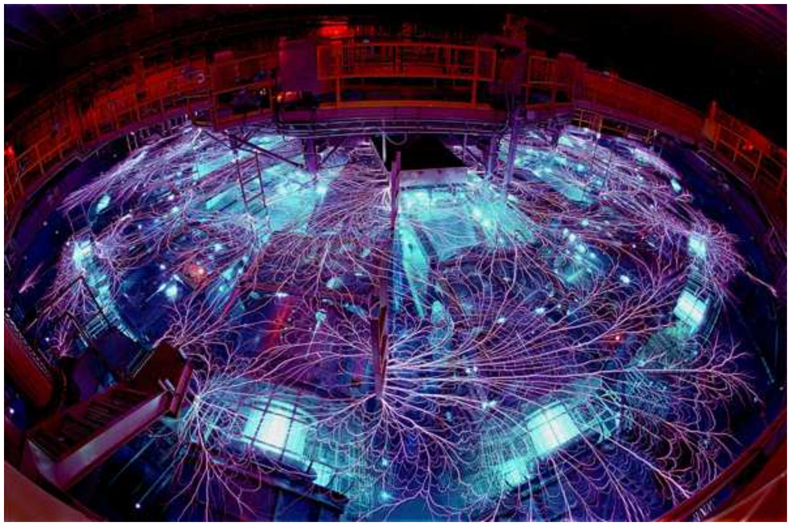

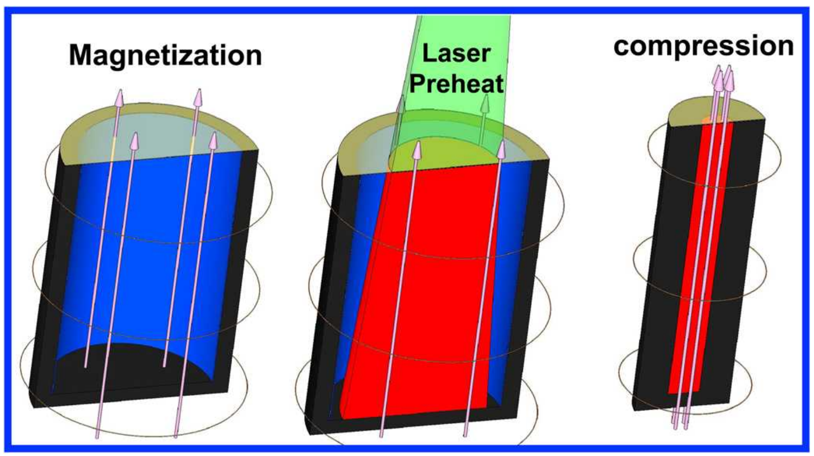

Design of Magnetized Liner Inertial Fusion (MagLIF) experiments using the Z facility

A. B. Sefkow

Sandia National Laboratories, Albuquerque, NM

American Physical Society
Division of Plasma Physics Meeting
Denver, Colorado, USA

Monday, November 11th, 2013

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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Collaborators

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and the entire MagLIF team

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[2] Lawrence Livermore National Laboratory, Livermore, CA

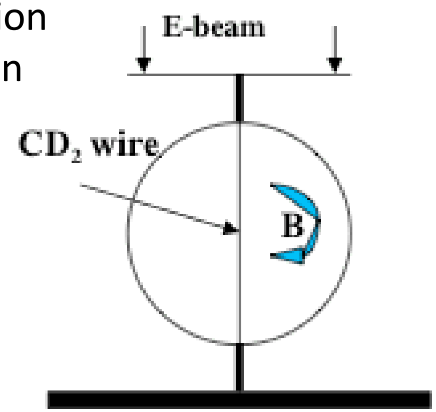
Questions to be addressed

- **What is the Magnetized Liner Inertial Fusion (MagLIF) approach at Sandia?**
- **Which details are included in integrated simulations?**
- **What are the expectations for near-term experiments with present parameters?**
- **What are the expectations for future experiments with upgraded parameters?**

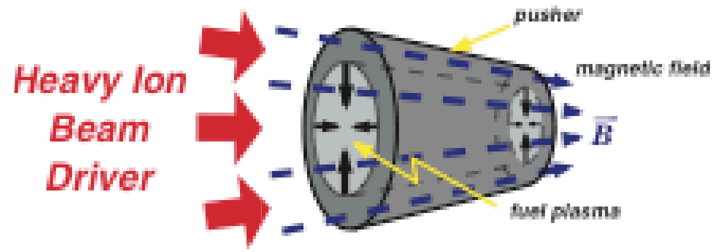
Many groups want to use magnetic fields to relax inertial fusion stagnation requirements

SNL Phi Target

1982 Demonstration of enhanced fusion yield with magnetization (~1e6 DD yield)



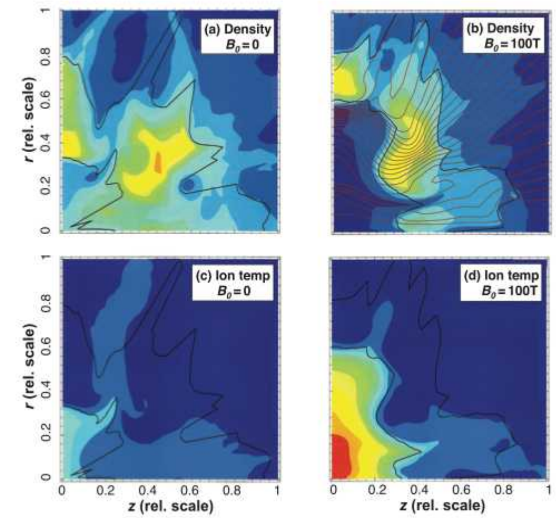
Max Planck/ITEP



Basko, Kemp, Meyer-ter-Vehn, *Nucl. Fusion* **40**, 59 (2000)
Kemp, Basko, Meyer-ter-Vehn, *Nucl. Fusion* **43**, 16 (2003)

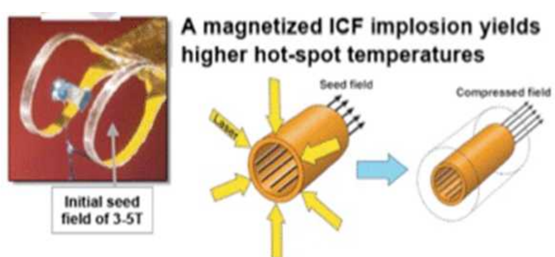
LLNL

(Perkins *et al.*, Phys Plasmas 2013)

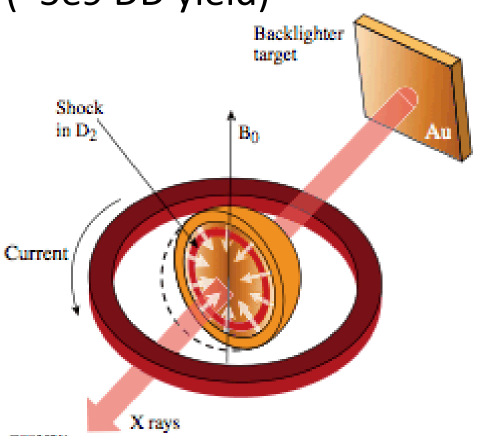


University of Rochester/LLE

2011 Demonstration of enhanced fusion yield with magnetization (~5e9 DD yield)



Gotchev *et al.*, *Rev. Sci. Instr.* **80**, 043504 (2009)

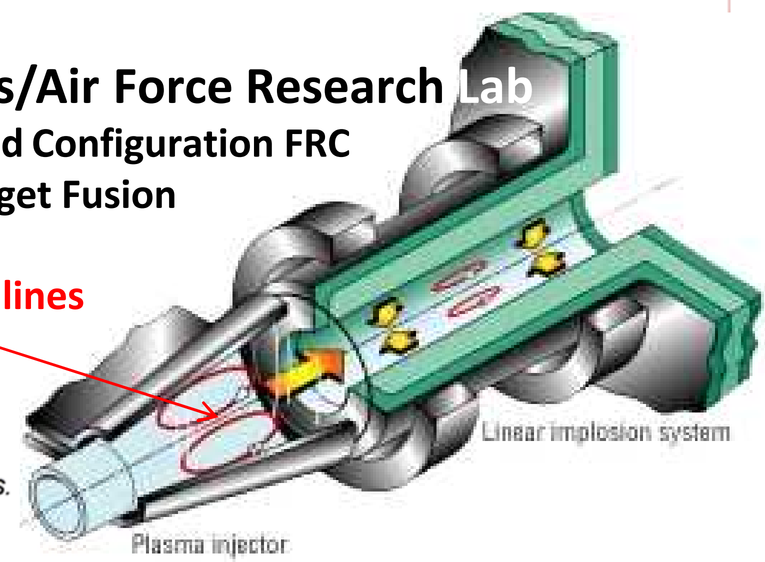


P.Y. Chang *et al.*, PRL (2011).

Los Alamos/Air Force Research Lab

Field Reversed Configuration FRC
Magnetic Target Fusion
Shiva Star

closed field lines
FRC



Taccetti, Intrator, Wurden *et al.*, *Rev. Sci, Instr.* **74**, 4314 (2003)
Degnan *et al.*, *IEEE Trans. Plas. Sci.* **36**, 80 (2008)

and many others…

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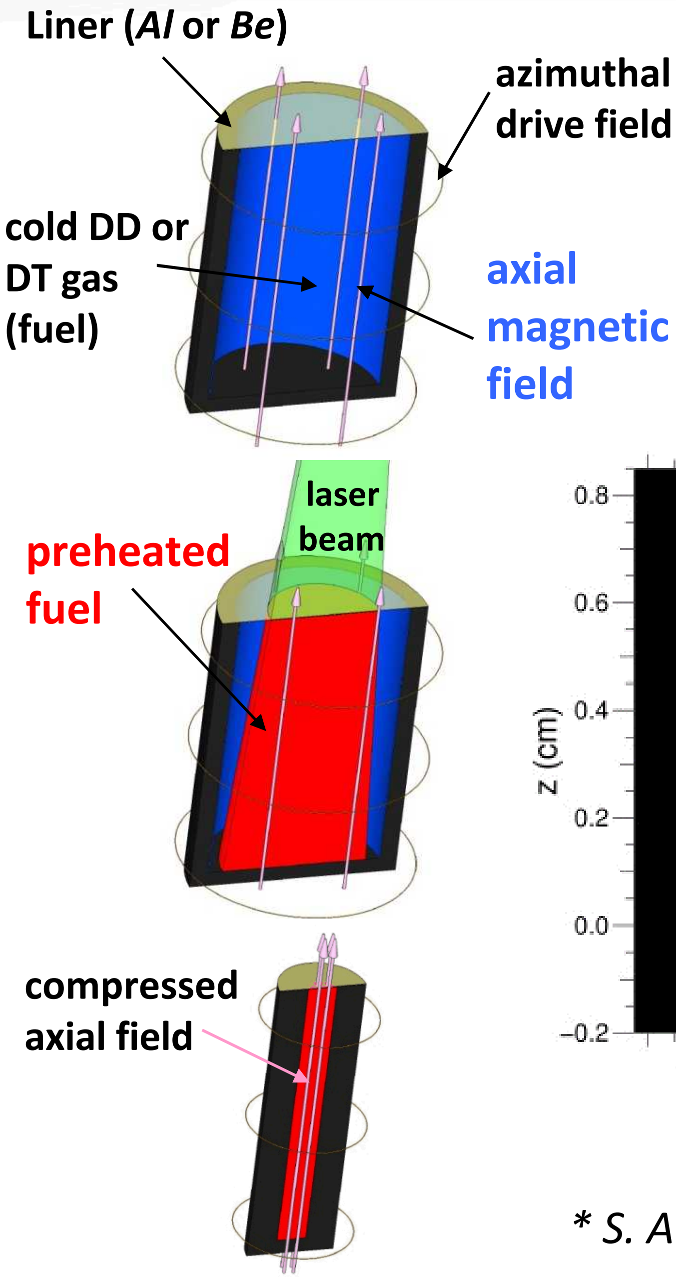
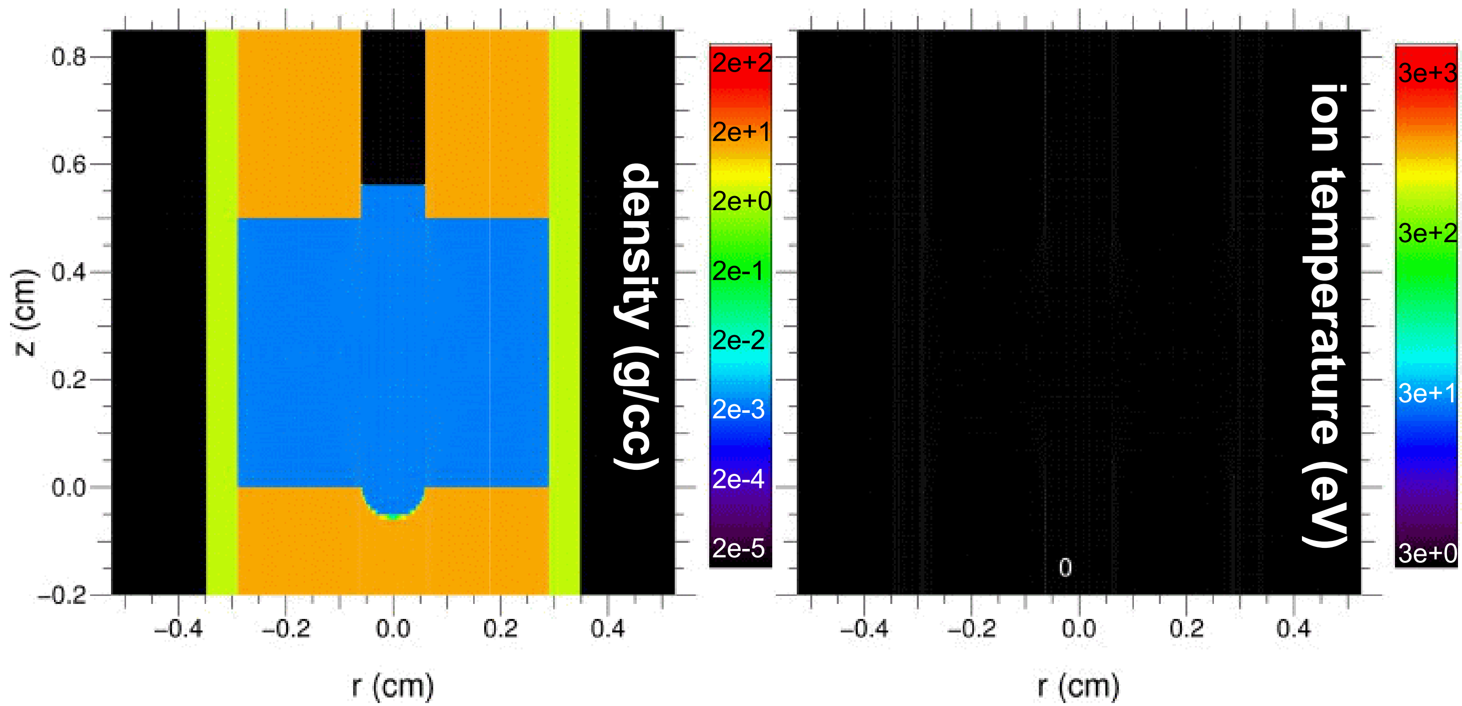
We are working toward the evaluation of the Magnetized Liner Inertial Fusion (MagLIF)* concept



- The initial B_z~10-50 T flux is compressed to ~5-15 kT (~50-150 MG)
  - to reduce thermal electron conduction losses
  - to enable low ρR_{fuel} ignition ($B_z R_{fuel}$ requirement instead)
- The fuel is **preheated** using the Z-Beamlet laser in order to reduce:
  - the convergence ratio (CR) needed to obtain T_{ion} > 4 keV
  - the implosion velocity needed to ≤ 100 km/s
  - the stagnation pressure needed to a few Gbar (not 100s Gbar)
- Measurable yields may be possible on Z + Z-Beamlet



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

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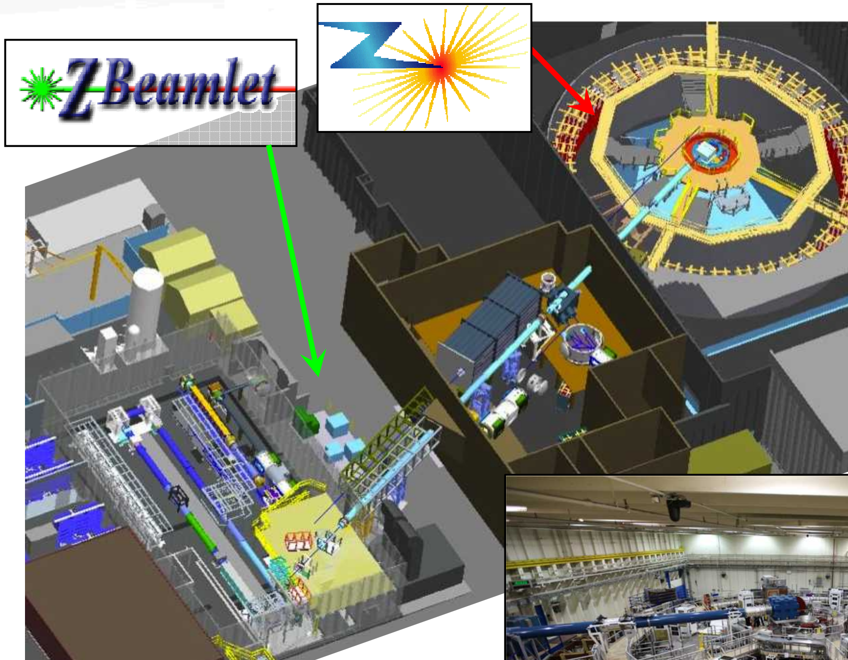
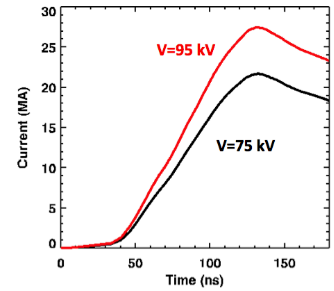
MagLIF uses the Z facility to compress a liner containing pre-magnetized and pre-heated D_2 gas

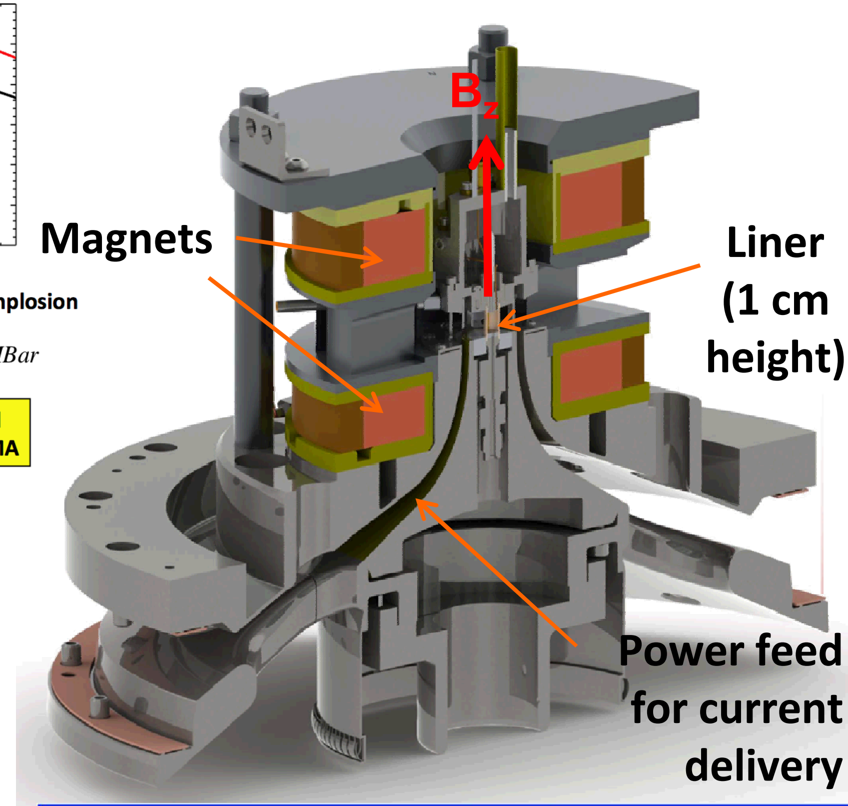


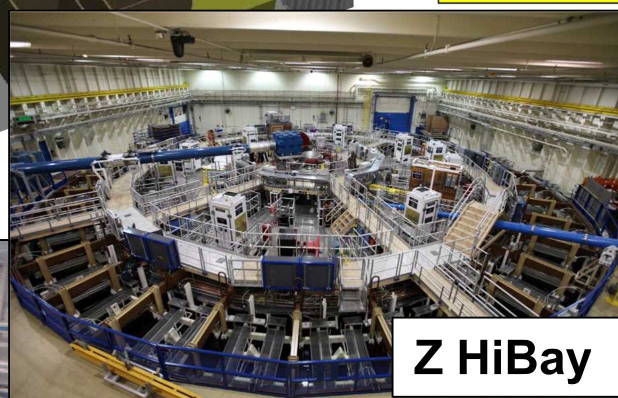


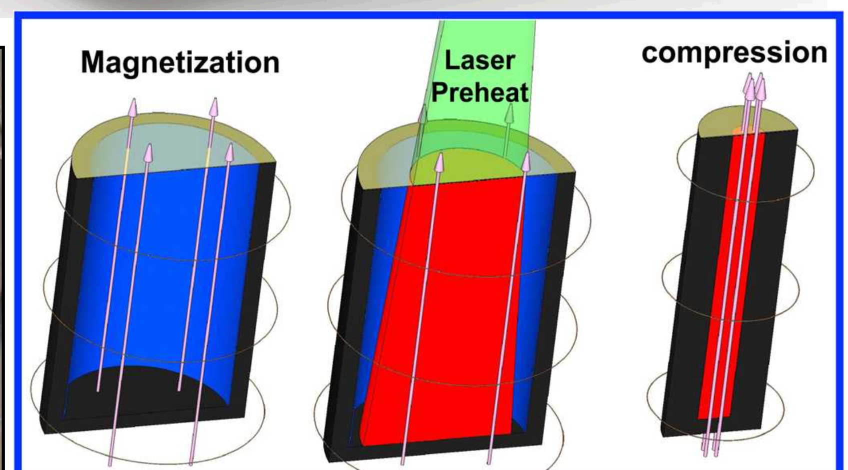
Magnetically-Driven Cylindrical Implosion

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

140 MBar is generated at R = 1 mm and I = 30 MA

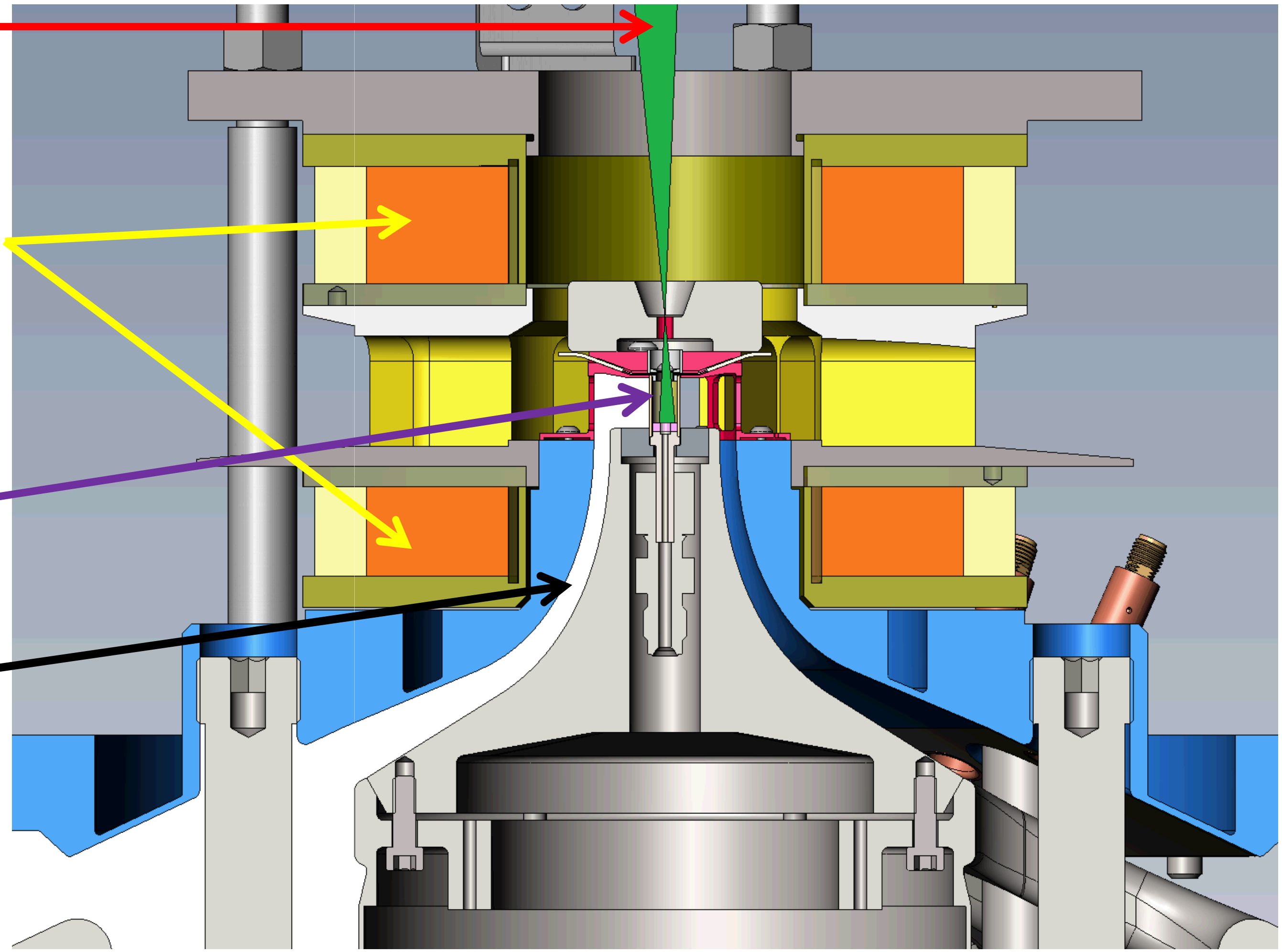






The necessary components are being separately tested in "focused" experiments

- Laser preheat
  - 8 laser-only experiments
- Applied magnetic field
  - 8 Z shots
  - 6 laser-only experiments
- Liner Stability
  - >30 Z shots
- Modified power flow
  - Geometry scan to minimize losses
  - 15 Z shots



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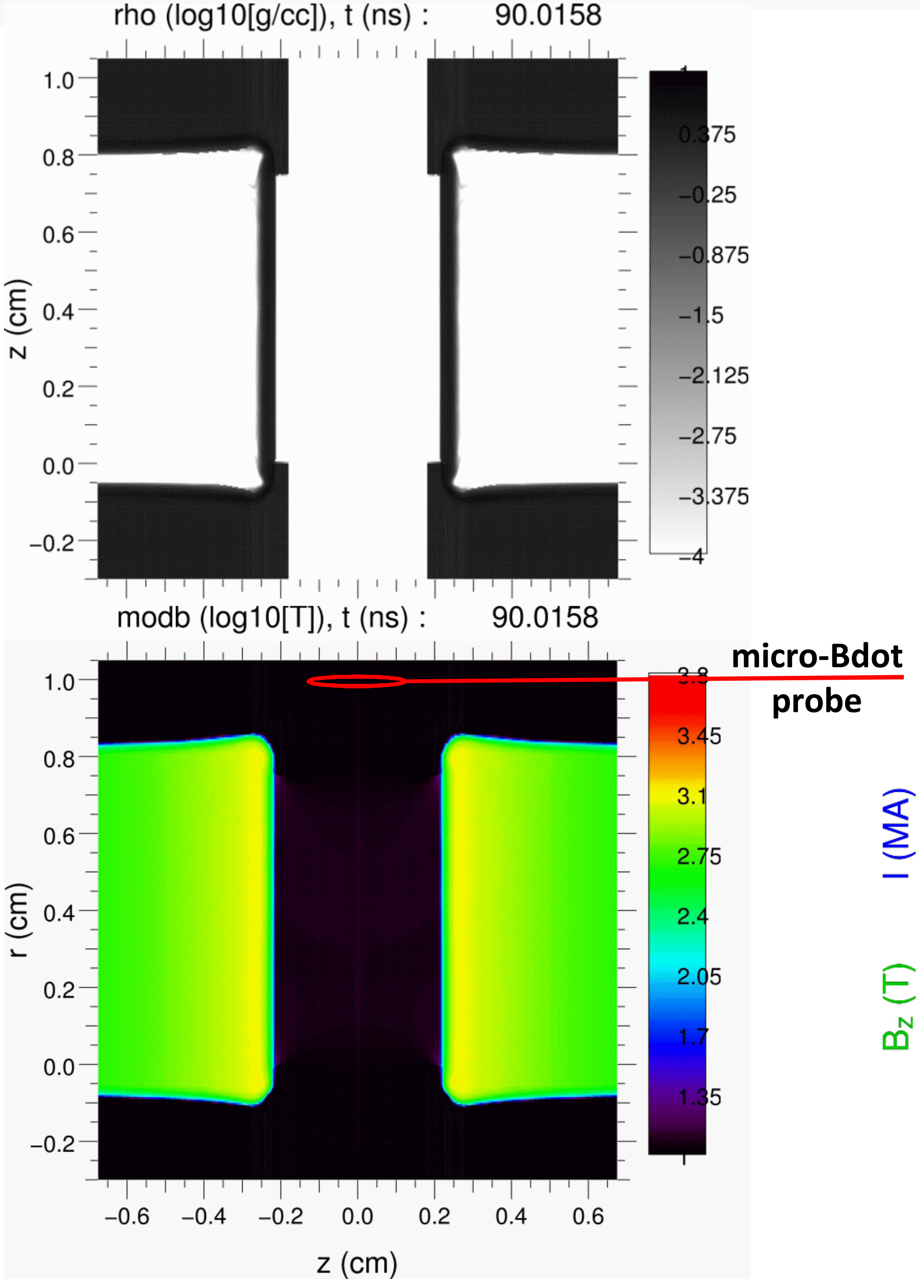
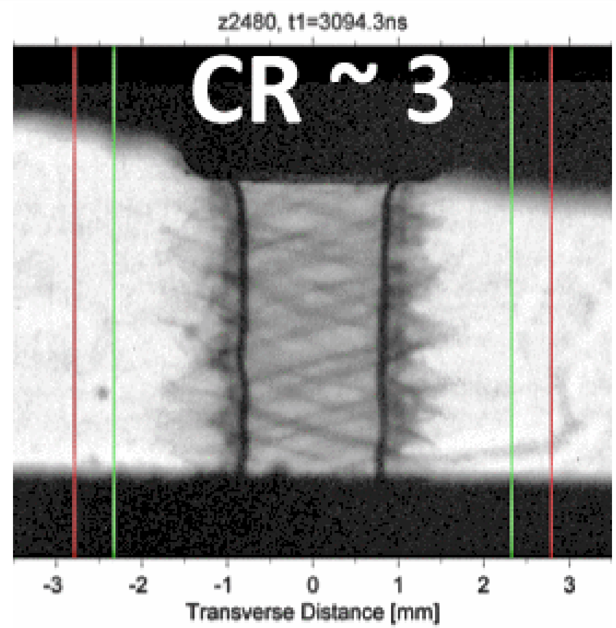
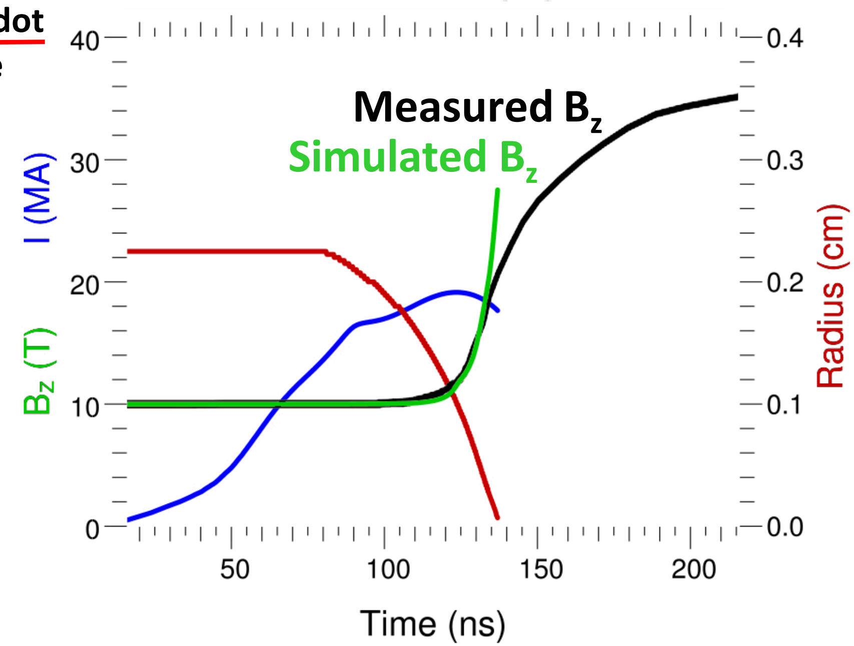
Liner-only flux compression experiments (with B_z, but without laser) measure $B_z(t)$ and $r_{inner}(t)$







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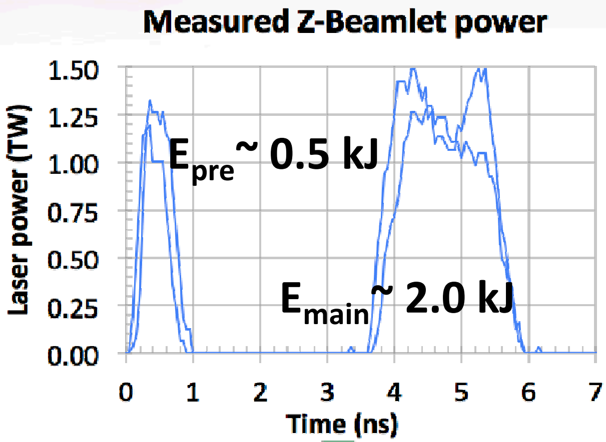
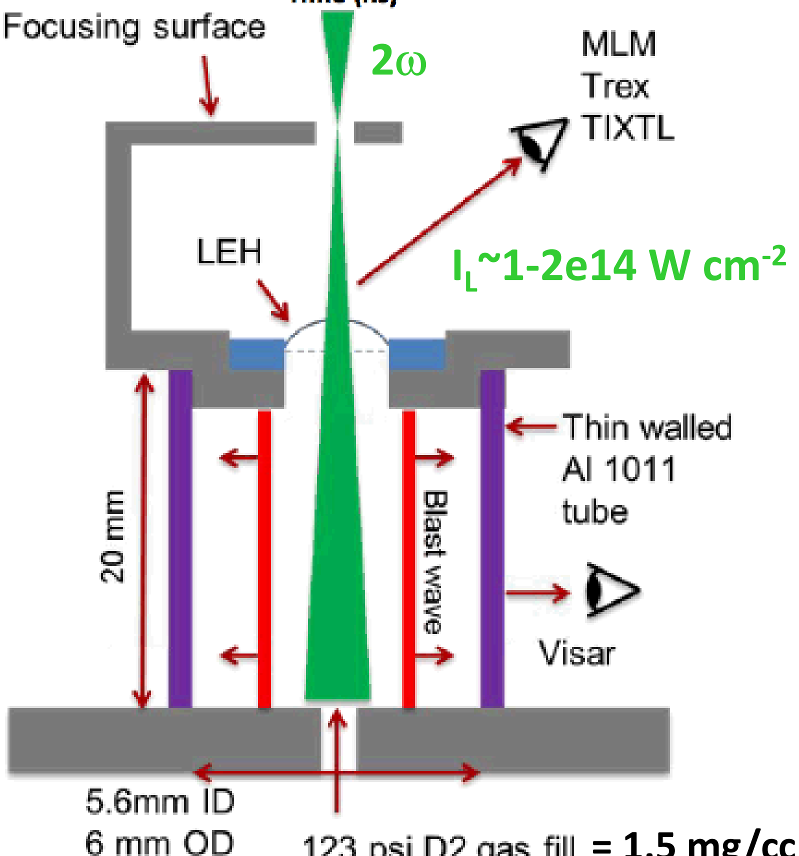
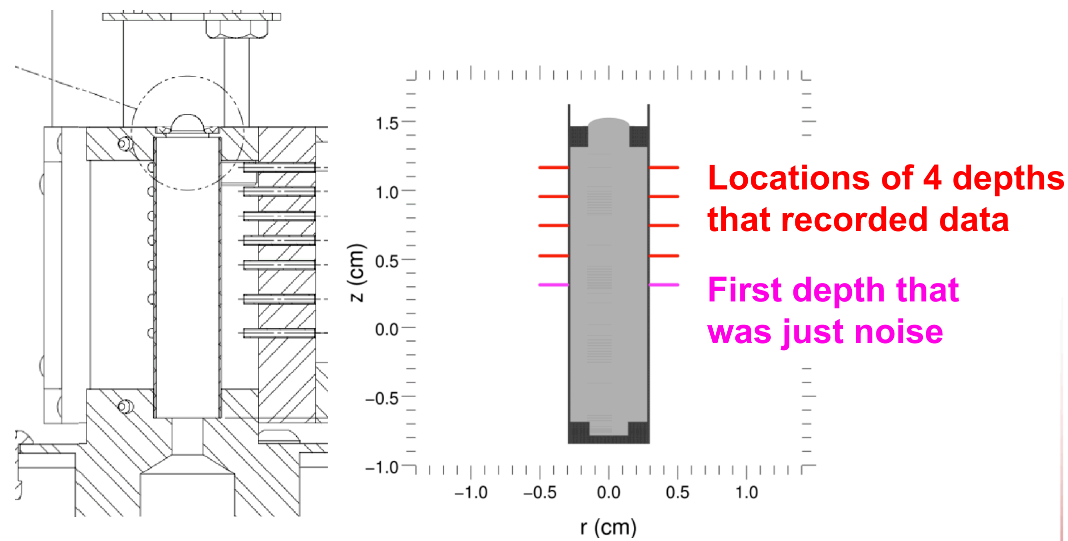
Laser-only fuel preheating experiments (with laser and B_z, but no implosion) measure absorption into gas

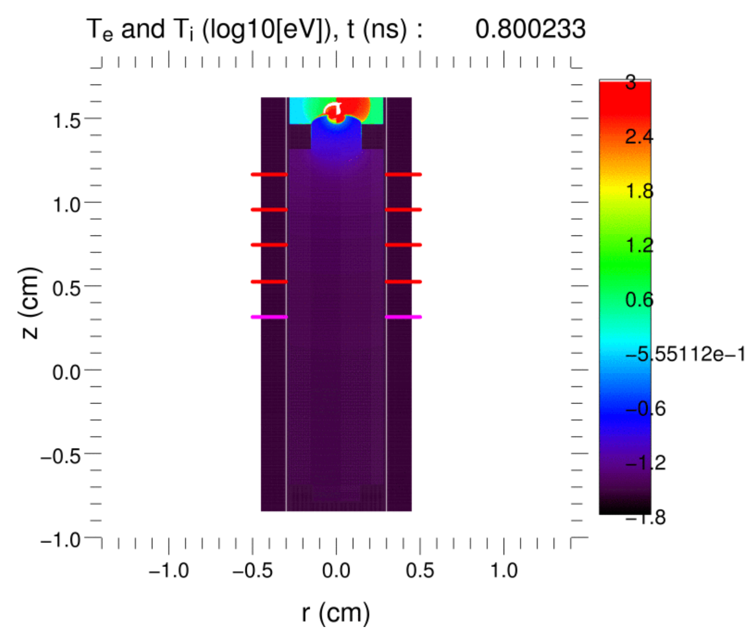




= 1.5 mg/cc

We can infer gas absorption energy as *f*(z) based on the signals' arrival time and VISAR velocity





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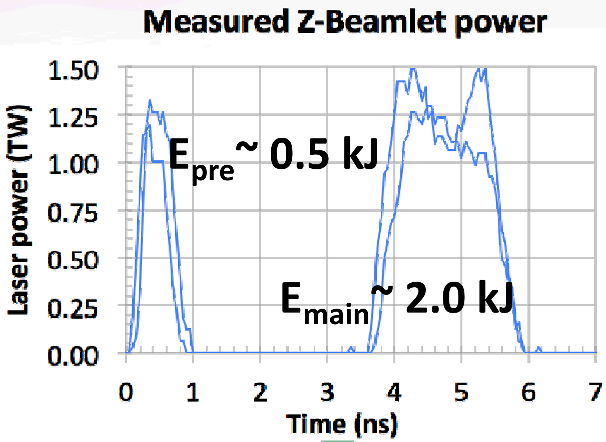
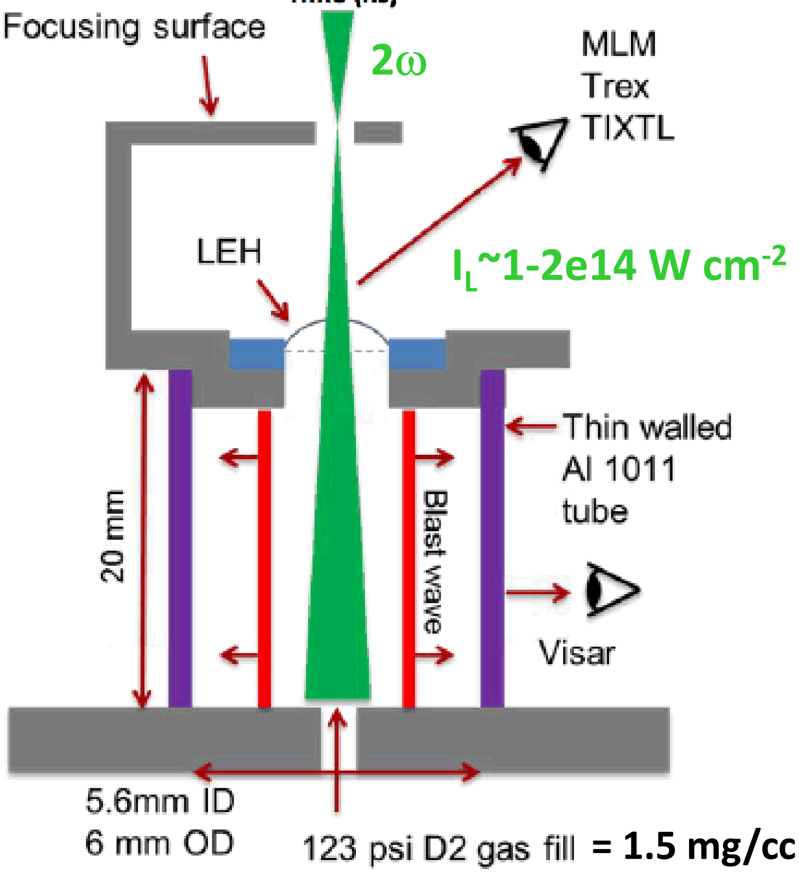
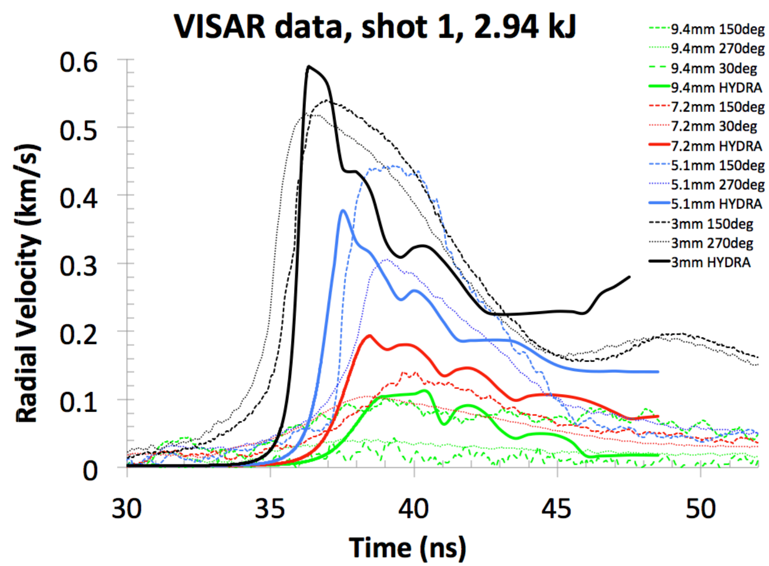
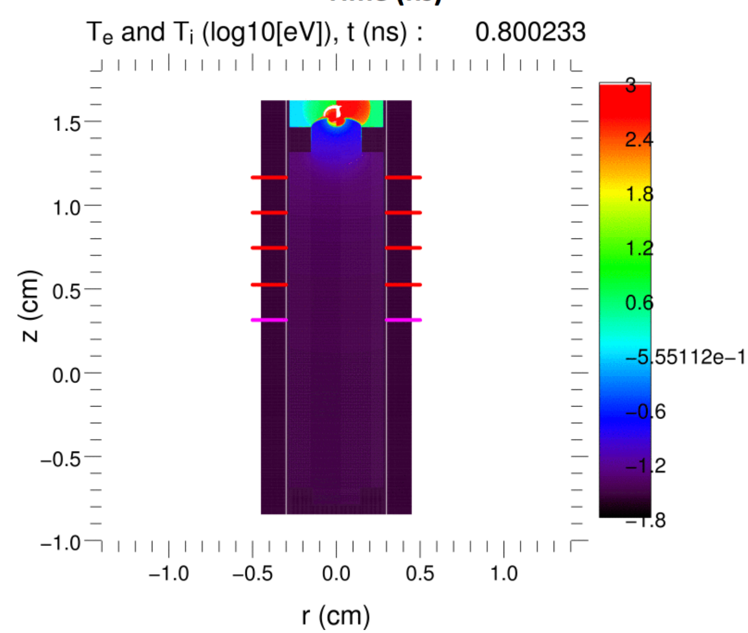
Laser-only fuel preheating experiments (with laser and B_z, but no implosion) measure absorption into gas





We can **infer gas absorption energy** as $f(z)$ based on the signals' arrival time and VISAR velocity





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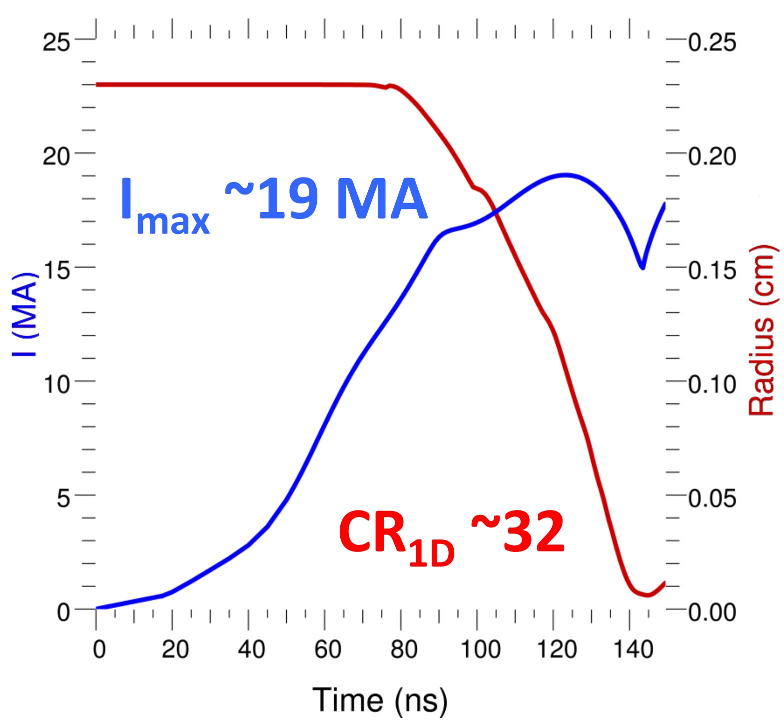
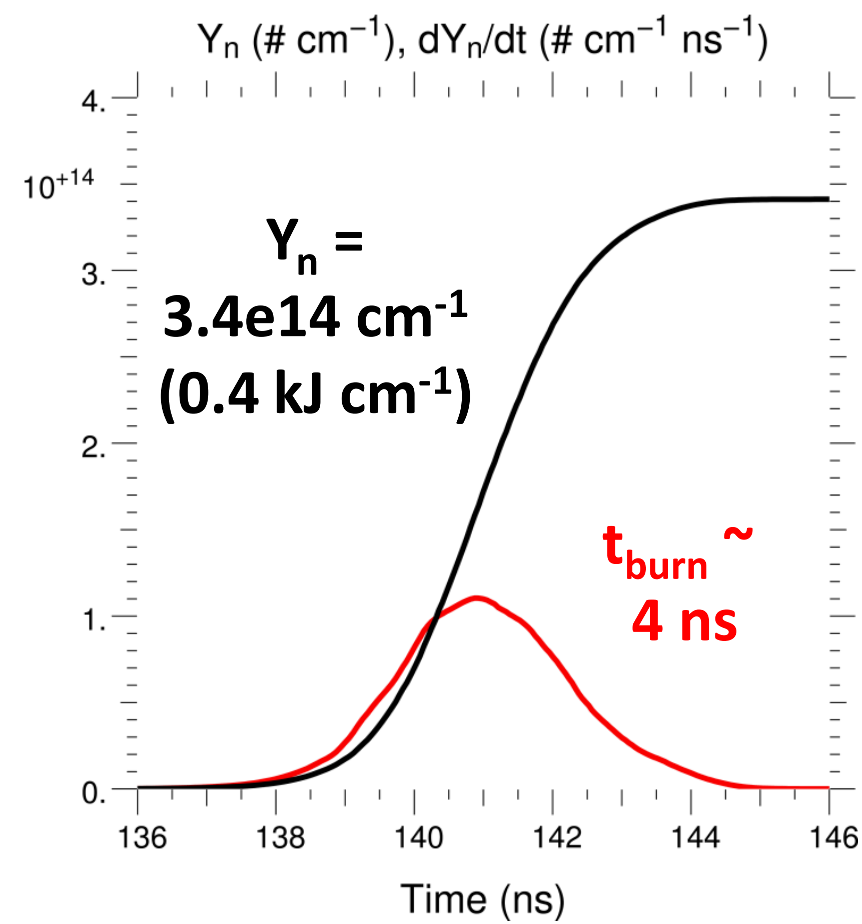
Ideal 1D HYDRA simulation of near term MagLIF experiments on Z using available parameters

Near-term MagLIF experiment:
L_{liner} = 7.5 mm, AR_{liner} = 6,
ρ_{gas} = 1.5 mg cm^{-3}, DD fuel,
B_z^0 = 10T, E_{laser} = 2 kJ (1 TW)





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Near-term MagLIF experiment:
L_{liner} = 7.5 mm, AR_{liner} = 6,
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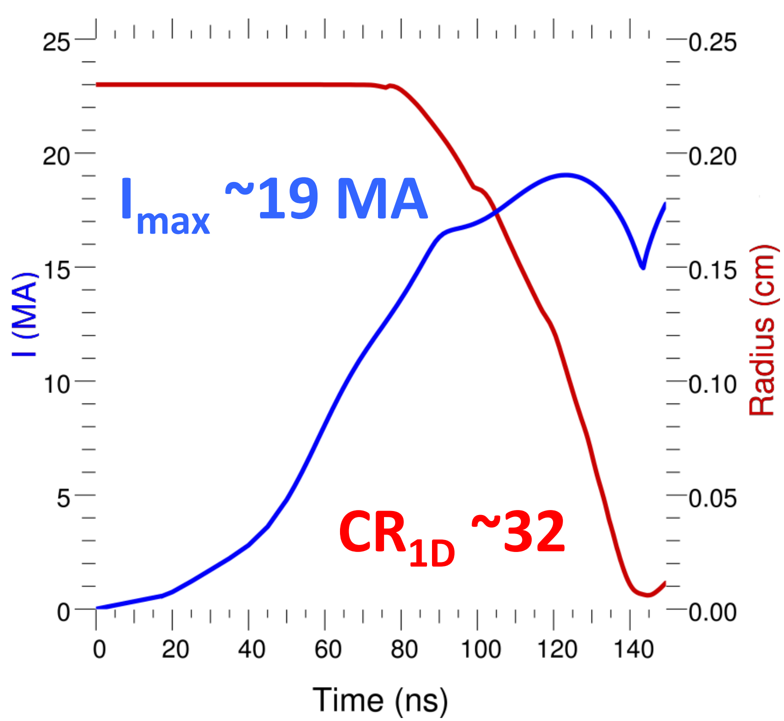
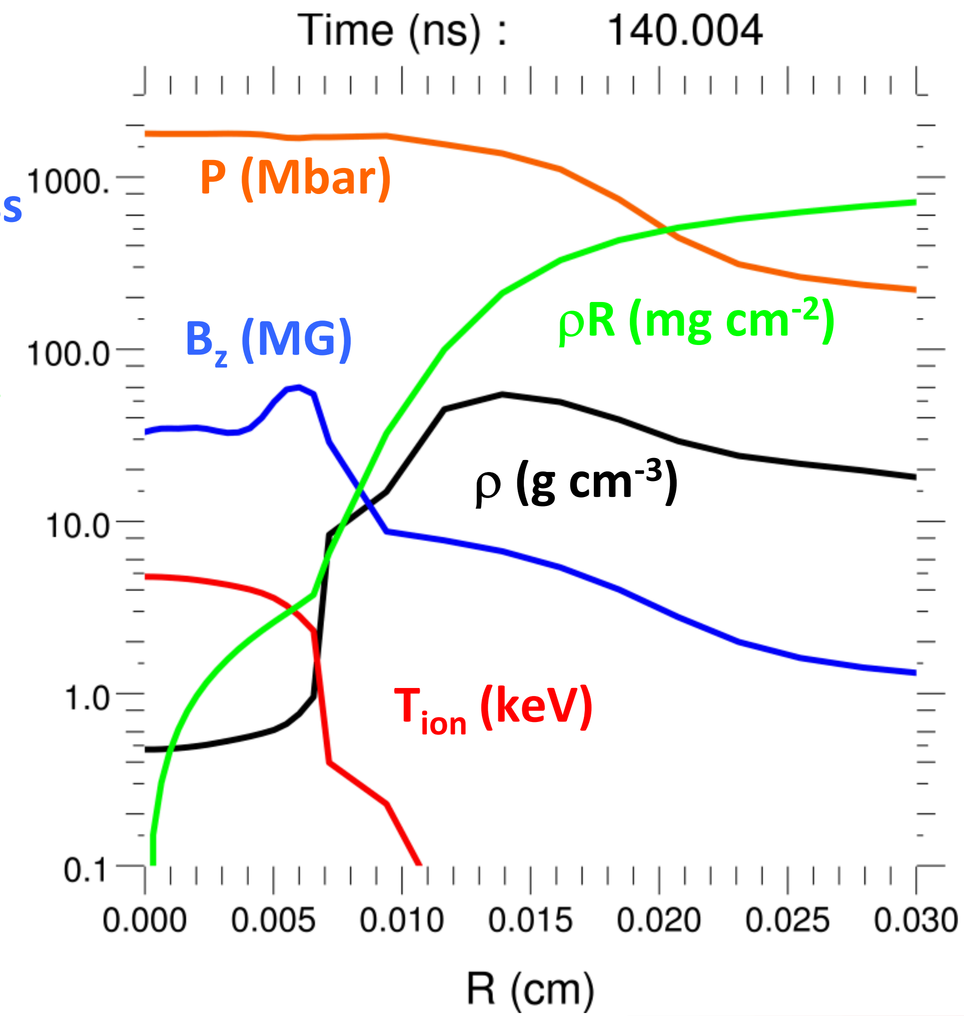
B_z^0 = 10T, E_{laser} = 2 kJ (1 TW)

~2-3 Gbar
~38% flux loss
~5 keV
~0.5 g cm^{-3}
~4e-3 g cm^{-2}



Stagnation profile



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An integrated model seeks to realistically simulate MagLIF experiments as they would occur on Z

A number of parameters and constraints must be self-consistently included and integrated into one simulation:

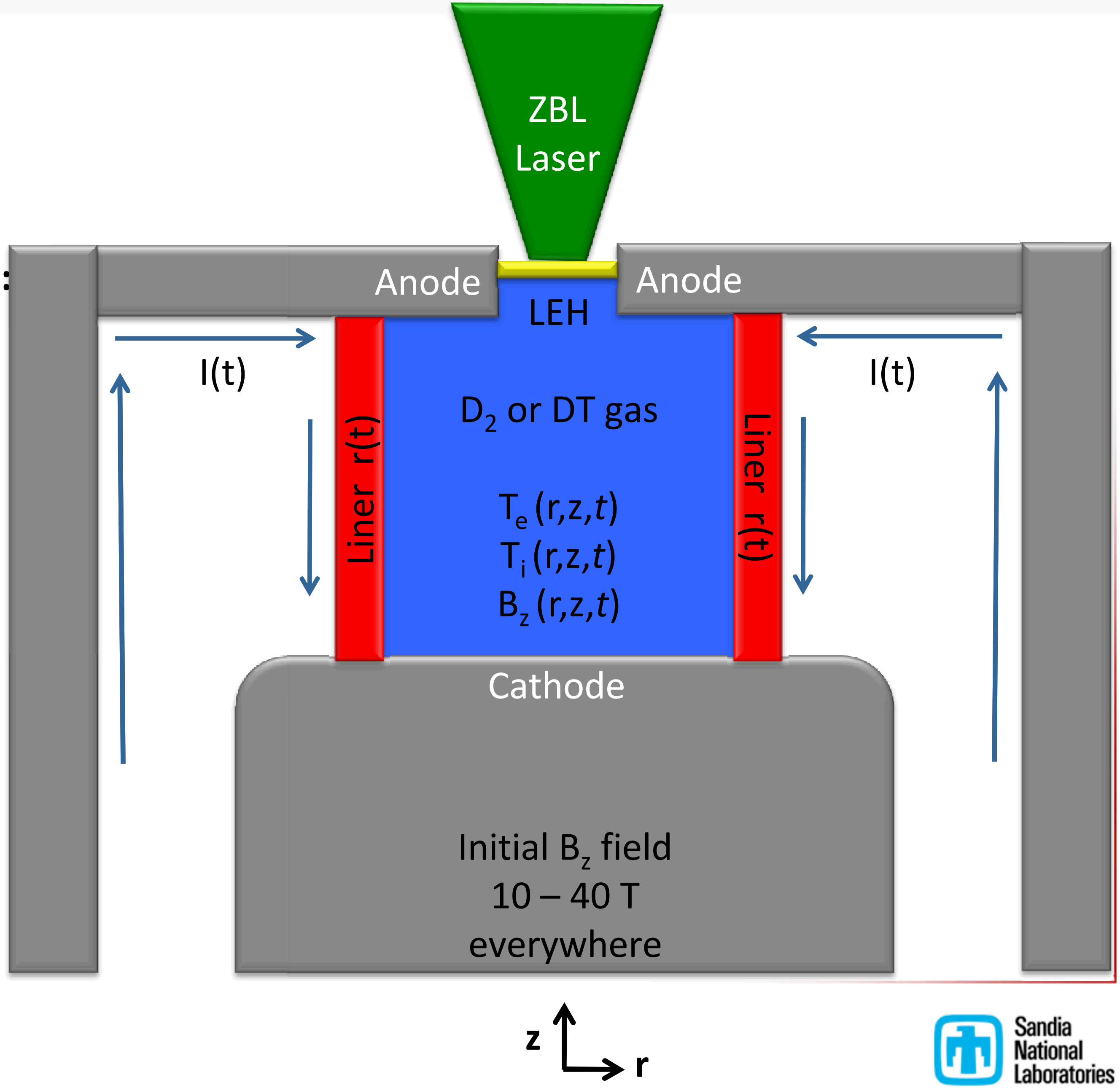
(1) Laser

(2) Laser entrance hole (LEH) and window

(3) Liner and circuit

(4) Electrode end caps

(5) Component interactions, timing, and optimization



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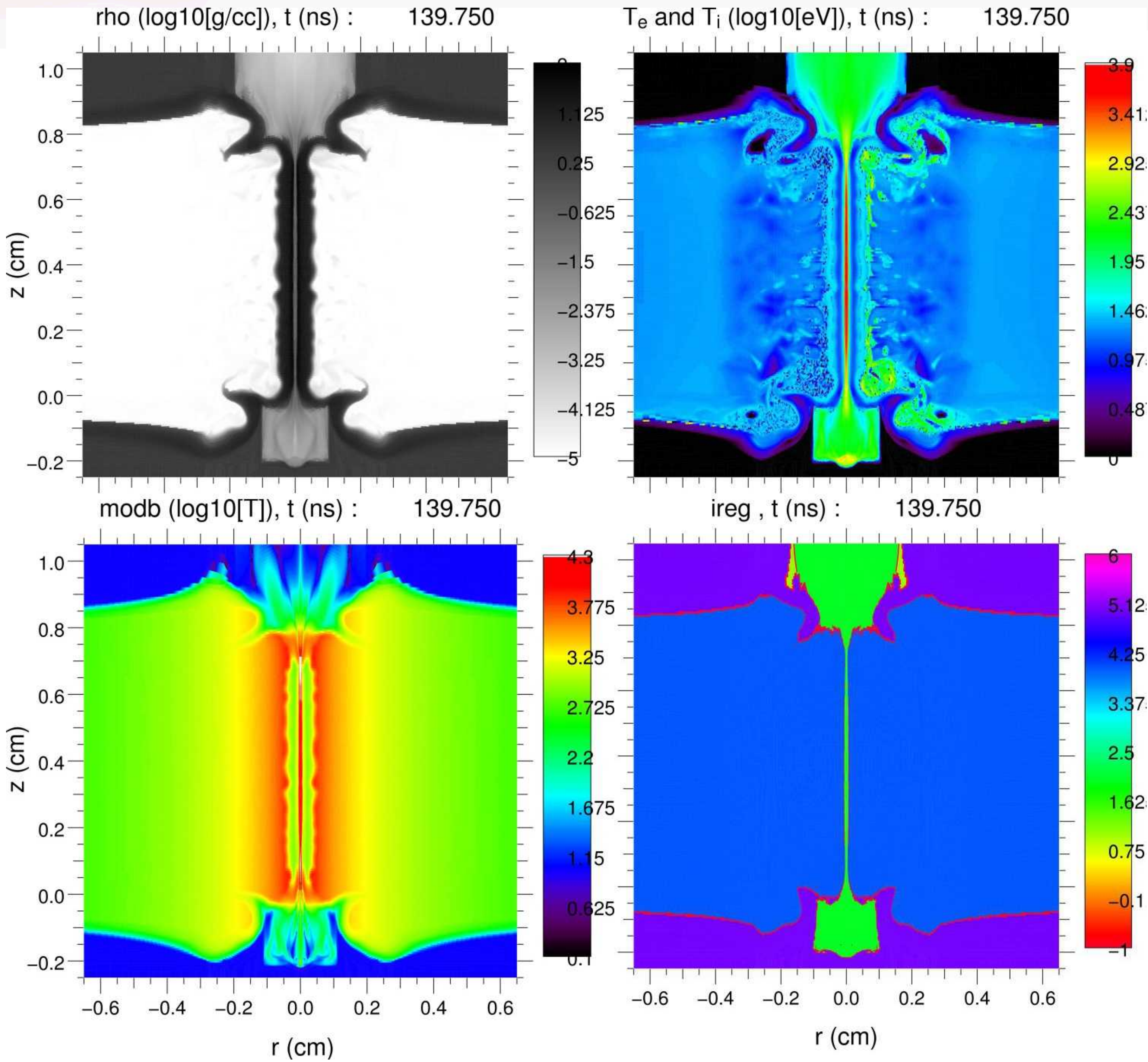
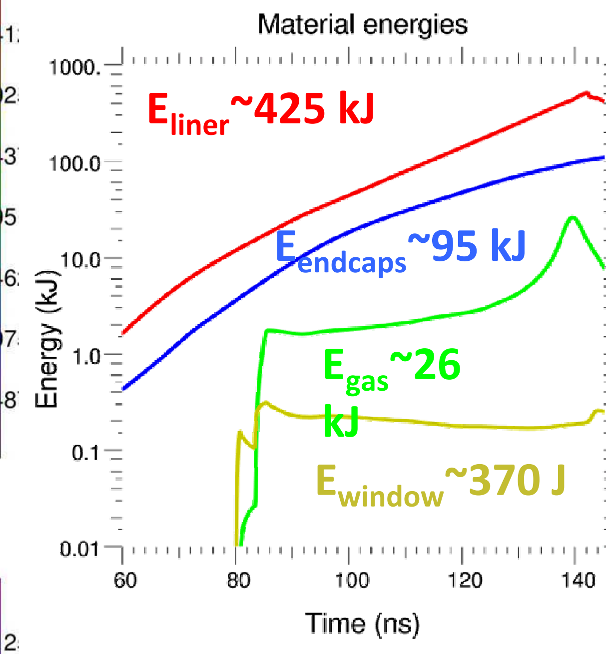
Integrated 2D HYDRA simulation of near-term MagLIF experiments on Z using available parameters





- Y_n = 6.1e13 (71 J) (24% of 1D)
- CR_{2D} 37
- m_{loss} 43%
- Φ_{loss} 38%

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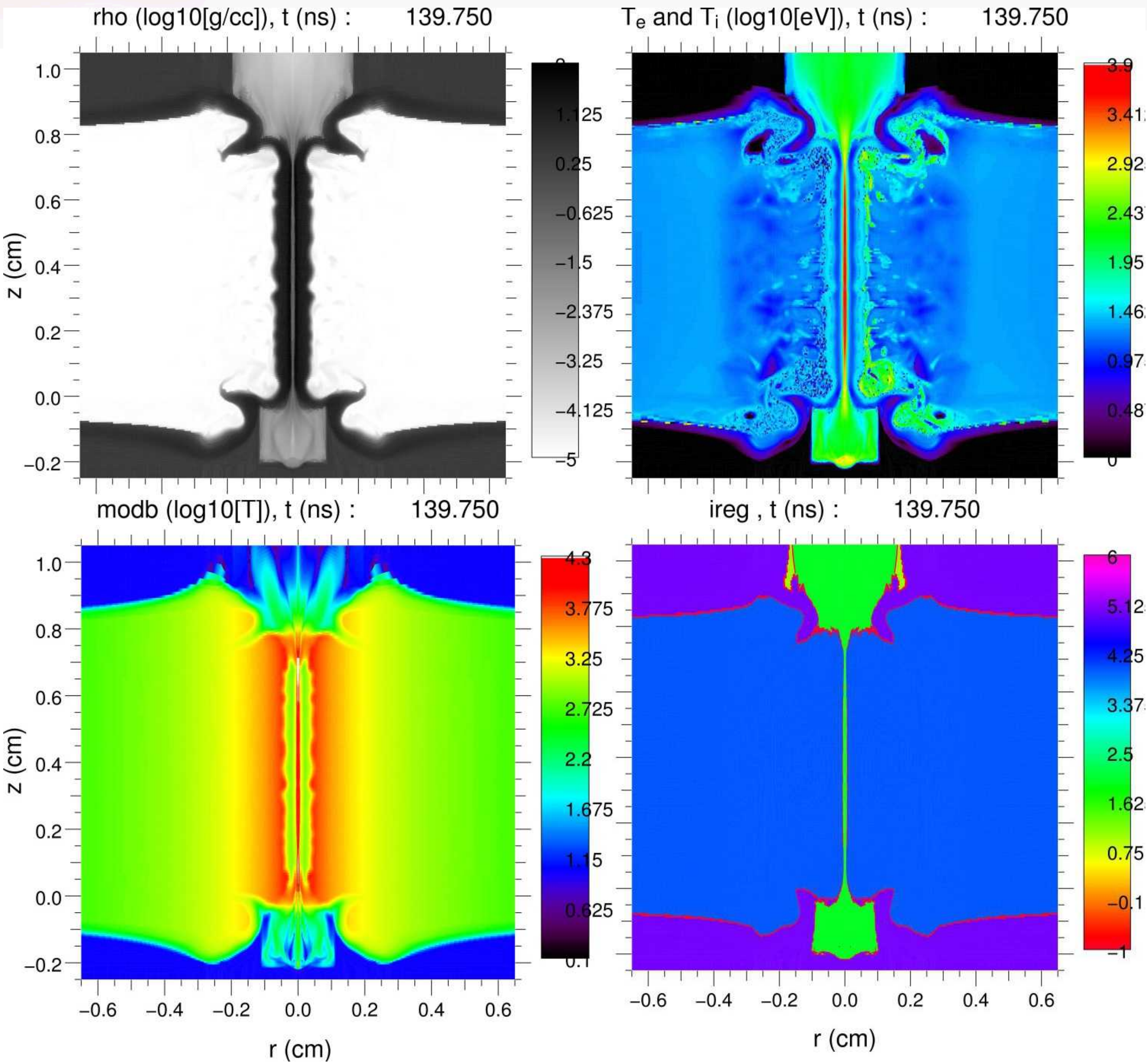
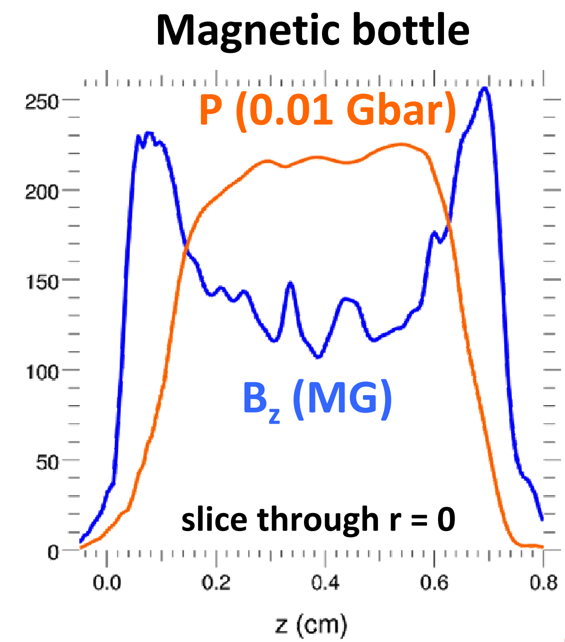
Integrated 2D HYDRA simulation of near-term MagLIF experiments on Z using available parameters





- Y_n = 6.1e13 (71 J) (24% of 1D)
- CR_{2D} 37
- m_{loss} 43%
- Φ_{loss} 38%

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Liner length and gas density variations for near-term integrated MagLIF experiments on Z

	Liner = 5 mm (I_{max}~20 MA)	Liner = 7.5 mm (I_{max}~19 MA)	Liner = 10 mm (I_{max}~18 MA)
ρ_{gas} **= 0.8 mg/cc** dz_{window} ~1.1 μm	r_{laser} 1100μm E_{gas}^{abs} 1.27 kJ	r_{laser} 840 μm E_{gas}^{abs} 1.54 kJ	r_{laser} 660μm E_{gas}^{abs} 1.74 kJ
ρ_{gas} **= 1.1 mg/cc** dz_{window} ~1.5 μm	r_{laser} 700μm E_{gas}^{abs} 1.49 kJ	r_{laser} 530μm E_{gas}^{abs} 1.78 kJ	r_{laser} 490μm E_{gas}^{abs} 1.85 kJ
ρ_{gas} **= 1.5 mg/cc** dz_{window} ~2.0 μm	r_{laser} 470μm E_{gas}^{abs} 1.67 kJ	r_{laser} 460 μm E_{gas}^{abs} 1.74 kJ	r_{laser} 440μm E_{gas}^{abs} 1.85 kJ
ρ_{gas} **= 2.0 mg/cc** dz_{window} ~2.7 μm	r_{laser} 440μm E_{gas}^{abs} 1.52 kJ	r_{laser} 380μm E_{gas}^{abs} 1.62 kJ	r_{laser} 360μm E_{gas}^{abs} 1.66 kJ

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Liner length and gas density variations for near-term integrated MagLIF experiments on Z

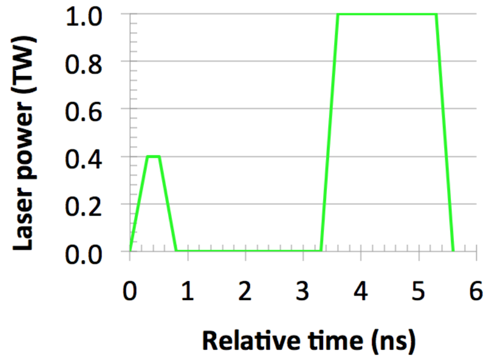
	Liner = 5 mm (I_{max}~20 MA)	**Liner = 7.5 mm** (I_{max}~19 MA)	**Liner = 10 mm** (I_{max}~18 MA)
ρ_{gas} **= 0.8 mg/cc** dz_{window} ~1.1 μm	CR_{2D} 46 m_{loss} 73%	CR_{2D} 42 m_{loss} 60%	CR_{2D} 33 m_{loss} 43%
ρ_{gas} **= 1.1 mg/cc** dz_{window} ~1.5 μm	CR_{2D} 42 m_{loss} 68%	CR_{2D} 37 m_{loss} 51%	CR_{2D} 33 m_{loss} 39%
ρ_{gas} **= 1.5 mg/cc** dz_{window} ~2.0 μm	CR_{2D} 40 m_{loss} 61%	CR_{2D} 37 m_{loss} 43%	CR_{2D} 33 m_{loss} 35%
ρ_{gas} **= 2.0 mg/cc** dz_{window} ~2.7 μm	CR_{2D} 42 m_{loss} 56%	CR_{2D} 39 m_{loss} 35%	CR_{2D} 36 m_{loss} 29%

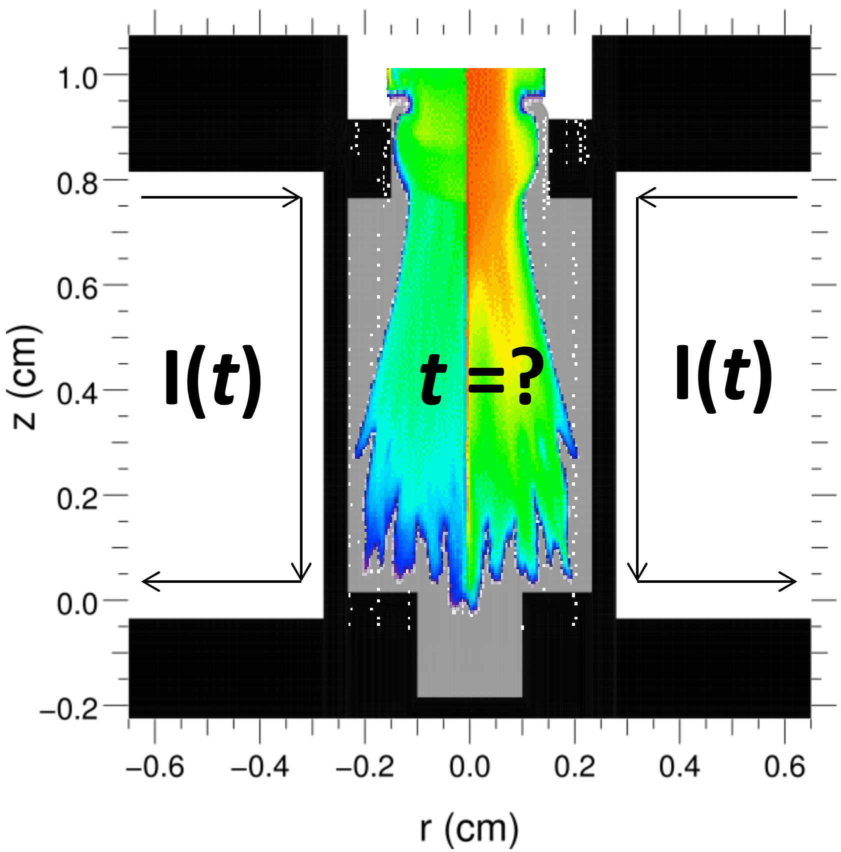
Liner length and gas density variations for near-term integrated MagLIF experiments on Z

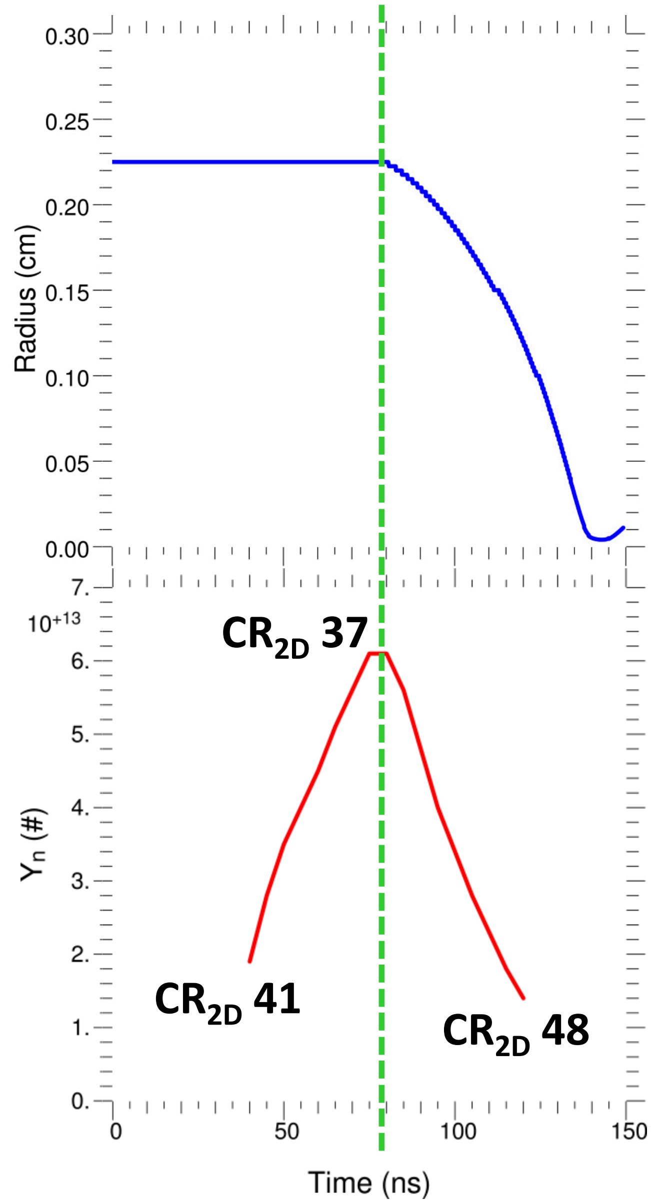
	Liner = 5 mm (I_{max}~20 MA)	Liner = 7.5 mm (I_{max}~19 MA)	Liner = 10 mm (I_{max}~18 MA)
ρ_{gas} = 0.8 mg/cc dz_{window} ~1.1 μm	Y_n 1.4e13	Y_n 6.5e13	Y_n 8.3e13
ρ_{gas} = 1.1 mg/cc dz_{window} ~1.5 μm	Y_n 2.0e13	Y_n 7.0e13	Y_n 6.5e13
ρ_{gas} = 1.5 mg/cc dz_{window} ~2.0 μm	Y_n 2.3e13 (5% of 1D)	Y_n 6.1e13 (24% of 1D)	Y_n 4.8e13 (32% of 1D)
ρ_{gas} = 2.0 mg/cc dz_{window} ~2.7 μm	Y_n 3.3e13	Y_n 2.5e13	Y_n 1.9e13

Independent Lasnex calculations of Y_n are generally within an approximate factor of 2

Laser timing variations for near-term integrated MagLIF experiments on Z







The **optimal laser timing** balances competing effects:

Earlier:
More fuel loss, plasma cooling, and potential mix

Later:
Less effective compression

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Simulated performance of how MagLIF scales up

	Benefit	Present	Upgrades	New machine
Length	End losses	7.5 mm	10 mm	10 mm
E_{laser}	CR	2 kJ	6 kJ	25 kJ
B_z	CR, losses	10 T	30-40 T	8 T
I_{max}	E_{drive}, v_{imp}	19 MA	24 MA	70 MA

$Temp_{ion}$		5-6 keV	20 keV	13 keV
ρR_{fuel}, ρR_{liner}		4e-3, 1.0 g cm^{-2}	4e-3, 2.0 g cm^{-2}	0.6, 3.1 g cm^{-2}
$Pressure_{stag}$		2-3 Gbar	5 Gbar	25 Gbar
$Yield_n$		6.1e13 (DD)	3.7e14 (DD) 3.0e16 (DT)	2.8e21 (DT)
$Gain_{fuel}$		2.7e-3 (DD)	1.5e-2 (DD) 1.2 (DT)	4400 (DT)

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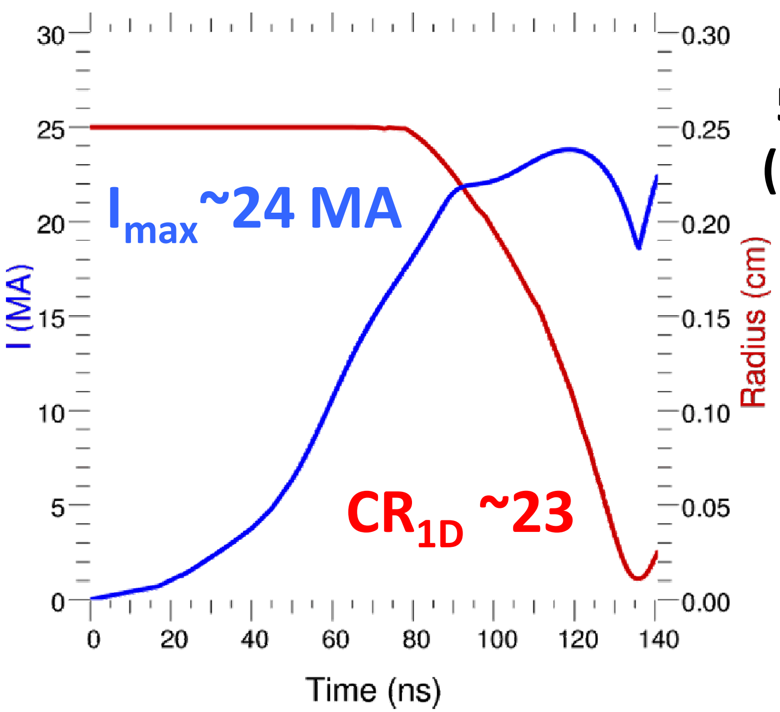
Ideal 1D HYDRA simulation of MagLIF experiments on Z using upgraded parameters

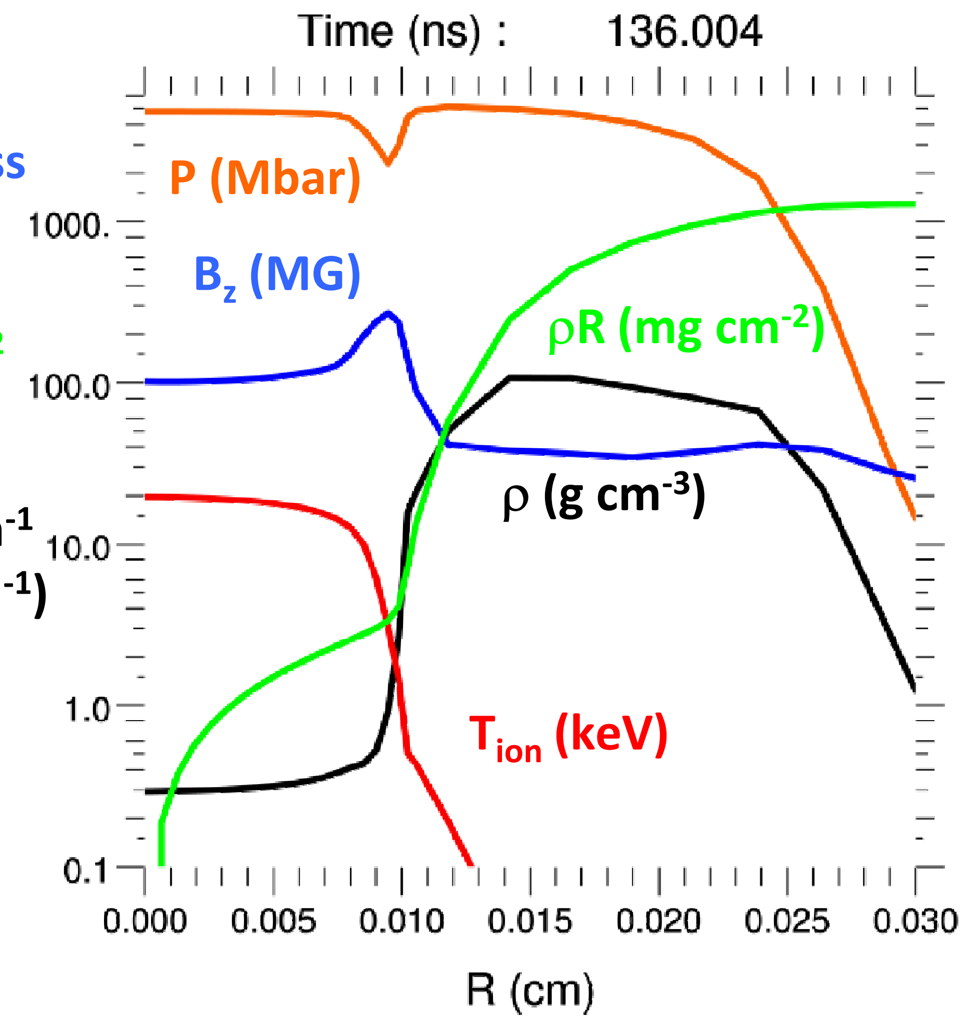
Upgraded MagLIF experiment:
L_{liner} = 10 mm, AR_{liner} = 6,
ρ_{gas} = 1.2 mg cm^{-3}, DT fuel,
B_z^0 = 40T, E_{laser} = 6 kJ (1 TW)

~5 Gbar
~32% flux loss
~20 keV
~0.2 g cm^{-3}
~4e-3 g cm^{-2}

Y_n =
5.0e17 cm^{-1}
(1.4 MJ cm^{-1})
G_t=1.3
G_f=6.8



Stagnation profile



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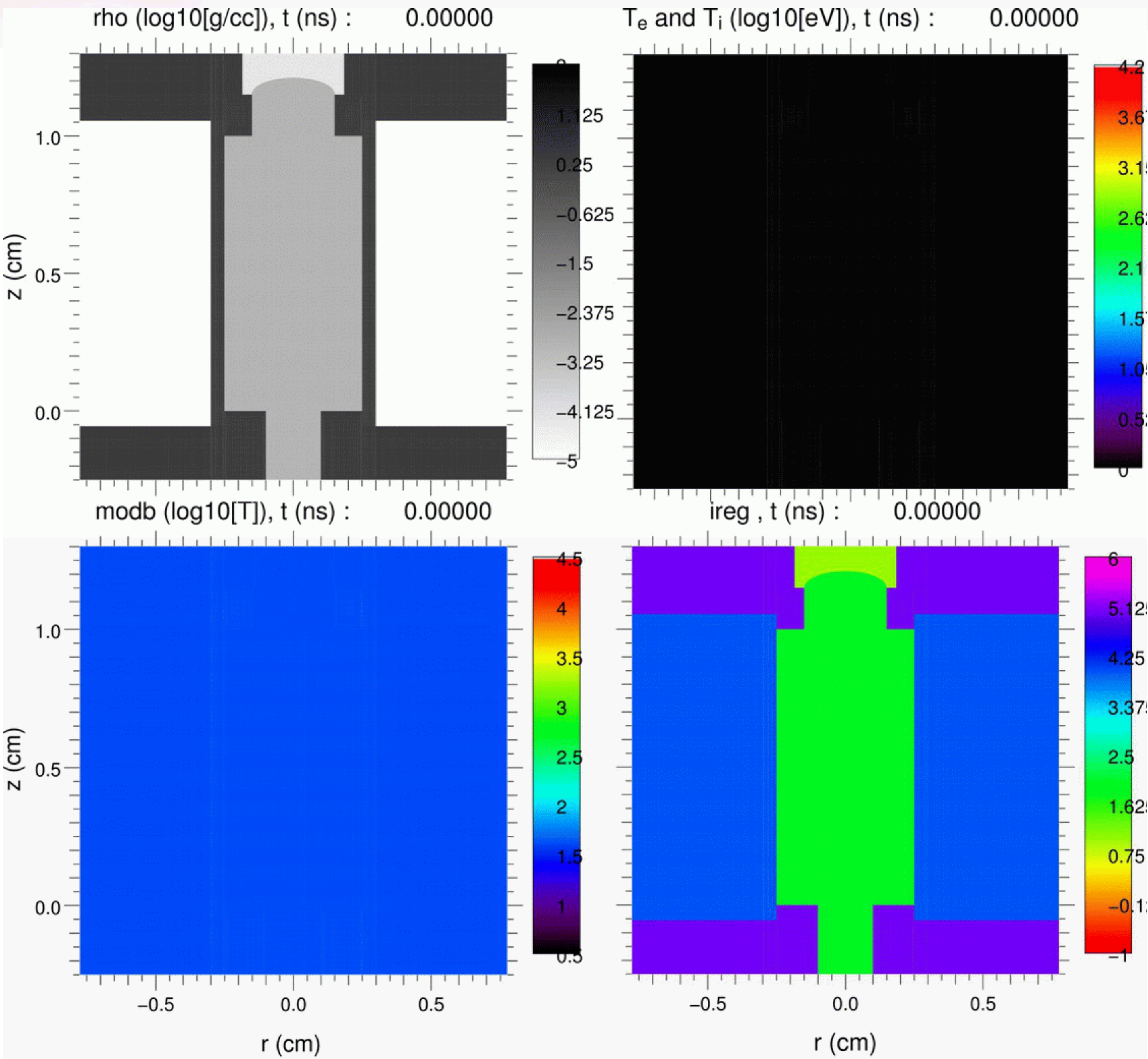
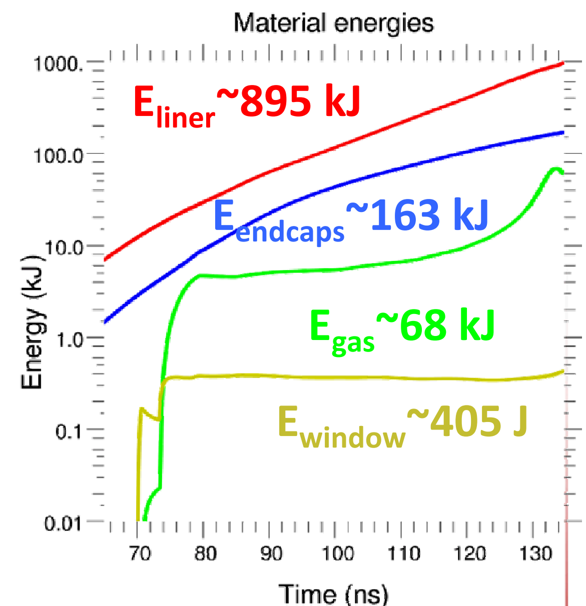
Integrated 2D HYDRA simulation of MagLIF experiments on Z using upgraded parameters





- Y_n= 3e16 (83 kJ)
- G_t = 0.07, G_f = 1.2
- CR_{2D} 26
- m_{loss} 44%
- Φ_{loss} 32%

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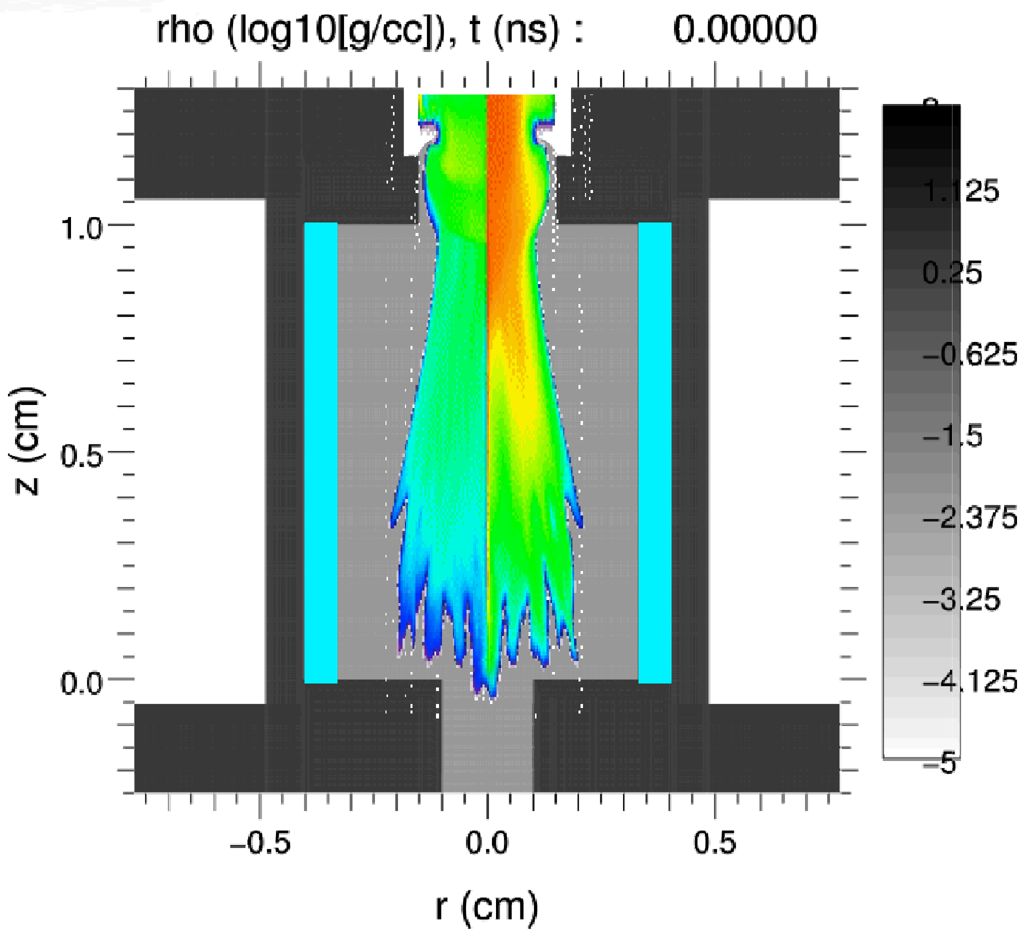
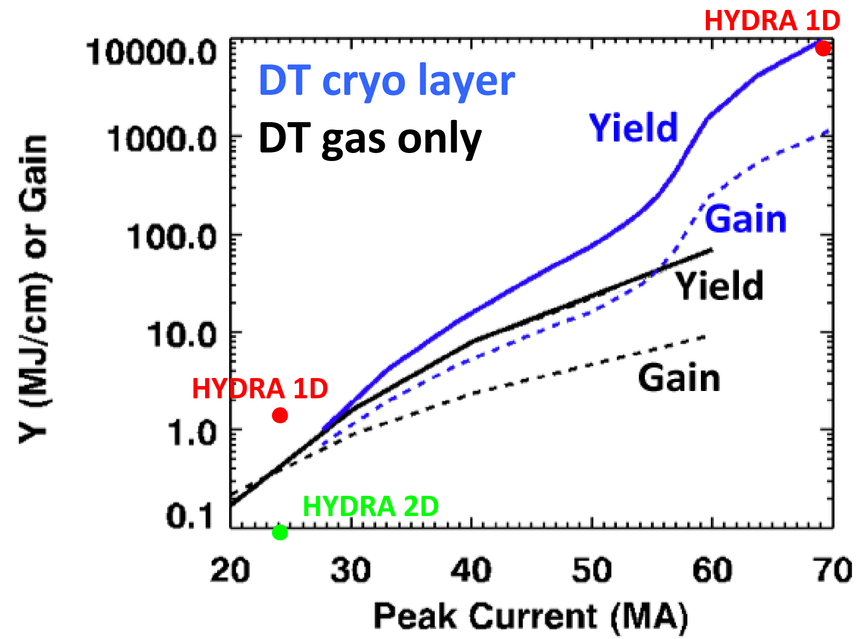
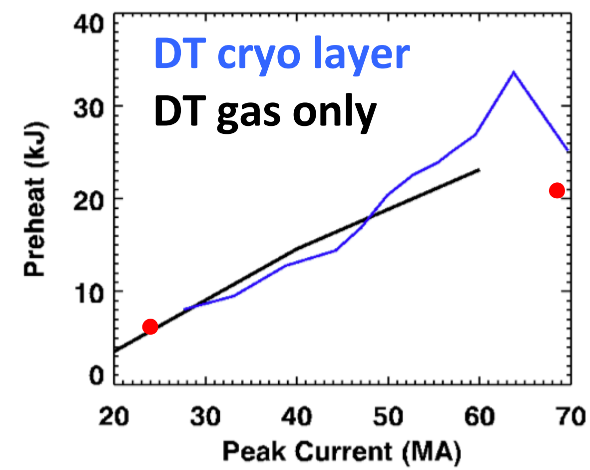
In principle*, MagLIF could achieve high gain using a cryogenic DT layer and substantial fuel preheat







An intermediate regime exists wherein the B_z field is

- ***strong enough*** **to reduce conduction losses, but**
- ***weak enough*** **not to inhibit the α deflagration wave**

** S. A. Slutz and R. A. Vesey, Phys. Rev. Lett. 108, 025003 (2012).*

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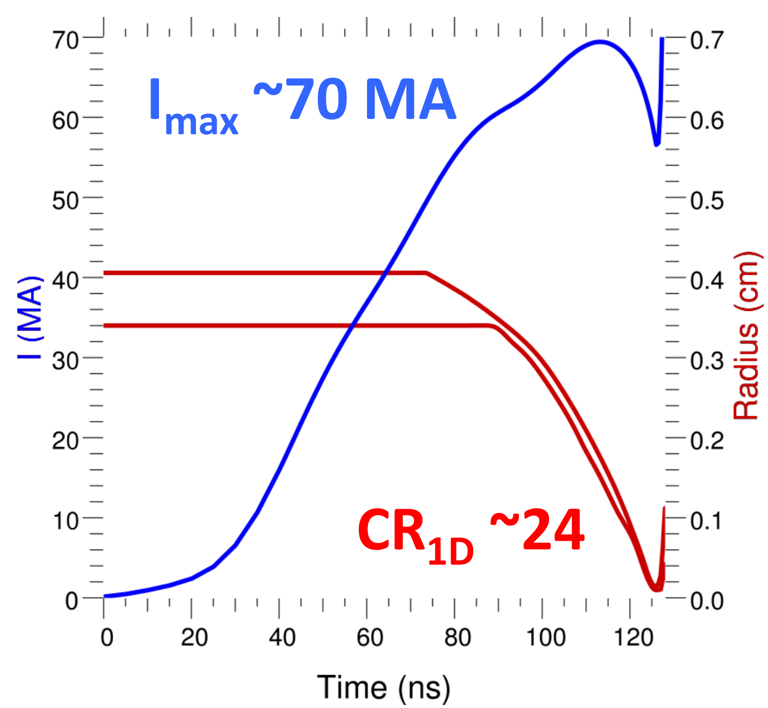
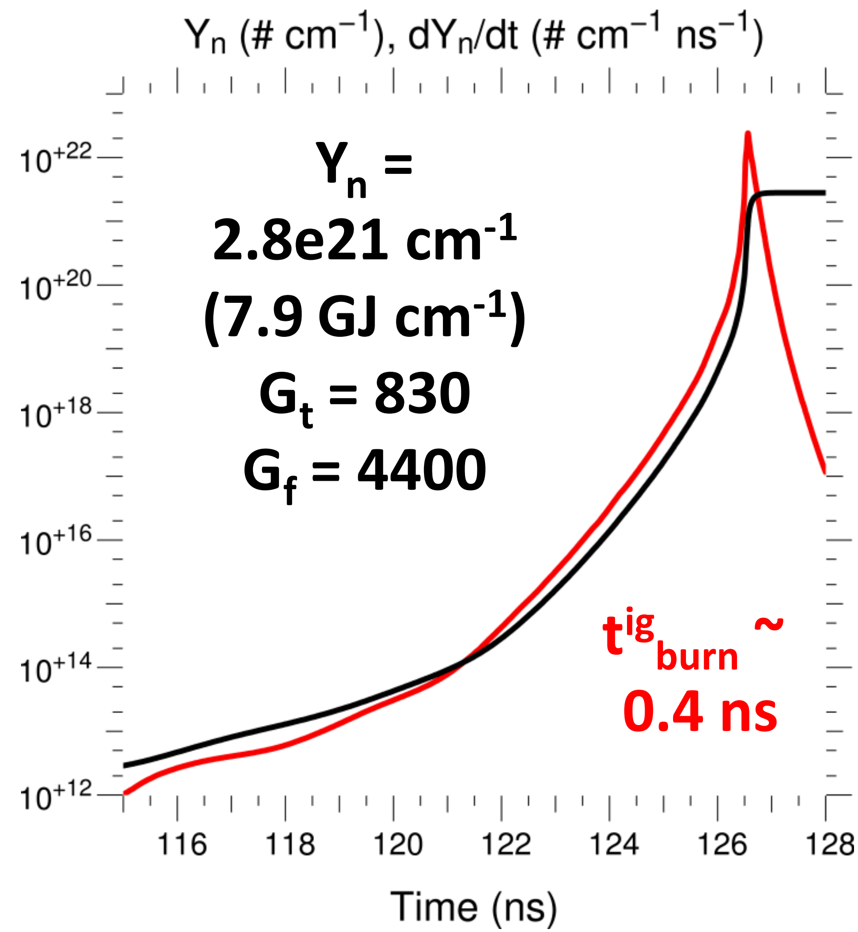
Ideal 1D HYDRA simulation of high-gain MagLIF experiments

High-gain MagLIF experiment:
L_{liner} = 10 mm, AR_{liner} = 6,
ρ_{gas} = 5 mg cm^{-3}, DT cryo fuel,
B_z^0 = 8T, E_{laser} = 21 kJ (0.66 TW)





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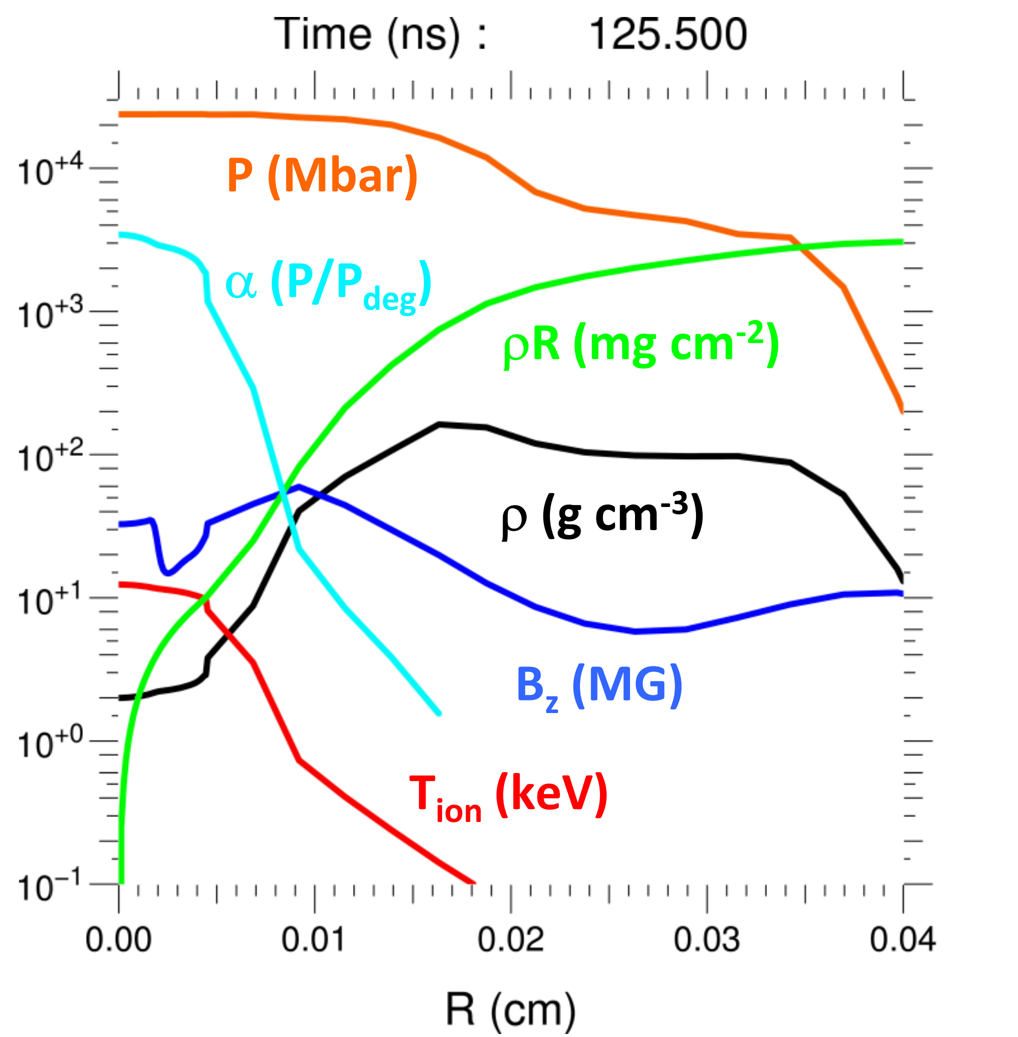
Ideal 1D HYDRA simulation of high-gain MagLIF experiments

High-gain MagLIF experiment:
L_{liner} = 10 mm, AR_{liner} = 6,
ρ_{gas} = 5 mg cm^{-3}, DT cryo fuel,
B_z^0 = 8T, E_{laser} = 21 kJ (0.66 TW)

~25 Gbar
~24% flux loss
~13 keV
~2 g cm^{-3} (hot spot)
~130 g cm^{-3} (main fuel)
~0.06 g cm^{-2} (hot spot)
~0.6 g cm^{-2} (main fuel)
~3.1 g cm^{-2} (liner)

Stagnation profile



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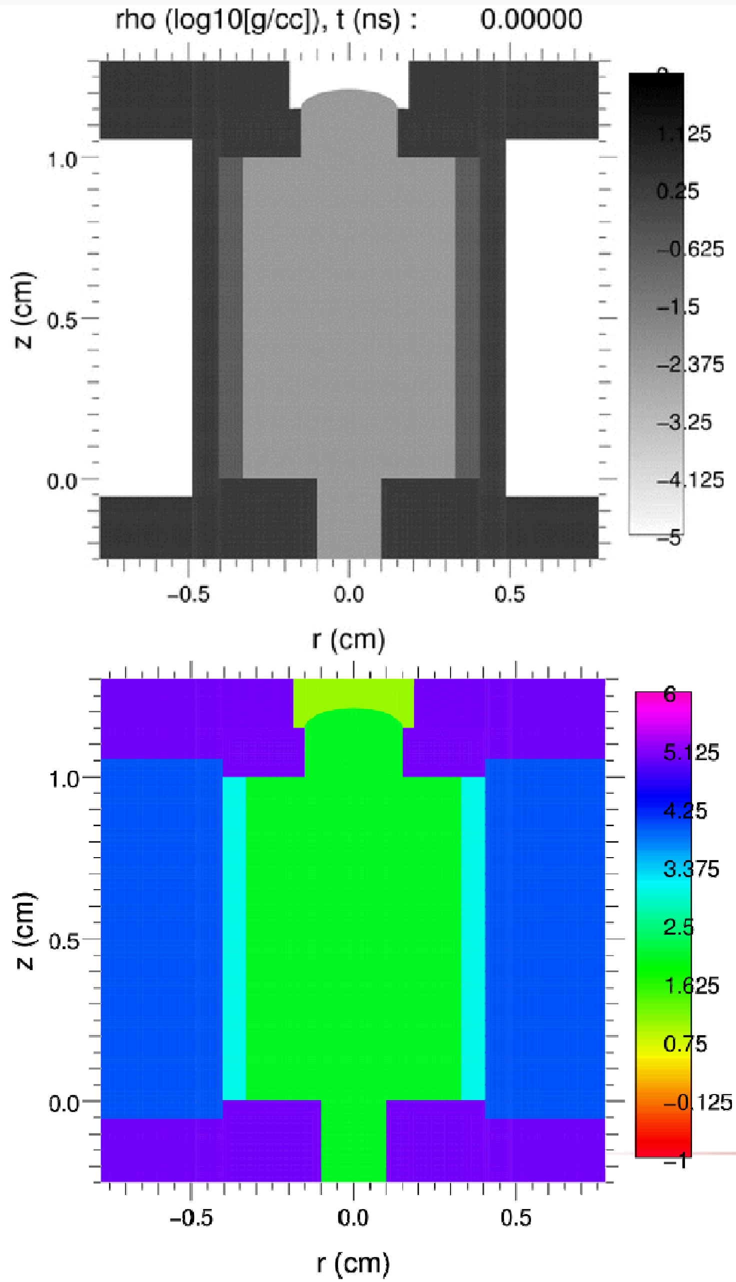
Integrated 2D HYDRA simulation of high-gain MagLIF experiments

High-gain MagLIF experiment:
L_{liner} = 10 mm, AR_{liner} = 6,
ρ_{gas} = 5 mg cm^{-3}, DT cryo fuel,
B_z^0 = 8T, E_{laser} = 25 kJ (0.78 TW)

Integrated 2D simulation uses 25 kJ laser in 32 ns = 0.78 TW (I_L~5e13 W cm^{-2}) and gives E_{gas} = 15 kJ at end of pulse

Ideal 1D case had E_{gas} = 17 kJ at end of heating (from 21 kJ total), since some is lost to radiation and the solid fuel

Integrated 2D simulations can ignite with CR_{2D} slightly higher than CR_{1D} and achieve a majority fraction of Y_{1D}.



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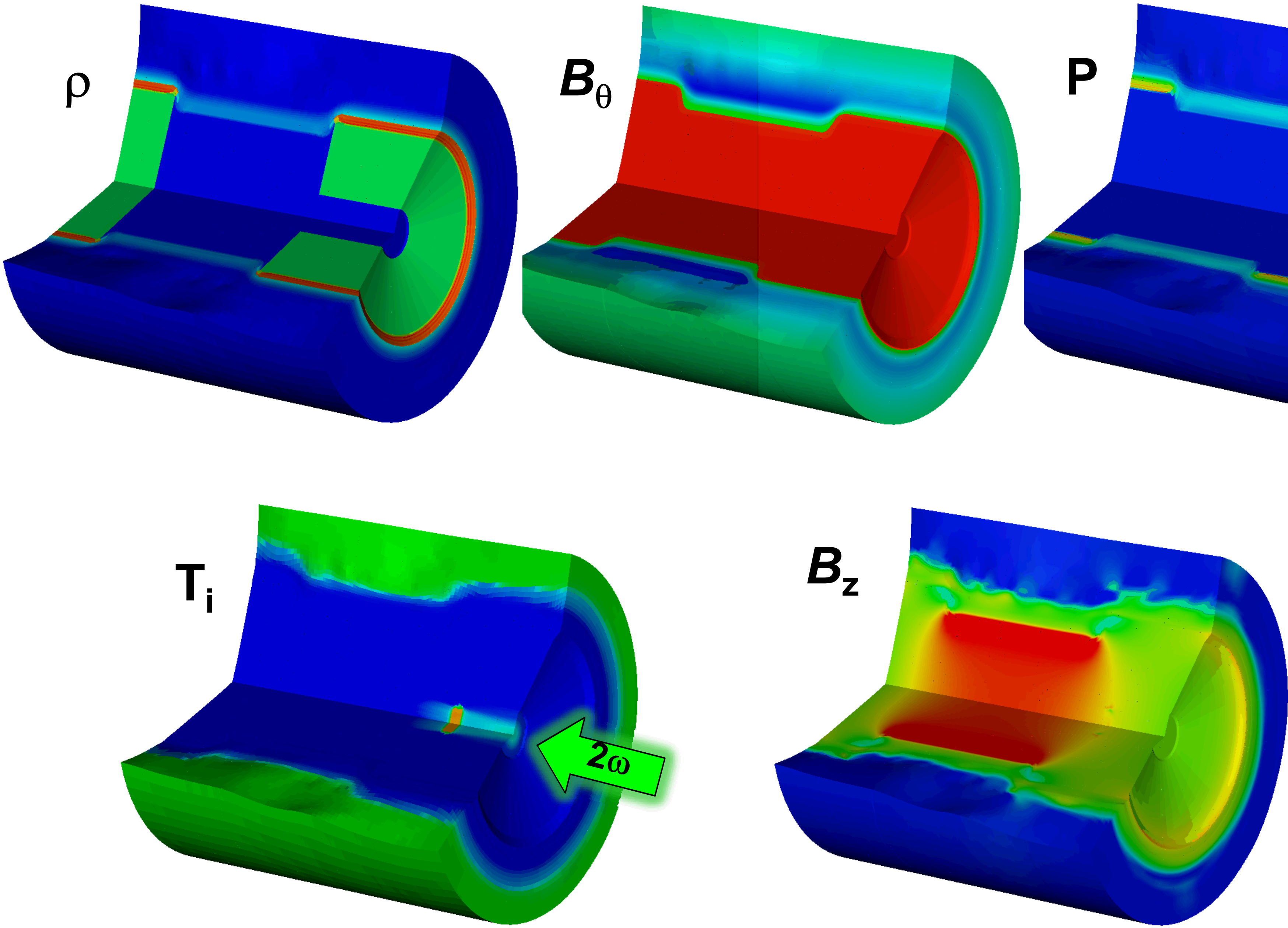
Integrated MagLIF simulations are making progress in 3D



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Summary

Magnetically-driven implosions of liners containing magnetized and preheated fuel may enable significant ICF yields on pulsed-power accelerators

We are benchmarking simulations to ongoing “focused” experiments involving flux compression (liner and B_z only) and fuel preheating (laser and B_z only)

Integrated calculations provide realistic design requirements for MagLIF experiments, as well as “clean 2D” integrated experiment predictions

Integrated experiments to measure neutrons will occur soon !