Integrated MagLIF calculations in HYDRA

A. B. Sefkow[1], J. M. Koning[2], M. M. Marinak[2], C. W. Nakhleh[1], K. J. Peterson[1], D. B. Sinars[1], S. A. Slutz[1], and R. A. Vesey[1]

[1] Sandia National Laboratories, Albuquerque, NM
[2] Lawrence Livermore National Laboratory, Livermore, CA

MagLIF Workshop
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MagLIF appears to be a very exciting concept in ideal 1D HYDRA simulations

Preliminary 1D point design:
Be liner, A.R.= 6, 180 mg/cm
DT gas at 3 mg/cc, 250 eV preheat, B_z^0=30 T
95 kV charge voltage on Z (27 MA)

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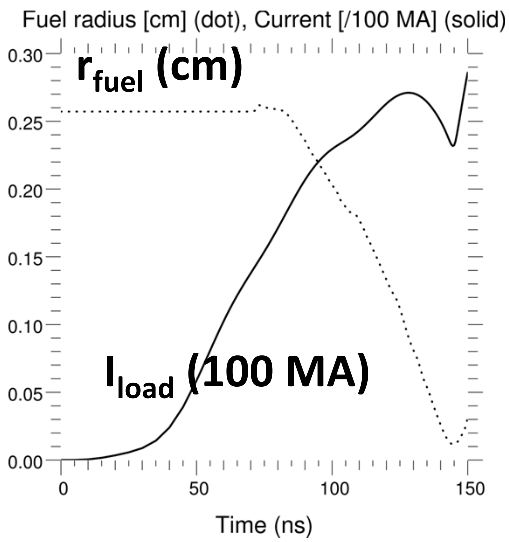

$\langle v_{imp}\rangle^{max}$ = 83 km s^{-1}
E_{fuel}^{abs} = 113 kJ cm^{-1}
E_{targ}^{abs}= 1026 kJ cm^{-1}

$E_{targ}^{abs}/E_{mag}^{load}$ = 47%
(drive efficiency)

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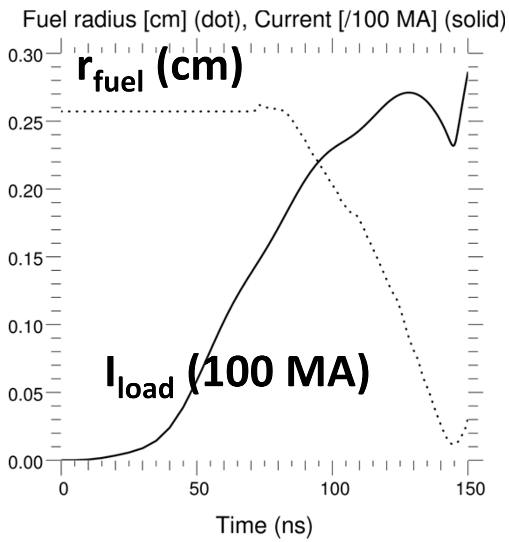

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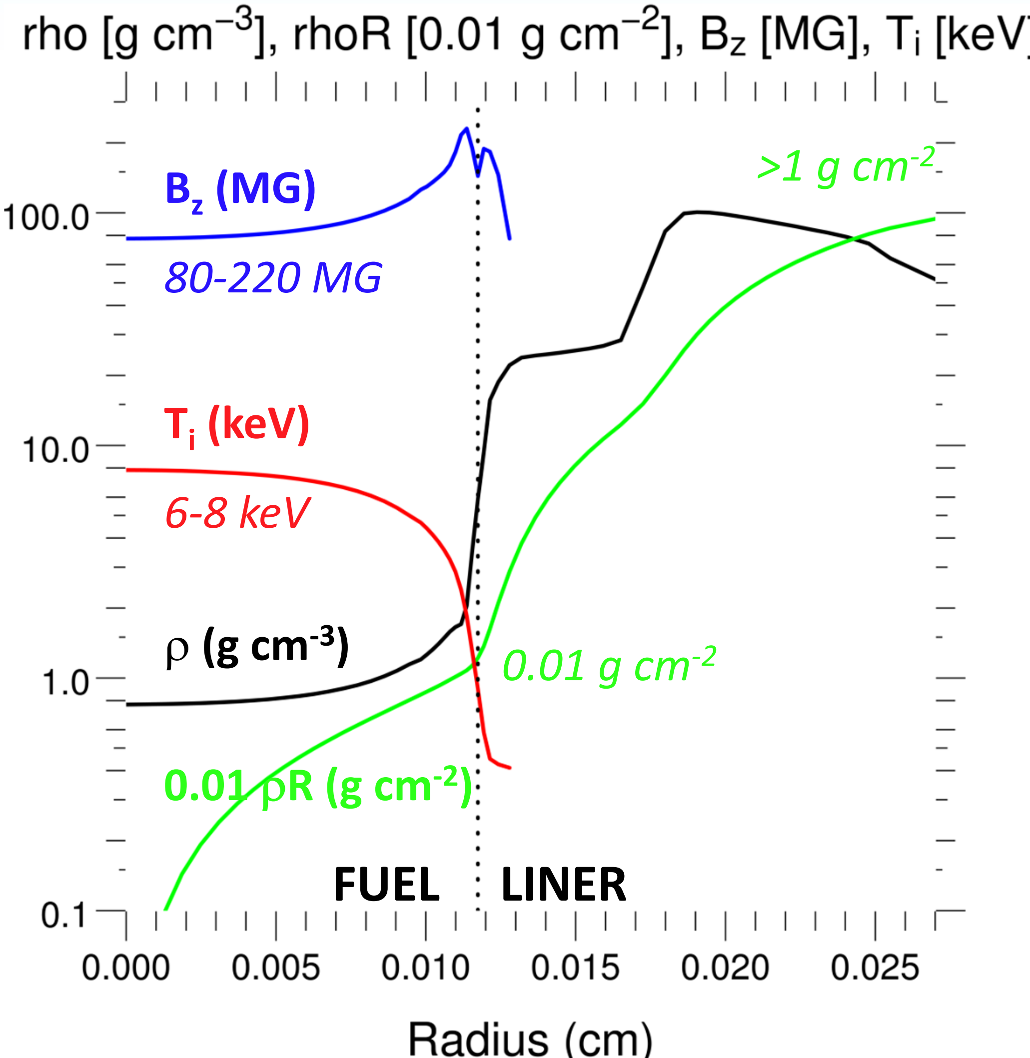
Stagnation parameters (t = 145 ns)



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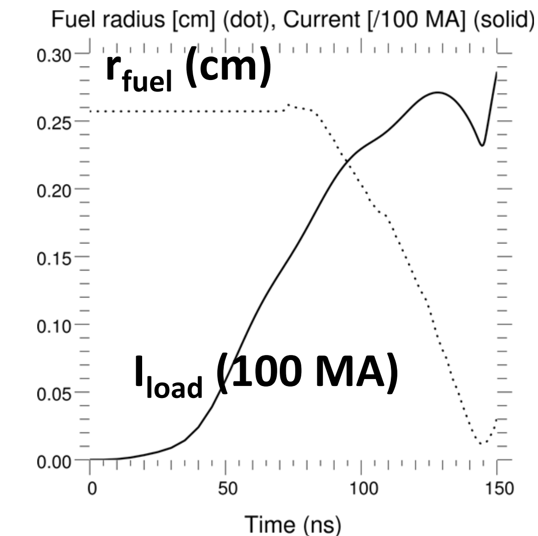

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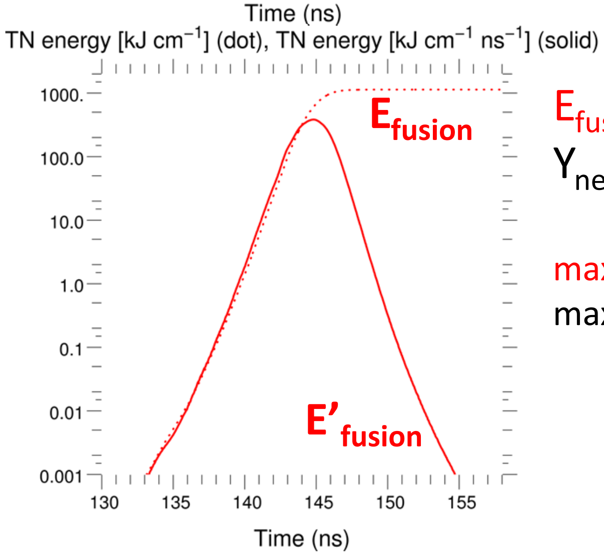
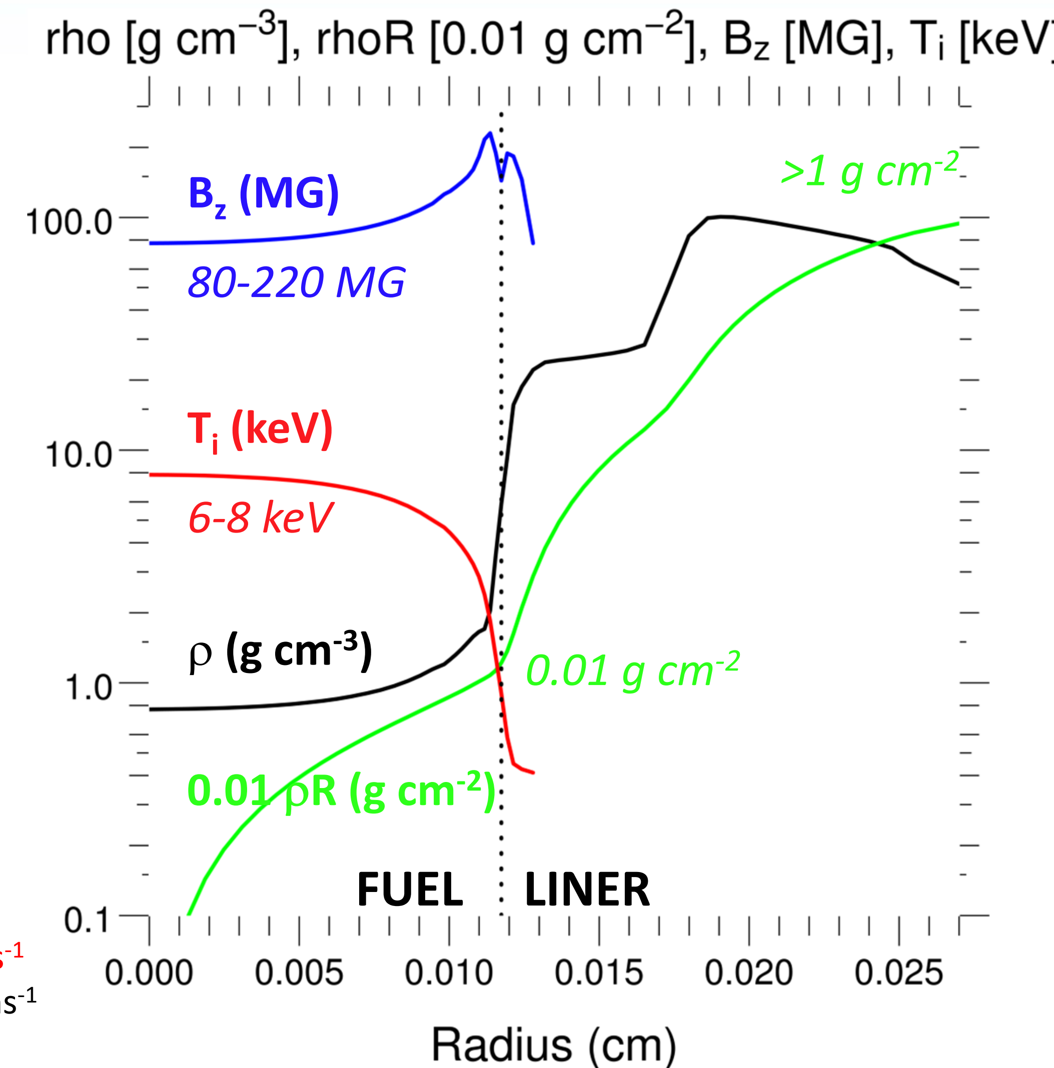


E_{fusion}= 1130 kJ cm^{-1}
Y_{neut} = 4e17 cm^{-1}

max(E'_{fusion}) = 383 kJ cm^{-1} ns^{-1}
max(Y'_{neut}) = 1.36e17 cm^{-1} ns^{-1}

Stagnation parameters (t = 145 ns)



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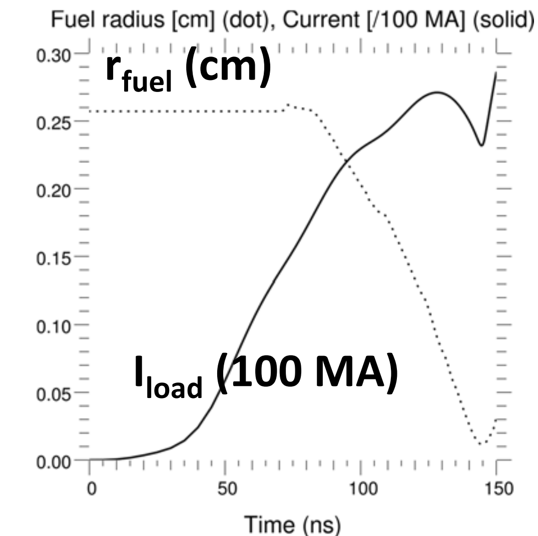

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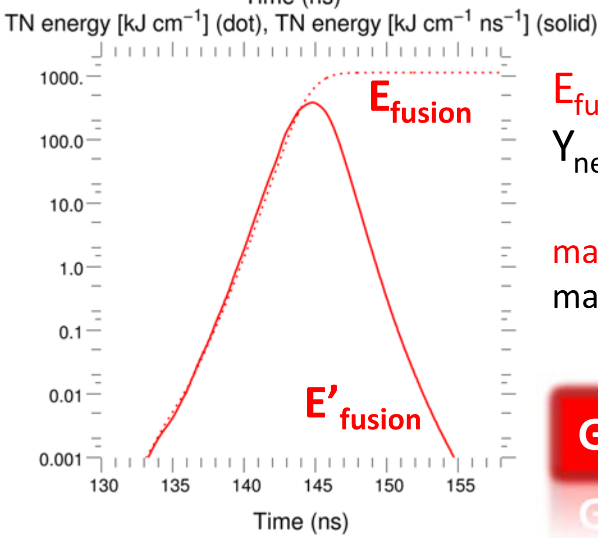

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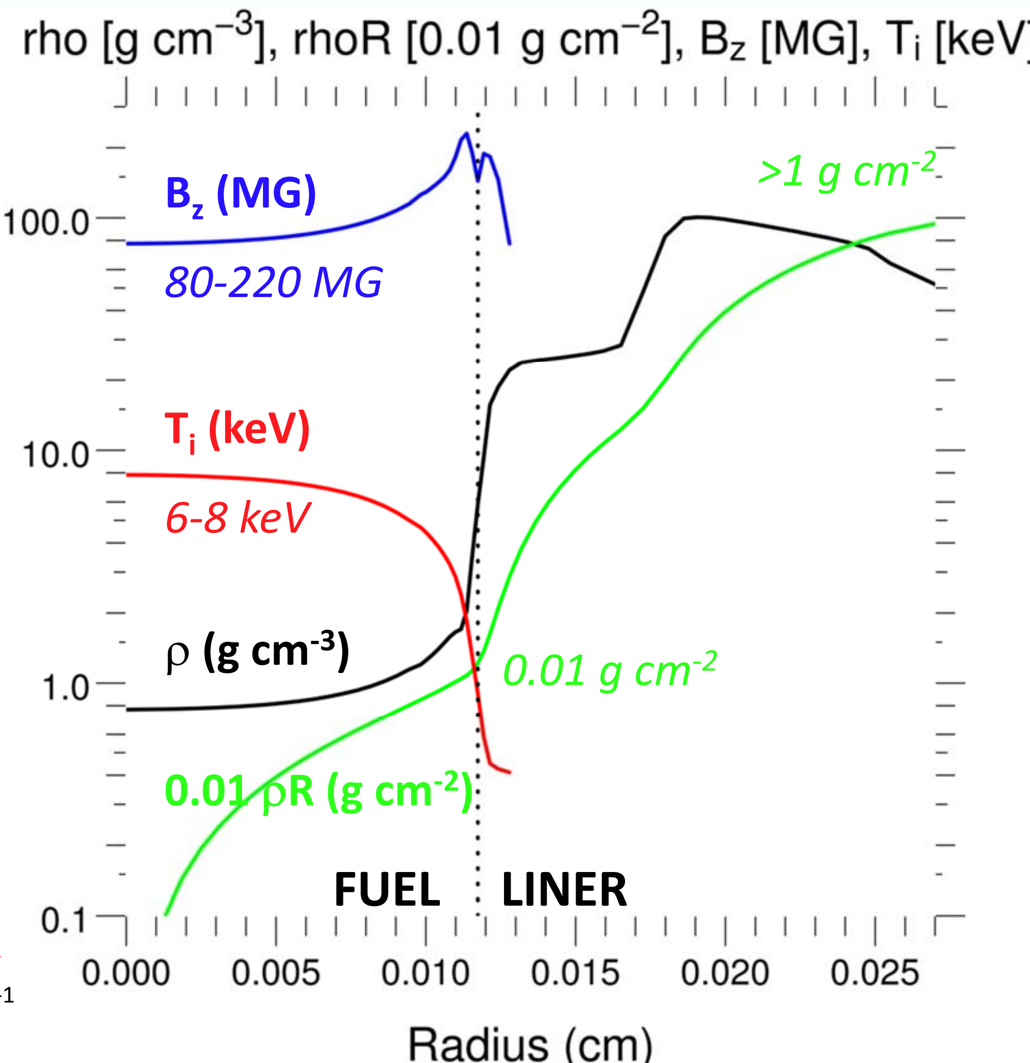

Gain = 10.0 (fuel), 1.1 (target)

C.R. = 22, P_{stag} = 5 Gbar

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C.R. = 22, P_{stag} = 5 Gbar

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:

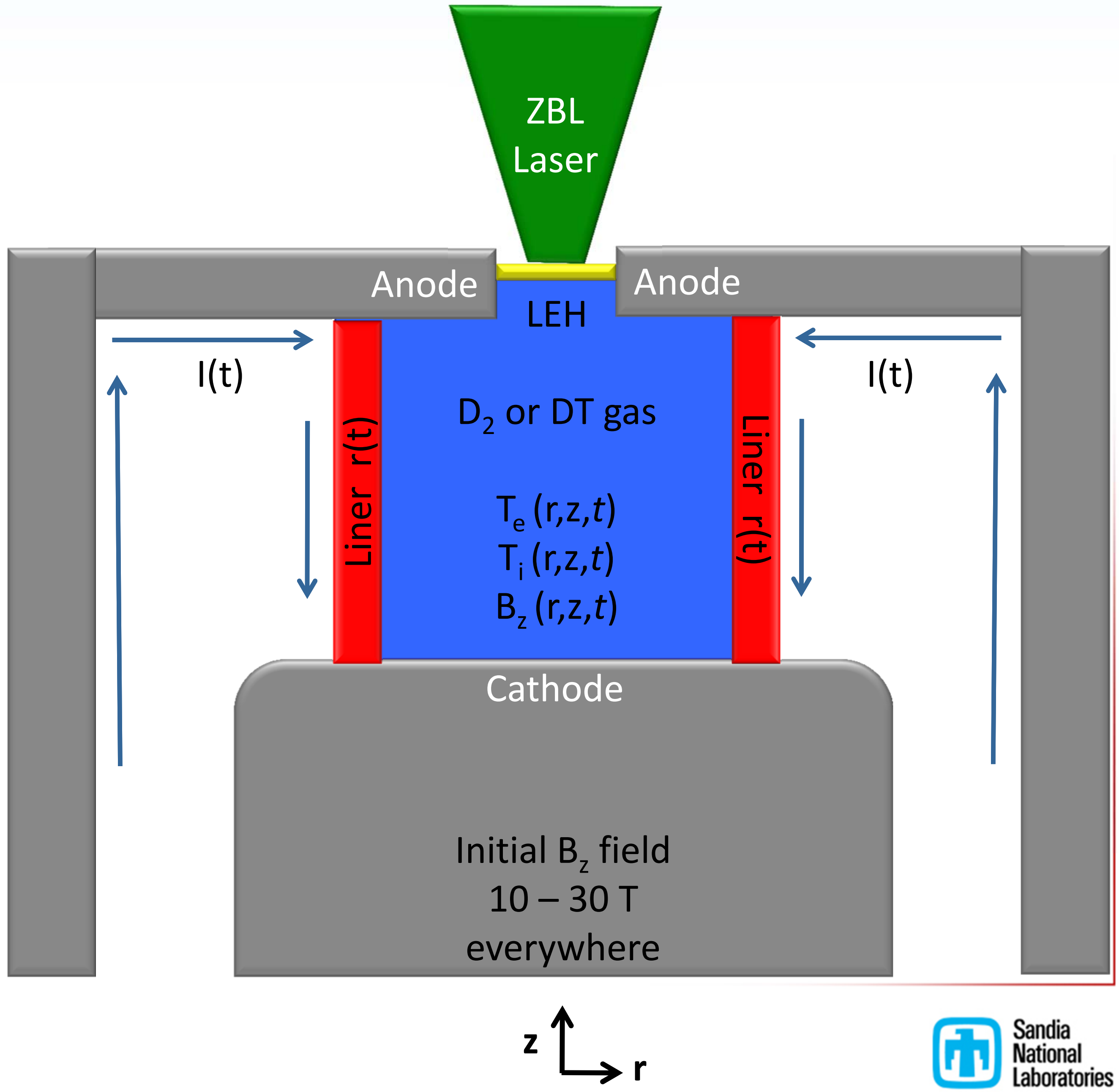
(1) Laser

(2) LEH and window

(3) Liner and circuit

(4) Electrode end caps

(5) Relative timing and optimization



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

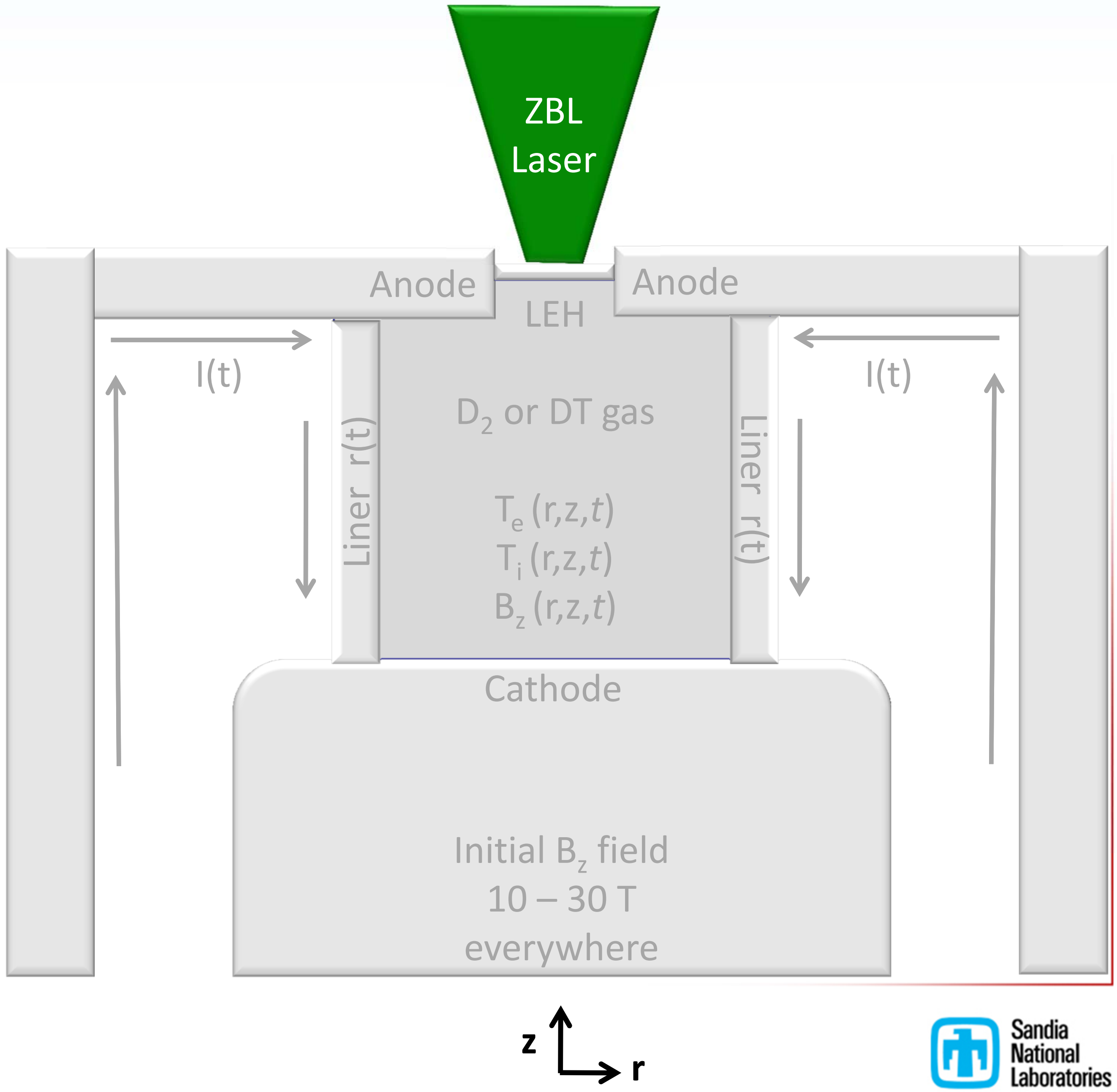
Laser parameters:
energy, spot size,
pulse duration, focal plane

Considerations:

(1) laser must not ablate anode material (wings or pointing error) and close the LEH before the end of heating phase

(2) asymmetric one-sided preheat necessitates evolving T(r,z) and B_z(r,z)

(3) must heat gas to required T_i, which is specific to the implosion (v_{imp}, C.R., B_z^0, ρR)



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

LEH and window parameters: material, thickness, location

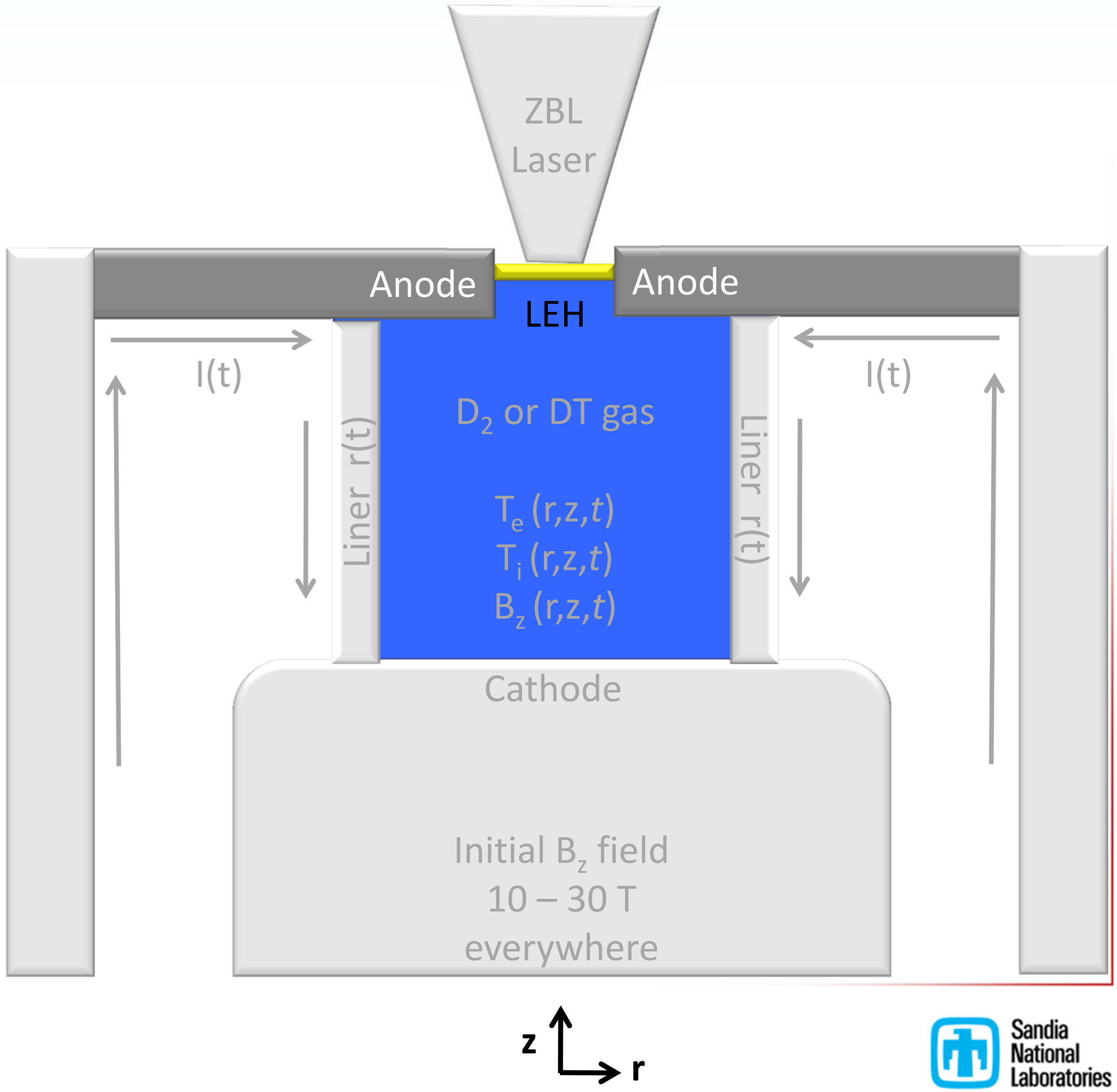
Considerations:

(1) window mass must hold gas pressure (≤25 atm), but not absorb too much laser energy ($\rho_{win}\Delta z << \rho_{gas}\Delta z$)

(2) recessed window relative to main fuel region, so heated plasma pressure prevents window material from mixing with fuel underneath liner

(3) laser launches shock from window into fuel

(4) expanding window can refract beam



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

Liner and circuit parameters: material, mass, aspect ratio, length, surface roughness, fuel density, B_z^0 strength

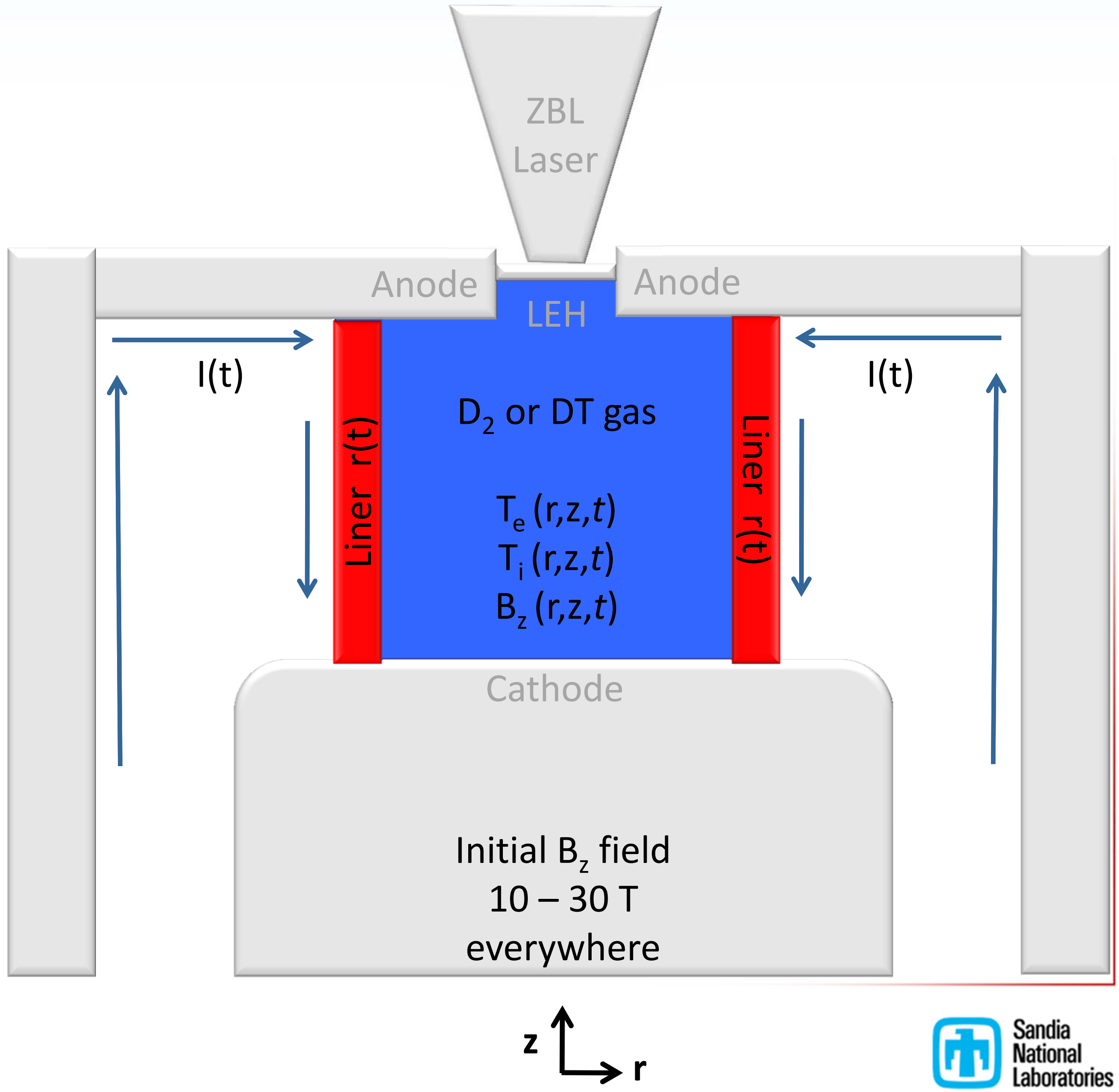
Considerations:

(1) drive liner implosion with circuit model to compress preheated and magnetized fuel

(2) achieve velocity, B_z^{stag}/B_z^0, convergence, stability, ρR

(3) evaluate growth of magneto-RT instability from liner surface perturbations

(4) 3D model for most realism



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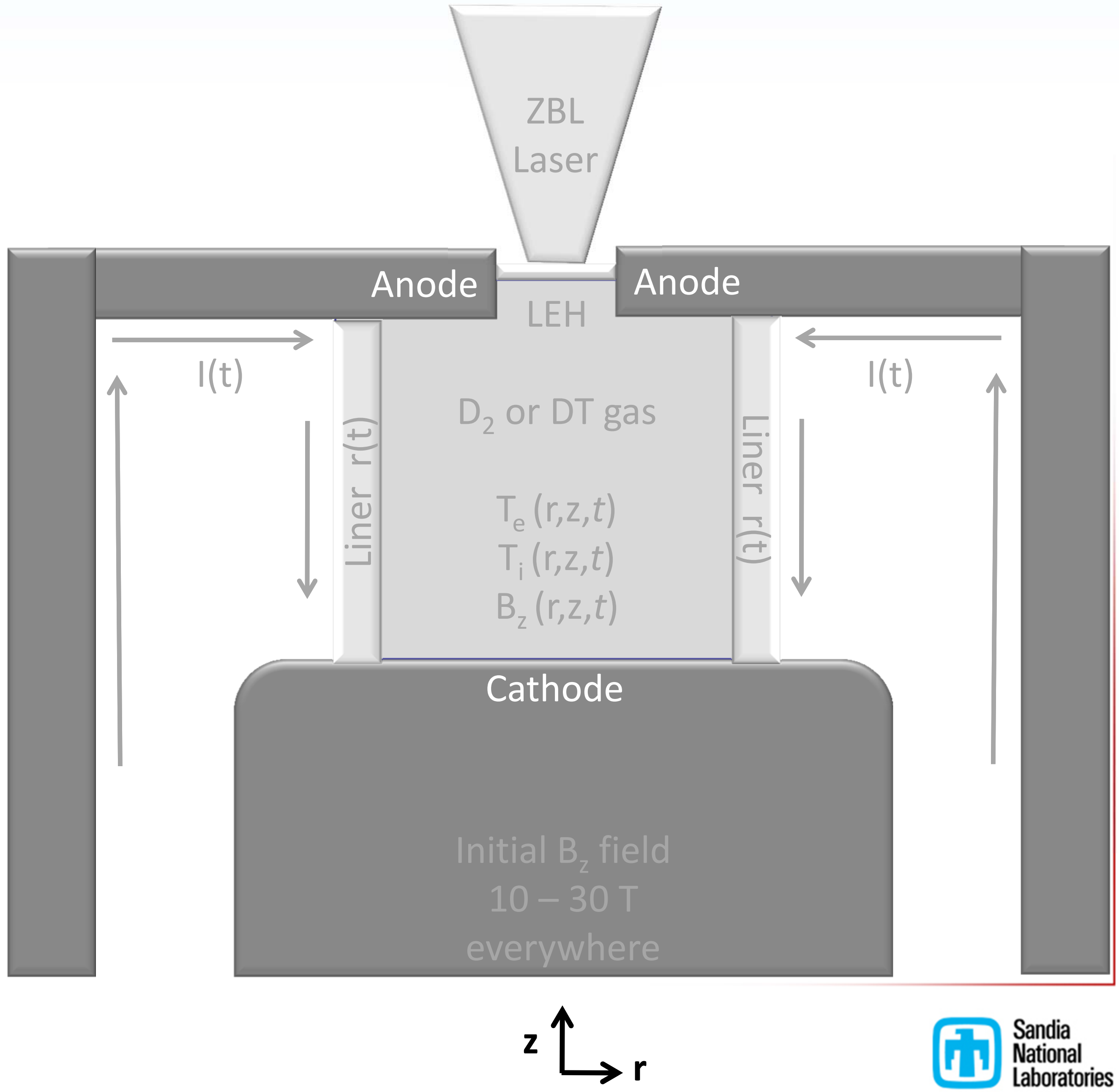
An integrated model seeks to realistically simulate MagLIF experiments as they would occur on Z

Electrode end cap parameters: material to provide boundaries for LEH and burn region

Considerations:

(1) LEH in anode should be large enough to allow sufficient deposition, but small enough to reduce flow losses

(2) evaluate non-ideal wall effects:
(a) liner-wall
(b) fuel-wall
(c) B_z-wall
(d) laser and radiation ablation



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

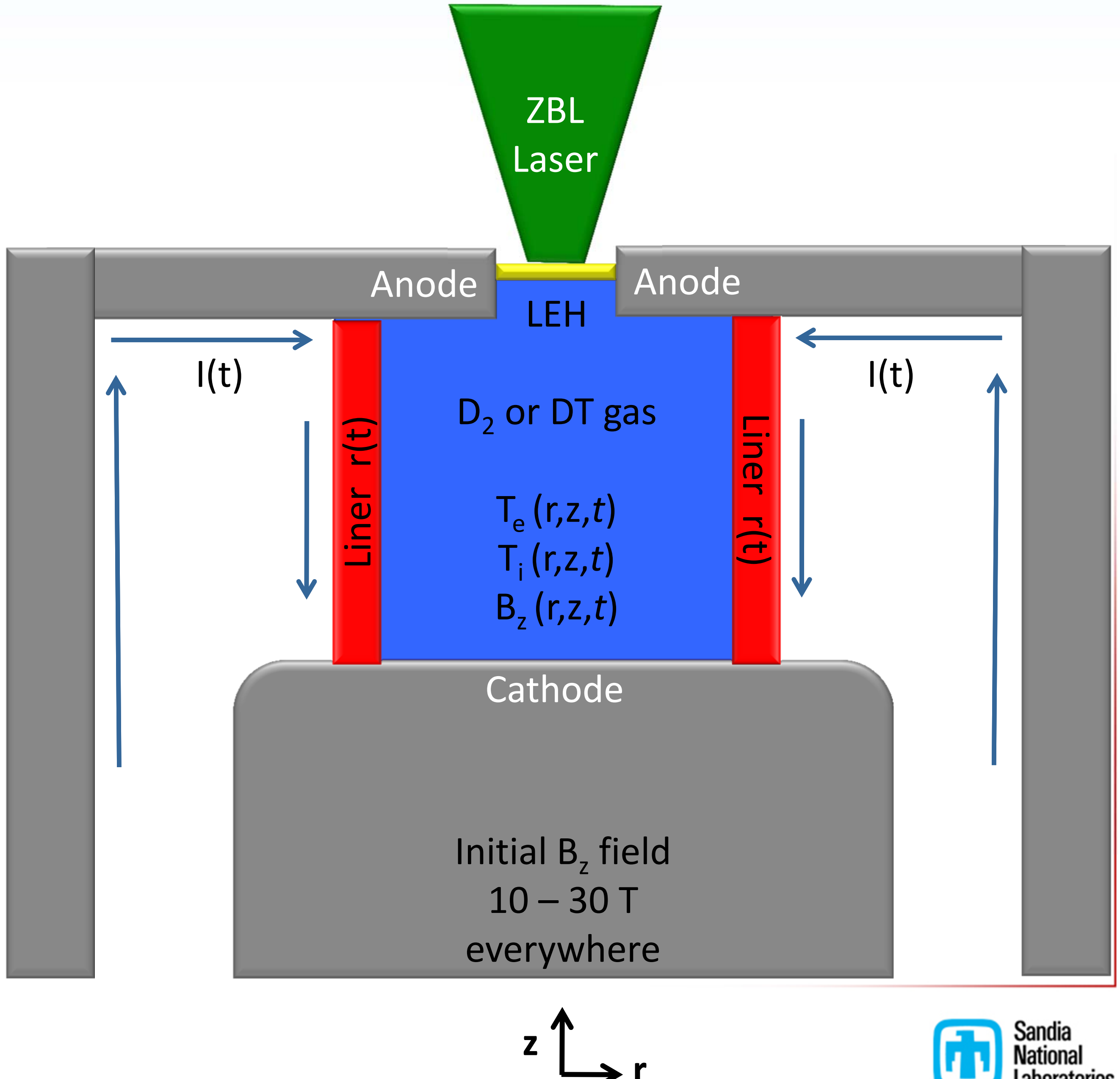
Relative timing and optimization issues

Considerations:

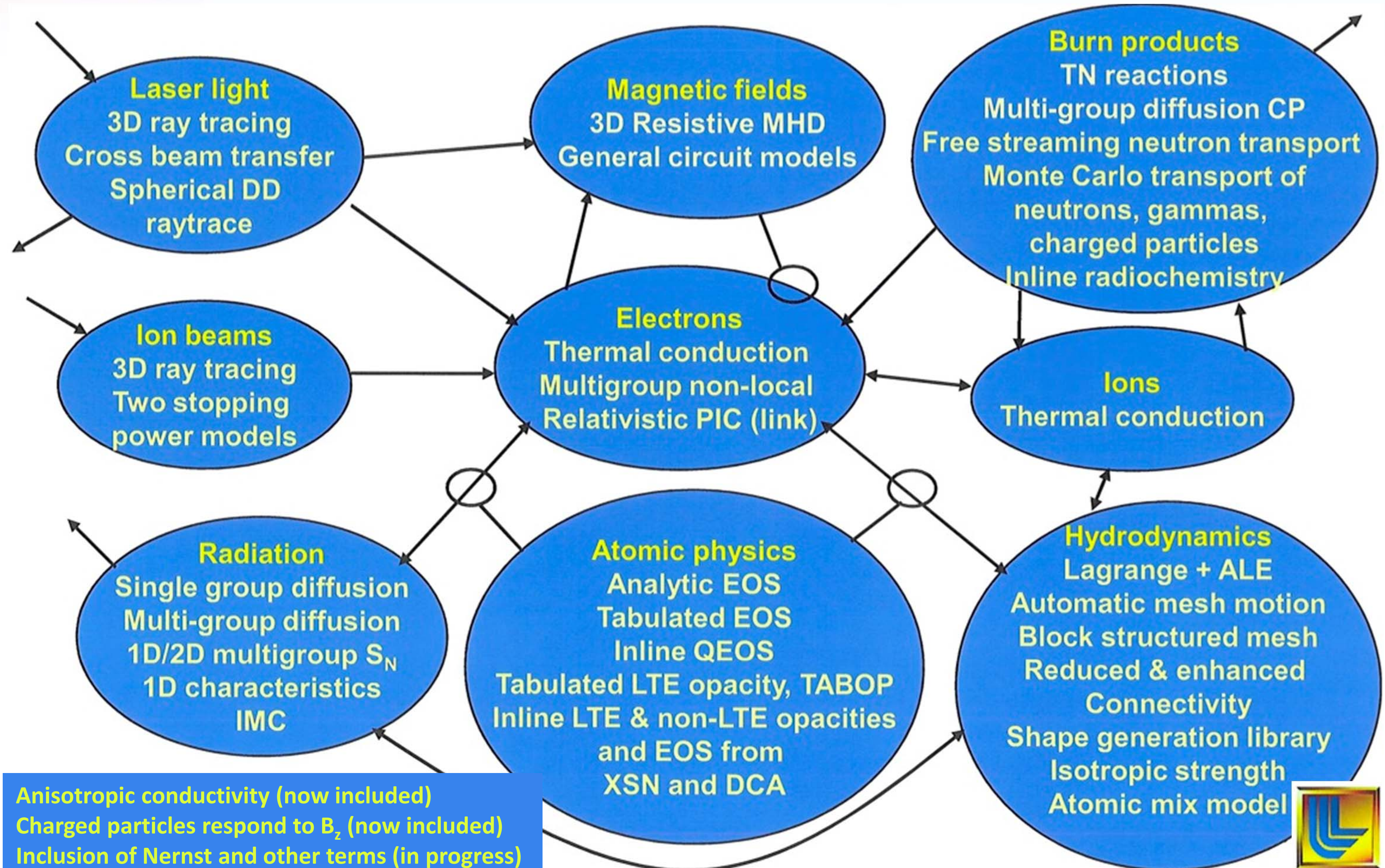
(1) optimization of laser deposition parameters and timing for a given implosion

(2) avoid or mitigate laser ablation of high-Z cathode material into fuel underneath liner

(3) the best combination of parameters for integrated simulations may not be identical (or similar) to those for ideal simulations

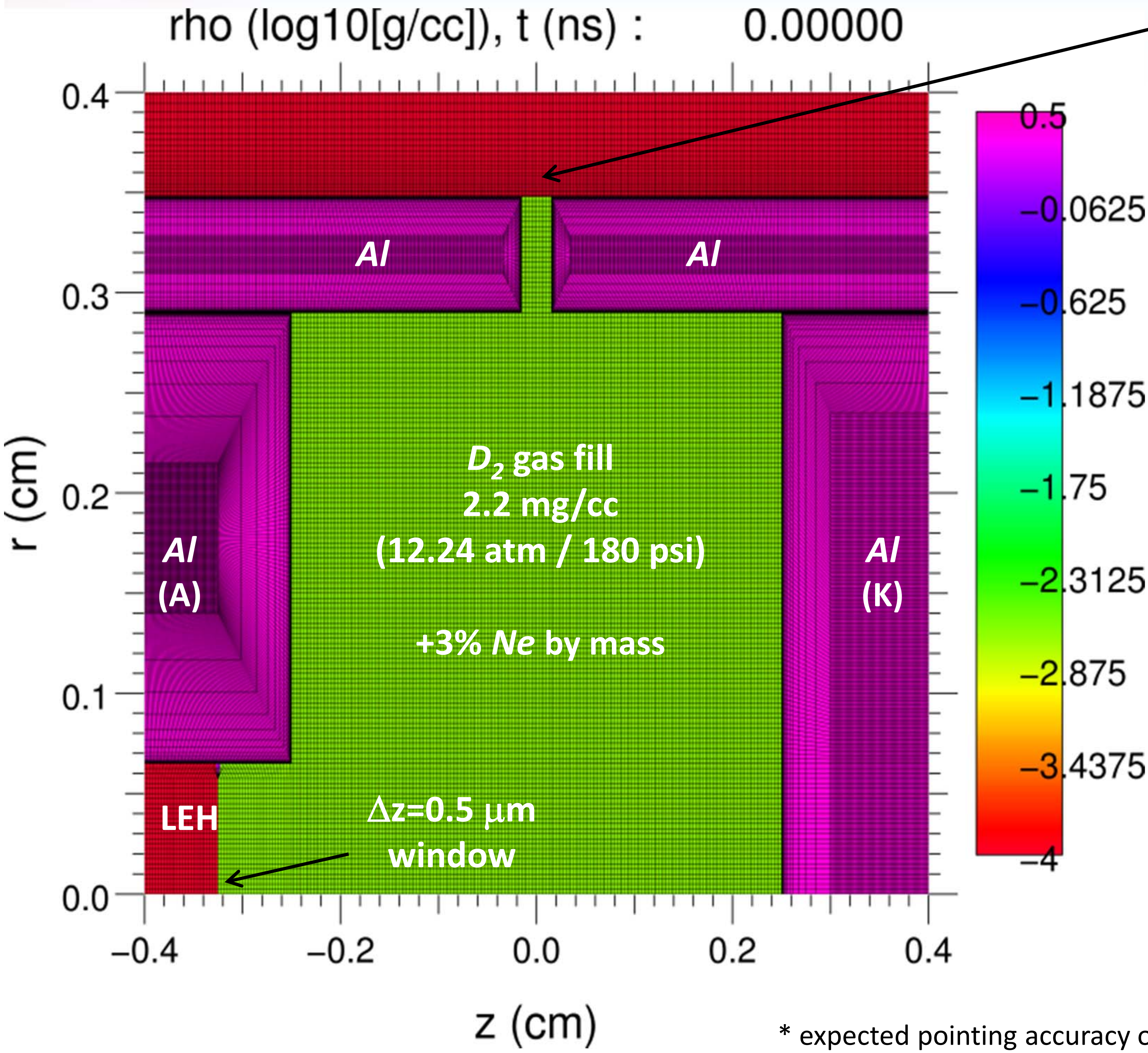


Physical processes modeled by the massively-parallel HYDRA code for ICF simulations

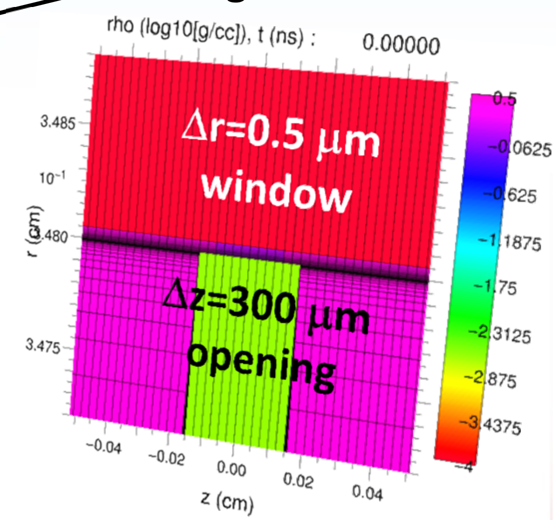


Anisotropic conductivity (now included)
Charged particles respond to B_z (now included)
Inclusion of Nernst and other terms (in progress)

HYDRA initialization for standalone MagLIF preheat ZBL experiments



Diagnostic Port

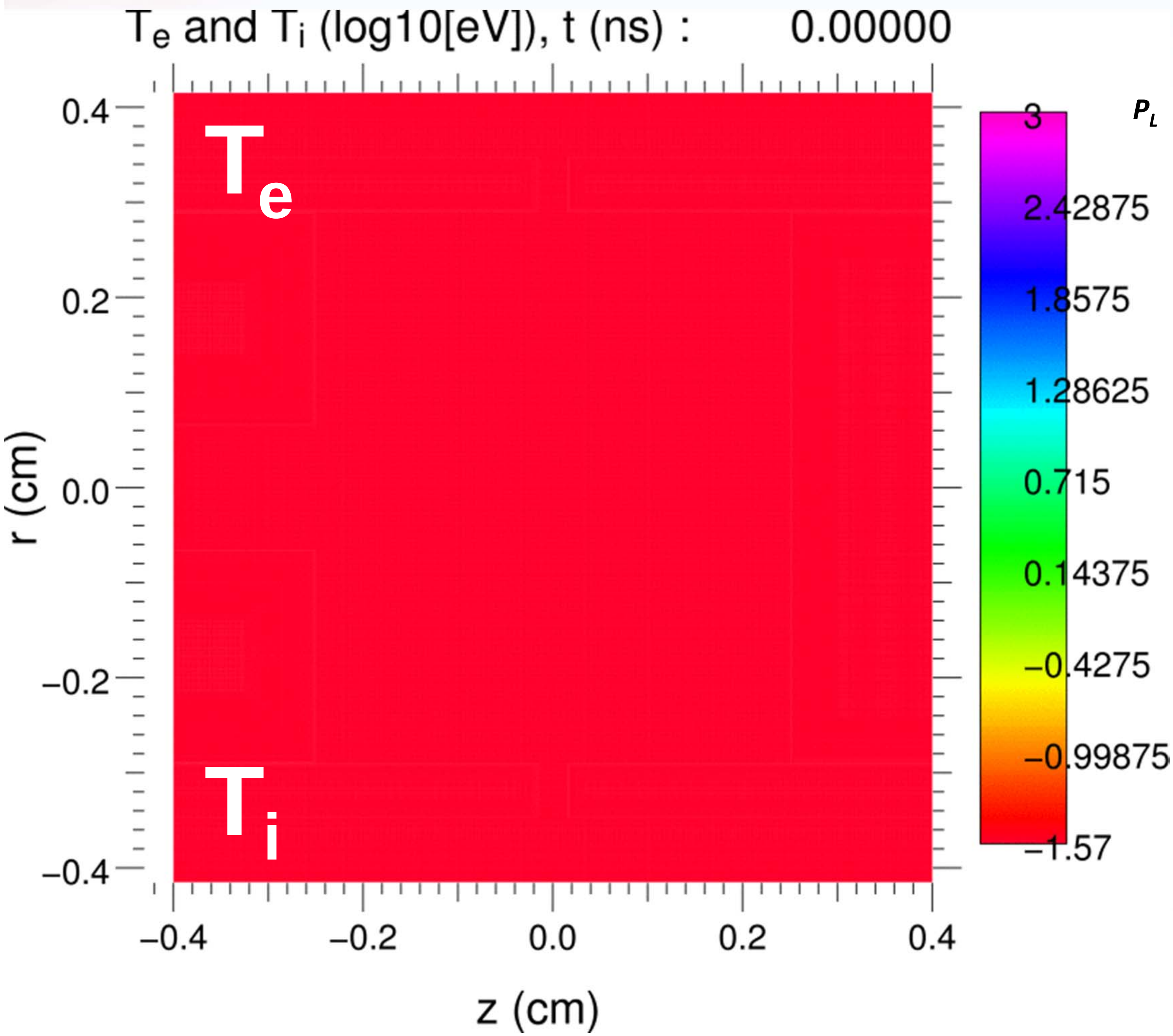


Laser Entrance Hole
1.3 mm diameter

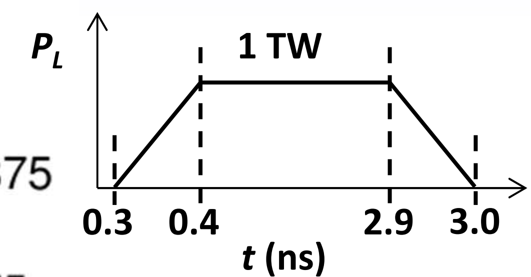
Laser Parameters
2.5 kJ of 2ω
2.5 ns duration (1 TW)
0.1 ns rise/fall time
0.4 mm FWHM (~$e^{-(r/spot)^2}$)
f/10 lens (cal chamber)
$I_L \approx$ 3e14 W cm^{-2}

* expected pointing accuracy on Z is 0.015 cm

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 may ablate far wall (cathode end cap); we will also try to measure this, since it mixes with fuel and critically impacts the target design.

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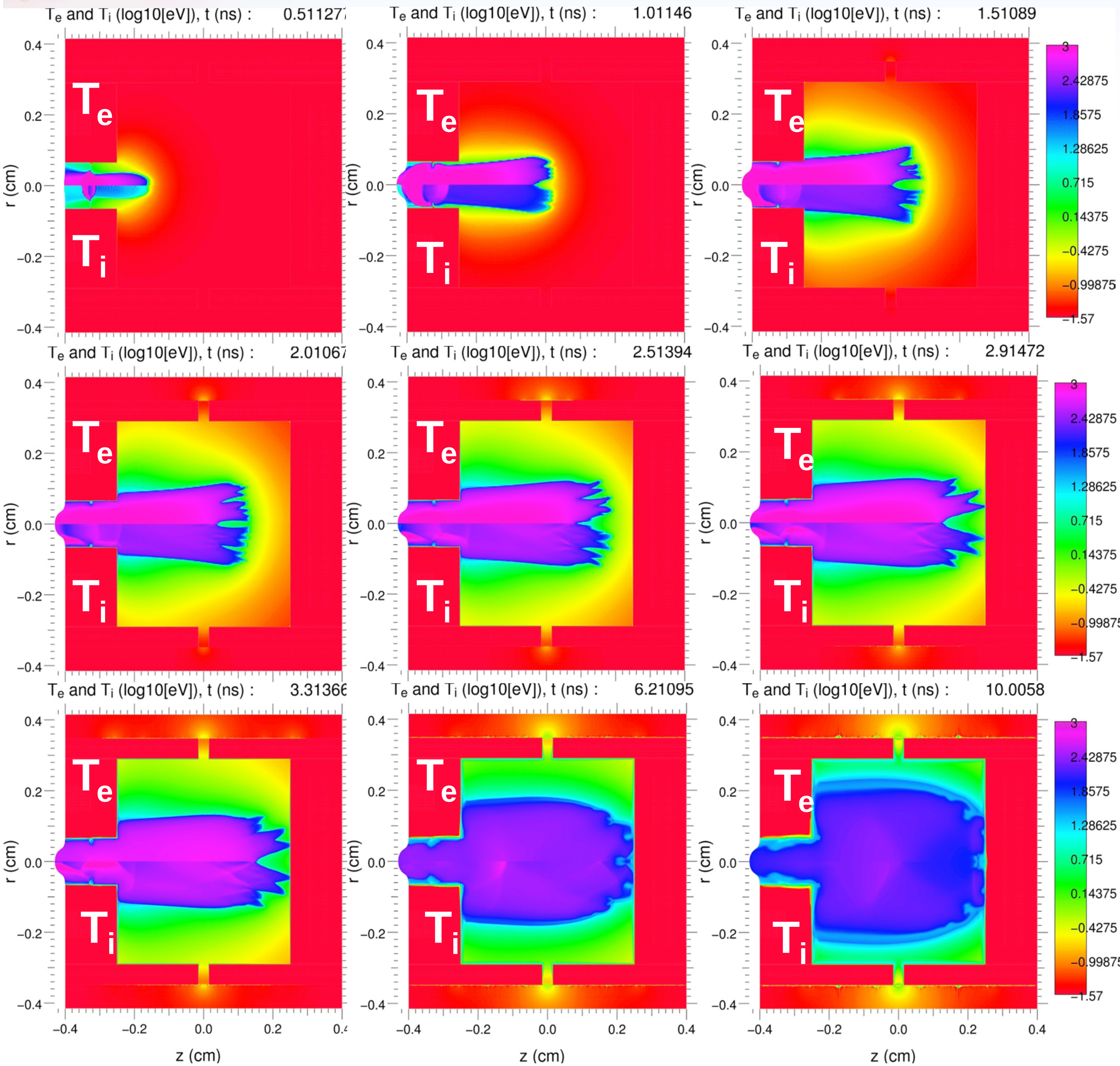

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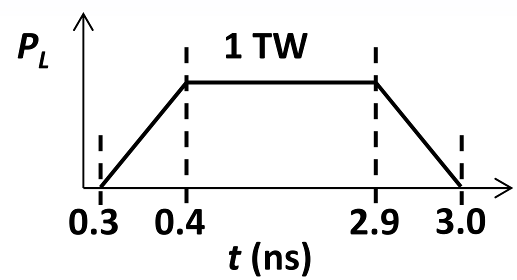

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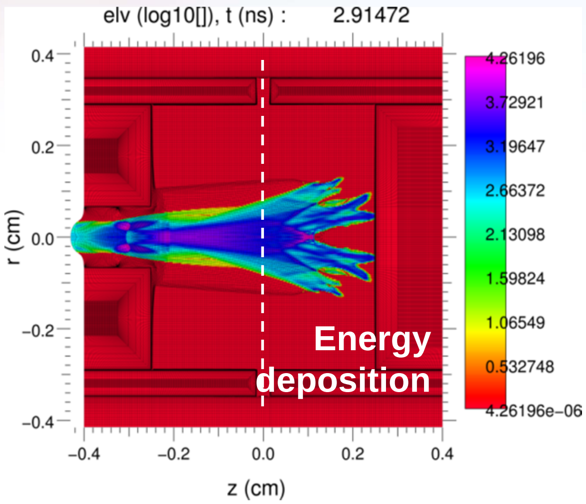
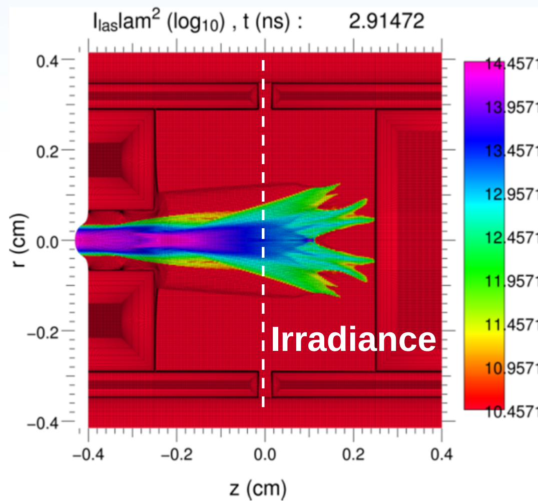
Experiments may measure T_e~900 eV and T_i~400 eV

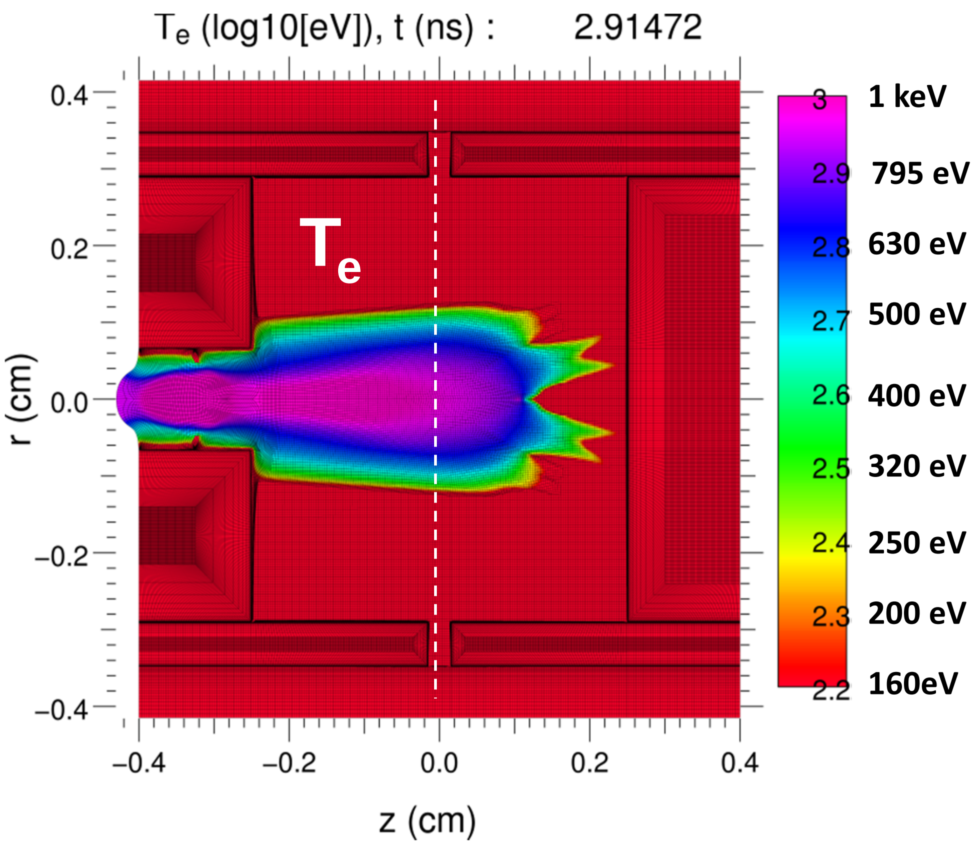


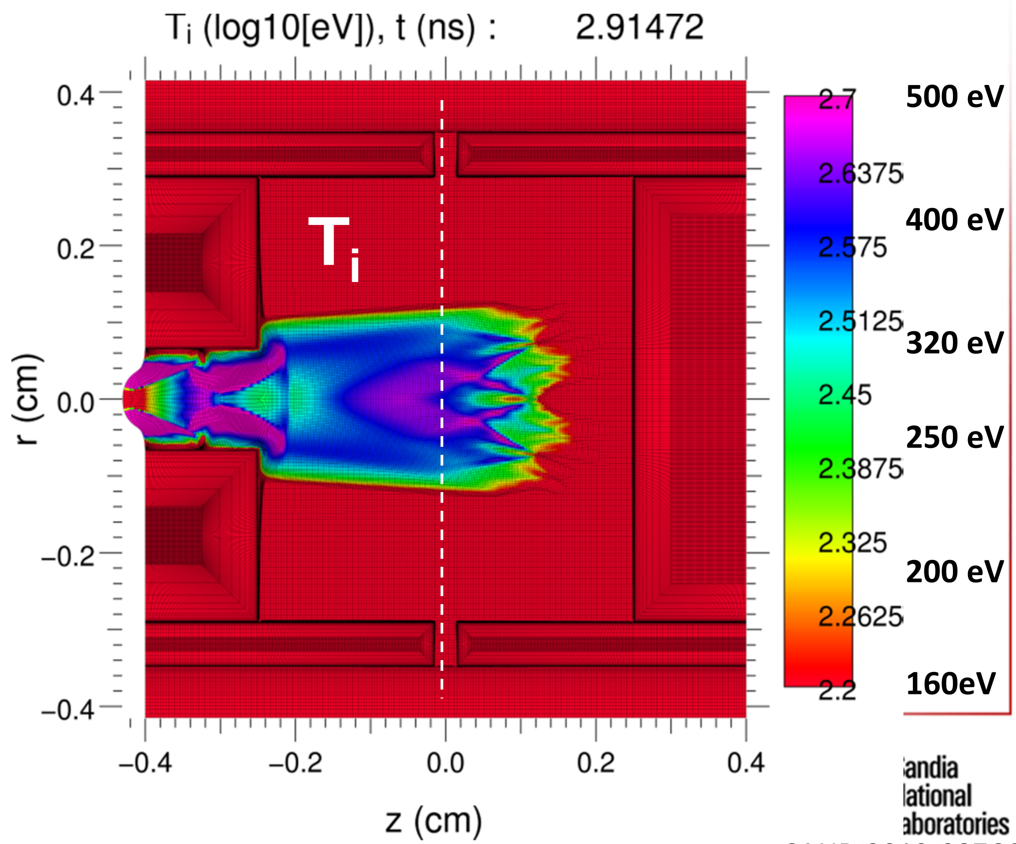


Self Thomson scattering of 2ω laser light

Snapshot diagnosis of T_e and T_i only occurs during laser pulse

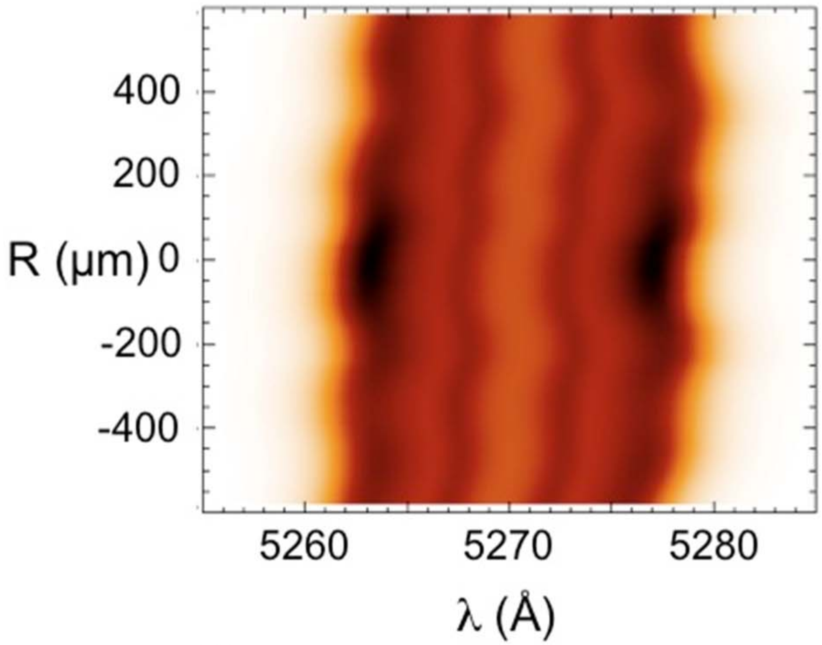
Axial resolution only through positioning of diagnostic port, and no radial resolution

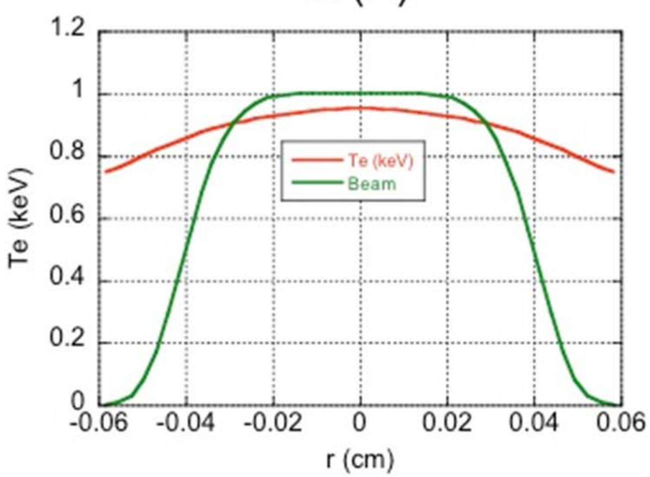




Effect of averaging over inhomogeneity provides reasonable lower bound on T_e and T_i

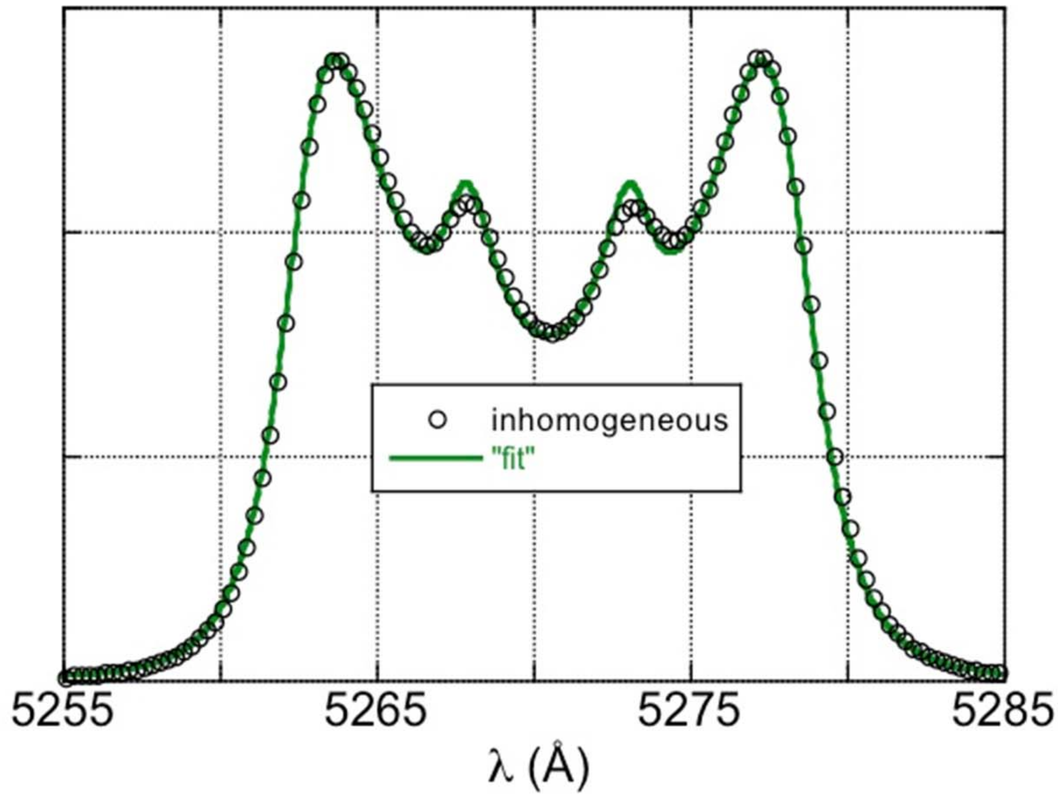
3% Ne, <Z> = 10





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

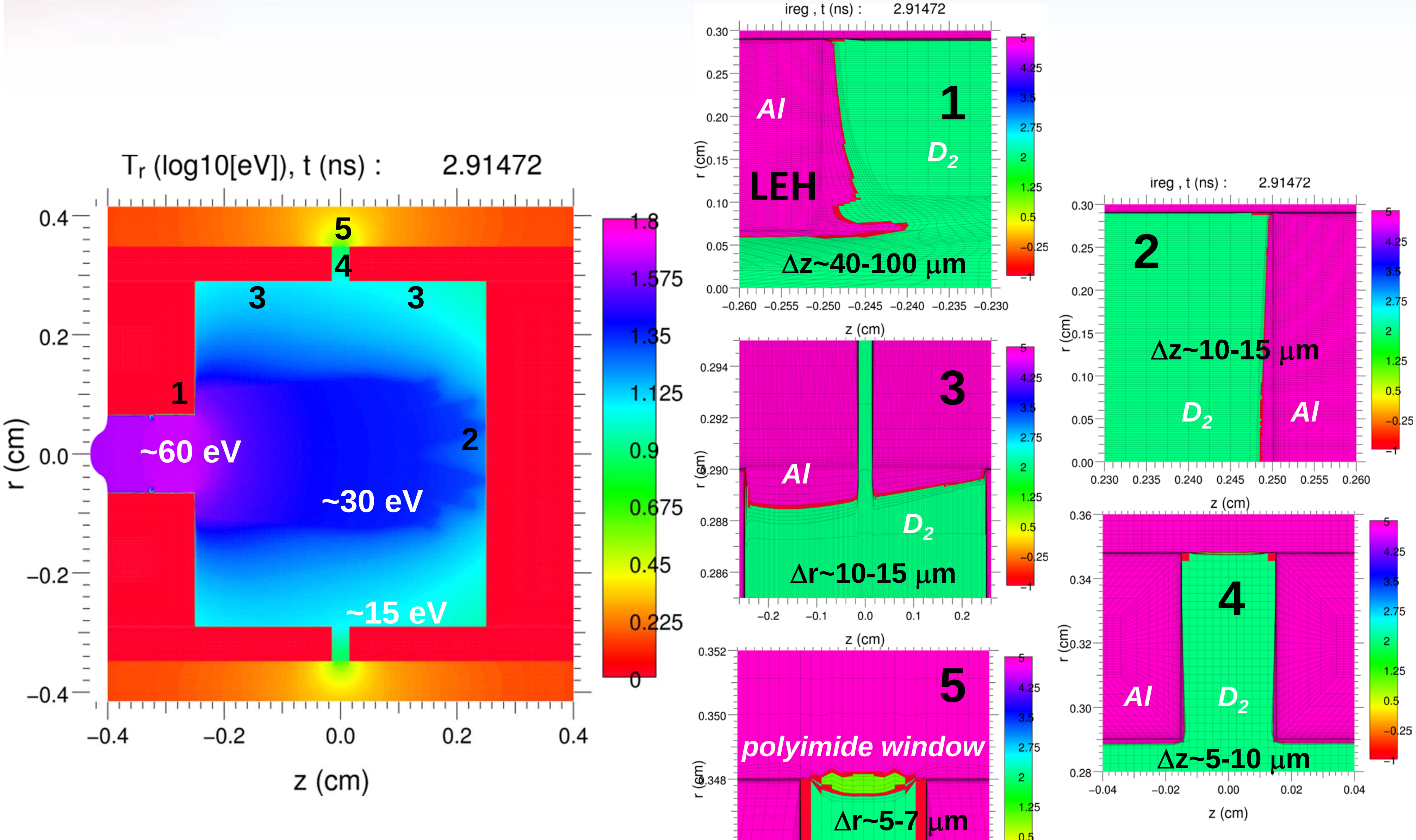
“Fit” T_e = 920 eV, “Fit” T_i = 430 eV



“fast mode” peaks have small blurring

“fit” values are close to beam-weighted values

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



* These issues must be re-examined for parameter changes that affect T_{rad} (e.g., higher E_{laser} used in "scientific break-even" and high-gain designs)

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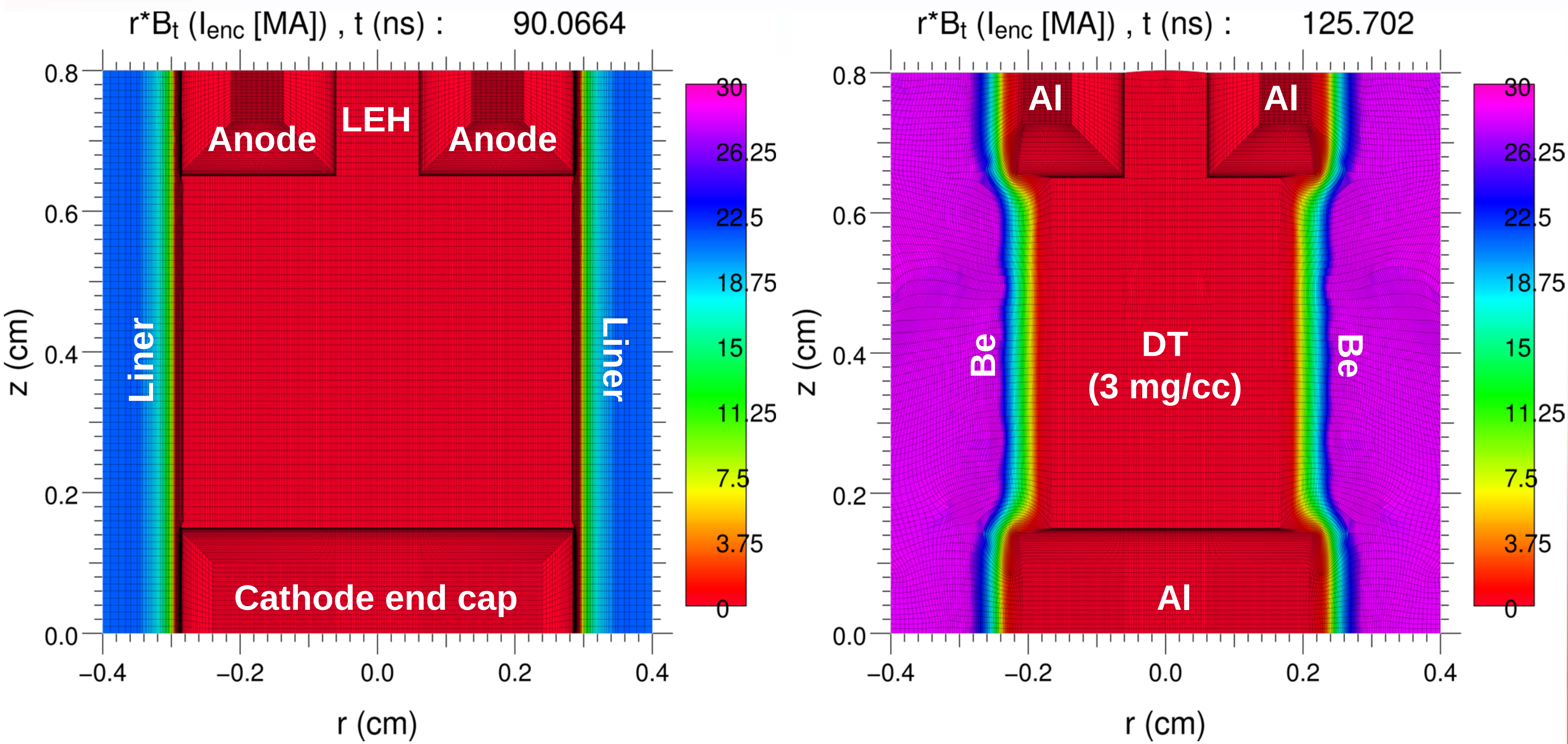
A complex, multi-block mesh is required in HYDRA in order to include all the relevant integrated details



- Multiple enhanced and reduced points of connectivity allow fine ablation zoning on all surfaces
- Anisotropic conductivity and magnetized fusion burn models for complex B field topology
- Boundary conditions now allow for both B_θ and B_z field component evolution

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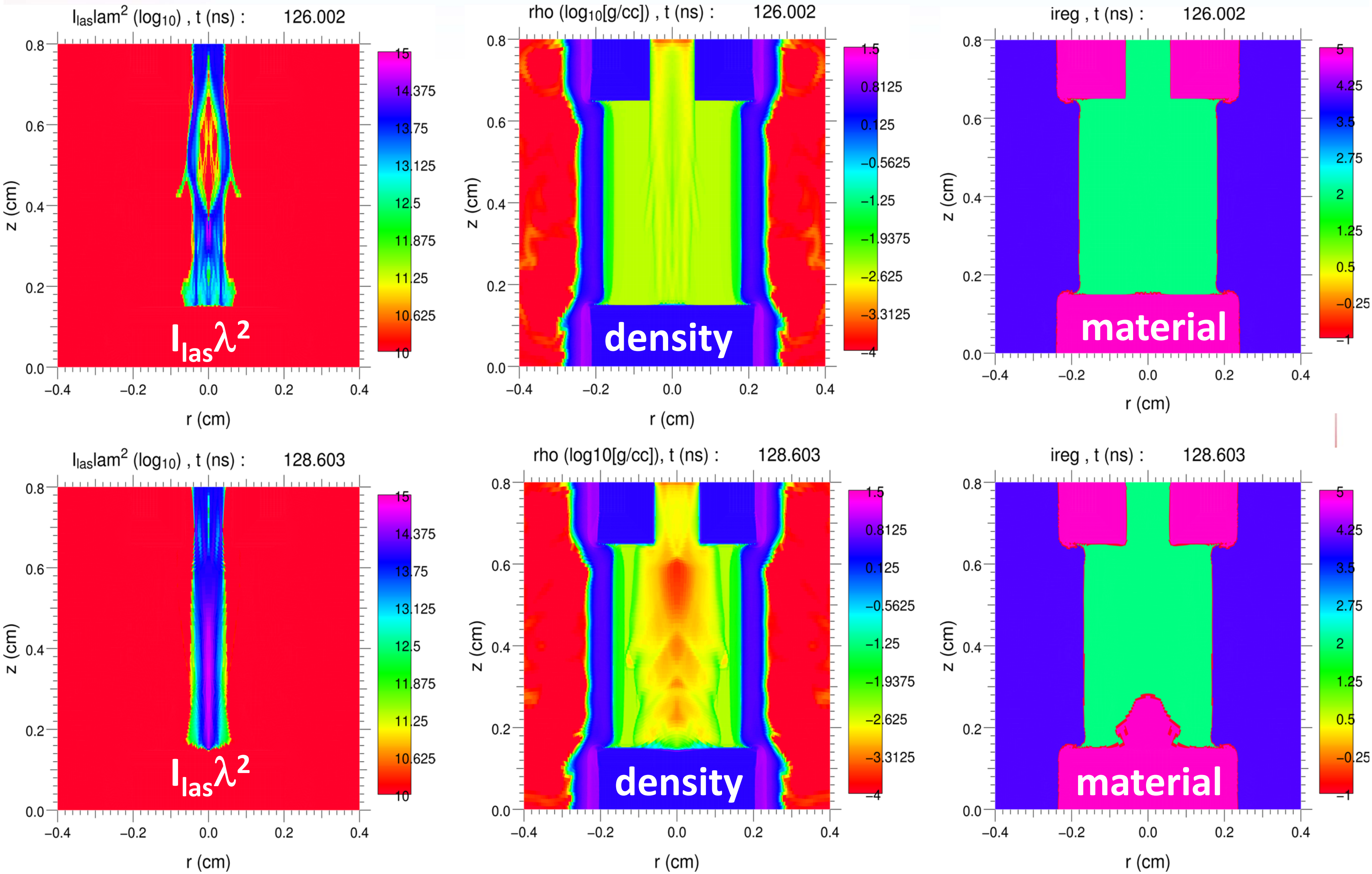
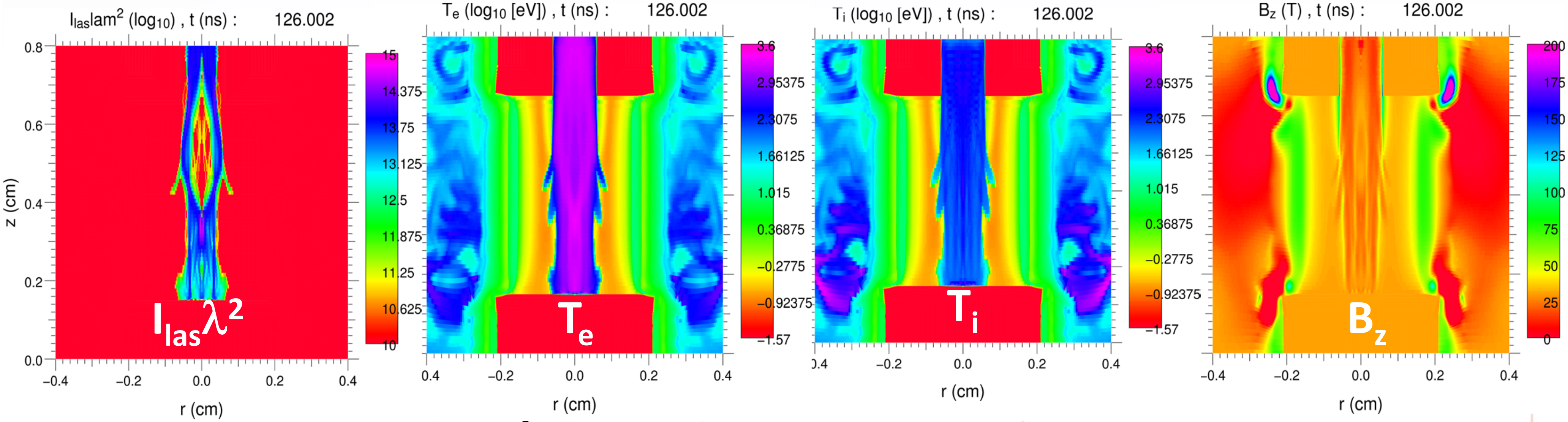
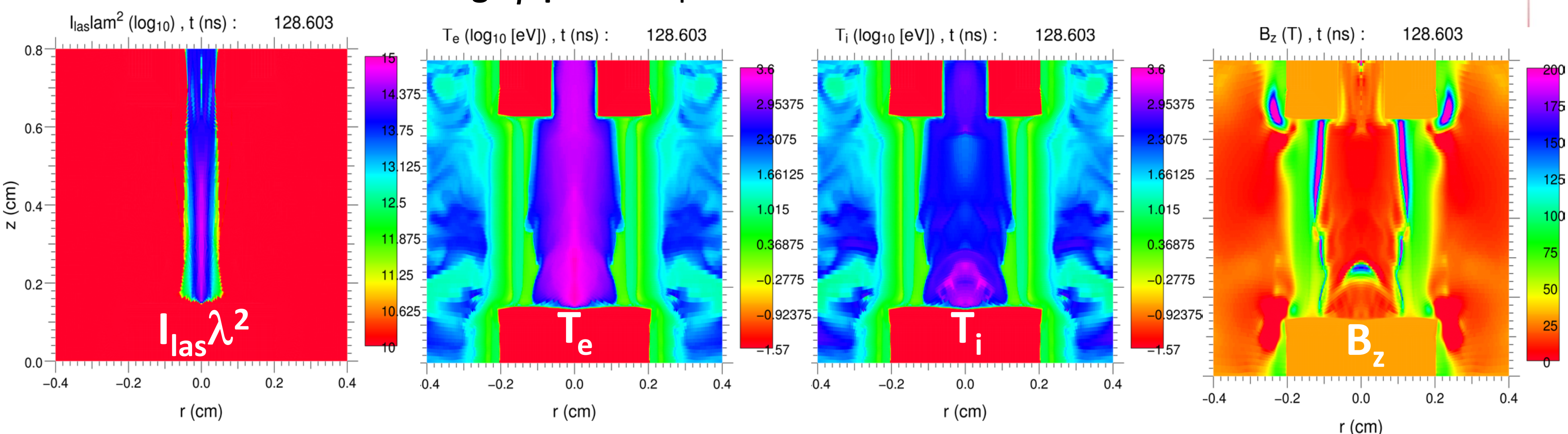
Laser deposition can ablate cathode material into the fuel region, and so must be avoided or mitigated



The compression and preheating processes alter the topology of the initially uniform B_z field



large β plasma : plasma motion moves flux



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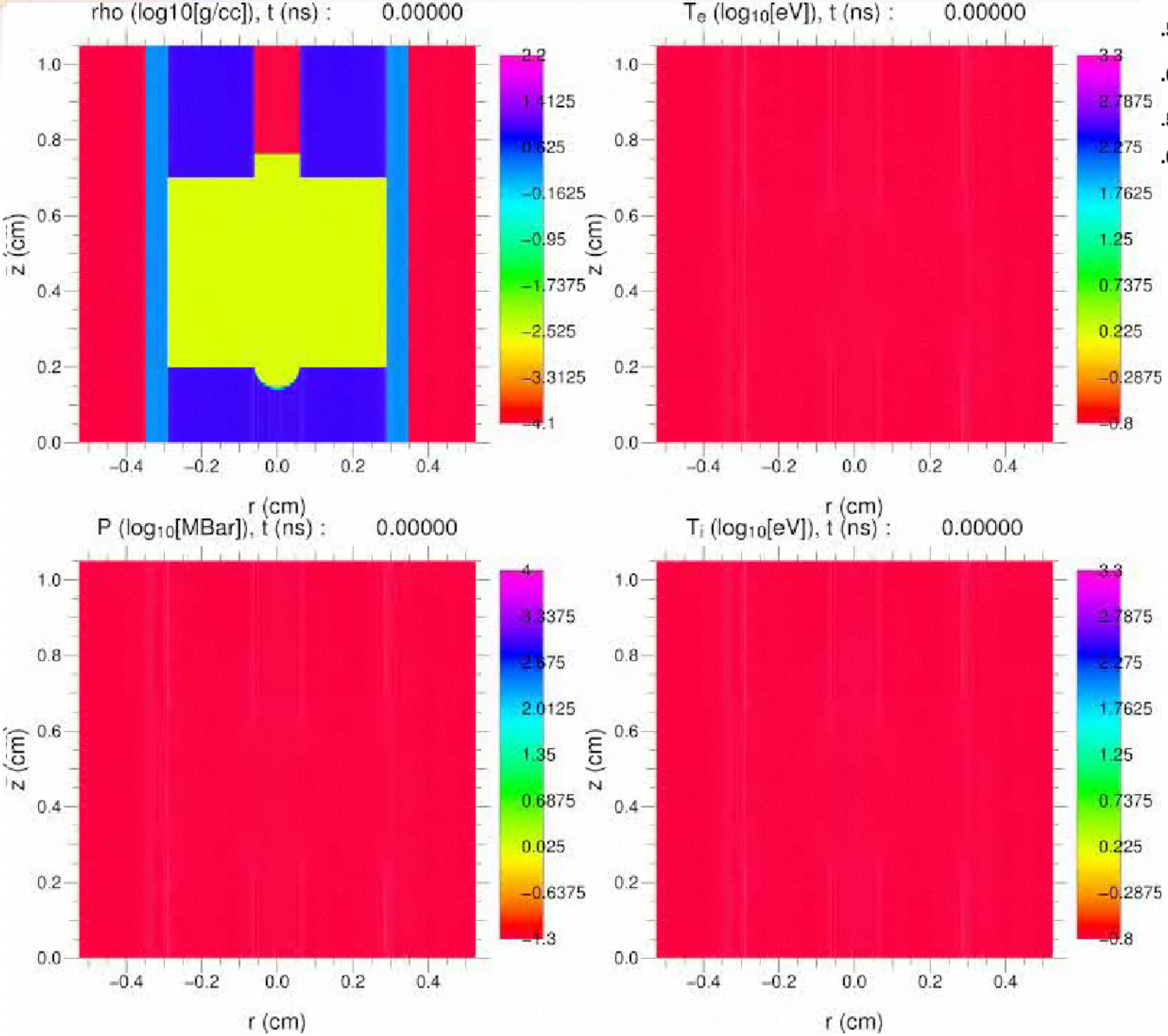
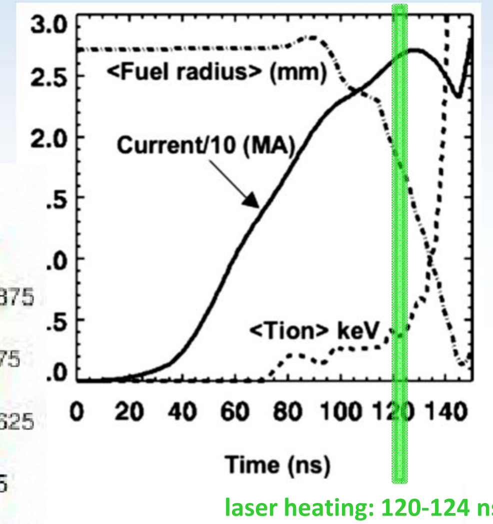
Integrated design movie





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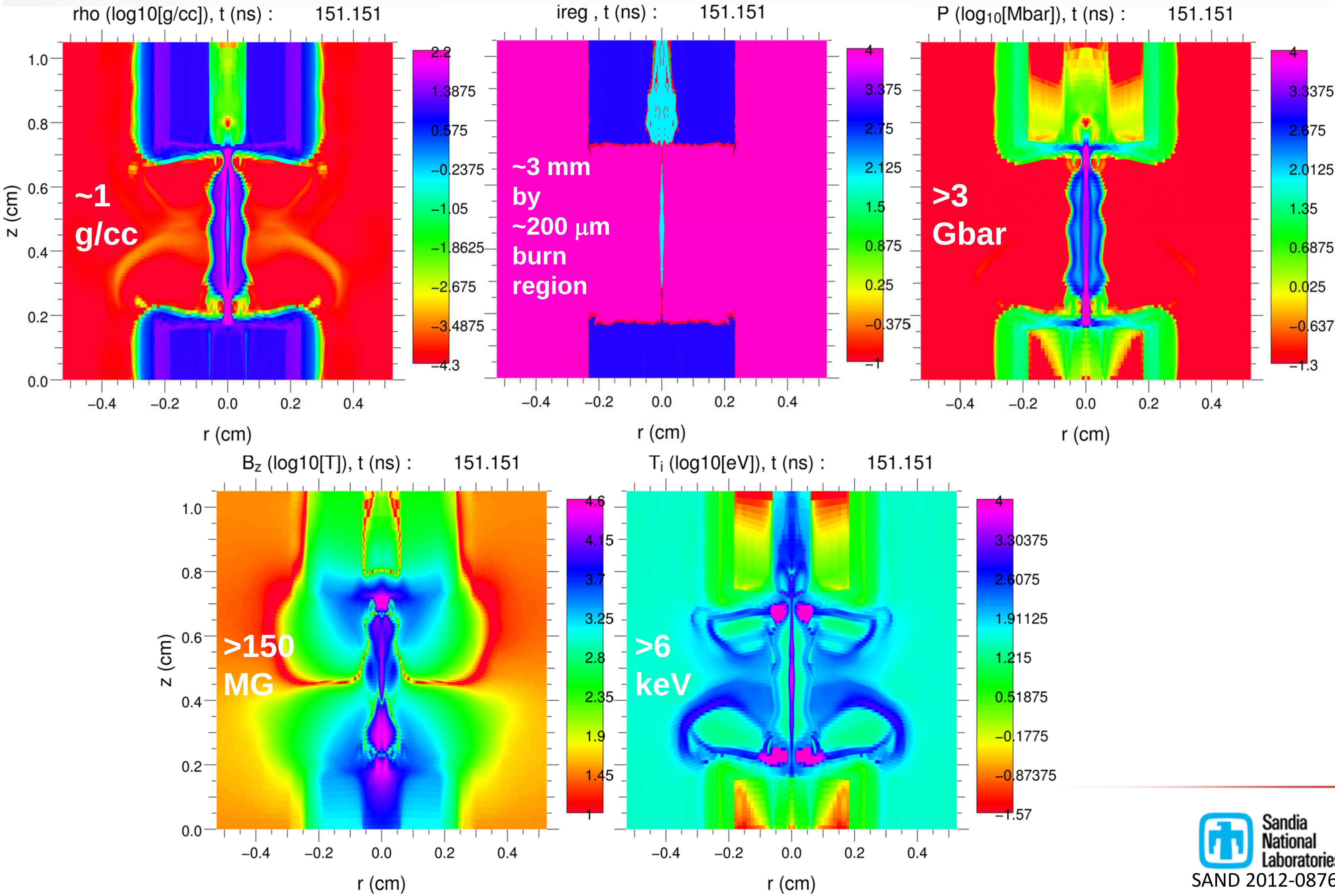
Excellent progress is being made in 2D integrated MagLIF simulations using HYDRA



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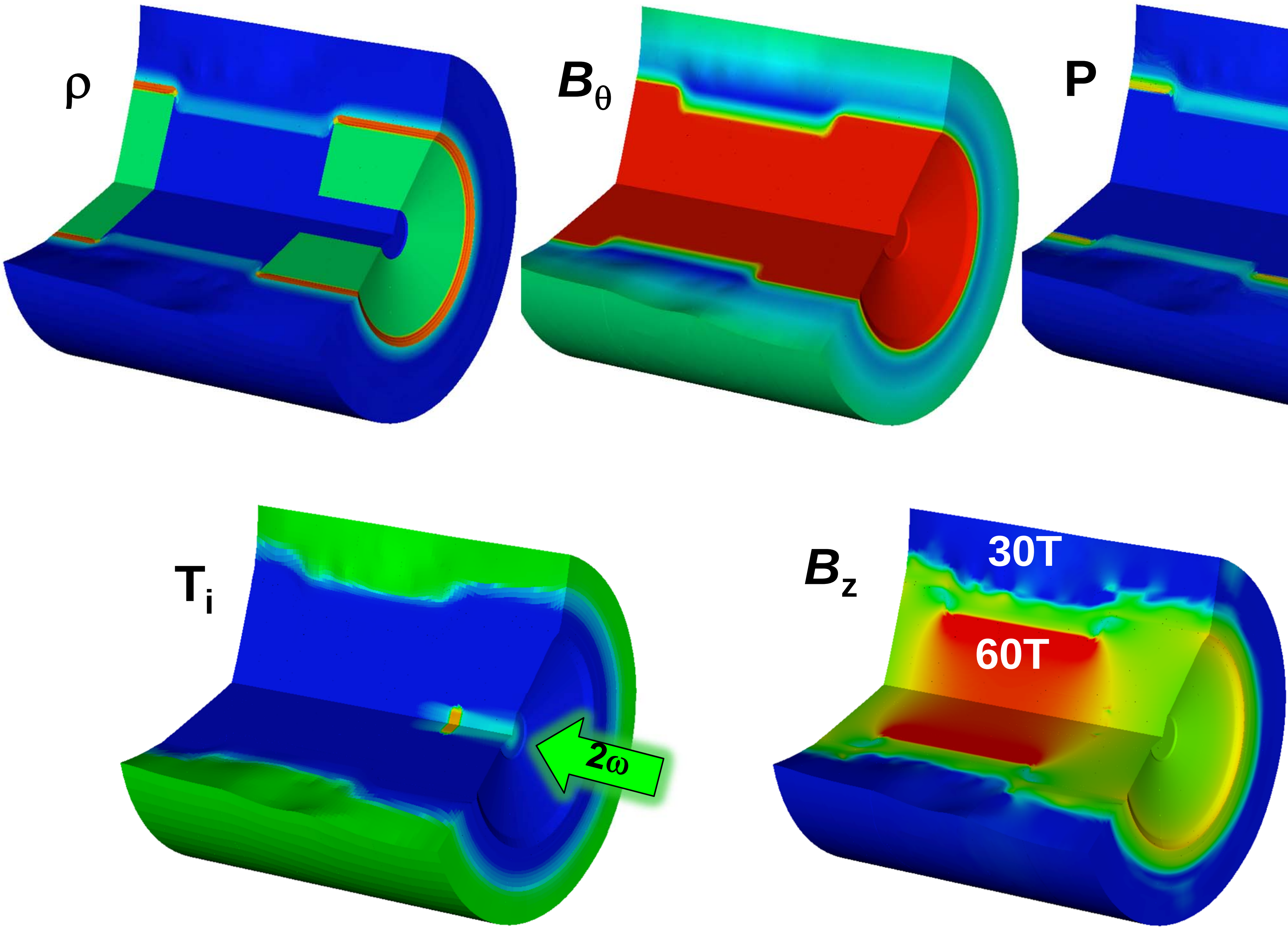
Excellent progress is being made in 3D integrated MagLIF simulations using HYDRA



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Summary

Integrated 2D and 3D simulations using the HYDRA code are **promising and ongoing**

Integrated simulations **include many realistic details** and **provide additional design constraints**:

(1) Laser (keep LEH open, one-sided heating, generates high-β plasma)

(2) LEH and window (mix with fuel, shocks, refraction, loss of heated gas)

(3) Liner and circuit (achieve ρR and T_i, compress flux, evaluate magneto-RT)

(4) Electrode wall effects (with liner, fuel, laser, T_{rad}, and B_z)

(5) Relative timing between preheat and implosion

(6) Optimization of all of the above, integrated together

The optimal parameters in **ideal versus integrated** simulations *may not be identical*

Future goals:

(1) Develop a design to achieve "scientific break-even" fusion yields

(in DT fuel with E_{laser}~ 6-8 kJ, B_z = 30 T, and 95 kV charge voltage on Z)

(2) Evaluate a design that "could be done today"

(in D_2 fuel with E_{laser} = 2.5 kJ, B_z = 10 T, and 85 kV charge voltage on Z)

(3) Assess the high-gain design in an integrated simulation

(include cryogenic DT layer, increase E_{laser} and gas density, and use ~ 60 MA driver)

Backups

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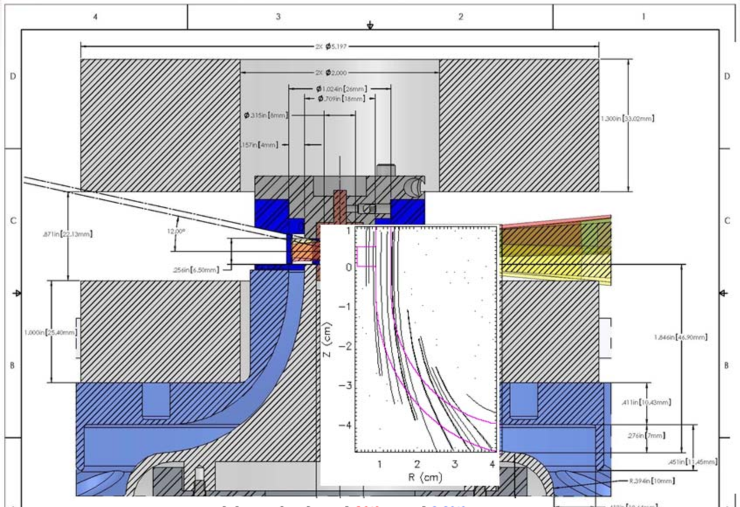
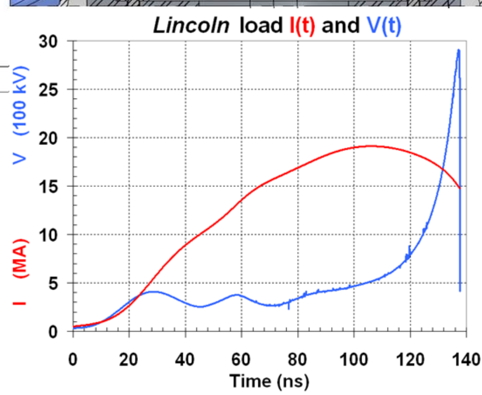
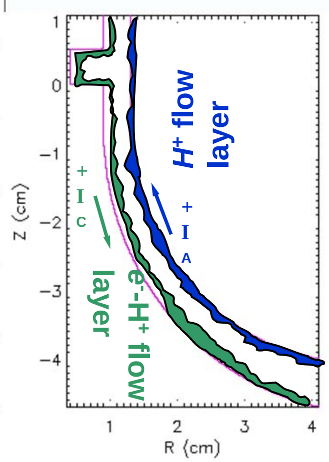
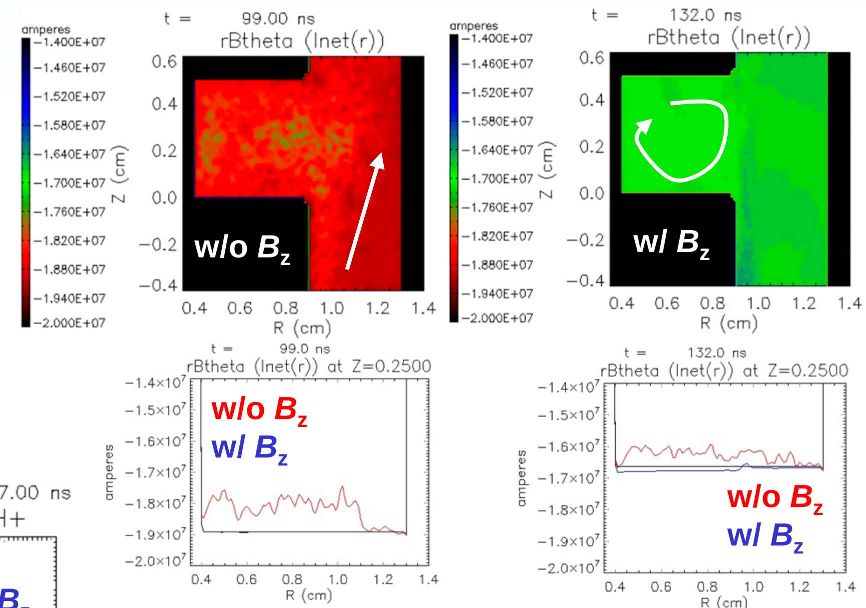
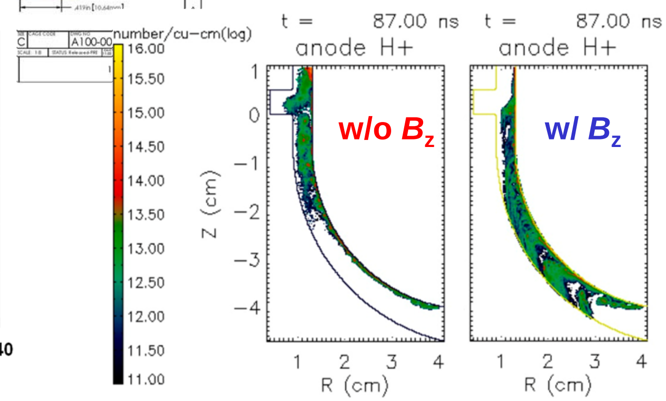
PIC simulations predict no significant current loss in final MagLIF feed due to external B_z field

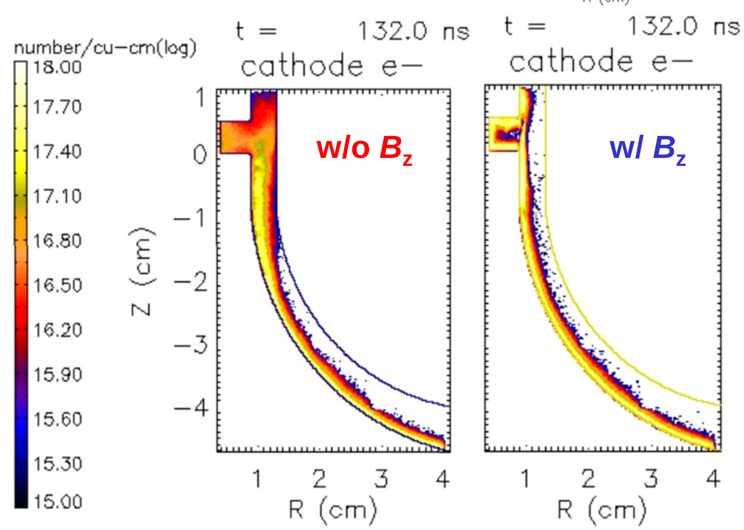












MODEL: Fully explicit and electromagnetic, 3D {r,□,z}, collisional, neutral desorption from conductors, energy deposition and heating of electrodes, solenoid B_z

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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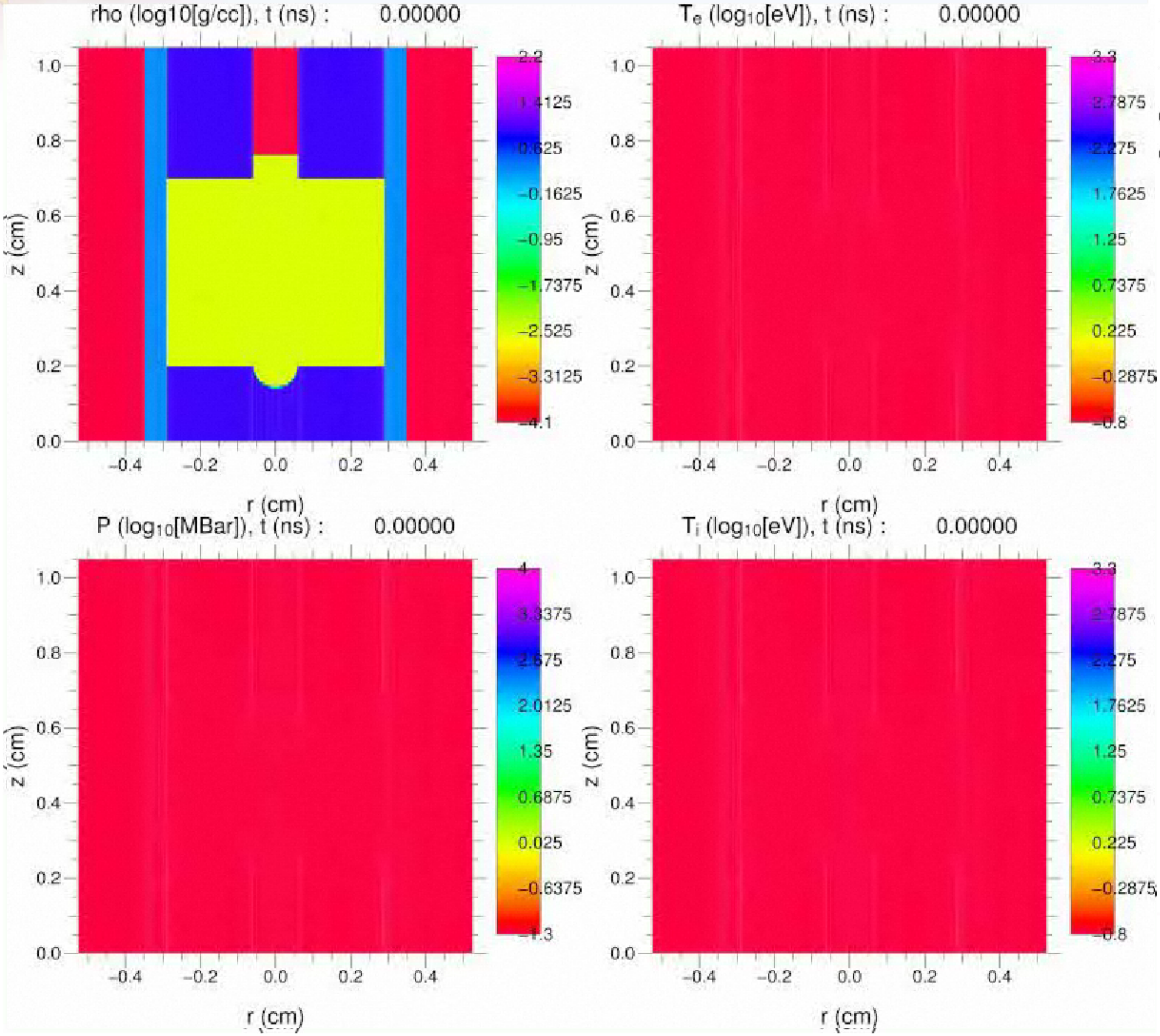
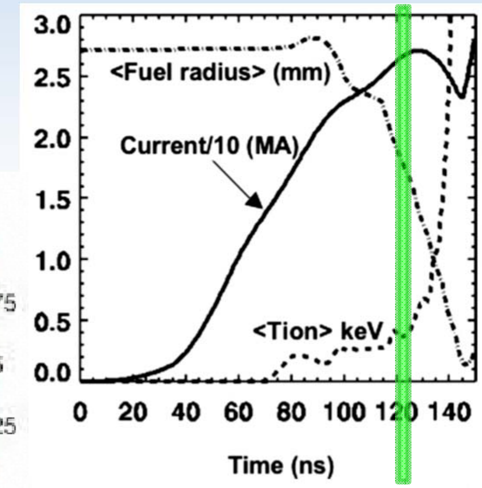
Integrated design movie





laser heating: 120-124 ns

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