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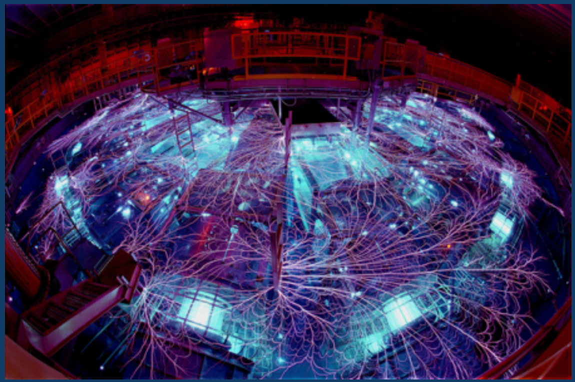

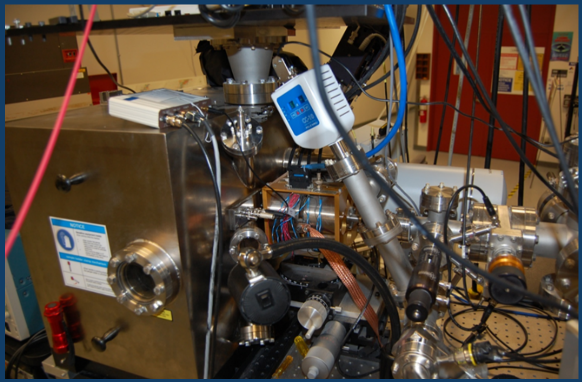

Design of MagLIF experiments

A. B. Sefkow

Radiation Effects and High Energy Density Sciences Research Foundation External Review, May 20-22, 2014

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

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Outline

Sandia National Laboratories

- What is the Magnetized Liner Inertial Fusion (MagLIF) approach at Sandia?
- What are the expectations for near-term experiments with present parameters?
- What are the expectations for future experiments with upgraded parameters?

Outline

- **What is the Magnetized Liner Inertial Fusion (MagLIF) approach at Sandia?**
- 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

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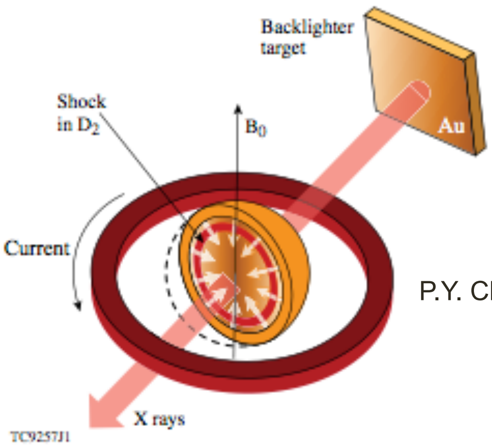
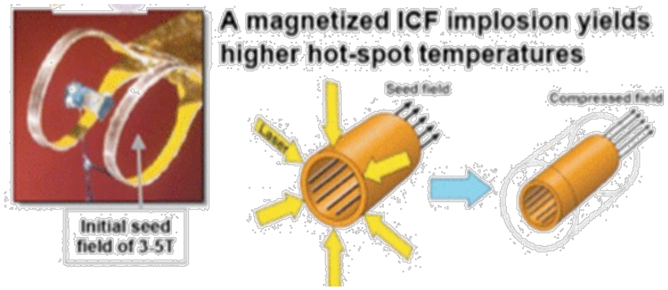
University of Rochester/LLE

2011 Demonstration of enhanced fusion yield with magnetization (Y_n^{DD} ~ 5e9)



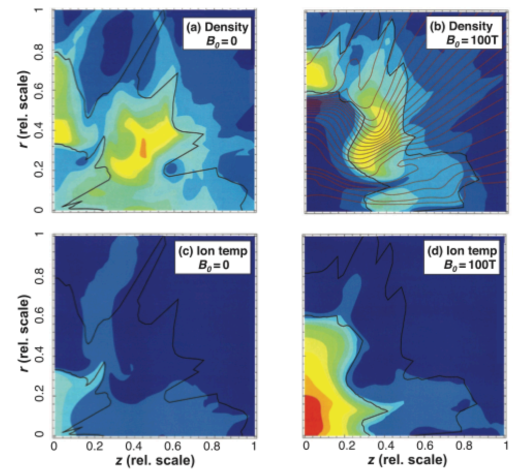
P.Y. Chang *et al.*, PRL (2011).



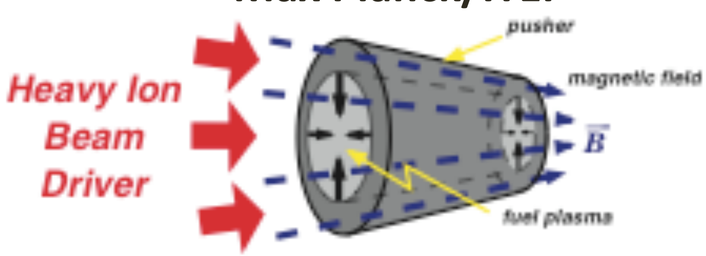
Gotchev *et al.*, *Rev. Sci. Instr.* **80**, 043504 (2009)

LLNL

(Perkins et al., Phys Plasmas 2013)



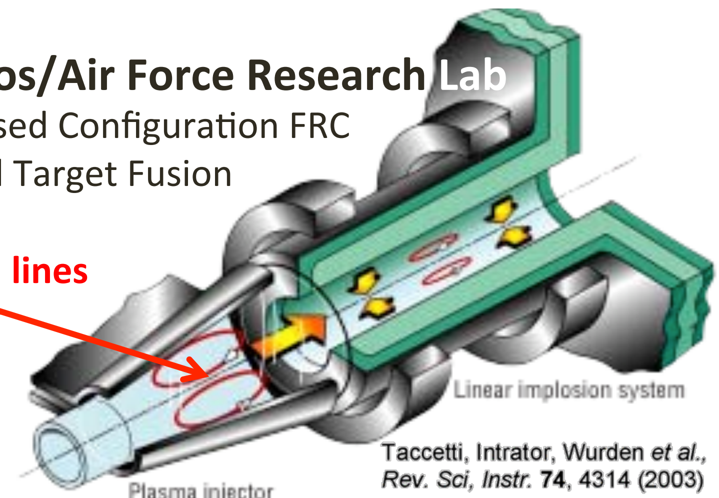
Max Planck/ITEP



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

Los Alamos/Air Force Research Lab

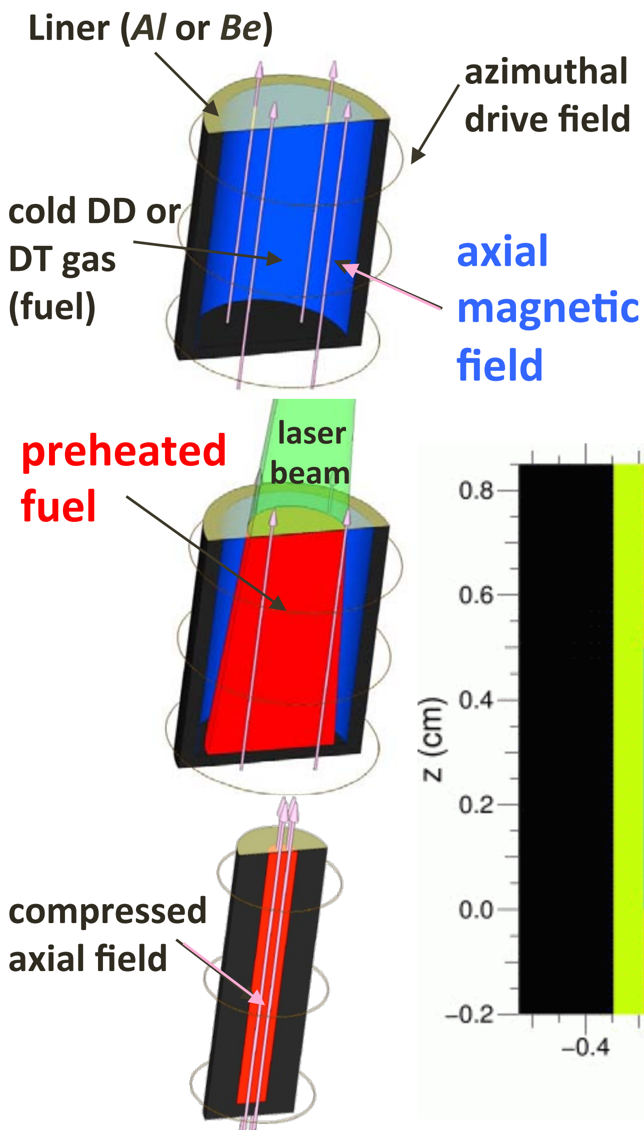
Field Reversed Configuration FRC
Magnetized Target Fusion
Shiva Star
closed field lines
FRC



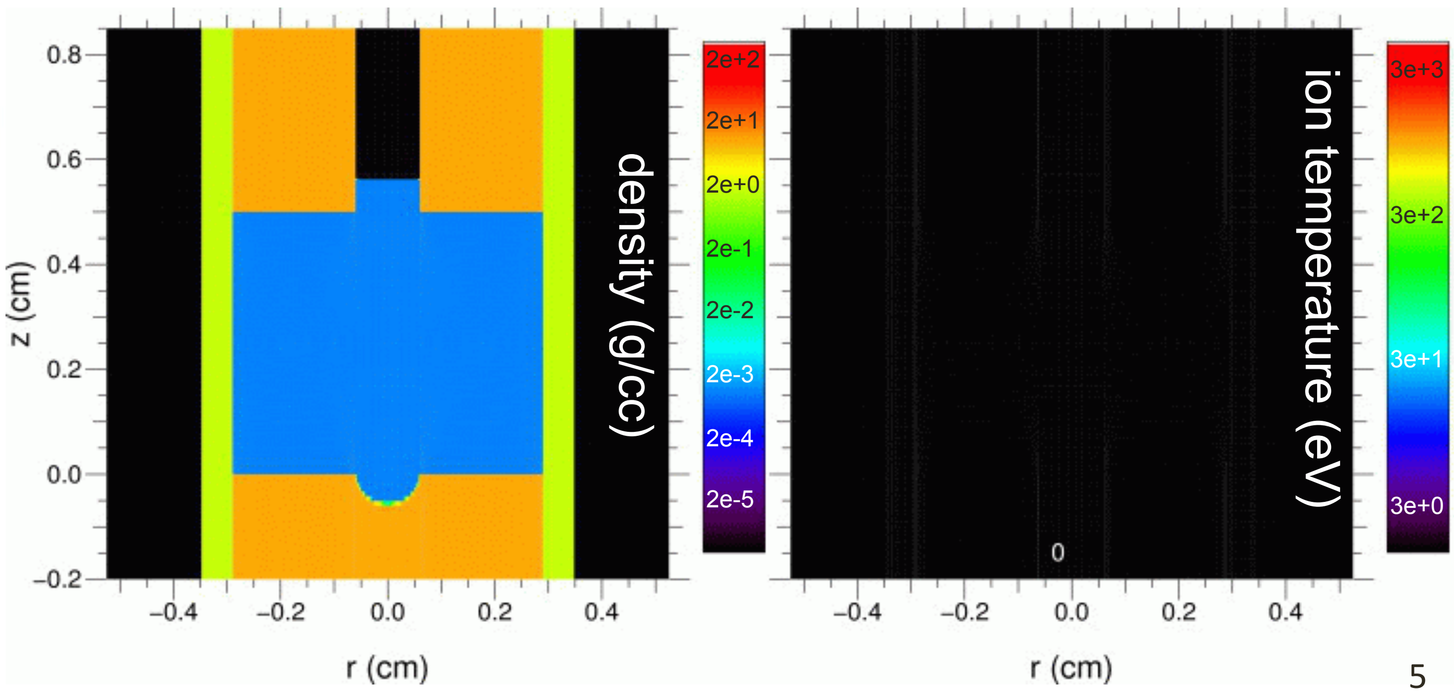
Taccetti, Intrator, Wurden *et al.*, *Rev. Sci, Instr.* **74**, 4314 (2003)
Degnan *et al.*, *IEEE Trans. Plas. Sci.* **36**, 80 (2008)

and many others…

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

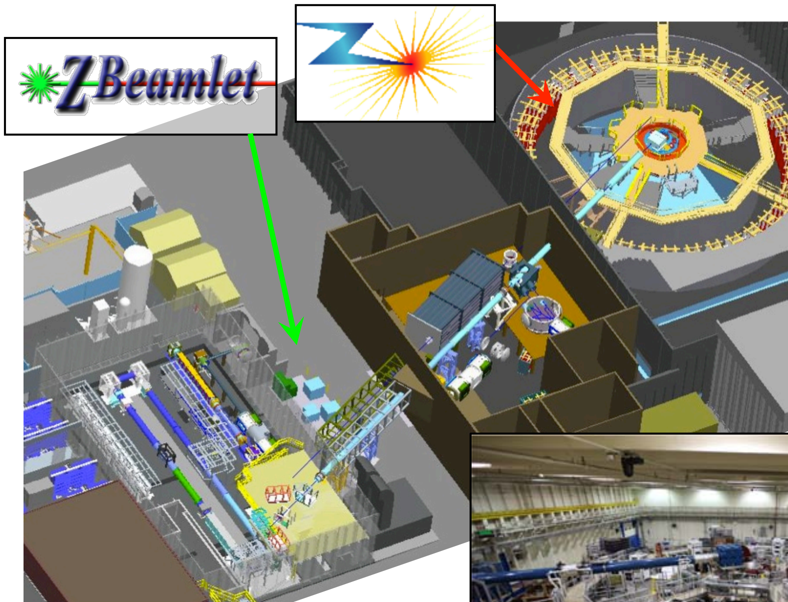


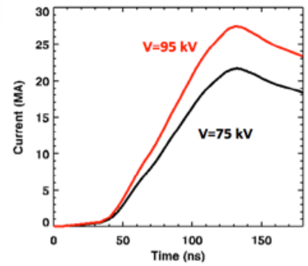
- The initial B_z~10-40 T flux is compressed to ~5-15 kT (~50-150 MG)
  - to reduce thermal electron conduction losses
  - to enable low ρR_{fuel} ignition ($B_z R_{fuel}$ and ρR_{liner} required instead)
- The fuel is **preheated** using the Z-Beamlet laser in order to reduce:
  - the convergence ratio (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)
- ***Thermonuclear yields have been measured on Z***



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

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

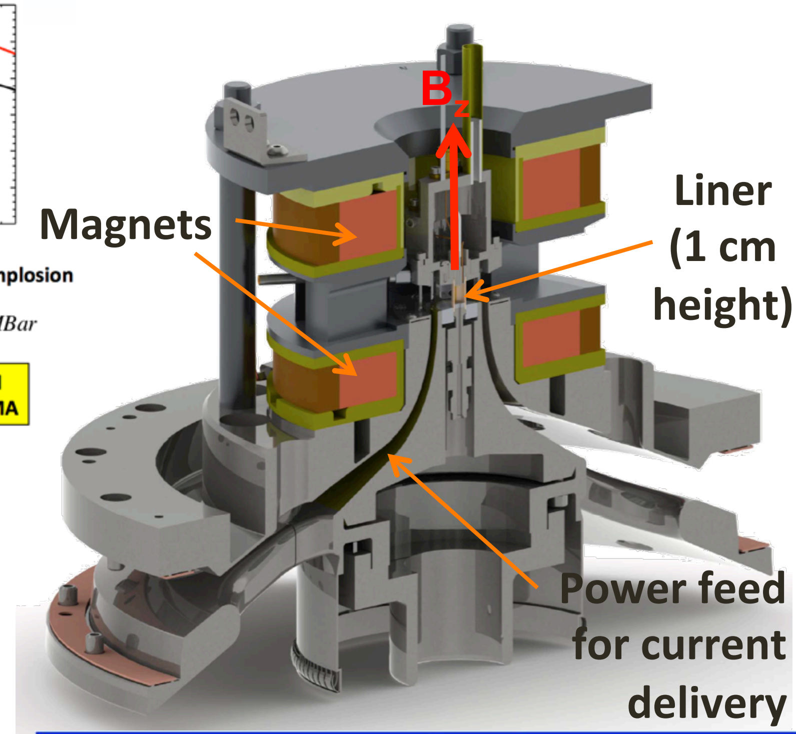


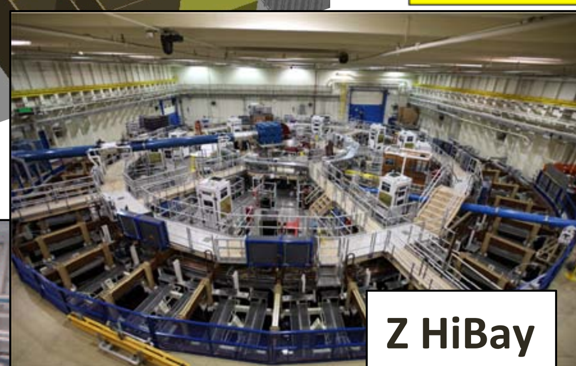


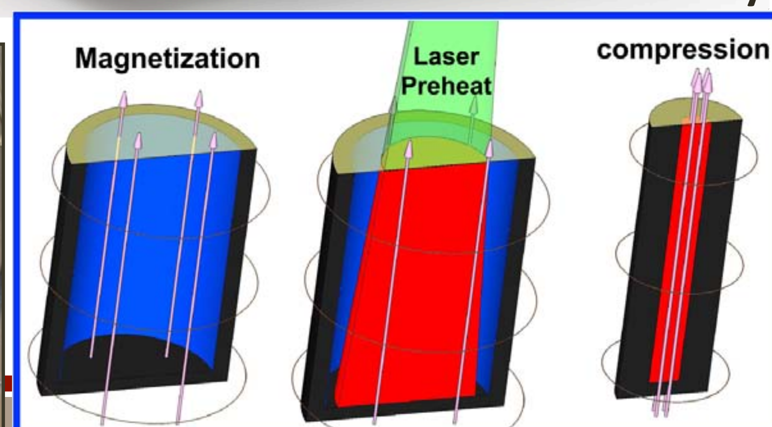
Magnetically-Driven Cylindrical Implosion

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

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







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- **What are the expectations for near-term experiments with present parameters?**
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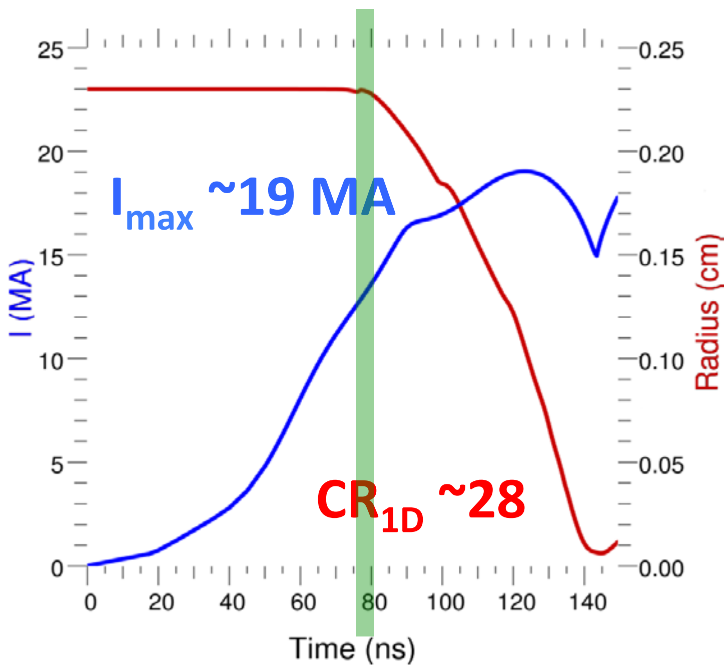
Ideal 1D HYDRA simulation of near-term experiments on Z using available parameters

Sandia National Laboratories

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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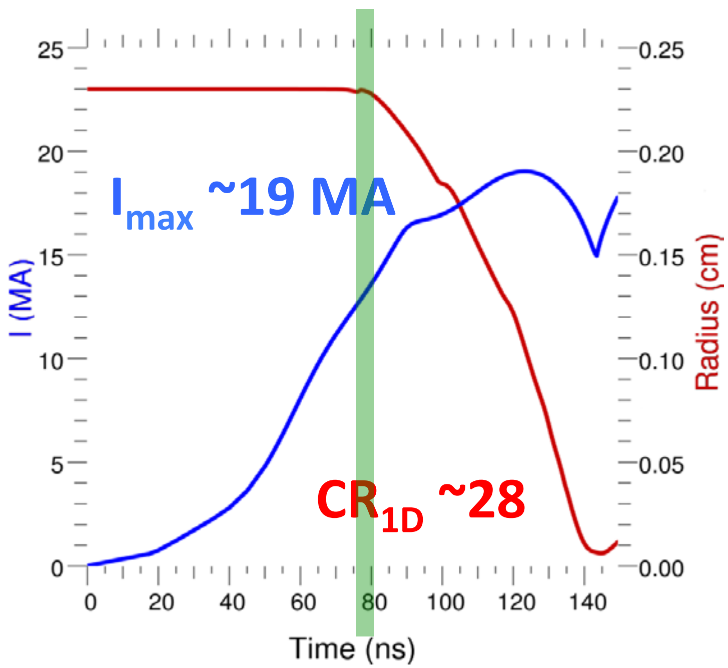

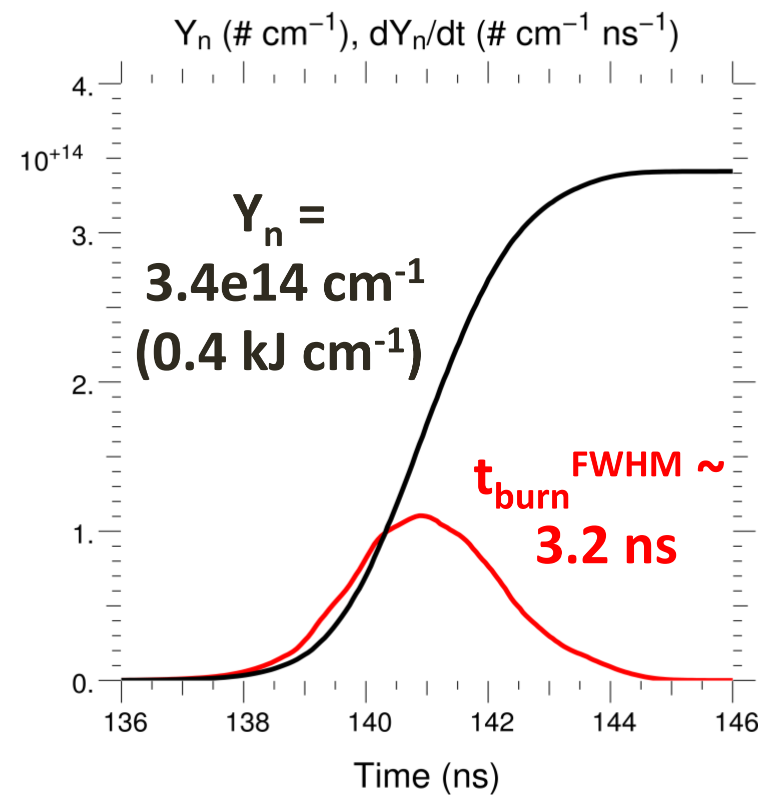

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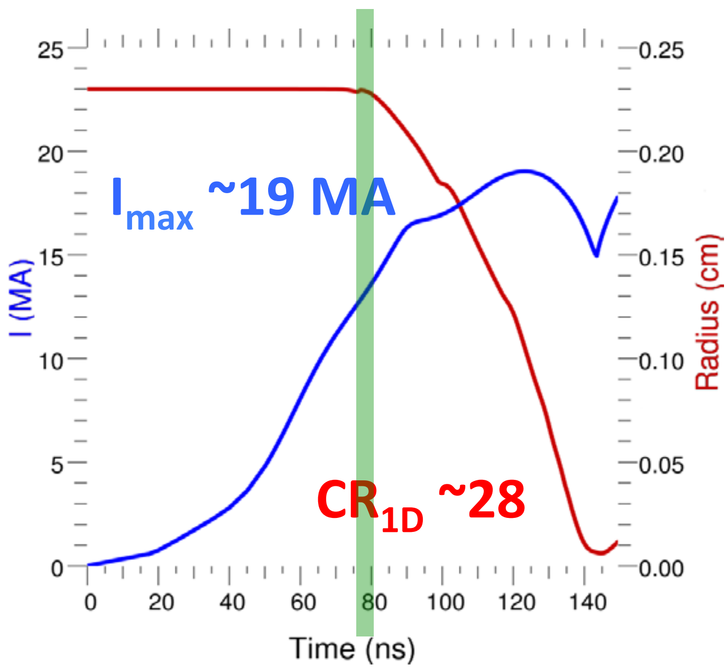
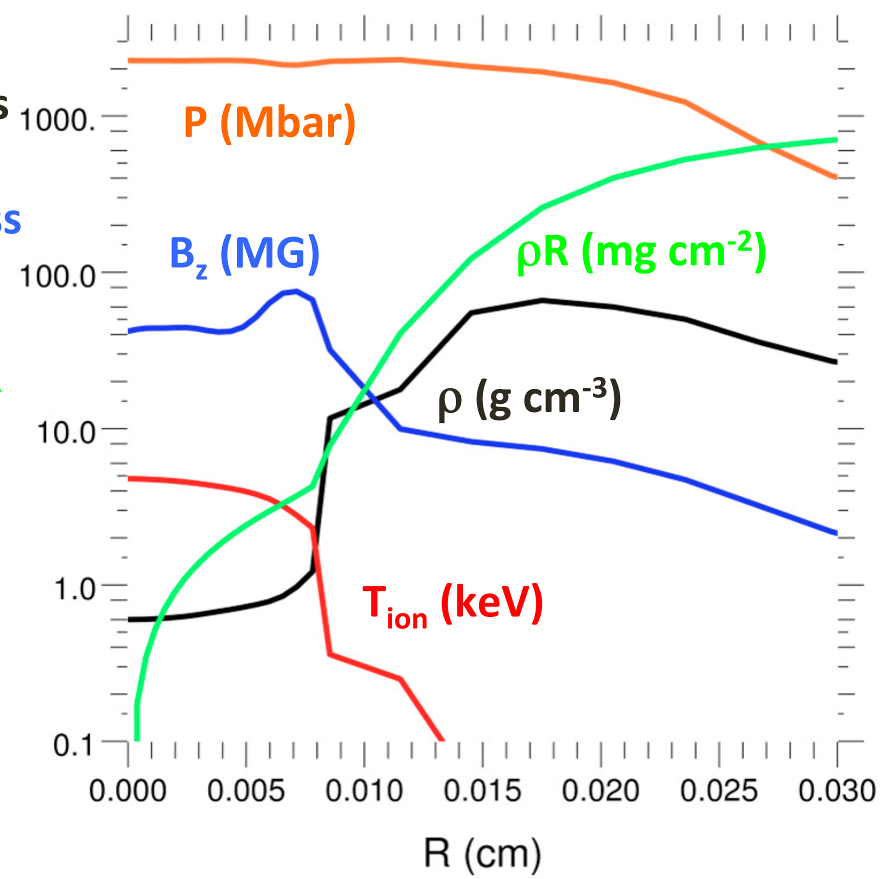


r_{stag}~84 μm
v_{imp}~70 km/s
~2.2 Gbar
~36% flux loss
~5 keV
~0.6 g cm^{-3}
~6e-3 g cm^{-2}

IFAR O[1]
at peak v_{imp}

Stagnation profile



An **integrated 2D** model seeks to realistically simulate experiments as they would occur on Z

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

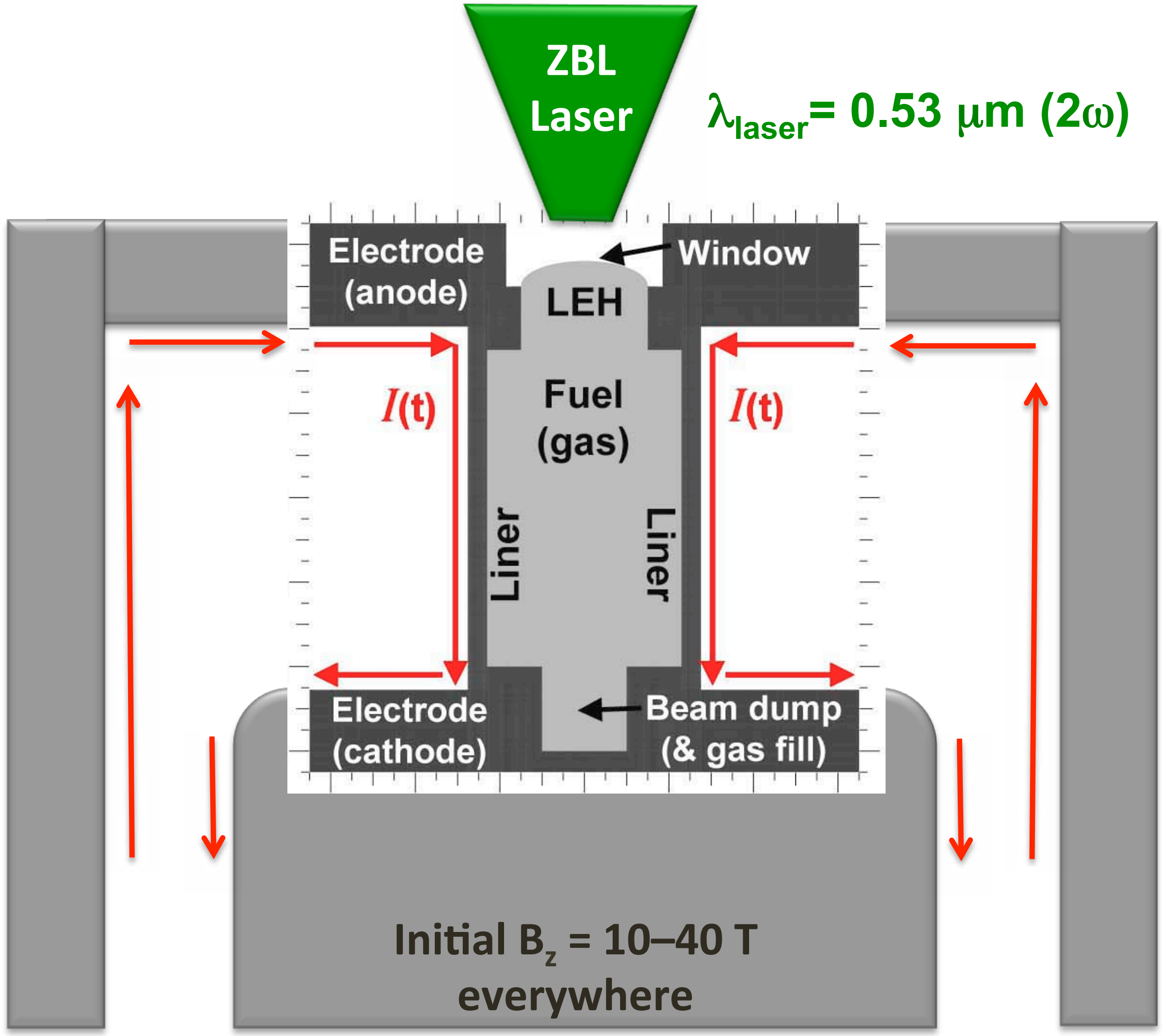
(1) Laser

(2) Laser entrance hole (LEH) and window

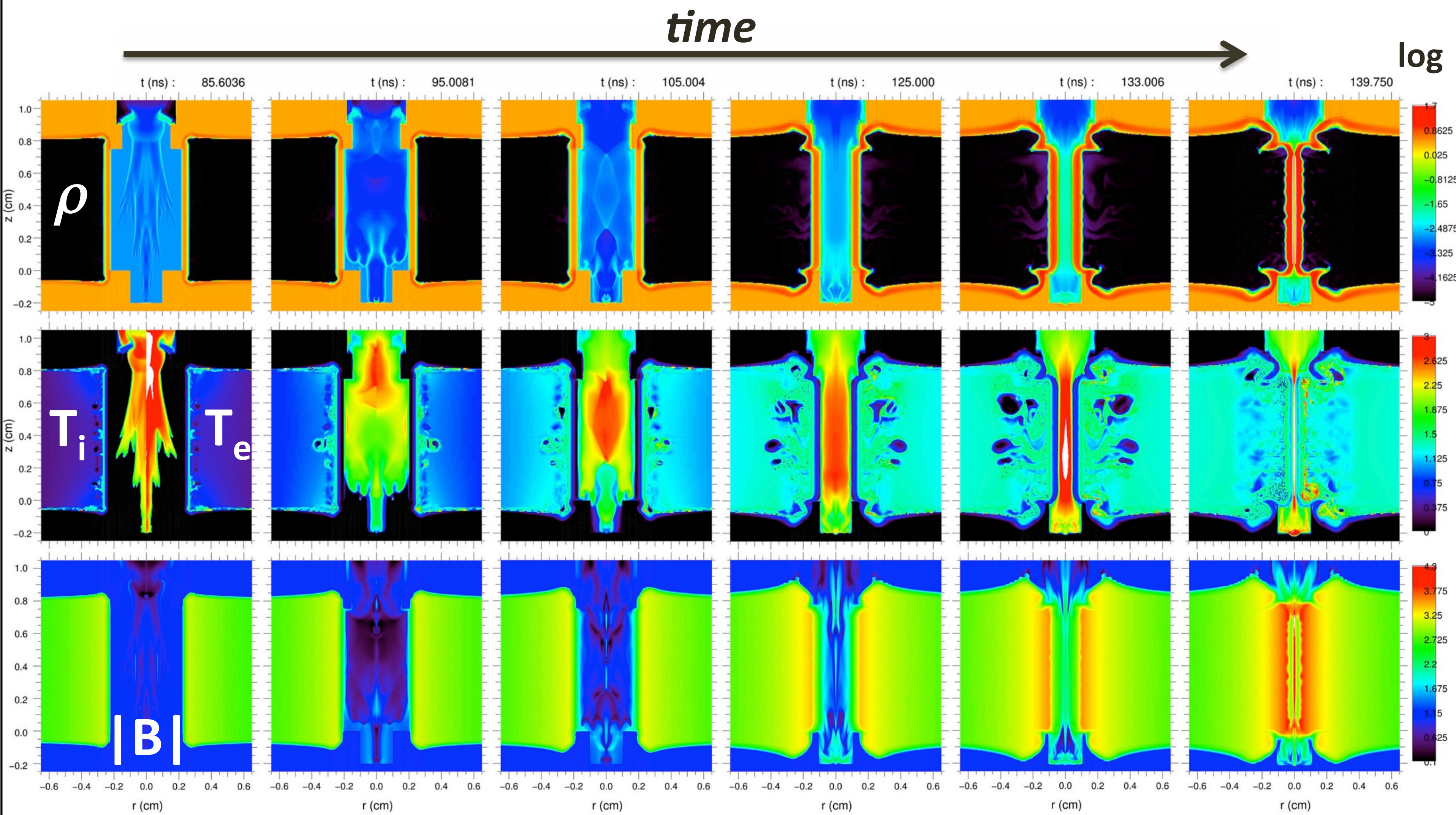
(3) Liner and circuit

(4) Electrode end caps

(5) Component interactions, timing, and optimization



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



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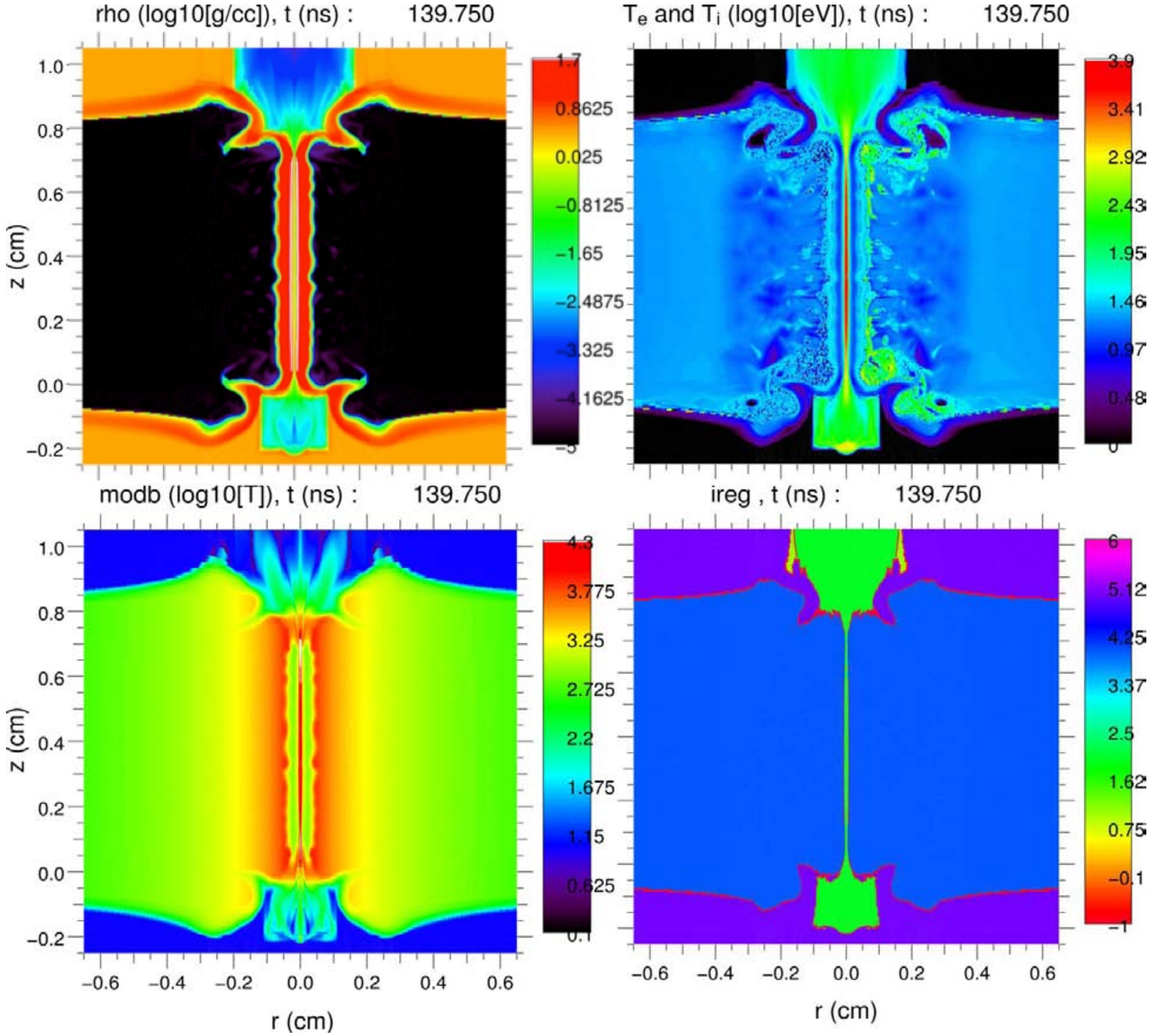

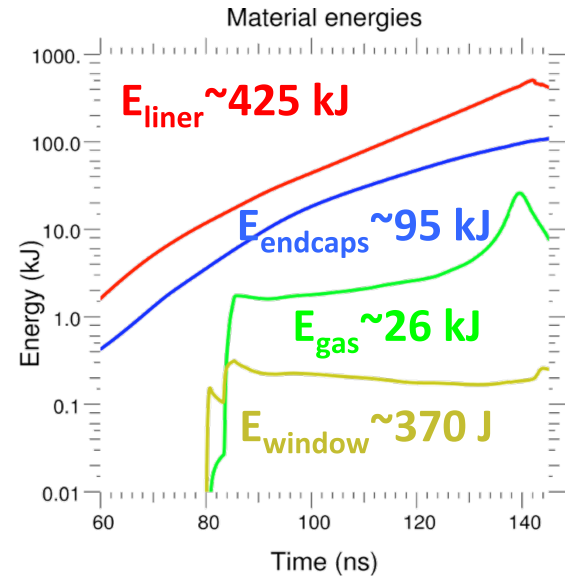

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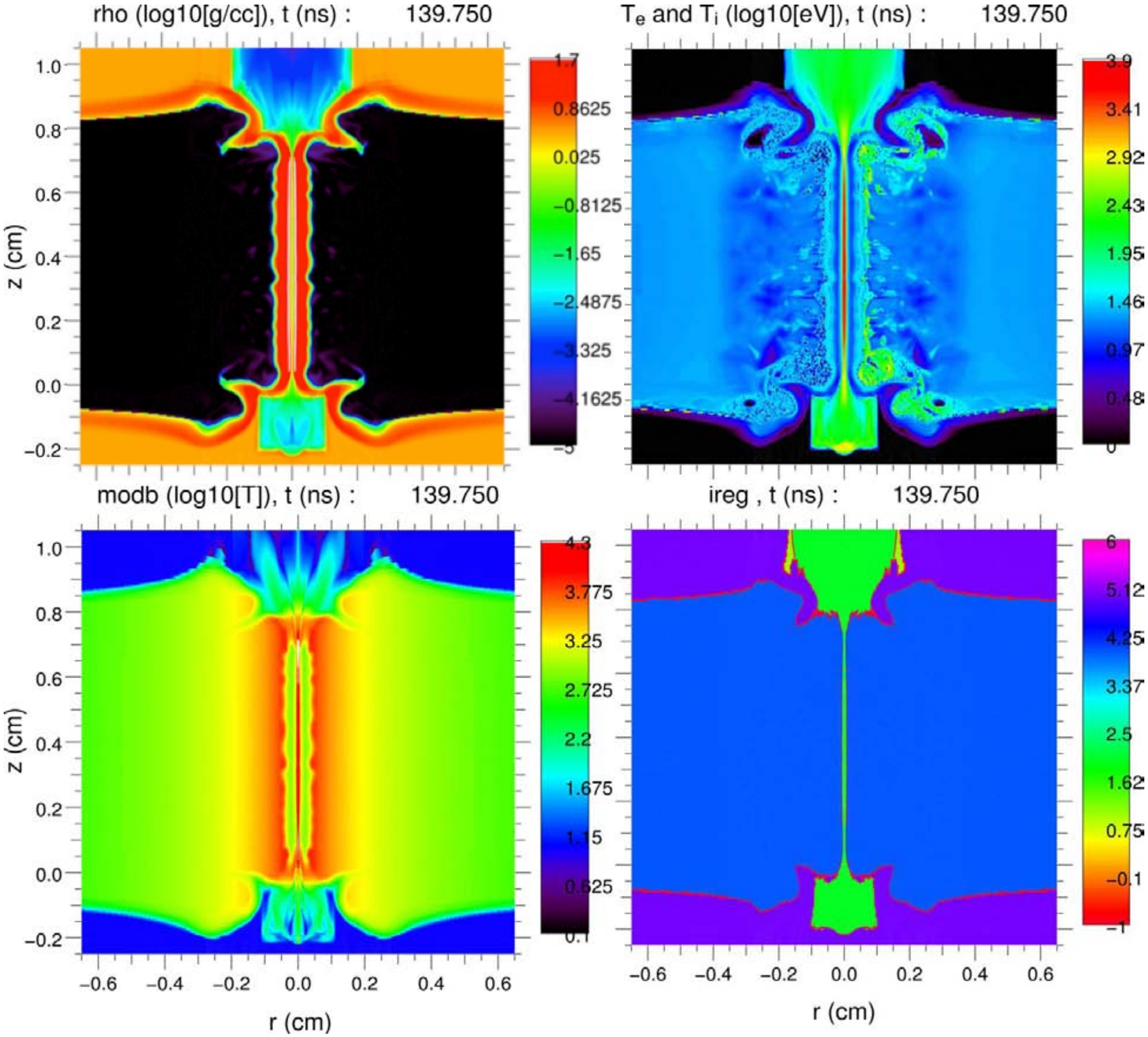
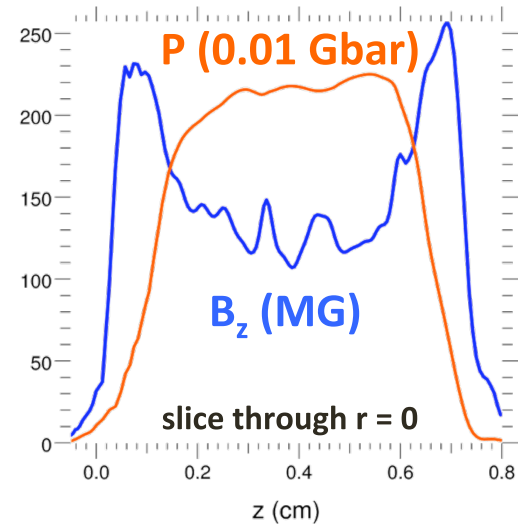


Magnetic bottle



β~0.25 β~4 β~0.25

Comparison between ideal 1D and integrated 2D simulation using available parameters

Parameter	1D ideal	2D integrated
• E_{gas}^{abs}	2.00 kJ	1.74 kJ
• m_{loss}	0%	43%
• Φ_{loss}	36%	38%
• CR_{2D}	28 (r_{stag} 84 μm)	37 (r_{stag} 63 μm)
• T_i^{peak}	5.0 keV	6.5 keV
• $\langle T_i \rangle^{DD}$	2.9 keV	3.2 keV
• ρ_{gas}^{stag}	0.6 g cm^{-3}	0.5 g cm^{-3}
• ρR_{liner}^{stag}	1.0 g cm^{-2}	0.9 g cm^{-2}
• P^{stag}	2.5 Gbar	2.2 Gbar (peak in bottle)
• $B_z^f r_{stag}$	4.1e5 G cm (r_{stag}/r_α 1.5)	5.3e5 G cm (r_{stag}/r_α 2.0)
• Y_n^{DD}	2.6e14 (in 7.5mm)	6.1e13 (24% of 1D)
• Y_n^{DD}/Y_n^{DT}	23	44
• t_{burn}^{FWHM}	3.2 ns	2.1 ns

Liner length and gas density variations for near-term integrated 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

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

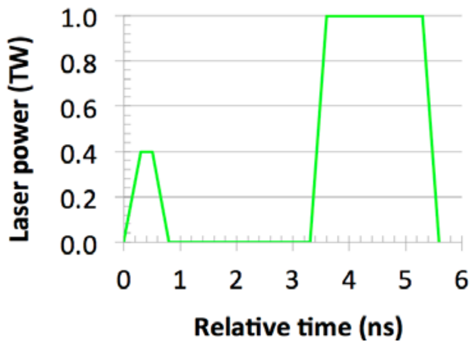
	Liner = 5 mm (I_{max}~20 MA)	Liner = 7.5 mm (I_{max}~19 MA)	Liner = 10 mm (I_{max}~18 MA)
ρ_{gas} = 0.8 mg/cc dz_{window} ~1.1 μm	CR_{2D} 46 m_{loss} 73%	CR_{2D} 42 m_{loss} 60%	CR_{2D} 33 m_{loss} 43%
ρ_{gas} = 1.1 mg/cc dz_{window} ~1.5 μm	CR_{2D} 42 m_{loss} 68%	CR_{2D} 37 m_{loss} 51%	CR_{2D} 33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

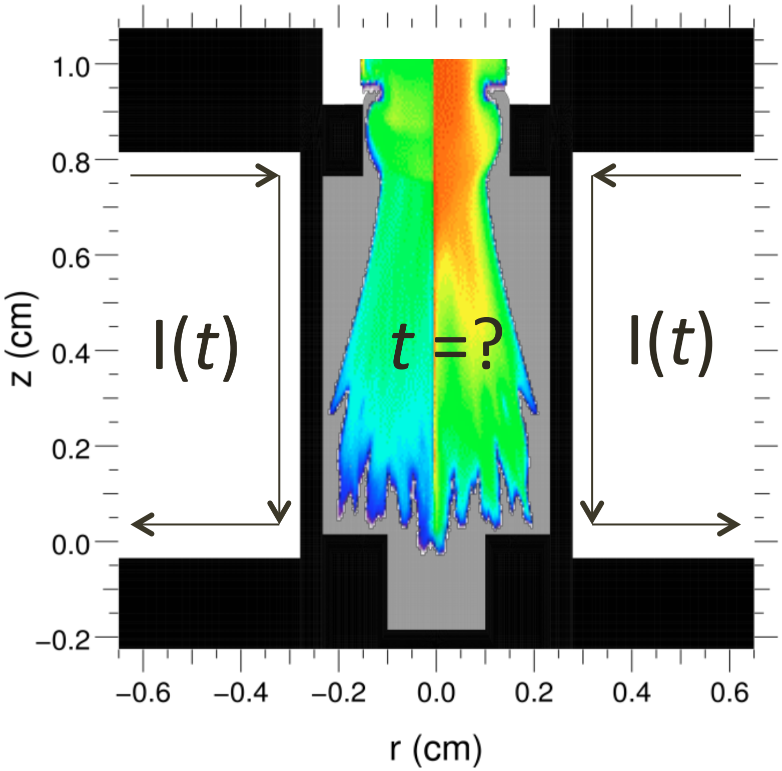
Liner length and gas density variations for near-term integrated experiments on Z

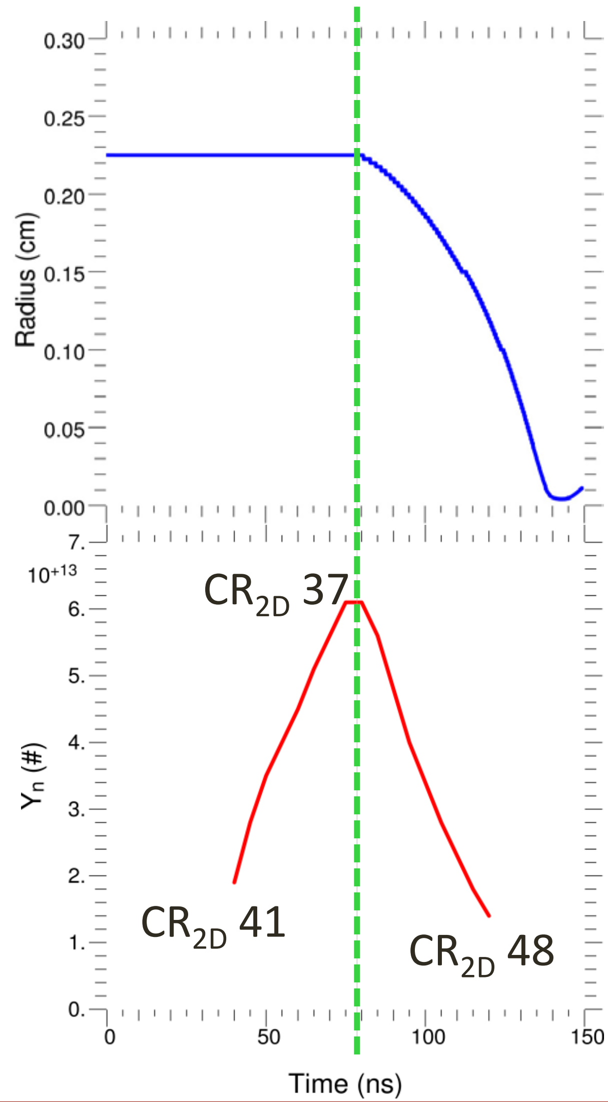
	Liner = 5 mm (I_{max}~20 MA)	Liner = 7.5 mm (I_{max}~19 MA)	Liner = 10 mm (I_{max}~18 MA)
ρ_{gas} = **0.8 mg/cc** dz_{window} ~1.1 μm	$\langle T_i \rangle$ 3.4 keV Y_n^{DD} $1.4*10^{13}$	$\langle T_i \rangle$ 4.4 keV Y_n $6.5*10^{13}$	$\langle T_i \rangle$ 3.6 keV Y_n^{DD} $8.3*10^{13}$
ρ_{gas} = **1.1 mg/cc** dz_{window} ~1.5 μm	$\langle T_i \rangle$ 3.8 keV Y_n^{DD} $2.0*10^{13}$	$\langle T_i \rangle$ 3.5 keV Y_n $7.0*10^{13}$	$\langle T_i \rangle$ 3.0 keV Y_n^{DD} $6.5*10^{13}$
ρ_{gas} = **1.5 mg/cc** dz_{window} ~2.0 μm	$\langle T_i \rangle$ 3.1 keV Y_n^{DD} $2.3*10^{13}$ **5% of 1D**	$\langle T_i \rangle$ 3.2 keV Y_n^{DD} $6.1*10^{13}$ **24% of 1D**	$\langle T_i \rangle$ 2.4 keV Y_n^{DD} $4.8*10^{13}$ **32% of 1D**
ρ_{gas} = **2.0 mg/cc** dz_{window} ~2.7 μm	$\langle T_i \rangle$ 2.9 keV Y_n^{DD} $3.3*10^{13}$	$\langle T_i \rangle$ 2.3 keV Y_n^{DD} $2.5*10^{13}$	$\langle T_i \rangle$ 2.2 keV Y_n^{DD} $1.9*10^{13}$

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

Laser timing variations for near-term integrated experiments on Z







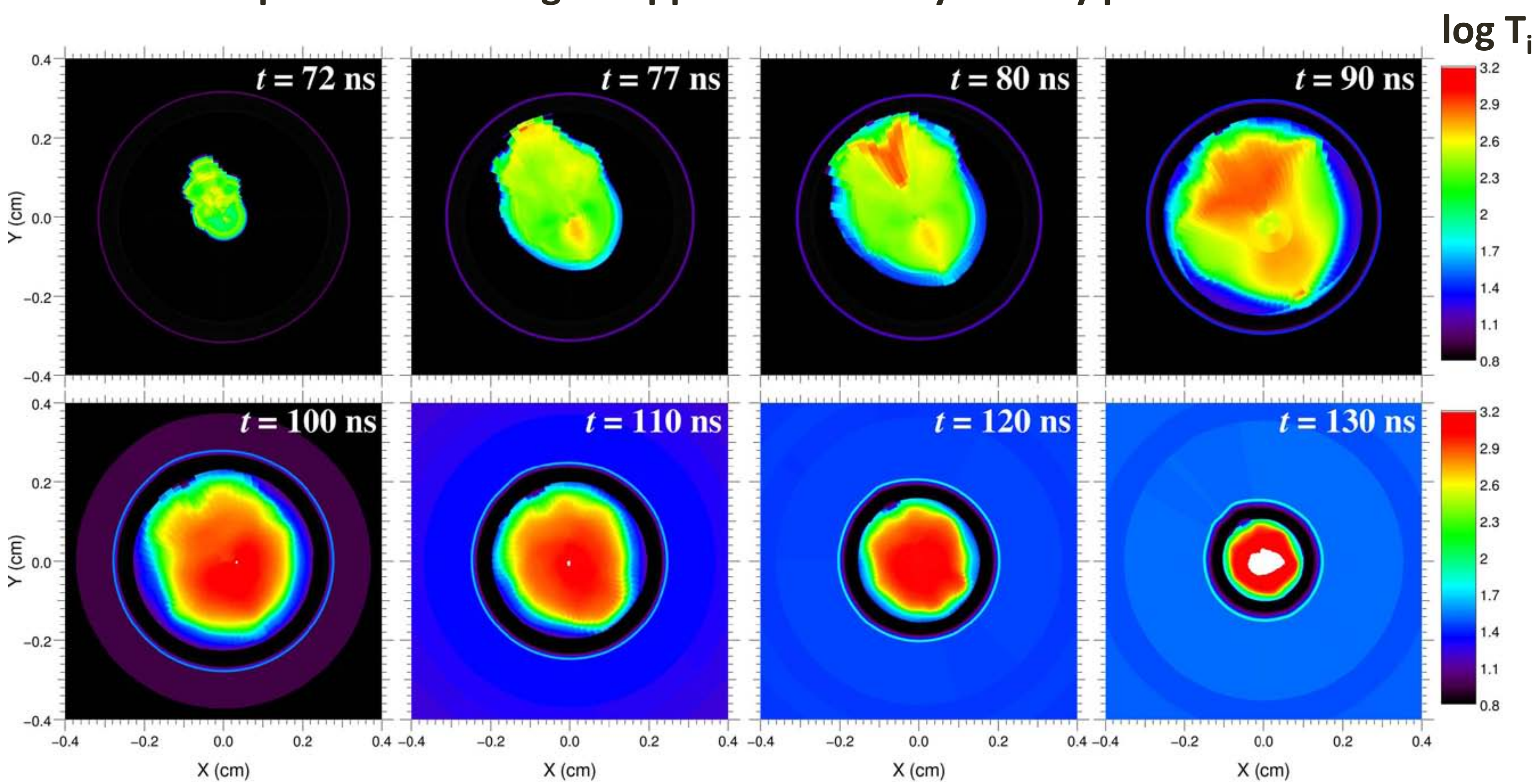
The **optimal laser timing** balances competing effects:

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

Later:
Less effective compression

Non-axisymmetric heating from a non-uniform laser is predicted to isotropize during compression

Off-centered and unsmooth laser heating can equilibrate and regain approximate axisymmetry prior to CR ~ 2



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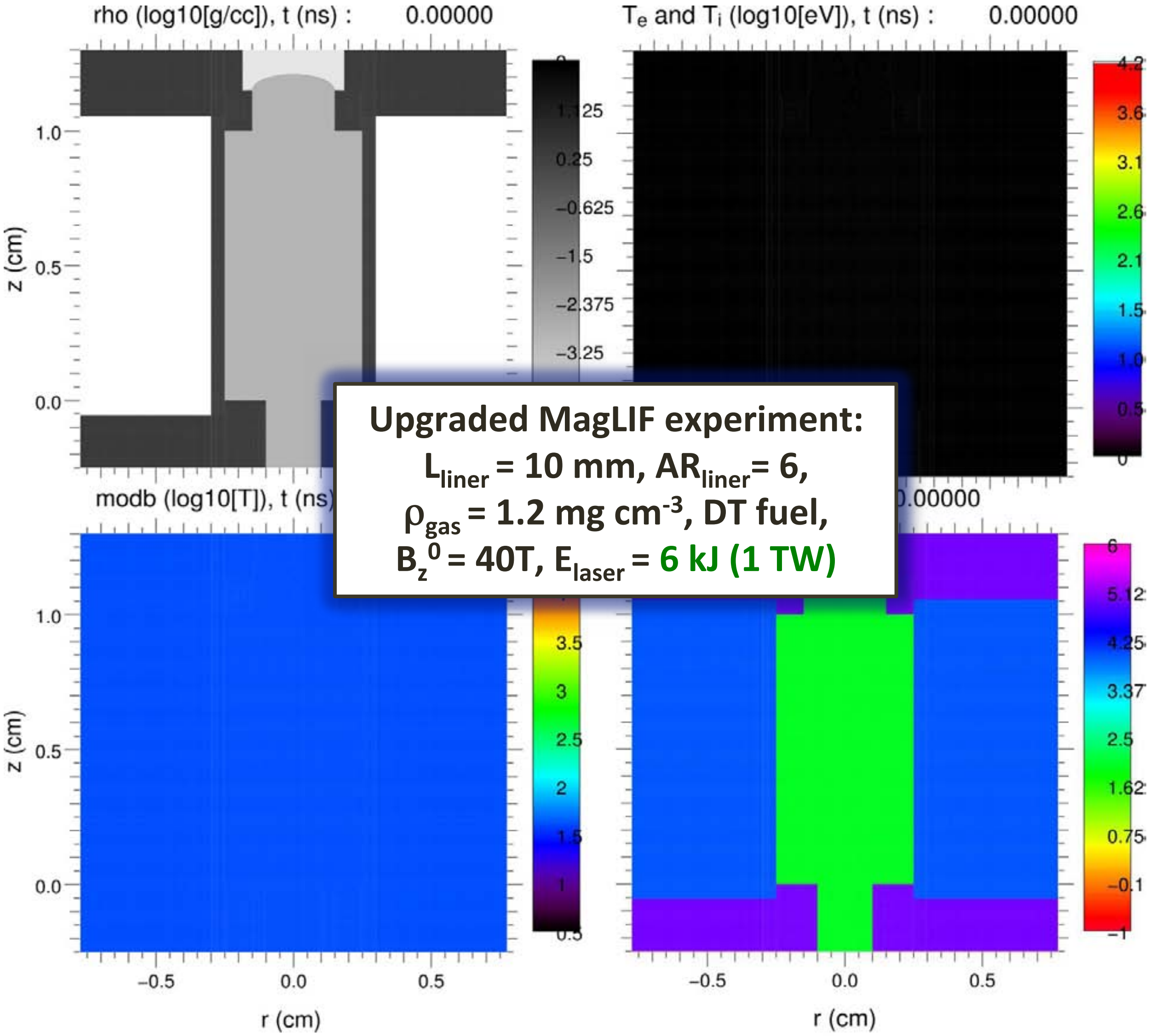
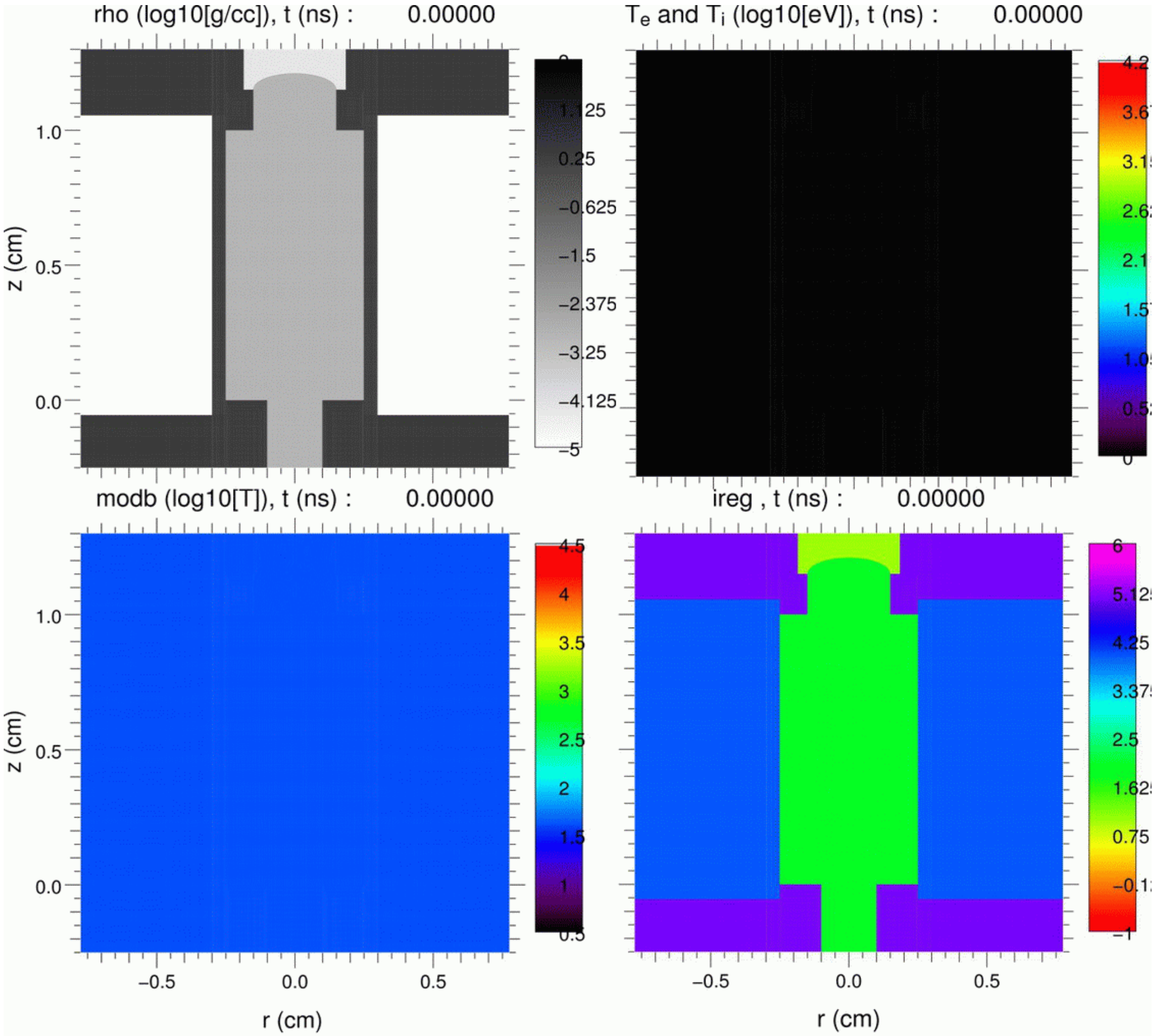
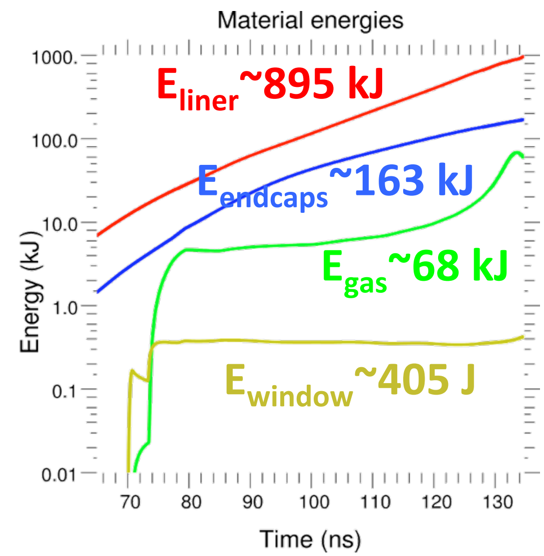
Integrated 2D HYDRA simulation of experiments on Z using upgraded parameters



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)

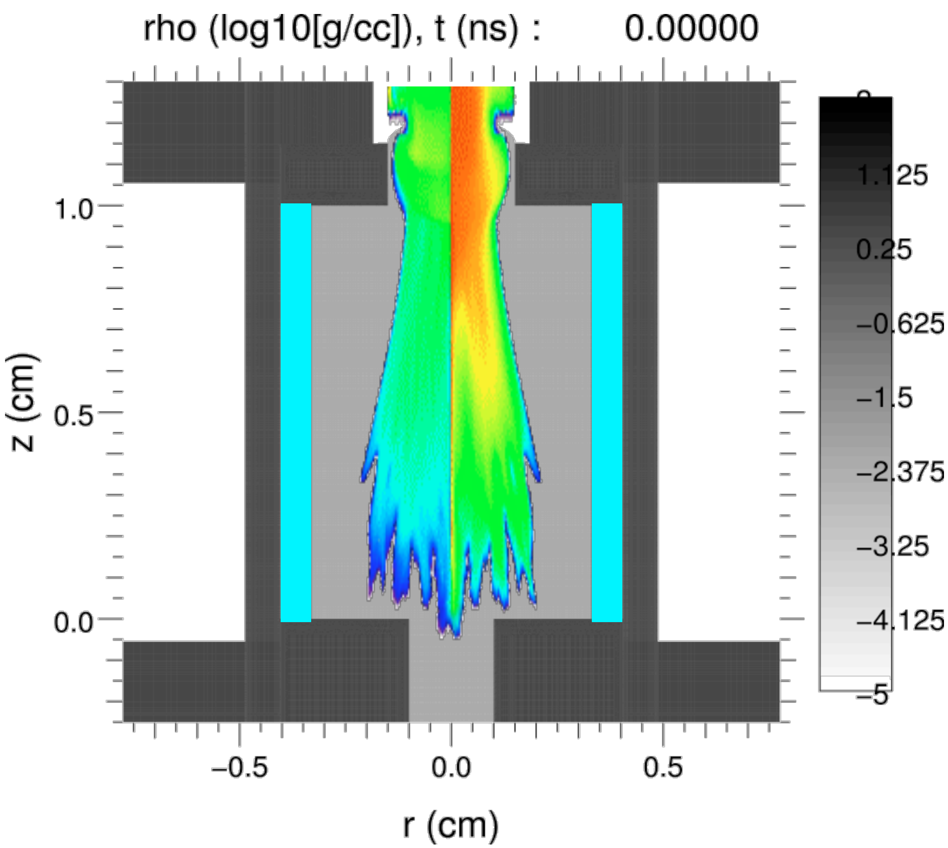
Integrated 2D HYDRA simulation of experiments on Z using upgraded parameters

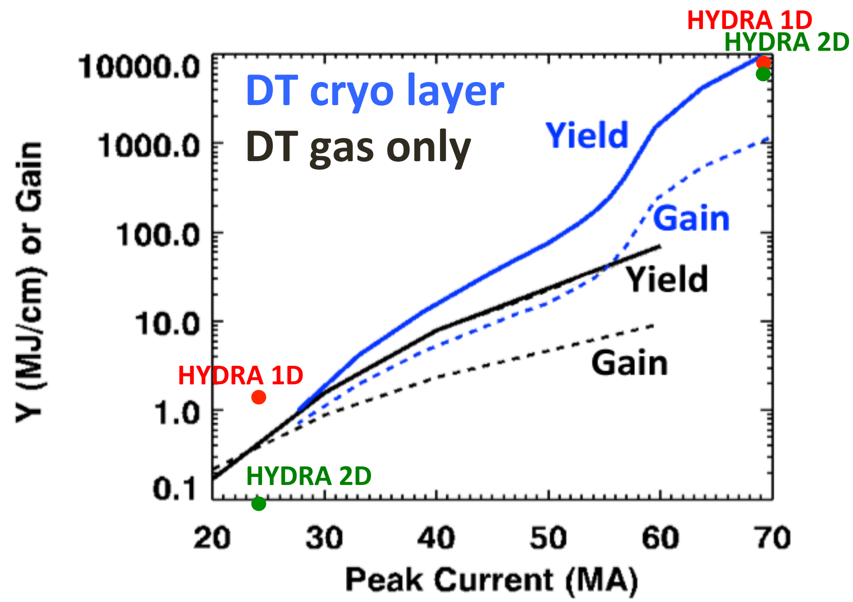


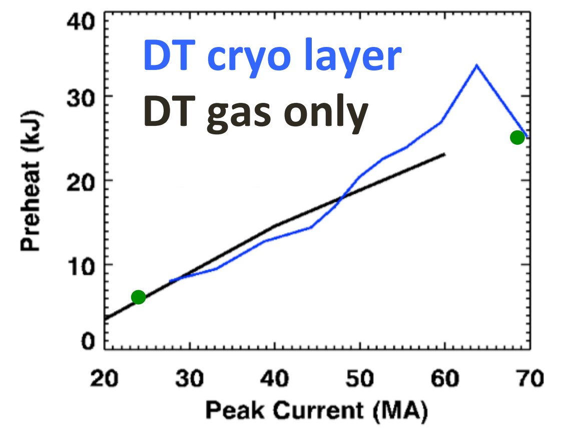


- CR_{2D} 26
- m_{loss} 44%
- Φ_{loss} 32%
- Y_n^{DT}= 3e16 (83 kJ)
- $Gain_{fuel}$ = 1.2

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







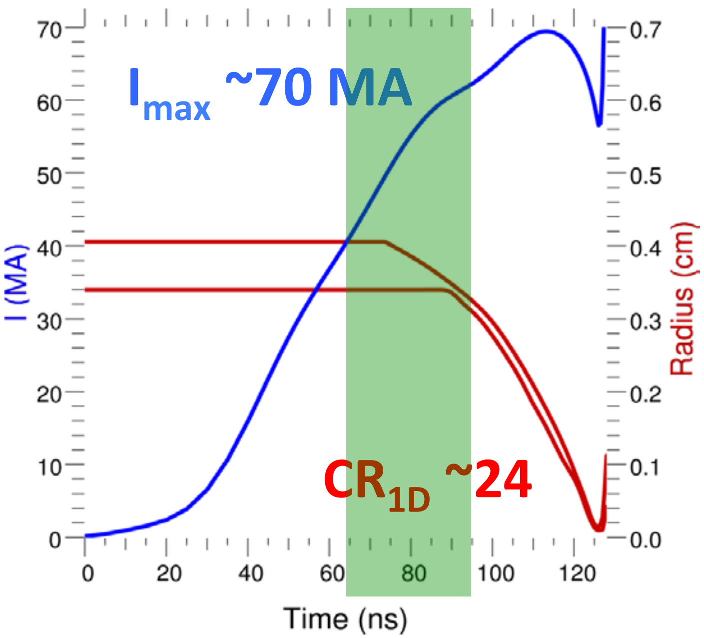
An intermediate regime exists wherein the B_z field is

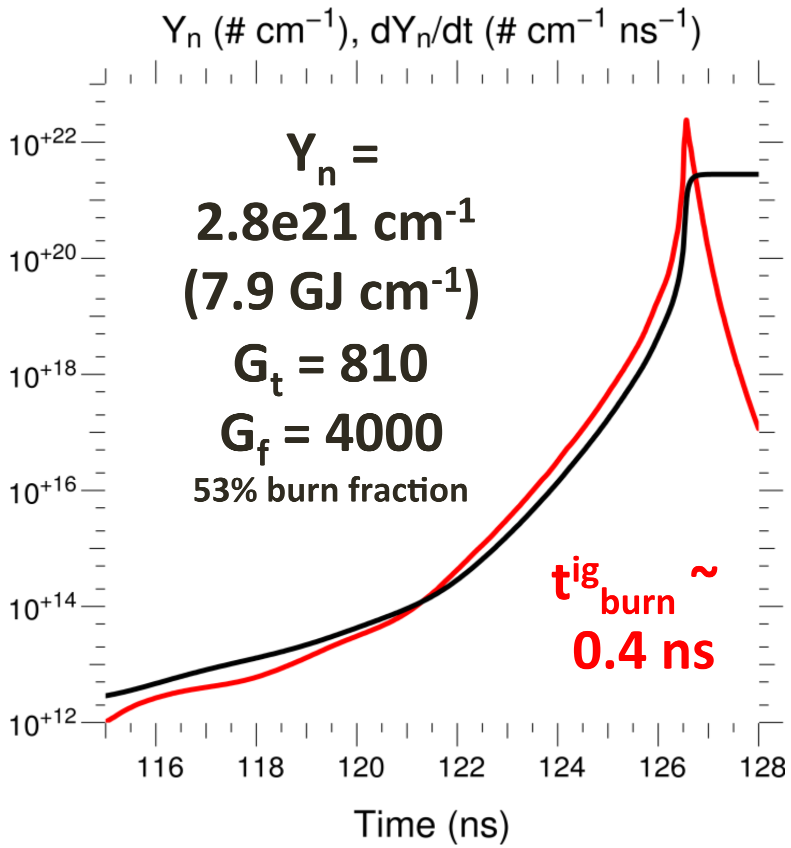
- *strong enough* to reduce conduction losses, but
- *weak enough* not to inhibit the α deflagration wave

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

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)





Ideal 1D HYDRA simulation of high-gain MagLIF experiments

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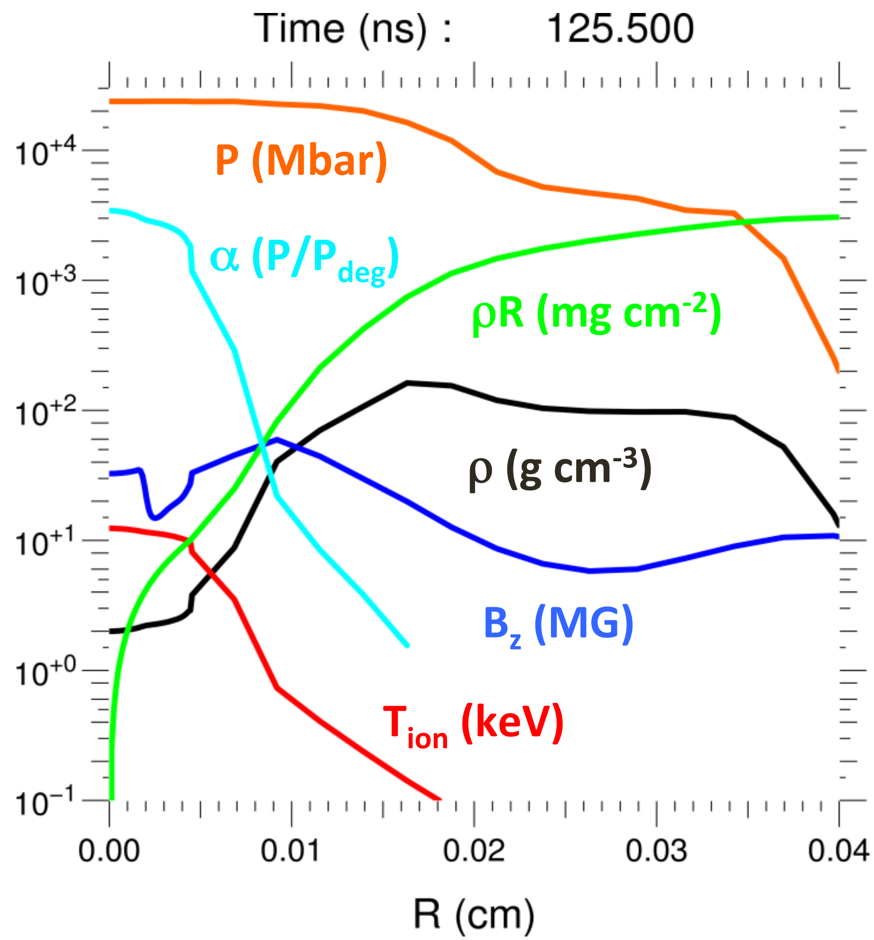
L_{liner} = 10 mm, AR_{liner} = 6,
ρ_{gas} = 5 mg cm^{-3}, DT cryo fuel,
B_z^0 = 8T, E_{laser} = 21 kJ (0.66 TW)

r_{stag} ~ 169 μm
~25 Gbar
(compare to 375 Gbar NIF point design → 15x)
~55% (gas) ~24% (fuel) flux loss
~13 keV
~2-45 g cm^{-3} (hot spot)
~45-160 g cm^{-3} (main fuel)
~0.1 g cm^{-2} (hot spot)
~0.8 g cm^{-2} (main fuel)
~3.1 g cm^{-2} (liner)

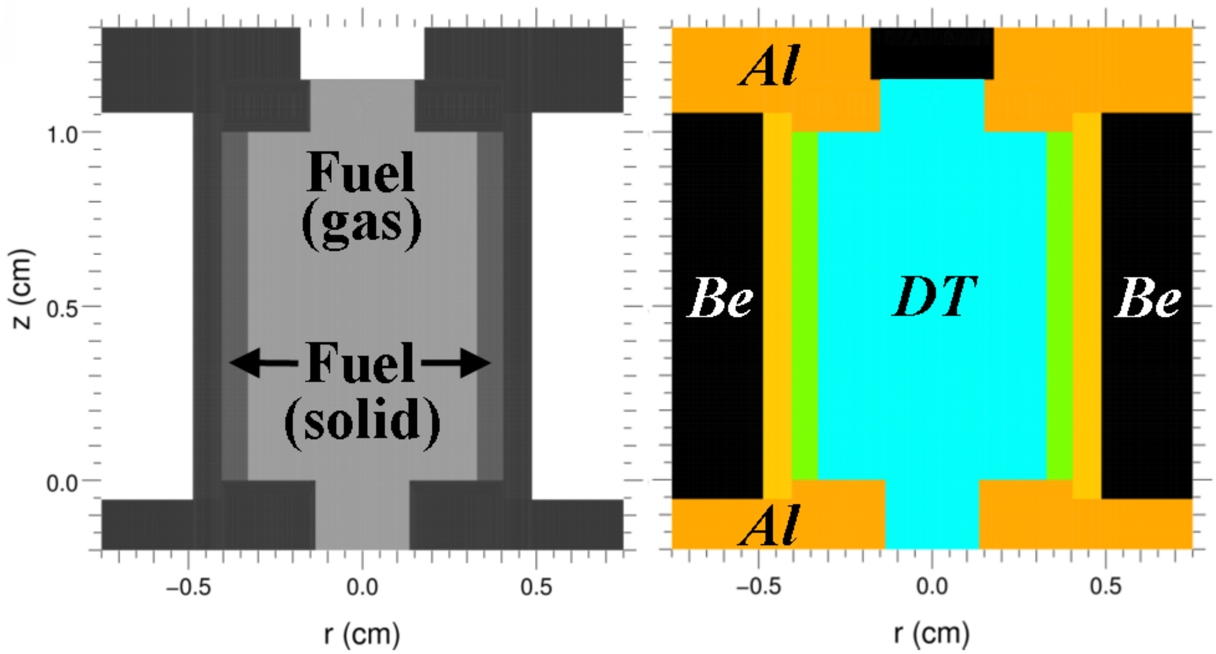
Stagnation profile



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

Integrated 2D simulations can ignite with $CR_{2D} \cong CR_{1D}$ and achieve a majority fraction of Y_{1D} since cool, high-density fuel cannot move out of the way.



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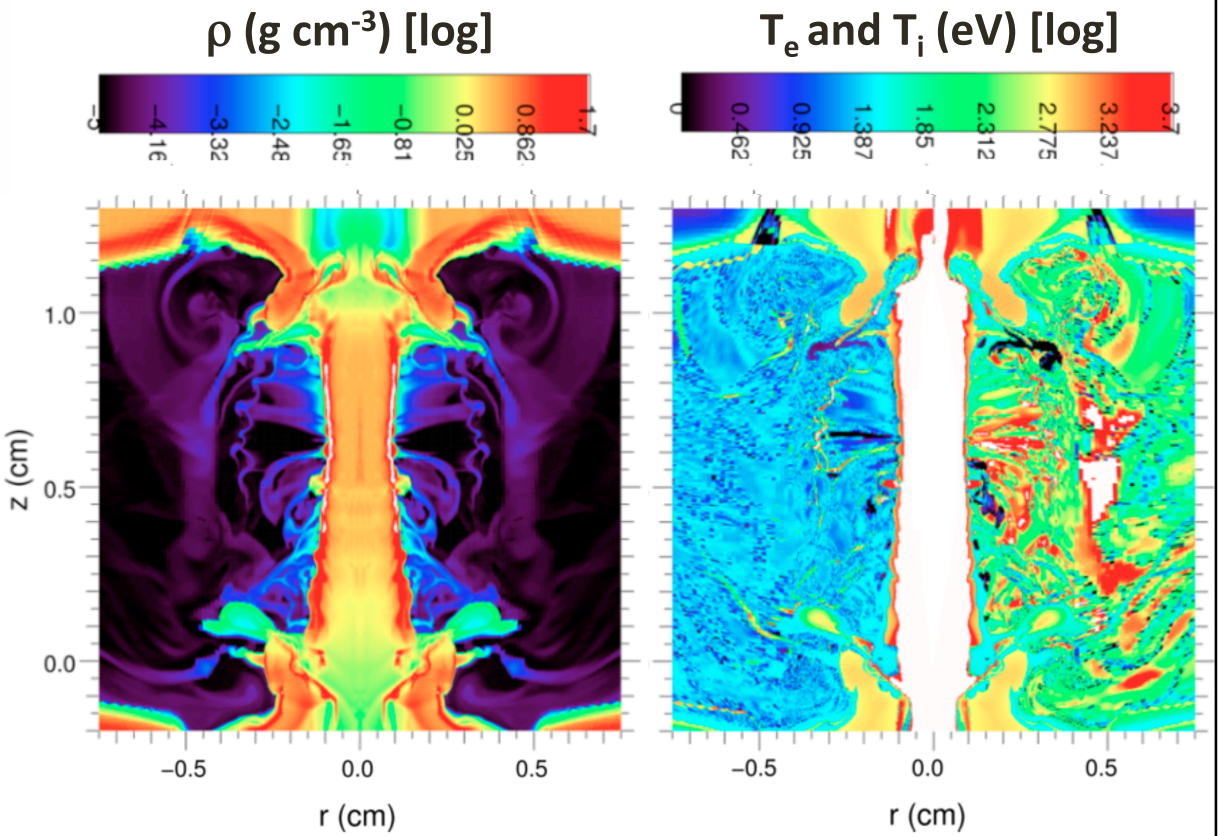
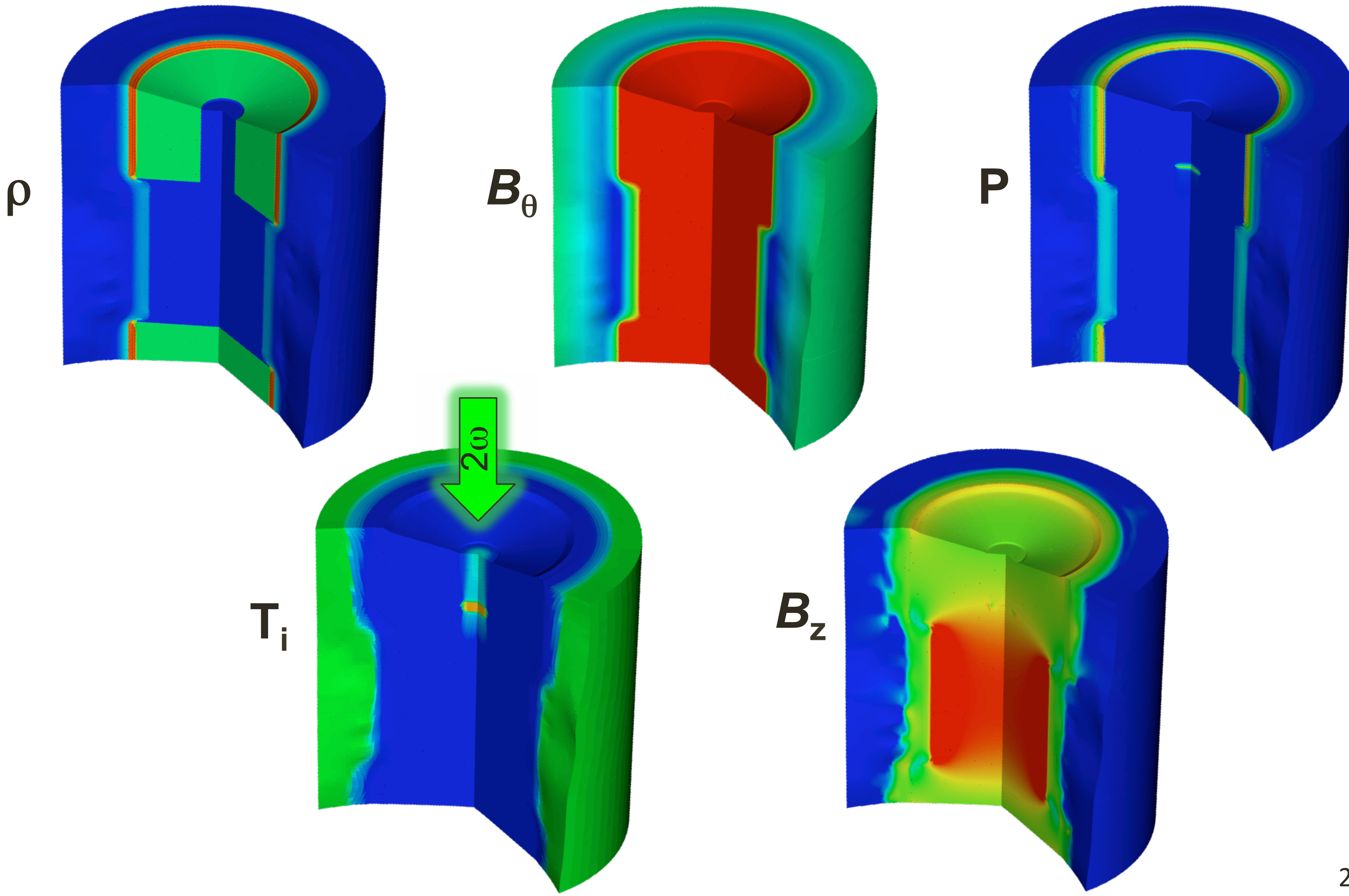
Integrated 2D simulations can ignite with $CR_{2D} \cong CR_{1D}$ and achieve a majority fraction of Y_{1D} since cool, high-density fuel cannot move out of the way.

- m_{loss} 30% (gas)
- T_i^{stag} ~ 10-15 keV
- T_i^{burn} ~ 50-80 keV
- $\langle T_i \rangle^{DT}$ ~ 34 keV
- $Y_n^{DT} = 2.1 \times 10^{21}$
- E_{fus} = 5.8 GJ (73% of 1D)
- G_f = 2900, G_t = 600
- 39% burn-up fraction



Integrated simulations are making progress in 3D



Summary

Sandia National Laboratories

MagLIF enables ICF yields on pulsed-power accelerators using slow < 100 km/s implosions

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" predictions

Detailed comparisons between "post-shot, degraded" simulations and experimental results are promising and ongoing

Integrated experiments have measured thermonuclear neutrons and show strong evidence of magnetized fuel