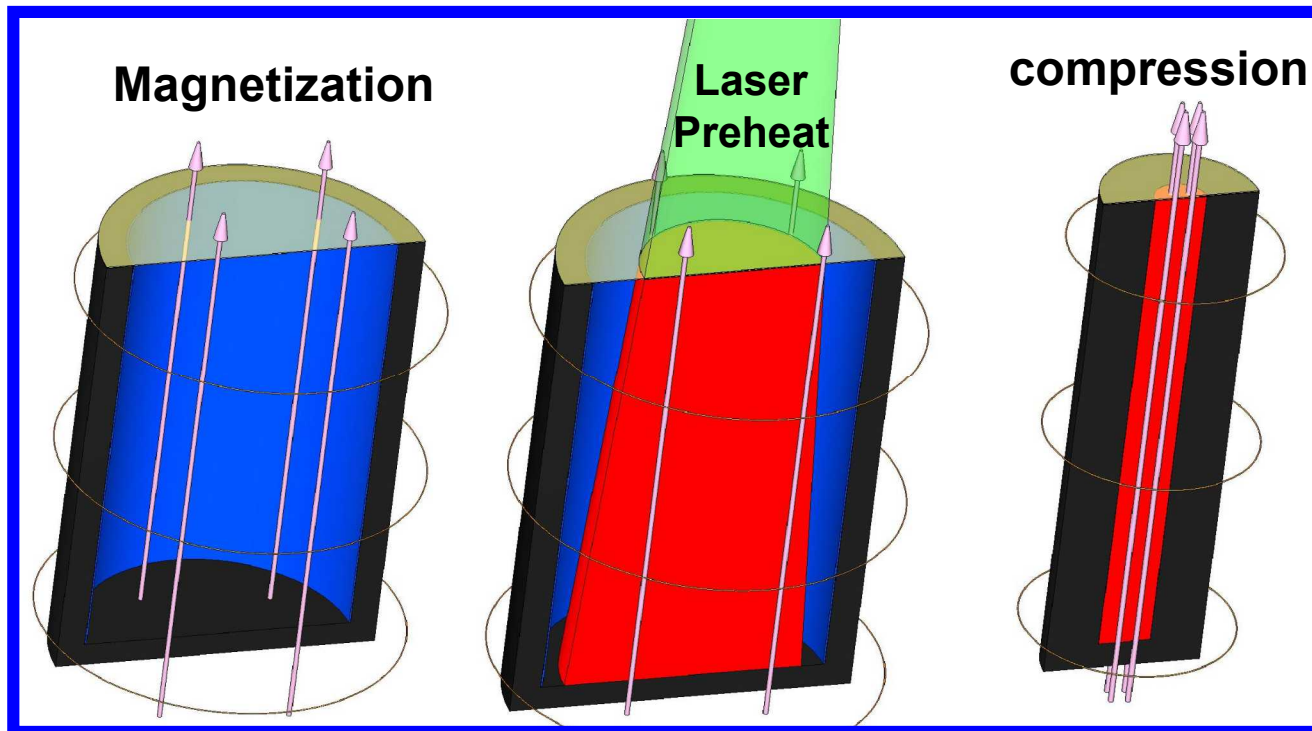


Scaling MagLIF targets to high yields on future accelerators



Pulsed Power Advisory

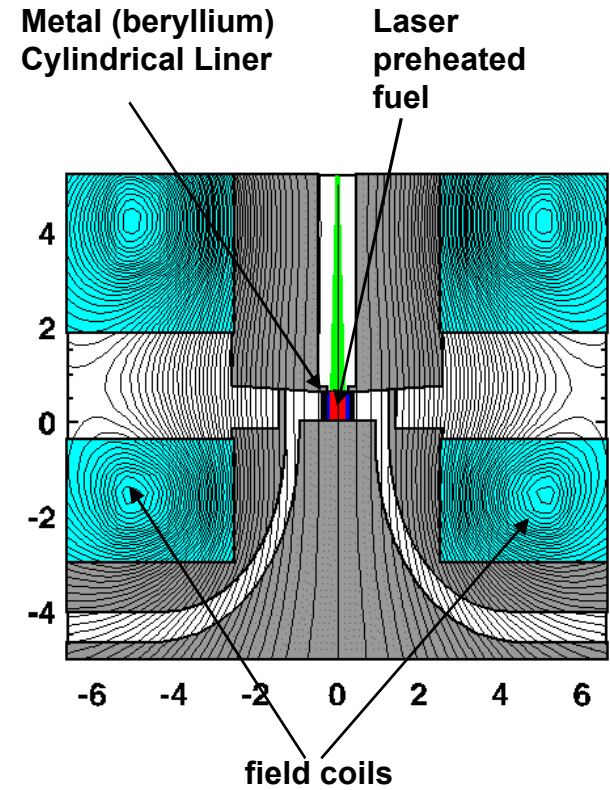
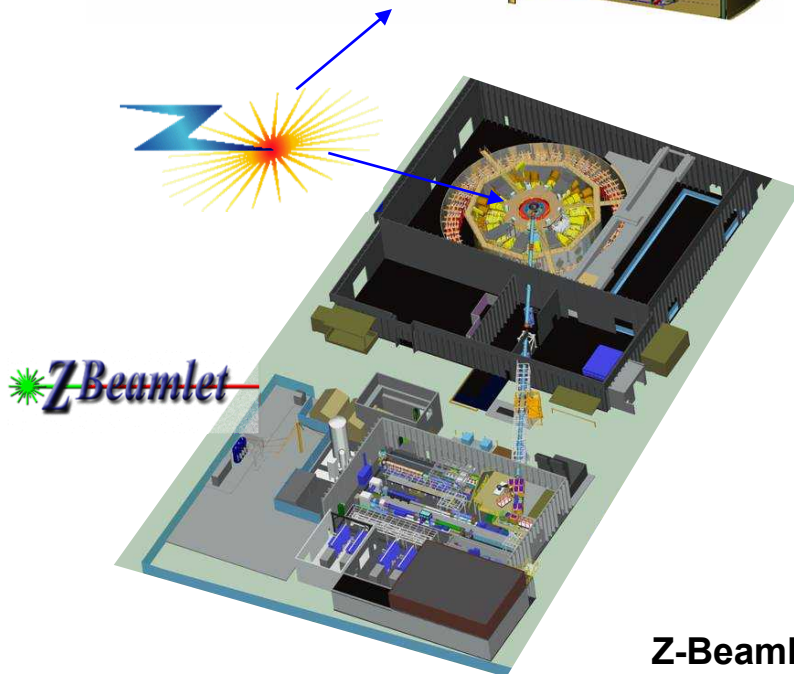
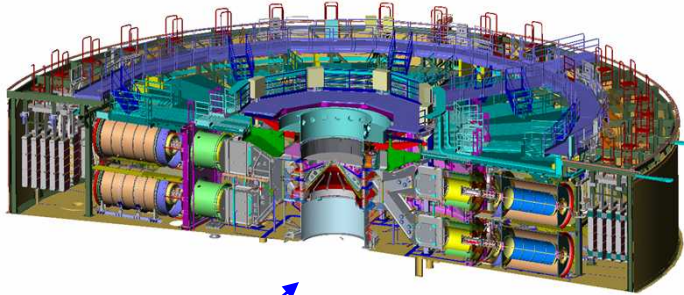
Albuquerque, NM, Feb 4, 2015

S. A. Slutz, W. Stygar, K. Peterson, A. B. Sefkow, R. A. Vesey

Sandia National Laboratories

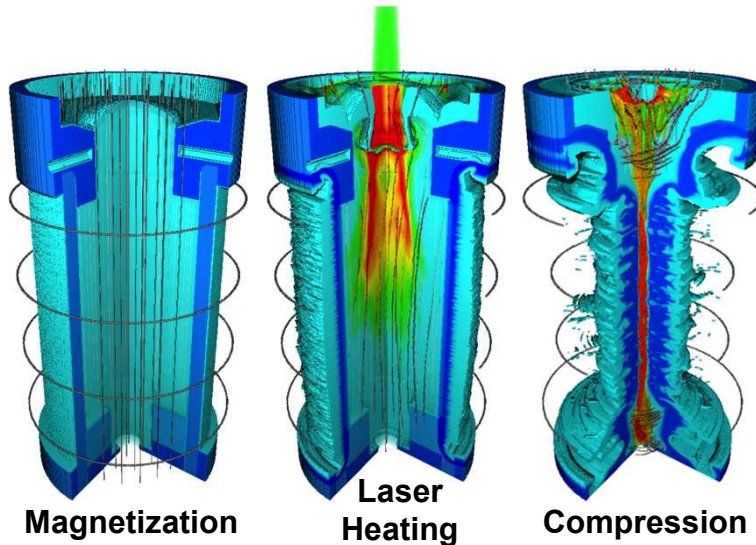
The Z facility, *the largest pulsed power machine coupled with a high power laser*, enables MagLIF¹ experiments

Z can generate high magnetic pressures to drive cylindrical implosions



Z-Beamlet provides fuel preheat

MagLIF combines three complementary design elements



2D simulations indicate MagLIF could produce 100 kJ on Z at full Marx charge

- 30 Tesla initial magnetic field
- Laser heating of $\sim 2 \text{ mg/cm}^3$ fuel produces initial $\sim 250 \text{ eV}$ plasma
- Thick ($A_R = R_{\text{out}}/\Delta R = 6$) Be liner with $R_{\text{out}} = 3.48$, $h = 10 \text{ mm}$, peak velocity $\sim 100 \text{ km/s}$ for a 27 MA peak current drive

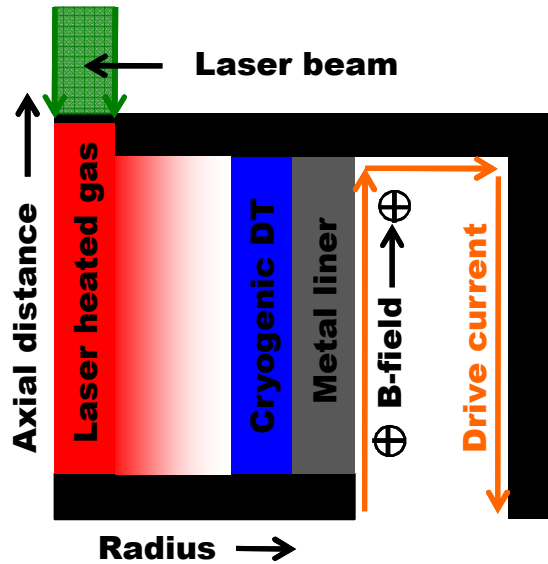
- Key target design elements
 - Magnetization
 - Laser heating
 - Liner compression

At stagnation:

- $E_{\text{fuel}} \sim 120 \text{ kJ}$
- $T_i \sim 8 \text{ keV}$
- density is $\sim 0.5 \text{ g/cm}^3$
- $B_z > 100 \text{ MG}$

Similar predictions are obtained using multiple codes

MagLIF could in principle provide high yield and gain¹ on future accelerators



A 2D integrated Hydra simulation² produced ~ 6 GJ

$$L_{\text{liner}} = 10 \text{ mm}$$

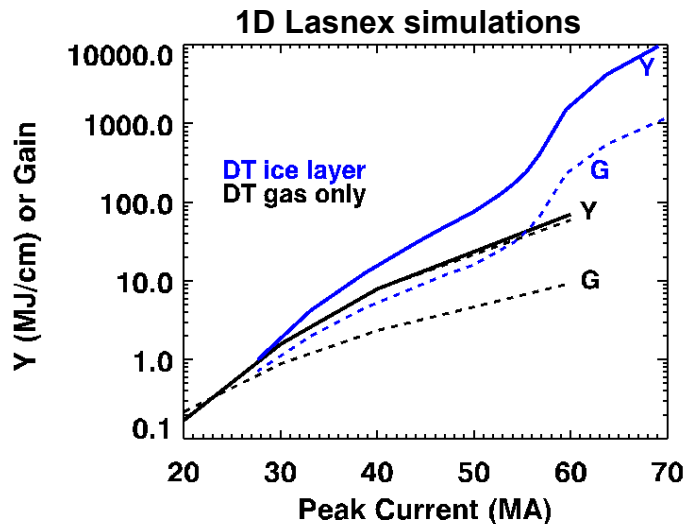
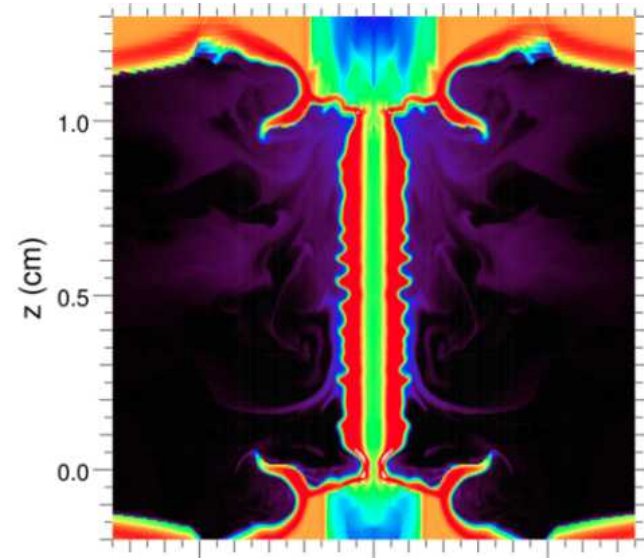
$$AR_{\text{liner}} = 6$$

$$\rho_{\text{gas}} = 5 \text{ mg cm}^{-3}$$

$$B_z^0 = 8 \text{ T}$$

$$E_{\text{laser}} = 25 \text{ kJ}$$

$$\text{Peak drive current} = 70 \text{ MA}$$



Advanced machines could deliver large currents to MagLIF e.g. conceptual designs¹ Z300 and Z800

$$P_{\text{LTDs}} = 315\text{-}870 \text{ TW}$$

$$E_{\text{LTDs}} = 47\text{-}130 \text{ MJ}$$

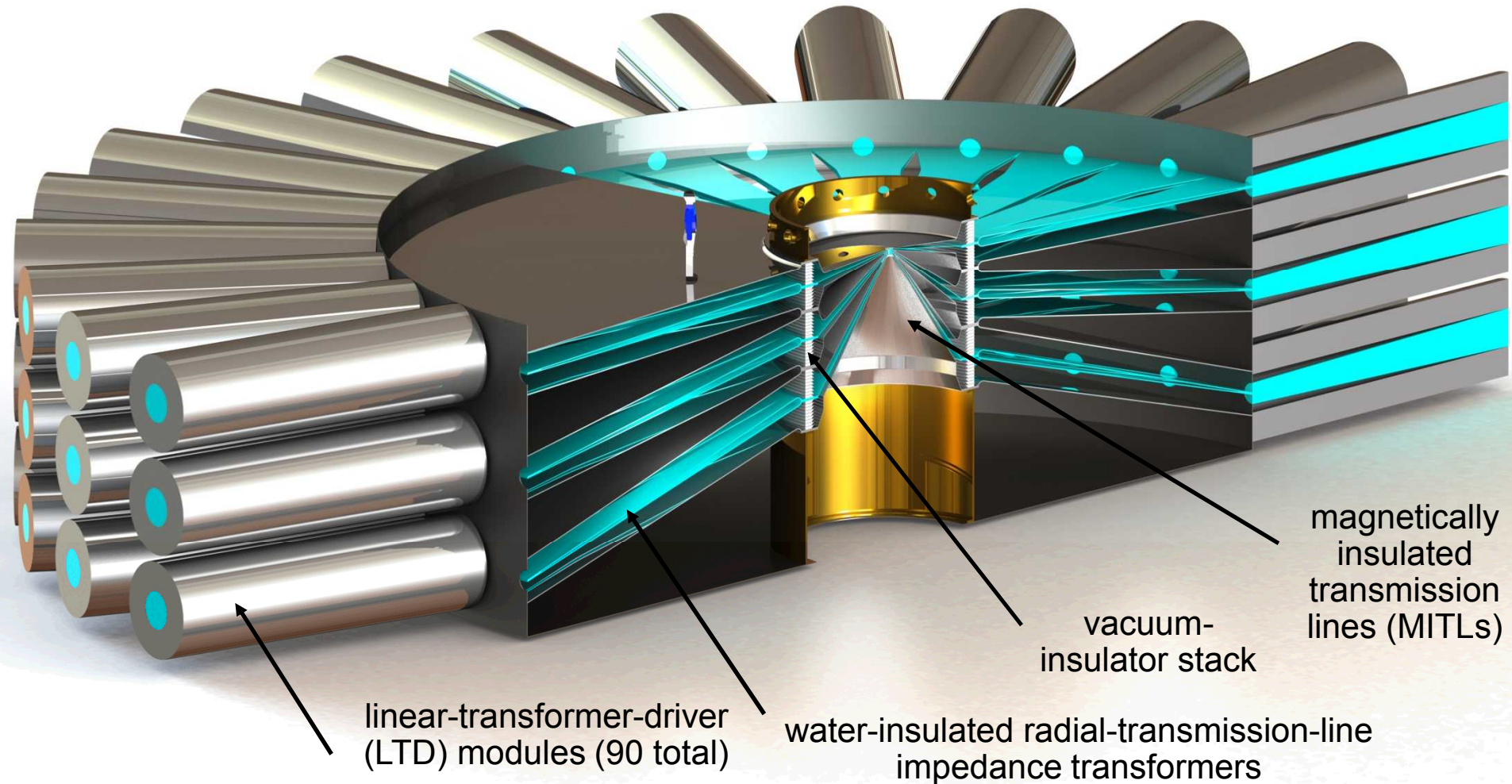
$$V_{\text{stack}} = 7.6\text{-}16 \text{ MV}$$

$$L_{\text{vacuum}} = 16\text{-}25 \text{ nH}$$

$$I_{\text{load}} = 47\text{-}61 \text{ MA}$$

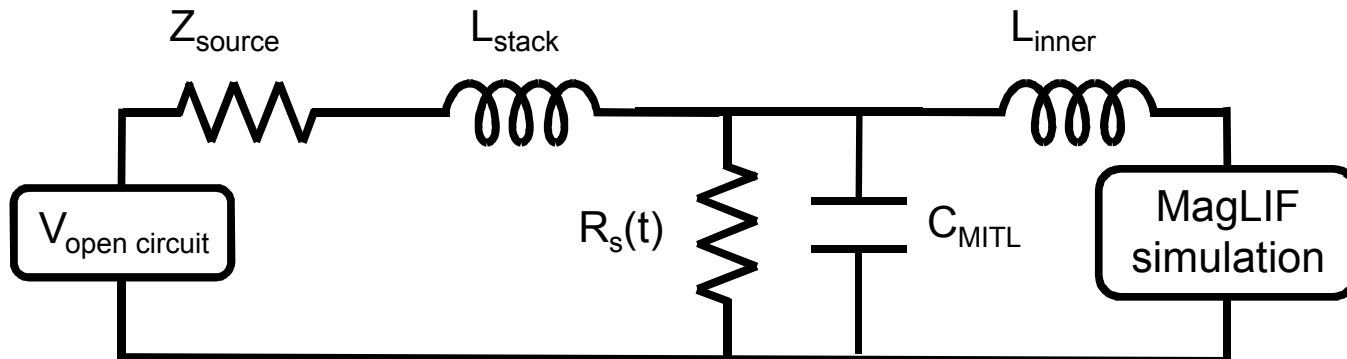
$$\tau_{\text{implosion}} = 133 \text{ ns}$$

$$\text{diameter} = 35\text{-}55 \text{ m}$$

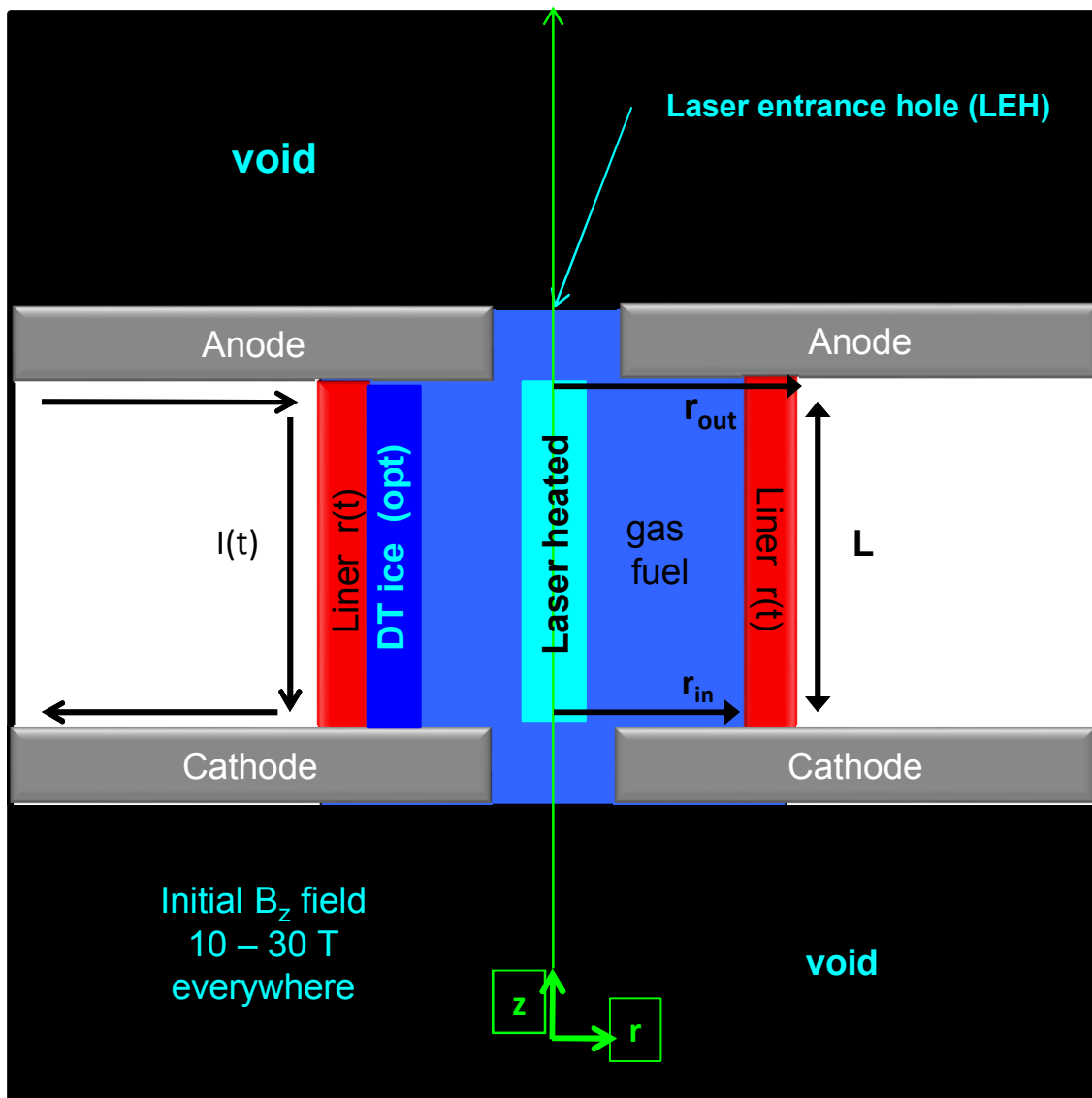


Equivalent circuit models of pulsed power machines are used to drive Lasnex simulations of MagLIF

Machine	Present Z	Z300	Z800
$Z_{\text{source}} \Omega$	0.18	0.16	0.30
$L_{\text{stack}} \text{ (nH)}$	9.57	13.24	21.93
$L_{\text{inner}} \text{ (nH)}$	3.1	3.14	3.14
$C_{\text{MITL}} \text{ (nF)}$	8.41	8.41	8.41



Simplified 2D Lasnex MagLIF simulation geometry used for this scaling study



Fully integrated Lasnex and Hydra simulations have been performed:

- laser deposition and foil complicate rezoning
- computationally expensive
- laser simulations are not in good agreement with experiments
- cumbersome for scaling studies

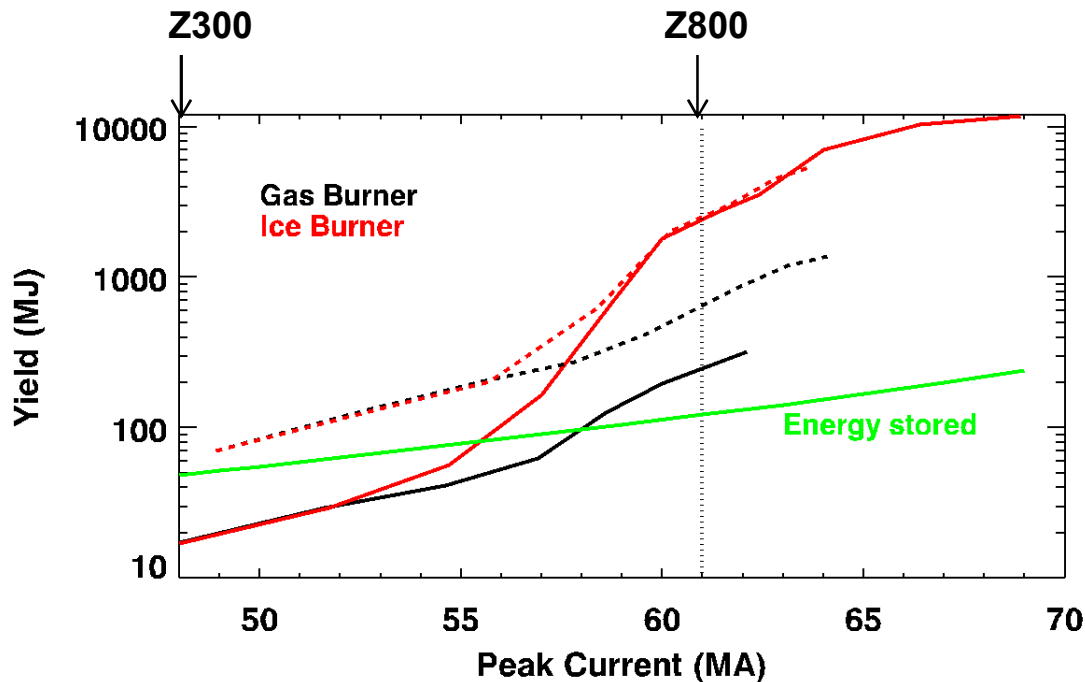
Simplification allows:

- robust rezoning
- overnight runs
- easy control of preheat
- optimization with many hundreds of runs

Important 2D effects retained:

- end losses
- wall/liner interaction
- axial gradients
- axial field distortion creating a mirror geometry

1D and 2D Lasnex simulations predict high yields for MagLIF on future LTD accelerators



Equivalent circuit parameters scaled from the Z300 and Z800 designs.

Gas burner 2D performance significantly below 1D

Ice burners approach 1D performance

Drive currents larger than Z300 will be necessary to burn ice

10 MJ yield could be possible with MagLIF gas burners driven by Z300

- target gain in excess of unity

1-2 GJ yields could be possible with MagLIF ice burners driven by Z800

- facility gas greater than 10
- gain adequate for fusion energy

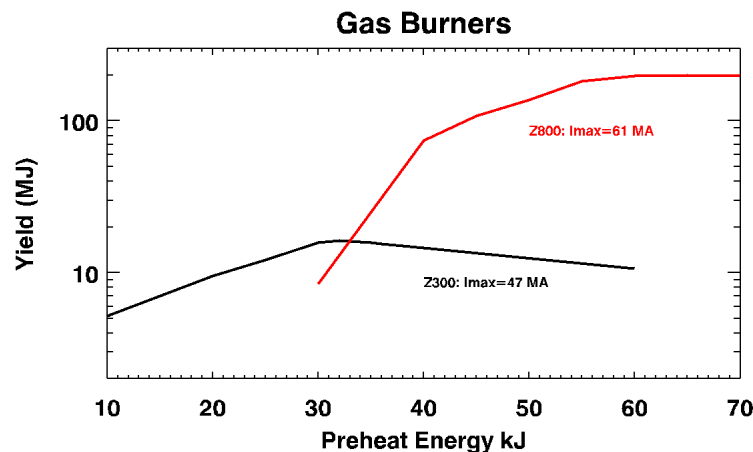
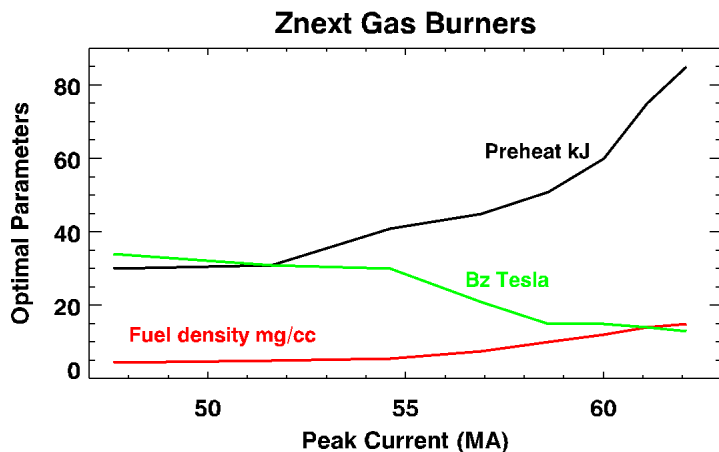
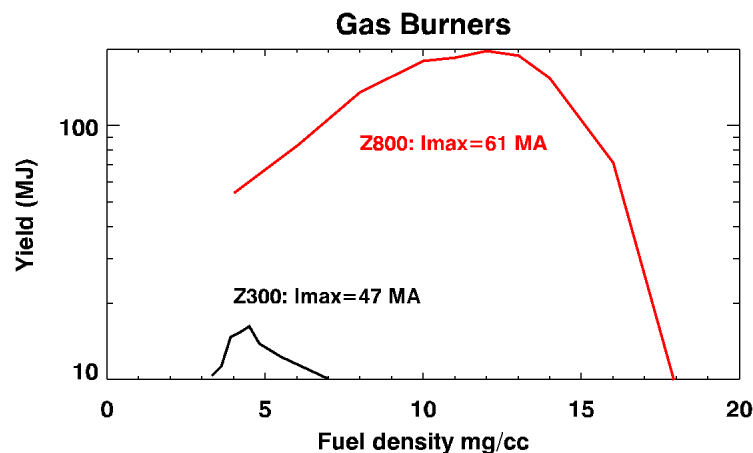
Optimum parameters insensitive to current for High-Yield Ice Burners:

Optimum parameters for ice burners:

- $B_z \sim 10$ Tesla
- Preheat = 38 kJ
- Fuel density = 4.5 mg/cc
- only ice thickness varies (increases with current)

Optimum parameters vary significantly for gas burners:

- B_z 10-35
- Fuel density 4.5-15 mg/cc
- Preheat 30-80 kJ



MagLIF physics learned on Z should transfer to Z300

As with MagLIF experiments on Z, liner designs for Z300 employ only gas fuel

Z300 MagLIF designs are a simple scale up in size, fuel density and preheat energy

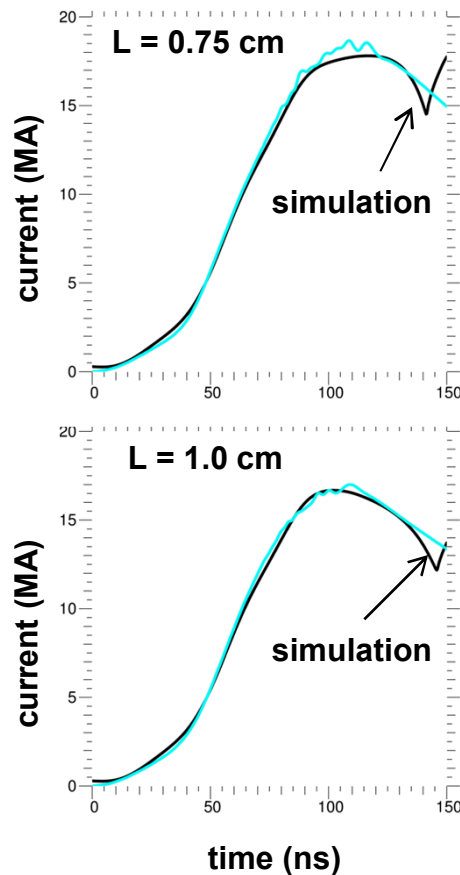
Machine	Present Z	Z300
L (cm)	0.75-1.0	1.0
r_{out} (cm)	0.276-0.35	0.5
r_{in} (cm)	0.23-0.29	0.416
$A_R=r_{out}/\Delta r$	6.0	6.0
Fuel density (mg/cc)	0.7-2.0	4.0-6.0
$E_{preheat}$ (kJ)	2-6	30-40

High-yield ice burning MagLIF will require drive currents above the Z300 level

2D Lasnex simulations are in reasonable agreement with the experimental results on Z

Shunt resistor tuned to match experimental current

- represents MITL and Convolute loss

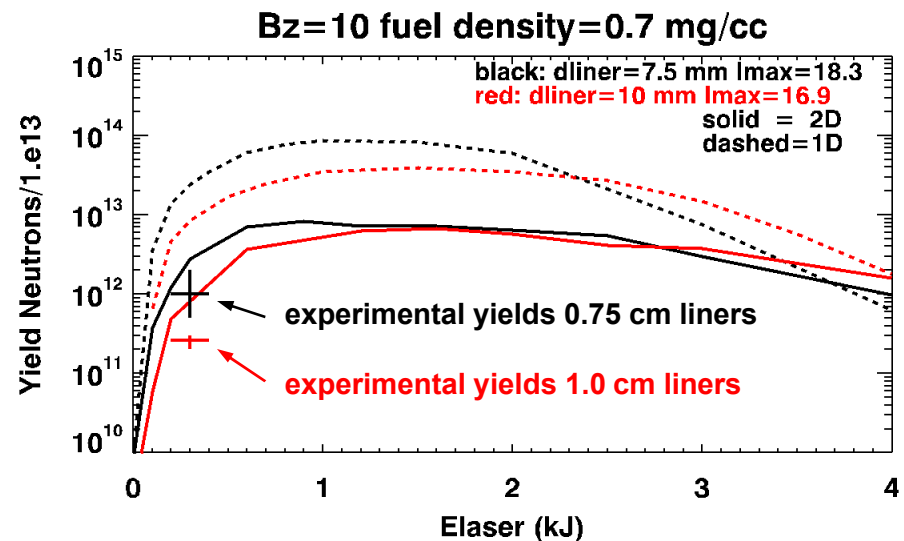


Laser transmission experiments indicate 200-400 J deposited in fuel ¹

The initial MagLIF experiments used 0.75 cm long liners: Yield $\sim 1.0 \times 10^{12}$ neutrons

Subsequent experiments used 1.0 cm liners: Yield $\sim 2.6 \times 10^{11}$ neutrons

Simulations indicate this is due to decreased drive current



Simple analytic theory predicts the laser penetration can be controlled by the beam radius and laser wavelength

The laser energy (30-40 kJ) needs to be deposited into the fuel in roughly $z_f = 1$ cm

Laser absorption coefficient dominated by inverse Bremsstrahlung

$$C_V \frac{d\theta}{dt} = \frac{dI}{dz} = -kI \quad k = \frac{v_{ei} \omega_p^2}{c \omega_L^2} \left(1 - \frac{\omega_p^2}{\omega_L^2}\right)^{-1/2} = \frac{k_0}{\theta^{3/2}} \quad k_0 \approx 1.23 \times 10^6 (\rho \lambda_L Z_b)^2 (1 - 227 \rho Z_b \lambda_L^2)^{-1/2}$$
$$I = I_0 \left(1 - \frac{z}{z_f}\right)^{2/3} \quad z_f = \frac{5}{3} \left(\frac{2}{5k_0}\right)^{2/5} \left(\frac{I_0 t}{2C_V \rho}\right)^{3/5} \quad R_{laser} = 5.4 \times 10^{-7} E_{laser}^{1/2} \lambda_L^{-.67} \rho^{-1.17} z_f^{-.83} (1 - 227 \rho \lambda_L^2)^{.17}$$

Hydrodynamics, refraction and LPI make this process more complicated

A short wavelength laser ($\lambda \sim 0.25-0.33 \mu$) could be used to penetrate the initially high density DT without excessive LPI, thus forming a low density channel

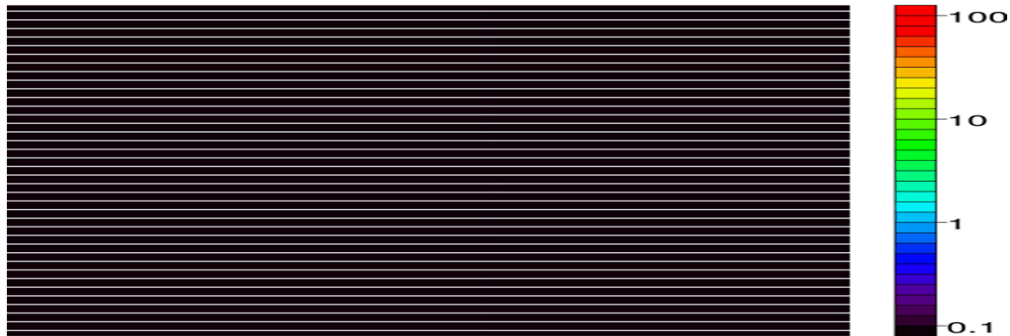
A second pulse of longer wavelength light ($\lambda = 0.5-1 \mu$) could then propagate down this channel and efficiently deposit its energy

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

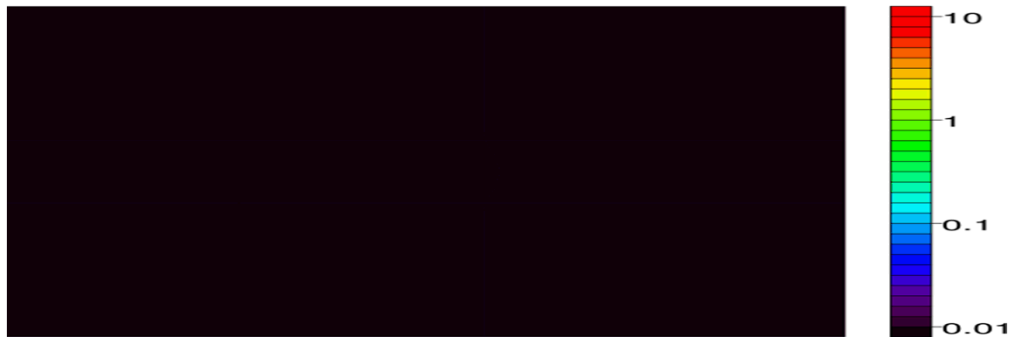
Materials/density kg/m³



0.25 μ m Laser Intensity 100TW/cm²



Te/Ti (keV)



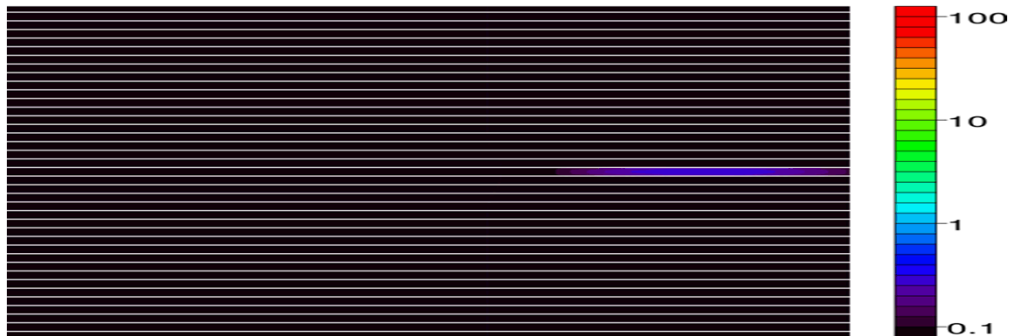
Hole boring phase:
3 kJ of 0.25 μ m light

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

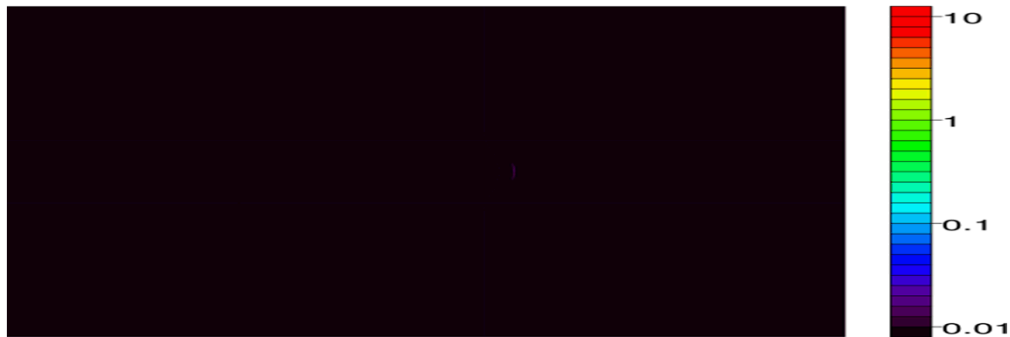
Materials/density kg/m³



0.25 μ m Laser Intensity 100TW/cm²



Te/Ti (keV)



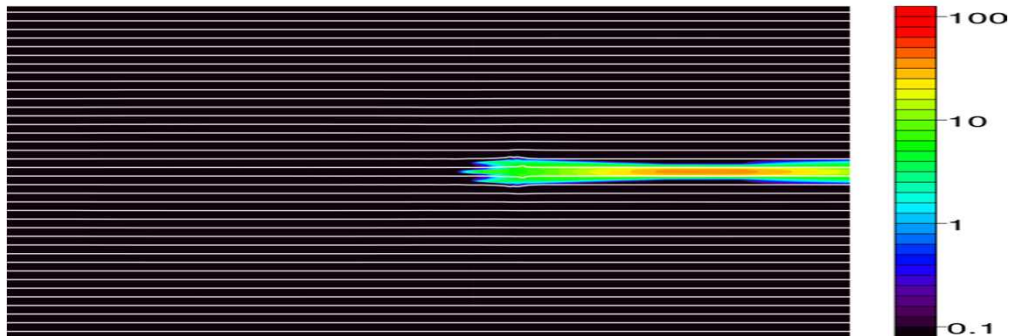
Hole boring phase:
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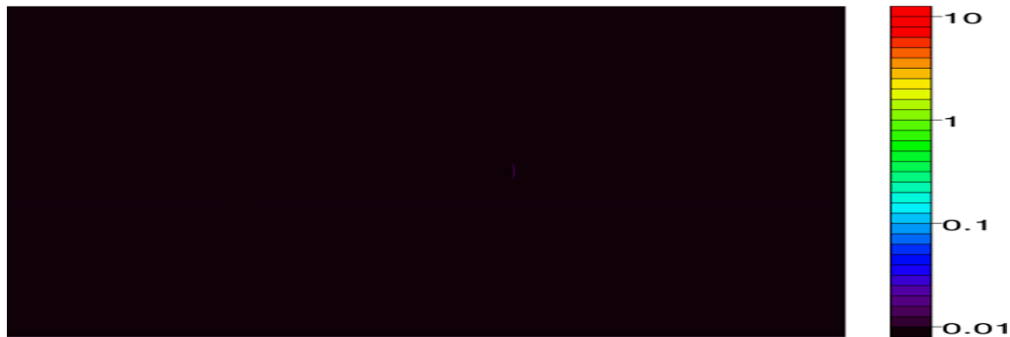
Materials/density kg/m³



0.25 μ m Laser Intensity 100TW/cm²



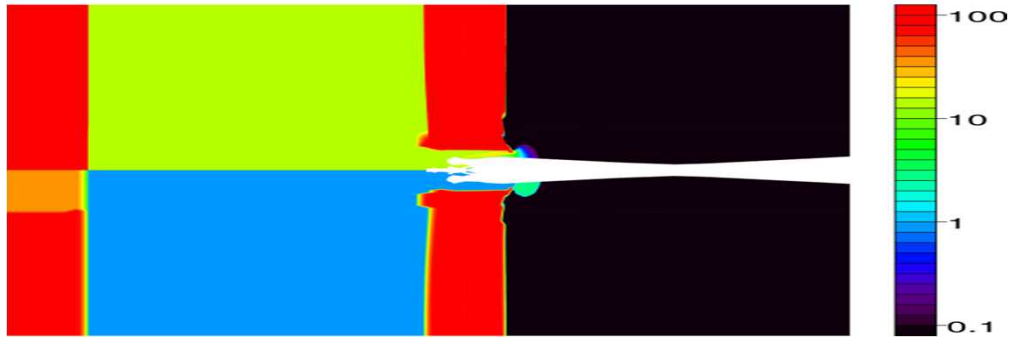
Te/Ti (keV)



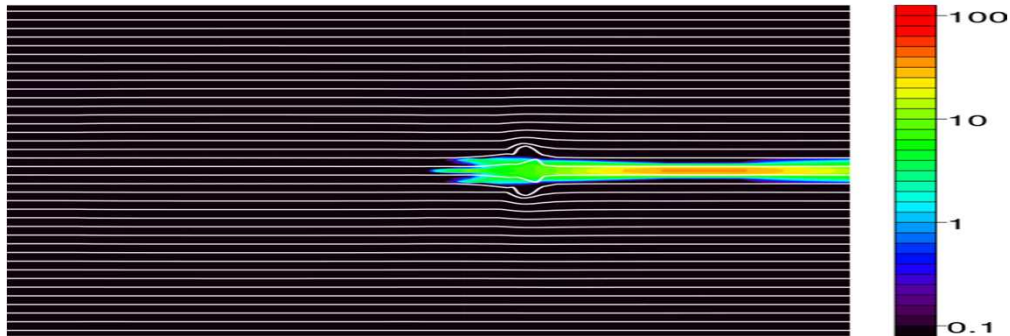
Hole boring phase:
3 kJ of 0.25 μ m light

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

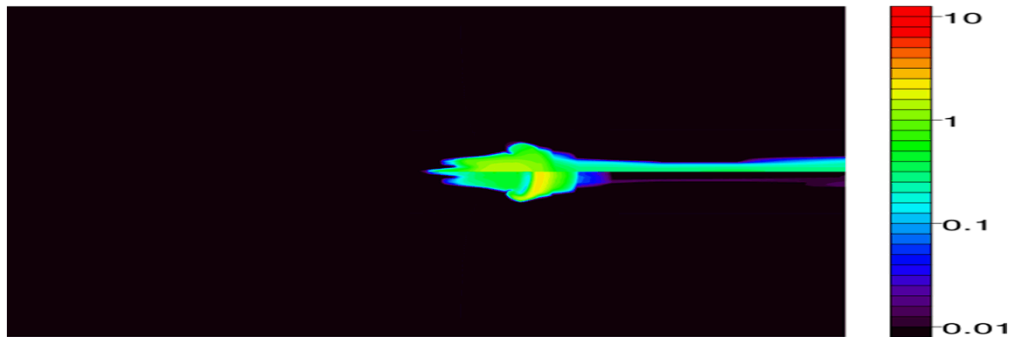
Materials/density kg/m3



0.25 um Laser Intensity 100TW/cm2



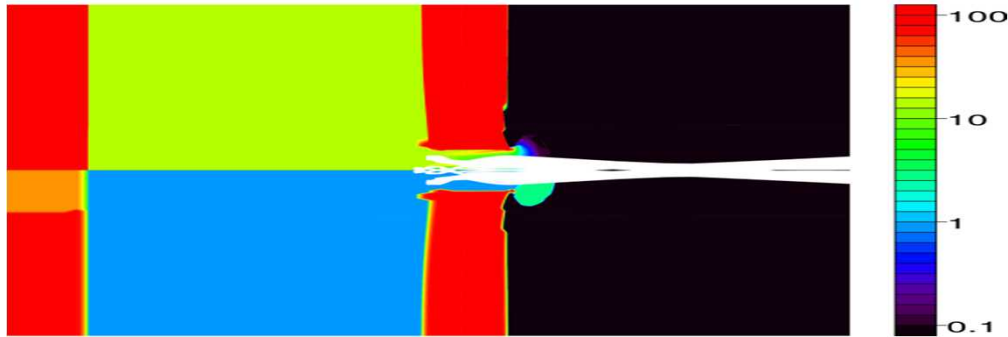
Te/Ti (keV)



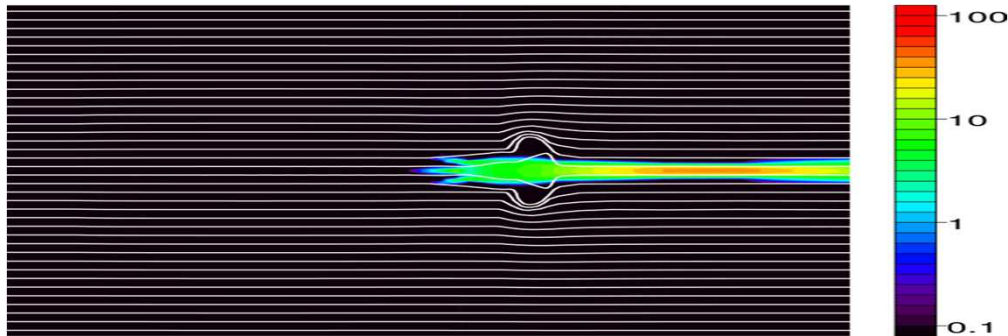
Hole boring phase:
3 kJ of 0.25 um light

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

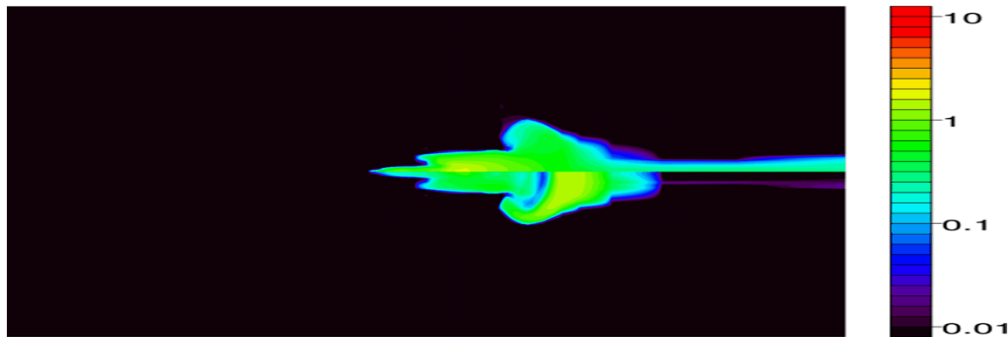
Materials/density kg/m³



0.25 μm Laser Intensity 100TW/cm²



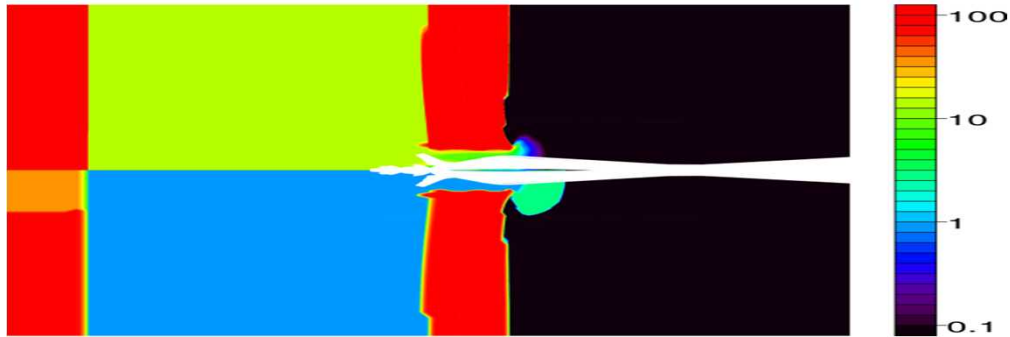
Te/Ti (keV)



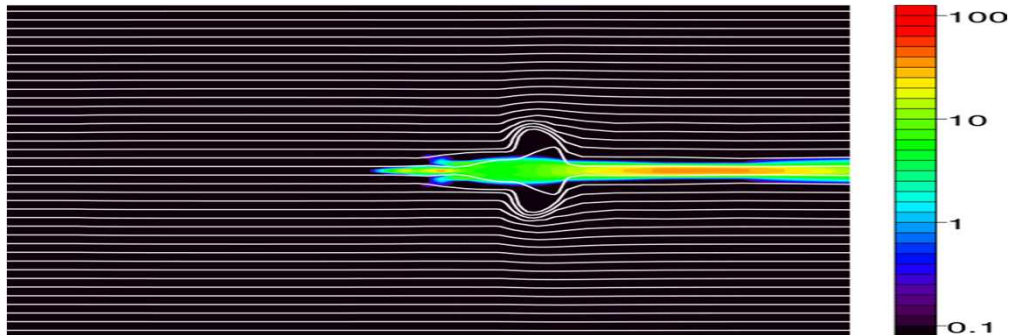
Hole boring phase:
3 kJ of 0.25 μm light

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

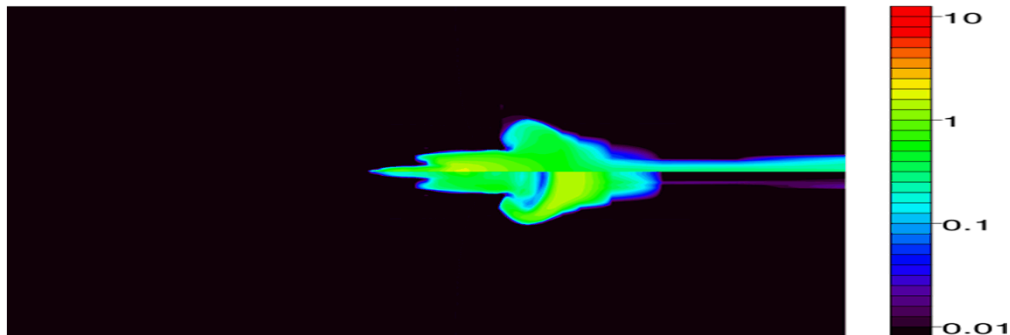
Materials/density kg/m³



0.25 μm Laser Intensity 100TW/cm²



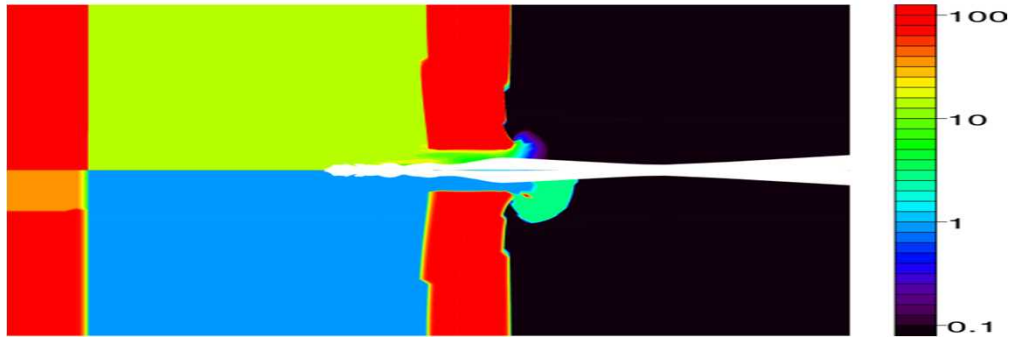
Te/Ti (keV)



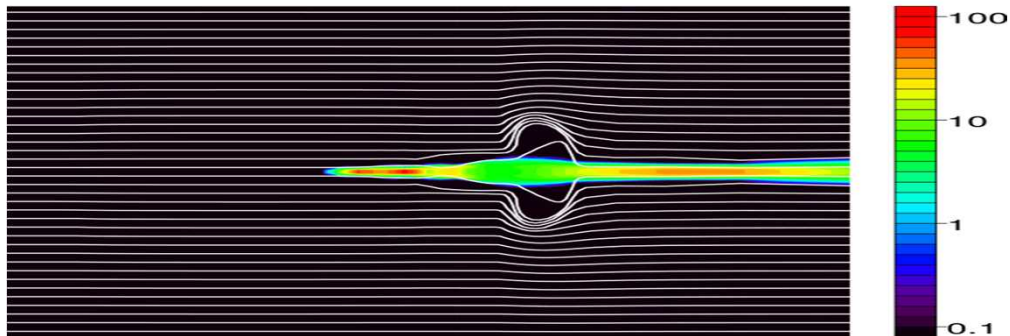
Hole boring phase:
3 kJ of 0.25 μm light

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

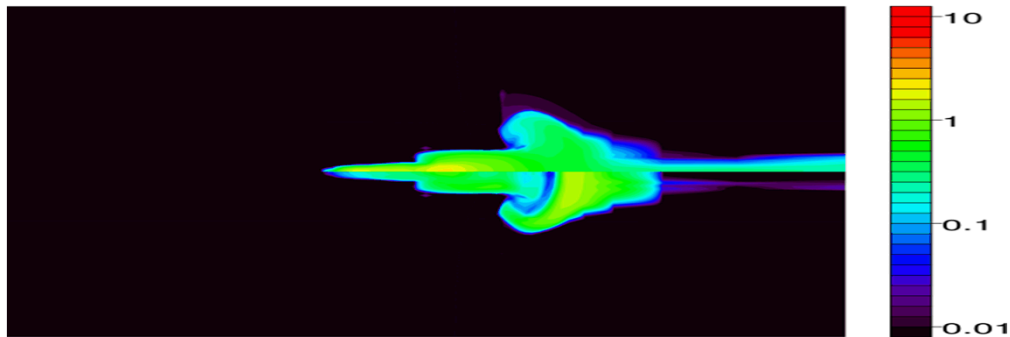
Materials/density kg/m3



0.25 um Laser Intensity 100TW/cm2



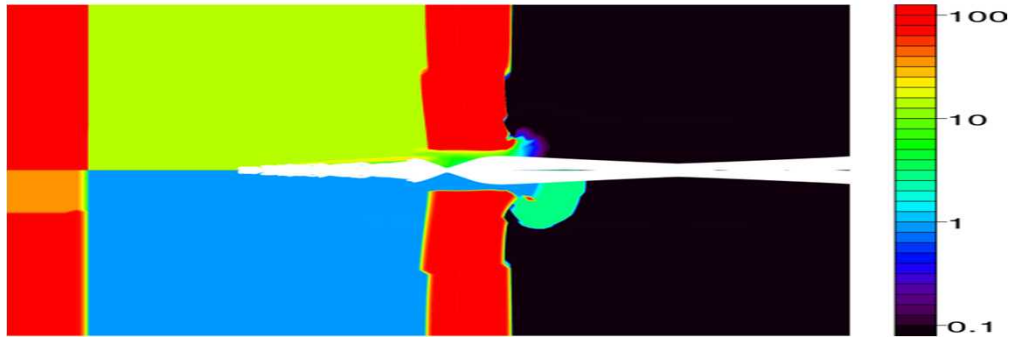
Te/Ti (keV)



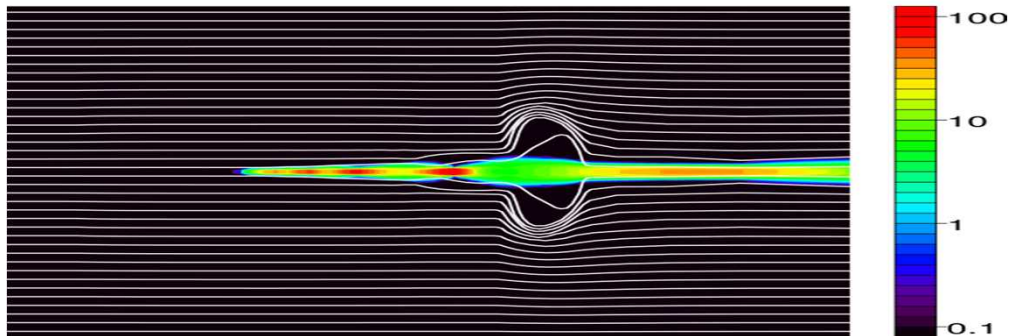
Hole boring phase:
3 kJ of 0.25 um light

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

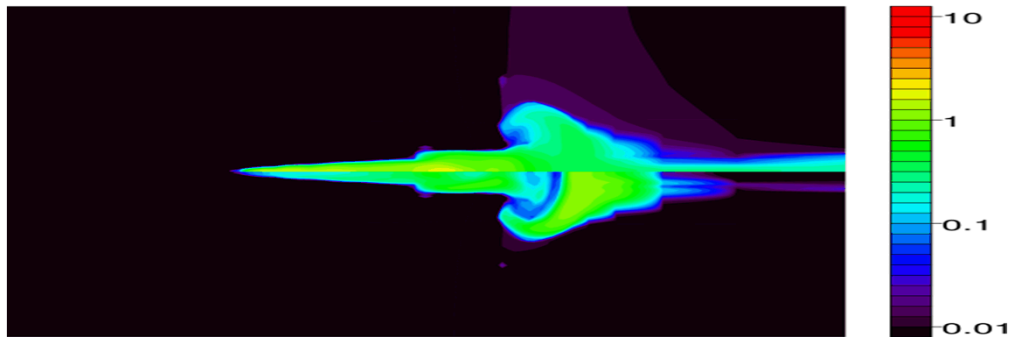
Materials/density kg/m³



0.25 um Laser Intensity 100TW/cm²



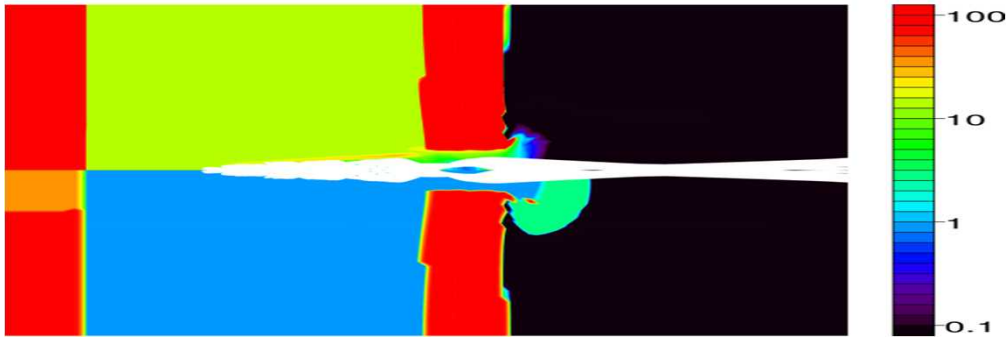
Te/Ti (keV)



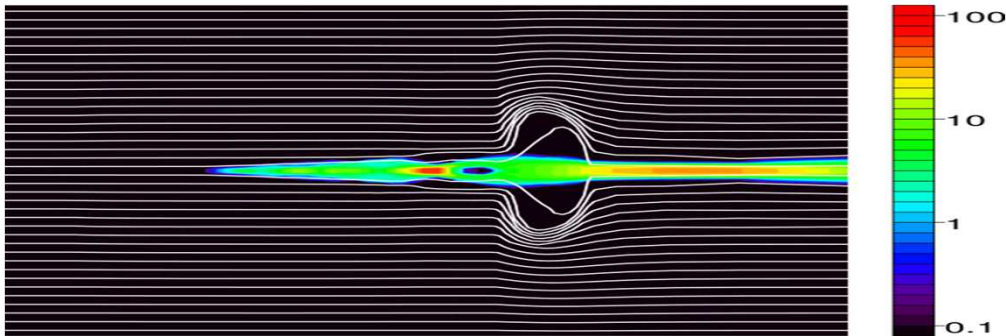
Hole boring phase:
3 kJ of 0.25 um light

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

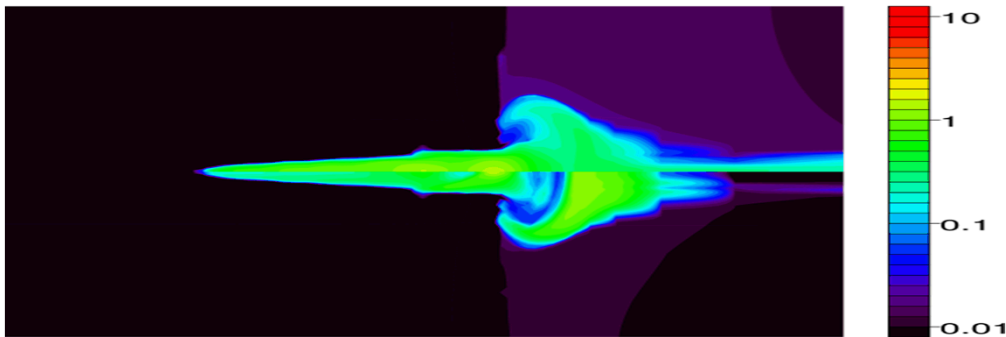
Materials/density kg/m³



0.25 μ m Laser Intensity 100TW/cm²



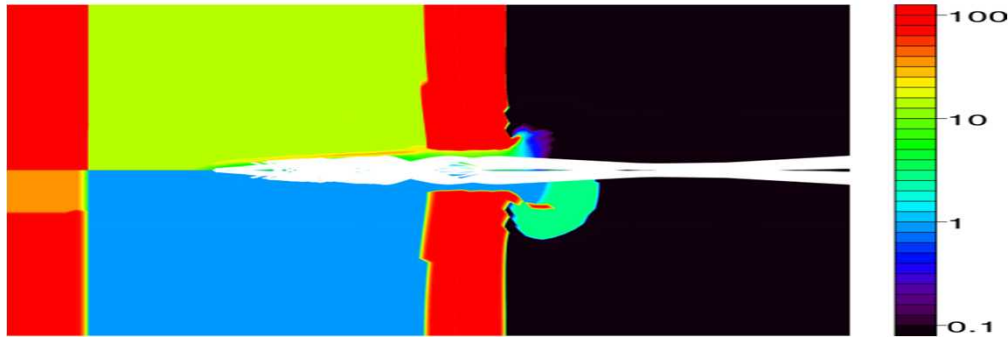
Te/Ti (keV)



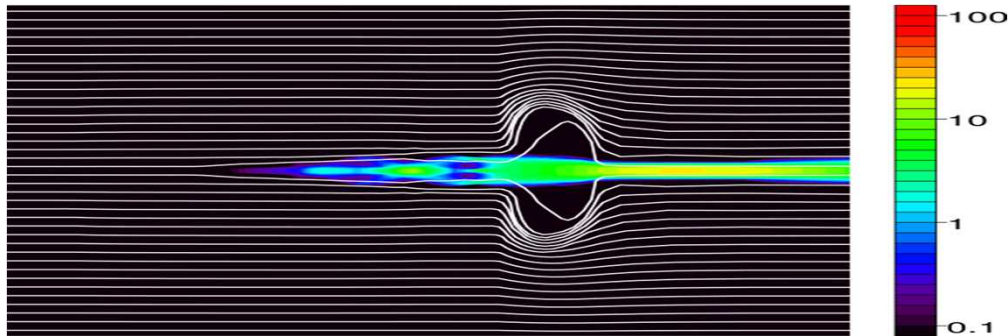
Hole boring phase:
3 kJ of 0.25 μ m light

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

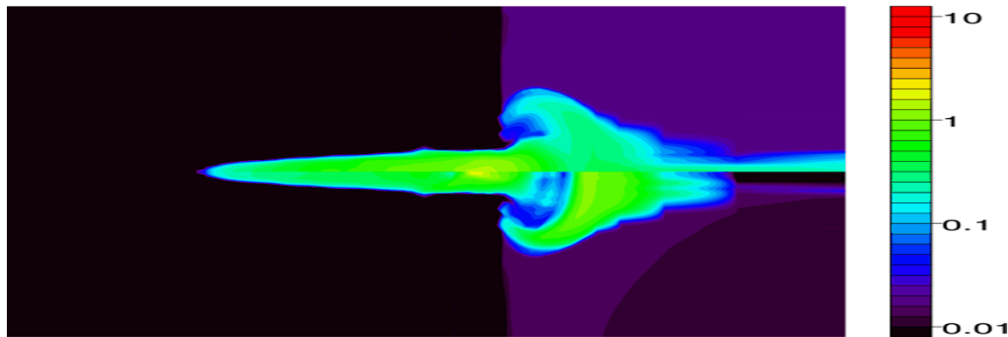
Materials/density kg/m³



0.25 μm Laser Intensity 100TW/cm²



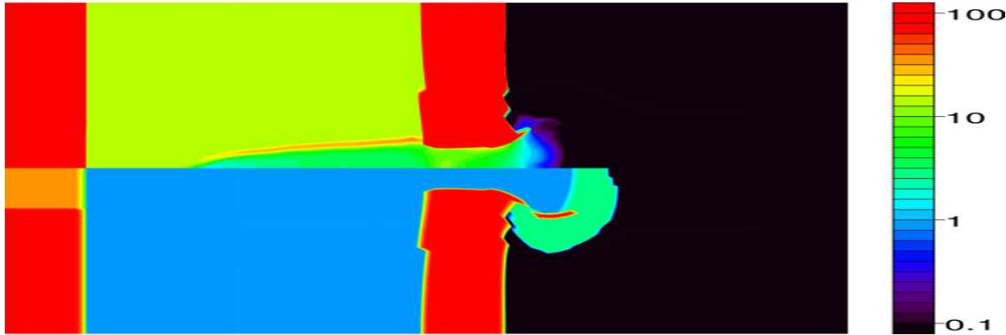
Te/Ti (keV)



Hole boring phase:
3 kJ of 0.25 μm light

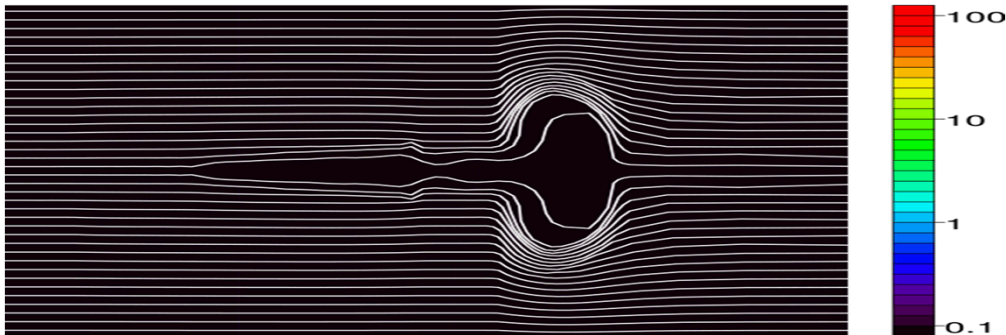
Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

Materials/density kg/m³

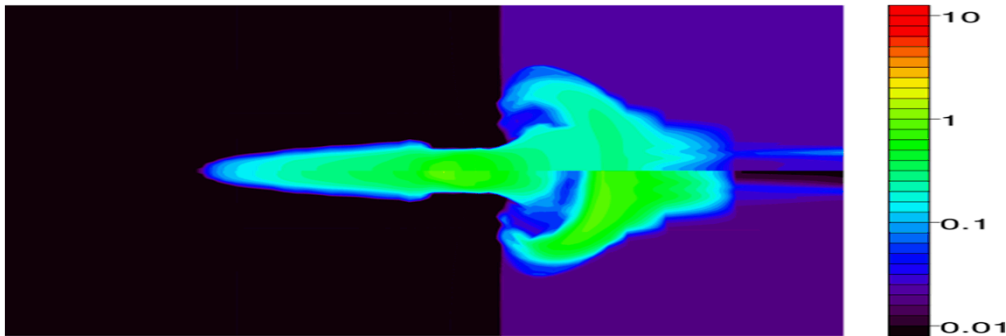


Laser off for 1 ns

1 μ m Laser Intensity 100TW/cm²

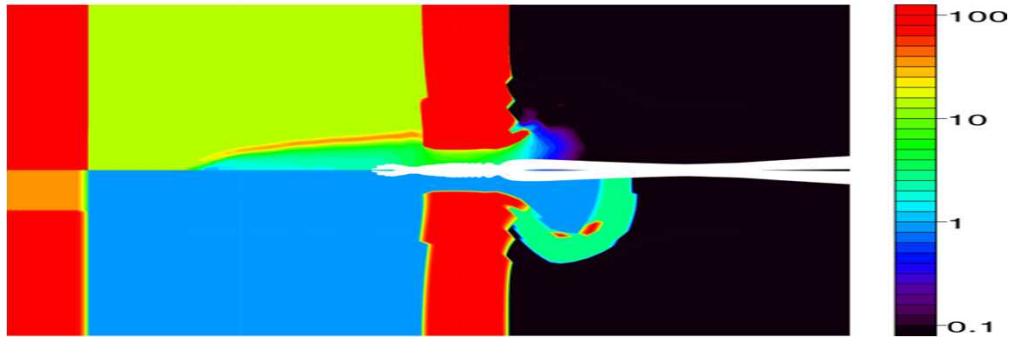


Te/Ti (keV)

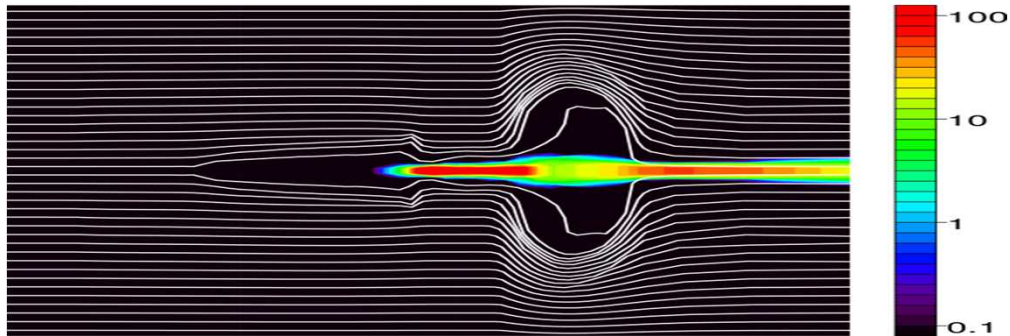


Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

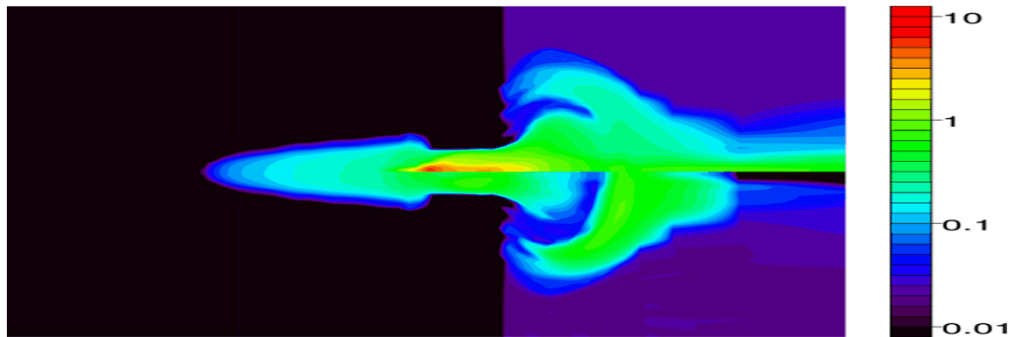
Materials/density kg/m³



1 μ m Laser Intensity 100TW/cm²



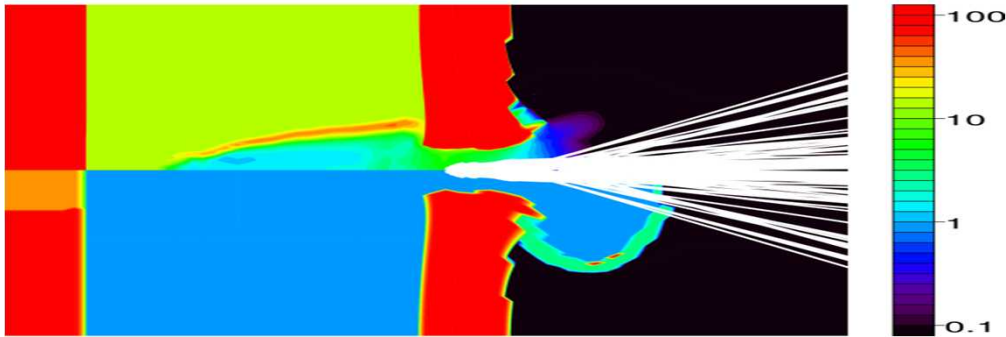
Te/Ti (keV)



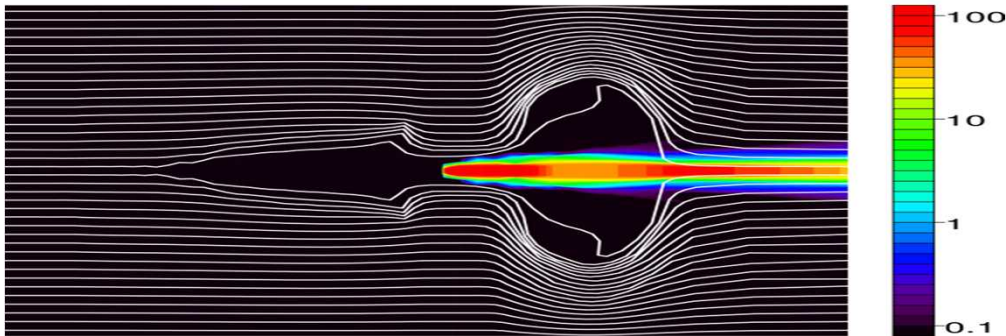
Energy deposition phase:
30 kJ of 1.0 μ m light

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

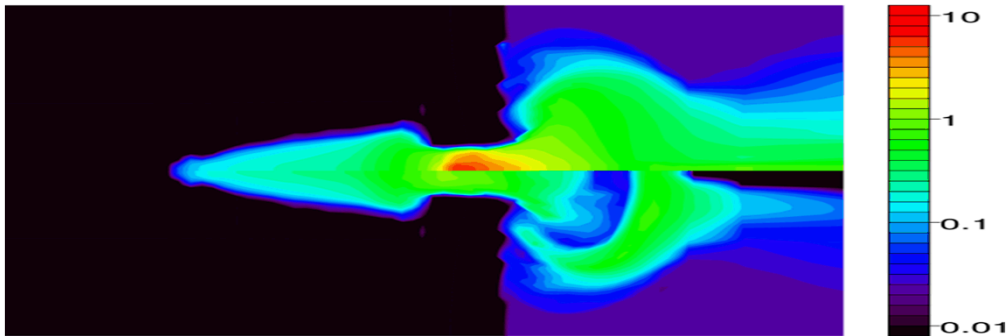
Materials/density kg/m³



1 μ m Laser Intensity 100TW/cm²



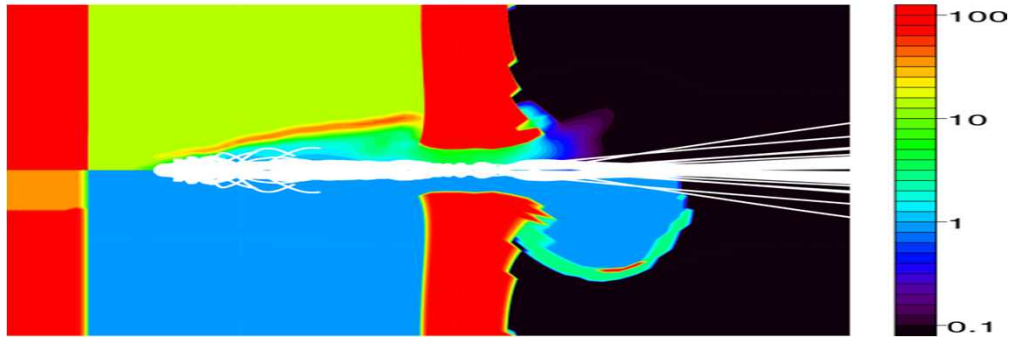
Te/Ti (keV)



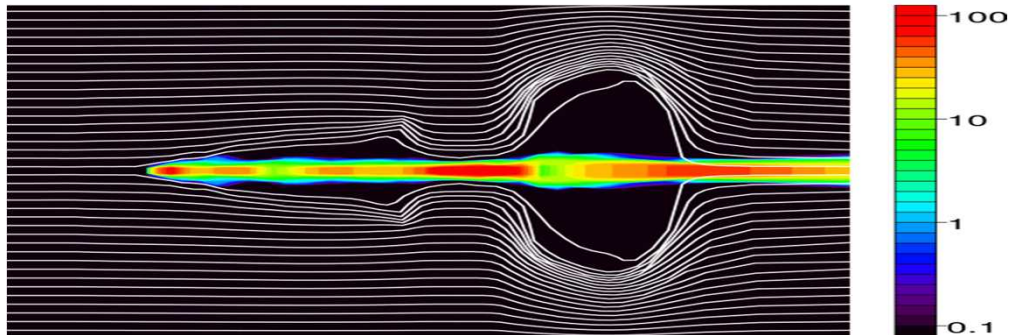
Energy deposition phase:
30 kJ of 1.0 μ m light

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

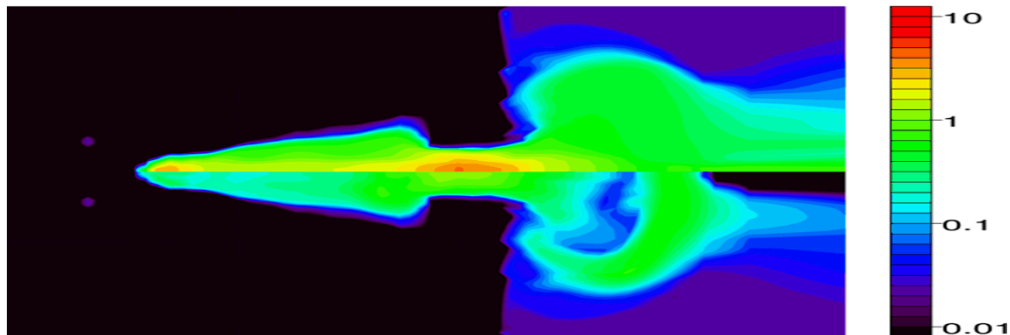
Materials/density kg/m³



1 μ m Laser Intensity 100TW/cm²



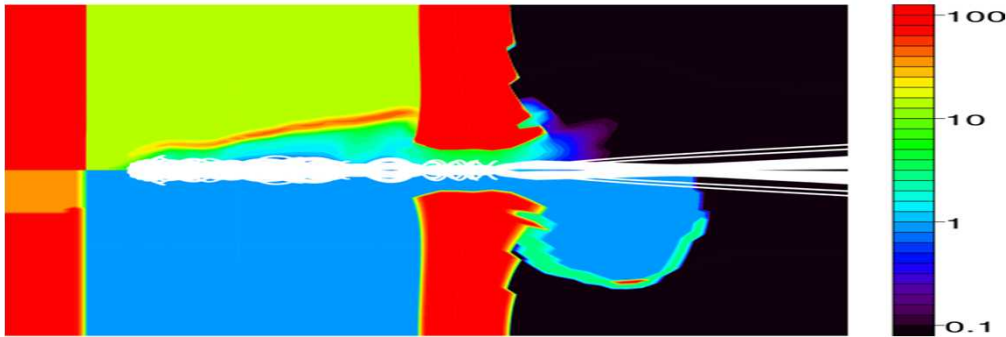
Te/Ti (keV)



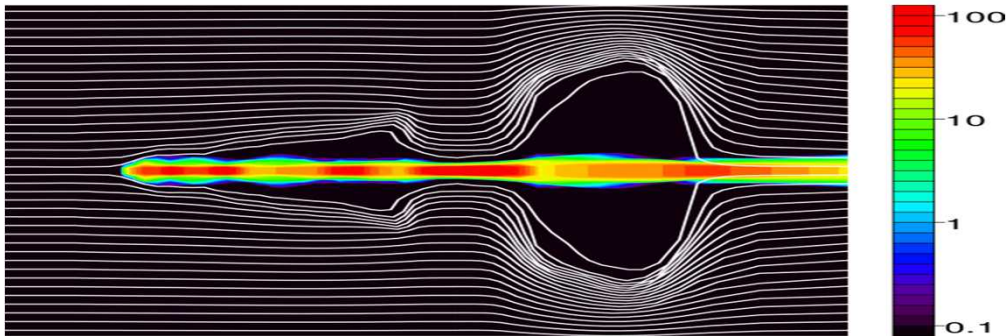
Energy deposition phase:
30 kJ of 1.0 μ m light

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

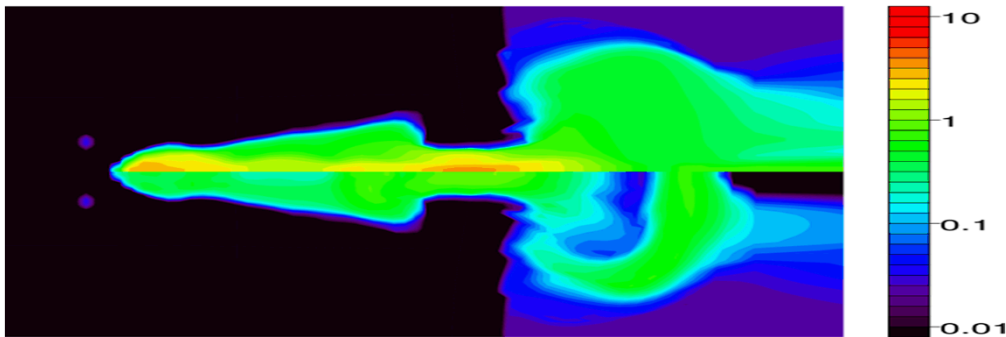
Materials/density kg/m3



1 um Laser Intensity 100TW/cm2



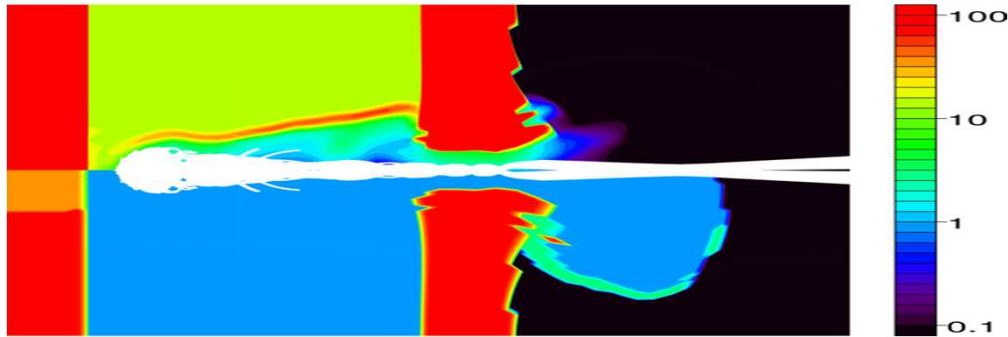
Te/Ti (keV)



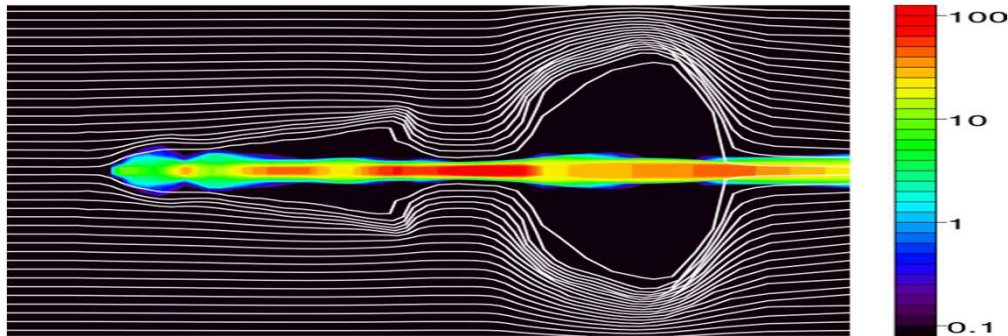
Energy deposition phase:
30 kJ of 1.0 μm light

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

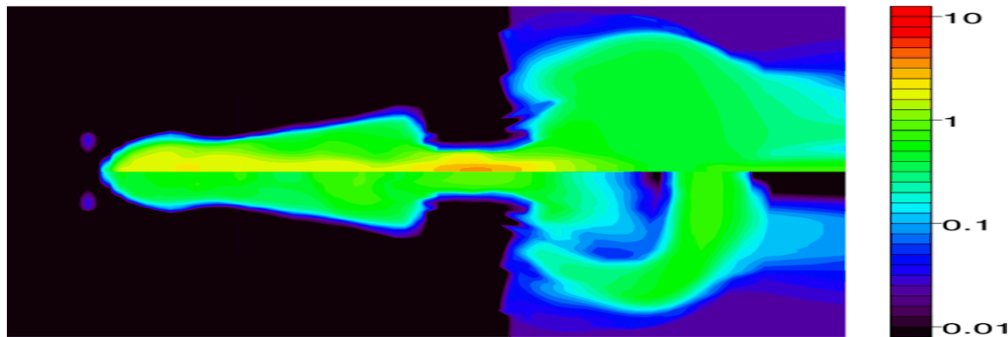
Materials/density kg/m³



1 μ m Laser Intensity 100TW/cm²



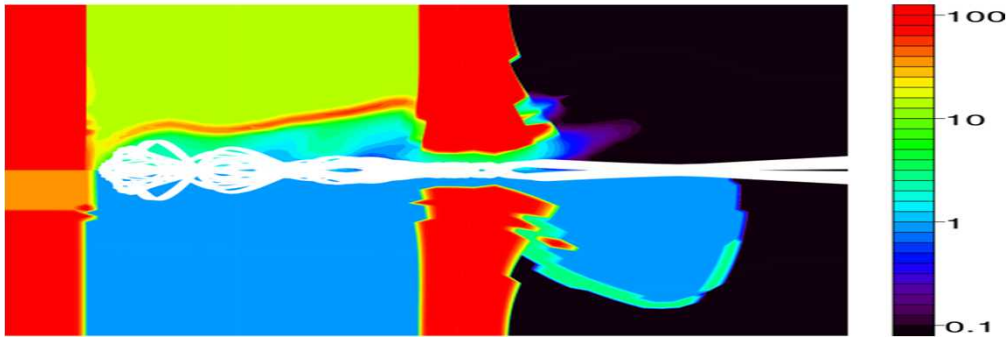
Te/Ti (keV)



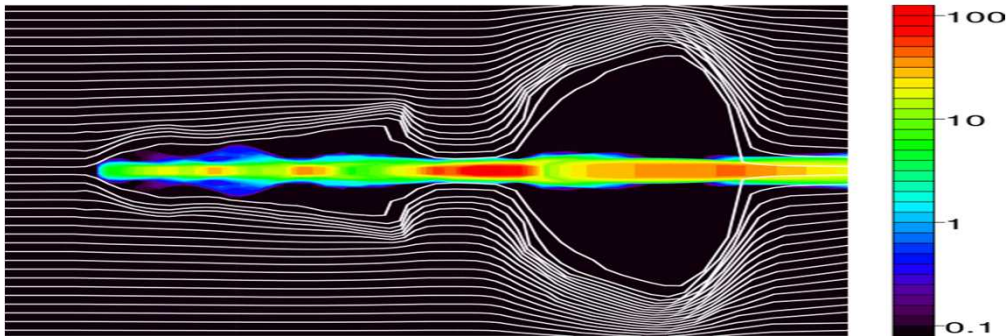
Energy deposition phase:
30 kJ of 1.0 μ m light

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

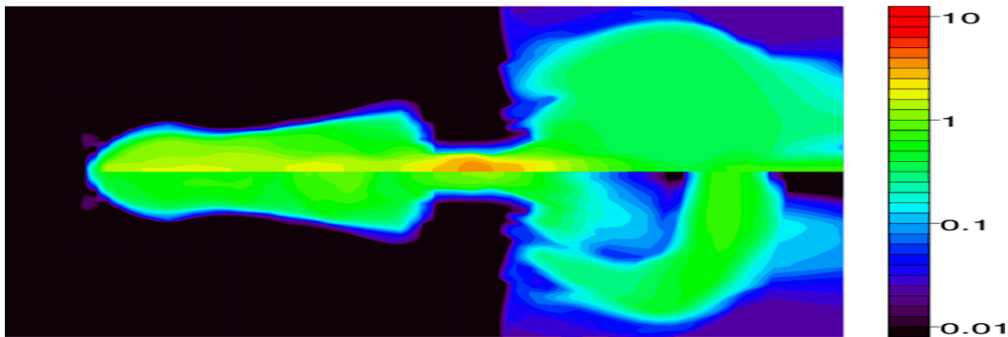
Materials/density kg/m³



1 μ m Laser Intensity 100TW/cm²



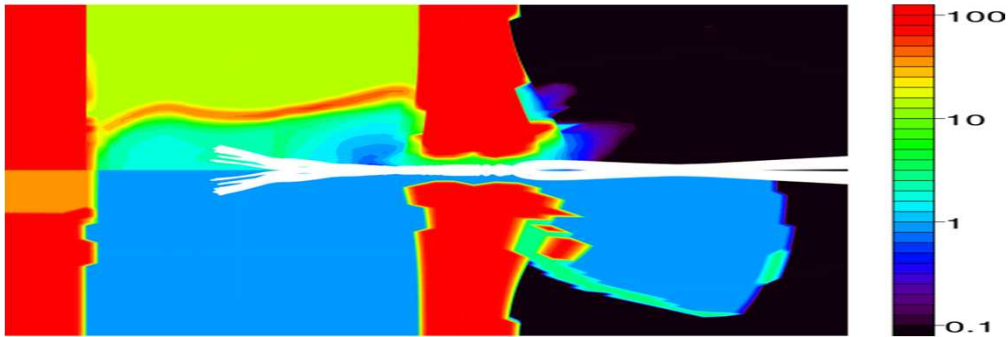
Te/Ti (keV)



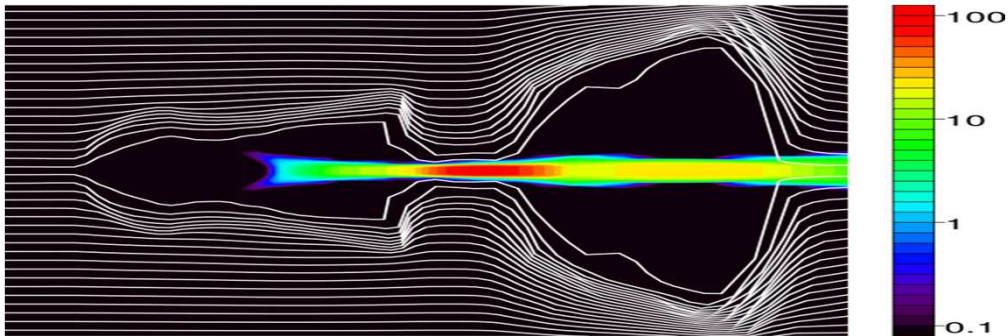
Energy deposition phase:
30 kJ of 1.0 μ m light

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

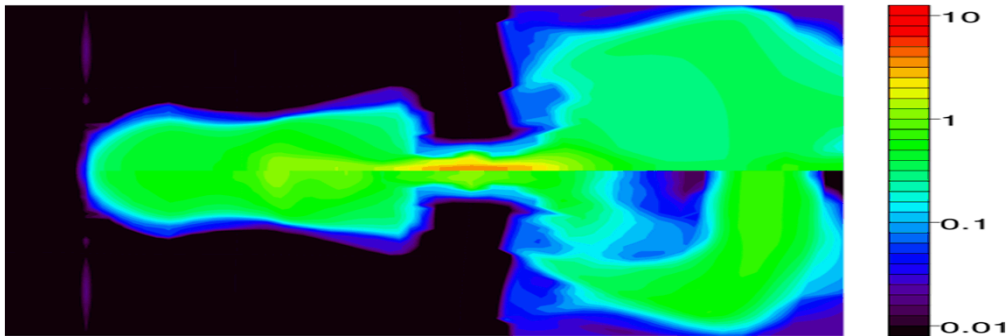
Materials/density kg/m³



1 μ m Laser Intensity 100TW/cm²



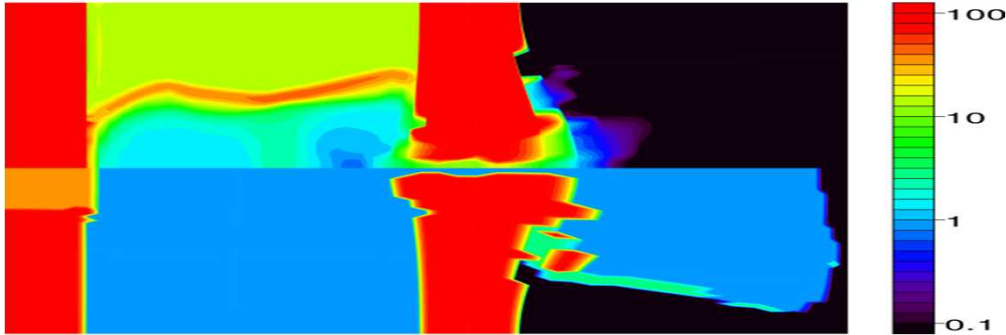
Te/Ti (keV)



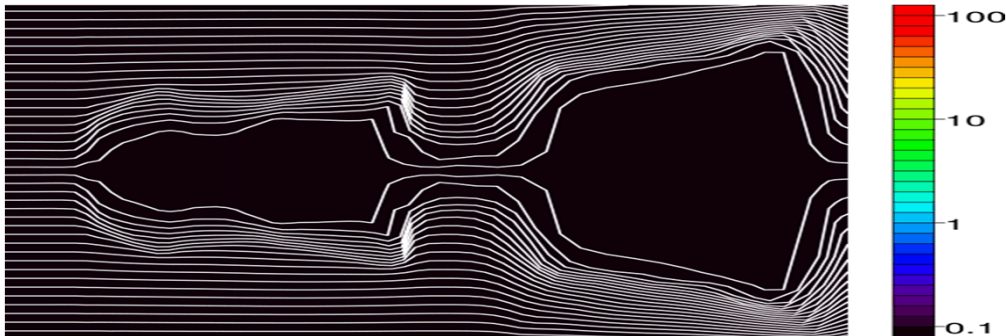
Energy deposition phase:
30 kJ of 1.0 μ m light

Simulation of a laser heating experiment depositing 30 kJ in 1 cm of DT at 12 mg/cc

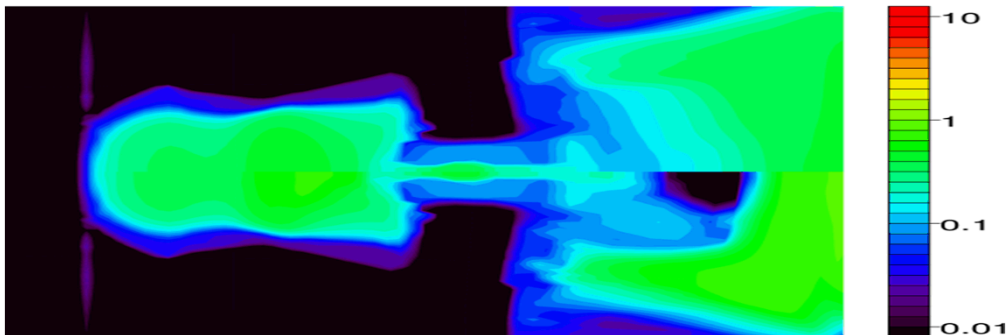
Materials/density kg/m3



1 um Laser Intensity 100TW/cm2



Te/Ti (keV)



Energy deposition phase:
30 kJ of 1.0 μm light

Preheat for High-Yield MagLIF can be demonstrated using the NIF

NIF can only provide either 0.53 μ or 0.35 μ light

- The initial hole boring is still effective at 0.35 μ
- It is difficult to stop a 0.53 μ beam in the relatively low density channel within the 1 cm length of the liner
- large beam diameters could be used, but this requires a large LEH

Laser absorption could be enhanced by injecting the second laser with a moderate cone angle

- small LEH could be used
- the beam reflects off the enhanced density at the blast wave boundary
- behaves like a light pipe, which should avoid beam spray
- the effective scale length of the plasma is decreased for less LPI

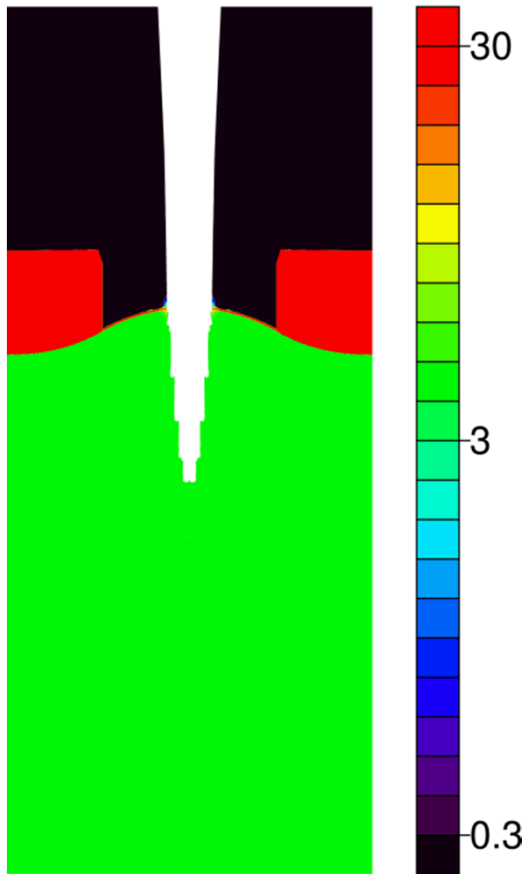
The following Lasnex simulation indicates 30 kJ can be deposited in 4.5 mg/cc using using this approach

- 30 degree cone angle used in this example

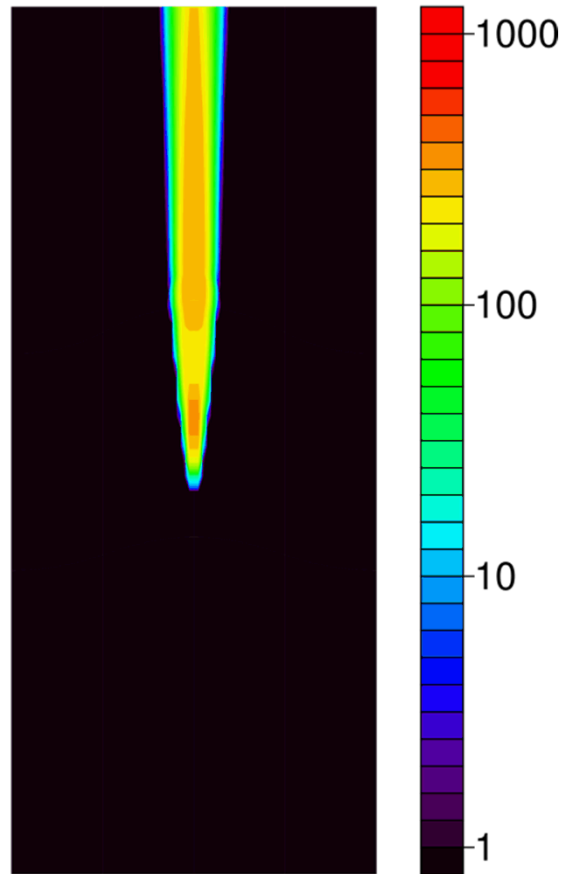
Simulation of a NIF laser heating experiment depositing 30 kJ in 1 cm of DT at 4.5 mg/cc

Hole boring phase:
3 kJ of 0.35 μm light

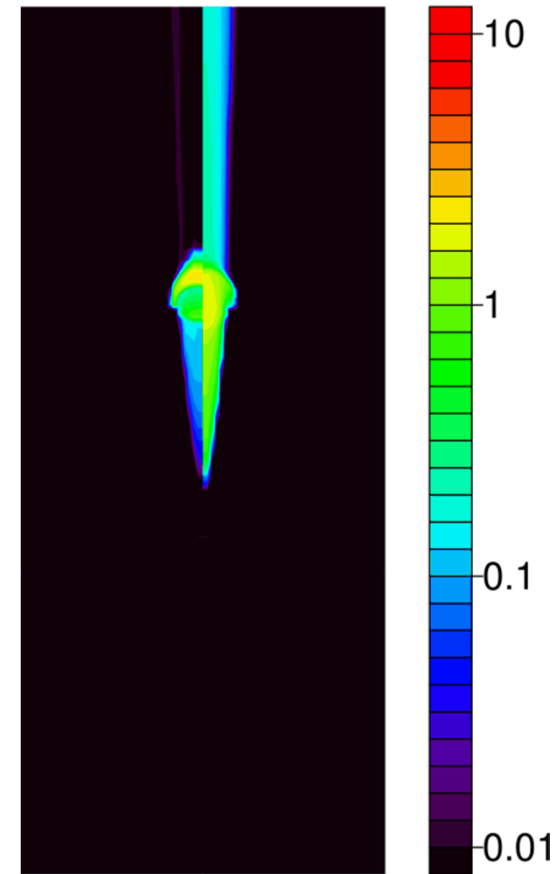
Density kg/m³



Intensity TW/cm²



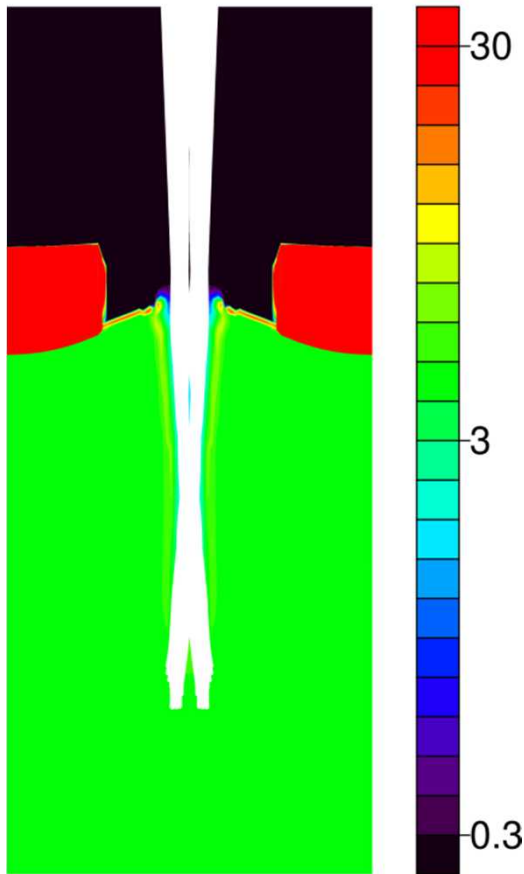
Te/Ti (keV)



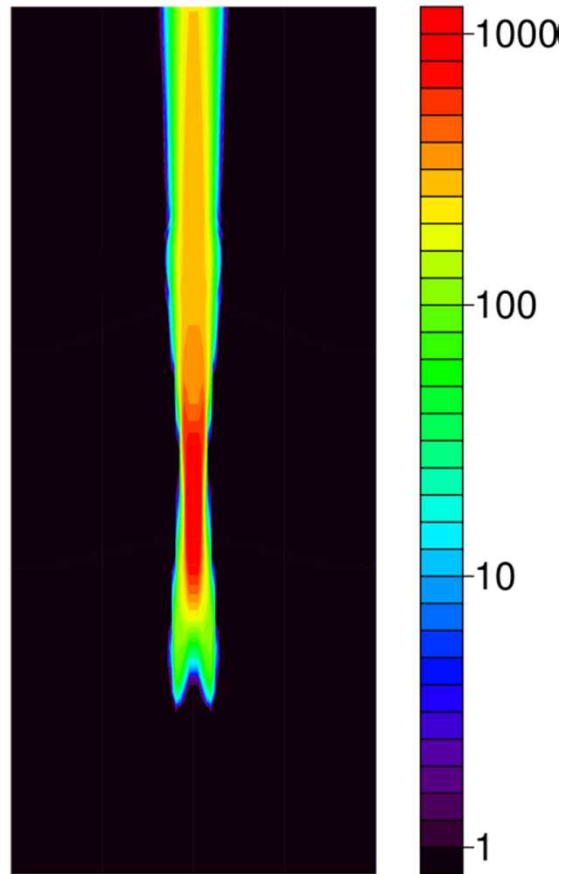
Simulation of a NIF laser heating experiment depositing 30 kJ in 1 cm of DT at 4.5 mg/cc

Hole boring phase:
3 kJ of 0.35 μm light

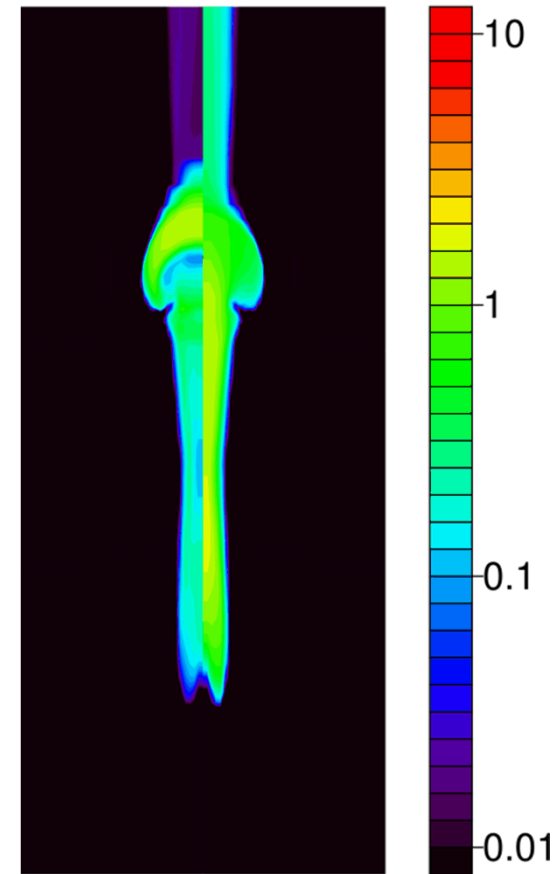
Density kg/m^3



Intensity TW/cm^2



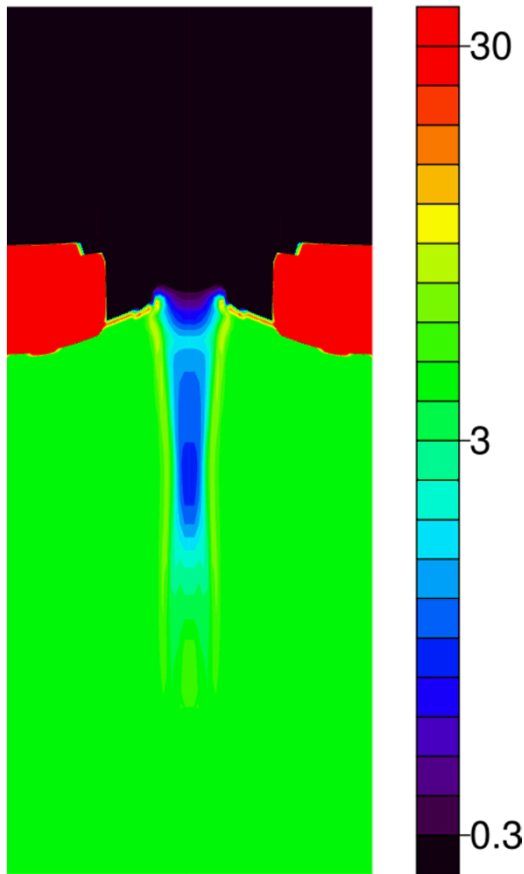
Te/Ti (keV)



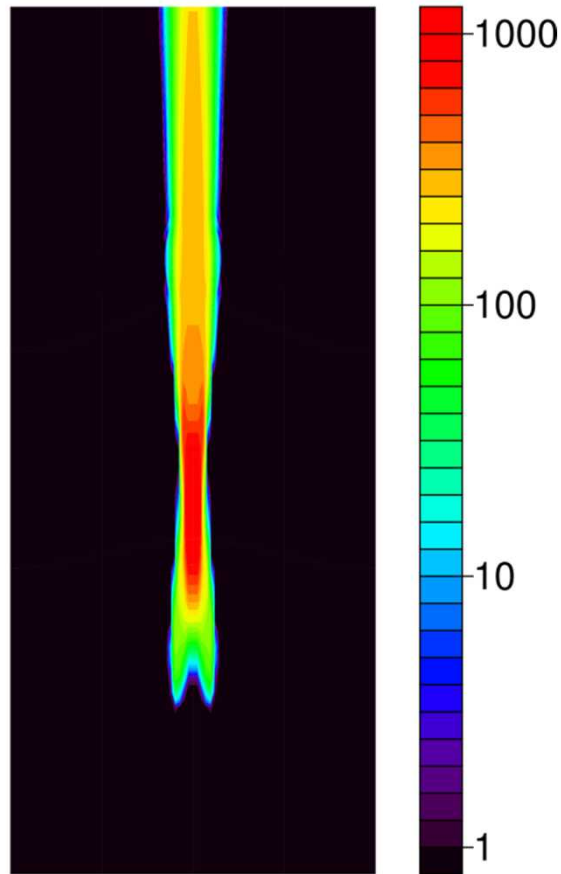
Simulation of a NIF laser heating experiment depositing 30 kJ in 1 cm of DT at 4.5 mg/cc

Hole boring phase:
3 kJ of 0.35 μm light

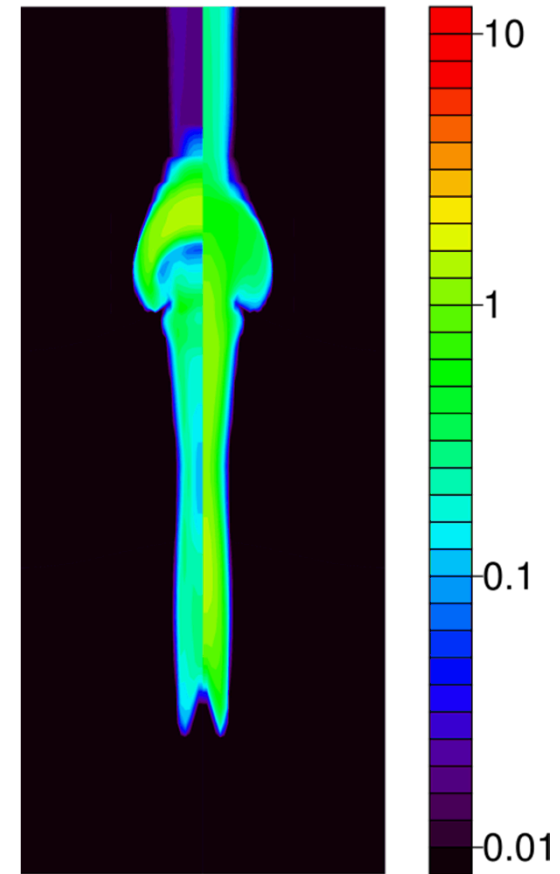
Density kg/m^3



Intensity TW/cm^2



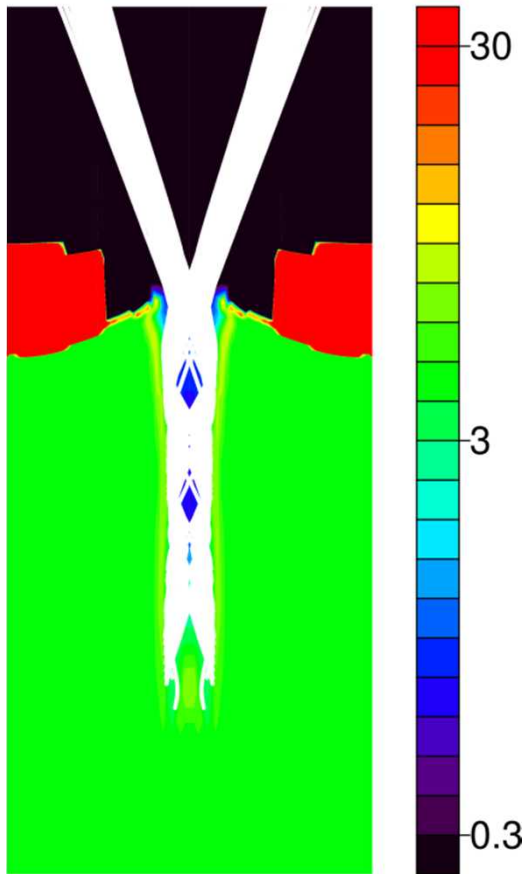
Te/Ti (keV)



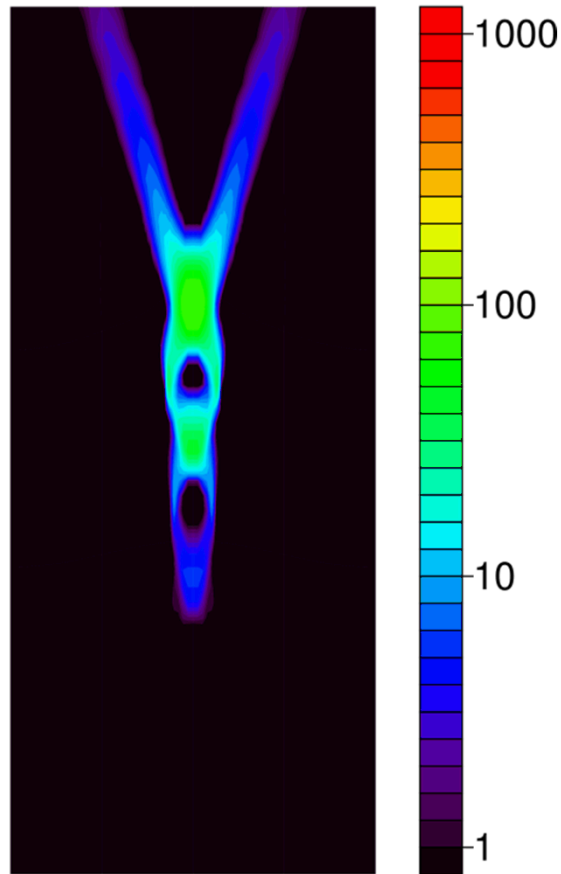
Simulation of a NIF laser heating experiment depositing 30 kJ in 1 cm of DT at 4.5 mg/cc

Energy deposition phase:
30 kJ of 0.53 μm light

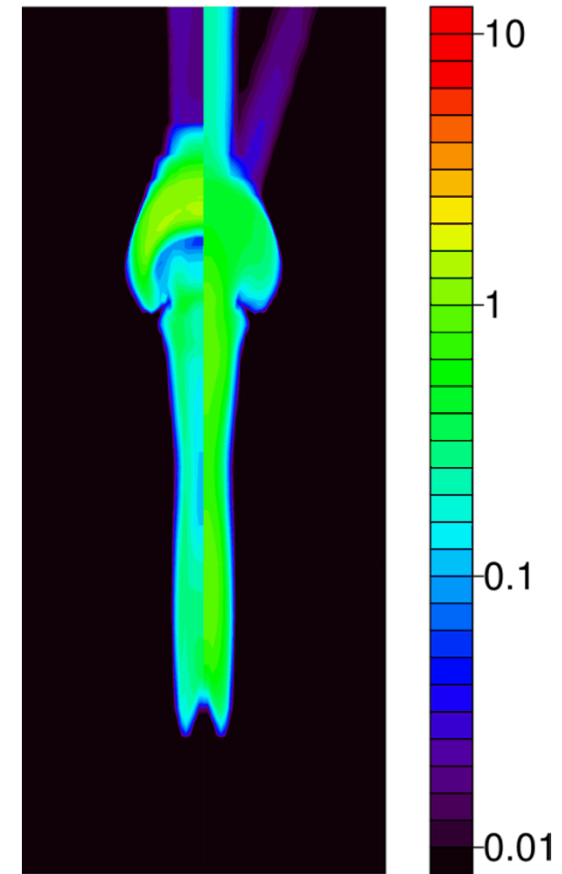
Density kg/m^3



Intensity TW/cm^2



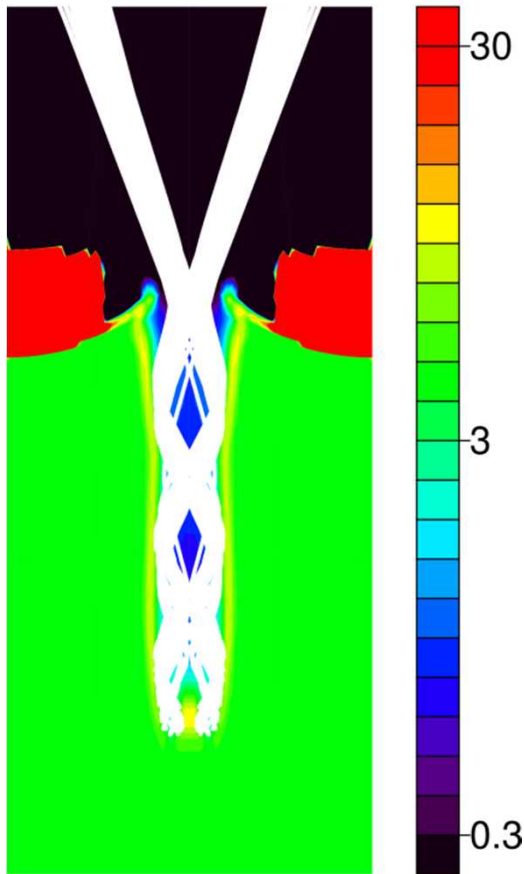
Te/Ti (keV)



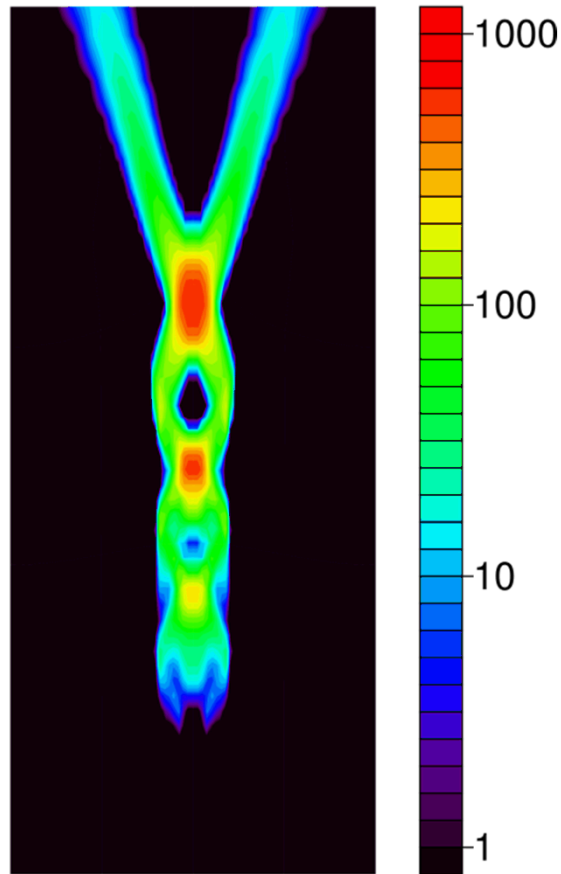
Simulation of a NIF laser heating experiment depositing 30 kJ in 1 cm of DT at 4.5 mg/cc

Energy deposition phase:
30 kJ of 0.53 μm light

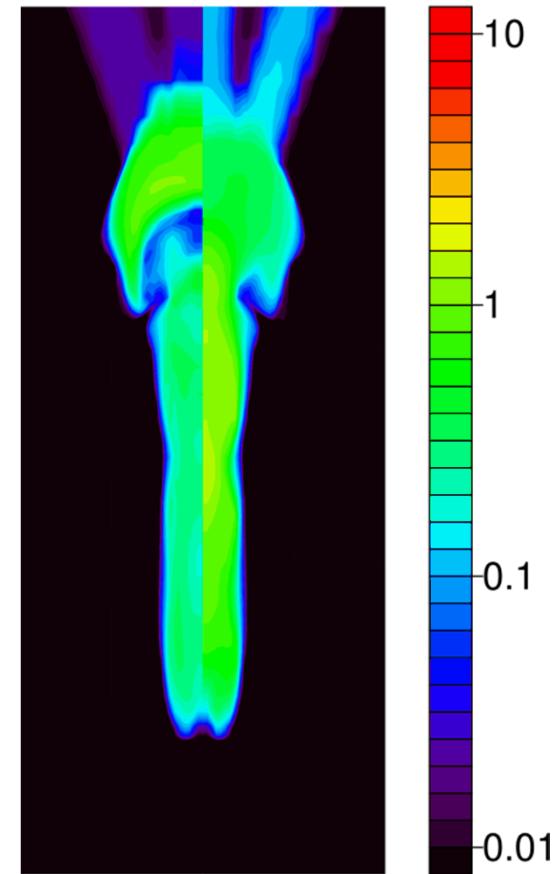
Density kg/m³



Intensity TW/cm²



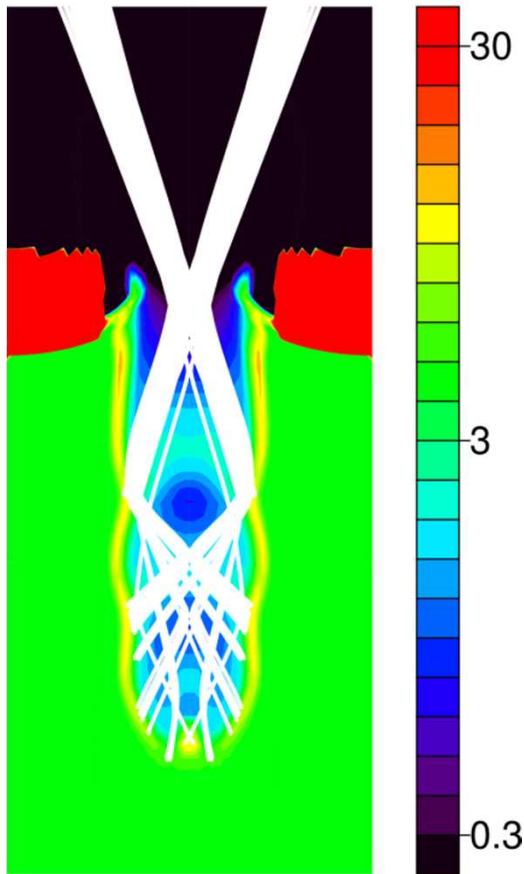
Te/Ti (keV)



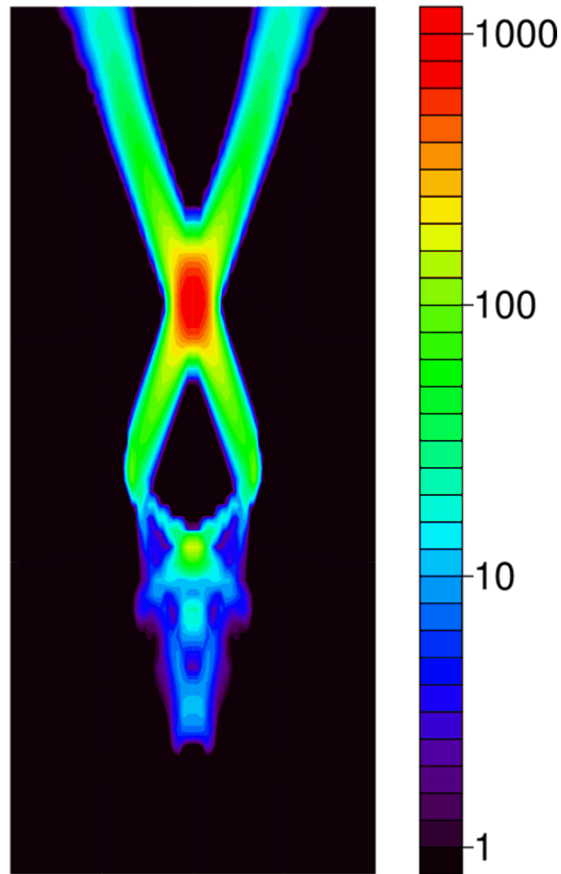
Simulation of a NIF laser heating experiment depositing 30 kJ in 1 cm of DT at 4.5 mg/cc

Energy deposition phase:
30 kJ of 0.53 μm light

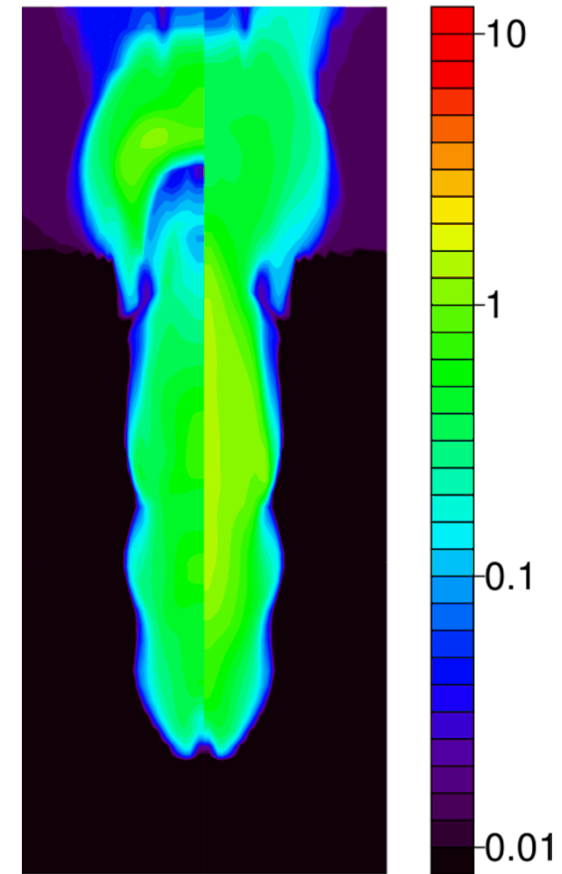
Density kg/m^3



Intensity TW/cm^2



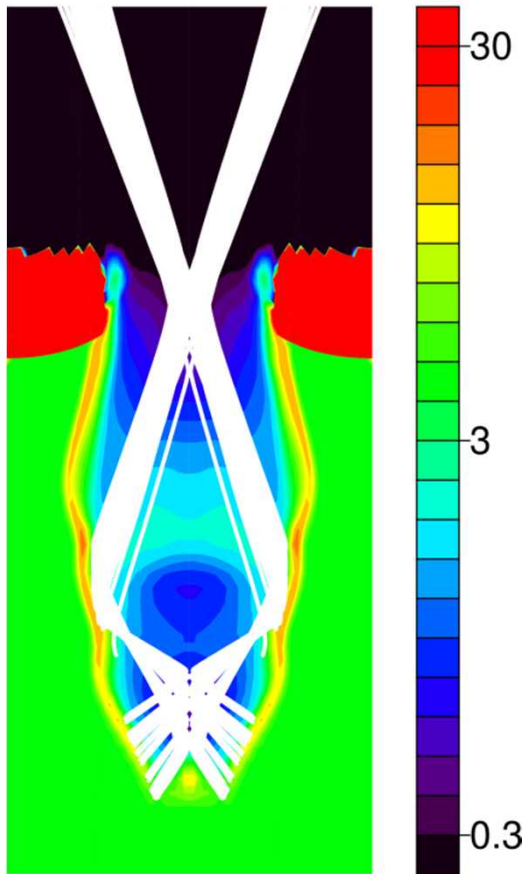
Te/Ti (keV)



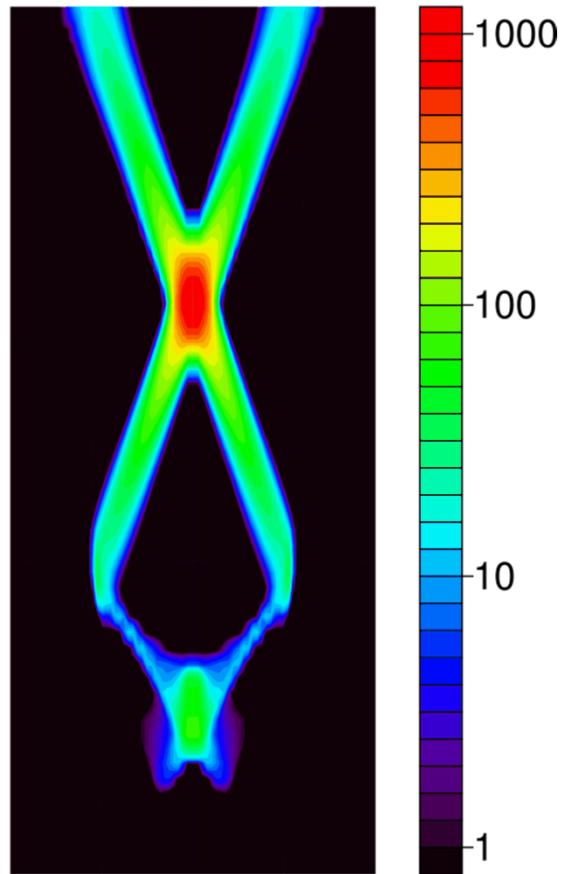
Simulation of a NIF laser heating experiment depositing 30 kJ in 1 cm of DT at 4.5 mg/cc

Energy deposition phase:
30 kJ of 0.53 μm light

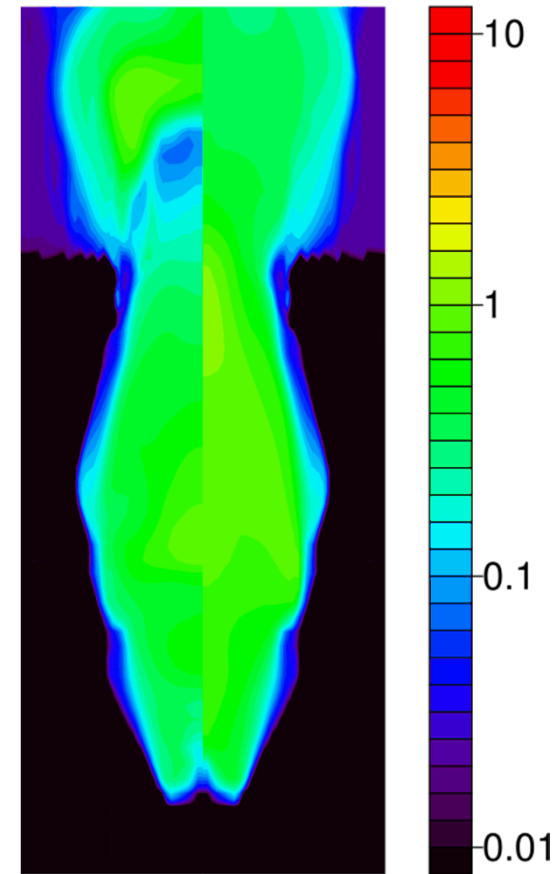
Density kg/m^3



Intensity TW/cm^2



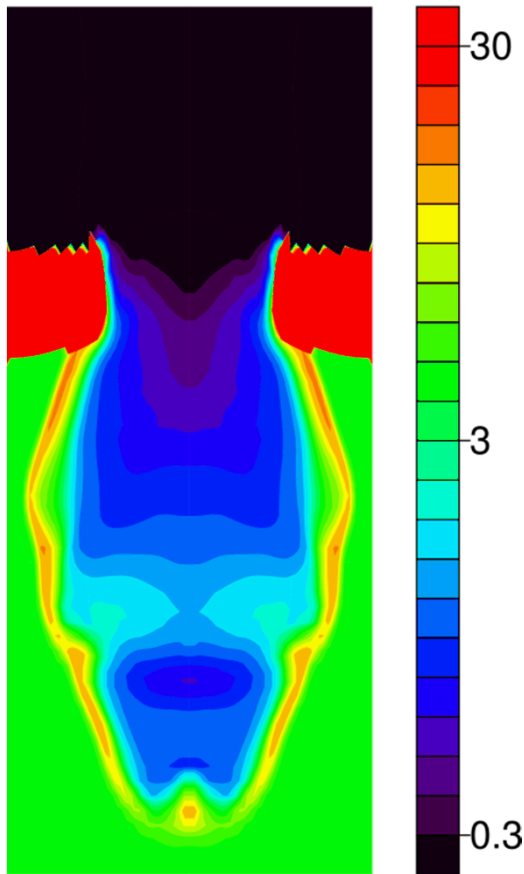
Te/Ti (keV)



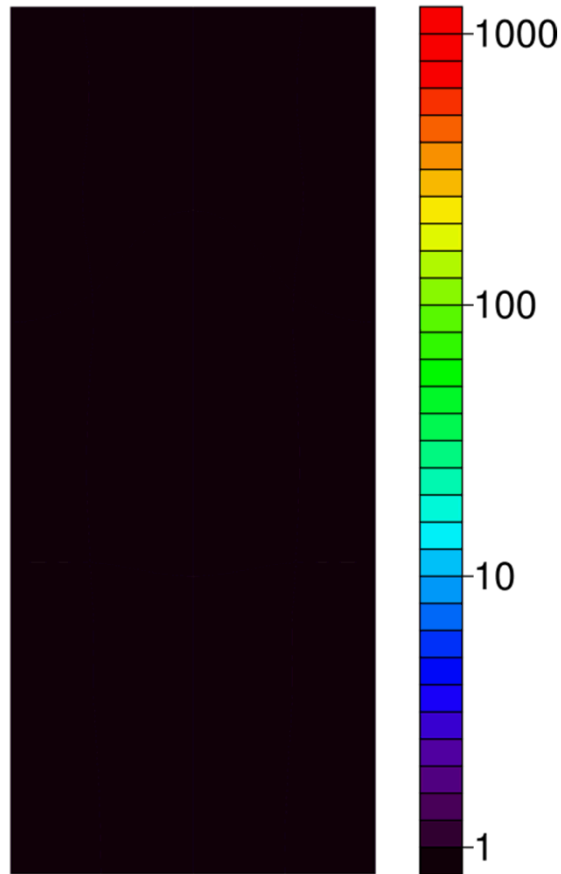
Simulation of a NIF laser heating experiment depositing 30 kJ in 1 cm of DT at 4.5 mg/cc

Energy deposition phase:
30 kJ of 0.53 μm light

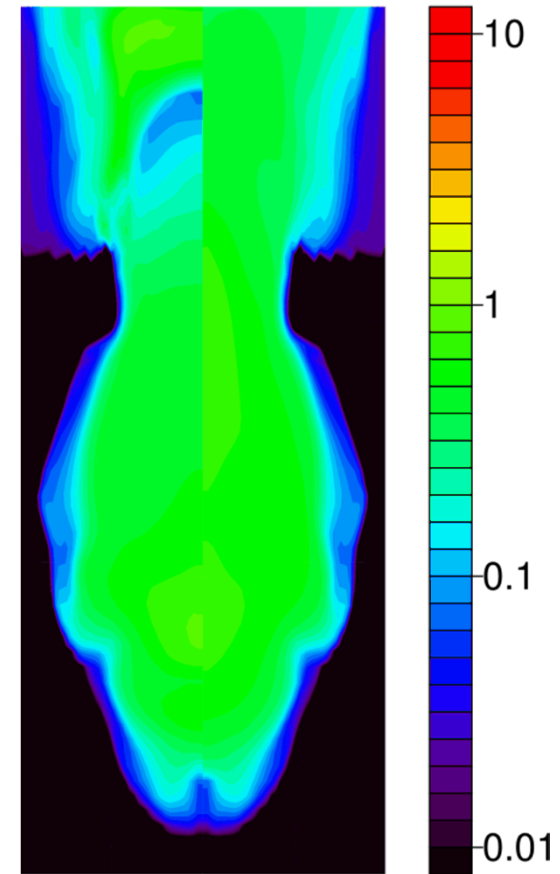
Density kg/m^3



Intensity TW/cm^2



Te/Ti (keV)



1D and 2D Lasnex simulations indicate large MagLIF yields could be possible on future accelerators

MagLIF Gas burners are being tested on Z. There should be little physics risk in fielding these on future accelerators

Substantial preheat energies will be required:

- Lasnex simulations indicate that 30 kJ of laser light can be efficiently deposited within 1 cm of DT at densities appropriate for high yield MagLIF

Refraction, filamentation and LPI could pose problems. Consequently:

- We are now studying laser preheating with both Z Beamlet and Omega
- Before a future pulsed power machine is seriously considered, full scale laser deposition experiments could be performed using the NIF