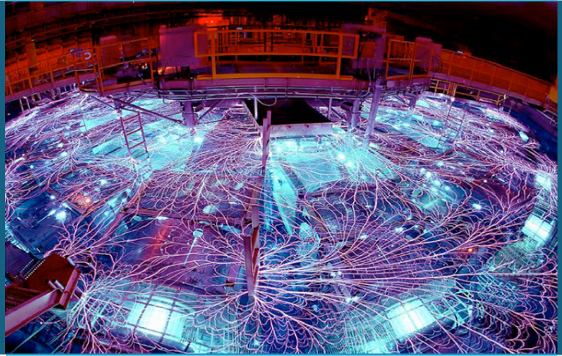
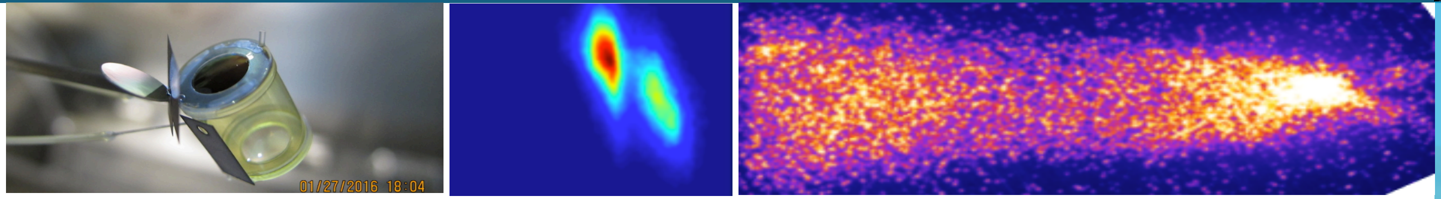


At ignition scale experiments on NIF of next generation MagLIF laser preheat



PRESENTED BY

Michael Glinsky

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SAND2018-12678 C

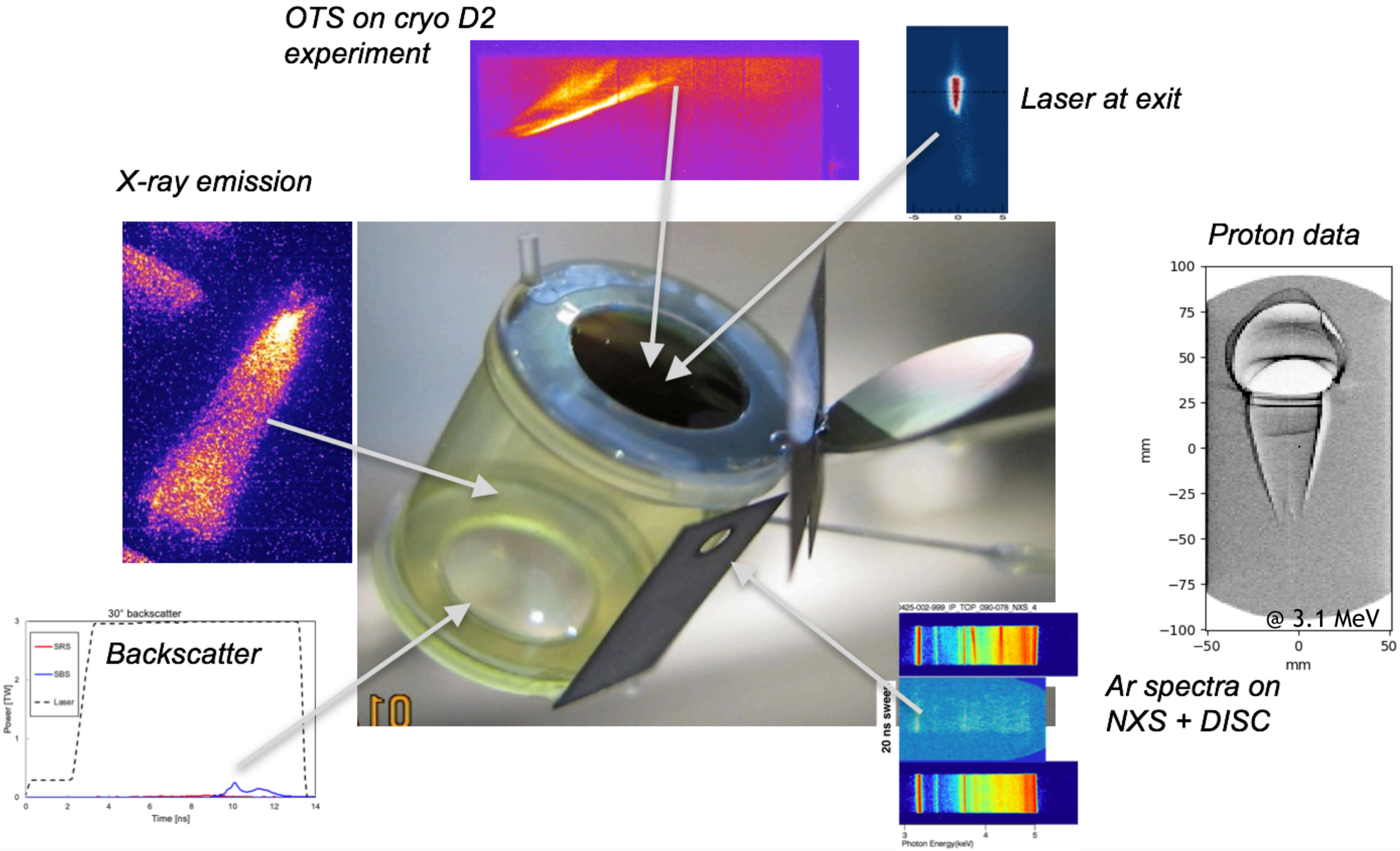
Abstract

Development of a cryogenic and magnetized gas pipe platform is underway at NIF. Experiments have been done into unmagnetized, room temperature, hydrocarbon and cryogenic D2 gases of densities that span 1.6 mg/cc to 4.8 mg/cc (5% to 16% critical electron density). 30 kJ of energy from one quad have been delivered into a oval spot of 1580 micron mean diameter over a time of about 11 ns with a power 2 TW and an intensity of 2x10^14 W/cm2. A large fraction of the laser energy has been absorbed by Inverse Bremsstrahlung absorption over the 1 cm length of the gas pipe. Temperatures of up to about 1300 eV have been reached in the core. Raman and Brillouin backscatter were measured to be “low” on all shots. Experiments in FY19 are planned that will apply a magnetic field of up to 30 Tesla along the axis of the laser deposition for warm hydrocarbons. Applying a magnetic field to the cryogenic D2 gas is possible in future years. These experiments are focused on doing “to ignition scale” Magnetized Liner Inertial Fusion (MagLIF) laser preheat experiments for the next generation pulse power machine.

Technical contributions from:

- Sandia National Laboratories
    - Matt Weis
    - Taisuke Nagayama
    - Kyle Peterson
    - Adam Sefkow
- Lawrence Livermore National Laboratory
    - Brad Pollock
    - John Moody
    - Dave Strozzi
    - Clement Goyon

Gas-pipe experiments are well diagnosed



OTS on cryo D2 experiment

Laser at exit

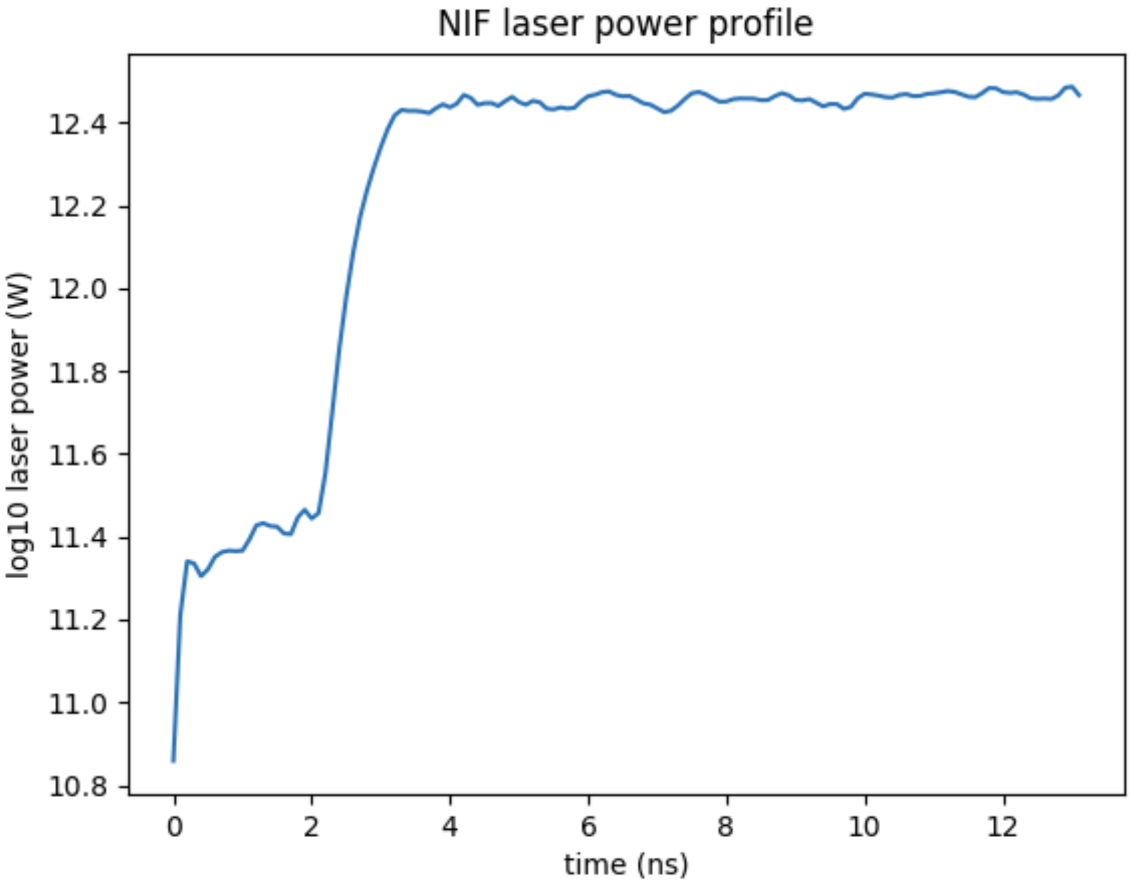
X-ray emission

Proton data

Backscatter

Ar spectra on NXS + DISC

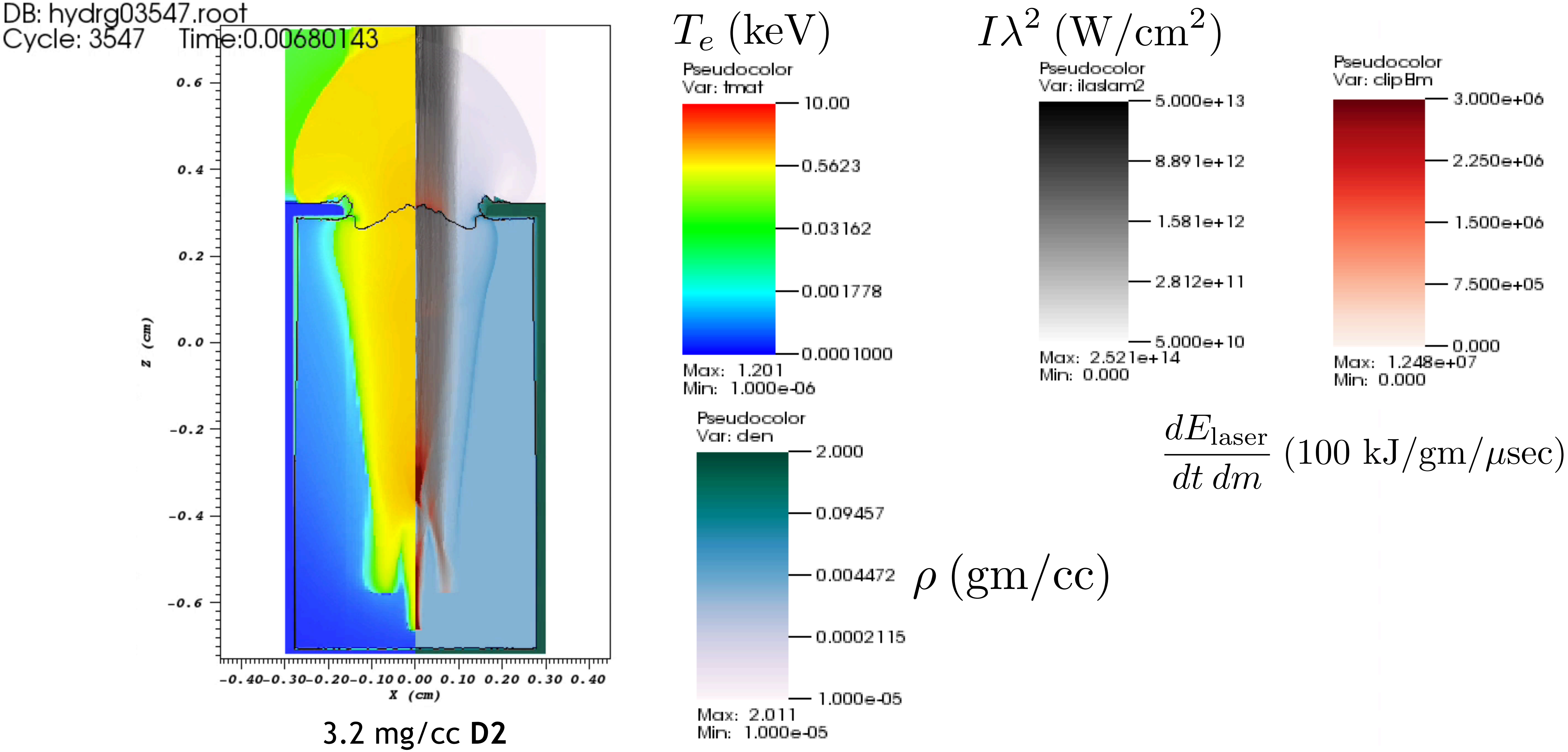
Laser pulse



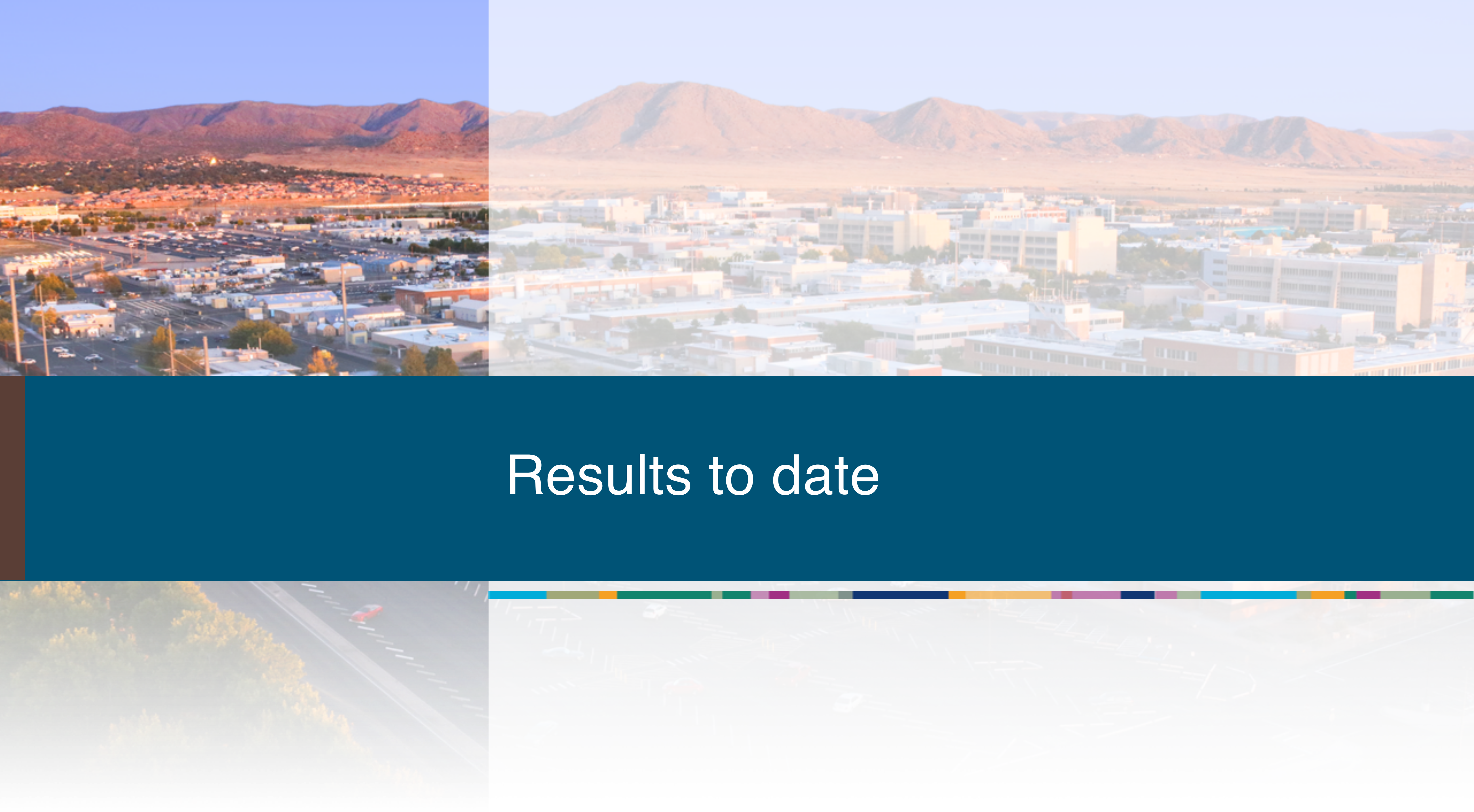
```
pre pulse energy = 534 J
pre pulse duration = 2.2 ns
main pulse energy = 29.7 kJ
main pulse duration = 10.8 ns
```

NIF quad
foot:
500 J, 2 ns
main pulse:
30 kJ, 11 ns, 3 TW, 2x10^{14} W/cm^2
1.58 mm mean diameter

Example of laser deposition into 3.2 mg/cc D2, 10% n_e/n_{cr}, 2D, 0.05 flux limiter, no MHD

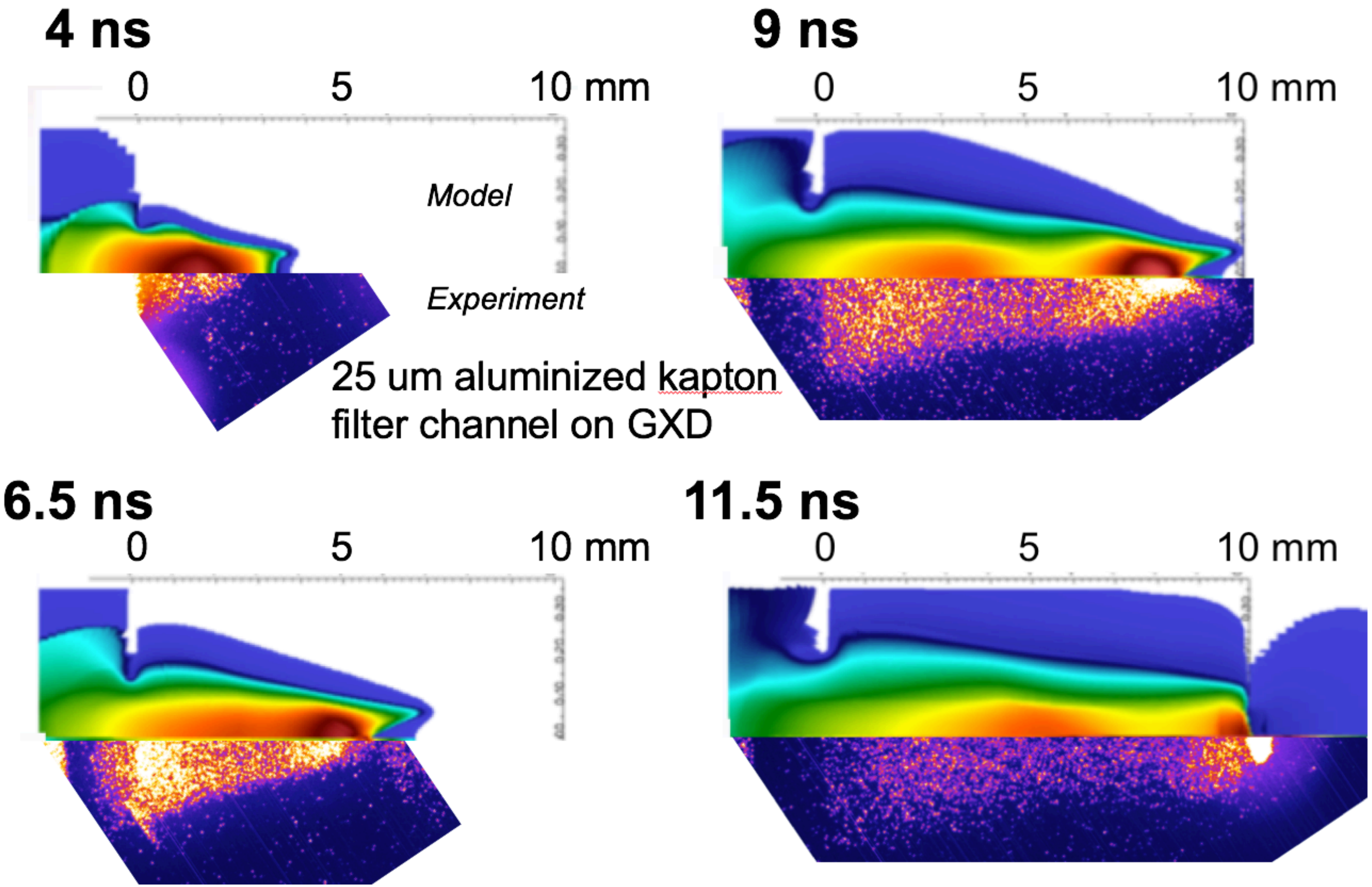


3.2 mg/cc **D2**



Results to date

The laser propagation at 2.9 gm/cc (12% n_e/n_{cr}) in C5H12 is in good agreement with pre-shot HYDRA simulations

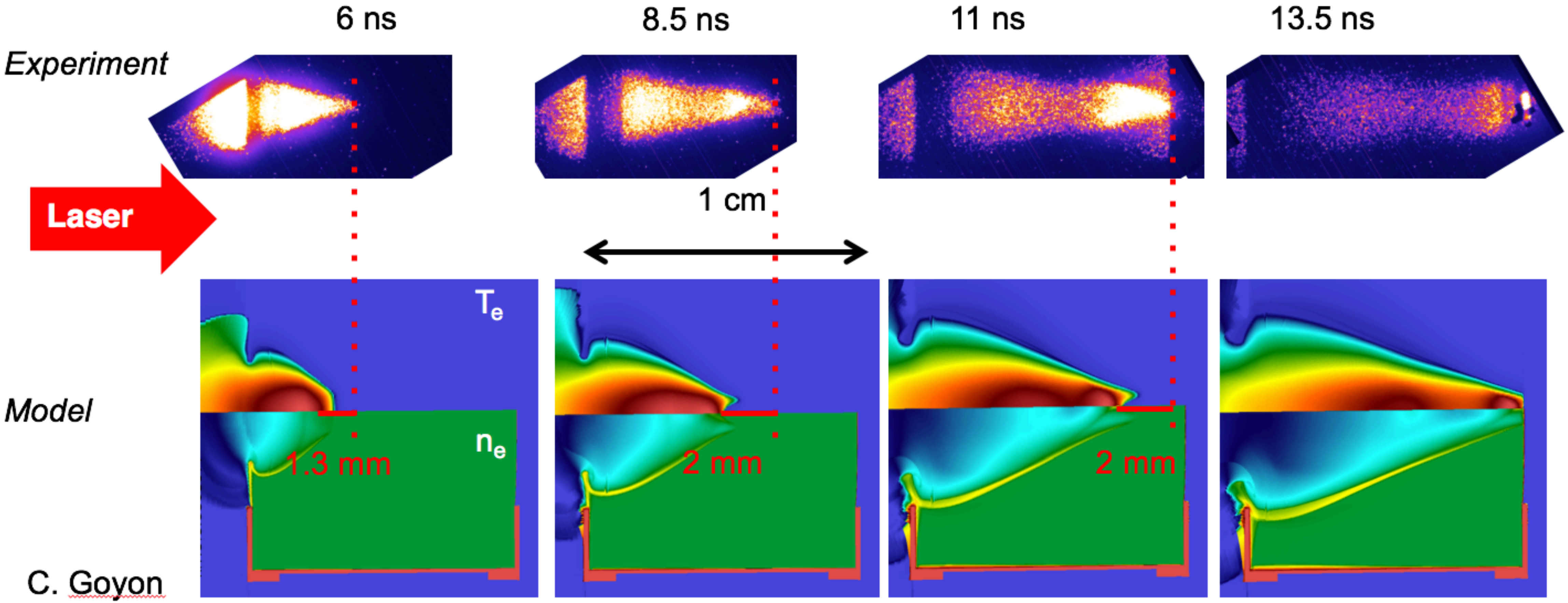


Model

Experiment

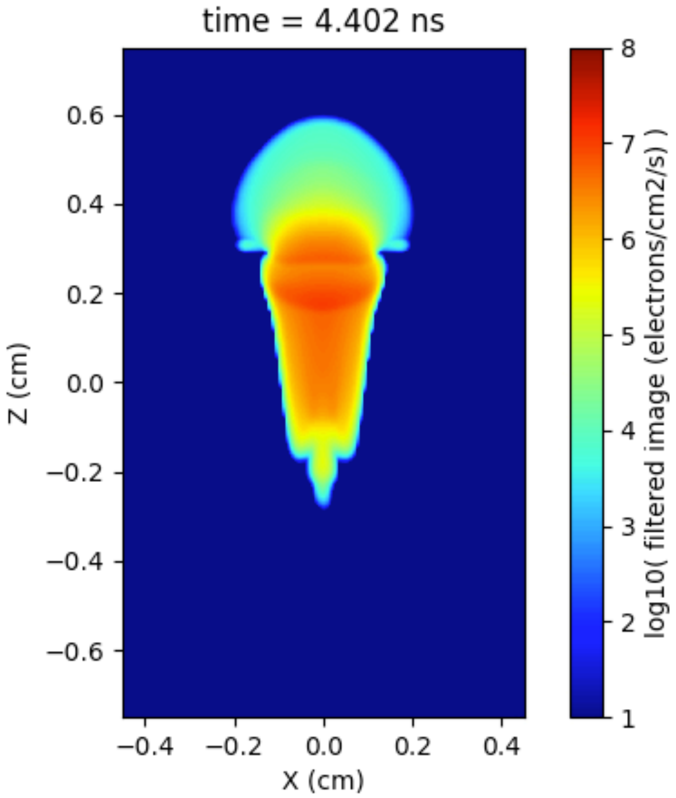
25 um aluminized kapton filter channel on GXD

The warm target platform has been extended to 3.9 gm/cc (16% n_e/n_{cr}), where the data leads the simulations

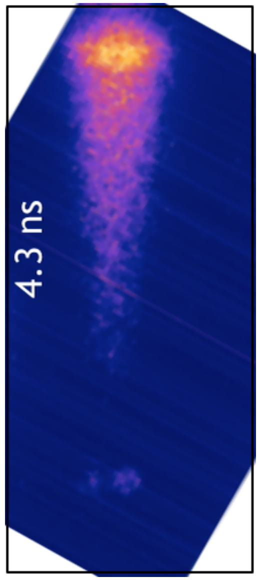


Cryogenic D2 shots

2 atm, 10% ne/ncr,
3.2 mg/cc + 2% Ne



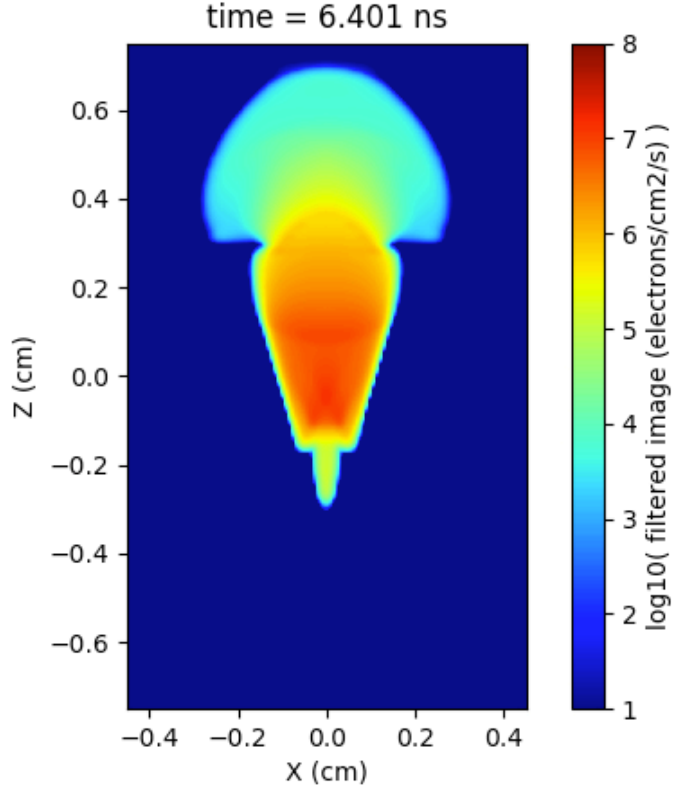
burn through @ 7.4 ns



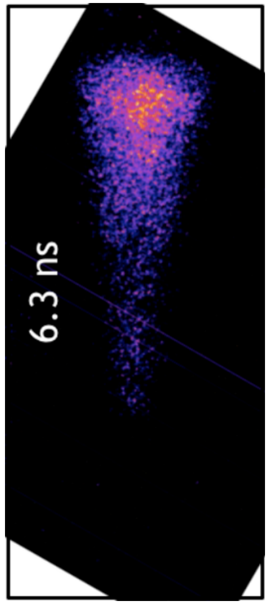
@ 6.3 ns

@ 10 ns, end of pulse
21 kJ total in laser
15 kJ in gas, 1.5 kJ in window
negligible SBS and SRS

3 atm, 16% ne/ncr,
4.8 mg/cc + 2% Ne



burn through @ 9.2 ns



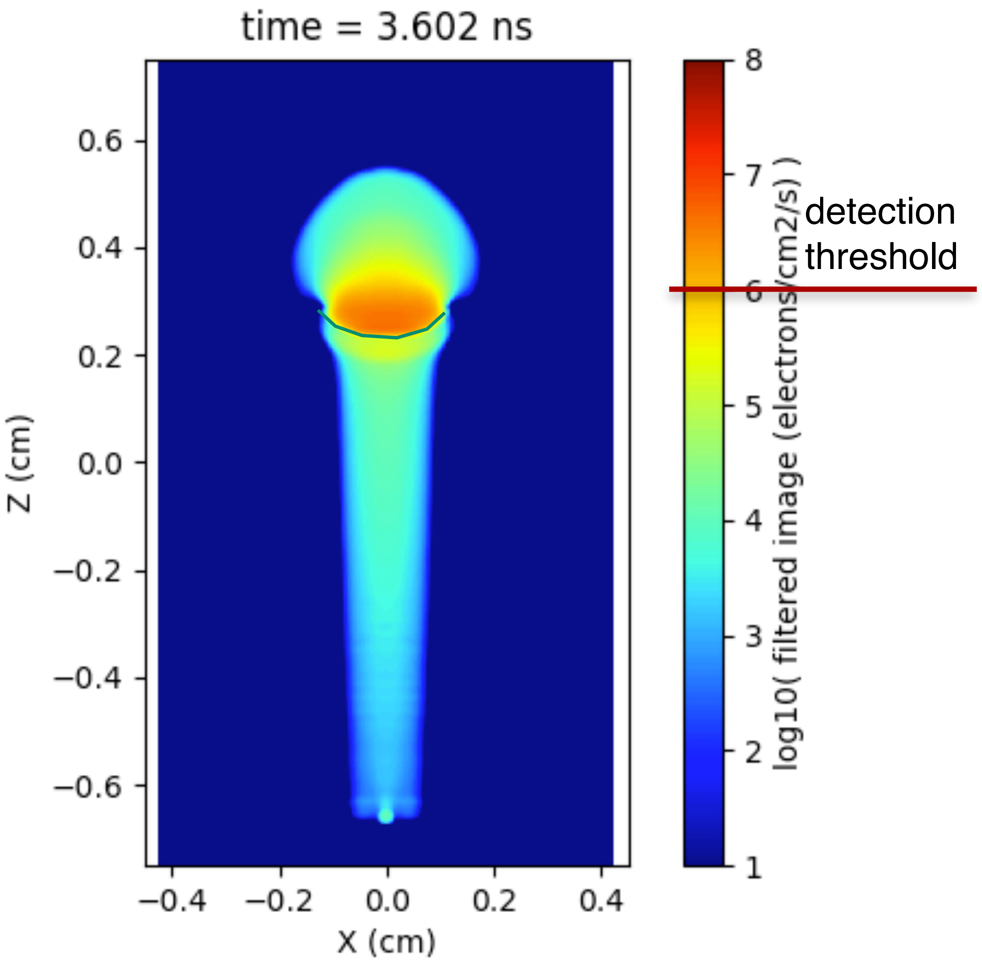
@ 8.3 ns

@ 10 ns, end of pulse
21 kJ total in laser
17 kJ in gas, 2.0 kJ in window
minimal SBS and SRS

More details on the underlying simulations

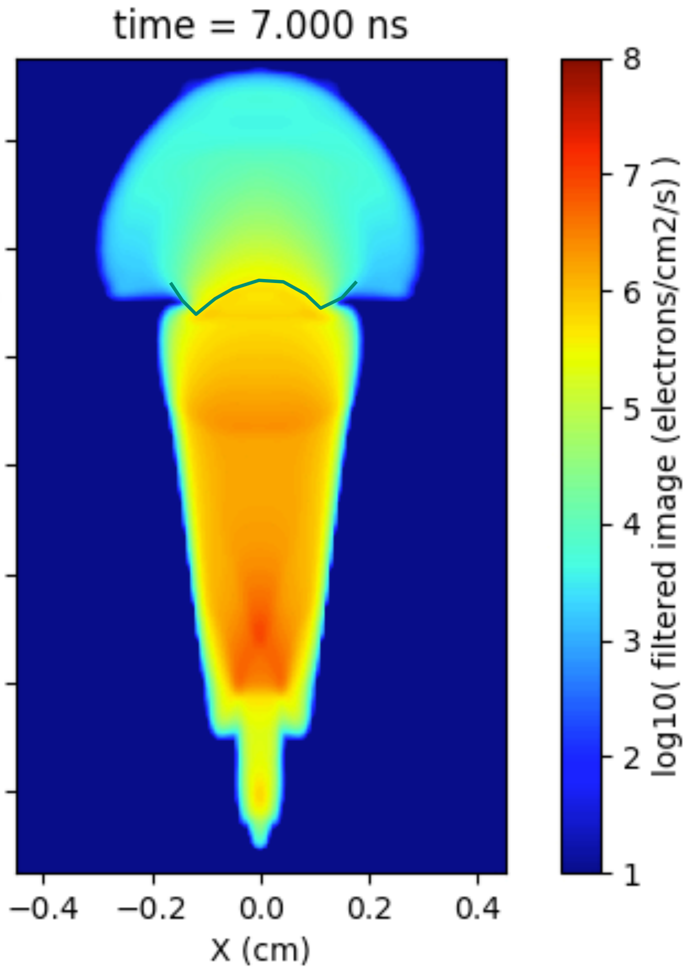
Three D2 shots to date, synthetic x-ray self emission image

1 atm, 5% n_e/n_{cr},
1.6 mg/cc



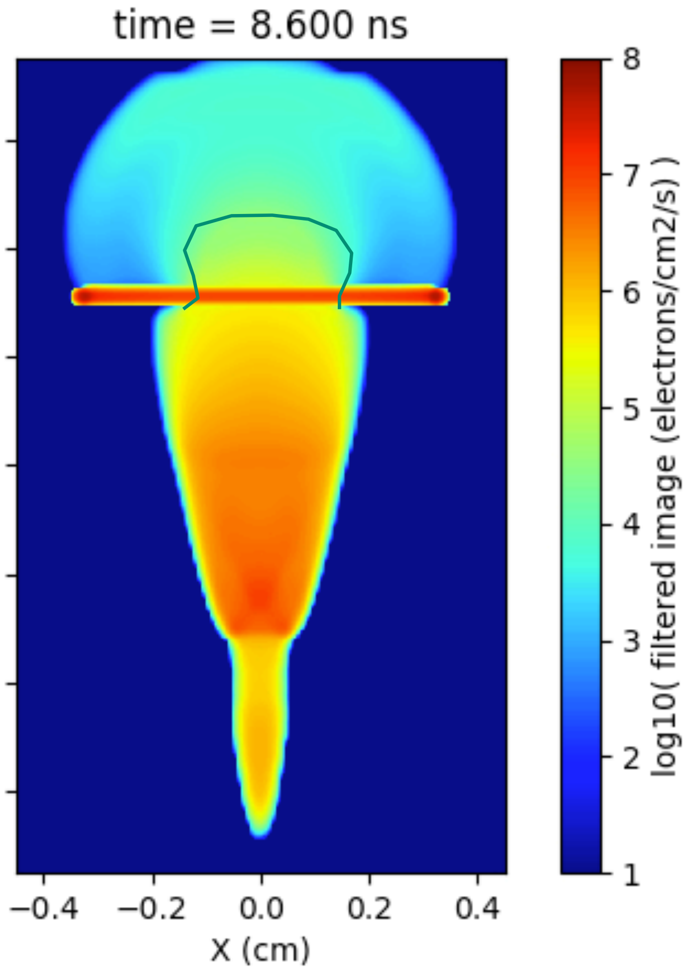
burn through @ 4.0 ns

2 atm, 10% n_e/n_{cr},
3.2 mg/cc + 2% Ne



@ 7.4 ns

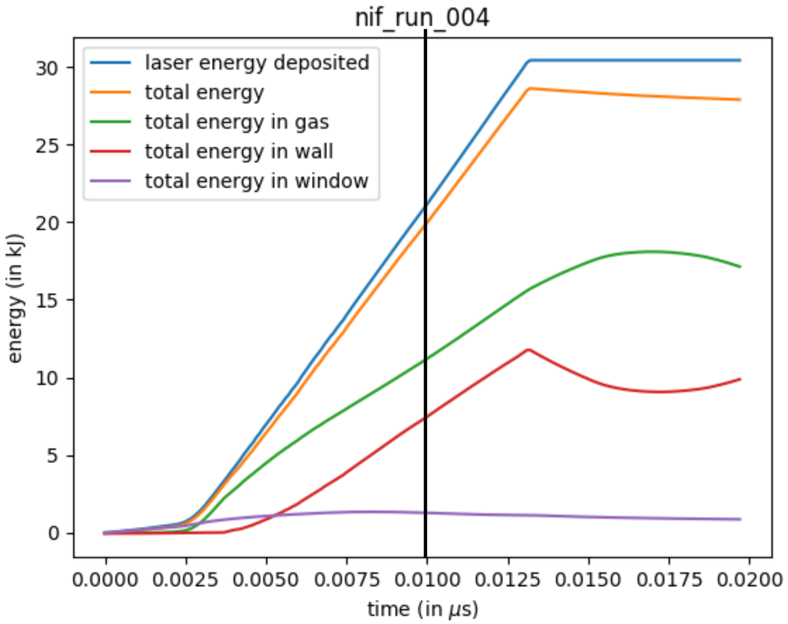
3 atm, 16% n_e/n_{cr},
4.8 mg/cc + 2% Ne



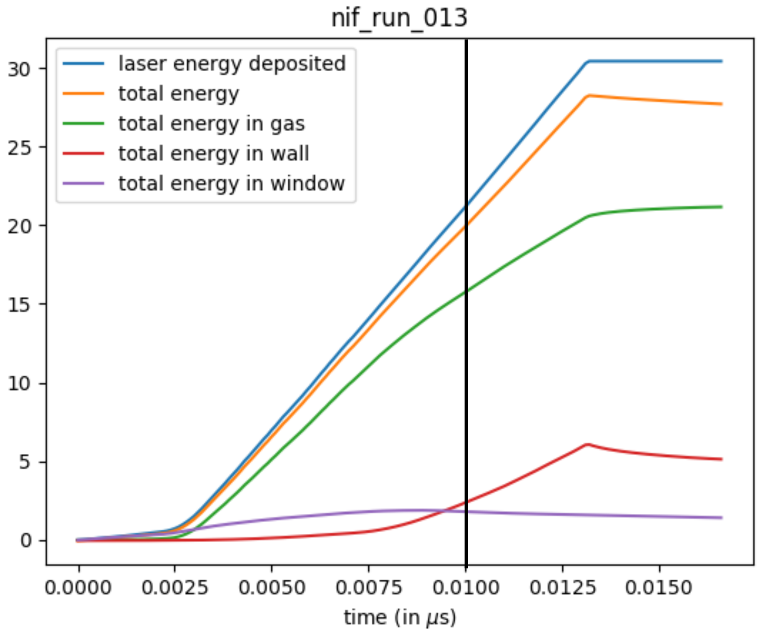
@ 9.2 ns

Energy accounting of shots to date, more energy into gas as density increases

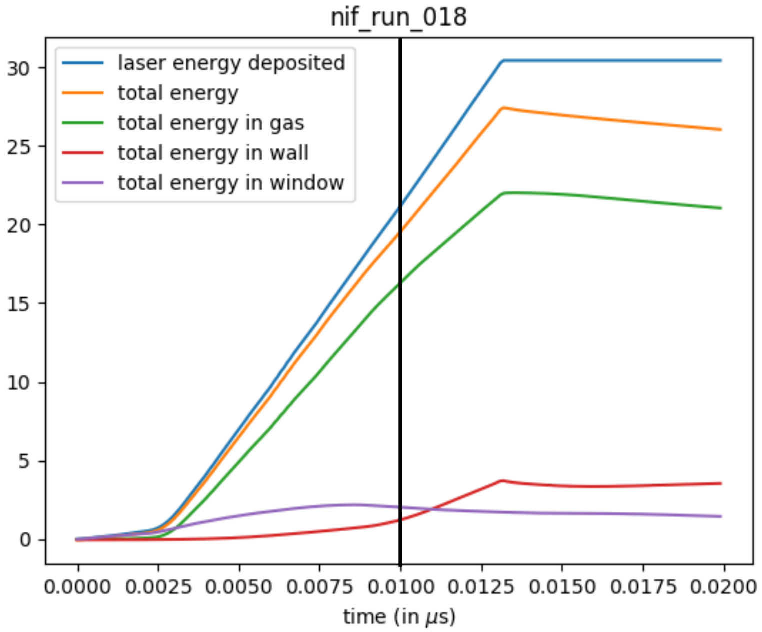
1.6 mg/cc **D2**



3.2 mg/cc **D2** + 2% Ne



4.8 mg/cc **D2** + 2% Ne



21.1 kJ in 10 ns delivered laser energy

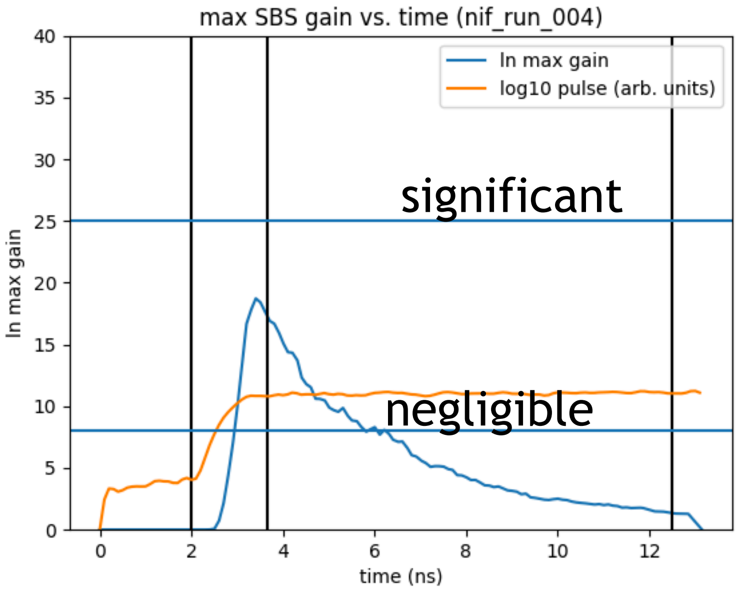
22 kJ / 30 kJ (73%) @ 13 ns

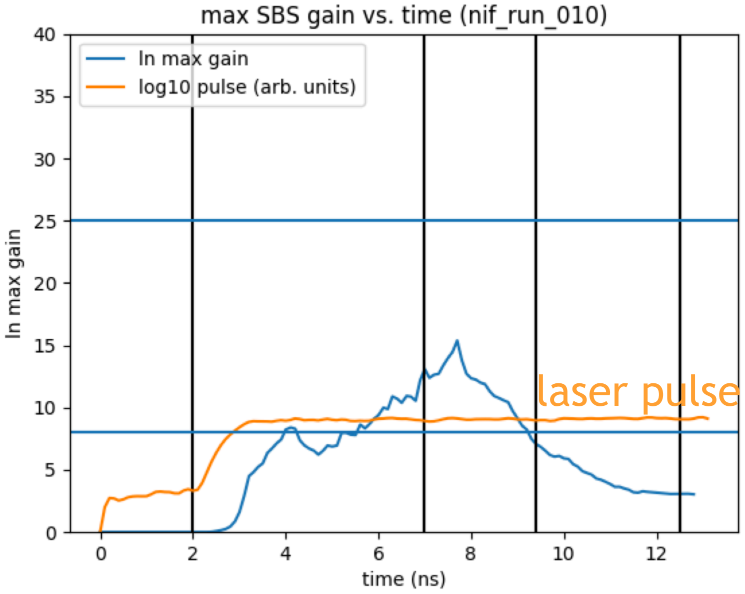
11.2 kJ in gas (53%)
1.2 kJ in window (6%)
7.5 kJ out the back (36%)
750 eV gas temperature

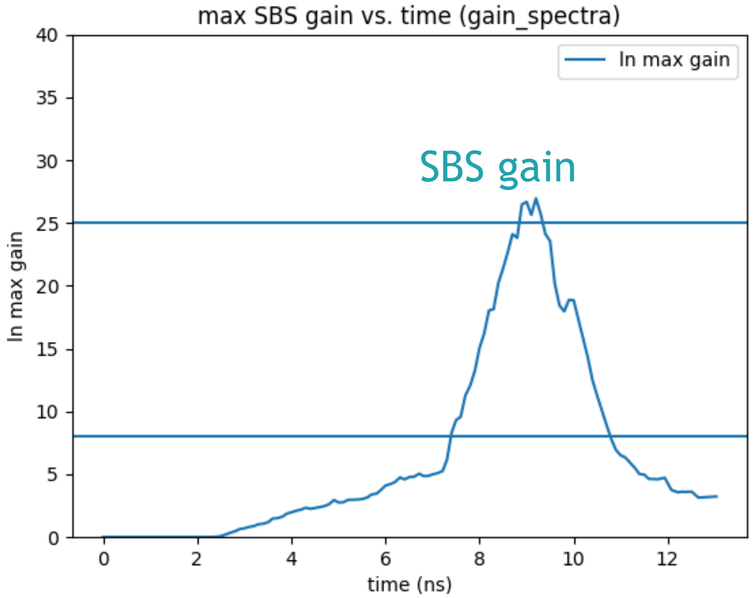
15.7 kJ in gas (74%)
1.7 kJ in window (8%)
2.3 kJ out the back (11%)
1500 eV gas temperature

16.3 kJ in gas (77%)
2.0 kJ in window (9%)
1.2 kJ out the back (6%)
1250 eV gas temperature

LPI threshold: SBS backscatter from Refractive Self Intensification is expected to become significant at 4.8 mg/cc



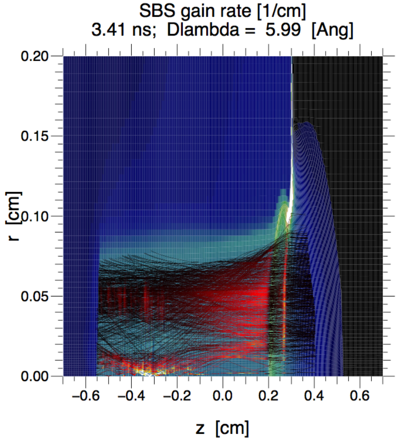


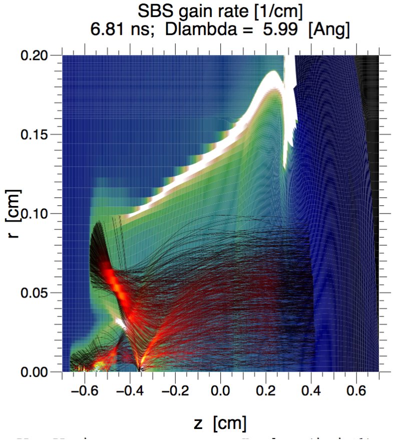


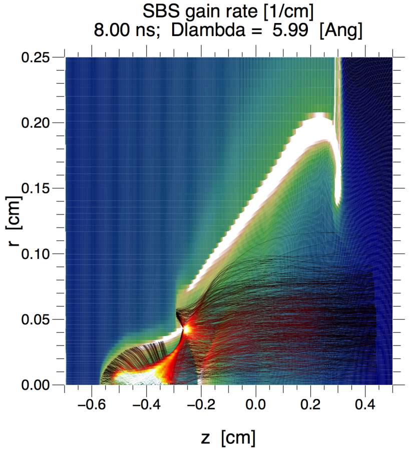
1 atm, 5% ne/ncr, 1.6 mg/cc

2 atm, 10% ne/ncr, 3.2 mg/cc

3 atm, 16% ne/ncr, 4.8 mg/cc



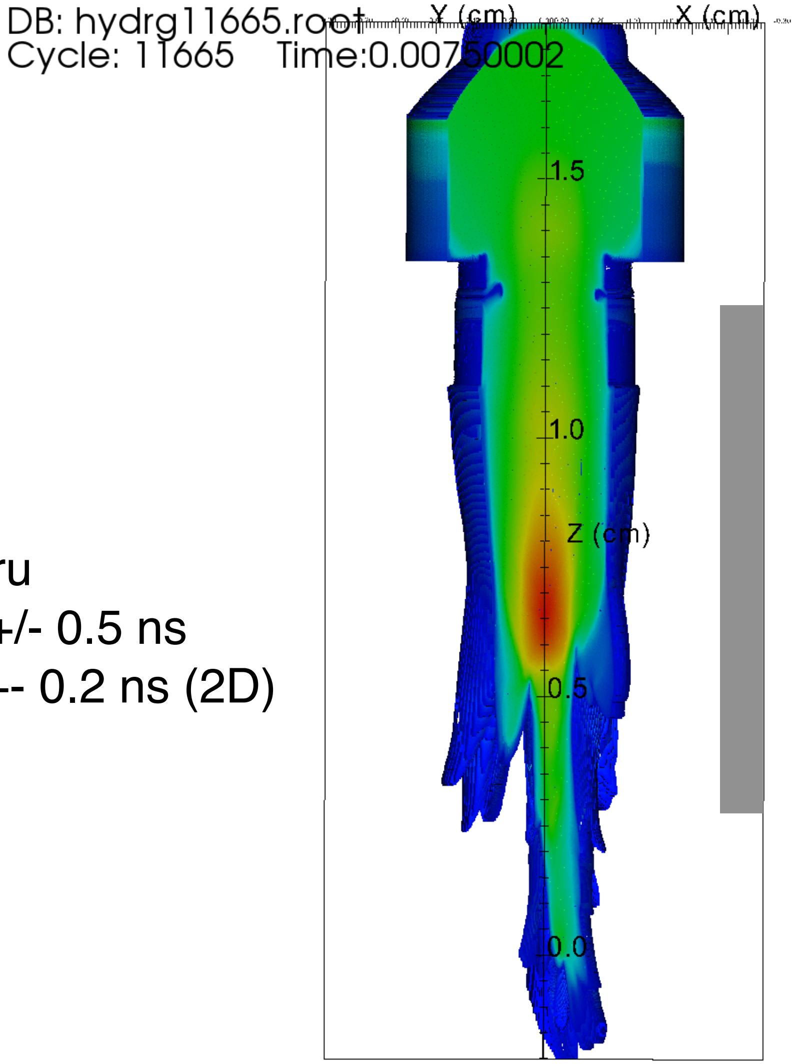




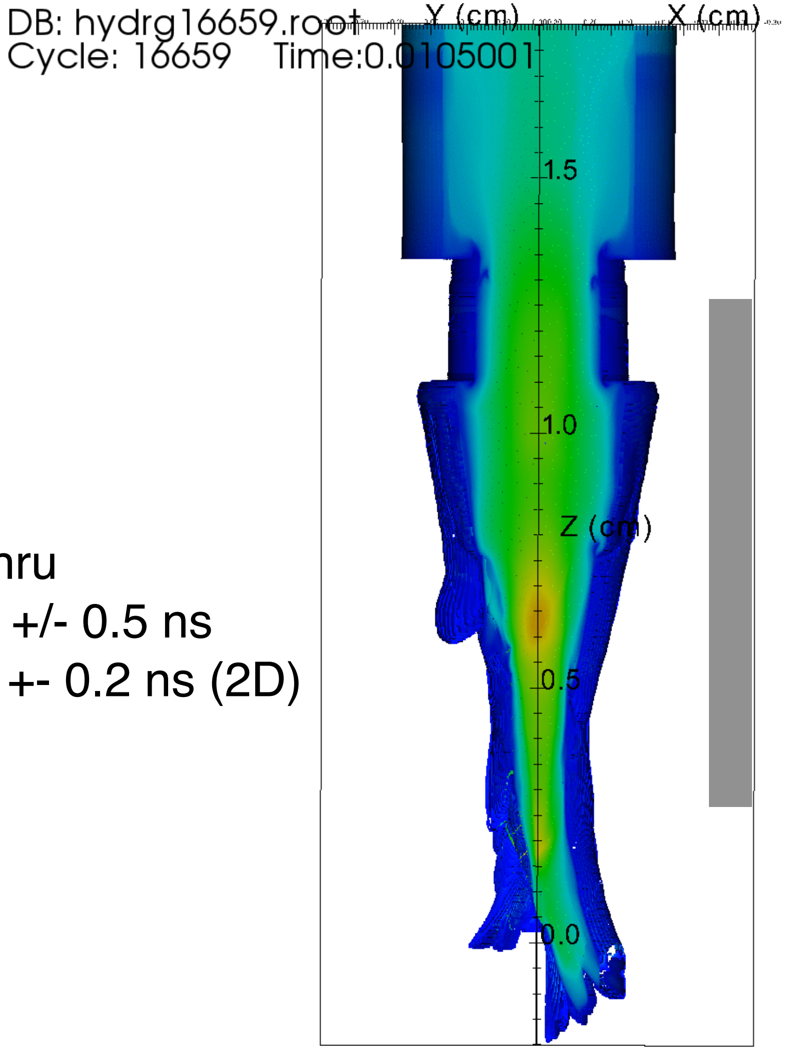
laser

3D effect on cyro D2: accretes propagation speed (as observed) and filaments the beam preventing refractive self intensification and resulting SBS (as observed)

D2
2 atm
burn thru
~ 6 ns +/- 0.5 ns
vs 7.4 +- 0.2 ns (2D)



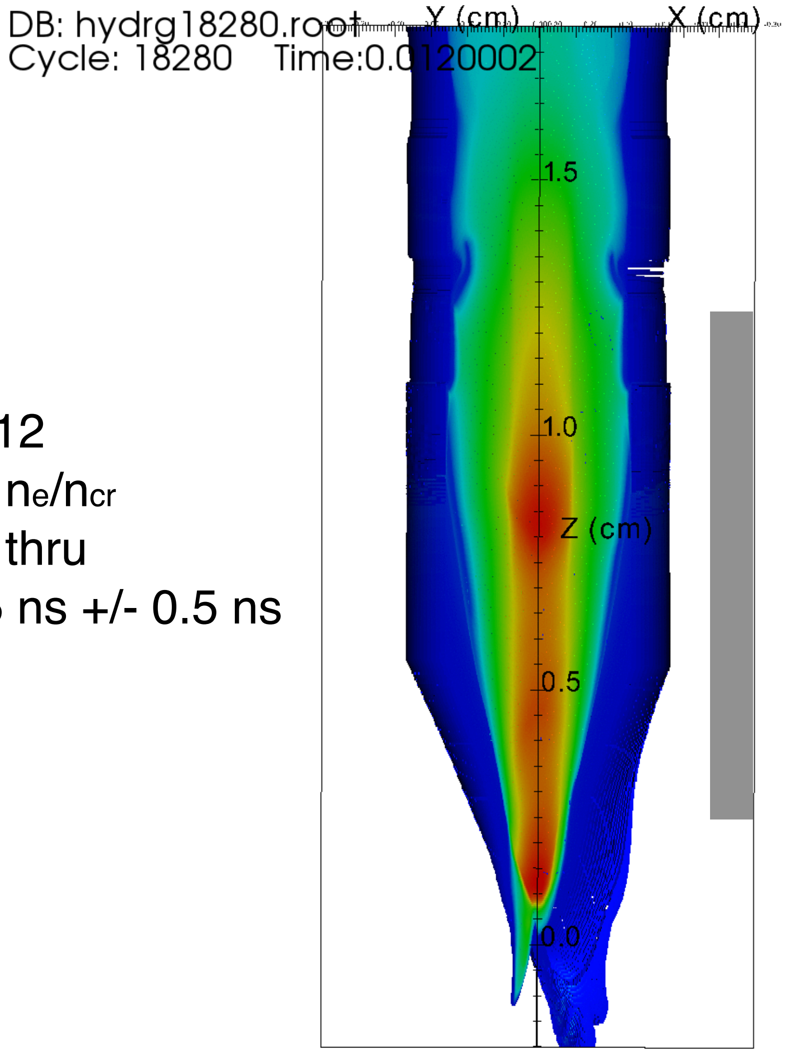
D2
3 atm
burn thru
~ 8 ns +/- 0.5 ns
vs 9.2 +- 0.2 ns (2D)



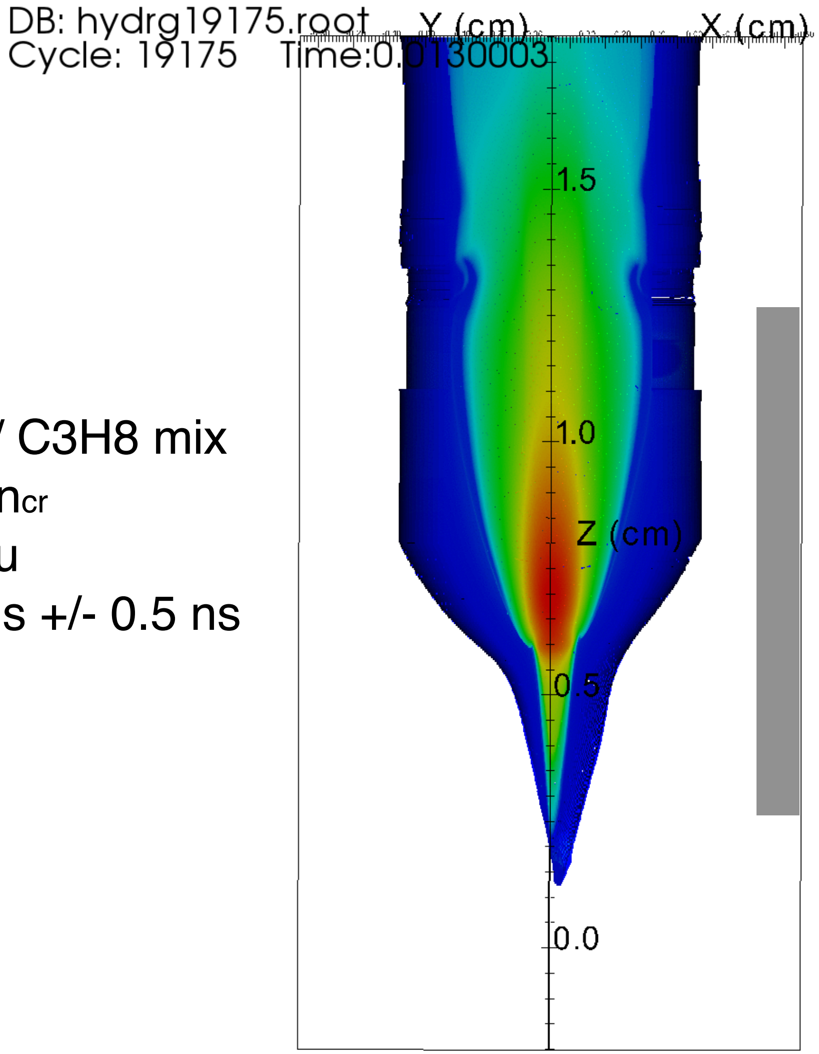
note: large scale filementation, probably more speckle scale, faster propagation

3D effects on warm C5H12: none

C5H12
12% n_e/n_{cr}
burn thru
~ 8.5 ns +/- 0.5 ns



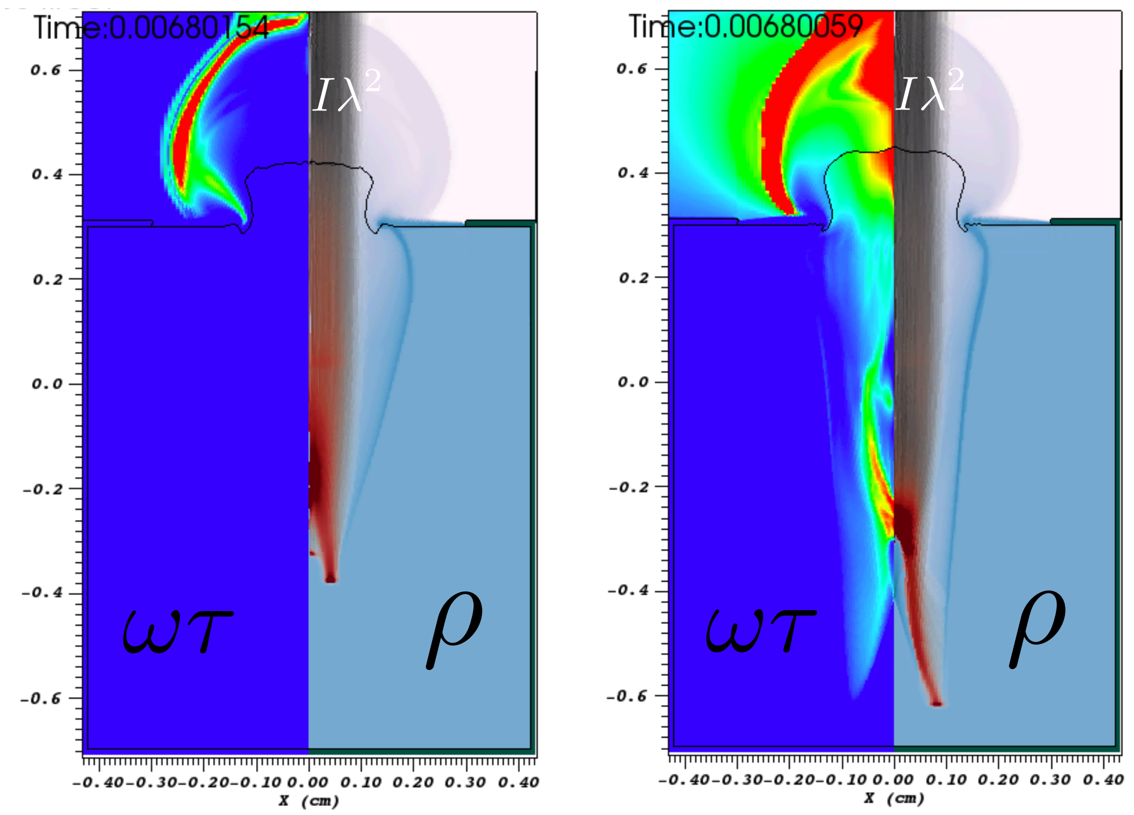
C5H12 / C3H8 mix
16% n_e/n_{cr}
burn thru
~ 13.5 ns +/- 0.5 ns



note: no noticeable filementation, large scale refractive (thermally driven) self intensification

Proton radiography, plenty of structure to see

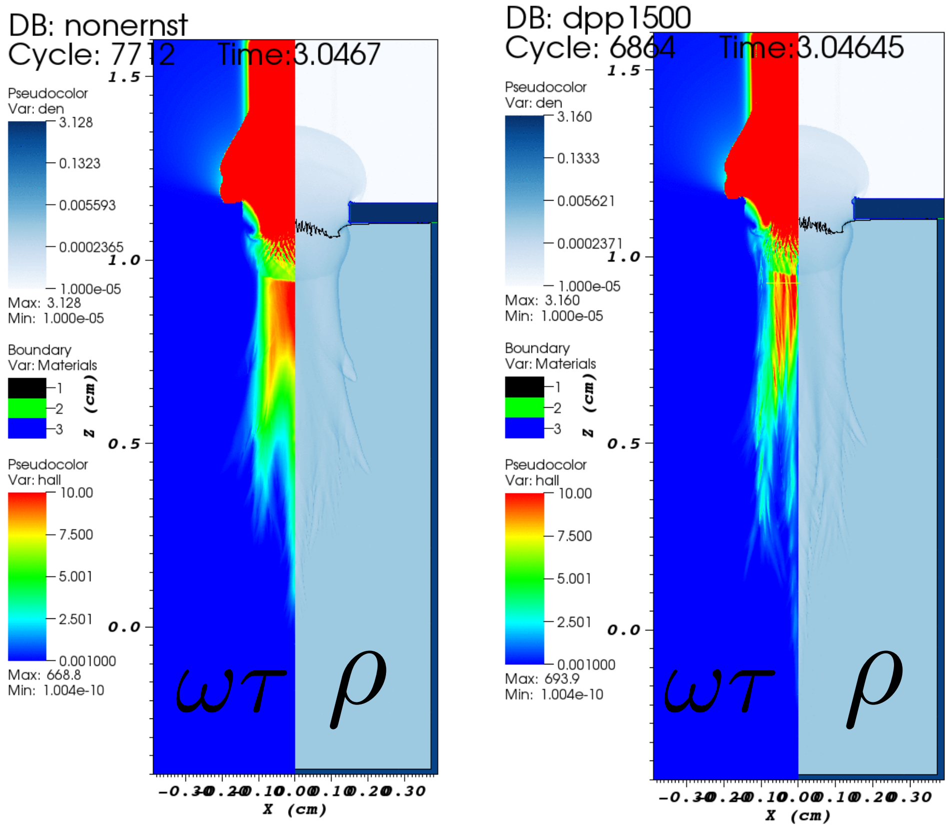
Bz = 0.5 T **Bz = 30 T**



2.9 mg/cc **C5H12**

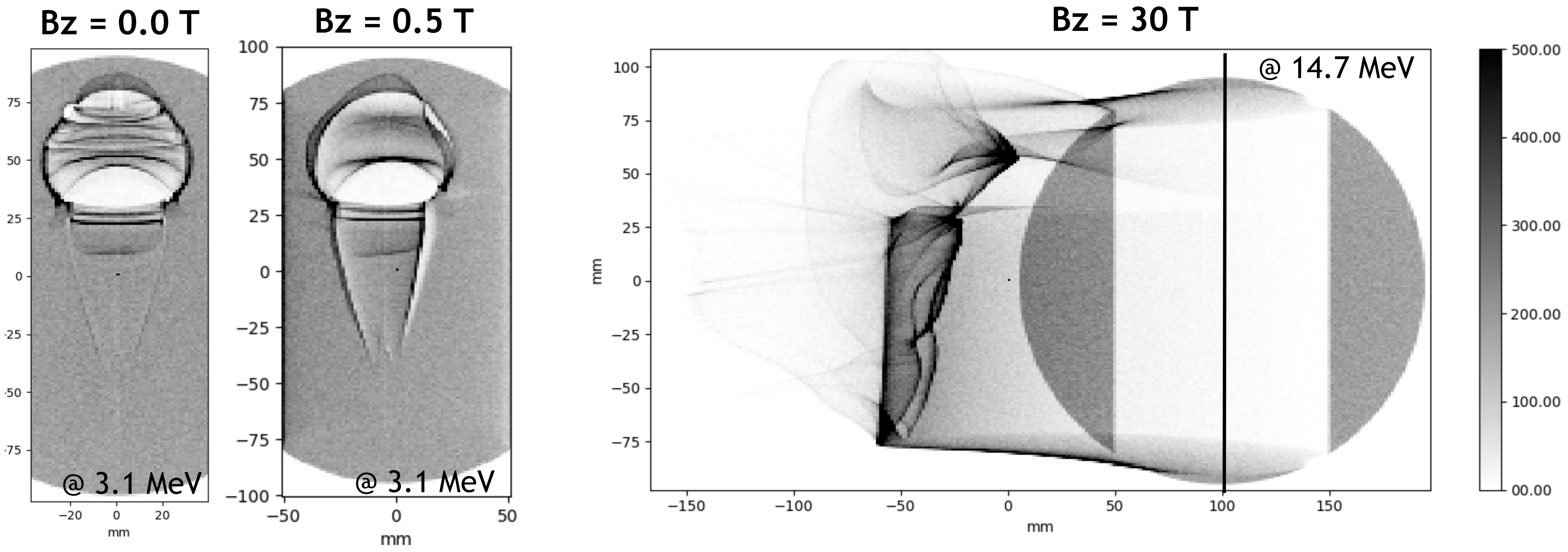
Bz = 15 T, ZBL 2.6 kJ pulse

no Nernst **w/ Nernst**



1.0 mg/cc **D2**

Potential value of proton radiography: shows density structure and B*L of applied and self generated fields



Bz = 0.0 T

Bz = 0.5 T

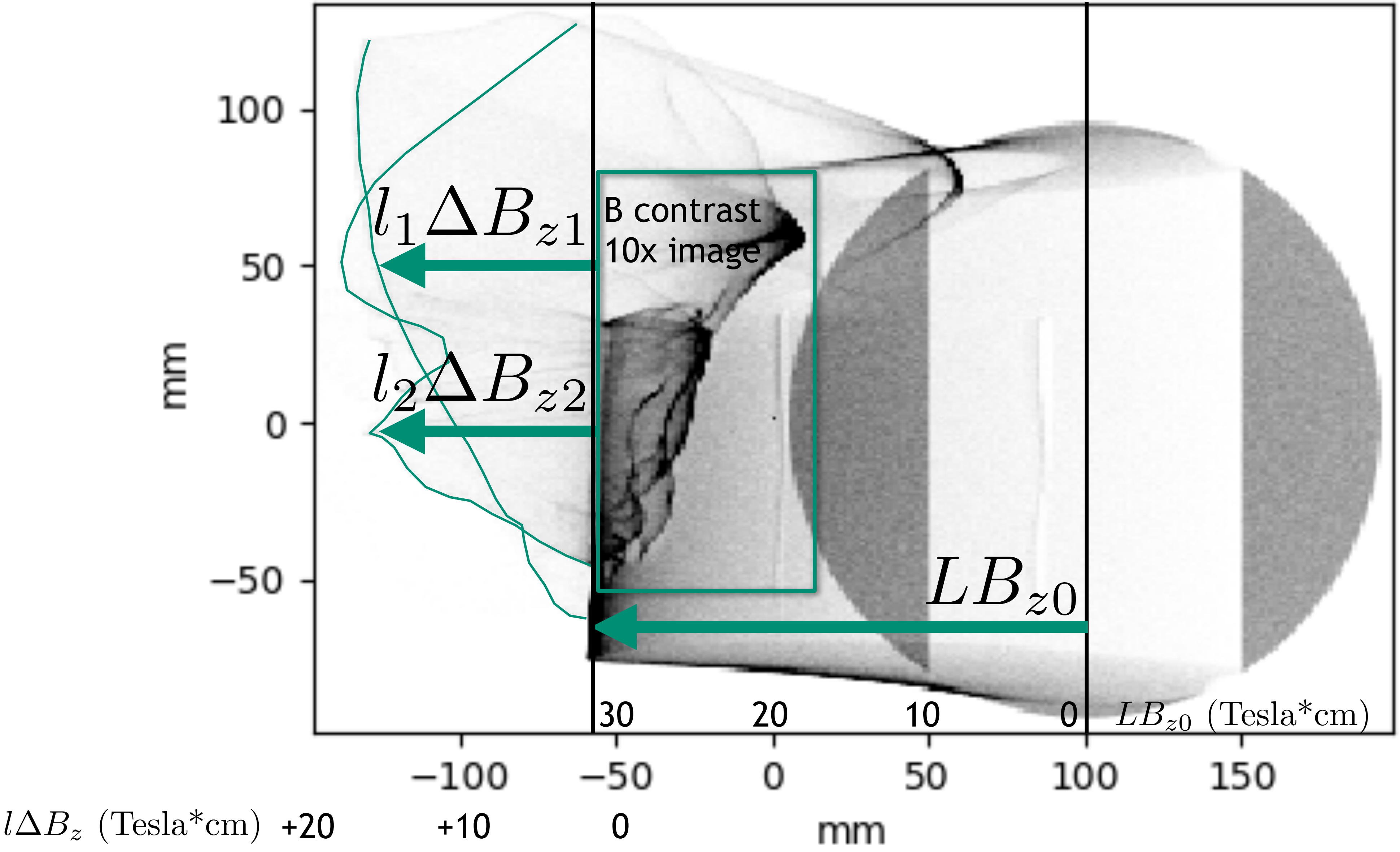
Bz = 30 T

2.9 mg/cc **C5H12** @ 6.8 ns

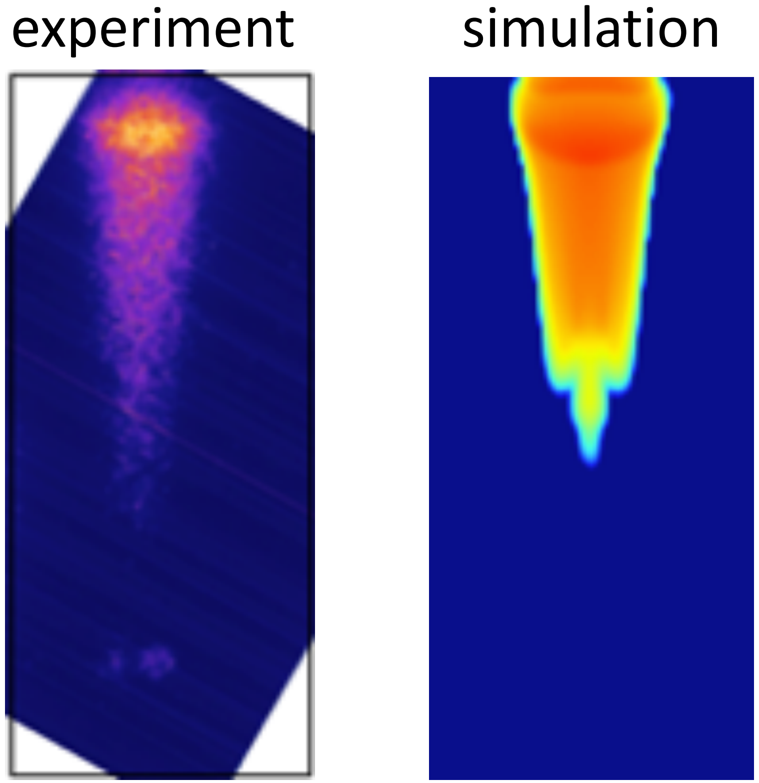
Interpretation of side on proton radiography

$L \equiv$ size of gas cell

$l \equiv$ path length over which B field is increased



Summary

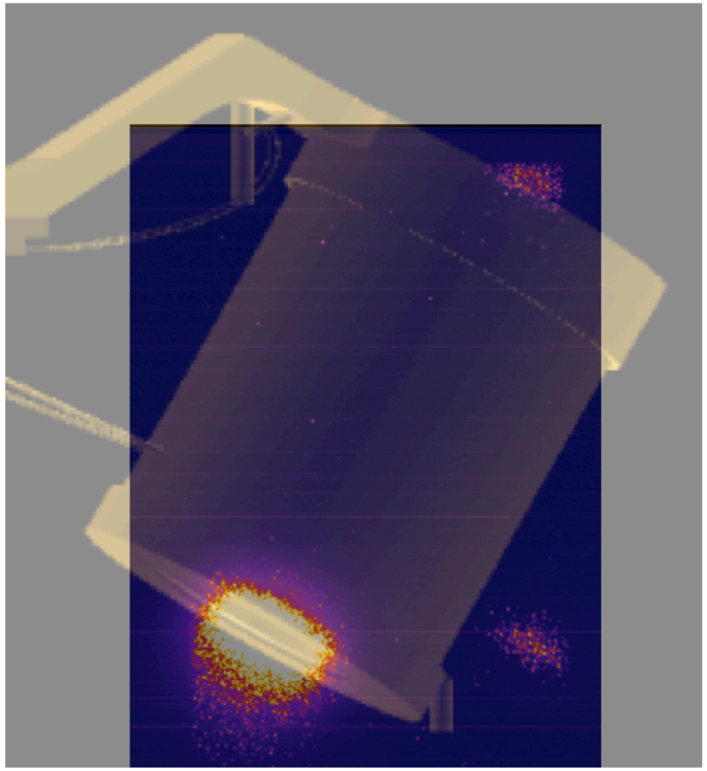


- Demonstrated 24 kJ absorption into warm hydrocarbon surrogate
- Demonstrated 16 kJ into 4.8 mg/cc D2
- Next steps: warm hydrocarbon with 30 Tesla, 22 kJ into D2, verify transport

BACKUP SLIDES

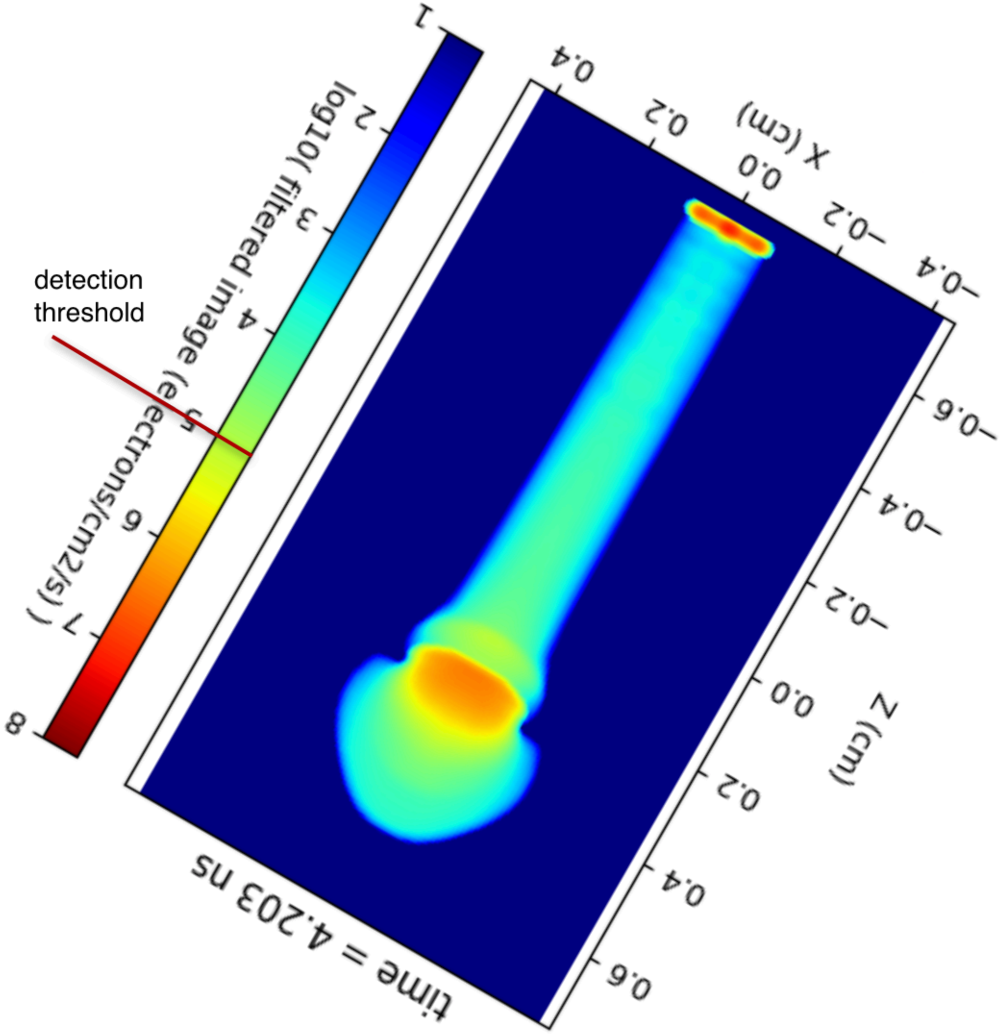
Cryogenic D2 shots, 1 atm

N170920-001
4.3 ns



1 atm 30K D2

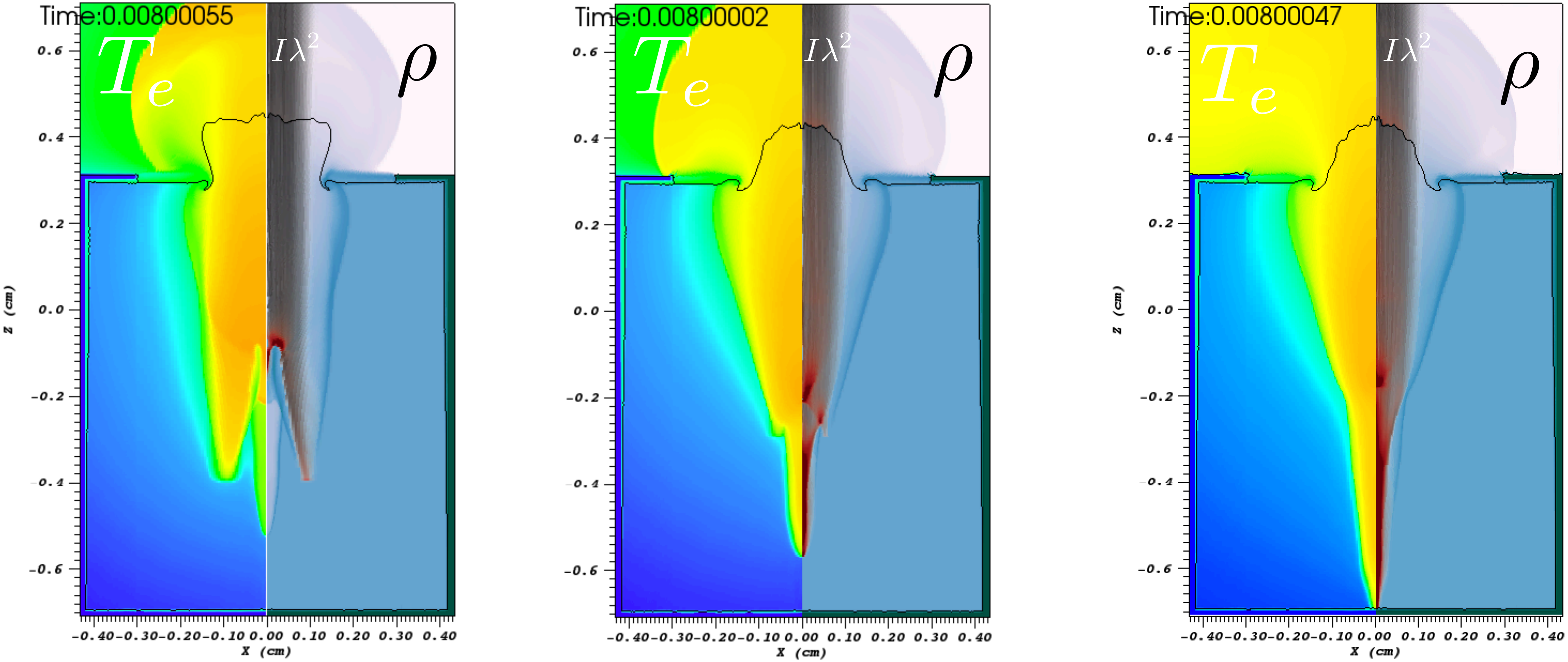
$n_e/n_{cr} = 5\%$



detection threshold

Simulation shows that thermal flux limit has significant effect on laser energy deposition

4.8 mg/cc **D2** + 2% Ne



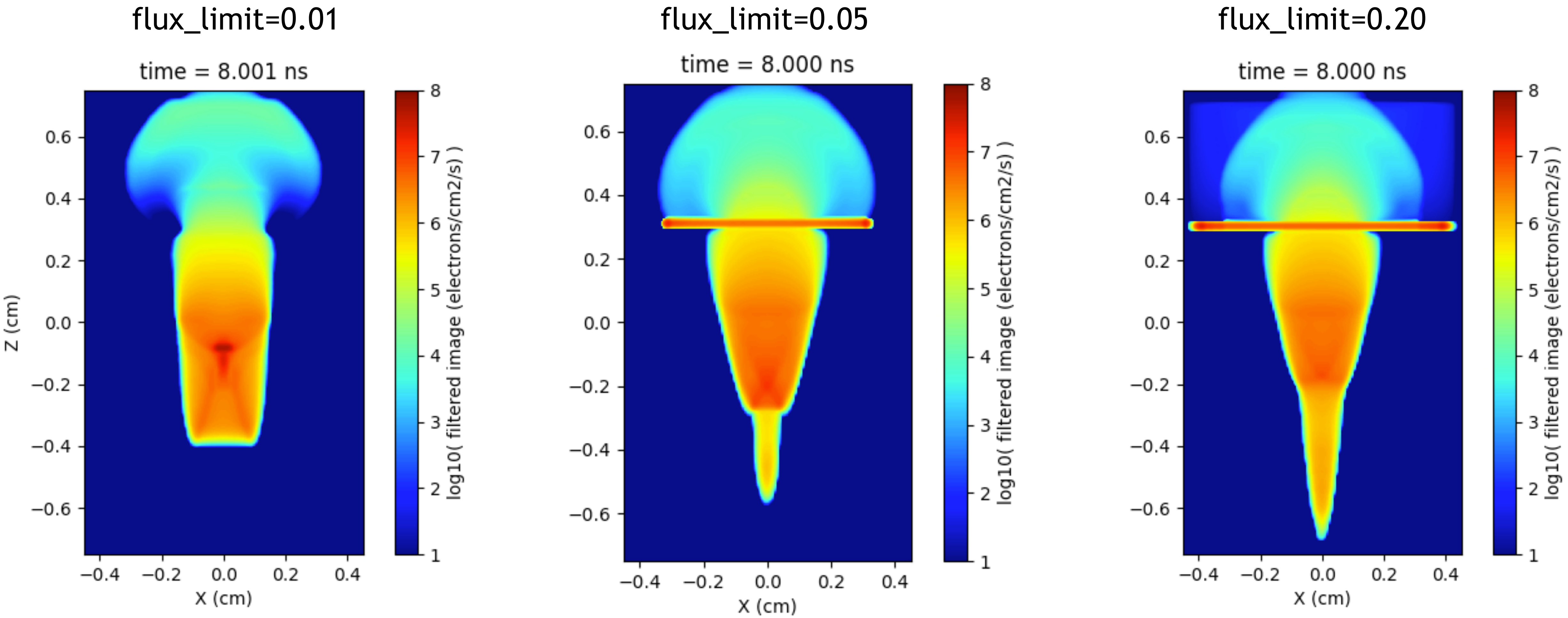
flux_limit=0.01

flux_limit=0.05

flux_limit=0.20

red is laser deposition, $\frac{dE_{\text{laser}}}{dm\,dt}$

Self emission of the flux limit scan



flux_limit=0.01

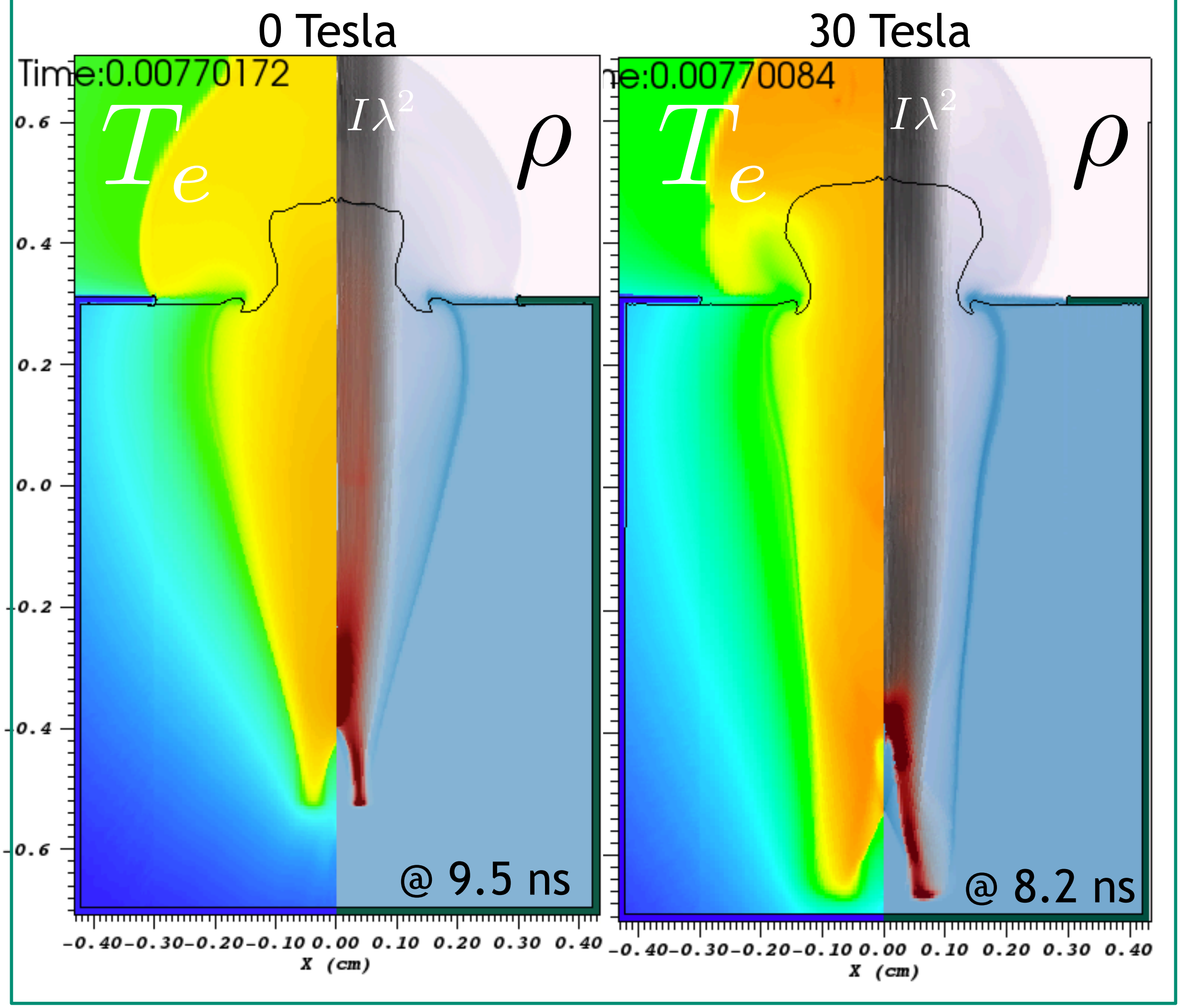
flux_limit=0.05

flux_limit=0.20

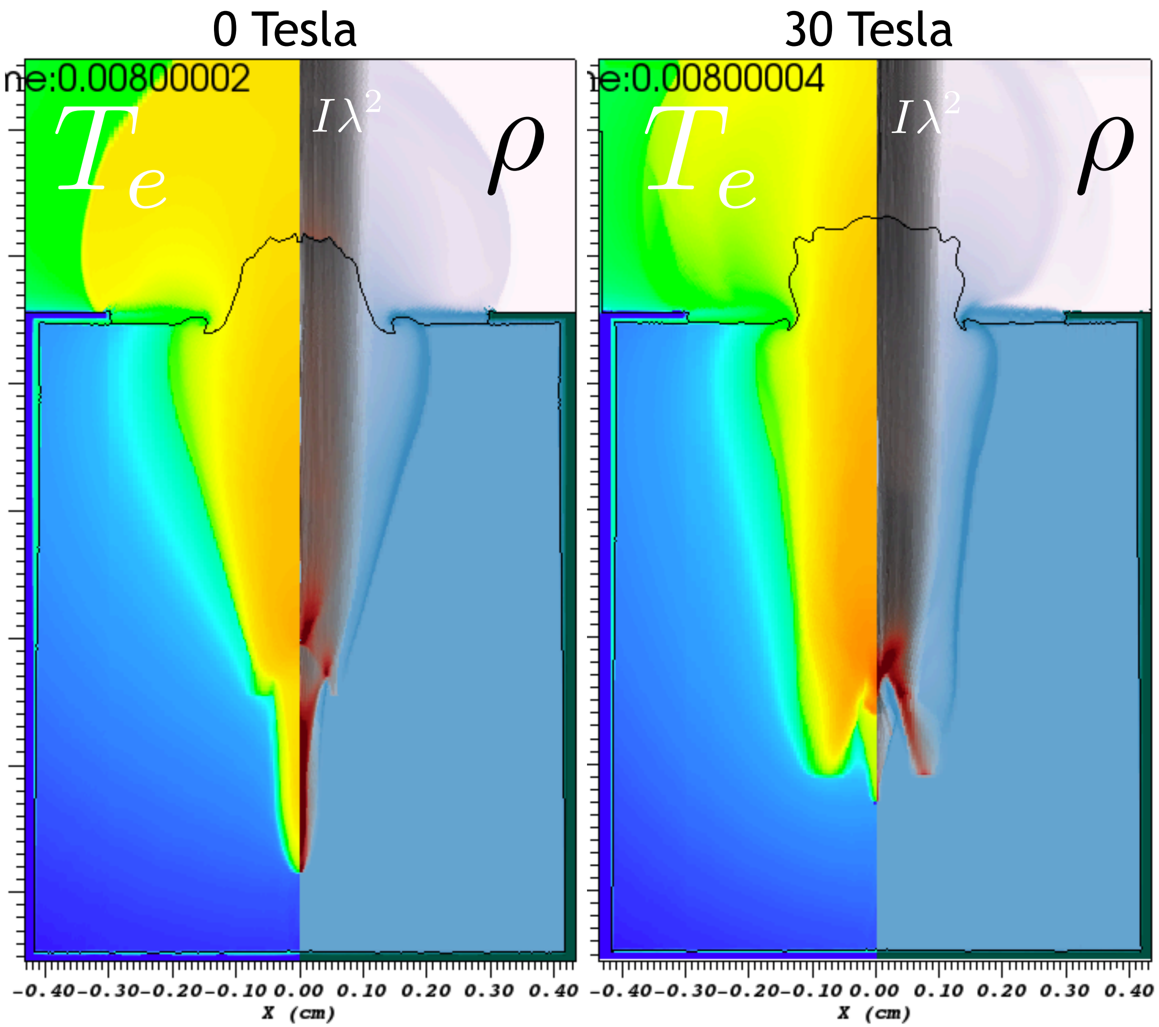
4.8 mg/cc **D2** + 2% Ne

Simulation shows that B-Field transport inhibition has significant effect on laser deposition

2.9 mg/cc **C5H12**



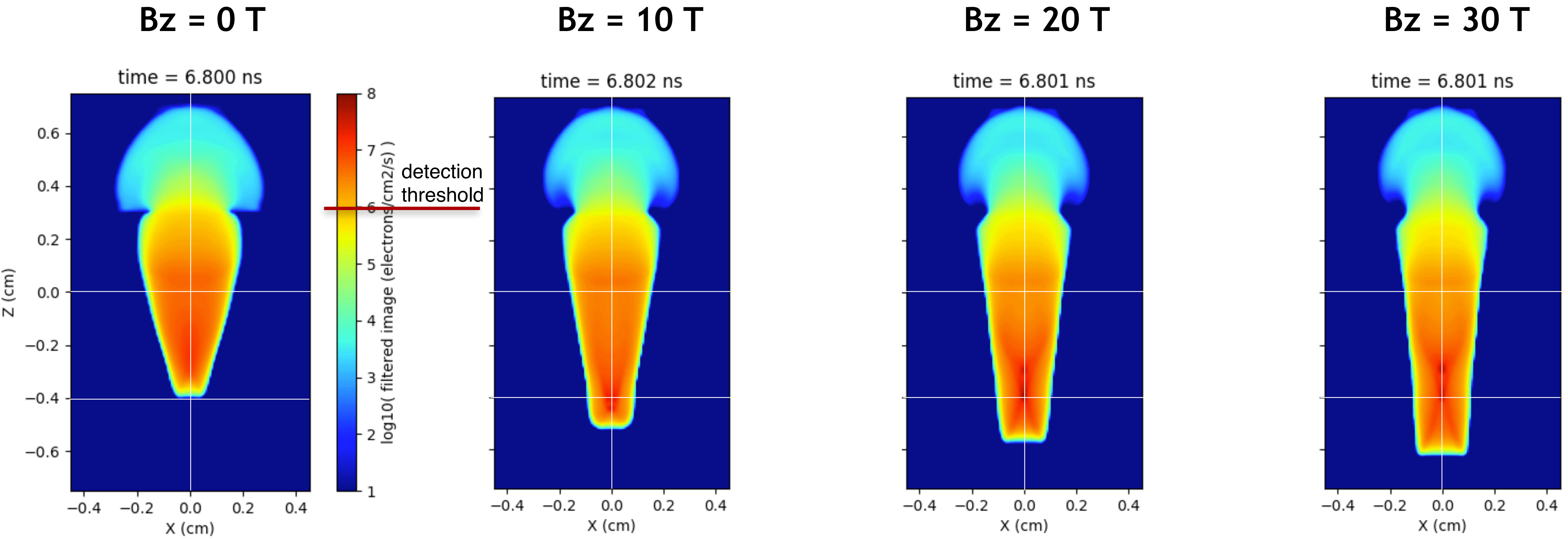
4.8 mg/cc **D2** + 2% Ne



note: B-field makes hotter and more narrow

red is laser deposition, $\frac{dE_{\text{laser}}}{dm\,dt}$

B-field scan, 1 atm C5H12 + 1 % Ar, self-emission movies

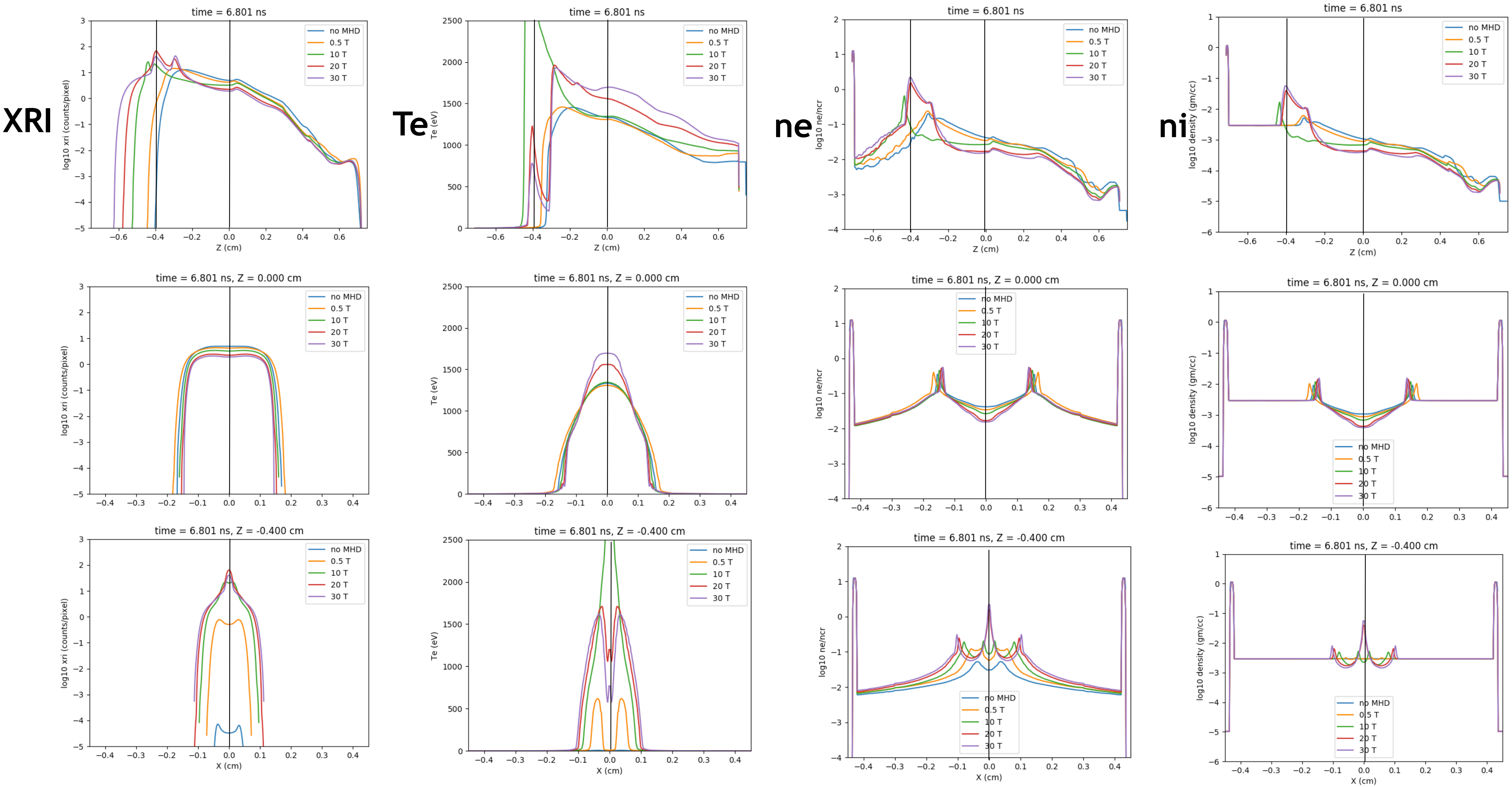


detection threshold

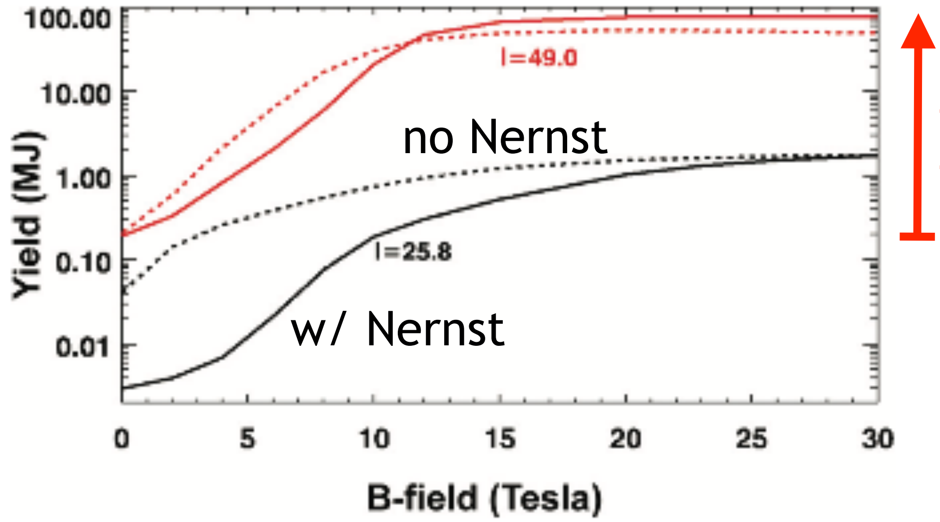
2.9 mg/cc **C5H12**

note: issue with 10 T case, blowup near washer is not real, I am also running 5 T and 15 T cases

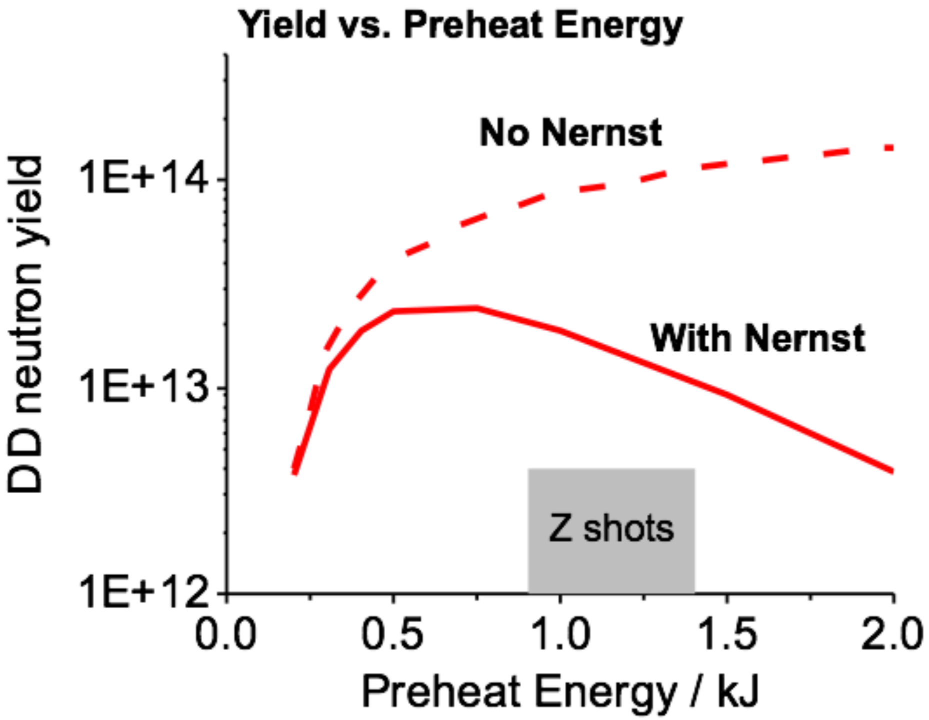
B-field scan, 2.9 mg/cc C5H12 + 1 % Ar, line out movies



Importance of transport to MagLIF performance

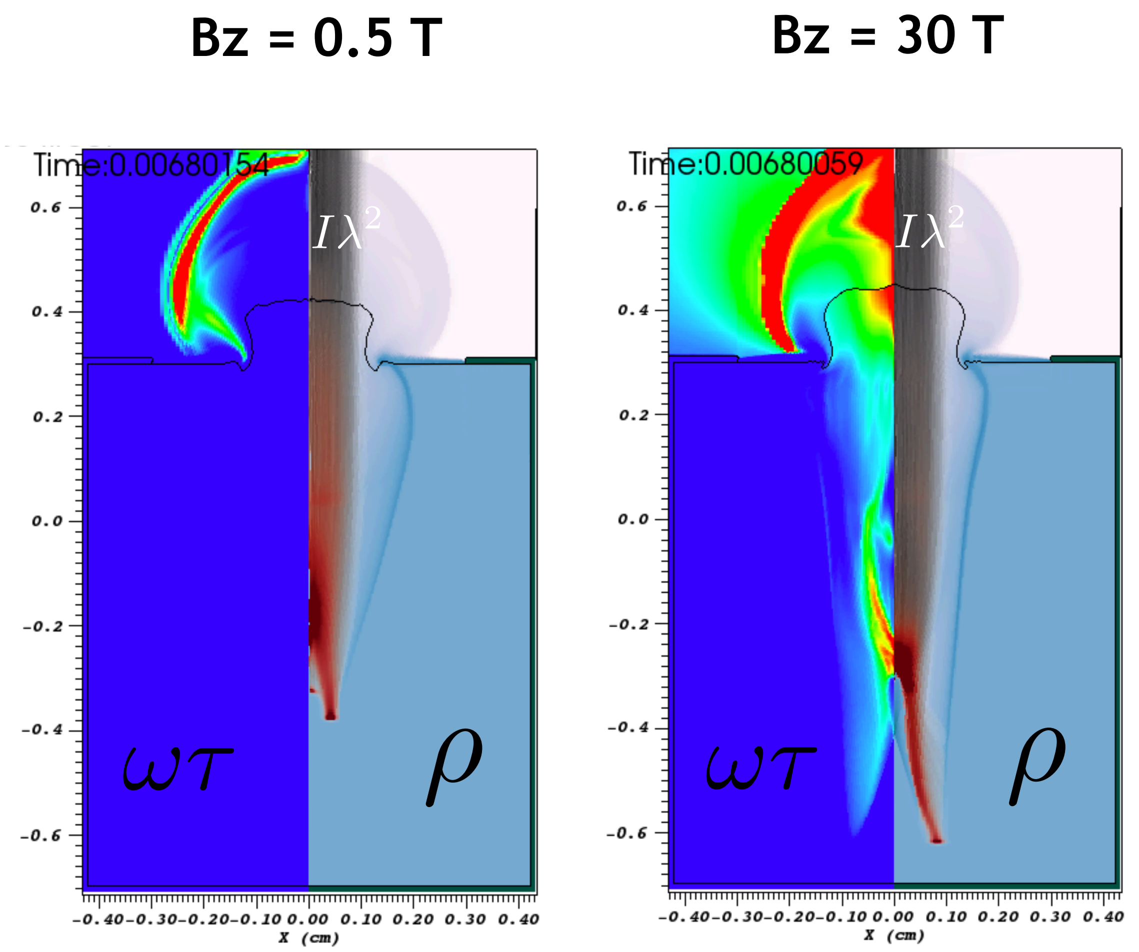


magnetic thermal flux inhibition



the impact of conventional flux limitation has not been studied, but could be significant

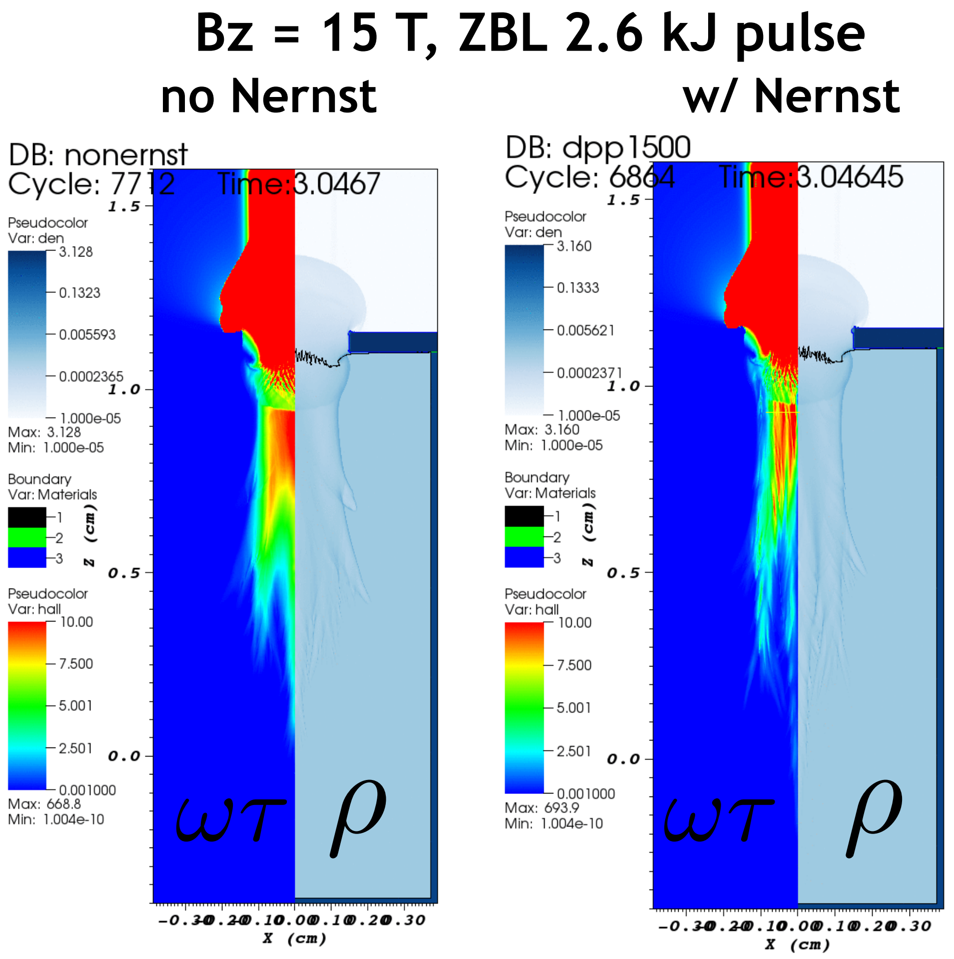
Proton radiography, plenty of structure to see



Bz = 0.5 T

Bz = 30 T

2.9 mg/cc **C5H12**



Bz = 15 T, ZBL 2.6 kJ pulse

no Nernst

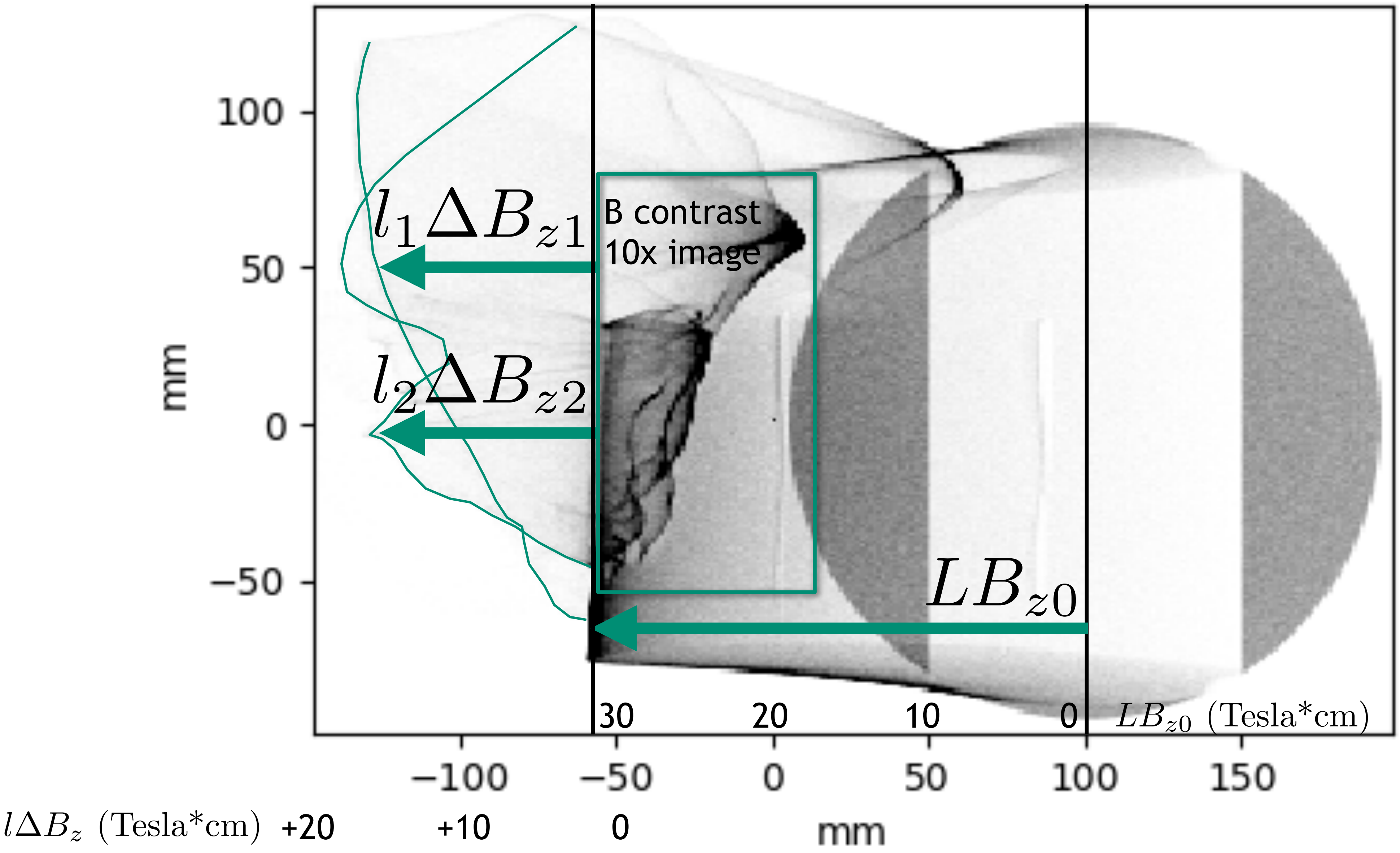
w/ Nernst

1.0 mg/cc **D2**

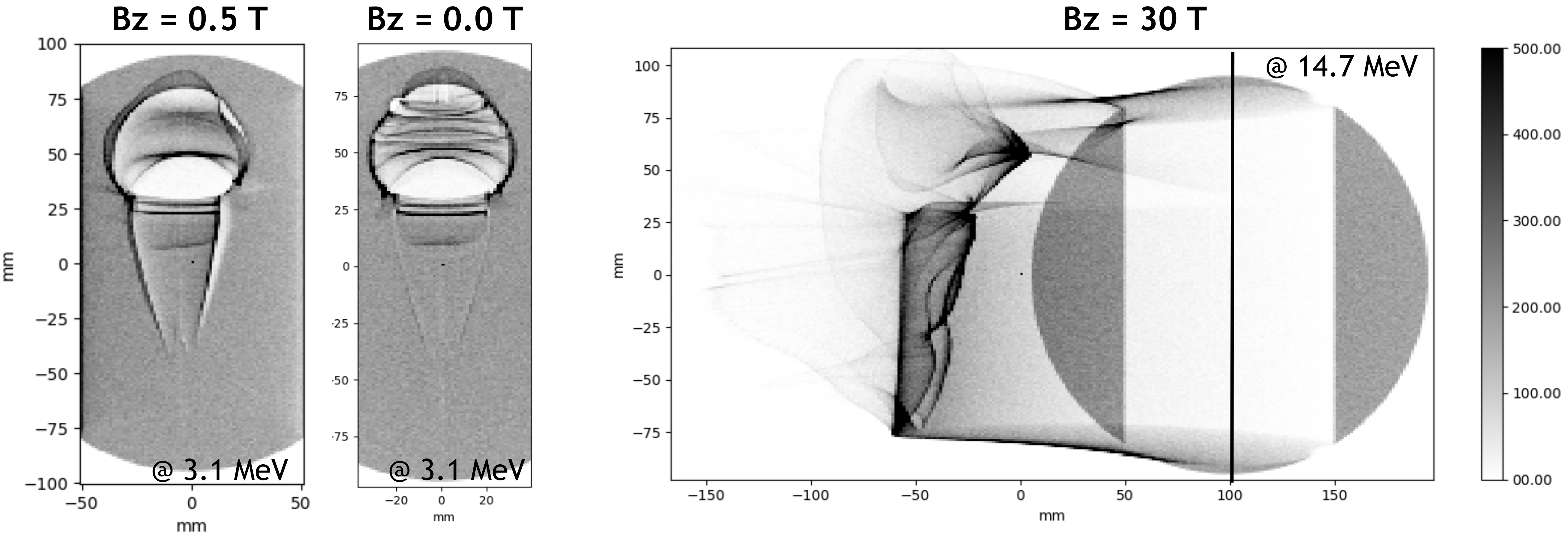
Interpretation of side on proton radiography

$L \equiv$ size of gas cell

$l \equiv$ path length over which B field is increased

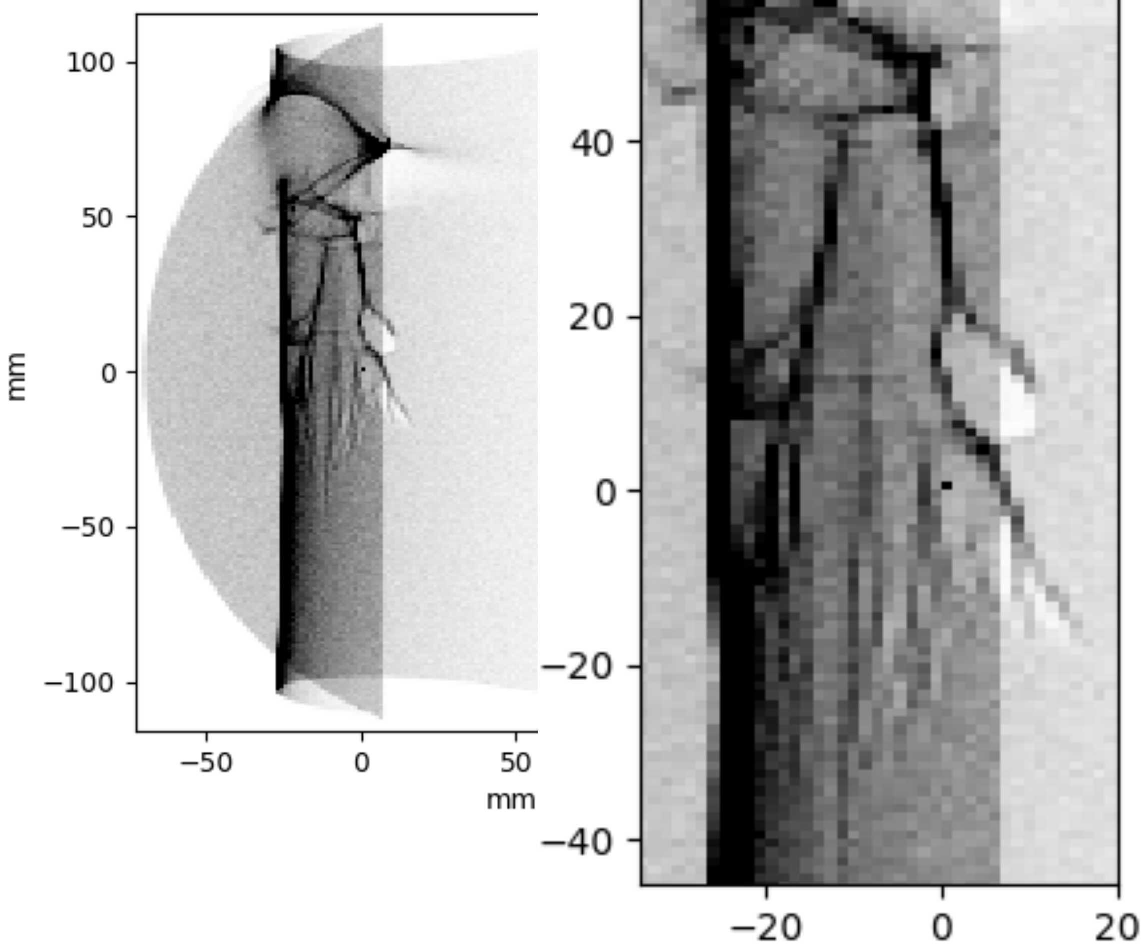


Proton radiography of C5H12

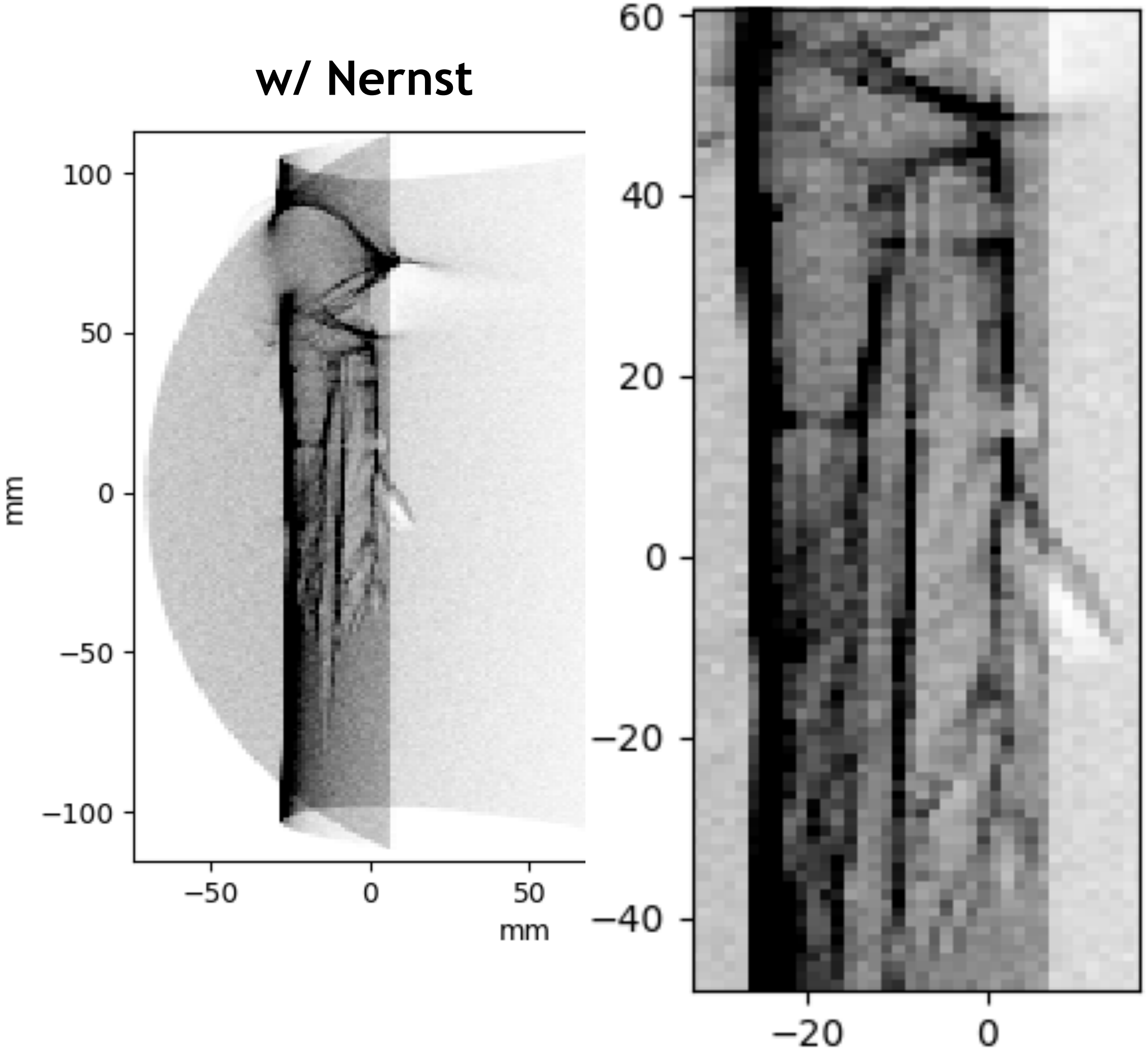


2.9 mg/cc **C5H12** @ 6.8 ns

Proton radiography, the effect of Nernst



no Nernst



w/ Nernst

Bz = 15 T, ZBL 2.6 kJ pulse

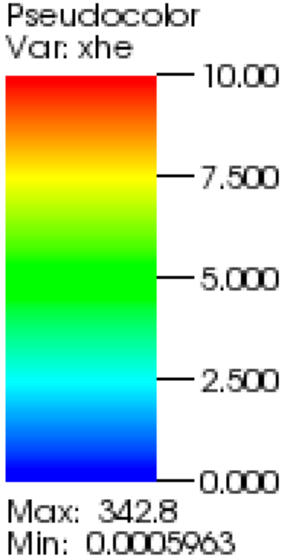
1.0 mg/cc **D2**

Summary

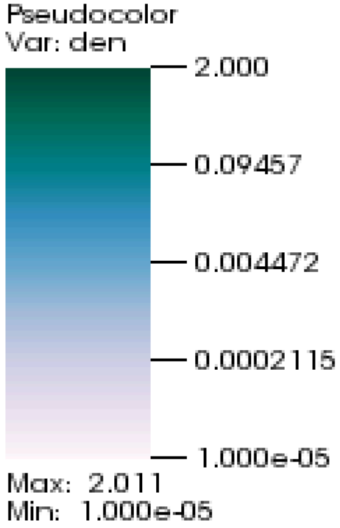
- Cryogenic, magnetized gas pipe platform developed at NIF
  - warm hydrocarbon, cryogenic D2, 1.6 gm/cc to 4.8 gm/cc (5% to 16% critical density)
  - initial axial magnetic fields up to 30 T
  - 30 kJ into 2 mm by 10 mm volume by inverse Bremsstrahlung, 11 ns, 2 TW, 2x10^{14} W/cm^2
- Diagnostics
  - x-ray self emission
  - optical Thompson scattering
  - proton radiography
  - x-ray spectroscopy
  - optical backscatter
  - VISAR
- Transport effects
  - thermal flux limitation
  - B-field flux inhibition
    - self generated fields (up to 3 T, $\omega\tau = 2$)
    - flux compressed (up to 200 T, $\omega\tau = 10$)
  - Nernst B-field transport

Colorbar scales

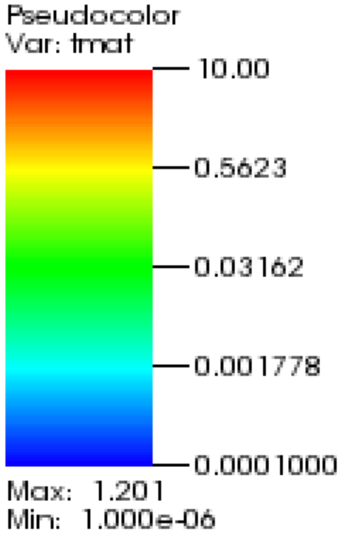
$\omega\tau$



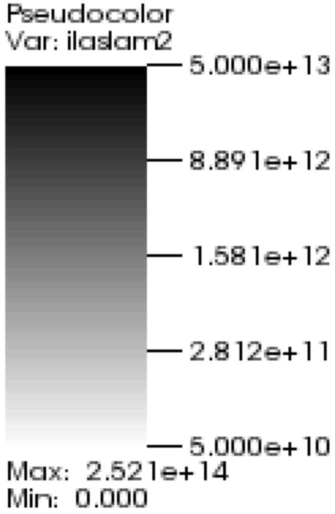
ρ (gm/cc)

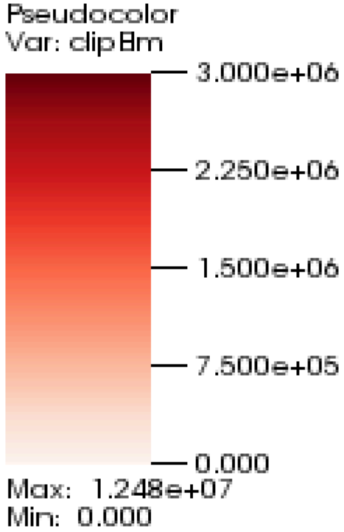


T_e (keV)

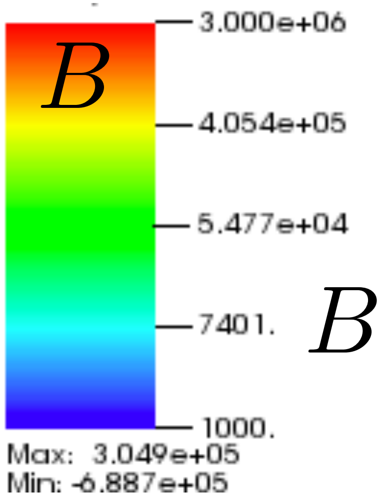


$I\lambda^2$ (W/cm^2)





B

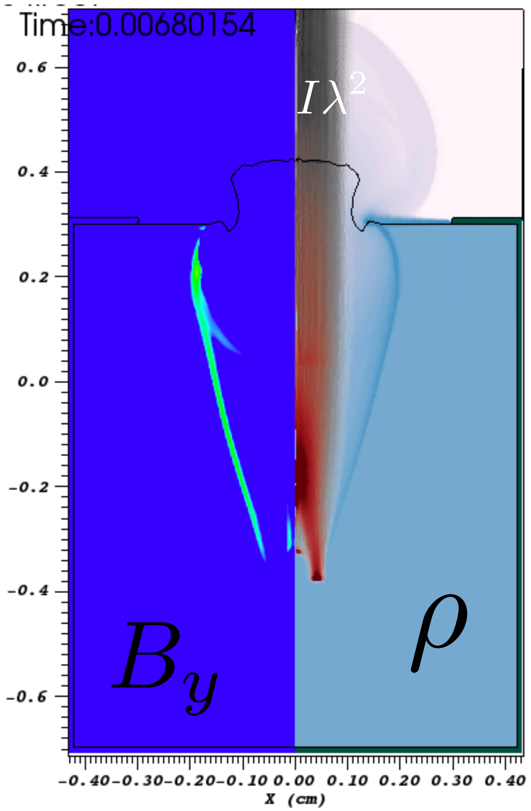


$B(G = 10^{-4}T)$

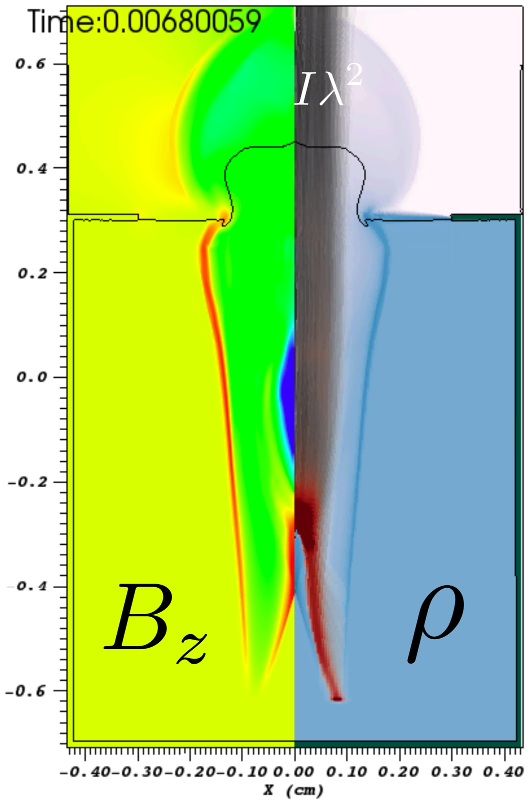
$$\frac{dE_{\text{laser}}}{dt\,dm}\ (100\ \text{kJ/gm}/\mu\text{sec})$$

B-fields for the C5H12

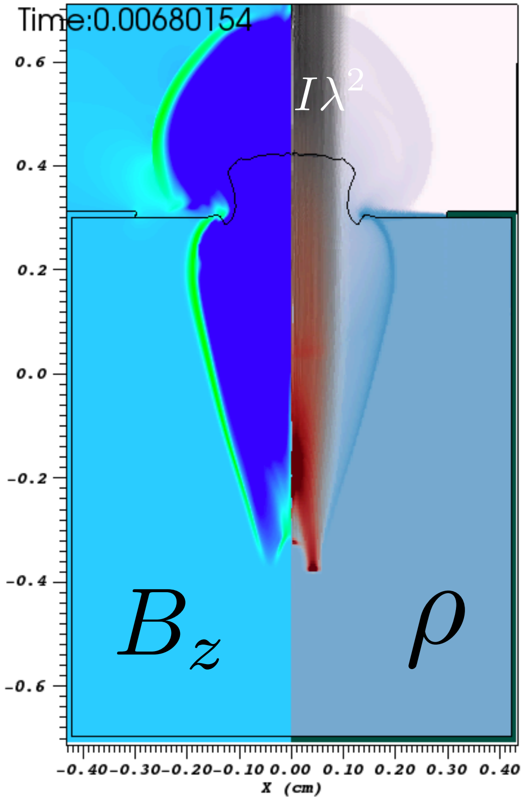
Bz = 0.5 T



Bz = 30 T

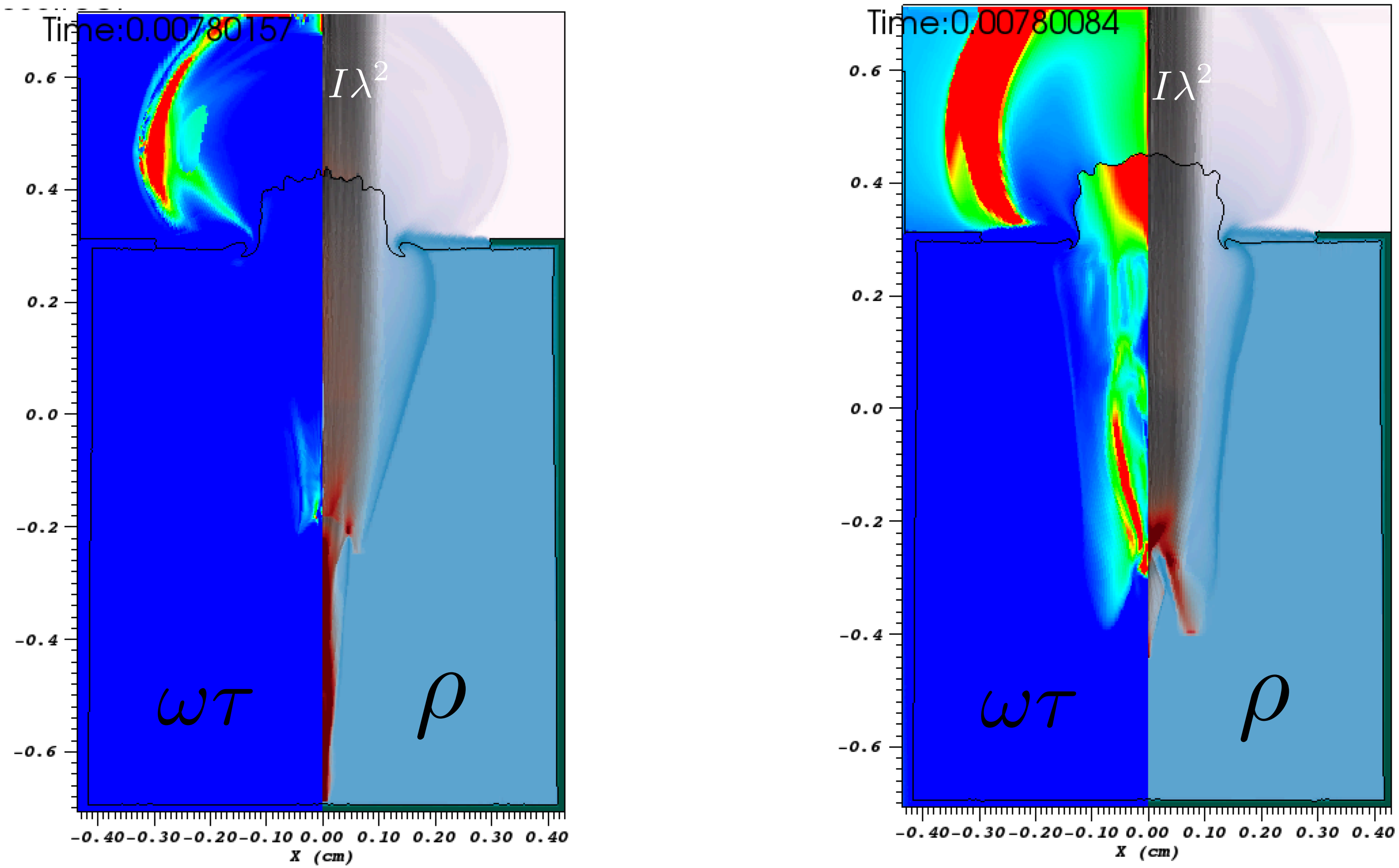


Bz = 0.5 T



2.9 mg/cc **C5H12**

Structure of B-field on D2 absorption (more self generated fields)



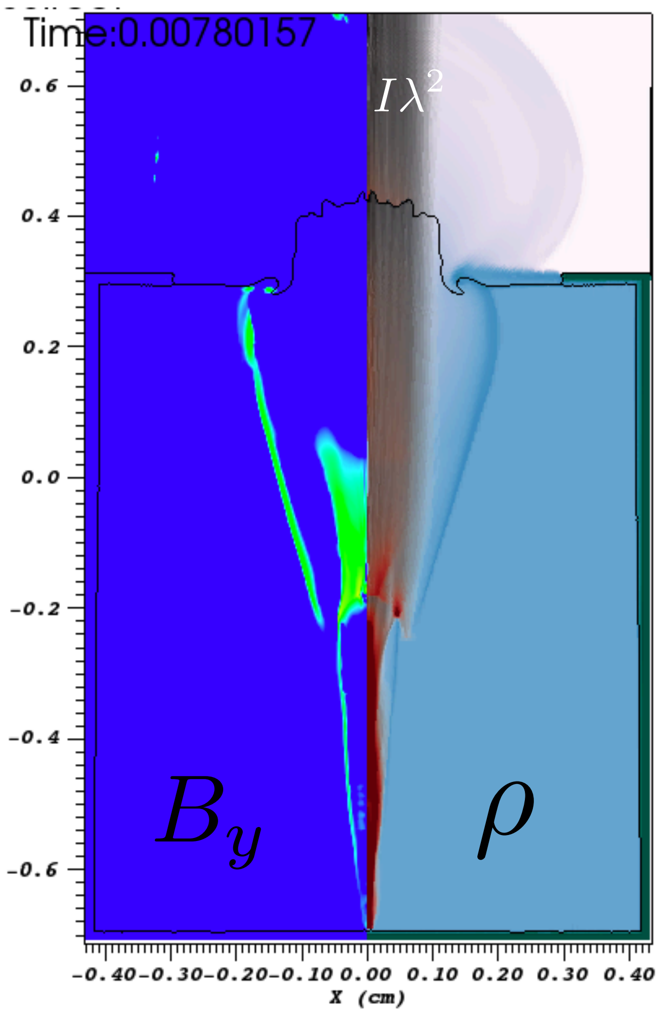
Bz = 0 T

Bz = 30 T

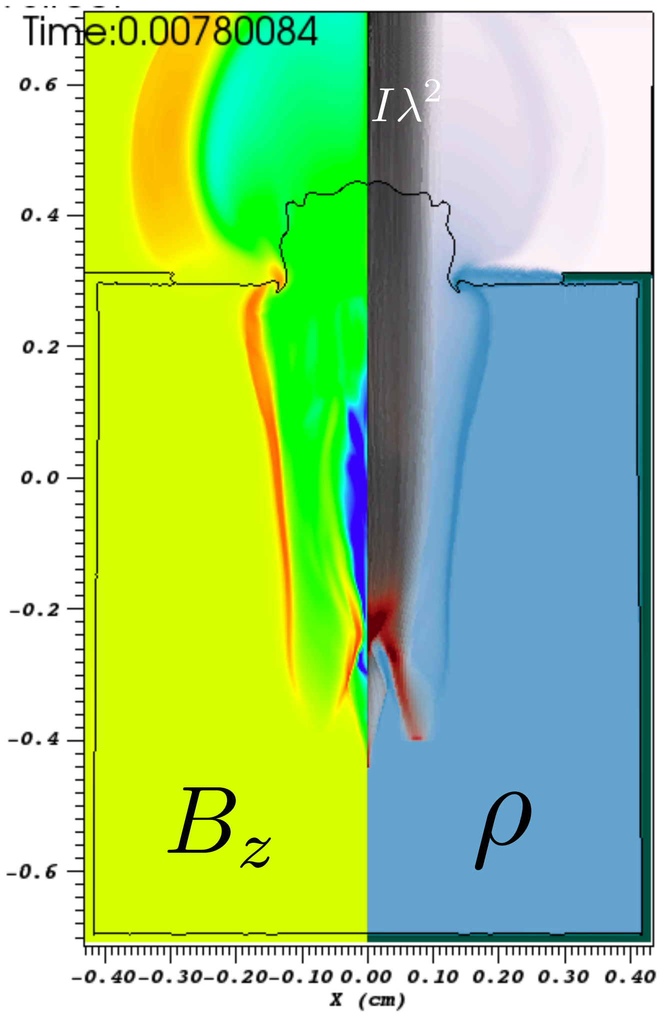
4.8 mg/cc **D2** + 2% Ne

Structure of B-field on D2 absorption (more self generated fields)

Bz = 0 T

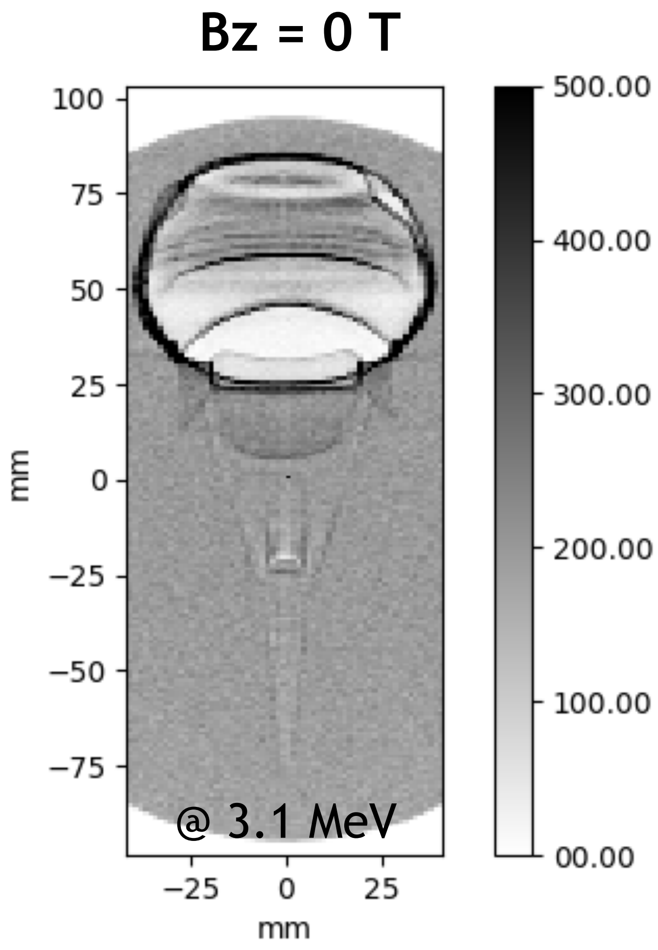


Bz = 30 T

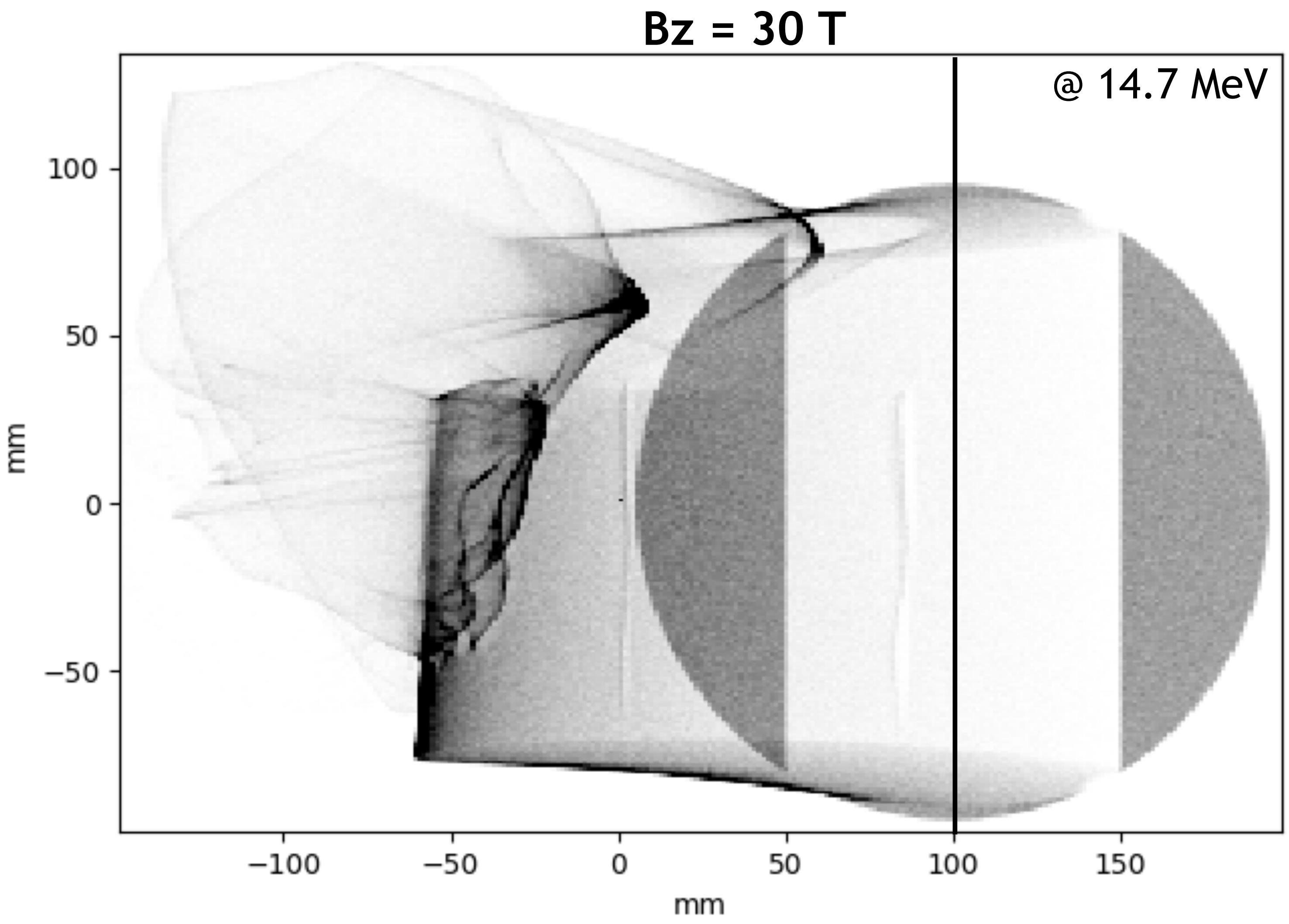


4.8 mg/cc **D2** + 2% Ne

Proton radiography of D2



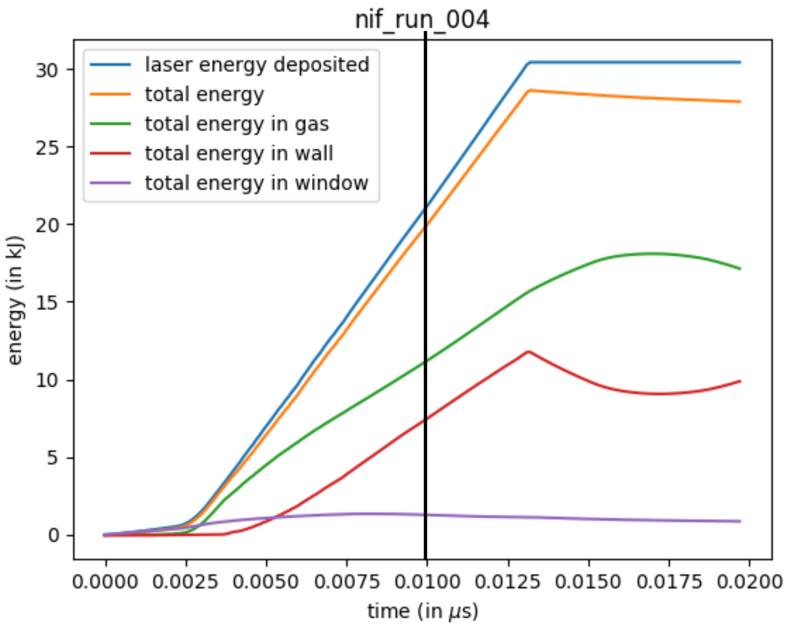
note: B-field too small to image with 14.7 MeV



4.8 mg/cc **D2** + 2% Ne @ 7.8 ns

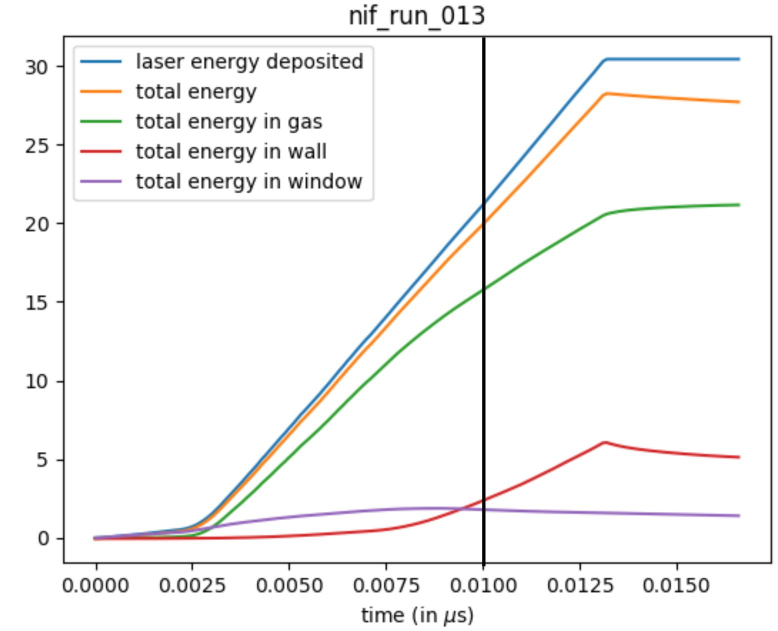
Energy accounting of shots to date

1.6 mg/cc **D2**



11.2 kJ in gas (53%)
1.2 kJ in window (6%)
7.5 kJ out the back (36%)
750 eV gas temperature

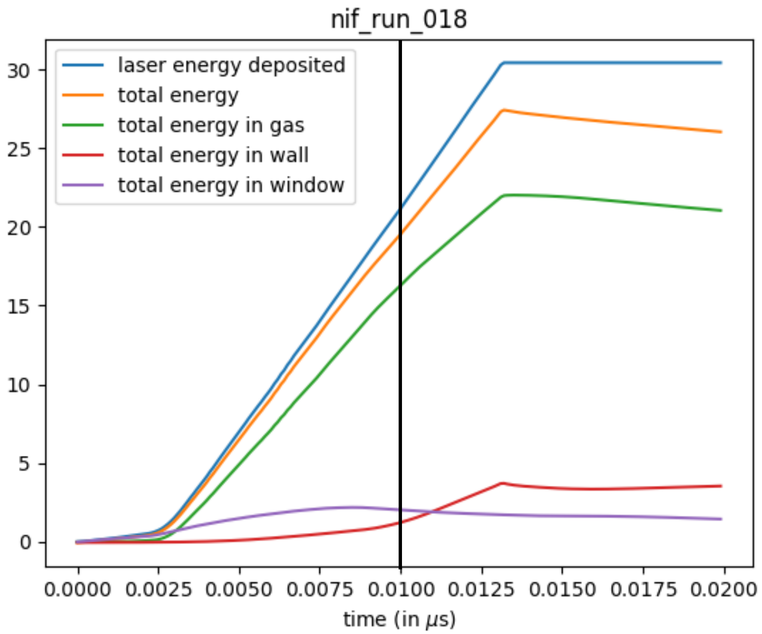
3.2 mg/cc **D2** + 2% Ne



21.1 kJ in 10 ns delivered laser energy

15.7 kJ in gas (74%)
1.7 kJ in window (8%)
2.3 kJ out the back (11%)
1500 eV gas temperature

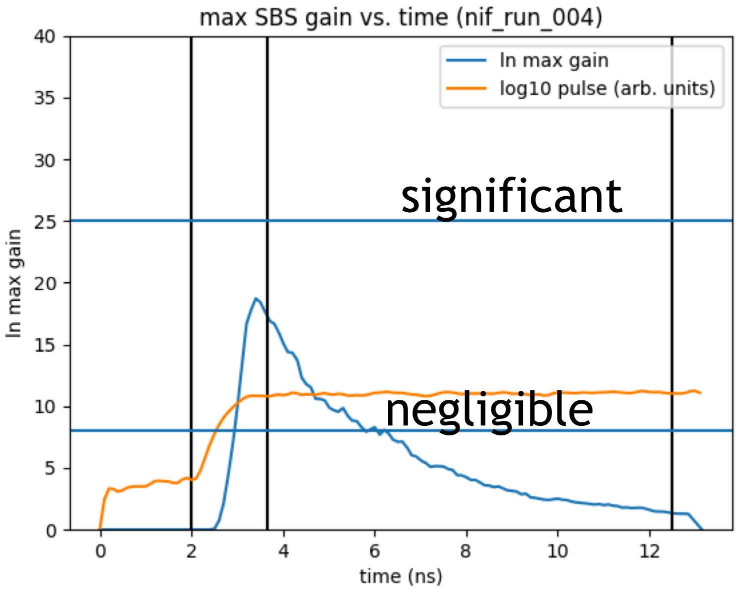
4.8 mg/cc **D2** + 2% Ne

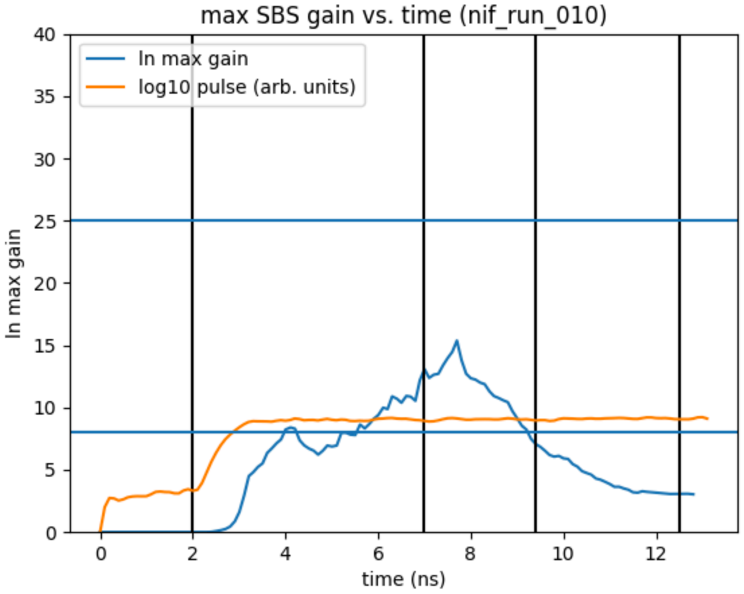


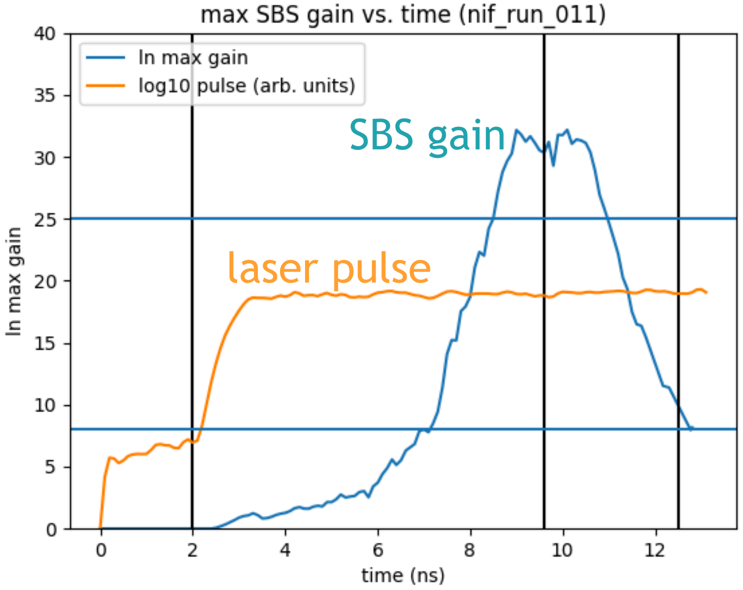
22 kJ / 30 kJ (73%) @ 13 ns

16.3 kJ in gas (77%)
2.0 kJ in window (9%)
1.2 kJ out the back (6%)
1250 eV gas temperature

LPI threshold: SBS backscatter from Refractive Self Intensification is expected to become significant at 6.4 mg/cc



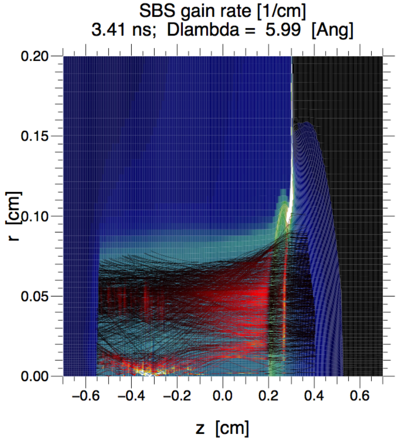


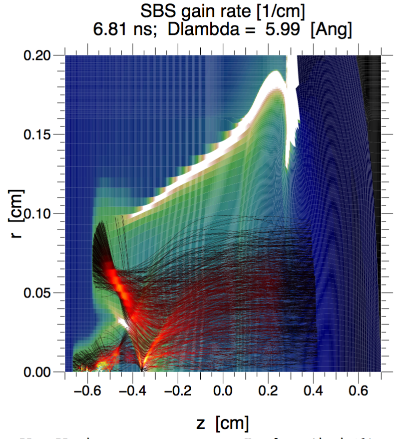


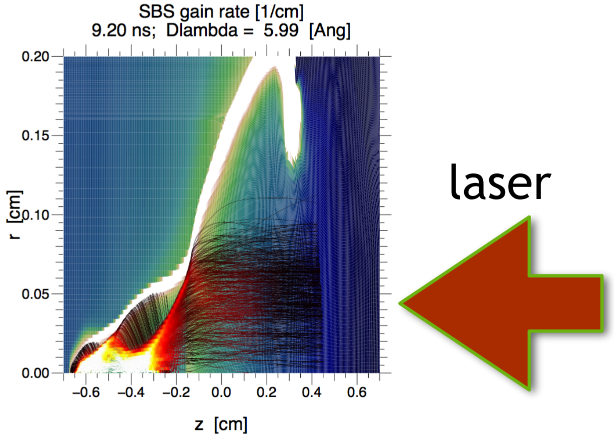
1 atm, 5% ne/ncr, 1.6 mg/cc

2 atm, 10% ne/ncr, 3.2 mg/cc

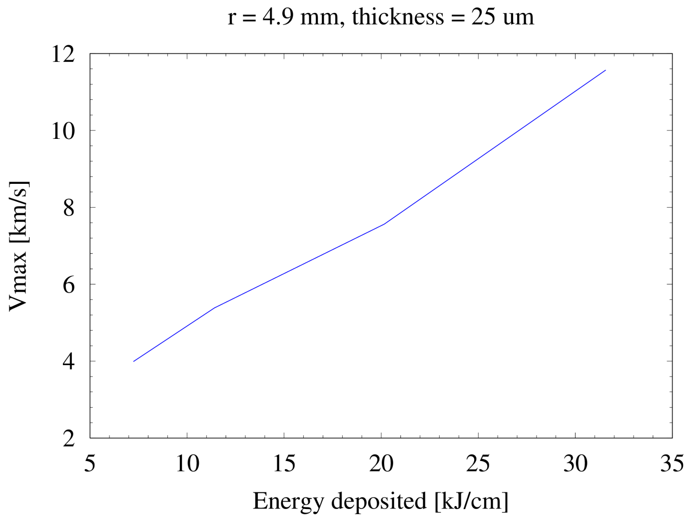
4 atm, 20% ne/ncr, 6.4 mg/cc

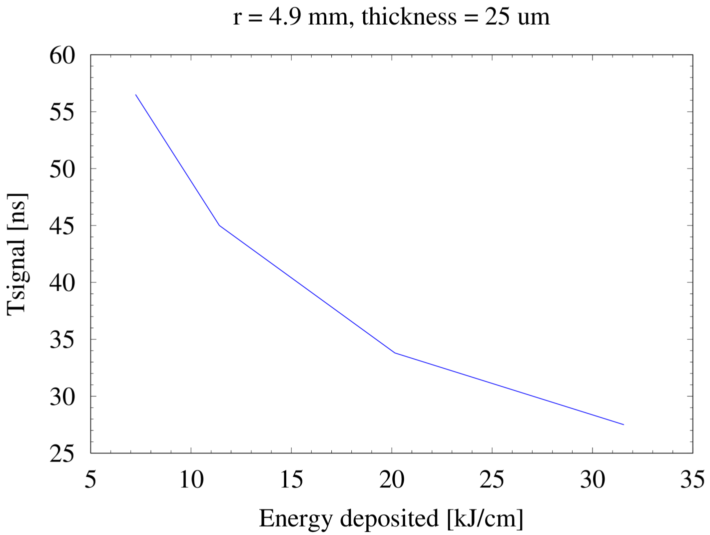






Uncertainty of VISAR energy deposition measurement





$$\frac{dE}{dv_{\max}} = \frac{25 \text{ kJ/cm}}{8 \text{ km/s}}$$

$$\sigma_E = \left|\frac{dE}{dv_{\max}}\right| \sqrt{\sigma_v^2 + \sigma_{\text{EOS}}^2}$$

$$\sigma_v \equiv \text{error in VISAR velocity} = 0.05\ v$$

$$\sigma_{EOS} \equiv \text{error in } v_{\max} \text{ from EOS} = 0.10\ v$$

$$\sigma_E = 3 \text{ kJ/cm}$$

$$\frac{dE}{dt} = \frac{25 \text{ kJ/cm}}{\text{-25 ns}}$$

$$\sigma_E = \left|\frac{dE}{dt}\right| \sqrt{\sigma_{t_s}^2 + \sigma_{t_0}^2 + \sigma_{\text{EOS}}^2}$$

$$\sigma_{t_s} \equiv \text{error in VISAR time} = 0.030 \text{ ns}$$

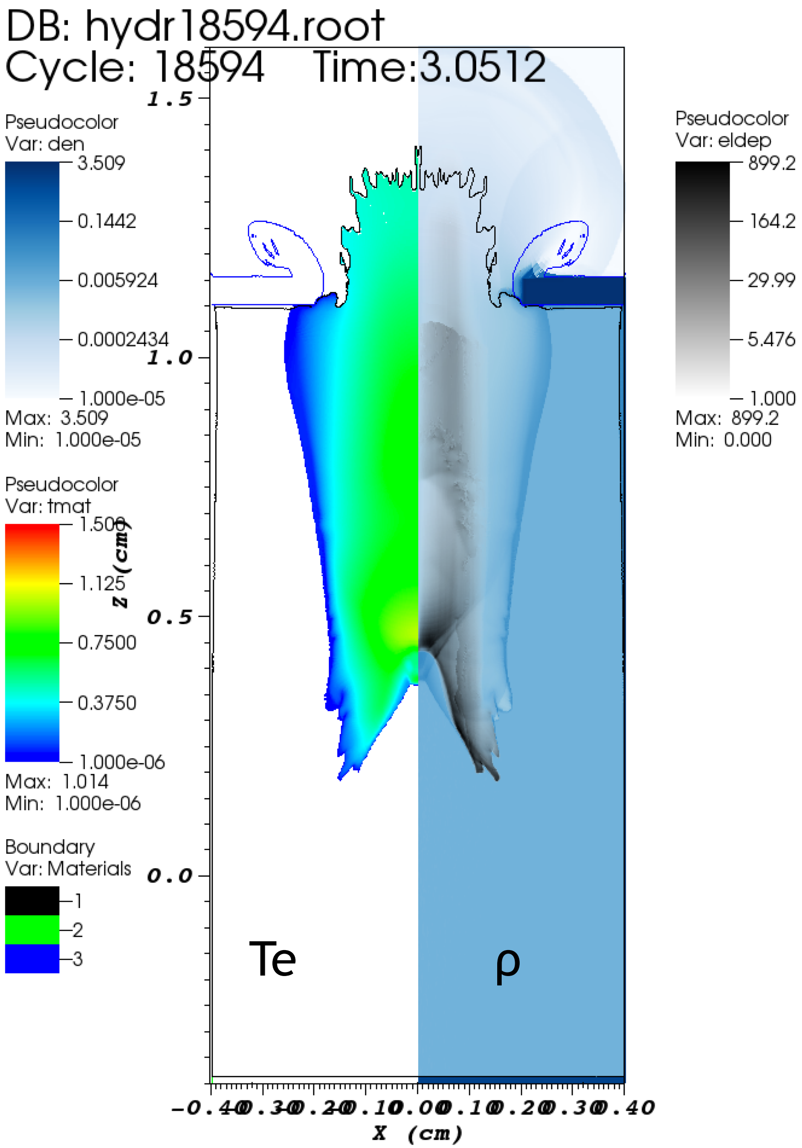
$$\sigma_{t_0} \equiv \text{error in deposition time} = 1 \text{ ns}$$

$$\sigma_{\text{EOS}} \equiv \text{error in time from EOS} = 1 \text{ ns}$$

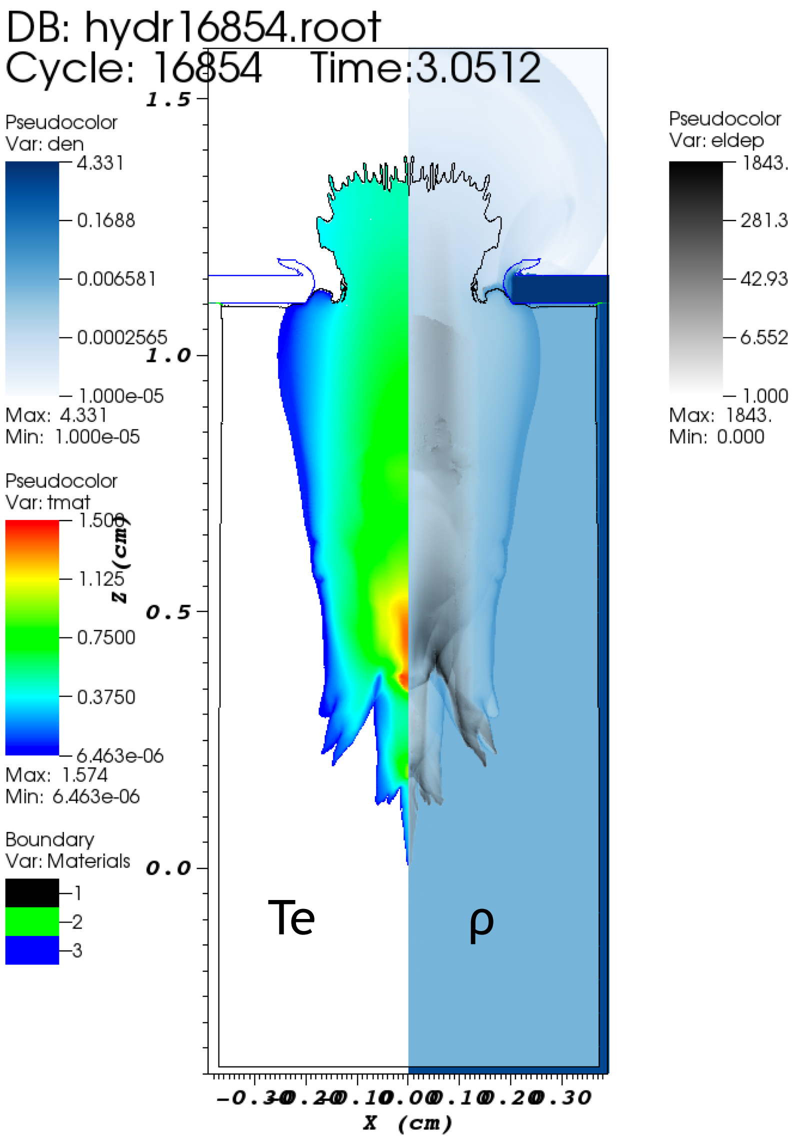
$$\sigma_E = 1.5 \text{ kJ/cm}$$

Magnetization in 4.0 mg/cc D2 NIF-like conditions @ 20 kJ

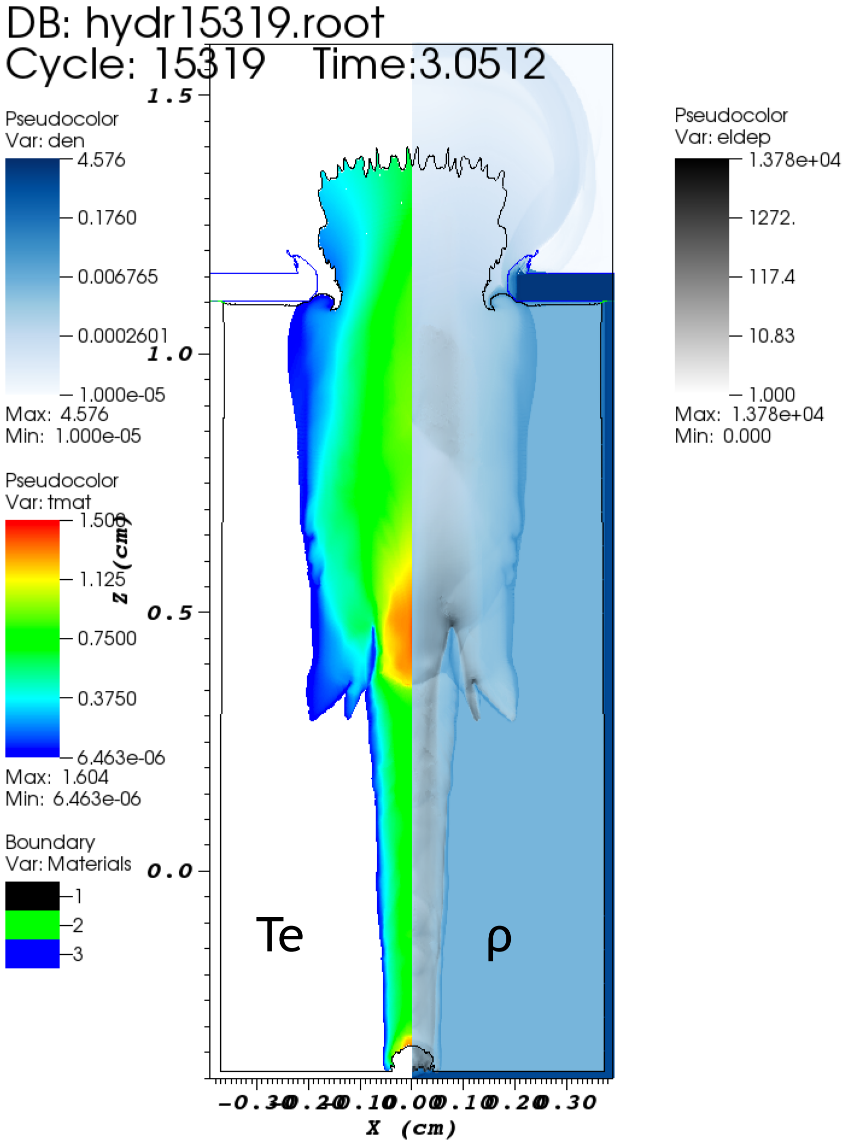
No MHD



MHD, Bz = 0 T

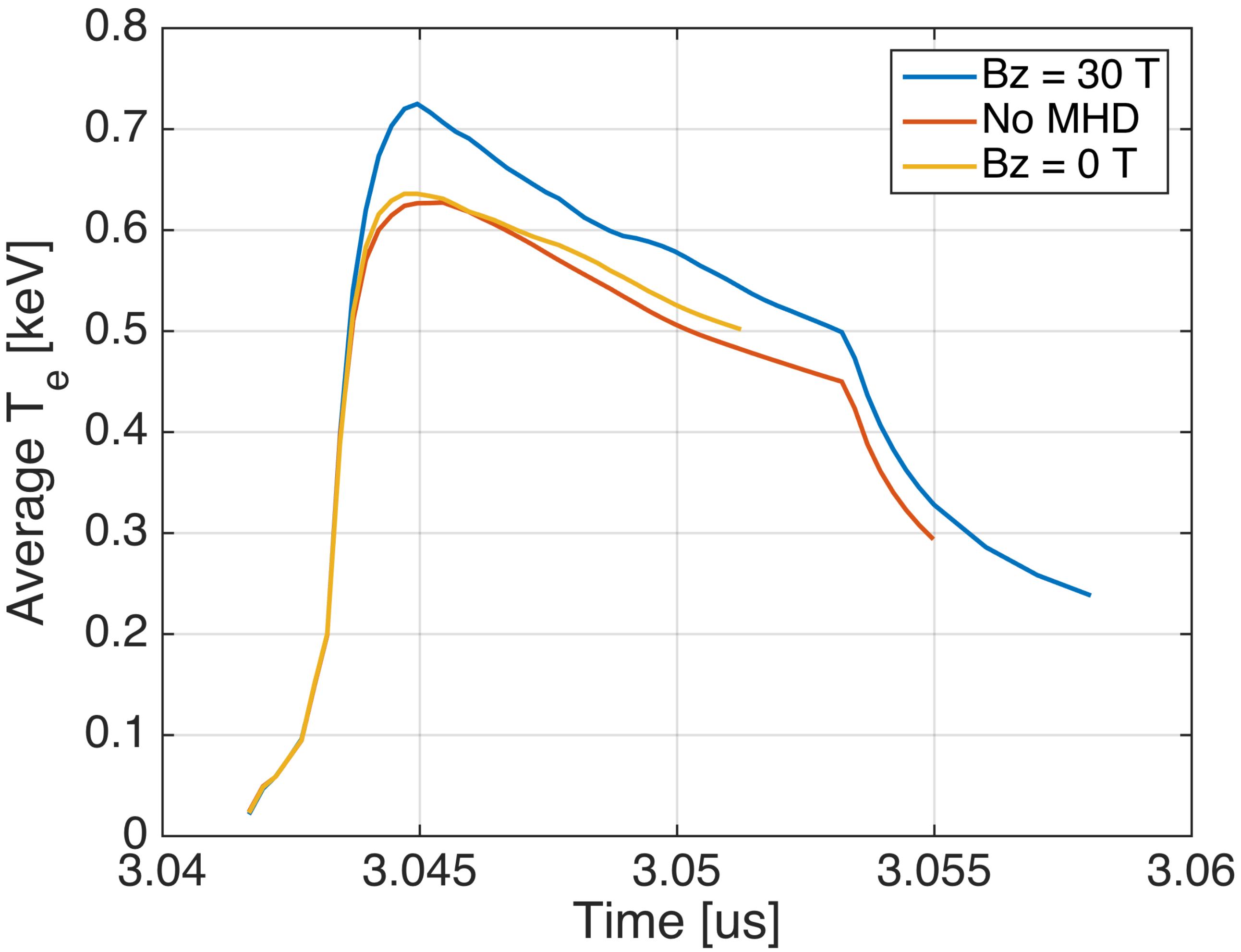


MHD, Bz = 30 T



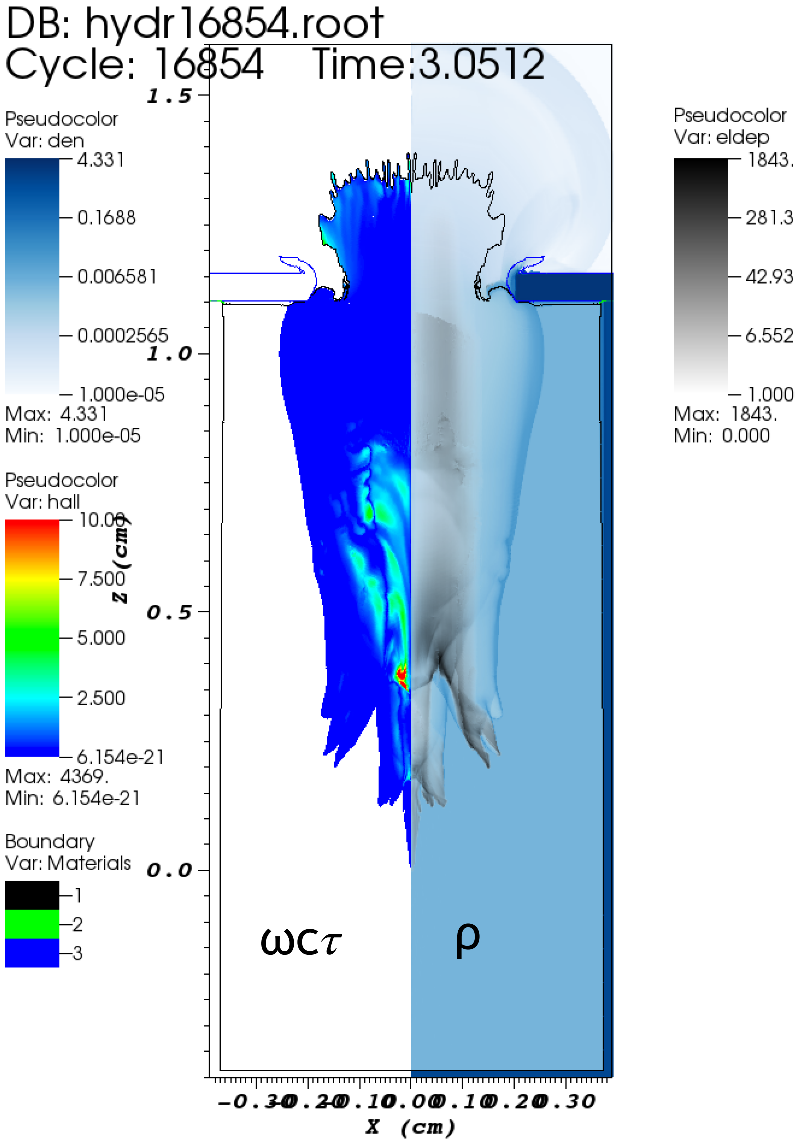
Overall temperature is higher with applied field

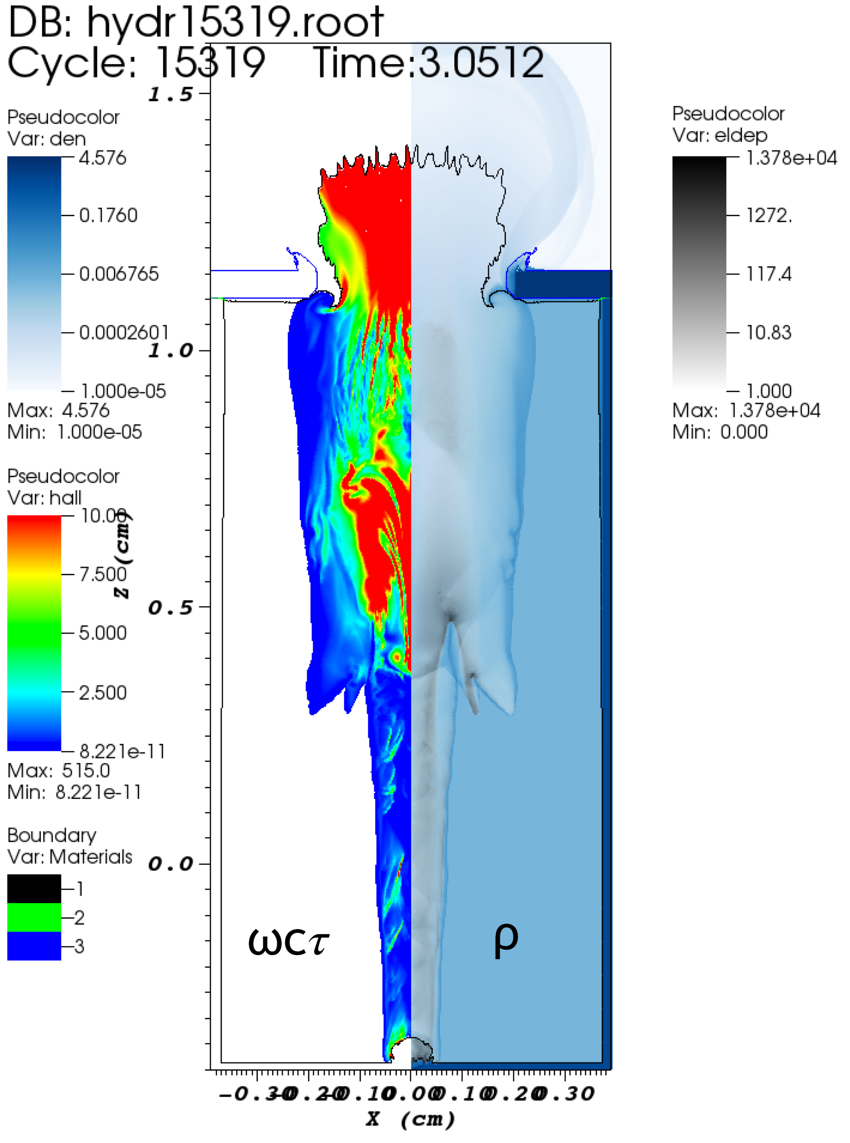
- There are localized hotspots when including self-generated fields but overall temperature is very similar to no MHD case
- Temperature difference is largest while laser is on
- Note no dopants included for these simulations that would extend emission



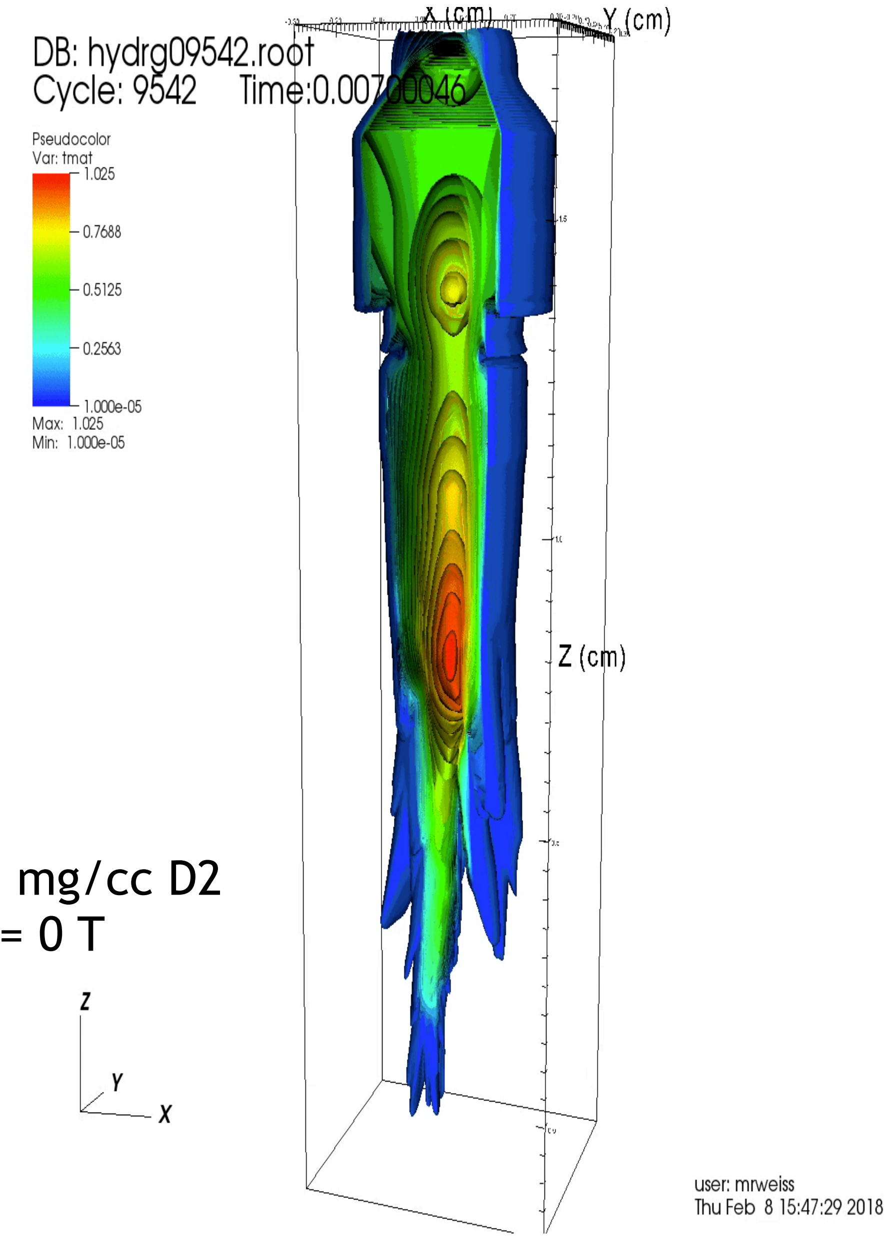
Magnetization is highly localized with self-generated fields

- Strong magnetization effects occurs with an applied 30 T
  - Much faster burn through
- Self-generated fields also alter on axis structure
  - Overall magnetization is much lower except for hotspots
- On-axis structure persists in 3D
- 30 T should also be sufficient for neopentane magnetization by comparing electron density

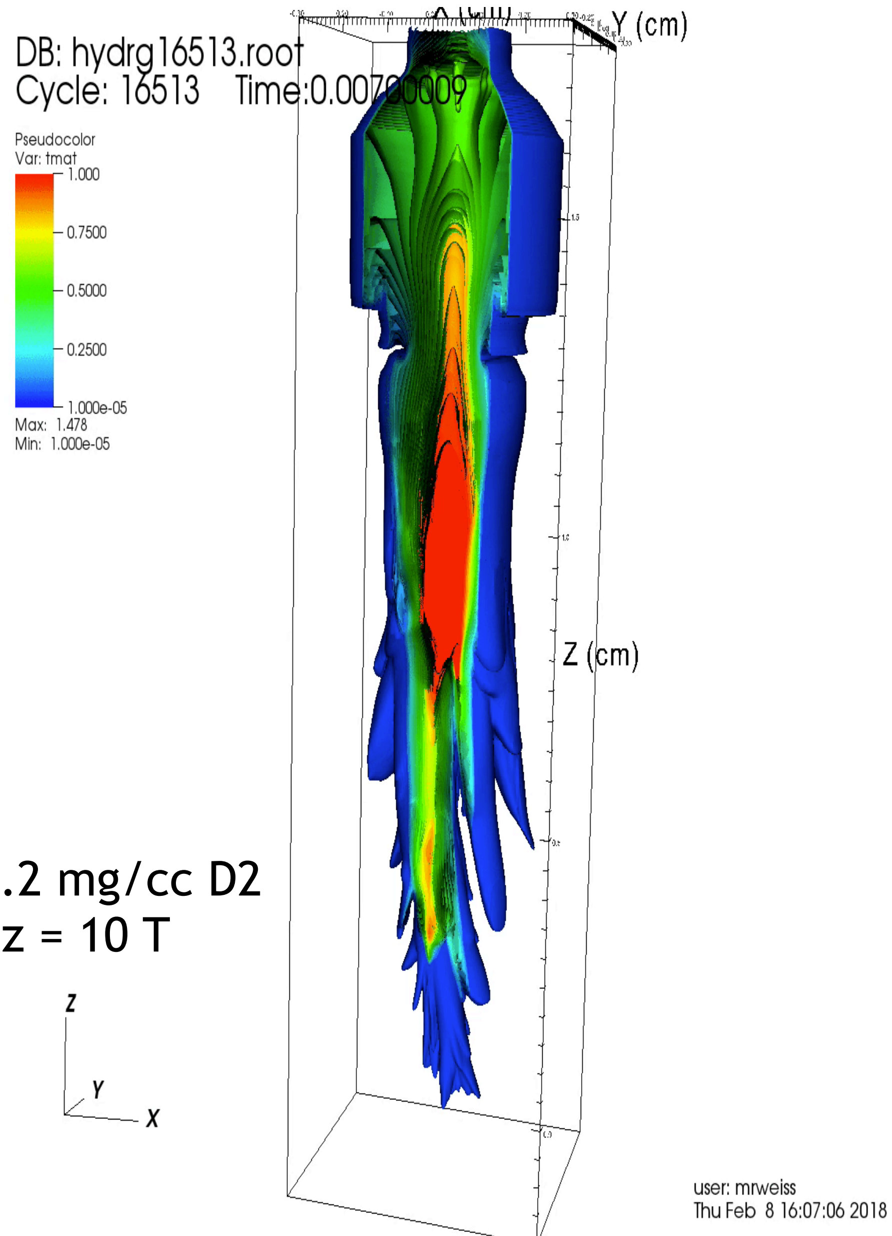




Burn through rate is affected by 3D propagation



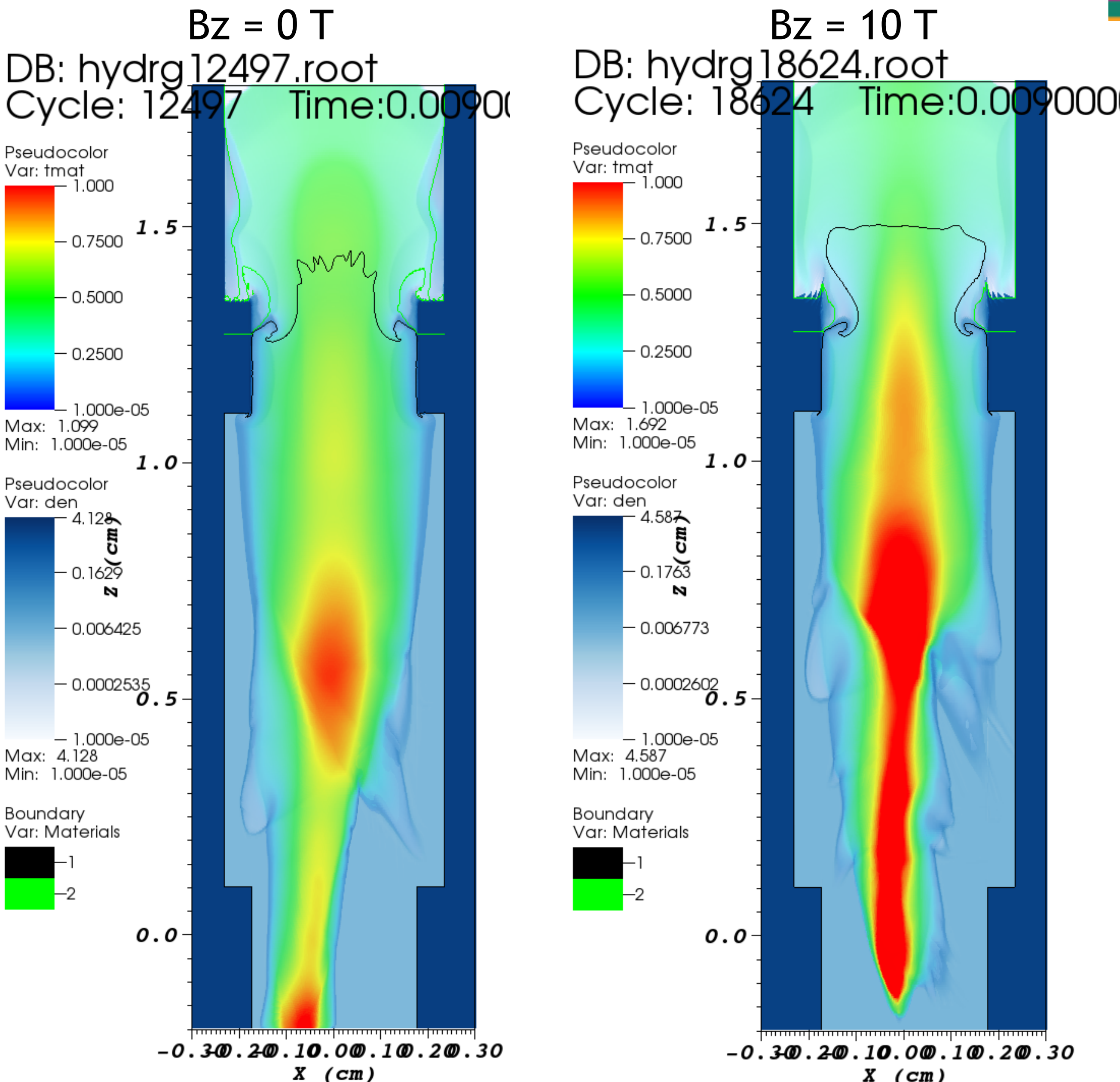
3.2 mg/cc D2
Bz = 0 T



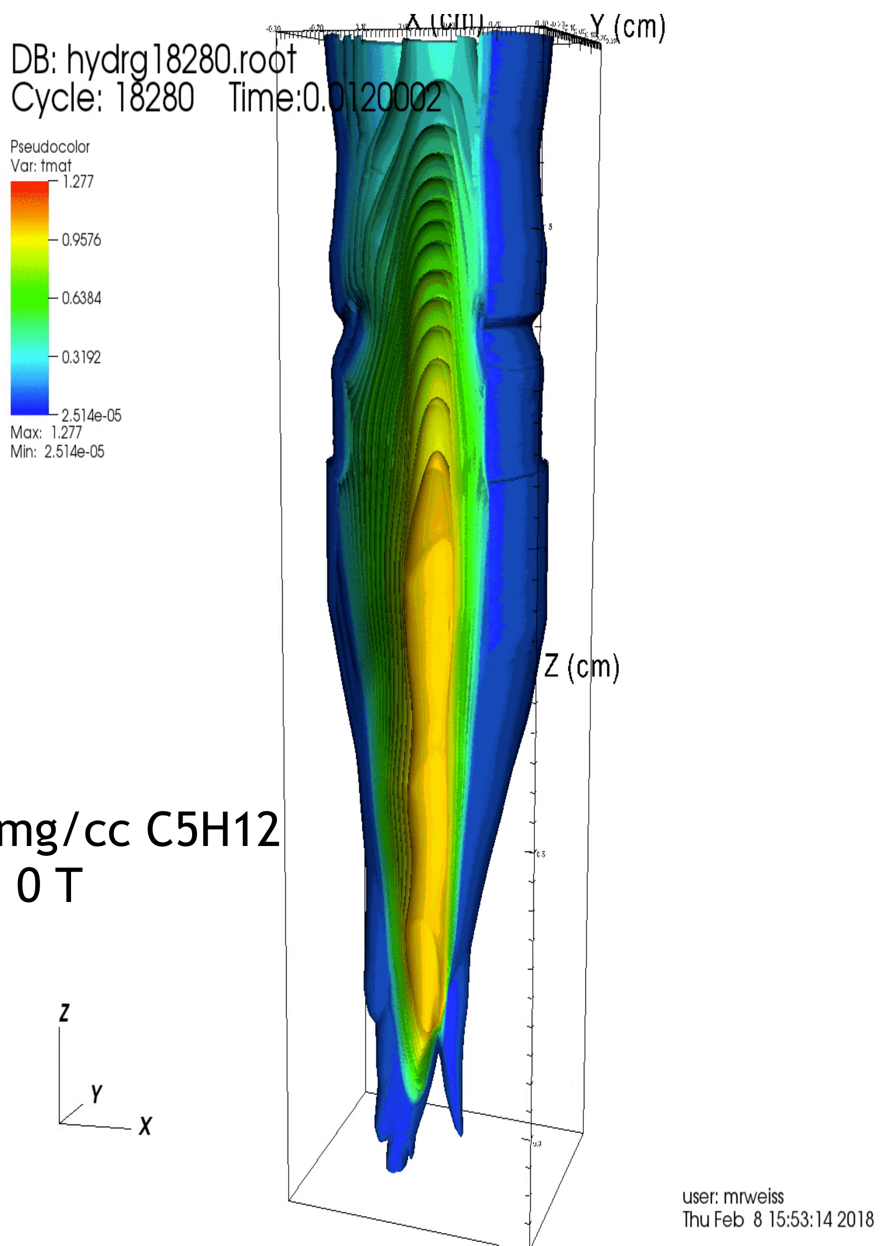
3.2 mg/cc D2
Bz = 10 T

Initial 3D calculations show increased temperature even with 10 T fields in 3.2 mg/cc D2

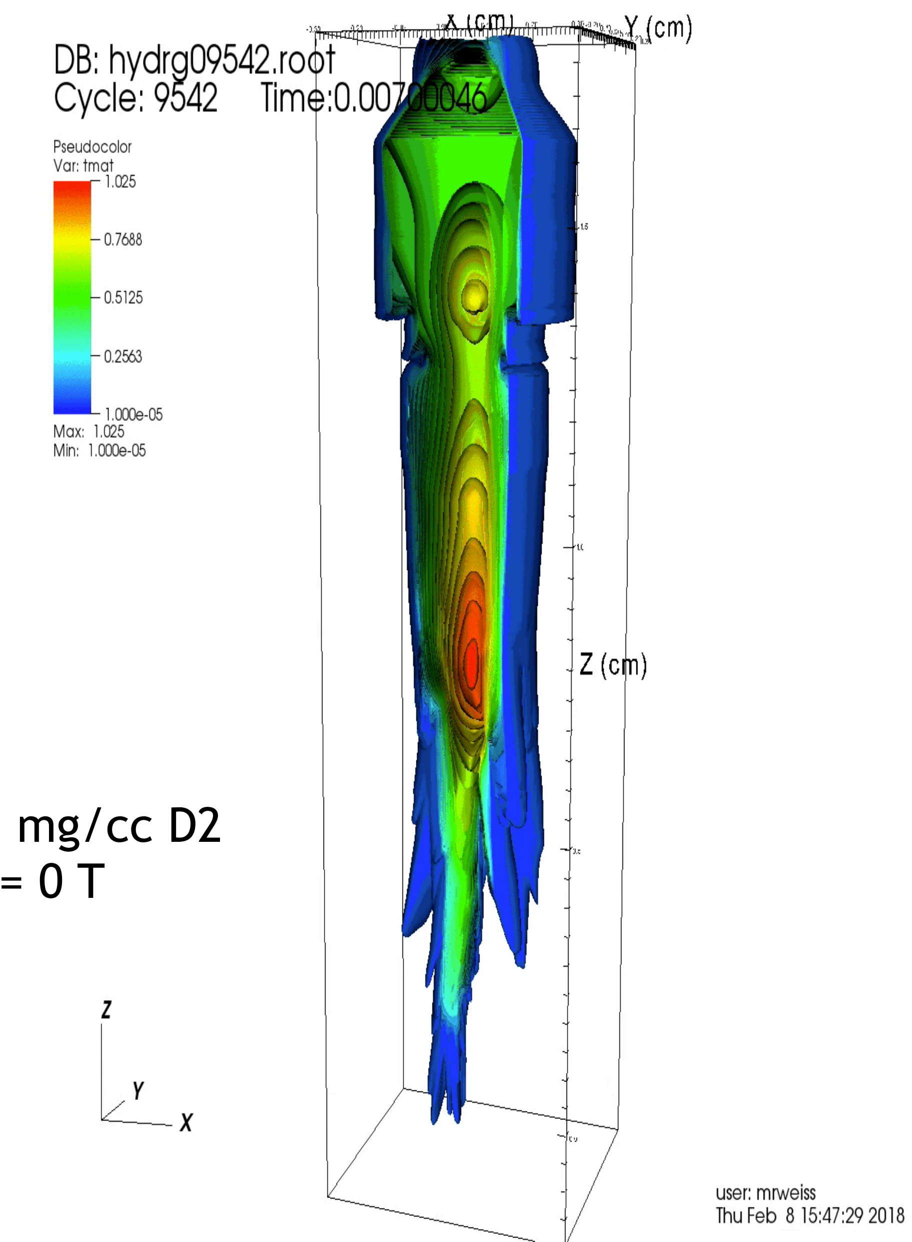
- Peak temperatures are higher
- 3D propagation affects the burn through rate
  - 30 T may show larger effect
- Thermal filaments are more prolific in 3D, particularly with Bz



Neopentane only very slightly strays off axis



2.9 mg/cc C5H12
Bz = 0 T



3.2 mg/cc D2
Bz = 0 T