SAND2011-8780C

Integrated Design for Magnetically-Driven Liner Inertial Fusion of Preheated and Magnetized Fuel on the Z Accelerator

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Abstract

Magnetically-driven implosions of metal liners containing magnetized and preheated fuel may enable significant ICF yields to be obtained on pulsed-power accelerators. Simulations of dense (ρ=1-5 mg/cc), axially-magnetized (B_z=3-30 T), and preheated (T_i=200-500 eV) DT fuel, driven by a pulsed-power accelerator similar to the Z machine (I_{max}=25-60 MA in 100-300 ns), indicate Gbar pressures and high yields (E_{fus}=100s kJ-10s MJ) may be feasible. Reduced heat conduction losses and alpha particle trapping can be provided by B_z flux compression, and the fuel ρR ignition requirement is replaced by one for B_zR. Preheating the fuel prior to compression permits access to ignition temperatures without large convergence ratios or implosion velocities. Integrated simulations allow realistic designs for Z experiments (I_{max}=27 MA) with fuel preheat provided by the ZBL laser (E_{las}=2-6 kJ). Physics issues include laser deposition timing, evolution of thermal energy and B_z field, magneto-RT instability growth, electrode and laser entrance hole end effects, and anisotropic conductivity and fusion burn in the B_z field. Fusion yields on the order of the absorbed target energy may be possible on Z+ZBL, and high-gain designs using I_{max}=60 MA are studied.

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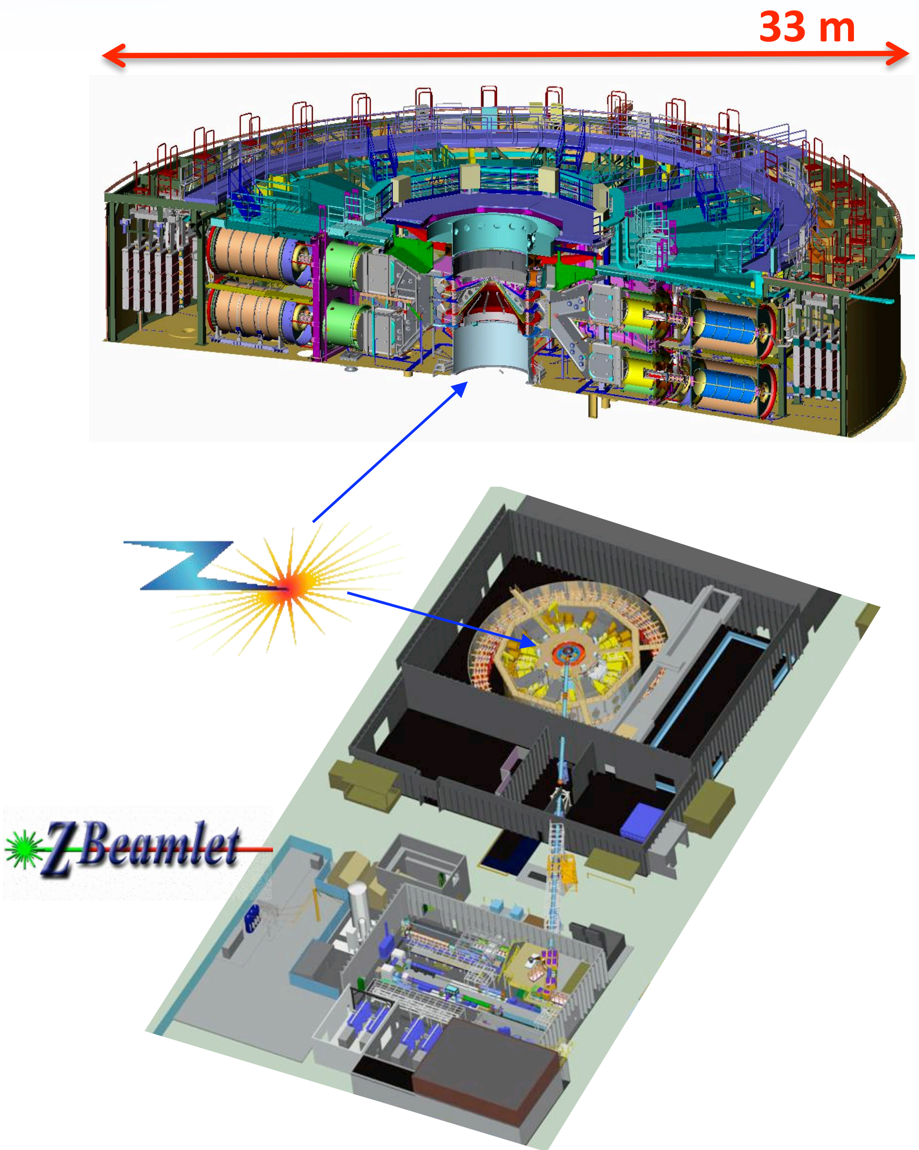
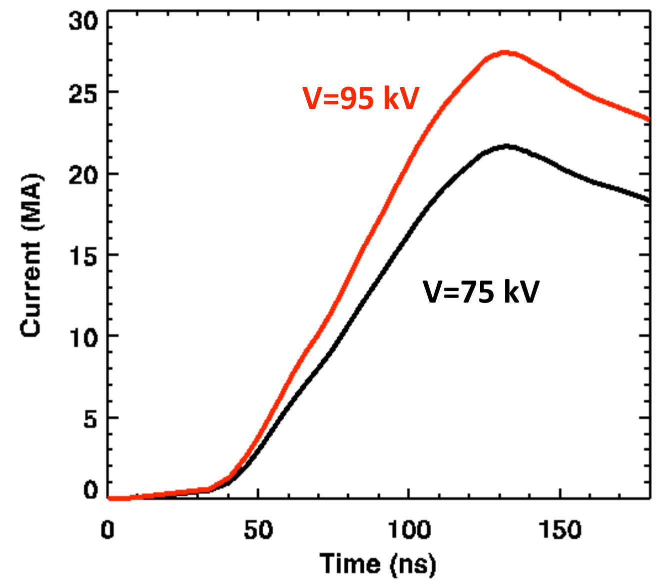
Magnetically-driven implosions on Z can be used to create extreme conditions in the laboratory





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 by 300 eV radiation drive (e.g., NIF capsule)

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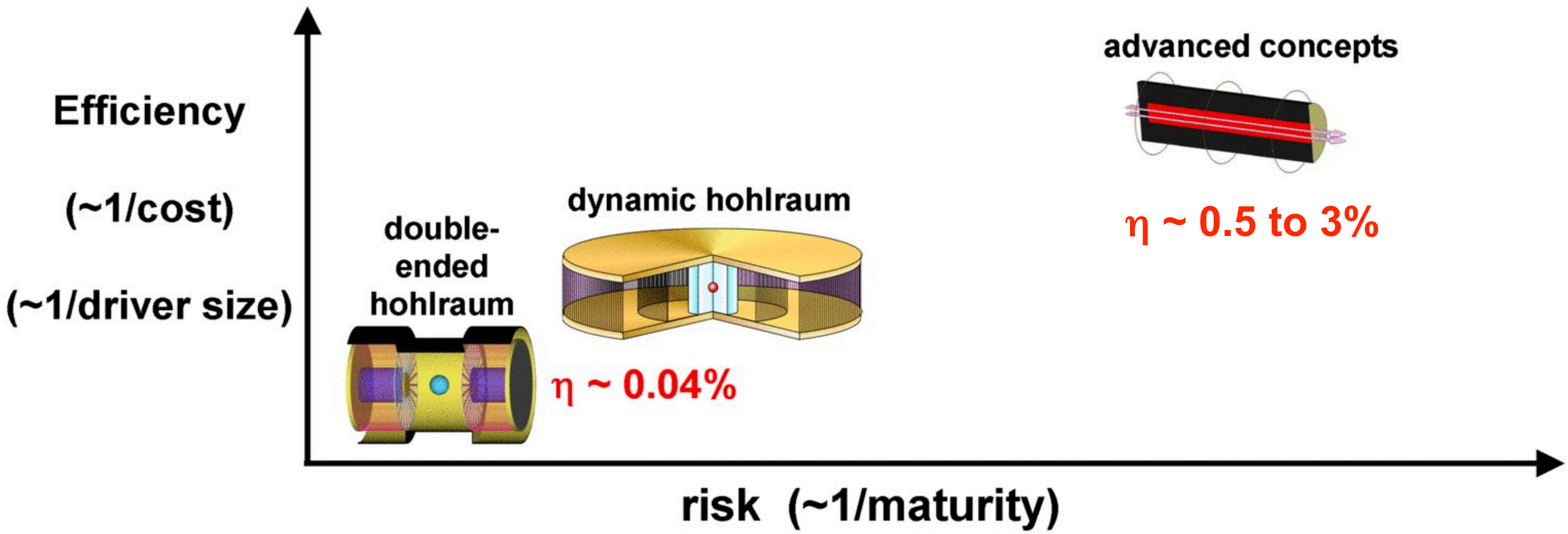
Are there more efficient pulsed-power methods for heating and compressing fusion fuel?



- Pulsed power can drive many kinds of experiments at ***high currents and high voltages***
- Large currents → large magnetic fields → large pressures → **access HED regimes**
- The Z machine creates large currents (~27 MA) and is the world's largest x-ray source
- Lasers have more energy deposition control than Z-pinches, however Z-pinches are **cheaper** and **more efficient** than lasers.
- The upper limits on Z-pinch performance for achieving high energy densities are not known. ***There is a lot of room for innovation!***

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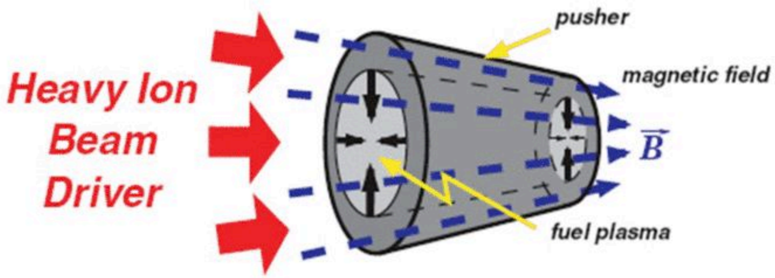
A number of implosion scenarios using magnetized fuel have been proposed in recent years

Max Planck / ITEP

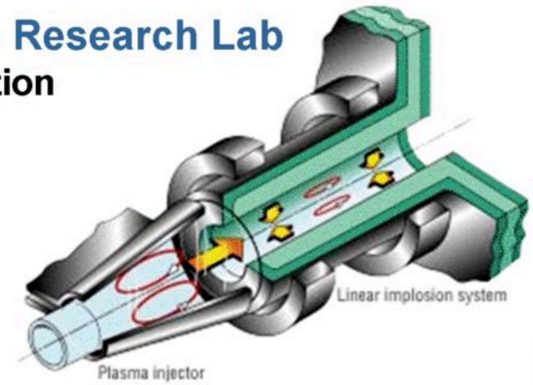


Basko, Kemp, Meyer-ter-Vehn, *Nucl. Fusion* **40**, 59 (2000)
Kemp, Basko, Meyer-ter-Vehn, *Nucl. Fusion* **43**, 16 (2003)

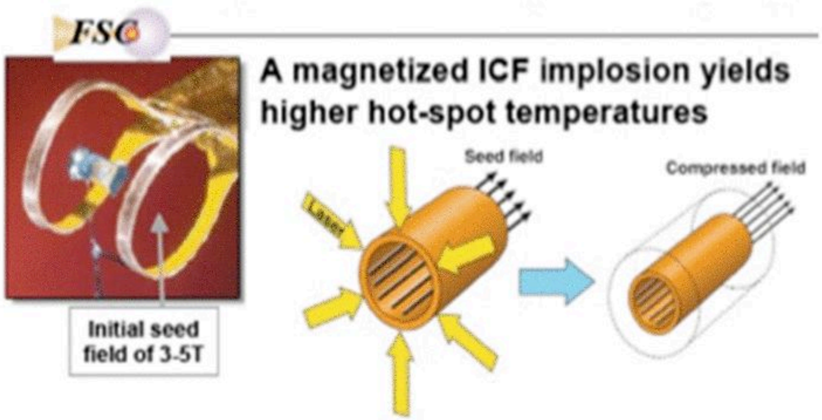
Los Alamos / Air Force Research Lab

Field Reversed Configuration
Magnetized Target Fusion
Shiva Star generator

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



U. Rochester LLE



Direct drive laser implosion of cylinders
…preheat not necessary due to high implosion velocity

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

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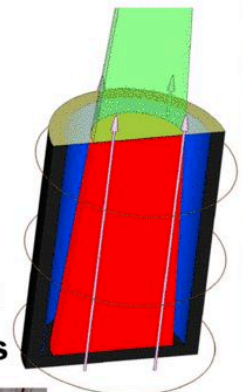
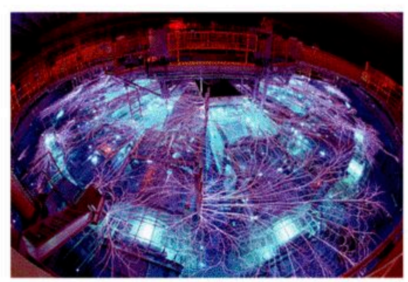
MagLIF Magnetized Liner Inertial Fusion
Laser preheated magnetized fuel
Backlighting to diagnose implosions (stability)
LASNEX simulations indicate interesting yields





See talks by Slutz, Sinars, McBride, Jennings
[THRS., THRS., THRS., TUES.]

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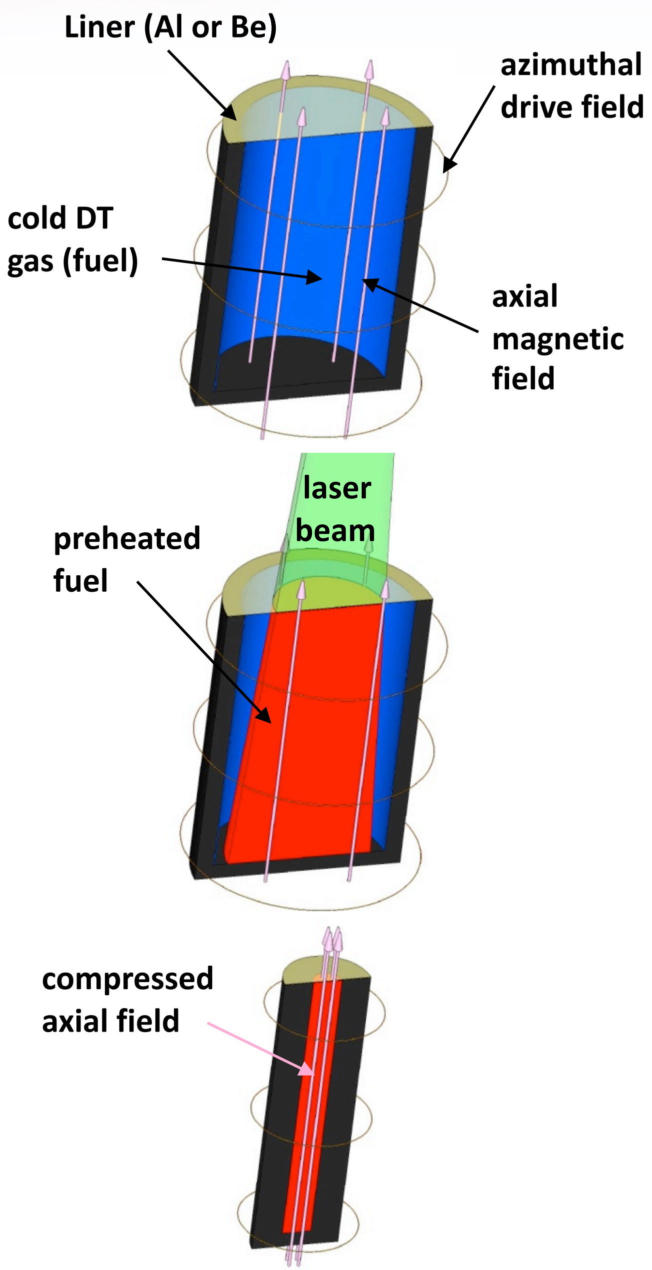
We are working toward the evaluation of a new Magnetized Liner Inertial Fusion (MagLIF)* concept



- Initial B_z~10-50 T flux is compressed to ~5-15 kT (~50-150 MG)
  - Inhibits thermal electron conduction losses
  - Enhances alpha particle energy deposition
  - Enables low ρR_{fuel} ignition (RB_z requirement instead)
  - May help stabilize implosion at late times
- During implosion, the fuel is preheated using the Z-Beamlet laser (<10 kJ needed)
  - Preheating reduces the compression needed to obtain ignition temperatures to 20-30 on Z
  - Preheating reduces the implosion velocity needed to "only" 100 km/s (slow for ICF)
  - Stagnation pressure required is few Gbar, not a few 100 Gbar
- Simulations suggest scientific breakeven may be possible on Z (fusion yield = energy into fusion fuel); something not yet achieved in any laboratory

** Slutz, et. al., Phys. Plasmas 17, 056303 (2009).*

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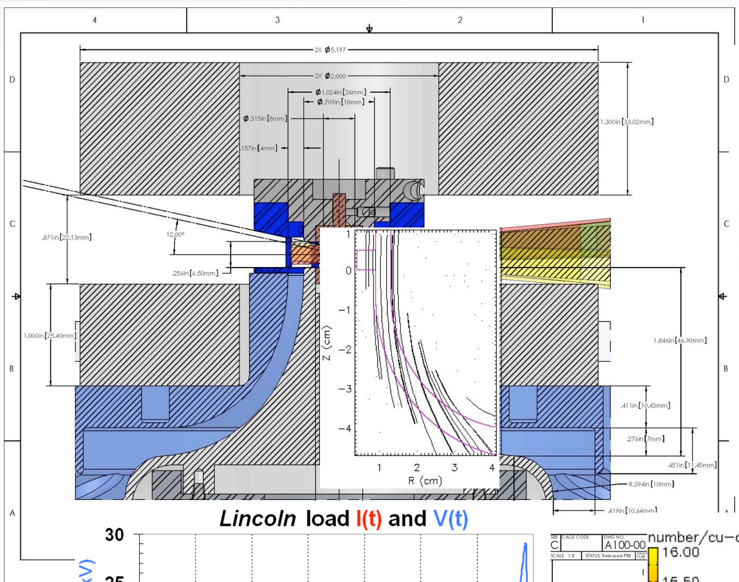
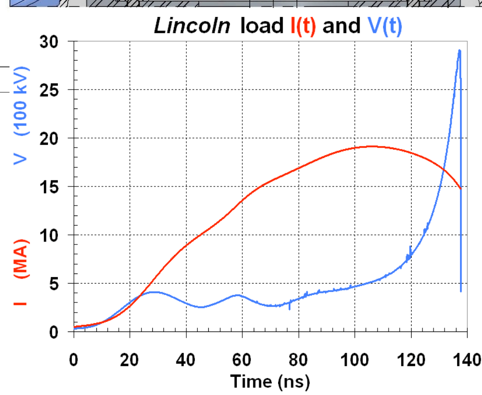
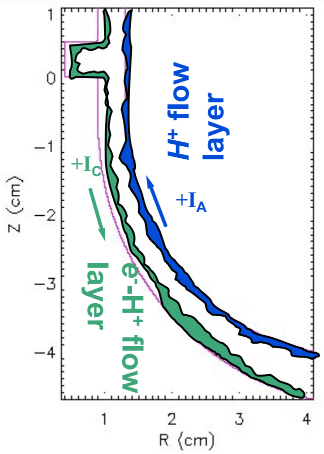
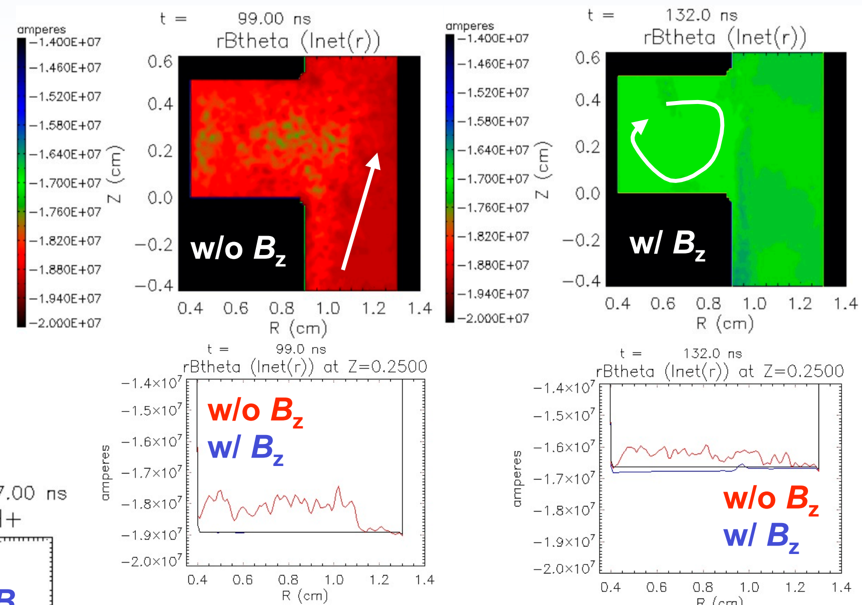
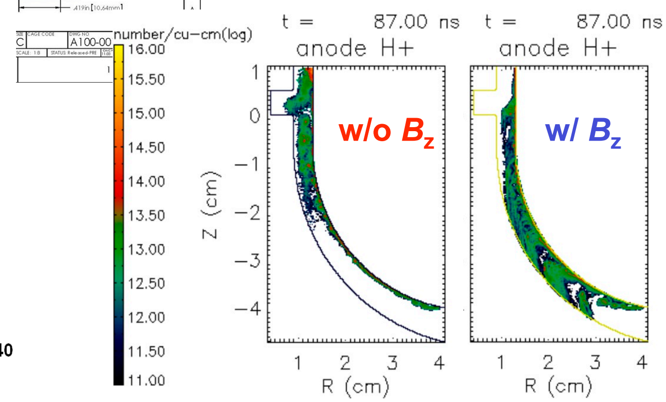
PIC simulations predict no significant current loss in final MagLIF feed due to external B_z field

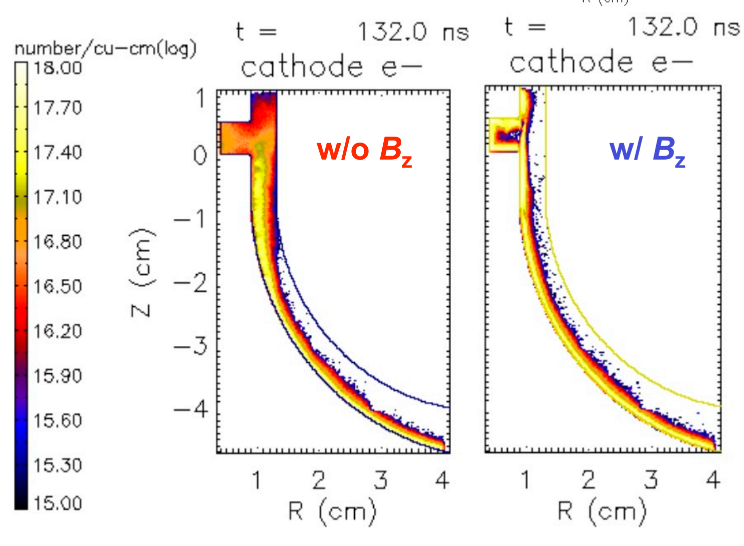












MODEL: Fully explicit and electromagnetic, 3D {r,θ,z}, collisional, neutral desorption from conductors, energy deposition and heating of electrodes, solenoid B_z

PARTICLE SOURCES: [1] Field-stress SCL e^- emission (from K); [2] Neutral H^0 thermal desorption of adsorbed monolayers at 1 ns^{-1} (rate needs to be measured); [3] Ionization of e^- H^- plasma; [4] Thermal H^+ ion emission (from A) at T=400K.

PREDICTIONS so far: Insignificant early-time power loss due to fringe-fields. Magnetic insulation of the A-K plasma is not lost due to B_z. A-K plasma does not redirect much current away from load. In cases without B_z where shorting occurs due to A-K plasma, the case with 30T B_z does not short and late-time losses are suppressed. Back EMF may enhance late current (dI/dt<0).

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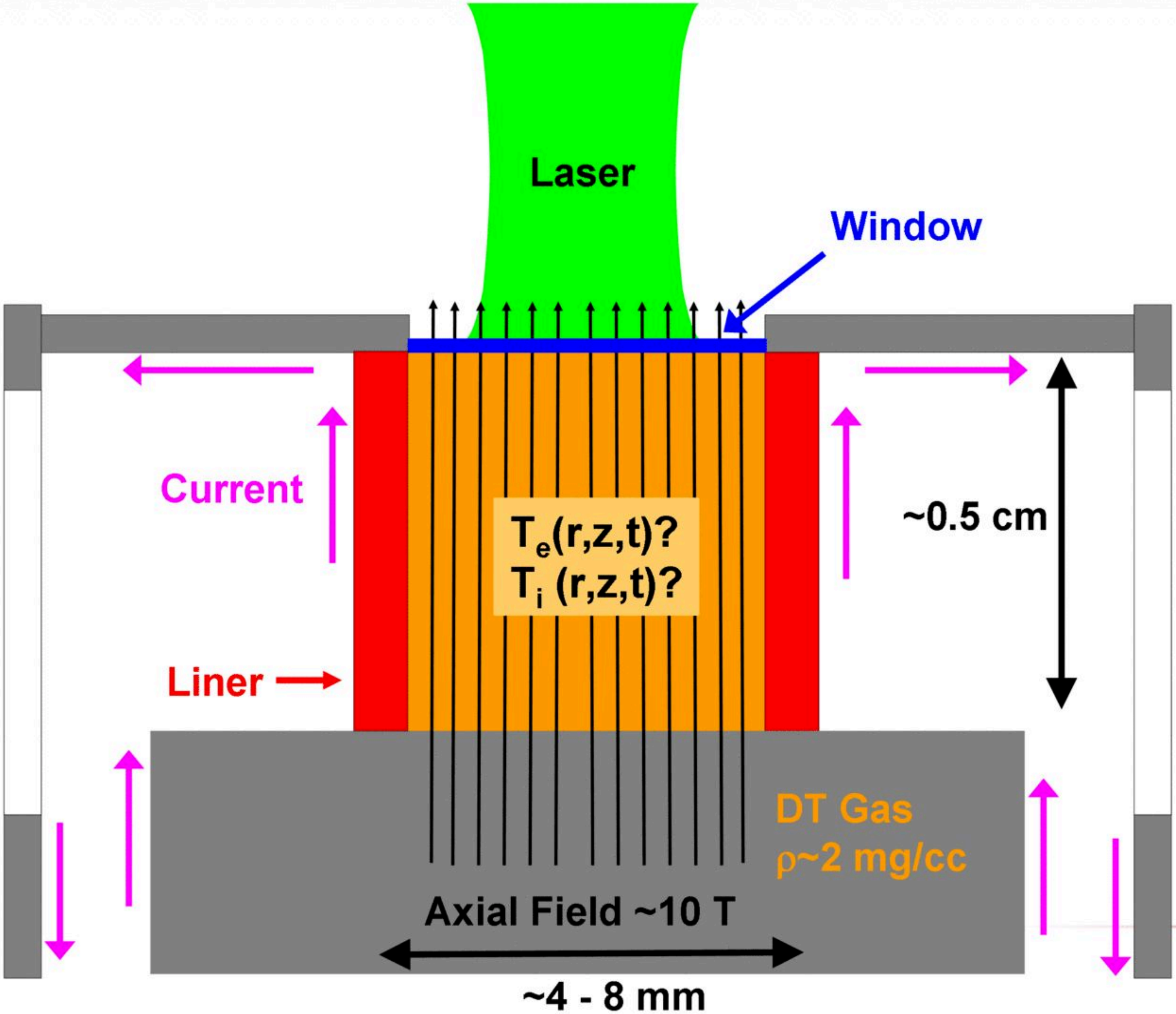
The Z-Beamlet laser will be used to preheat plasma for initial MagLIF experiments on Z



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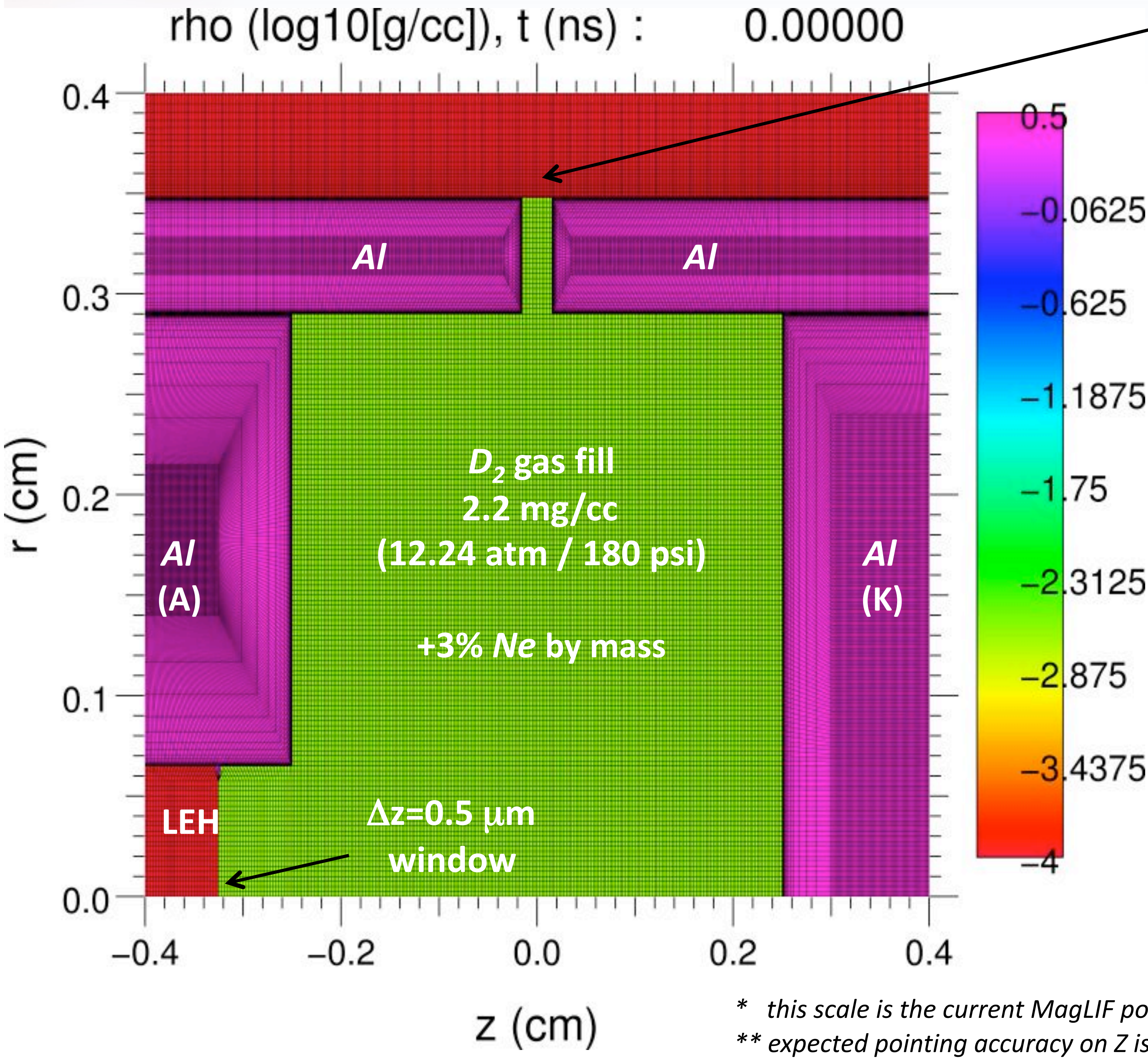
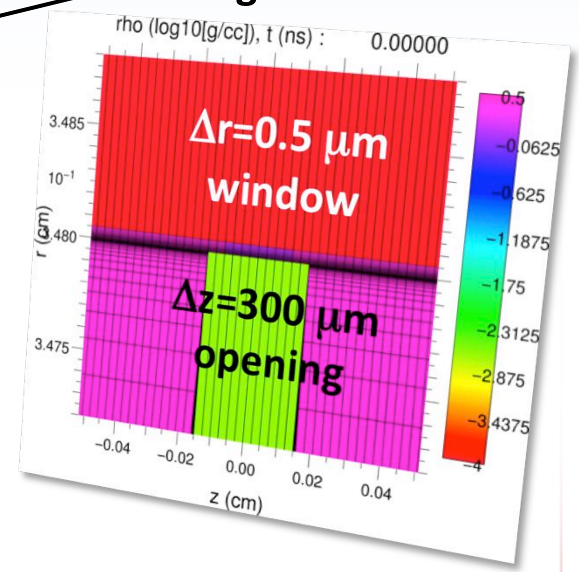
HYDRA initialization for standalone MagLIF preheat ZBL experiments



Diagnostic Port



Laser Entrance Hole
1.3 mm diameter

Laser Parameters
2.5 kJ of 2ω
2.5 ns duration (1 TW)
0.1 ns rise/fall time
0.4 mm FWHM ($\sim e^{-(r/spot)^2}$)
f/10 lens (cal chamber)
$I_L \approx 3e14$ W cm^{-2}

* *this scale is the current MagLIF point design*
** *expected pointing accuracy on Z is 0.015 cm*

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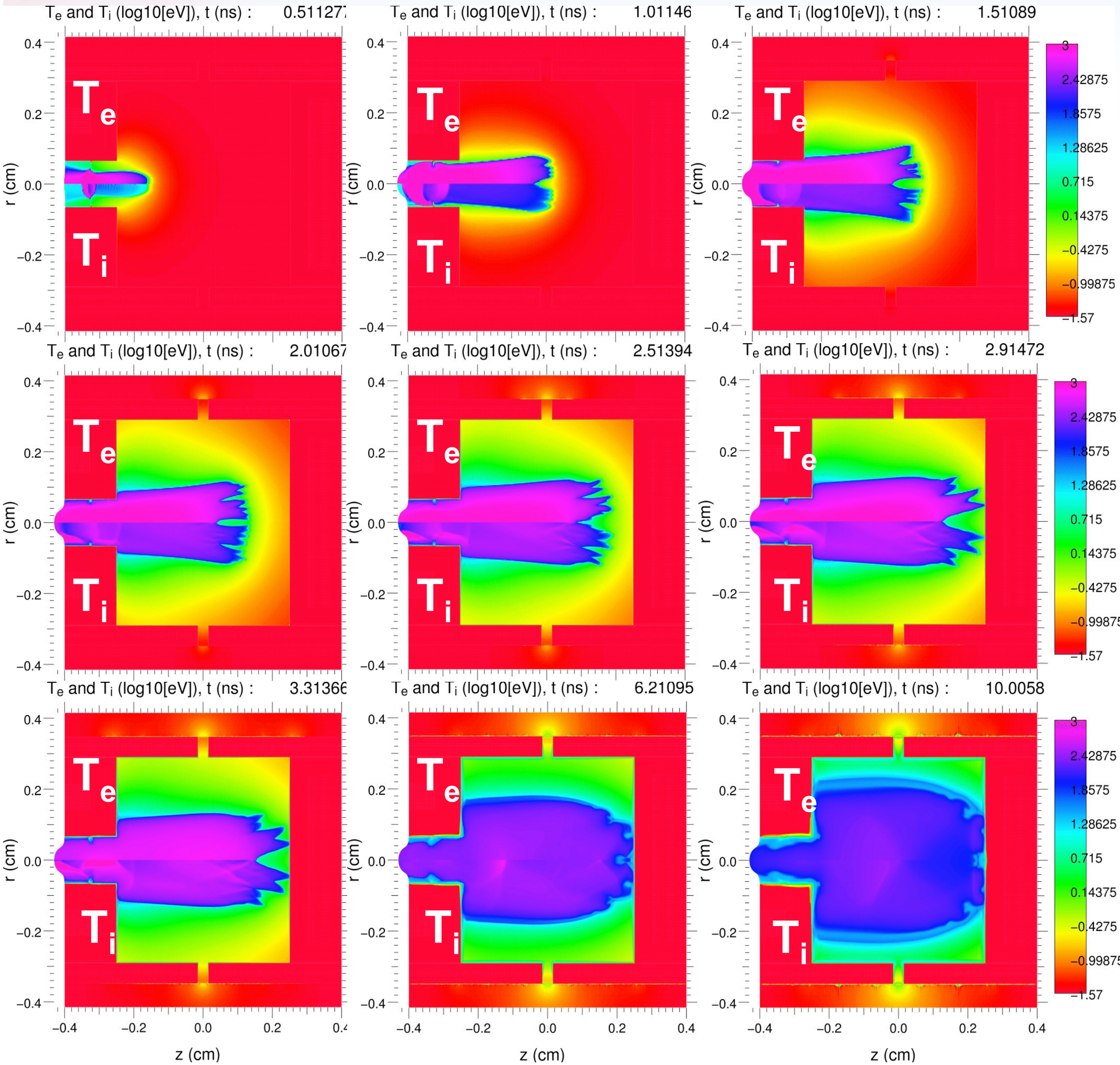
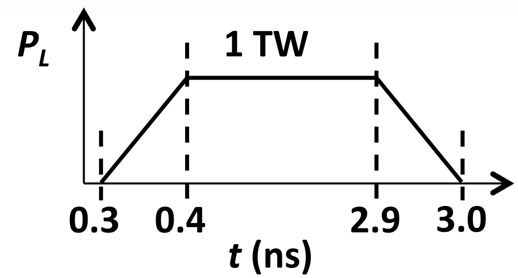
HYDRA predictions for MagLIF preheat ZBL experiments



2.5 kJ of 2ω in 2.5 ns



The laser pulse ends just as it reaches the far wall in this example.

The higher energies and powers typical of MagLIF will ablate far wall material (end cap); we will also try to measure this, since it mixes with fuel and critically impacts the target design.

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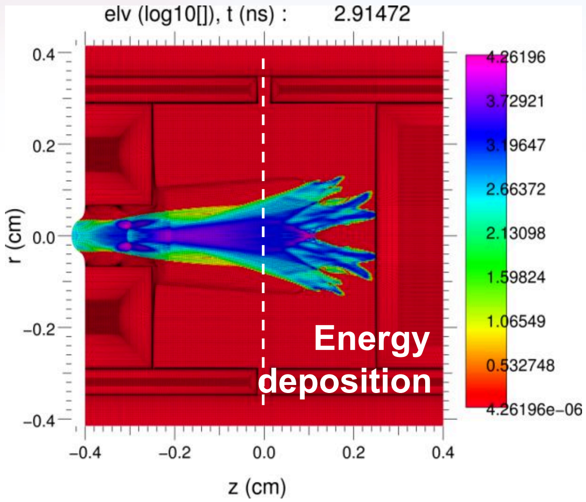
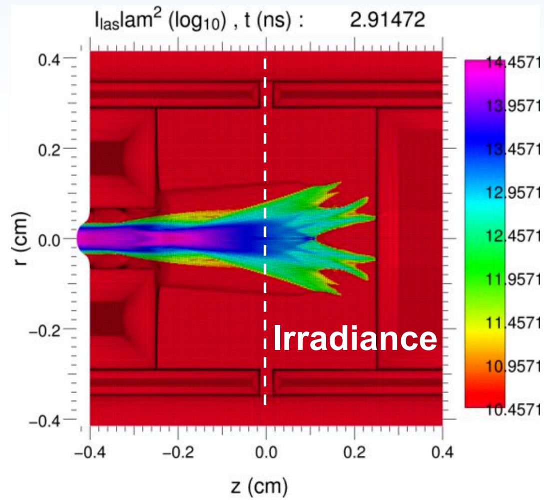
Experiments may measure T_e~900 eV and T_i~400 eV

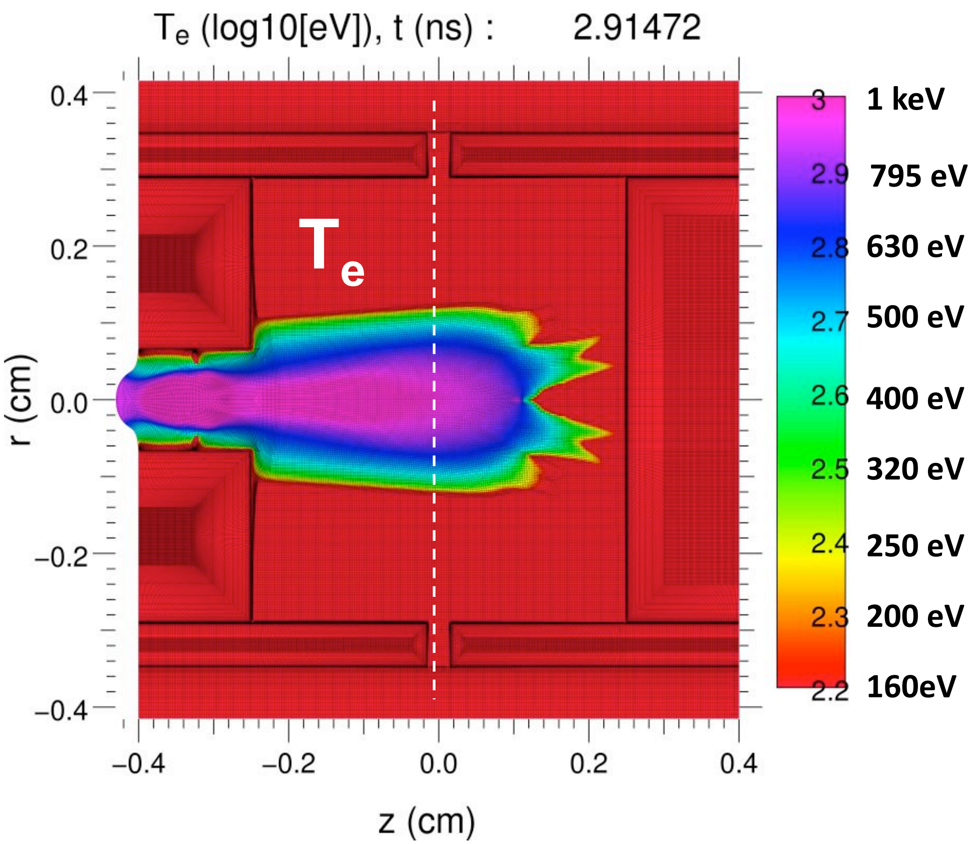


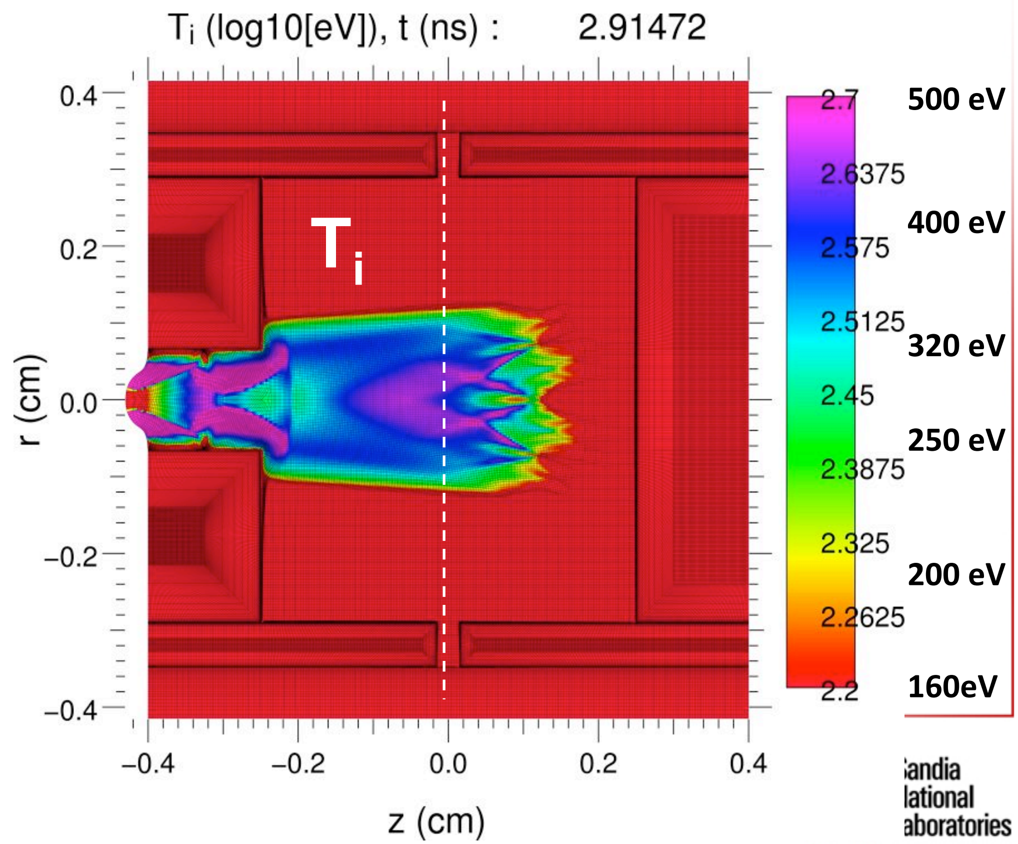


Self Thomson scattering

Snapshot diagnosis of T_e and T_i only occurs during laser pulse

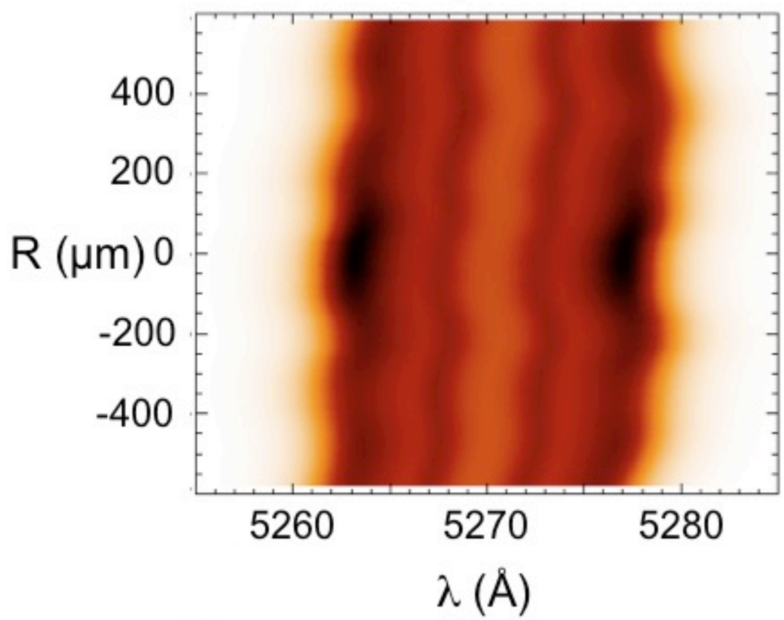
Axial resolution only through positioning of diagnostic port, and no radial resolution

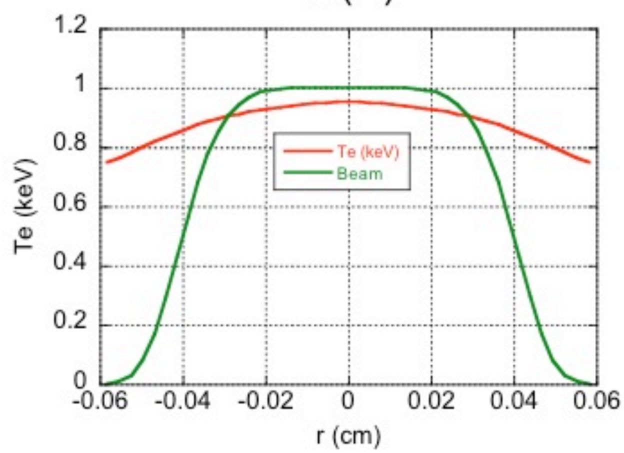




Effect of averaging over inhomogeneity provides reasonable lower bound on T_e and T_i

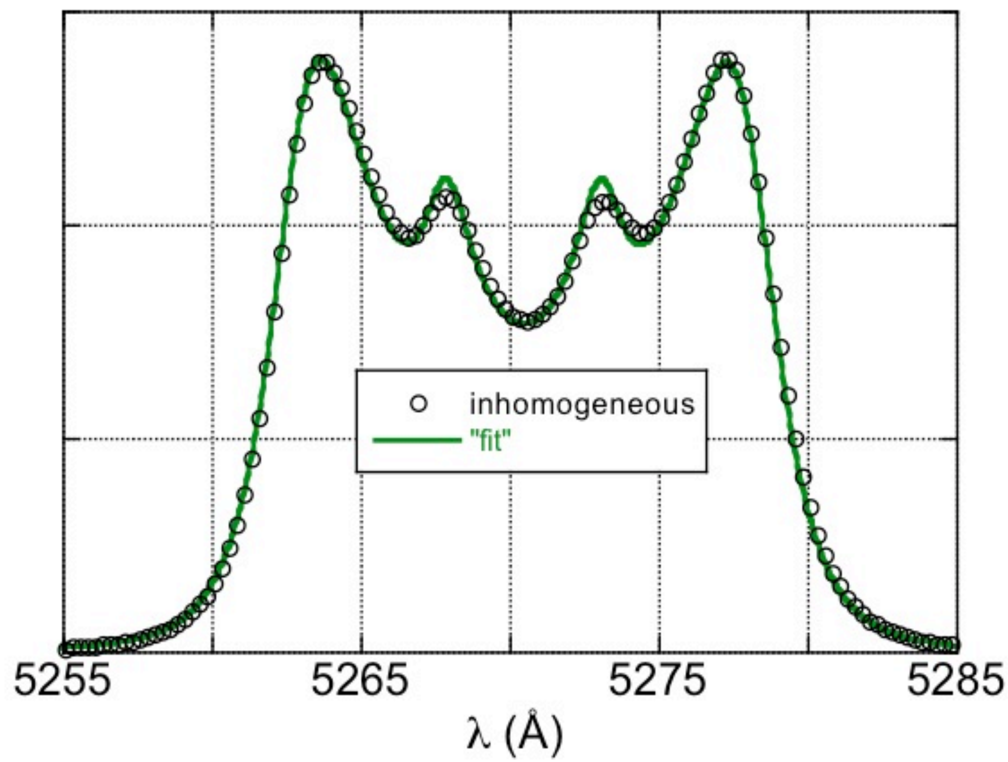
3% Ne, <Z> = 10





Max[$T_e(r)$] = 952 eV, T_i = 455 eV

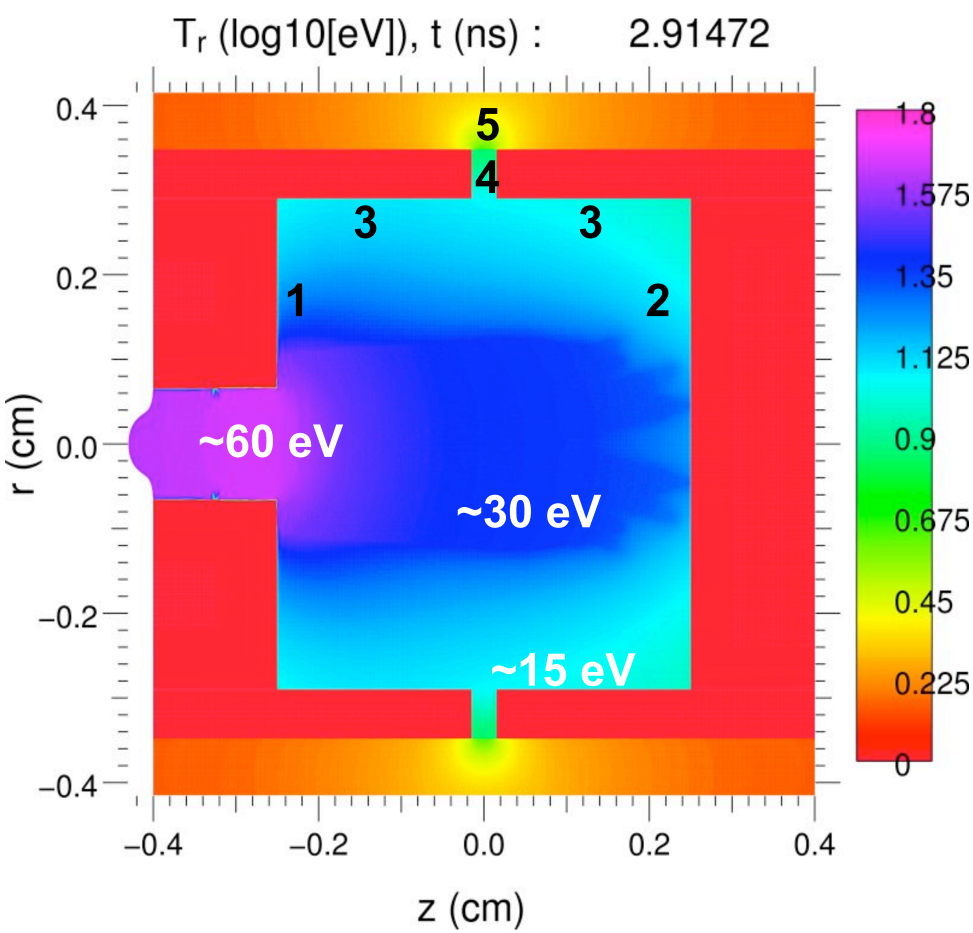
"Fit" T_e = 920 eV, "Fit" T_i = 430 eV

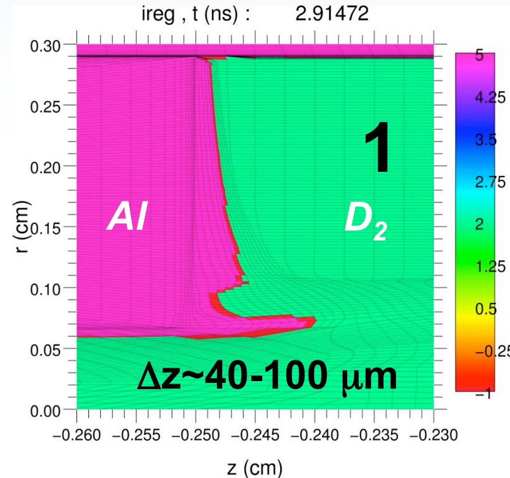


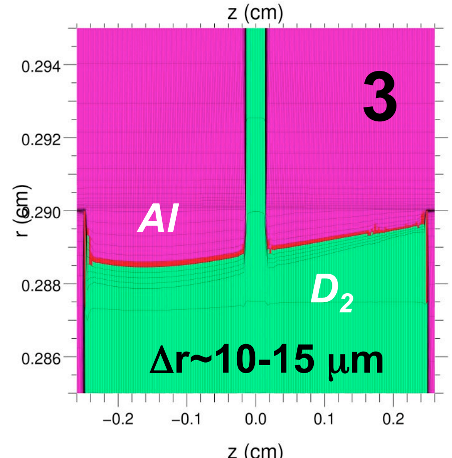
"fast mode" peaks have small blurring

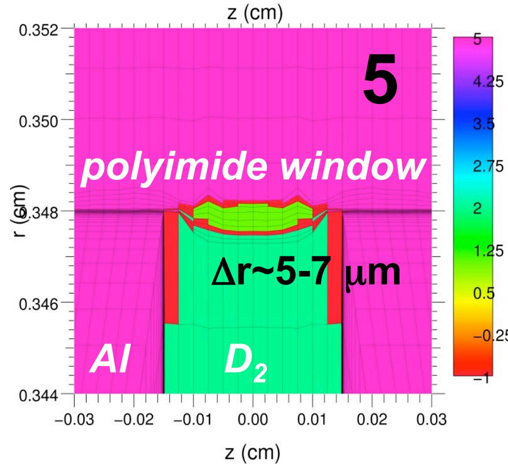
"fit" values are close to beam-weighted values

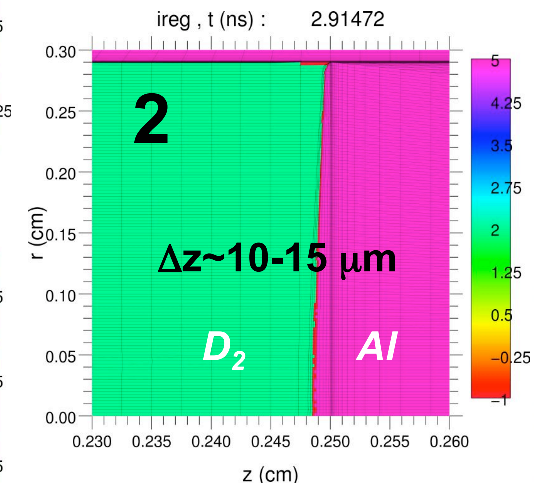
The T_{rad} field does not close the diagnostic port or ablate much of the *Al* wall material

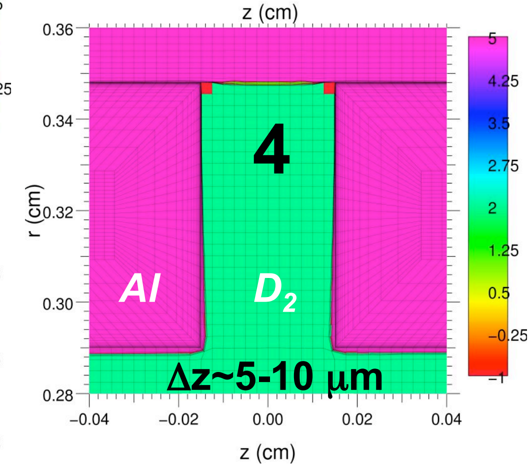












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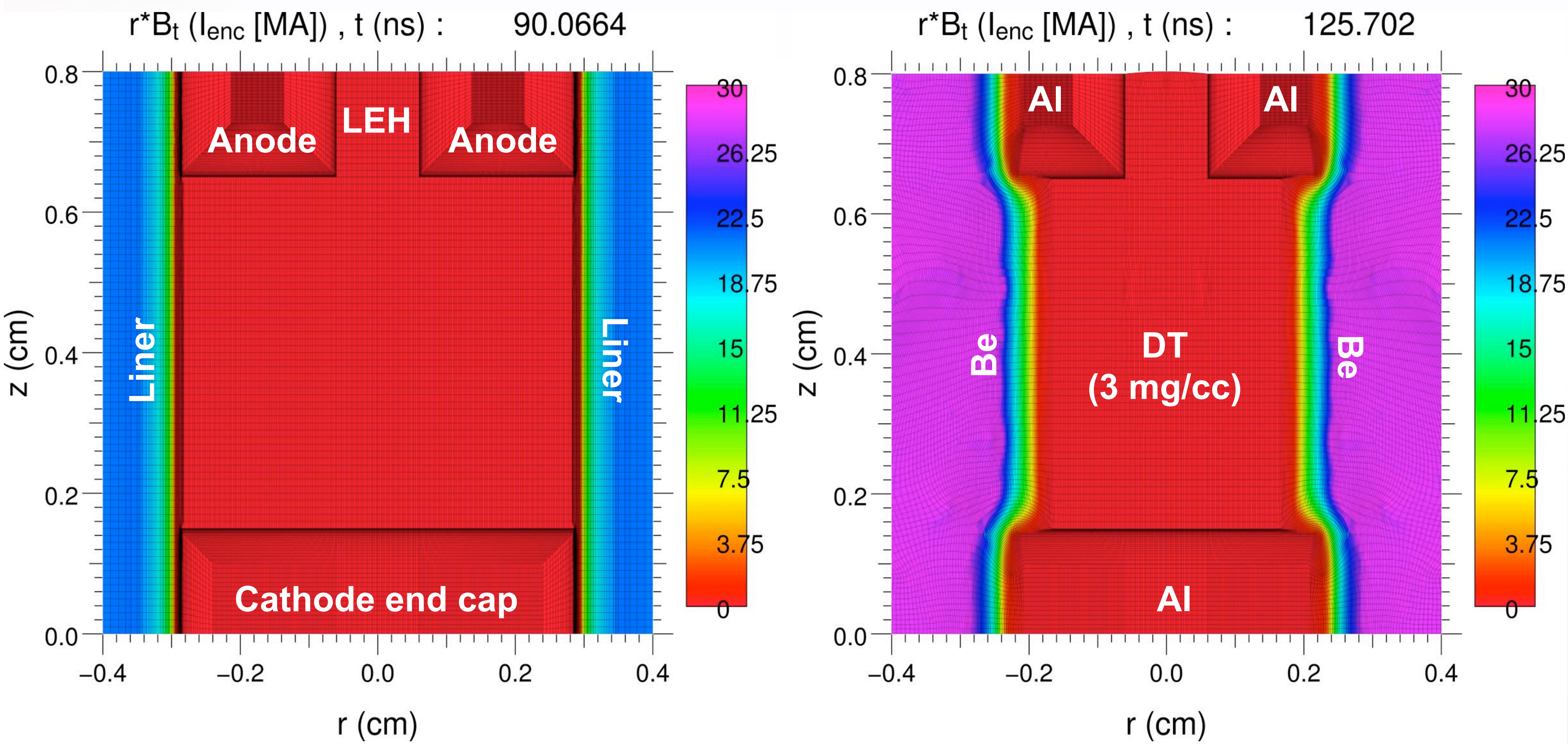
A complex, multi-block mesh is required in HYDRA in order to include all the relevant integrated details



- Multiple enhanced and reduced points of connectivity allow ablation zoning on all surfaces
- The laser entrance hole (LEH) can include a thin polyimide window
- Realistic inclusion of laser deposition on the cathode end cap, and mix mitigation strategies
- New boundary conditions to allow both a driving B_θ field and background B_z field to be compressed
- Allows fine resolution of liner to study magneto-Rayleigh-Taylor instability growth
- Anisotropic conductivity and fusion burn models for complex magnetic field topology

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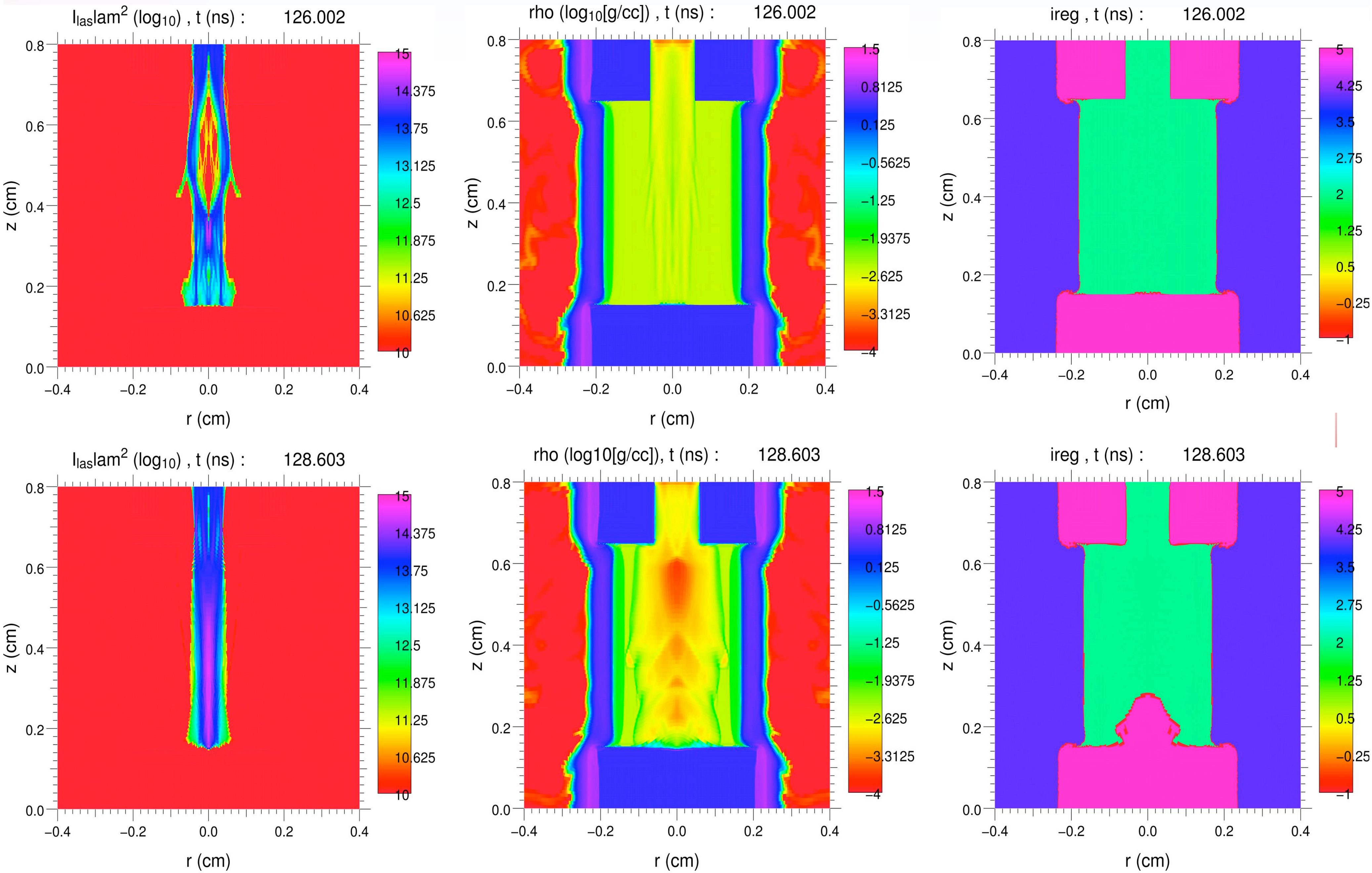
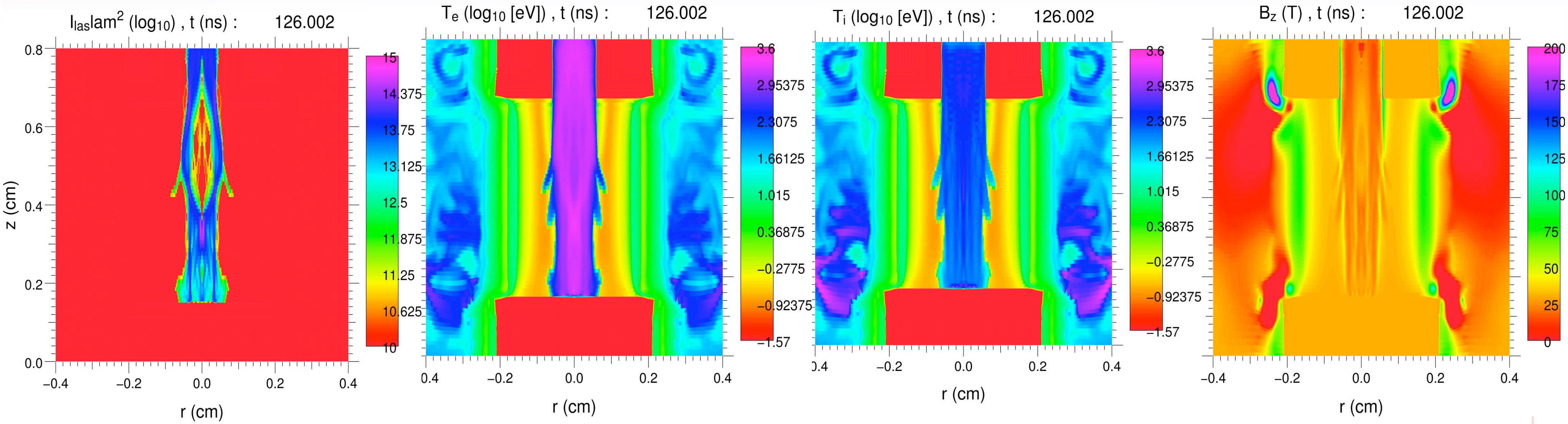
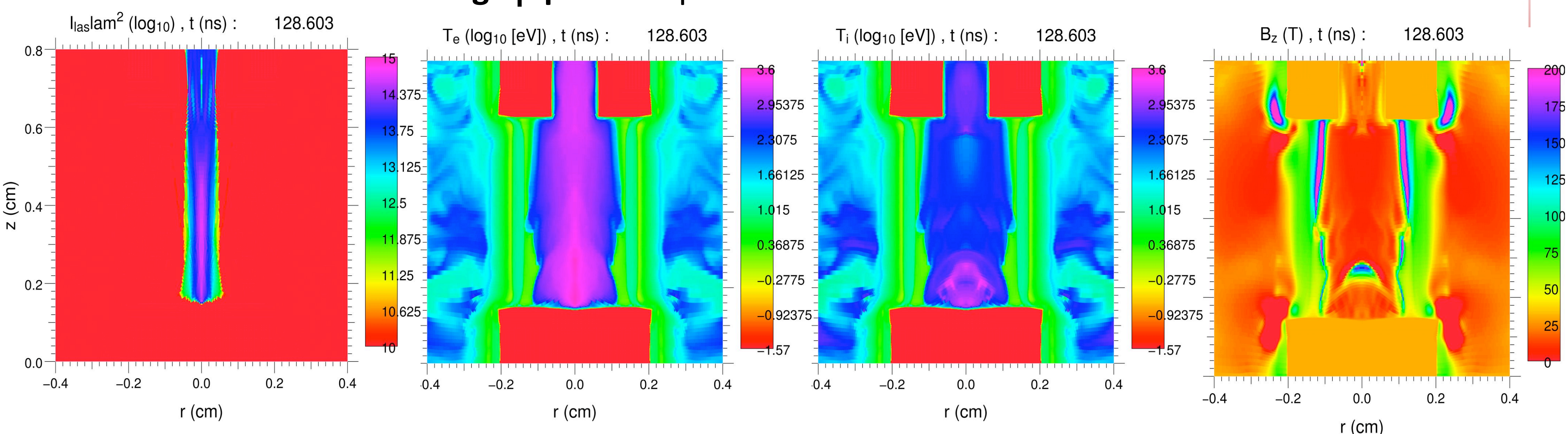
Laser deposition on the end cap ablates material into the fuel region, and must be avoided or mitigated



The preheating process significantly alters the seeded B_z field, resulting in a complicated topology



large β plasma : plasma motion moves flux



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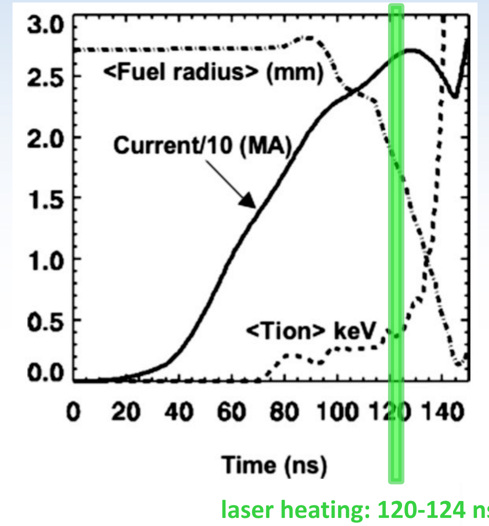
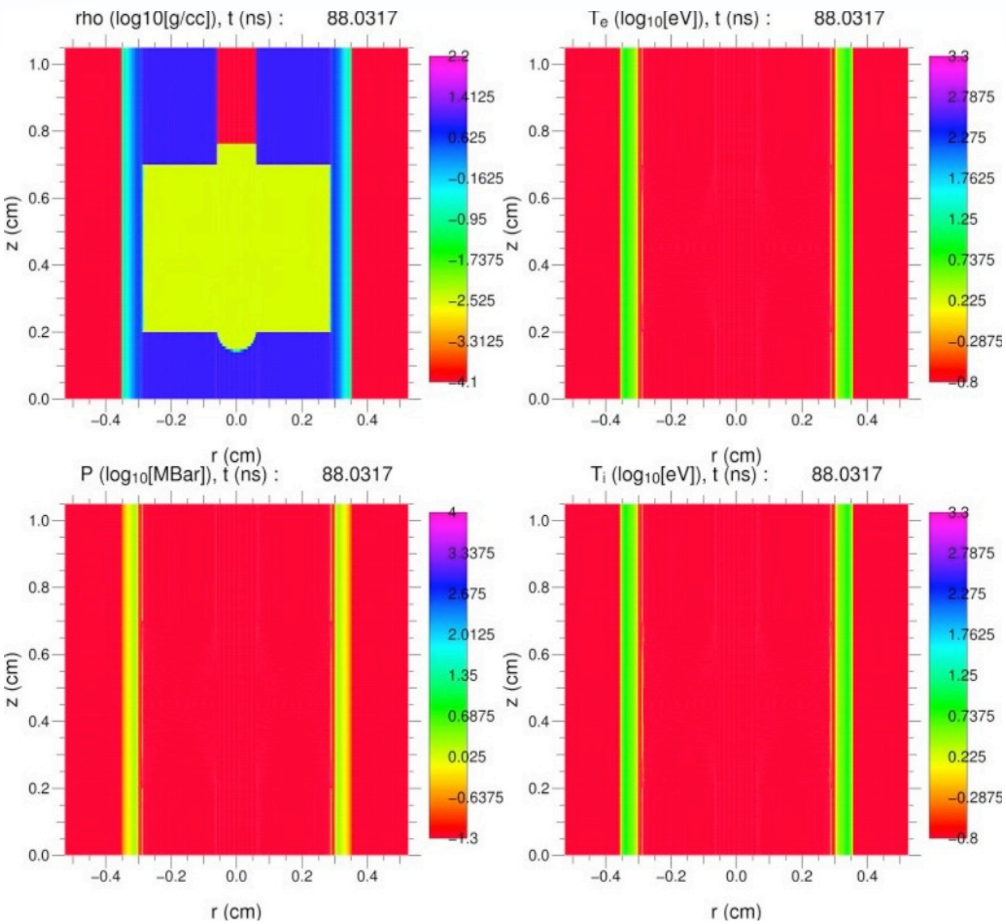
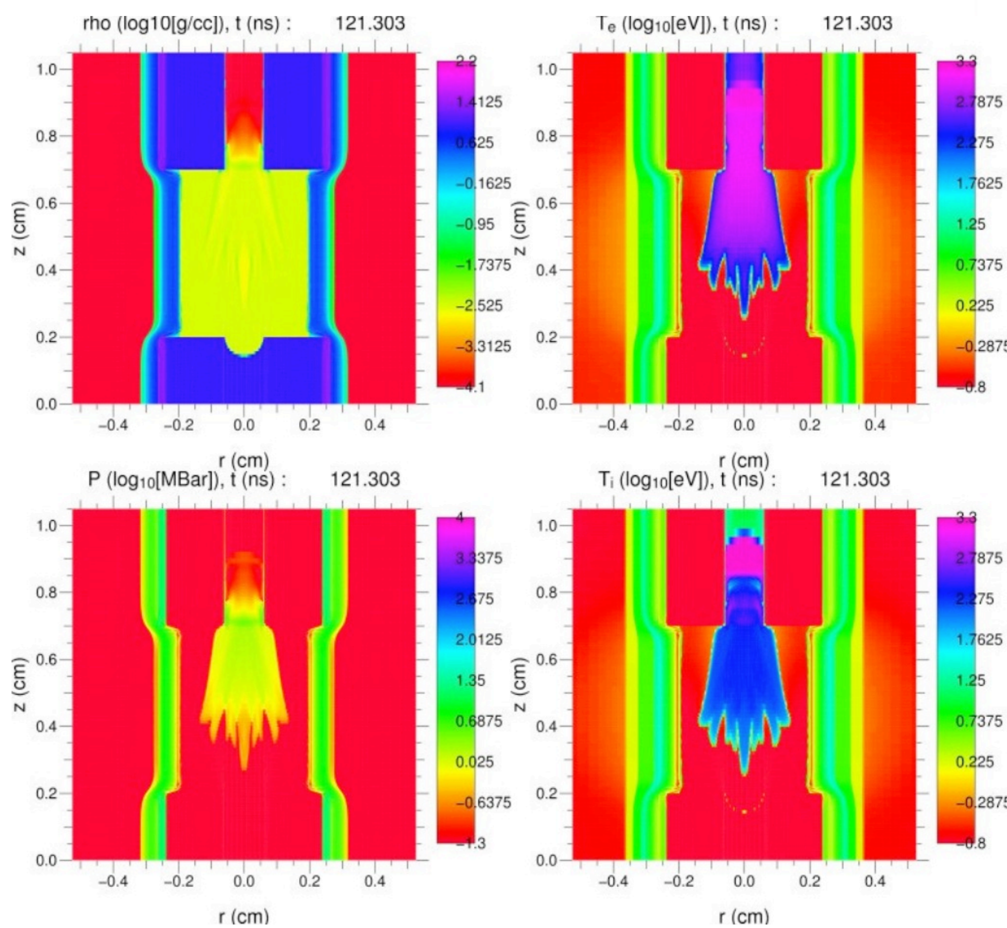
Integrated point design (with notch)



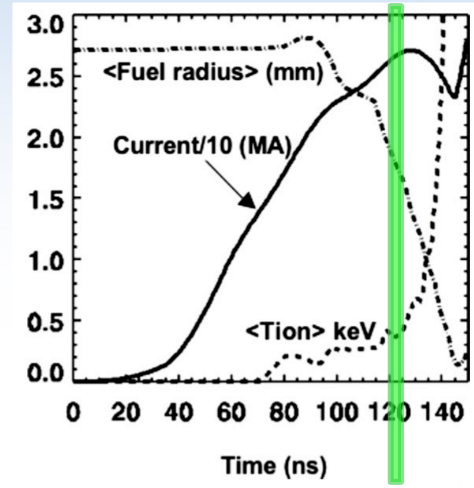
Time = 88 ns



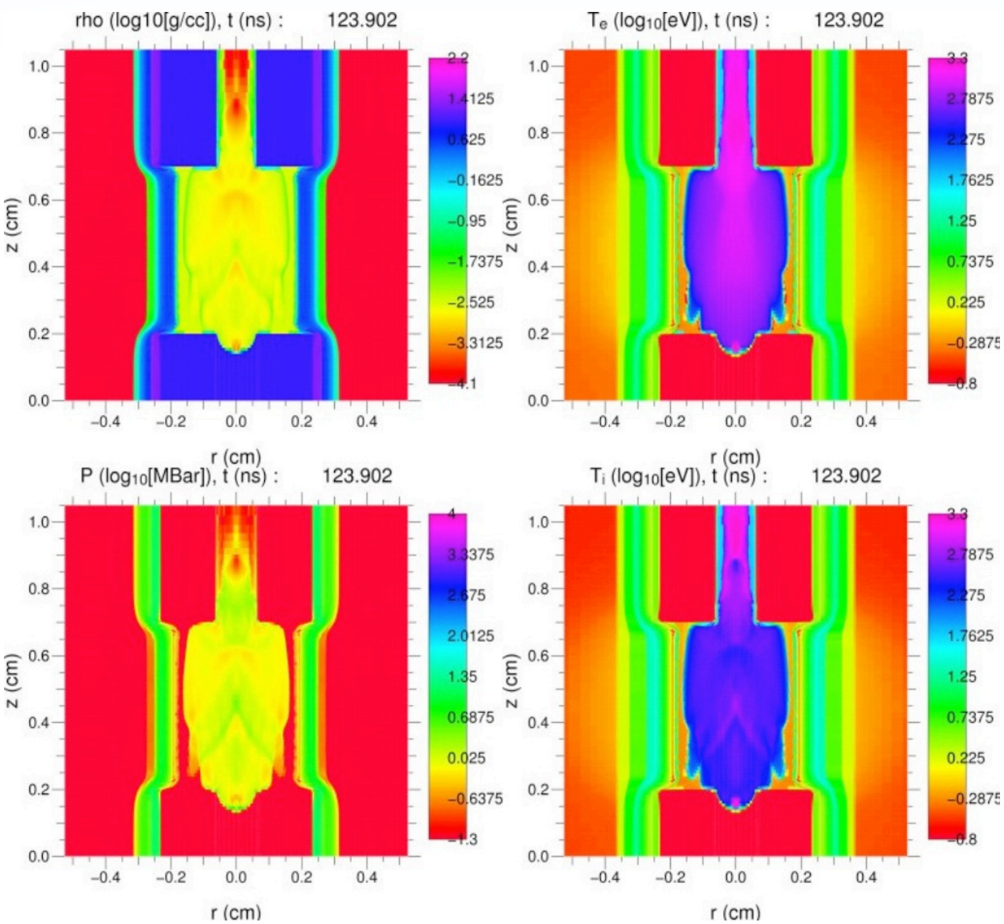
Time = 121 ns



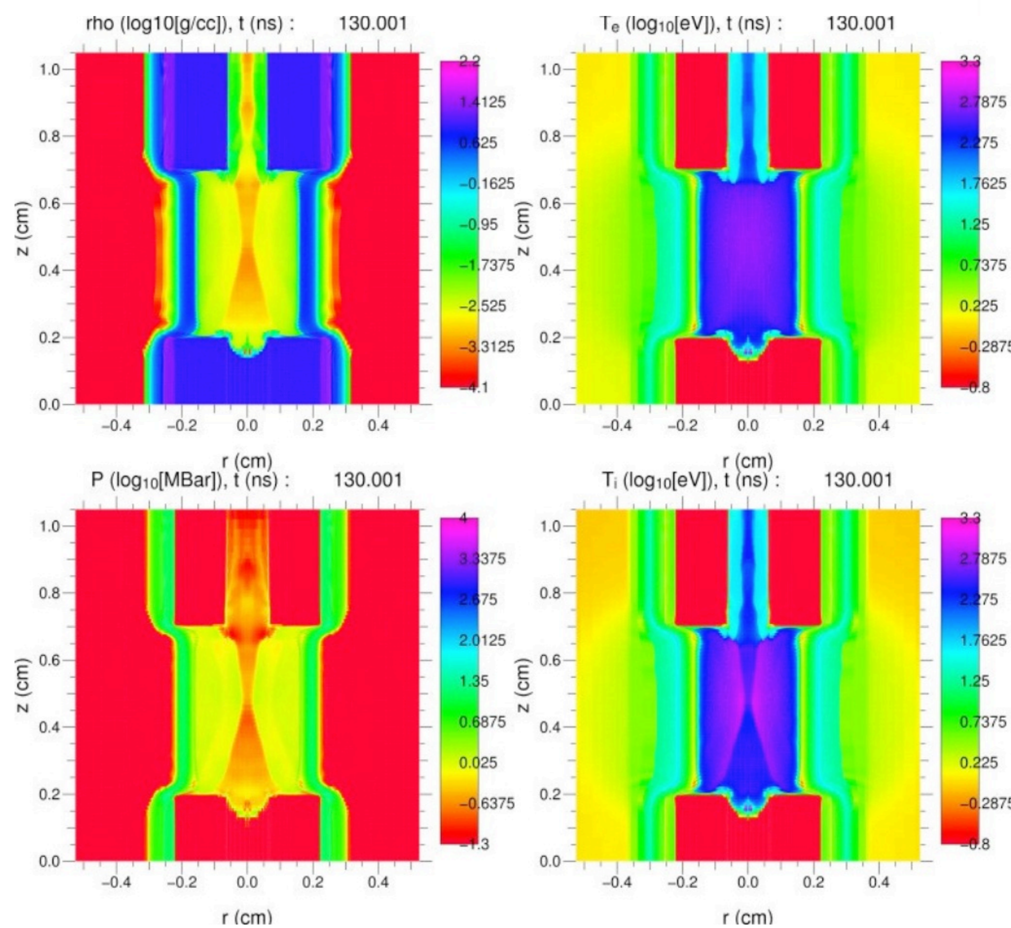
Integrated point design (with notch)



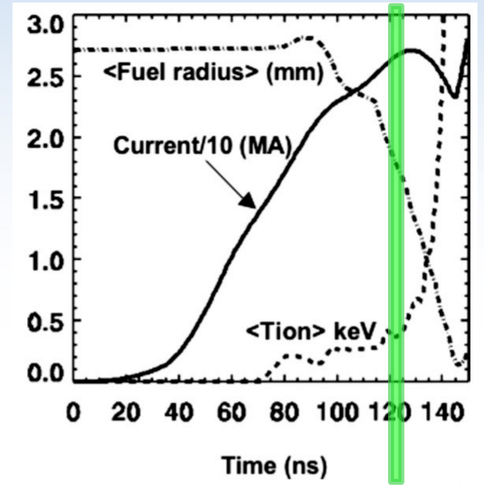
Time = 124 ns



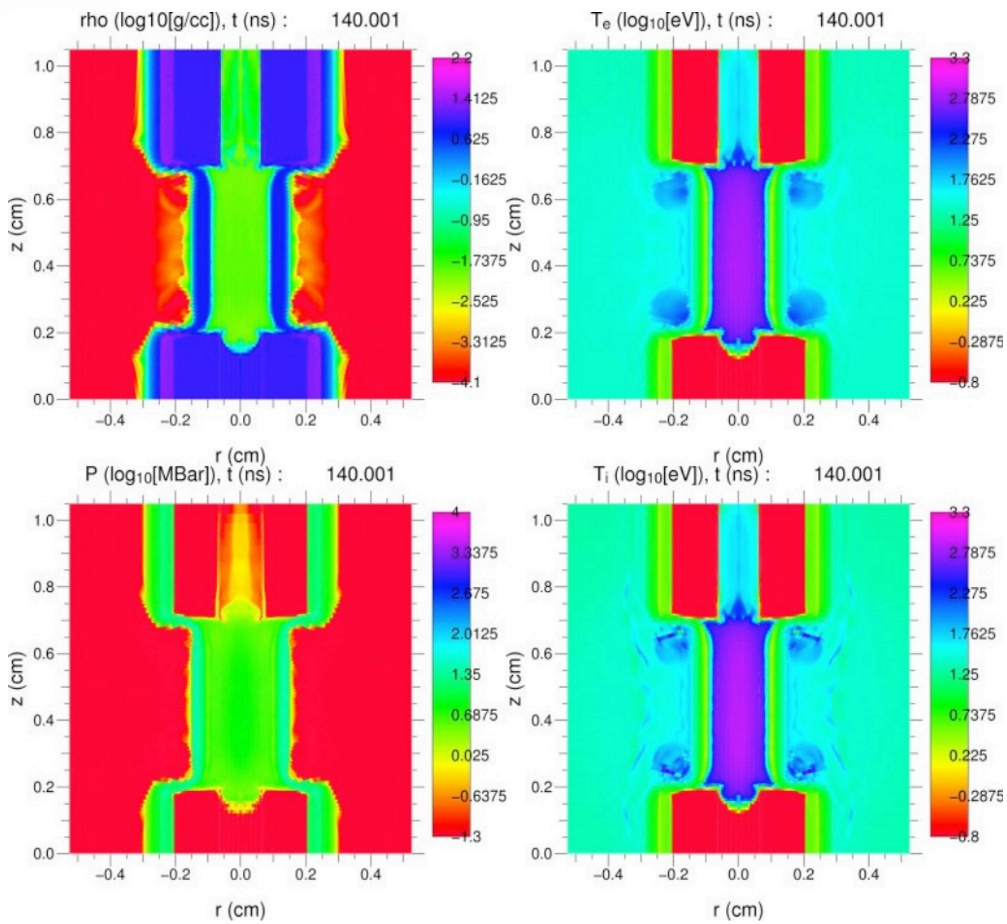
Time = 130 ns



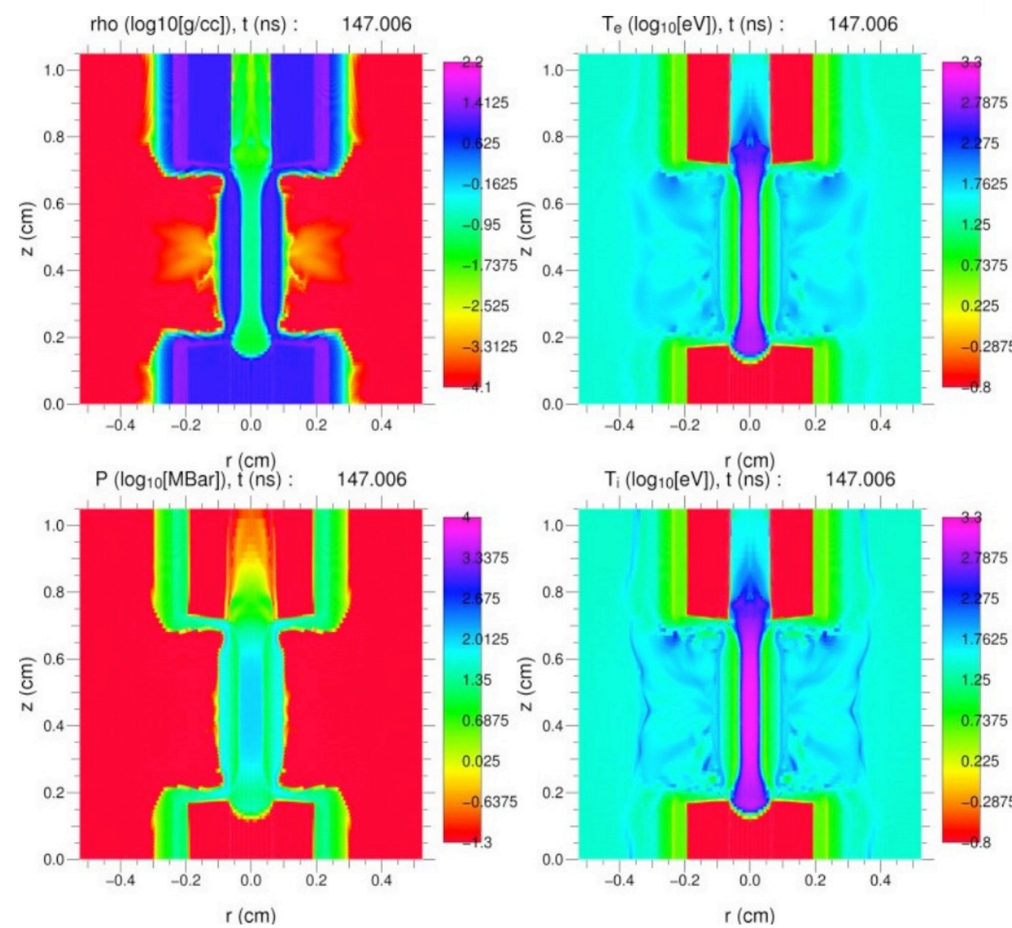
Integrated point design (with notch)



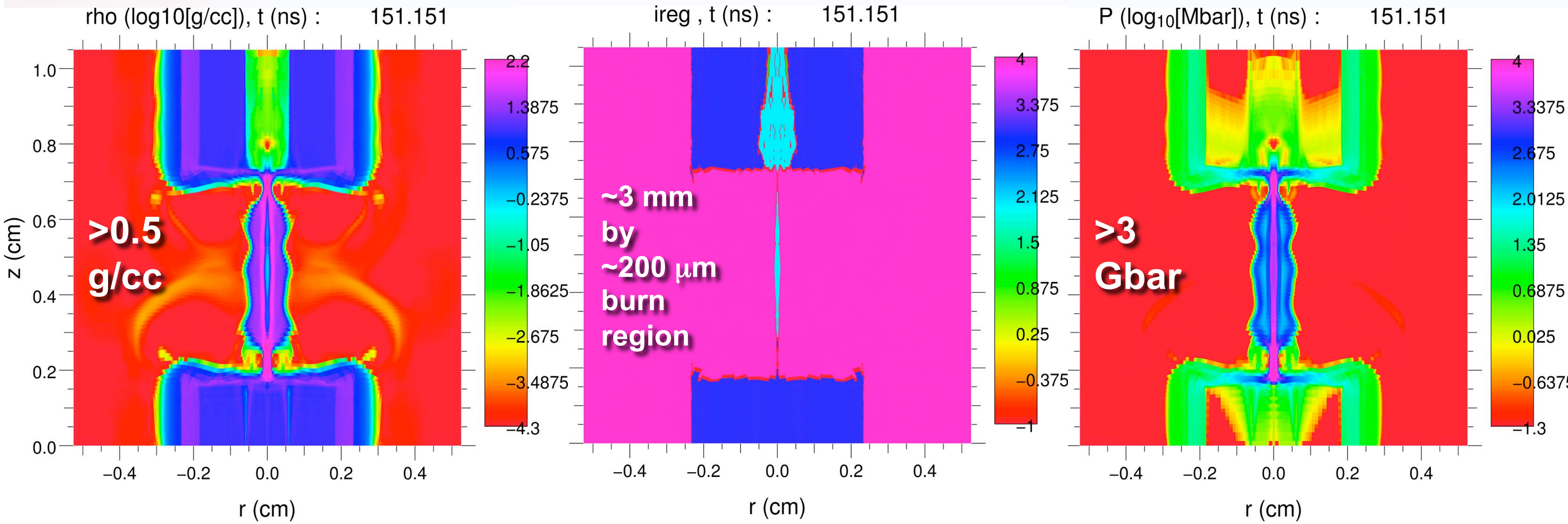
Time = 140 ns

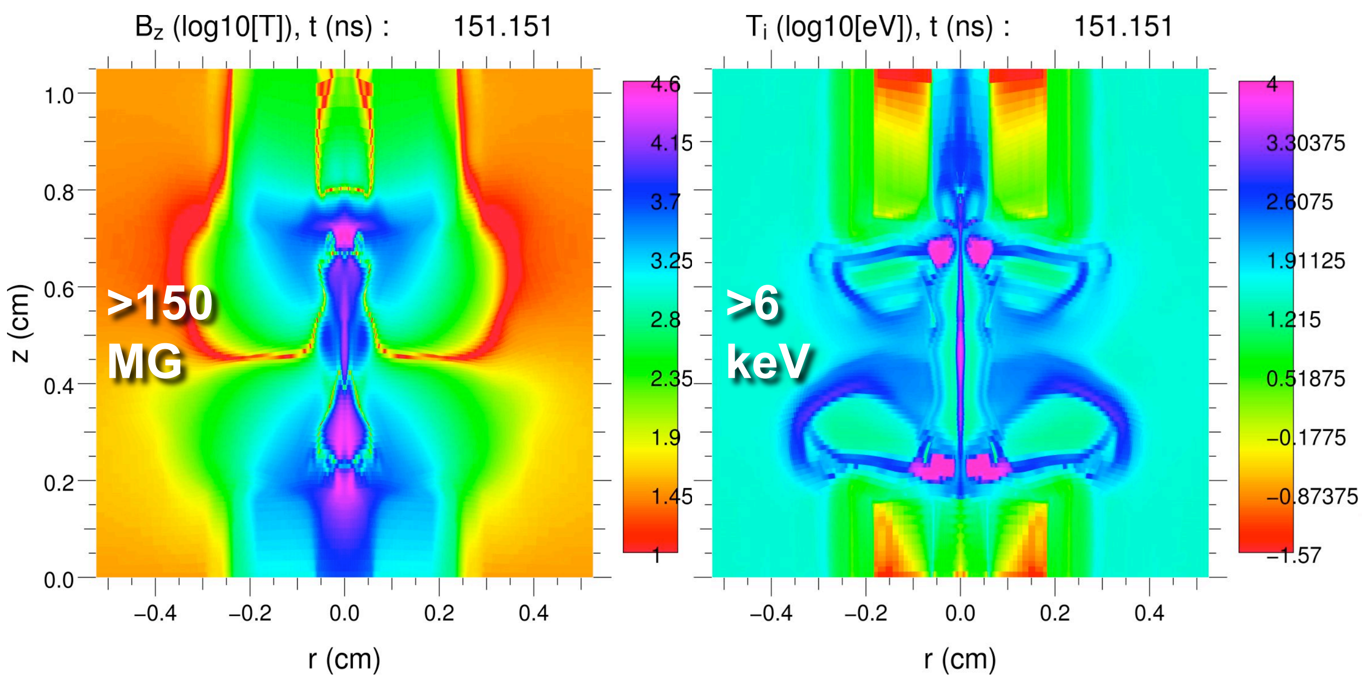


Time = 147 ns



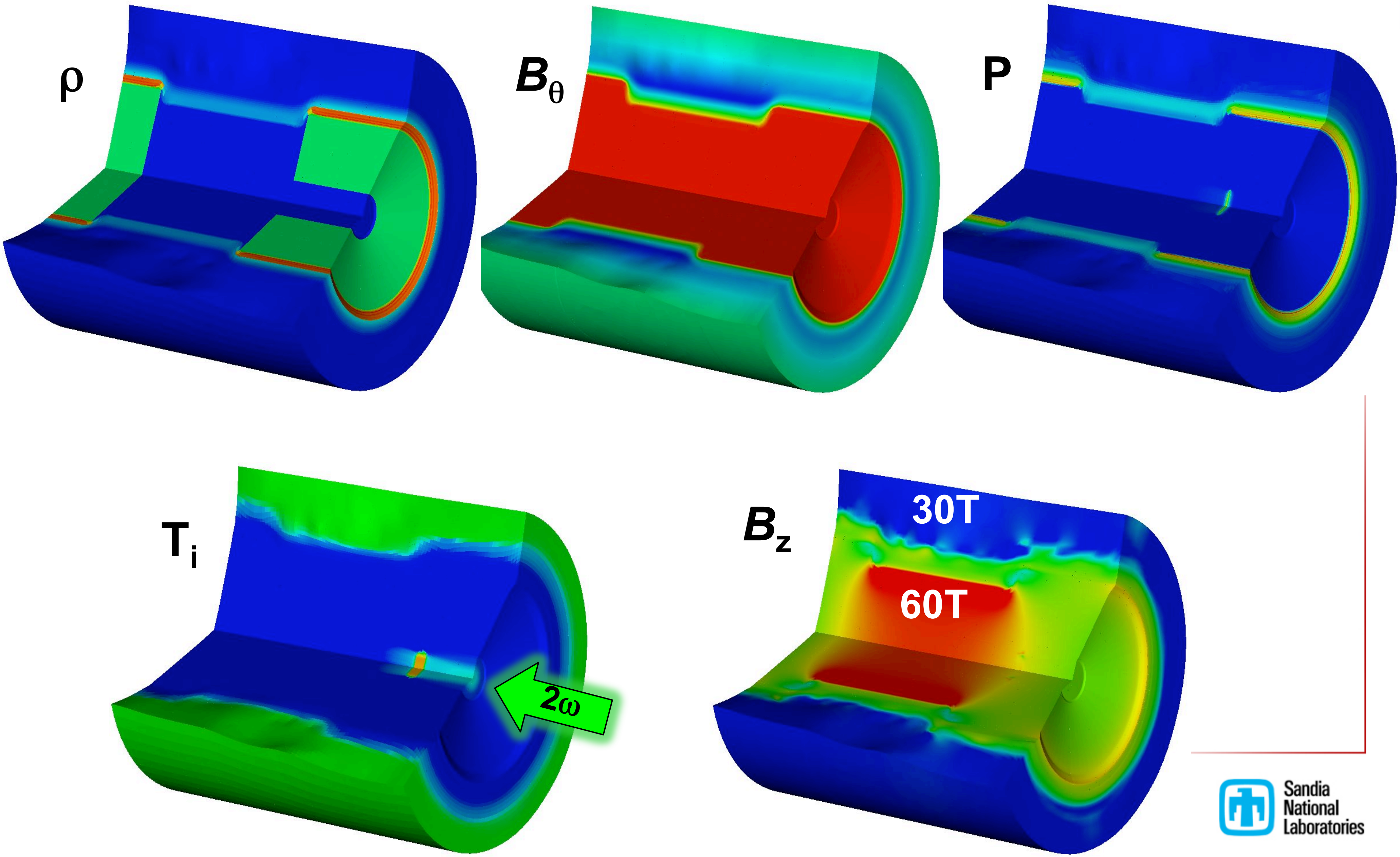
Excellent progress is being made in 2D integrated MagLIF simulations using HYDRA





This preliminary and not optimized design gives a fusion yield of ~50 kJ/cm

Excellent progress is being made in 3D integrated MagLIF simulations using HYDRA



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Summary

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

Integrated 2D & 3D radiation-MHD simulations using the HYDRA code are promising and ongoing

Integrated simulations are required for the most realistic performance expectations:

(1) inclusion of the end cap walls is necessary for liner-wall, laser/T_{rad}-wall, and B_z-wall effects
(2) liner and B_z flux compression are complicated by the need for one-sided laser preheat
(3) the LEH must be large enough to sufficiently heat fuel, but small enough to reduce flow losses
(4) the laser strikes the LEH window and launches magnetosonic shocks
(5) the laser preheat creates a high β plasma that considerably alters the B field topology
(6) relative timing between laser preheating and implosion requires optimization
(7) must avoid or mitigate any high-Z material end cap ablation by the laser near the fuel region
(8) complex anisotropic conductivity and fusion burn in possible asymmetric environment
(9) 2d and 3d simulations necessary to evaluate magneto-Rayleigh-Taylor instability in liner

Fusion yields on the order of the target's absorbed energy may be possible on Z + Z-Beamlet with improved design considerations from integrated calculations

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