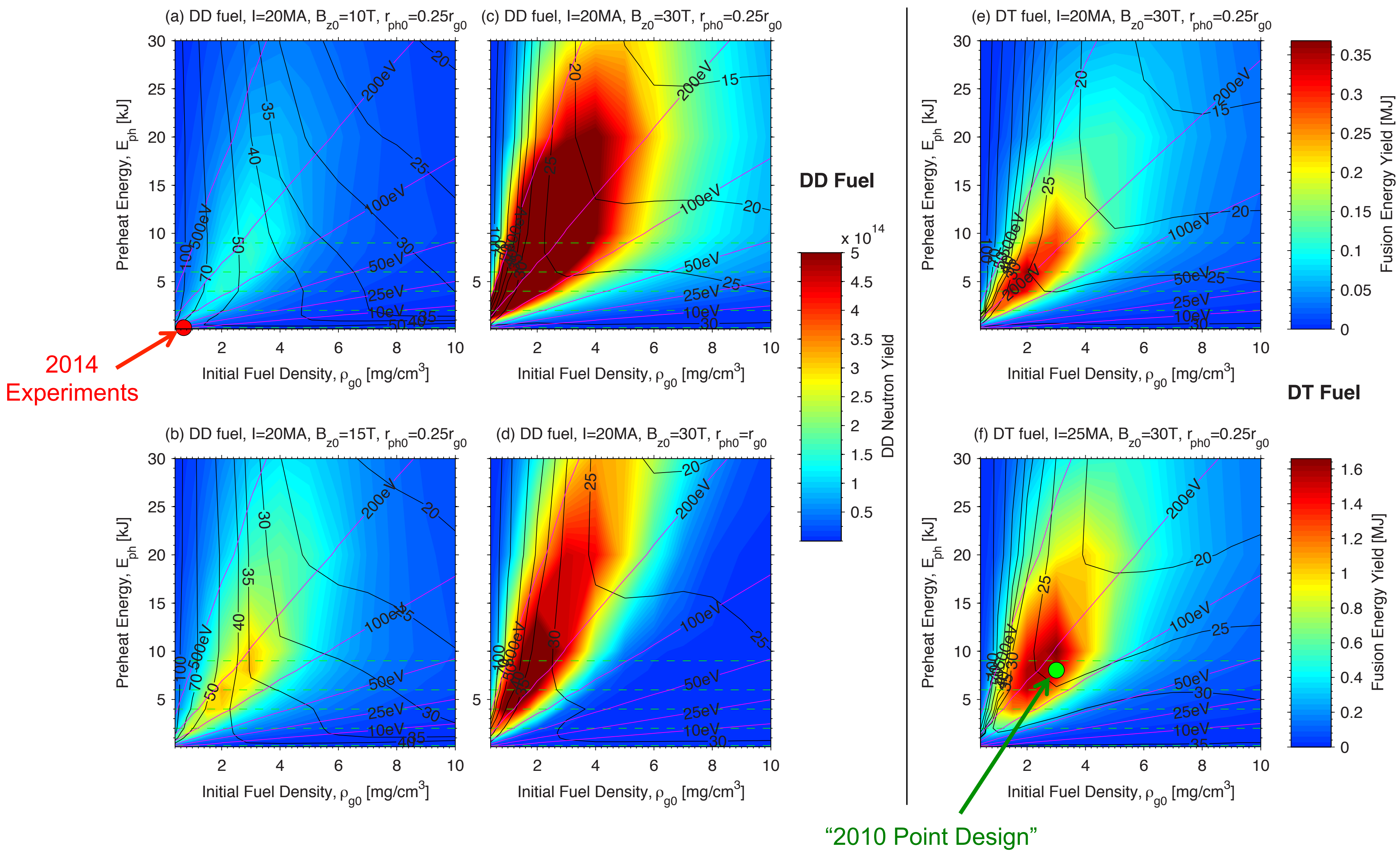


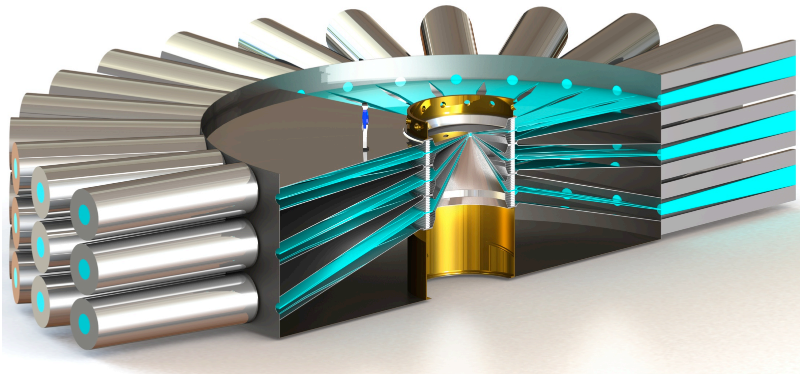
- DD Fuel, 10 T, 2-kJ laser, 18 MA, 2 x 10^{12} DD neutrons:
  - 155 J of preheat energy, clean
  - 396 J of preheat with 10% Be mix (by atom)
- $r_{ph0} < r_g(t_{ph})$ results in a fuel structure with two regions:
  - A hotspot region with fusion-relevant temperatures at stagnation
  - A cold dense shelf region that surrounds the hotspot and provides a buffer region between the hot fuel and the liner, which reduces radiative, thermal conduction, and magnetic flux losses from the fuel to the liner



Near-term MagLIF parameter space:



MagLIF Scans for Z300 & Z800:



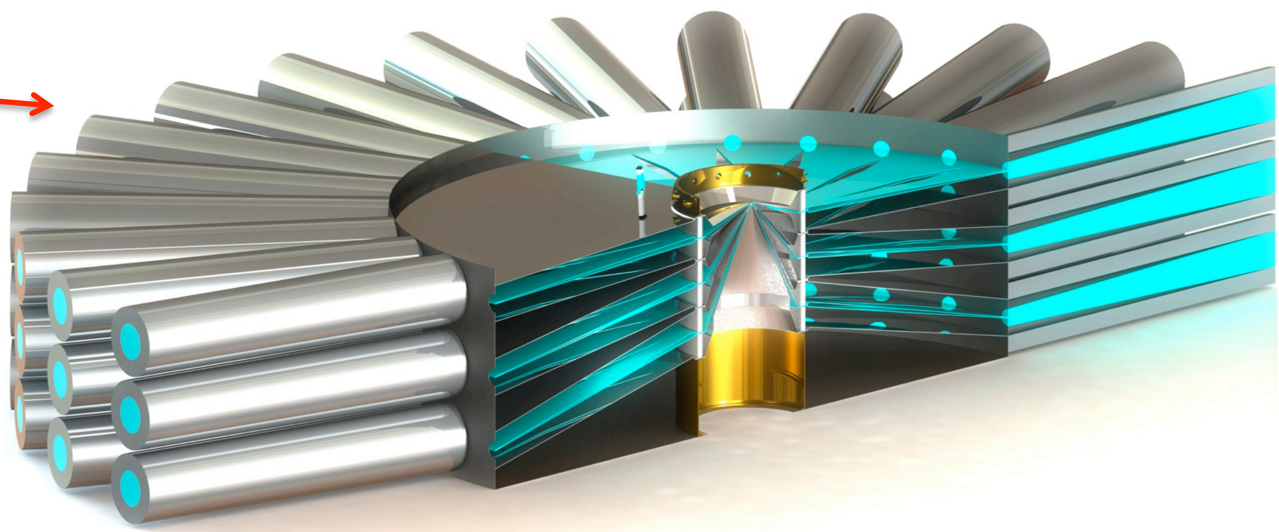
LTD-based architectures

Z300:

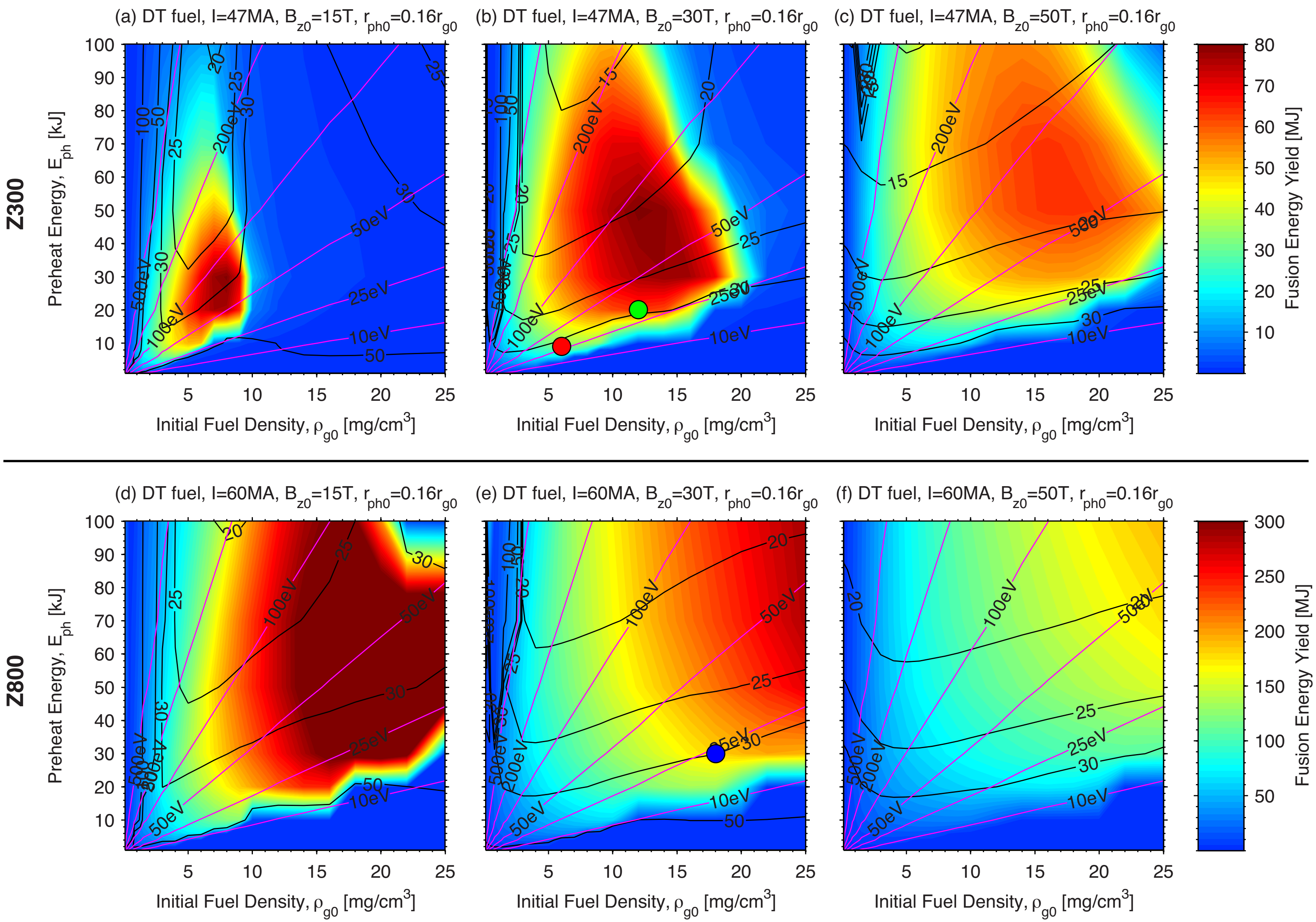
- 320 TW delivered
- 48 MJ stored
- 48 MA
- 120–150 ns rise
- 35 m in diameter (size of Z today)

Z800:

- 890 TW delivered
- 130 MJ stored
- 60–65 MA
- 110–120 ns rise
- 52 m in diameter



MagLIF Scans for Z300 & Z800:

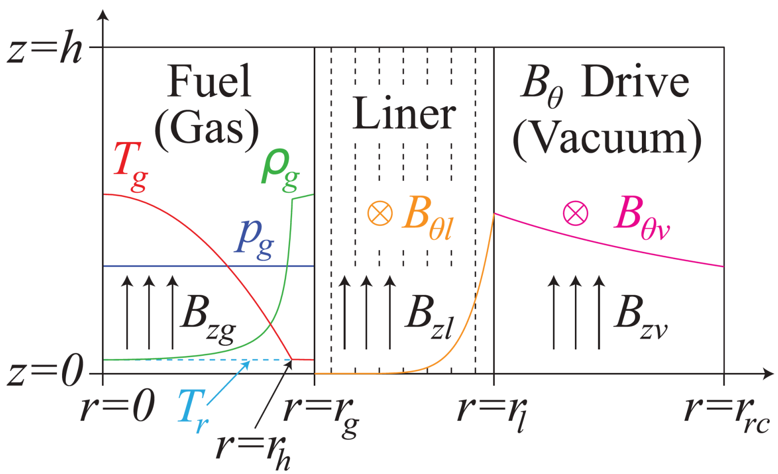


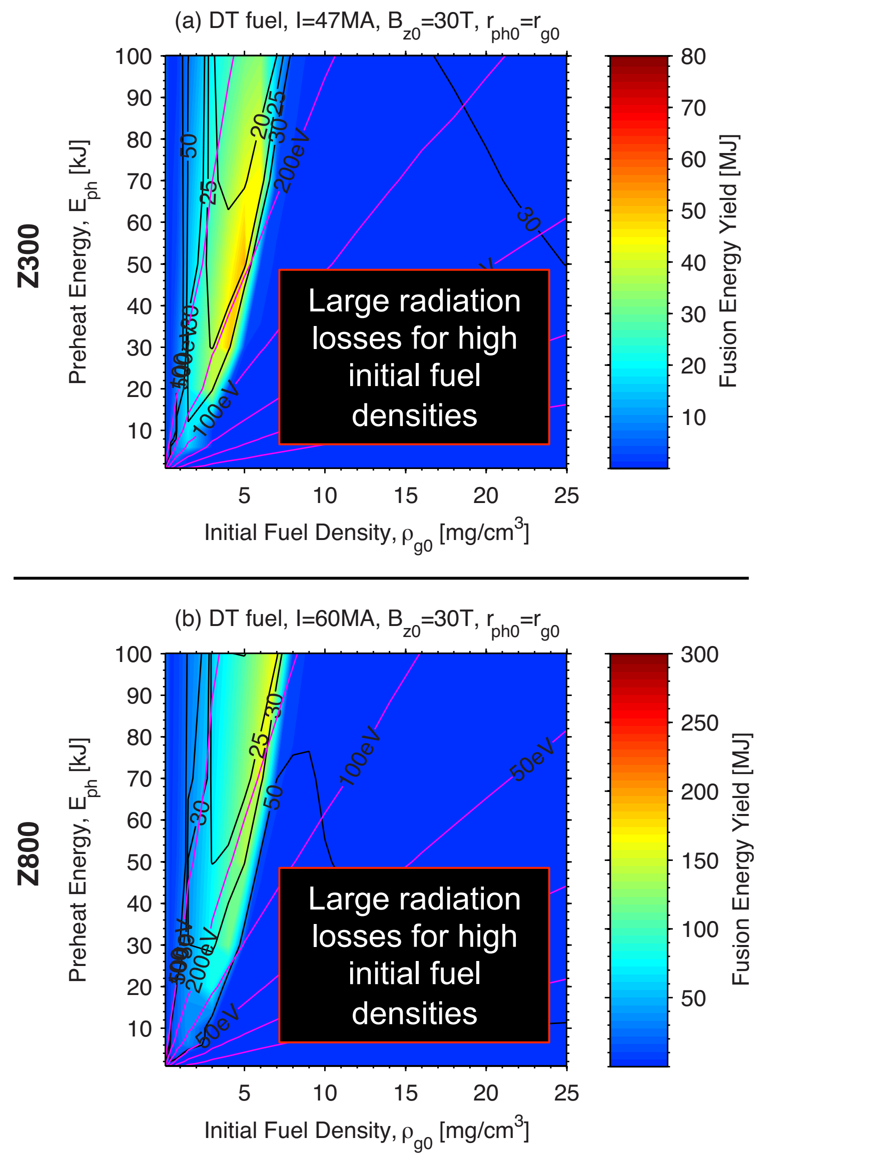
MagLIF Scans for Z300 & Z800:

Particularly for large drive currents, setting $r_{ph0}=r_{g0}$ is <u>not optimal</u> due to increased radiative losses:

$$P_{rv}(r) = A_{br} \cdot 2\pi h \cdot \bar{Z}_g^2 \int_0^r n_i n_e \sqrt{T_g} \left[1 - \left(\frac{T_r}{T_g}\right)^4\right] r' dr'$$

$$P_{rs}(r) = (1-\alpha_s)\sigma T_r^4(r) \cdot 2\pi r \cdot h$$





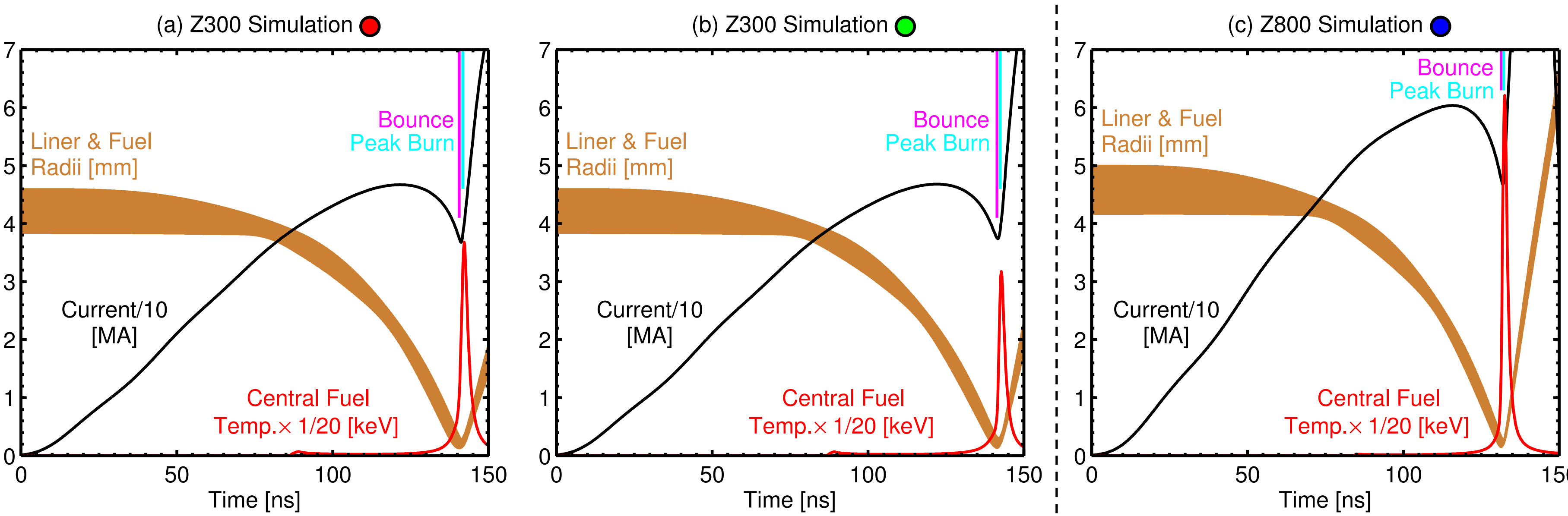
MagLIF Scans for Z300 & Z800:

Z300:

- 48 MJ stored
- 4.3 MJ absorbed by target
- 38 MJ fusion energy (w/ 9 kJ preheat)
- 77 MJ fusion energy (w/ 20 kJ preheat)
- CR~23–32
- B_{z0} = 30 T
- LTD-based architecture with footprint the size of Z today

Z800:

- 130 MJ stored
- 8.2 MJ absorbed by target
- 218 MJ fusion energy (w/ 30 kJ preheat)
- CR~23–30
- B_{z0} = 30 T



Summary & Conclusions

- The development and use of this semi-analytic model has been a fun, useful, and insightful exercise
  - Led to several physical insights, including the relationship between the preheat radius and bremsstrahlung loss rates
- This model's accessible physics and fast run times (~30 seconds/simulation unoptimized) make it a useful pedagogical tool, especially for students, experimentalists, or any researcher interested in MagLIF
- For more details on this model and its uses, see manuscripts (and pinups):
  - R. D. McBride and S. A. Slutz, "A semi-analytic model of magnetized liner inertial fusion", Phys. Plasmas **22**, 052708 (2015).
  - R. D. McBride *et al.*, "Exploring magnetized liner inertial fusion with a semi-analytic model", submitted to Phys. Plasmas (2015).