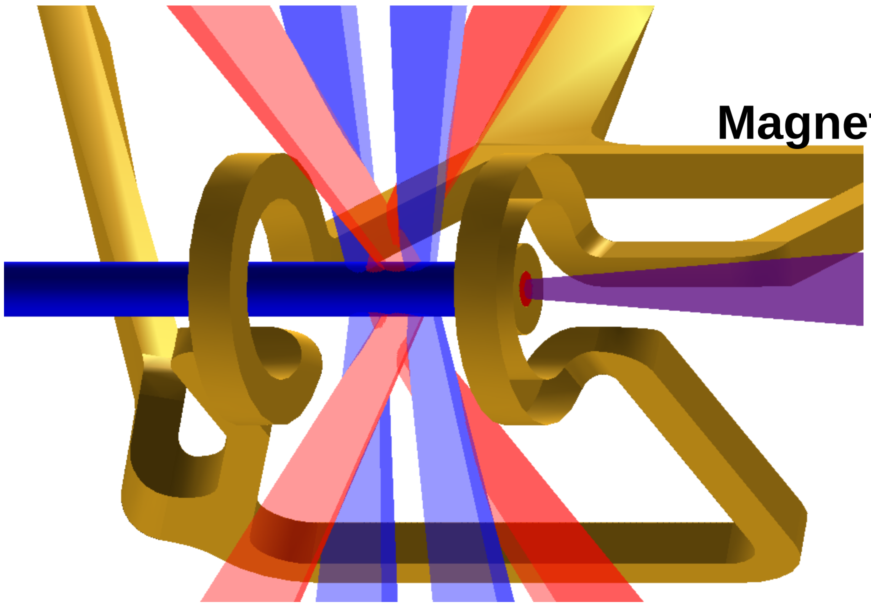
Laser-Driven Magnetized Liner Inertial Fusion on OMEGA



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Magnetic Meeting
Laboratory for Laser Energetics
Rochester, New York
23 Apr. 2018

Fiche #

Collaborators

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Outline

- **Point design considerations and 1D MHD simulations**
- **Obtaining a uniform cylindrical compression on OMEGA**
- **LEH window burn-through and gas preheating**
- **First "fully-integrated" MagLIF experiments on OMEGA**

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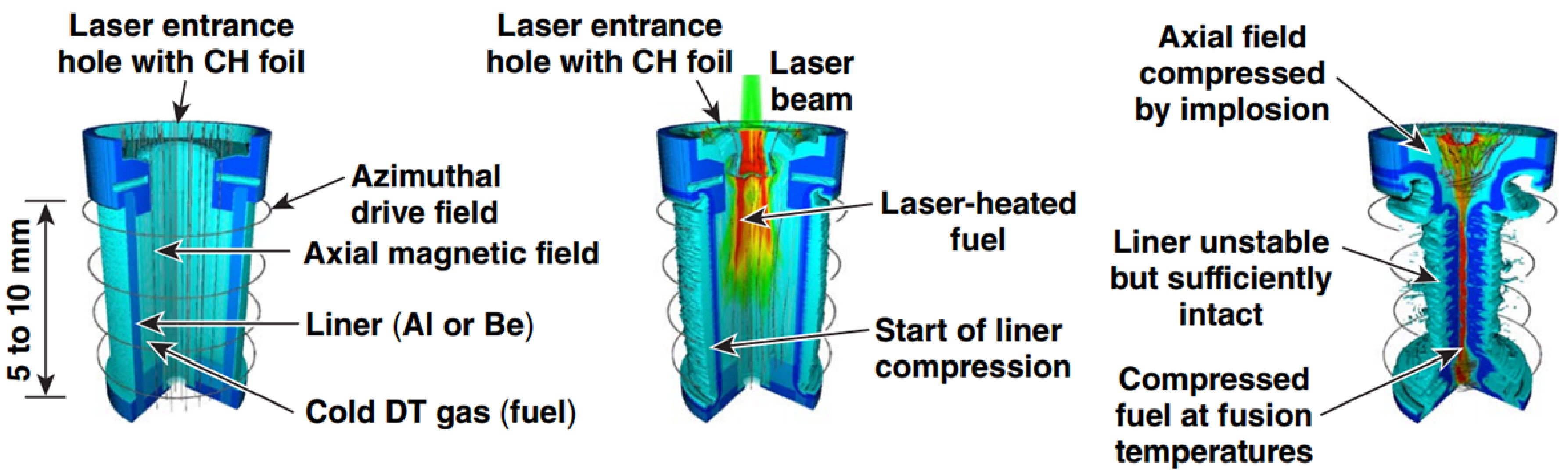
MagLIF uses a Z-pinch driven implosion, laser preheating, and magnetization to limit thermal flux and confine alpha particles



- An axial magnetic field lowers electron thermal conductivity, allowing a near-adiabatic compression at lower implosion velocities and confines alpha particles, allowing a lower areal density
- Laser preheating to ~100 eV allows >1 keV to be reached at a convergence ratio <30

I2185c

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

MagLIF implosions on OMEGA provide a platform for studying the basic science and scalability of the concept

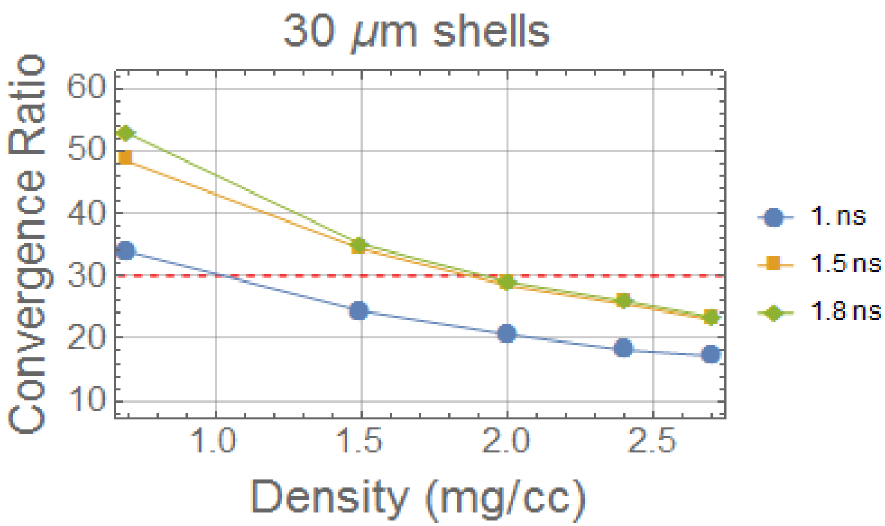
- **Faster shot cycle allows for more shots, better statistics, and wider scans of the MagLIF parameter space**

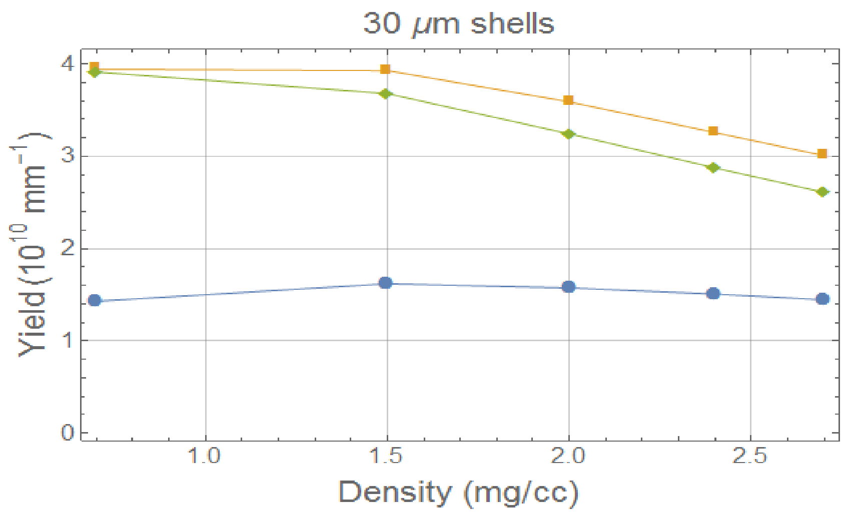
- **Better diagnostic access allows for measurements that cannot be performed at the Z scale.**
  - **Magnetic field/Nernst effect measurements, shell trajectories**

- **OMEGA scale experiments provide code validation over 10^3 times in energy**
  - **Ultimately, we will have the confidence in extrapolating to ignition scale designs**

1D Lilac-MHD modeling was used to optimize the OMEGA MagLIF design

- **Pulse length, shell thickness, and fuel density were varied for a fixed 10 T magnetic field and 200 eV preheat temperature**





Pulse length of 1.5 ns and a fuel density above 1.5 mg/cc gives the maximum yield within the constraint of CR<30

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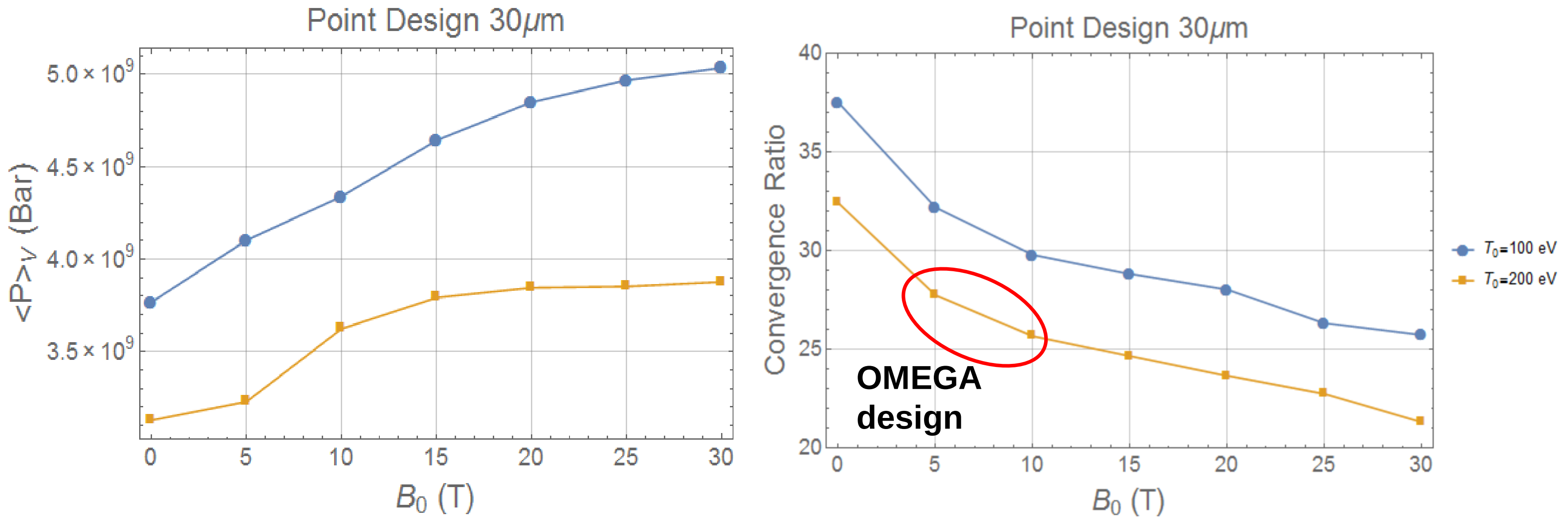
Magnetic field and preheat reduce convergence ratio and implosion speed and provide a more stable cylindrical implosion

- **Higher core pressures are achieved due to the suppression of radial conduction loss by the magnetic field**



J.R. Davies et al., Phys. Plasmas **24,** 062701 (2017).

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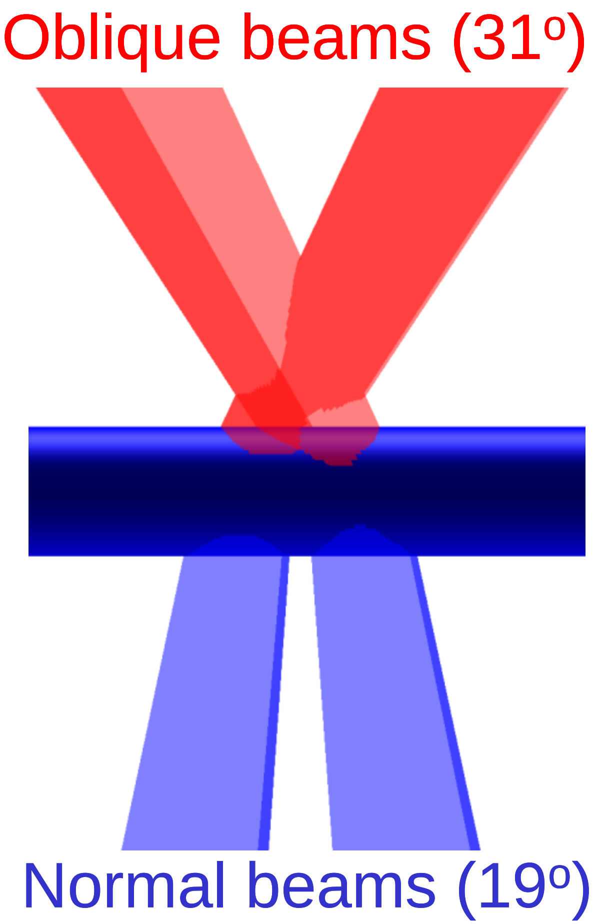
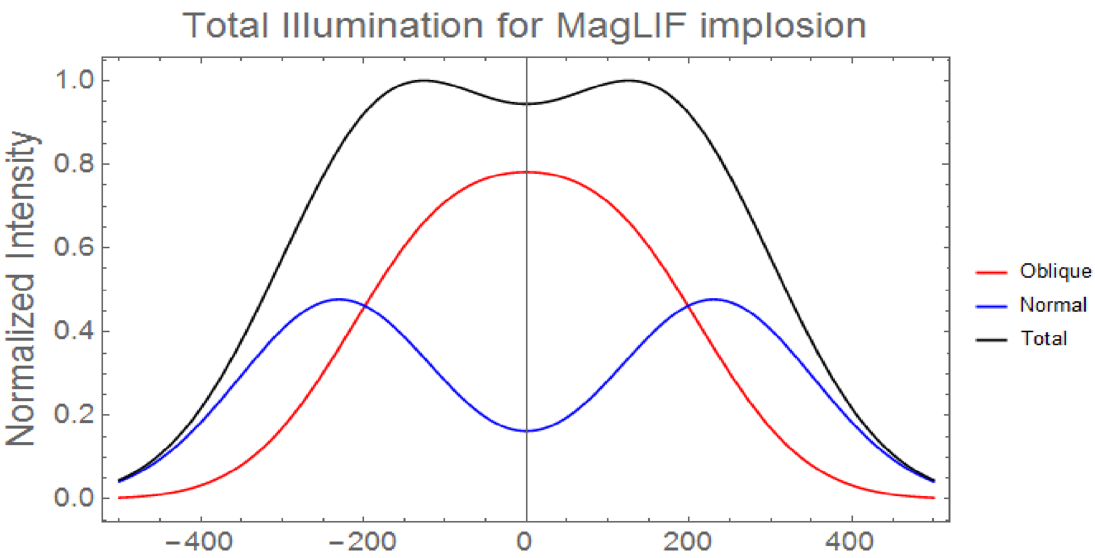
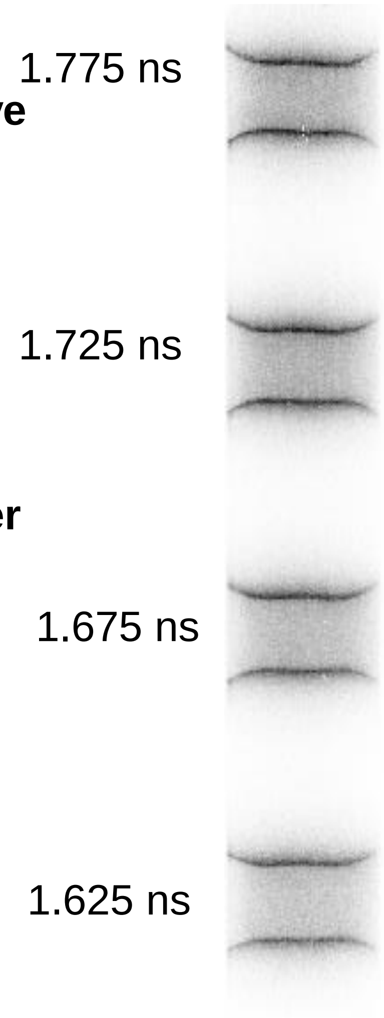
Implosion only experiments were used to optimize the beam pointing and balance between normal and oblique beams

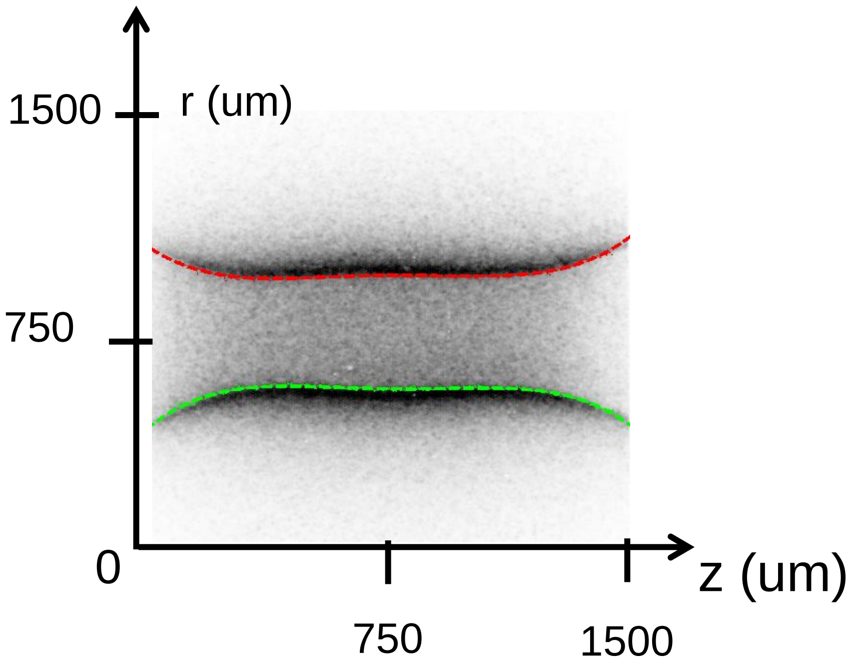




X-ray self-emission images show that obtaining a uniform implosion over the maximum length requires reduced energy in the normal beams

- **Each image is curve fit to find the shell shape in terms of polynomial coefficients**
- **The ratio of b/a determines whether the shell ends are over/underdriven**





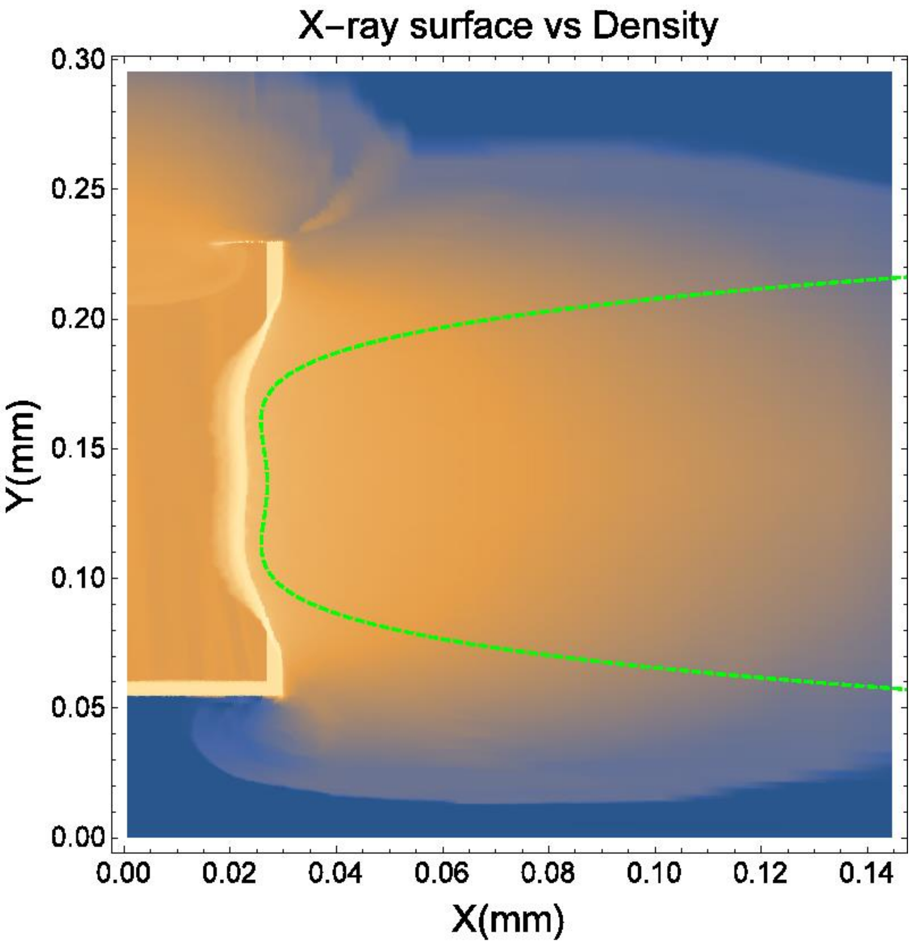
Fitting function:

$$R(z) = a + b(z - z_0)^2 + c(z - z_0)^4$$

E.C. Hansen, et al., Plasma Phys. And Contr. Fus., **60**, 054014(2018)

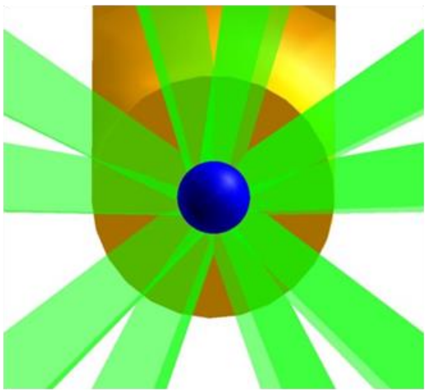
SAGE 2-D hydrocode results post-processed in Spect3D confirm that x-ray shape corresponds to shell shape

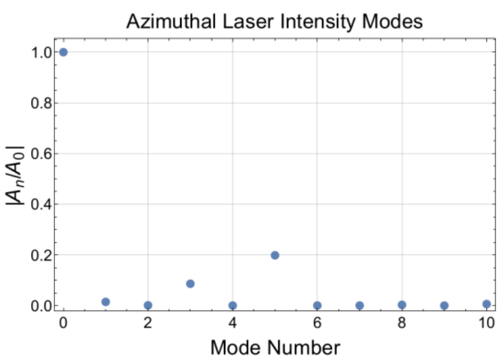
- SAGE is a 2-D rad-hydro code with identical radiation transport and beam tracing as DRACO
- Hydrocode results were post-processed using Spect3D atomic physics code with a 20 um point-spread function
- Results from polynomial fitting the x-ray image were superimposed on the density profile results from SAGE

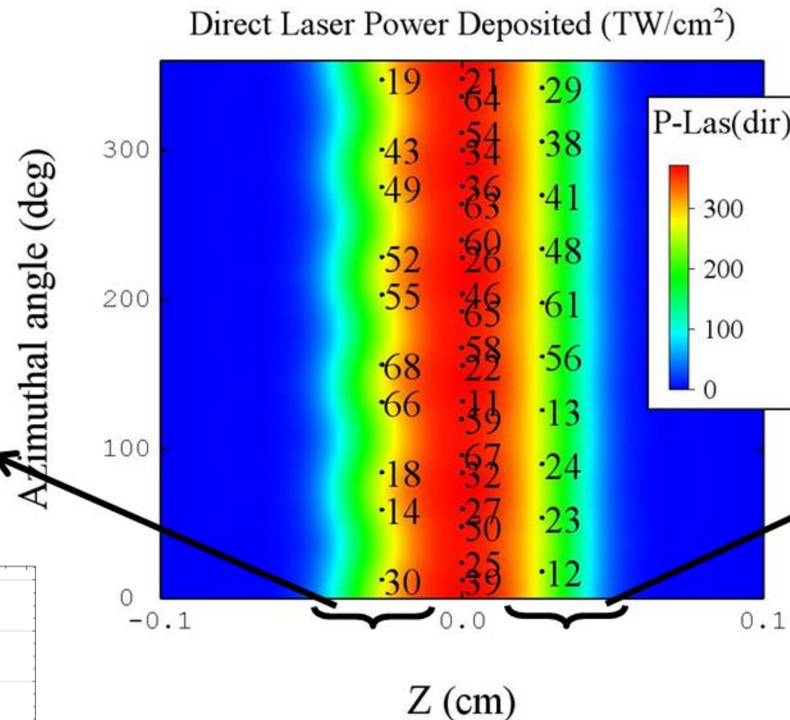


Unadjusted beam pointing for OMEGA rings in polar drive configuration lead to natural P5 asymmetry

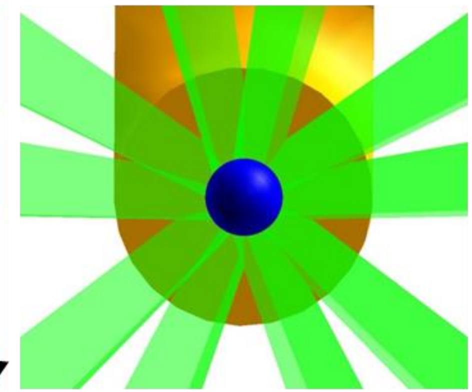
Standard beam distribution

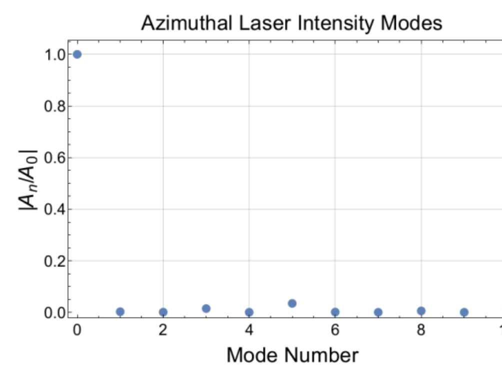






Uniform beam distribution

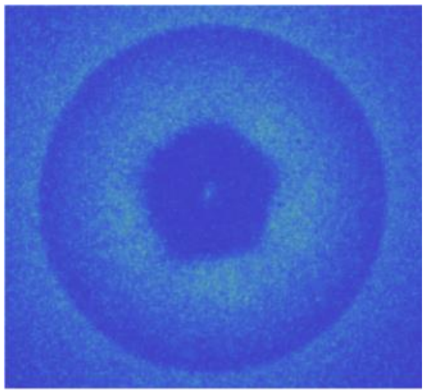


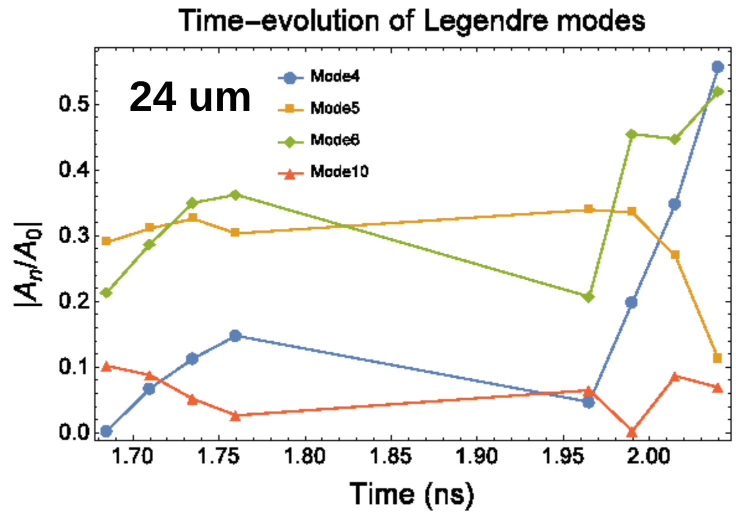


Shifted "uniform" beam configuration azimuthal uniformity remains unmeasured

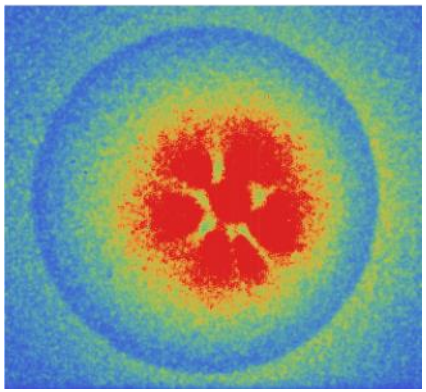
Legendre mode analysis of end-on x-ray framing camera images shows growth in mode 5 over time

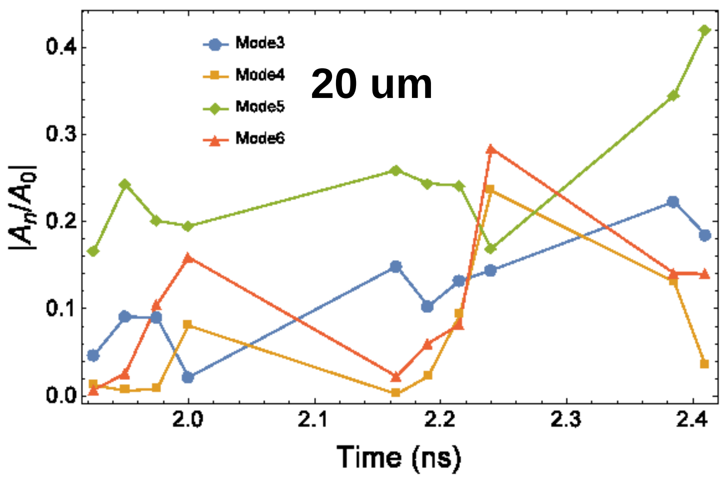
30 um

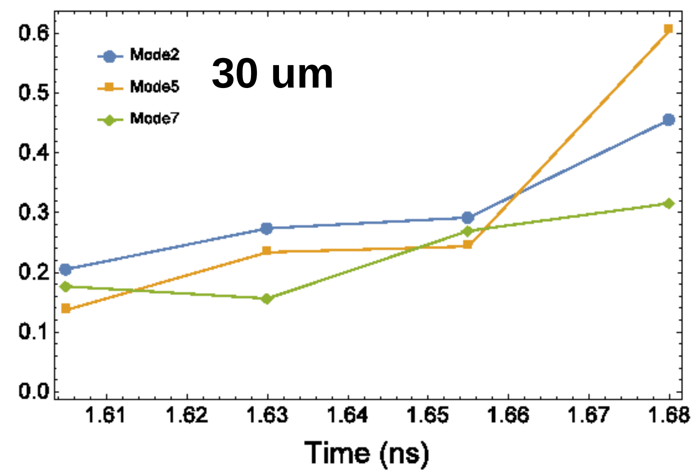




20 um

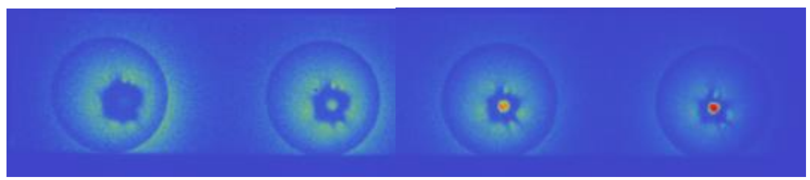


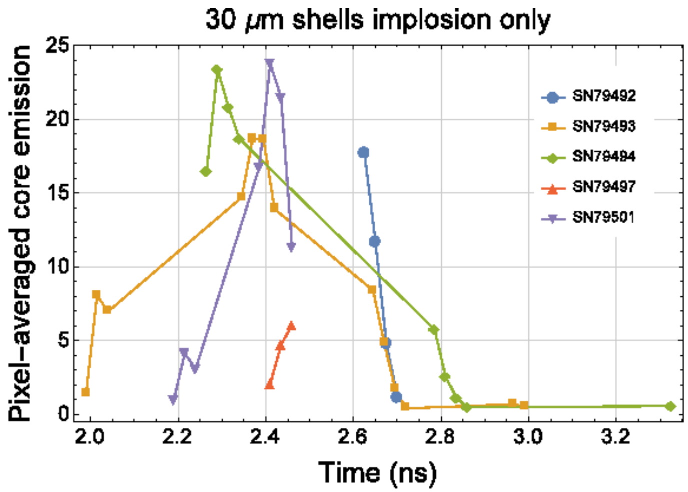


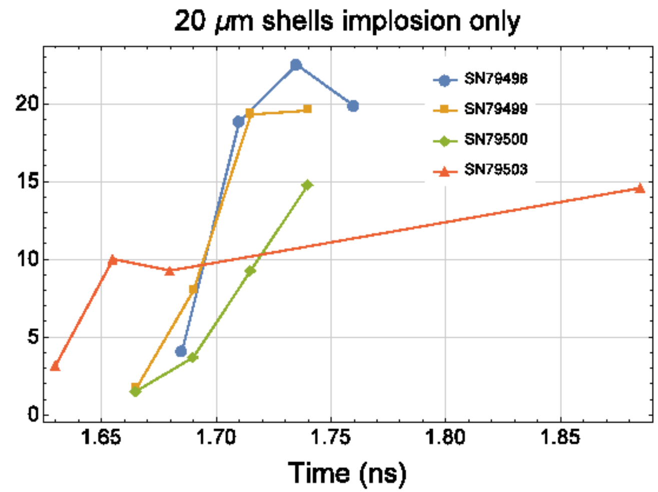


End-on core emission can be used to determine an x-ray bang time

- Spatially integrated core emission vs. time provides an excellent 2nd measure to neutron bang time
  - Very hard to capture core formation over long periods of time due to dynamic range of XRFC







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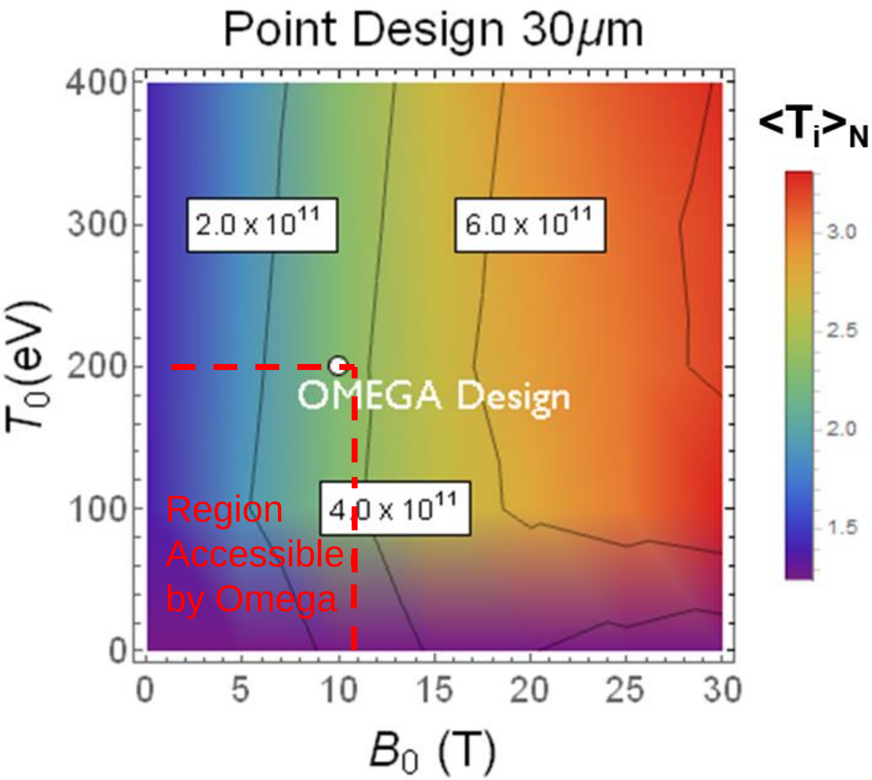
A minimum preheat temperature of 100 eV is required for yield increase for any shell thickness and magnetic field

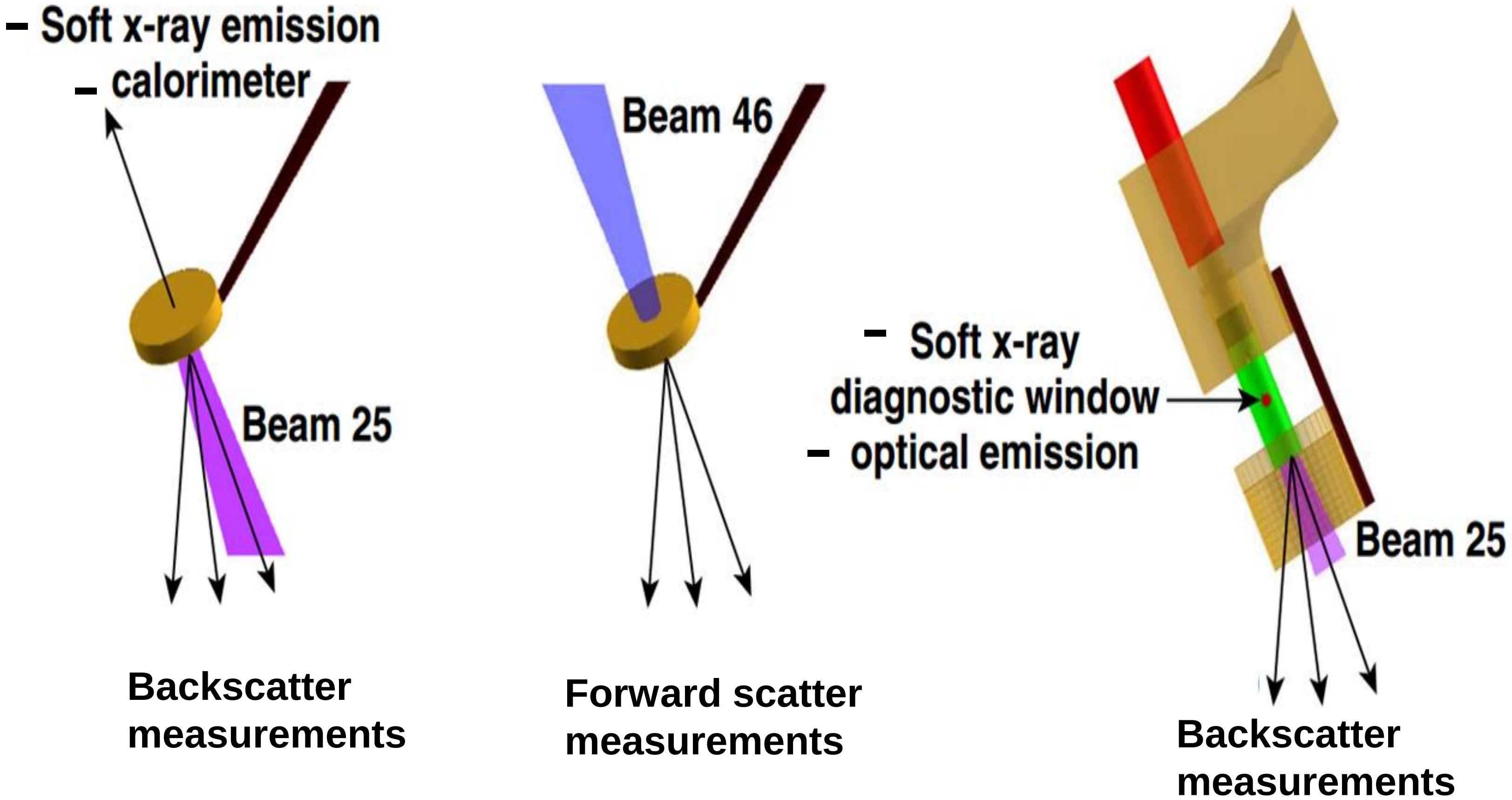


LILAC MHD results

B_0 (T)	T_0 (eV)	$\langle T_i \rangle_N$ (keV)	Y_N ($x10^{11}$/cm)	CR
0	0	1.24	.393	49
0	100	1.37	.528	37
10	100	2.27	3.56	30
10	200	2.28	3.36	26

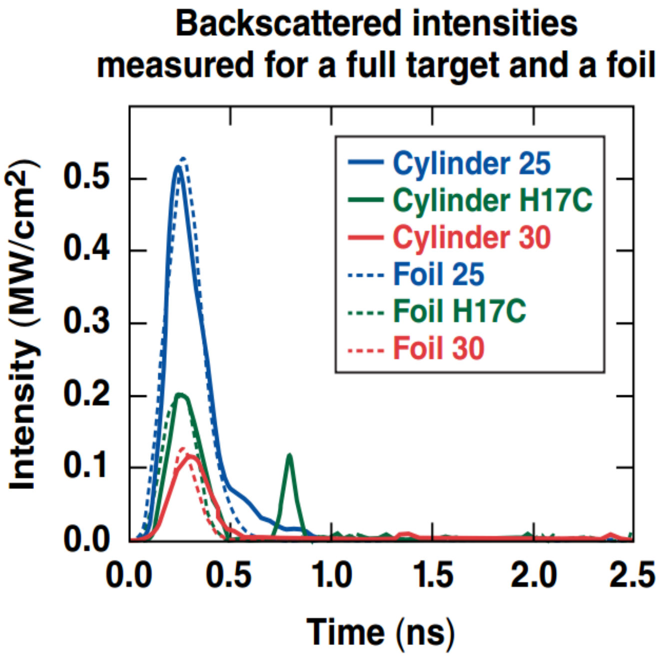
TC11605a

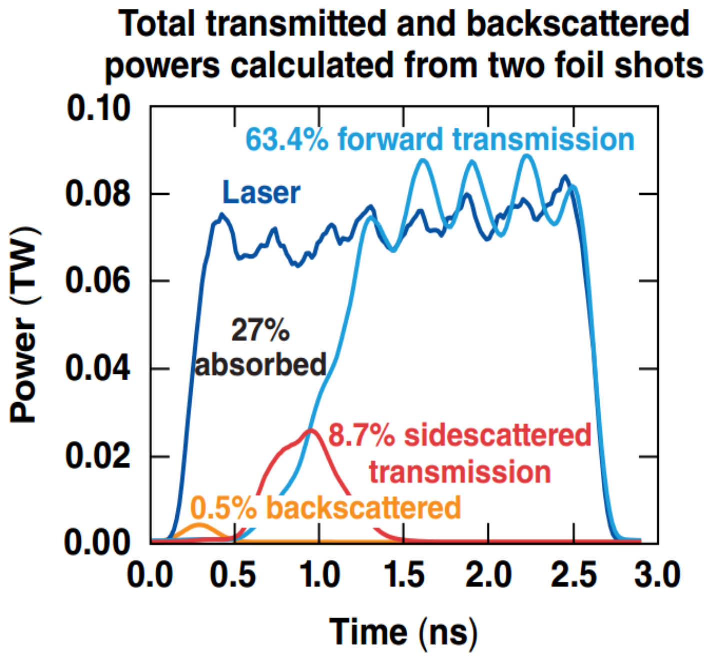
The preheat experiments measured LEH window transmission and gas heating using a single OMEGA beam



TC12451a

Foil transmission exceeds 50% with no backscatter from the gas and less than 10% sidescatter of transmitted light





36% absorption predicted by DRACO 2D Hydro

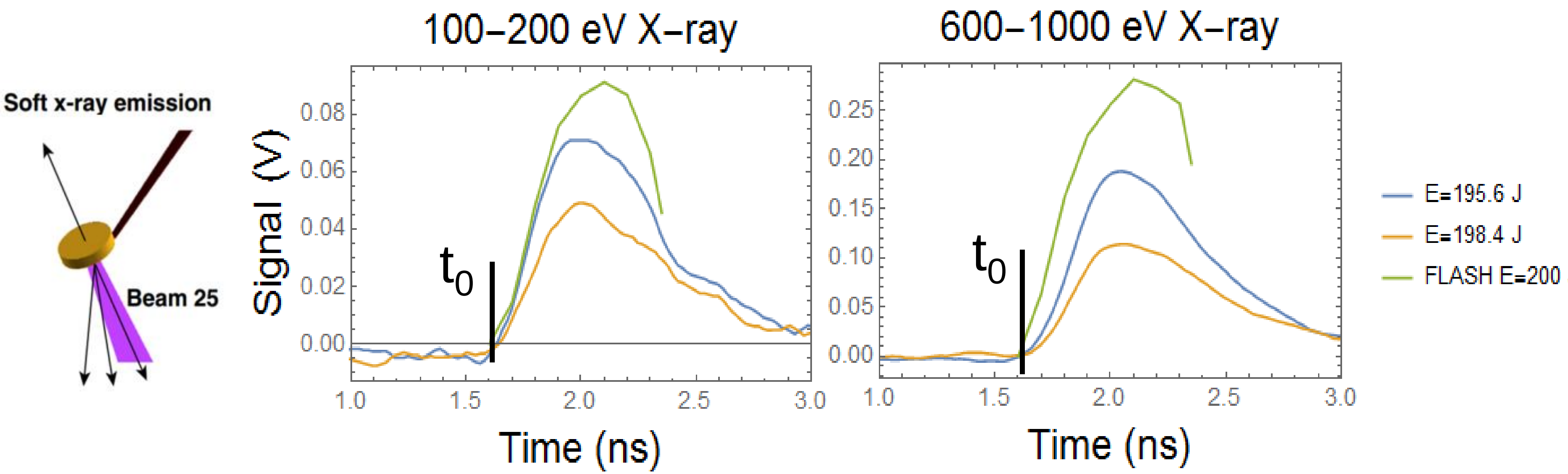
Backscatter from foils and from full targets are very similar and contain a negligible amount of the laser energy.

J.R. Davies, et al., ***Laser entrance window transmission and reflection measurements for preheating in magnetized liner inertial fusion***, submitted to Phys. Plasmas 20 Mar 2018

TC12456a

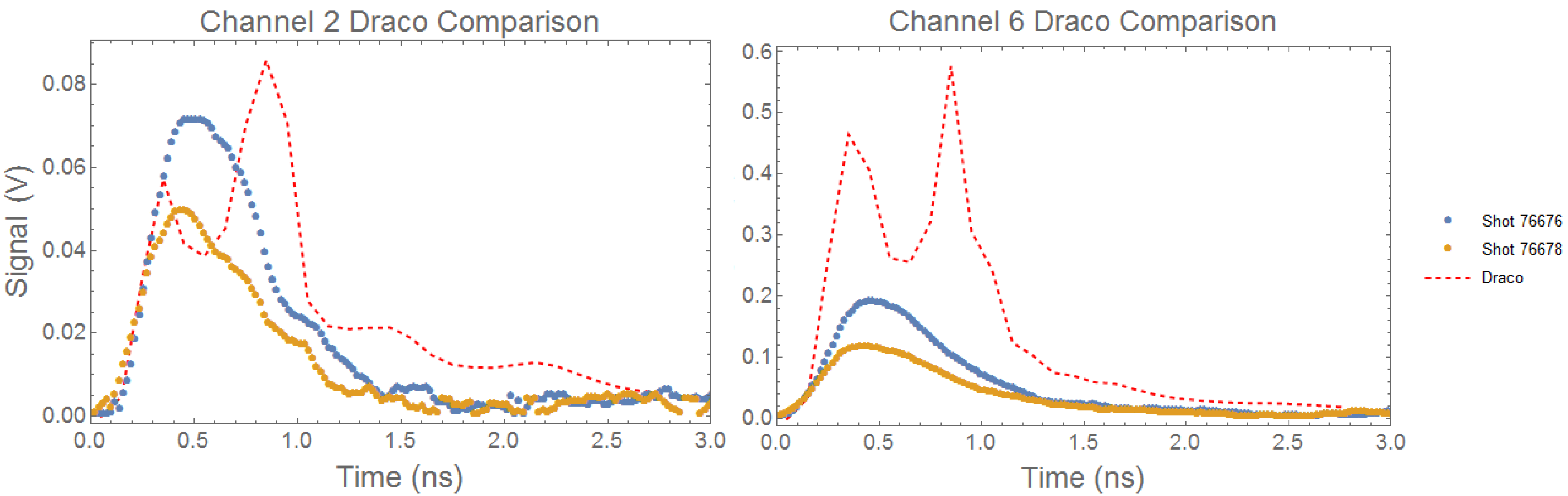
X-ray measurements of the LEH window disassembly is in good agreement with the 2D hydrodynamics code FLASH*

- **Output from the FLASH code is post-processed using SPECT3D atomic modelling to generate simulated Dante traces**



*B. Fryxell et al., Astrophys. J. Suppl. Ser. 131, 273 (2000).

X-ray measurements of the LEH window disassembly is in poor agreement with the 2D hydro code DRACO

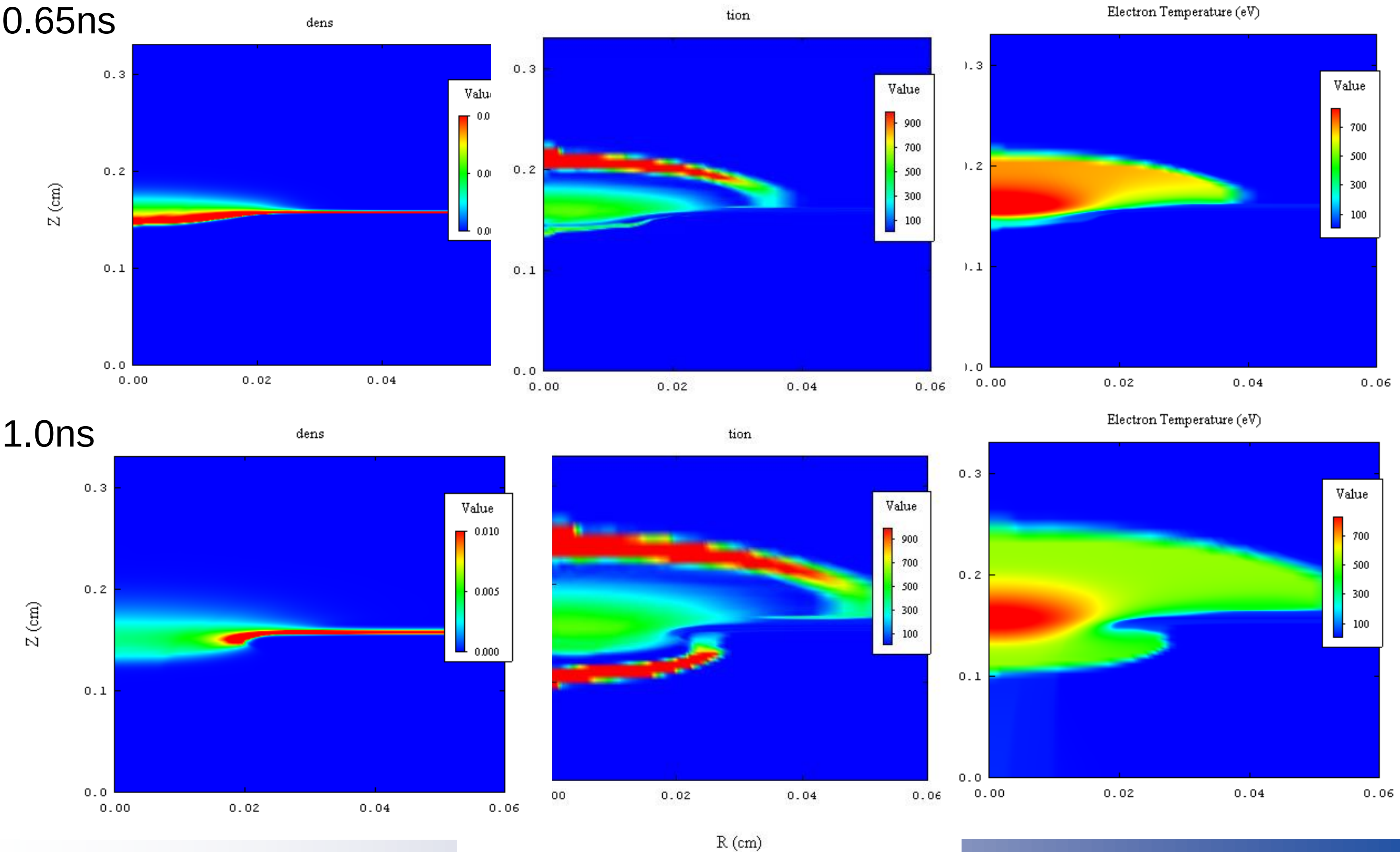


- **DRACO vastly overestimates higher energy photon emission and underestimates lower energy photon emission**
- **DRACO has a much smoother ray tracing algorithm and therefore creates a uniform plasma that slowly expands and constantly absorbs**
- **What's with that double hump??**

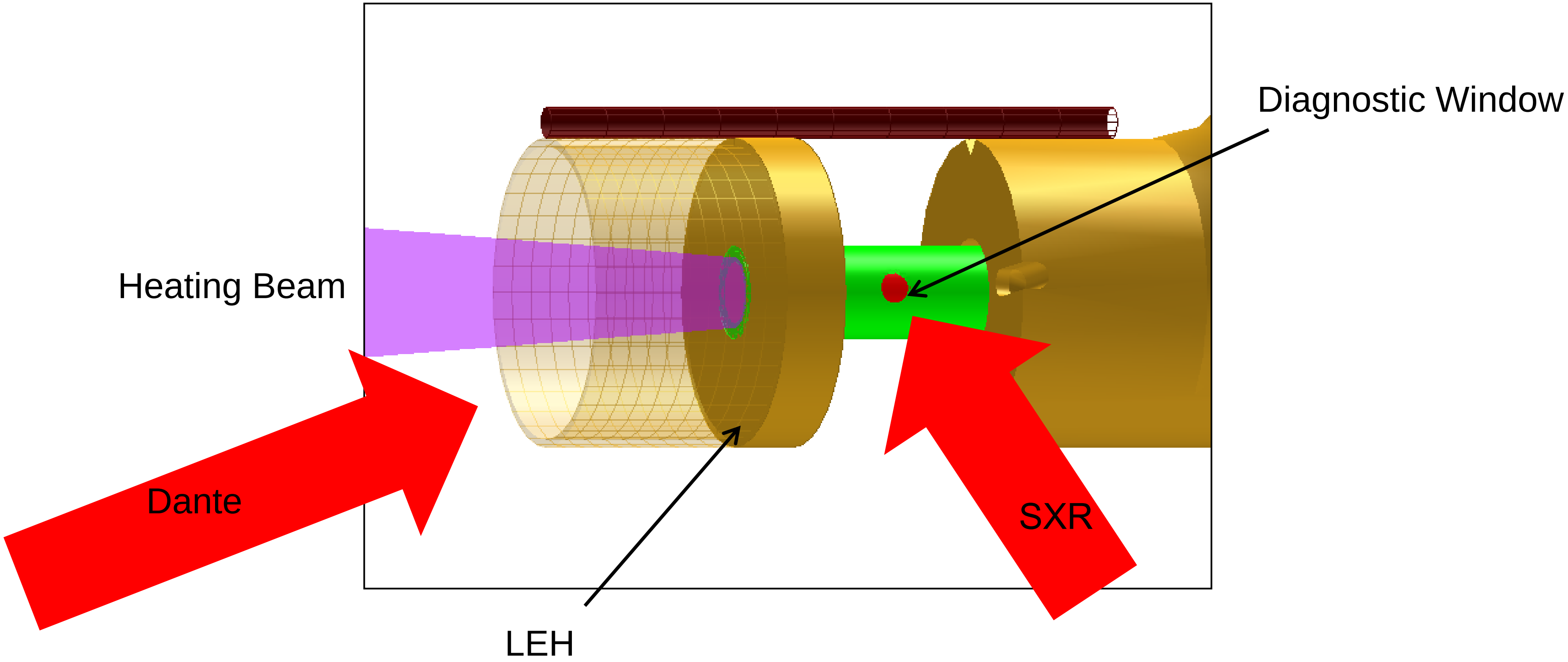
The double hump is from a "space heater" effect of the plasma expanding but not blowing out of the way

t=0.65ns

t=1.0ns



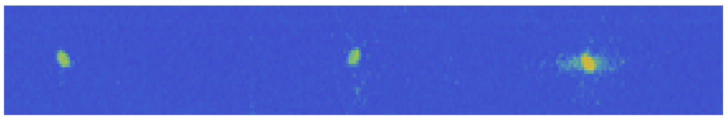
Up to 200 J in a 2.5 ns square pulse was used to heat neon doped (2%$_{at}$) deuterium gas in a fluorinated plastic cylinder with a polyimide entrance window

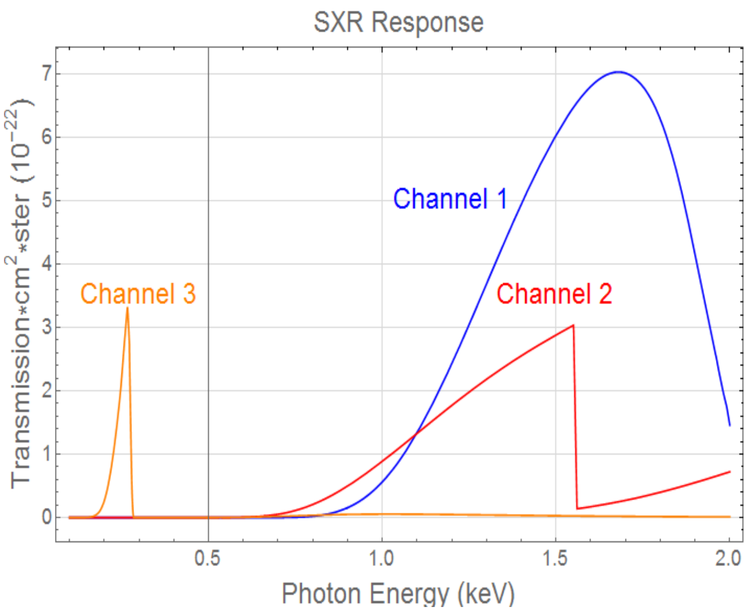


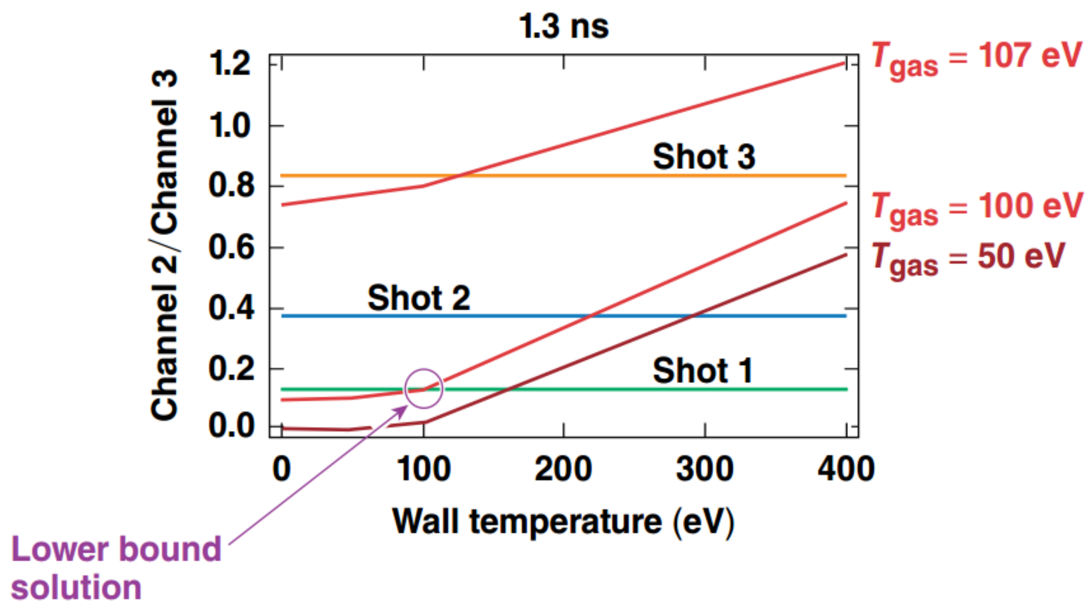
Analysis of soft x-rays from the side window infer a minimum possible gas temperature of 100 eV at 1.3 ns into the laser pulse

Raw soft x-ray data

Ch 1 | Ch 2 | Ch 3

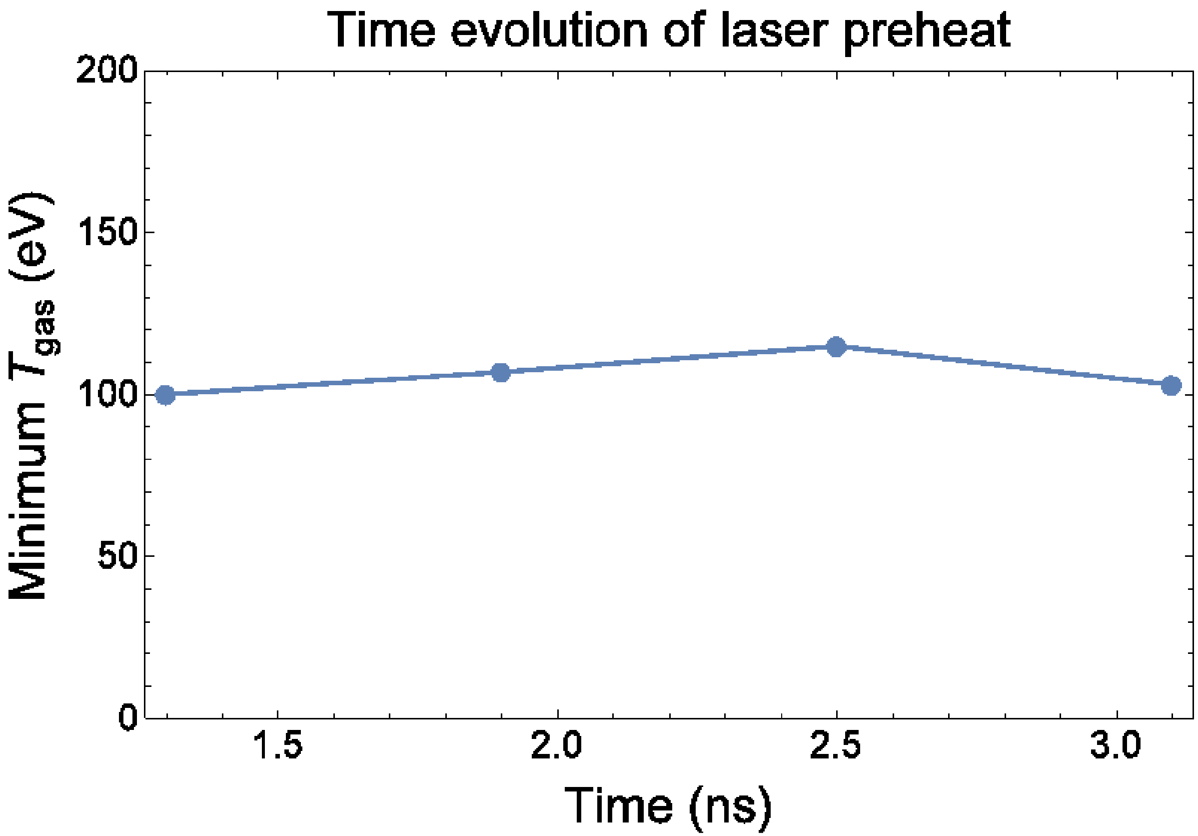




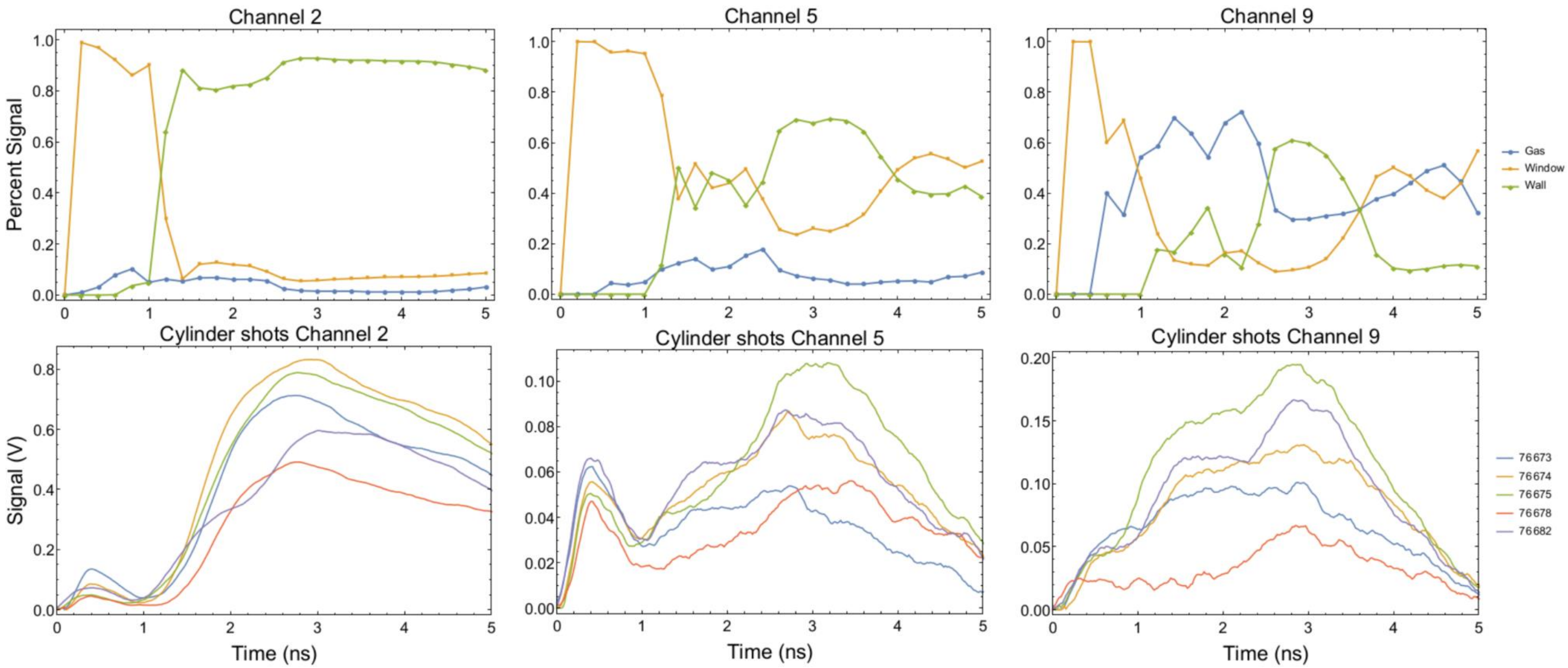


The minimum preheat requirement has been obtained

Time evolution of the laser preheat according to SXR analysis

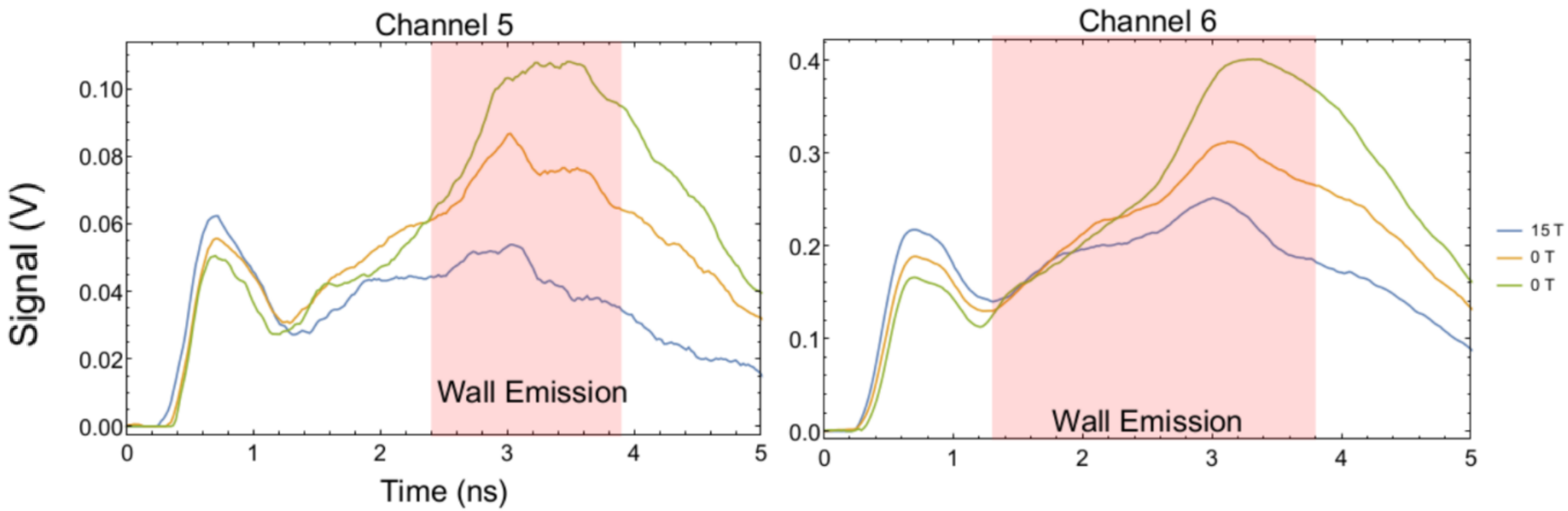


Signal decomposition from 2D DRACO predictions sheds light on what channel signals mean



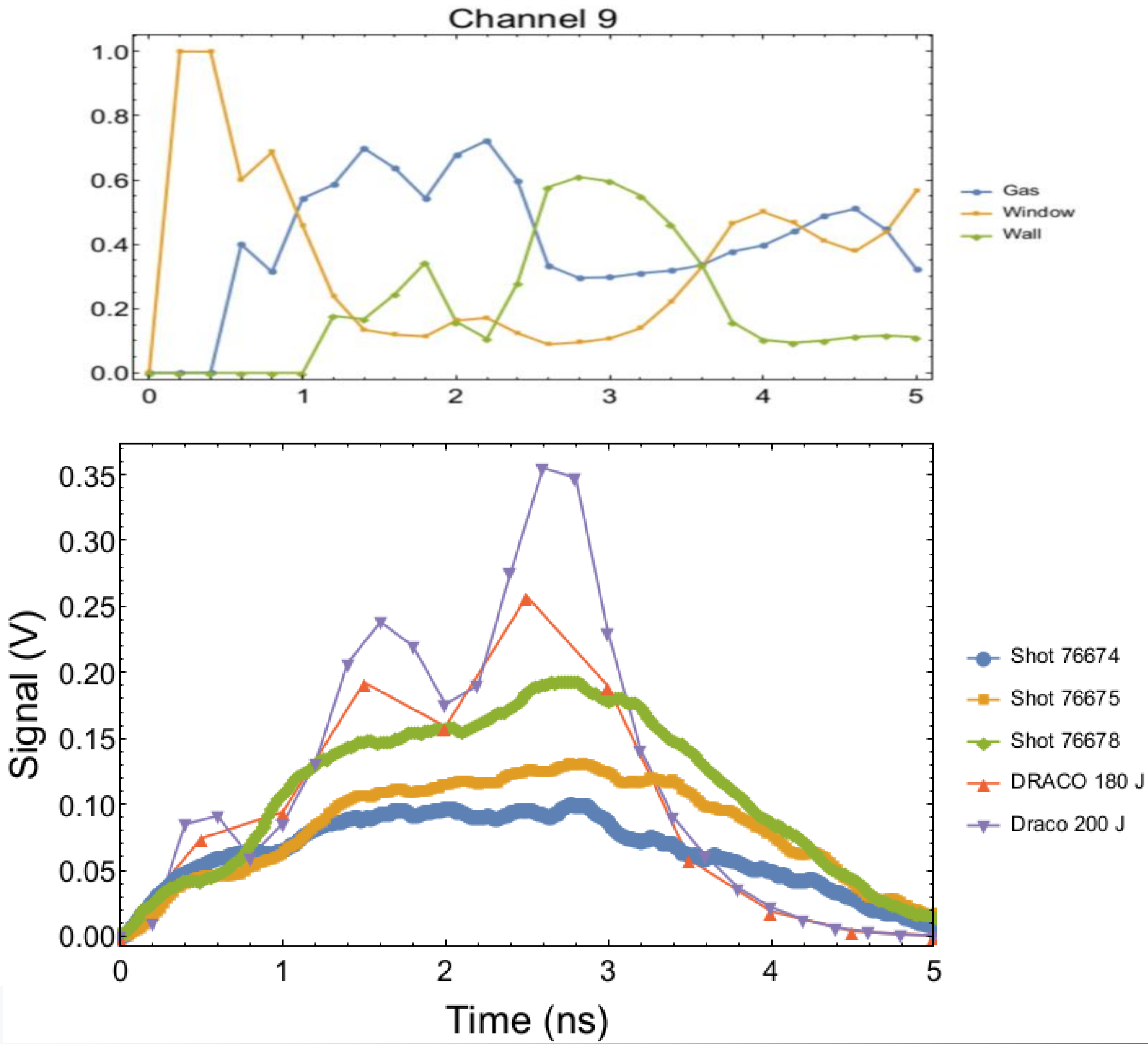
- **All lower photon energy channels of Dante (2-6) see only window and wall emission primarily**
- **Ch 9 sees the gas!**

Wall emission from experiment decreases in the presence of a 15T magnetic field

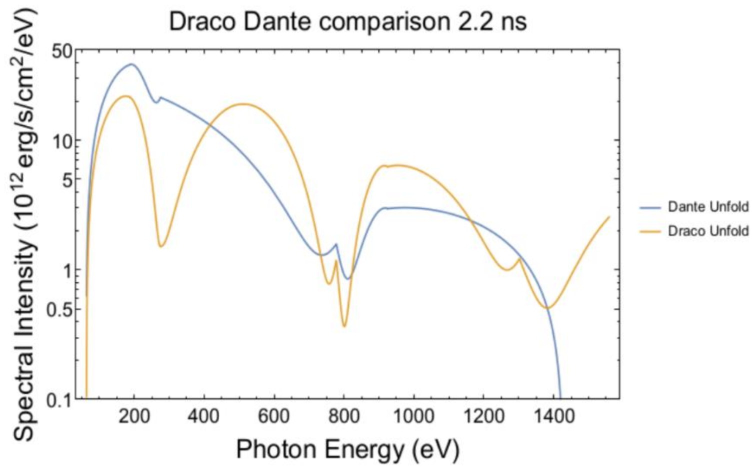


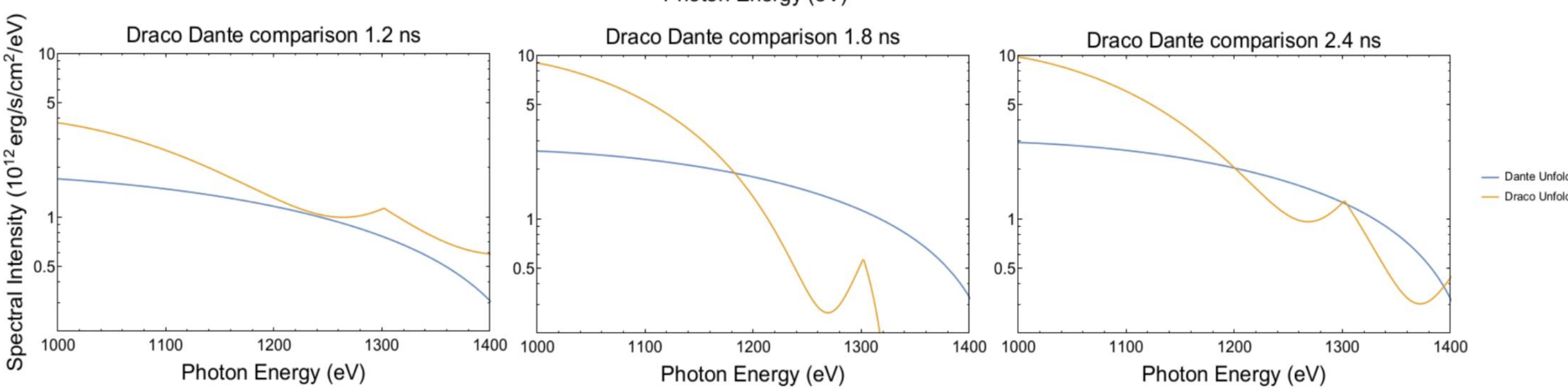
- **Times highlighted in red is when wall emission is predicted to exceed 50% of the signal composition**
- **The trace with magnetic field (blue) shows reduced emission from the wall across all channels**

Gas emission confirms that gas temperature within first 1 mm of the cylinder matches DRACO predictions



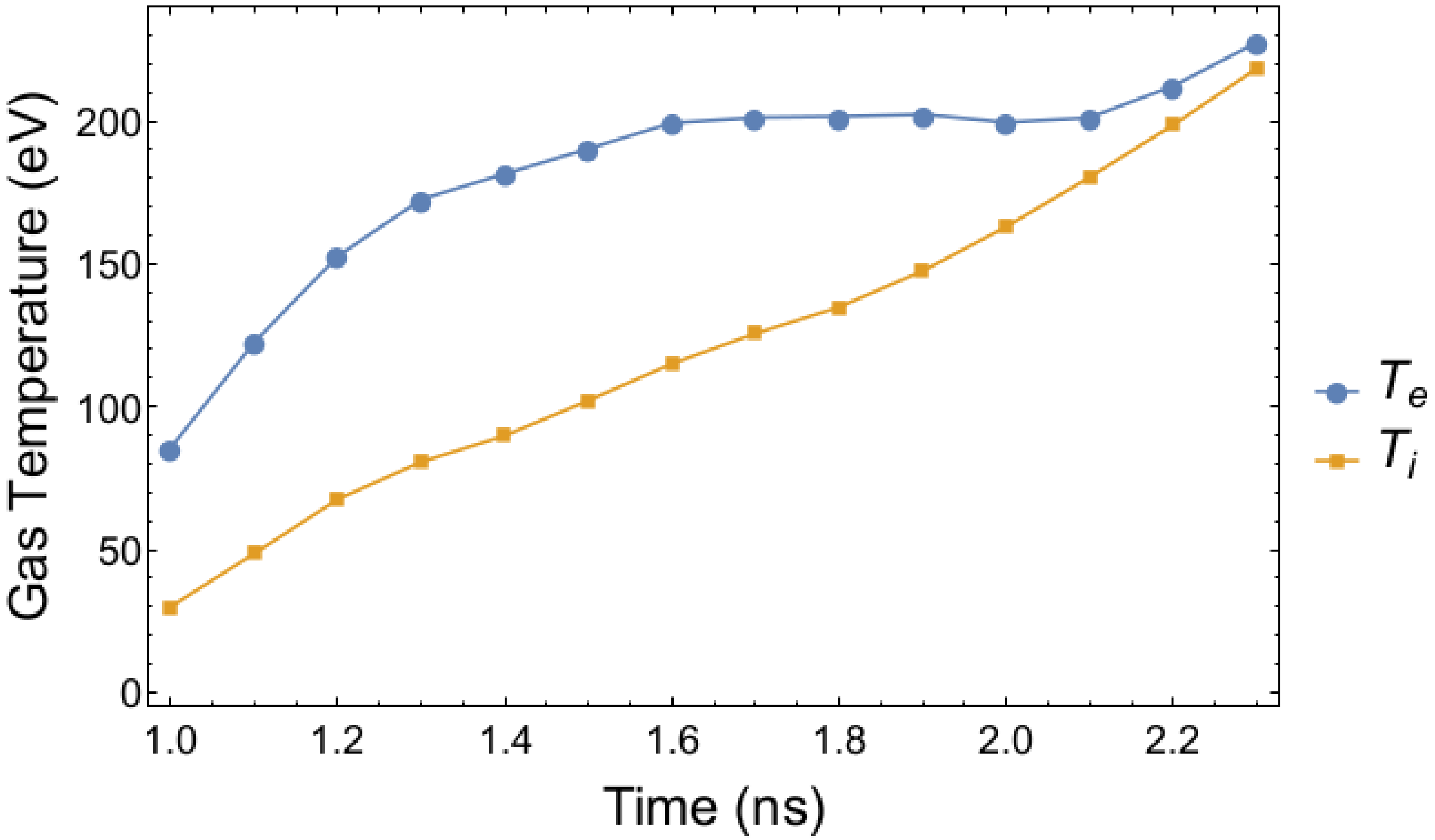
Dante unfold spectrum that contributes to Ch9 signal is within a factor of 4 or better of DRACO spectra





A factor of 10 in intensity corresponds to temperature difference of ~50 eV

Volume averaged electron and ion temperatures of the first 1mm of cylinder according to DRACO



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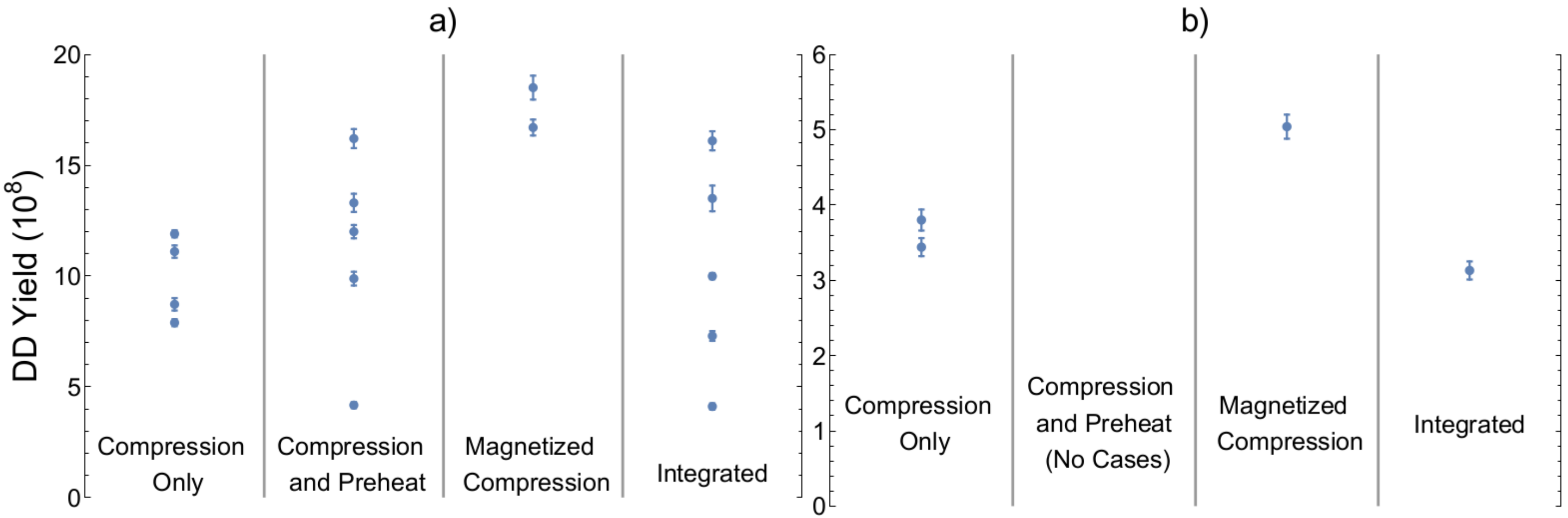
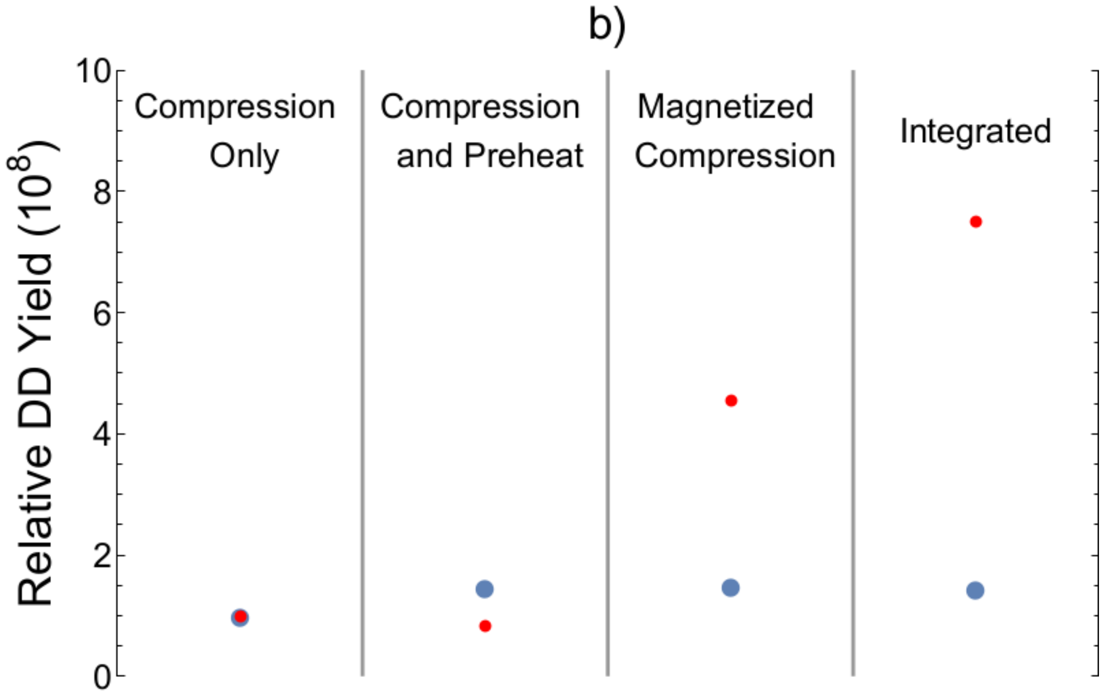
Average neutron yields of all MagLIF shots to date shows a yield enhancement due to magnetization

- **Neutron yields are averaged over all detectors using a $1/\sigma^2$ weighting**
- **Laser preheat varies yield drastically because of preheat beam mis-pointing**
- **No significant benefit from preheating when the compression is magnetized**



1D LILAC predictions exceed experimental measurements

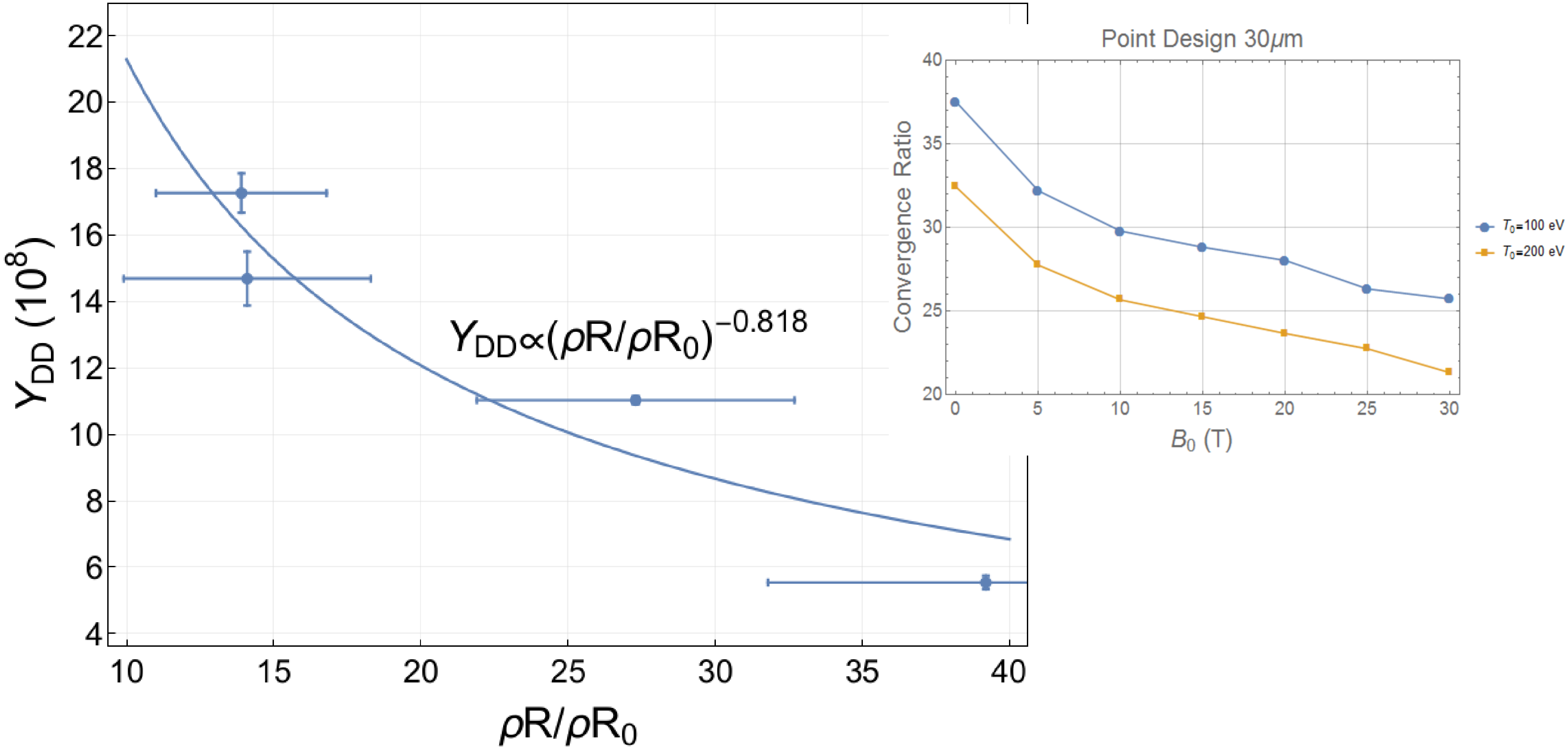
- **1D simulation s matched implosion speed from experiments**
- **Yield enhancement predicted from 1D code is drastically overestimated because of unrealistic convergence ratios**



Secondary DT neutrons can be used to infer gas ρR and convergence ratio experimentally

- The yield of 1 MeV T in DD fusion is the same as the neutron yield
- For $\rho R \ll 12T_{keV}^{3/2}$ mg cm^{-2} energy loss of the T will be negligible
- The DT fusion neutron velocity is much greater than the T velocity so DT neutron emission will be nearly isotropic
- The ratio of DT to DD neutrons is therefore
- $\frac{Y_{DT}}{Y_{DD}} = \frac{1}{m_D}\langle\rho R\rangle\sigma$
  - Where $\langle\rangle$ refers to the T averaged D areal density and σ is the cross section for DT fusion for 1 MeV T and effectively 0 energy D, which corresponds to a CoM energy of 0.4 MeV, which according to Bosch and Hale is 4.13×10^{-29} m^2 (I assume a $\pm$20% error in this cross section)
- For an isotropic point source at the center of a cylinder of radius R and length L the mean path length to the edge $\rightarrow$ (π/2)R for L >> R
- Use $\rho R = \frac{2}{\pi}\frac{m_D}{\sigma}\frac{Y_{DT}}{Y_{DD}} \approx 5.18\frac{Y_{DT}}{Y_{DD}}$ g cm^{-2}

MagLIF experiments show a decrease in neutron yield with increasing convergence ratio



Magnetic field and preheat reduce convergence thereby increasing yield

Estimates of electron and ion Hall parameters demonstrate the need for higher magnetic fields

- Hall parameters calculated using neutron-averaged T_i and assuming flux loss predictions from 1D for each shot type
- Electron Hall parameters for integrated shots are lower due to additional flux loss from preheat.
- Higher initial magnetic fields are required to ensure the fuel is magnetized throughout the compression

Shot Number	Shot Type	χ_e	χ_i
85561	Compress+Mag (11 atm)	7.06 ± 2.53	0.165 ± 0.06
85562	Compress+Mag (11 atm)	7.65 ± 1.50	0.179 ± 0.04
85564	Compress+Mag (7 atm)	9.91 ± 1.10	0.232 ± 0.03
85567	Compress+Mag (7 atm)	9.62 ± 1.76	0.225 ± 0.04
84313	Integrated (11 atm)	6.22 ± 0.98	0.146 ± 0.02
85558	Integrated (11 atm)	5.39 ± 0.16	0.126 ± 0.01
85559	Integrated (7 atm)	9.99 ± 0.92	0.23 ± 0.02
85560	Integrated (11 atm)	5.51 ± 2.21	0.13 ± 0.05