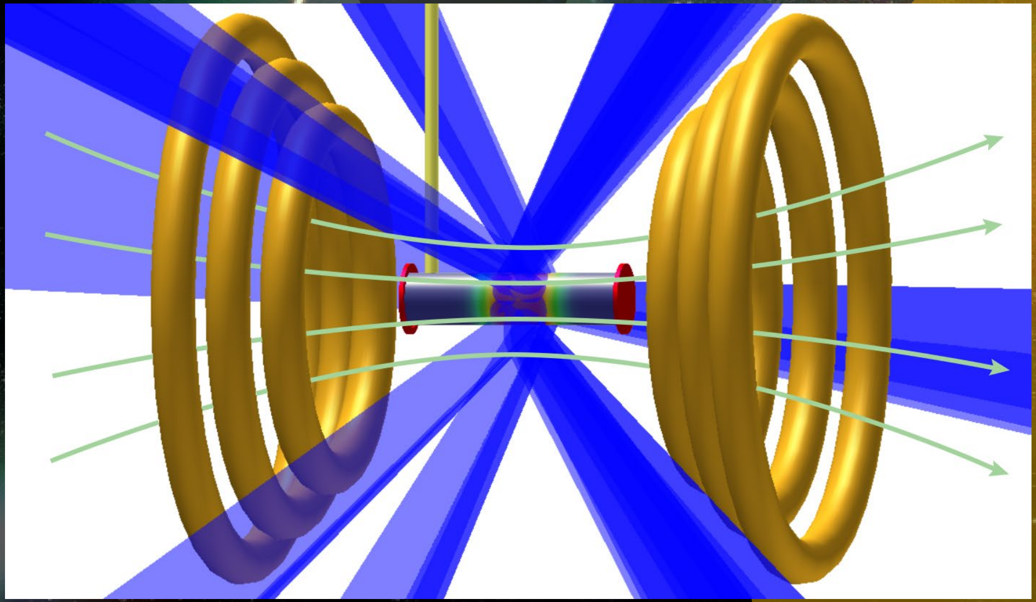
Quantifying compressed magnetic field and its effects on the imploded core conditions

Characterizing the effect of strong magnetization in cylindrically imploded hot dense plasmas



Project funded by DOE Office of Science
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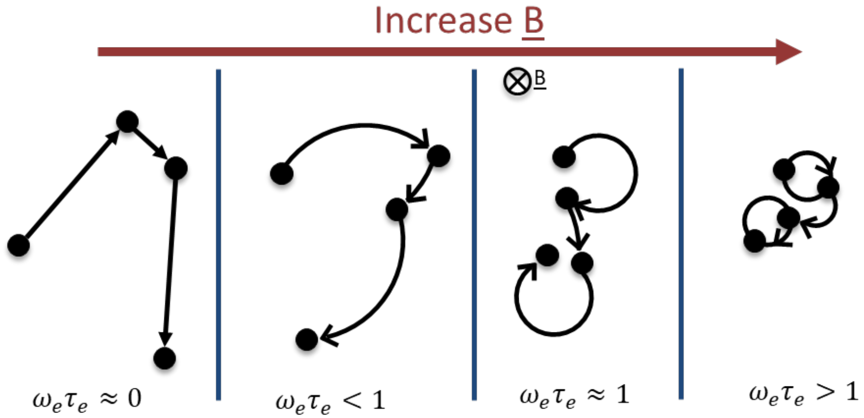
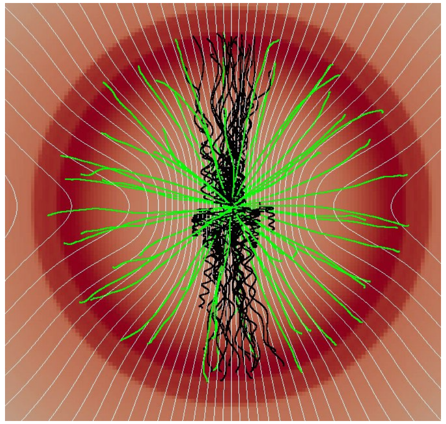
MAGNETIZATION CAN ENHANCE CORE TEMPERATURES AND CONFINE ALPHAS IN THE FUSION PLASMA

Magnetizing electrons reduces thermal conduction losses



$$\frac{dE}{dt} = \overset{\alpha\ \text{heating}}{P_\alpha} + \underset{\text{mechanical work}}{P_{PdV}} - \overset{\text{thermal losses}}{P_k} - \underset{\text{radiative losses}}{P_{rad}} > 0$$

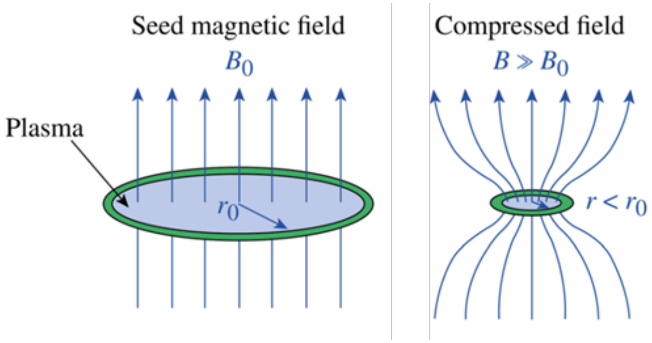
Magnetizing alphas reduces ρR requirements



Magnetized and **unmagnetized** α-particles trajectories over the hot spot of an ICF imploded target

Courtesy of Phil Maloney and Jerry Chittenden, ICLondon)

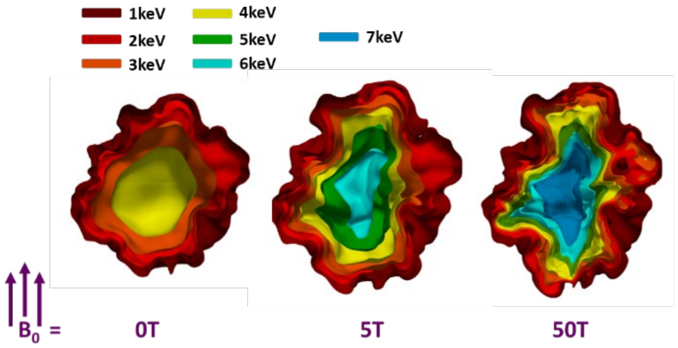
B-field compressibility



$$B_f \overset{?}{\approx} B_0\left(\frac{r_0}{r}\right)^2$$

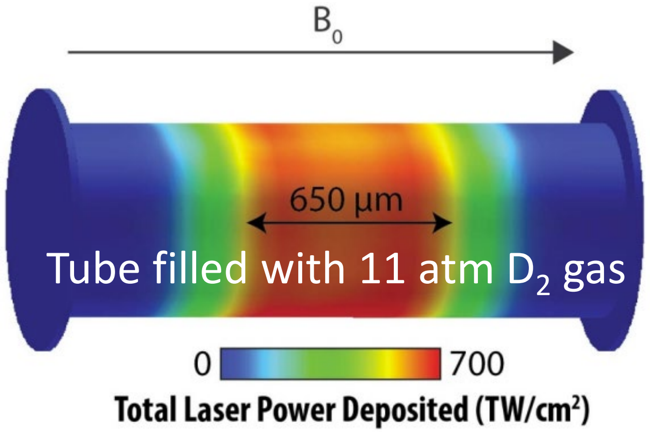
B-field resistive diffusion and extended-MHD effects (Nernst, Hall) can reduce B-field compression

Magnetized heat transport during hot spot formation

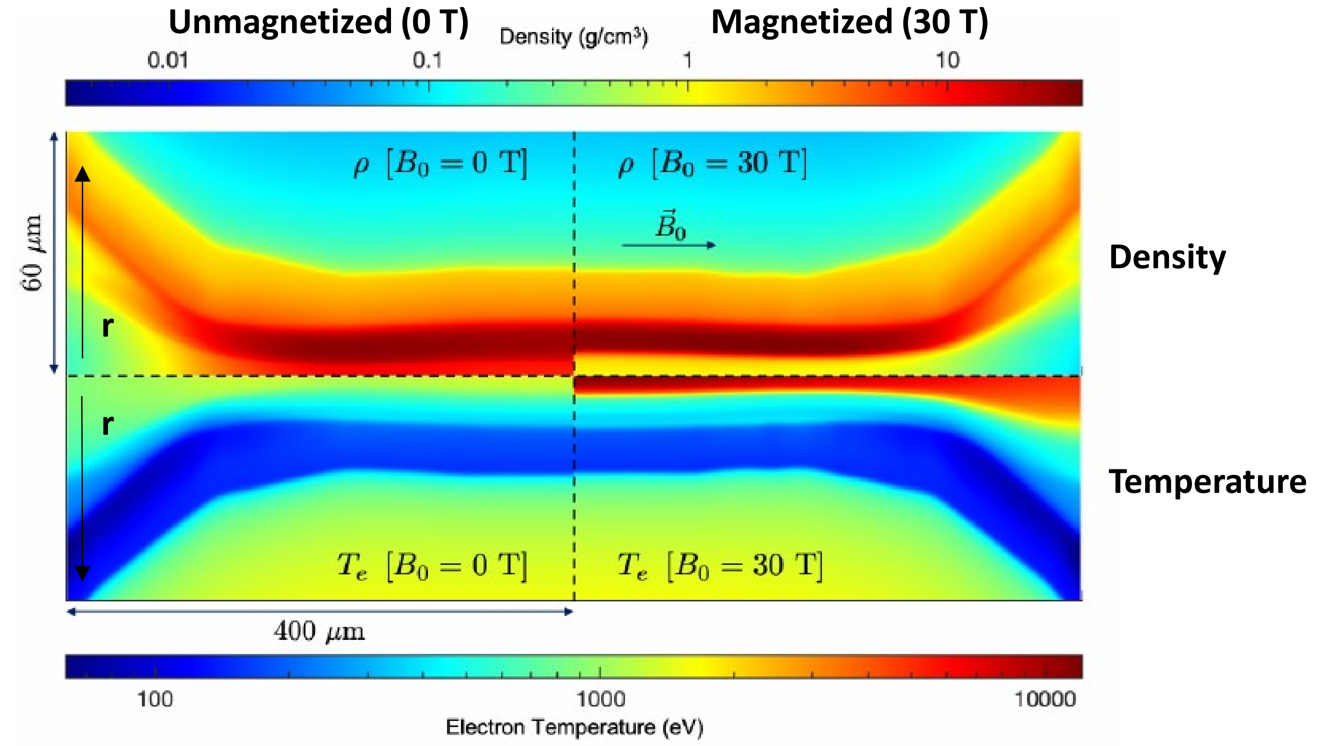


C. A. Walsh, et. al, Physics of Plasmas (2019)

EXTENDED-MHD SIMULATIONS SHOW A STRONG MODIFICATION OF THE COMPRESSED CORE CONDITIONS BY THE COMPRESSED B-FIELD



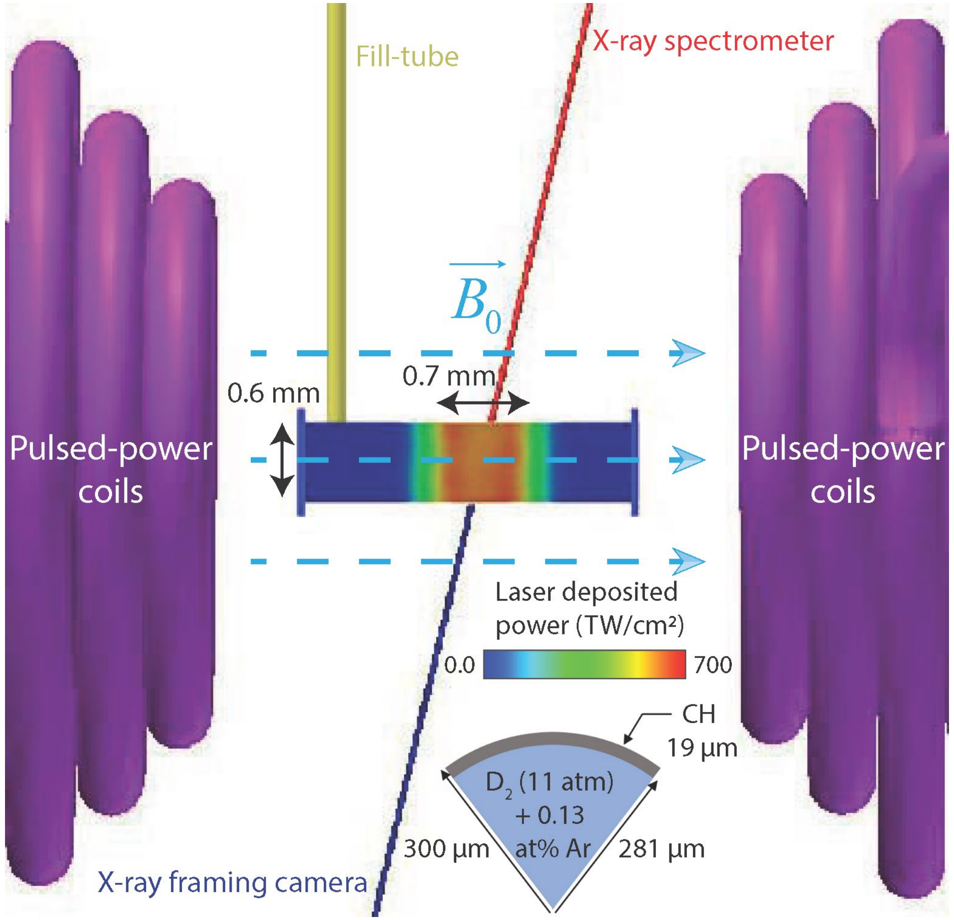
Cylindrical illumination on OMEGA
40 beams, 14.5 kJ in 1.5 ns



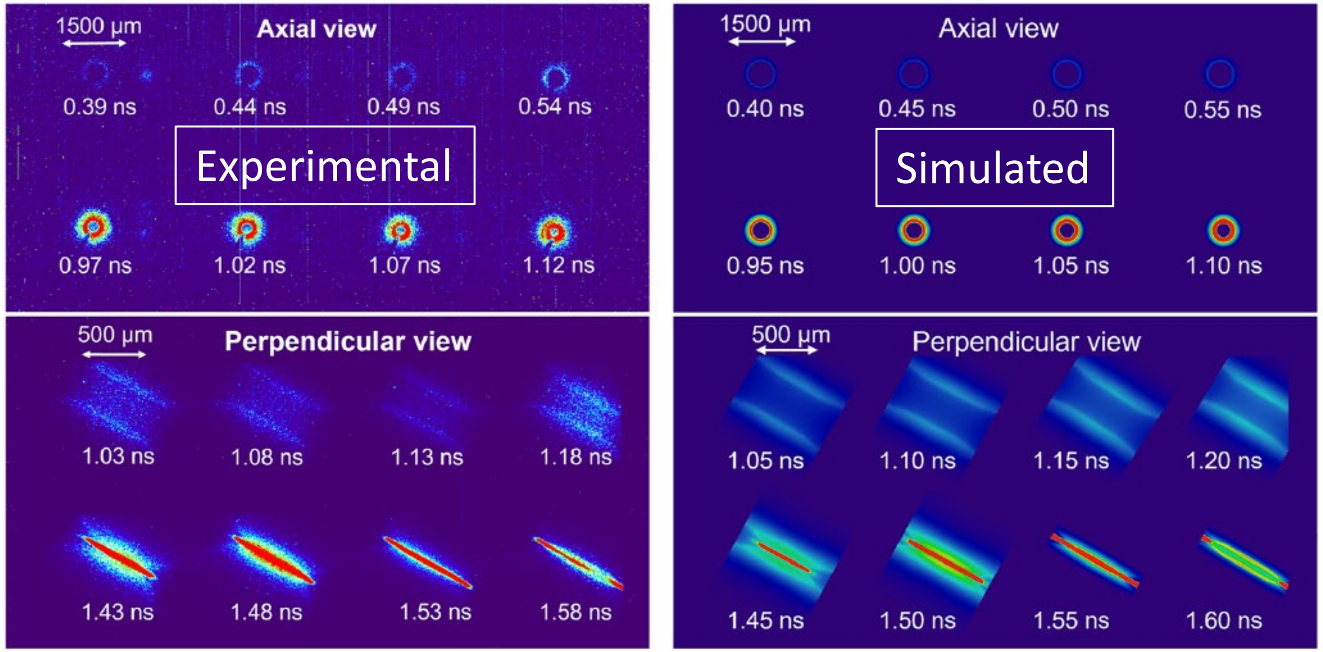
With $B_0 = 30\,\mathrm{T}$, the compressed core is **highly magnetized** and hosts a **large magnetic pressure**, which strongly affects the compressed core plasma conditions.

C. A. Walsh, R. Florido, M. Bailly-Grandvaux, *et al.*, *"Exploring extreme magnetization phenomena in directly driven imploding cylindrical targets"*, Plasma Phys. Control. Fusion **64**, 025007 (2022)

NOVEL EXPERIMENTS WITH DOPANT K-SHELL EMISSION SPECTROSCOPY TO INFER PLASMA CONDITIONS OF THE CORE



Applied 30 T magnetic field to a D_2 gas-fill implosion



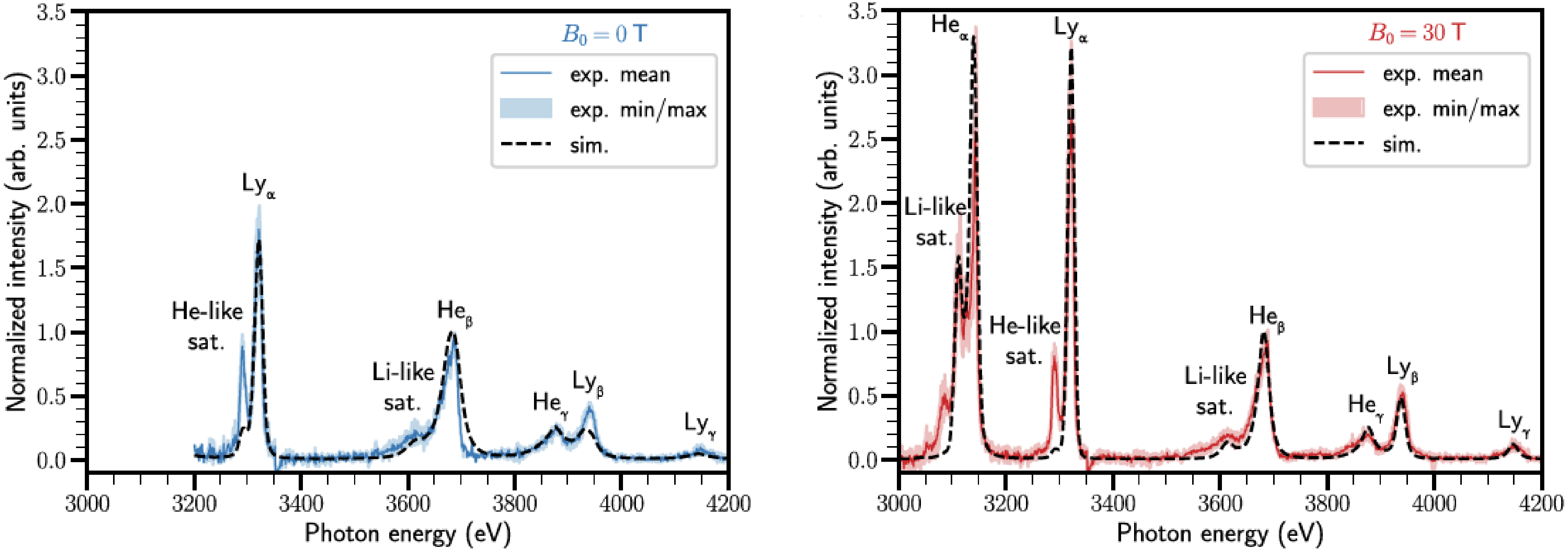
G. Peréz-Callejo, M. Bailly-Grandvaux *et al., Review of Scientific Instruments* ***93****, 113542 (2022)*

The implosion has been characterized with X-ray imaging

Convergence ratio CR~20

THE IMPACT OF A 10 kT B-FIELD ON CORE CONDITIONS ARE MEASURED VIA X-RAY EMISSION SPECTROSCOPY

Comparison with synthetic spectra from MHD simulations

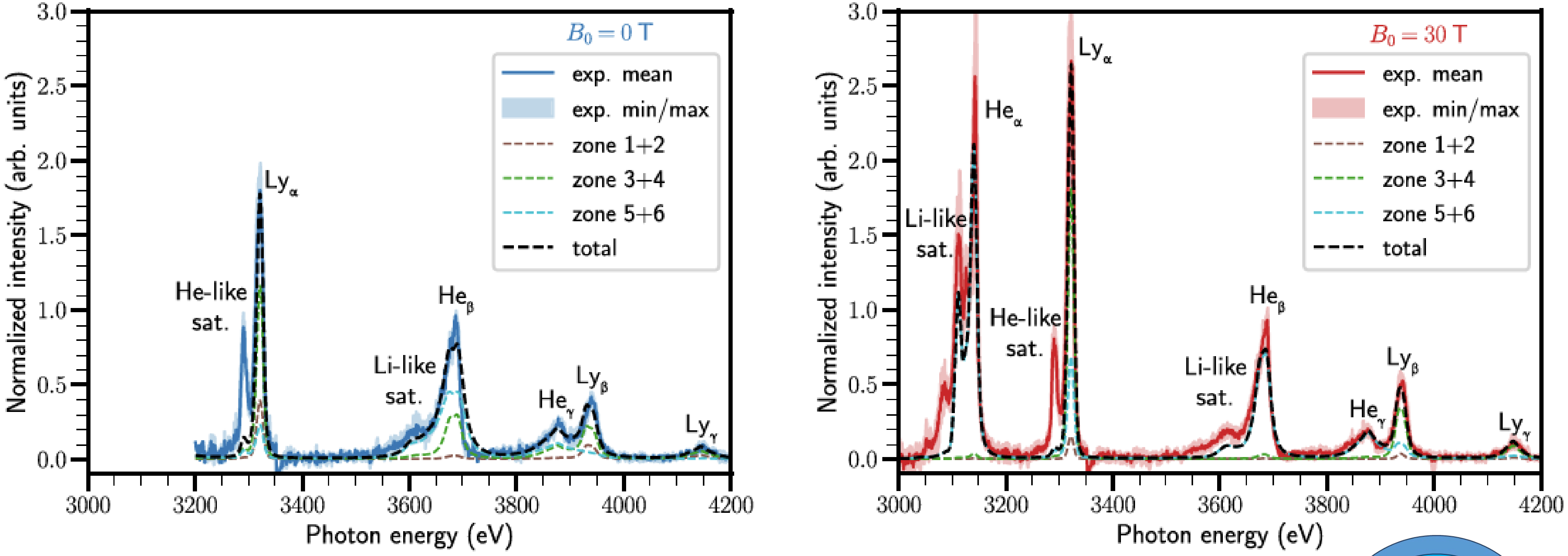


M. Bailly-Grandvaux *et al., Physical Review Research* ***6****, L012018 (2024)*

- Systematic changes in the Ar K-shell spectra are observed between unmagnetized (B_0=0 T) and magnetized (B_0=30 T) cases, with a high level of reproducibility.
- Good agreement with synthetic spectra calculated from MHD simulations (CR~20, ~10 kT compressed B-field).

THE IMPACT OF A 10 KT B-FIELD ON CORE CONDITIONS ARE MEASURED VIA X-RAY EMISSION SPECTROSCOPY

Comparison with a multi-zone spectroscopic model of the core

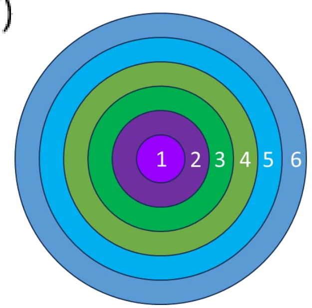


M. Bailly-Grandvaux *et al.*, *Physical Review Research* ***6****, L012018 (2024)*

- A multi-zone spectroscopic analysis (6 core radial zones) confirms a record core temperature increase of 50% and halved density with B_0=30 T.

$\langle\rho\rangle = 3.22 \pm 0.11\ \mathrm{g/cm^3}$ $\langle\rho\rangle = 1.46 \pm 0.14\ \mathrm{g/cm^3}$

$\langle T_e\rangle = 998 \pm 44\ \mathrm{eV}$ $\langle T_e\rangle = 1460 \pm 90\ \mathrm{eV}$

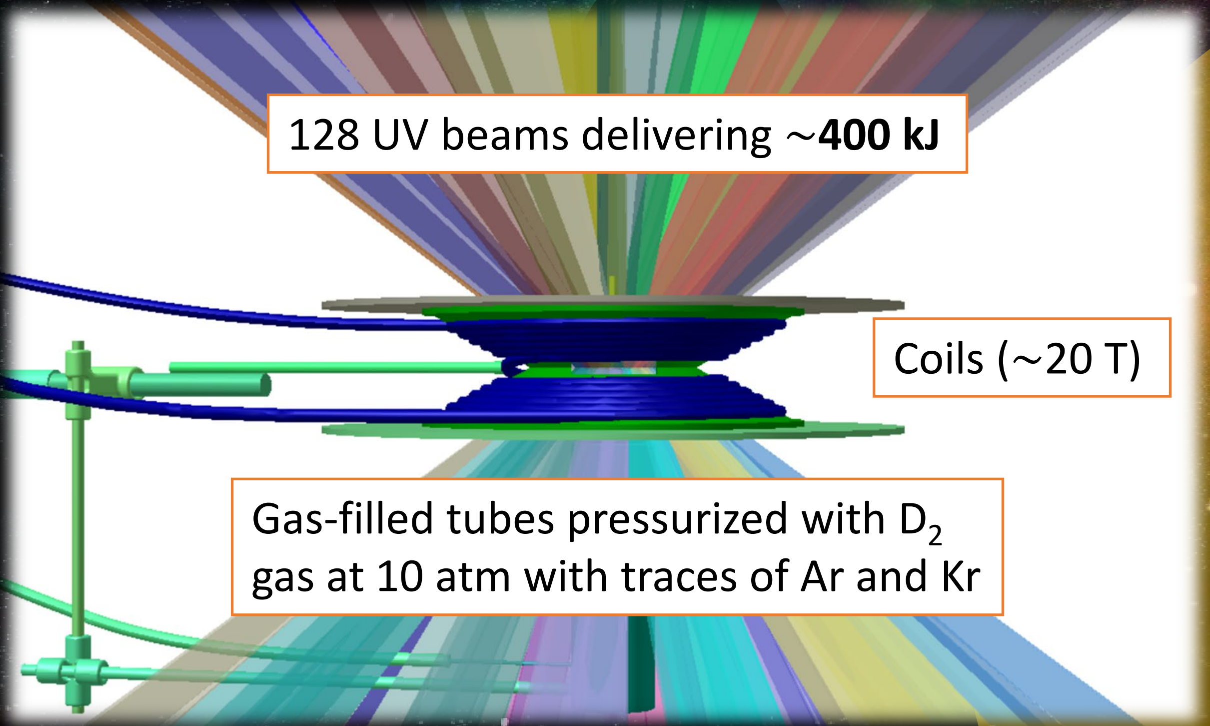


$B_f \approx \mathrm{CR}^2$
≈ 12 kT

Measure:
≈ 10 kT

Discovery Science project on NIF

Quantifying extended-MHD effects and confinement properties of strongly magnetized cylindrical implosions



128 UV beams delivering ~**400 kJ**

Coils (~20 T)

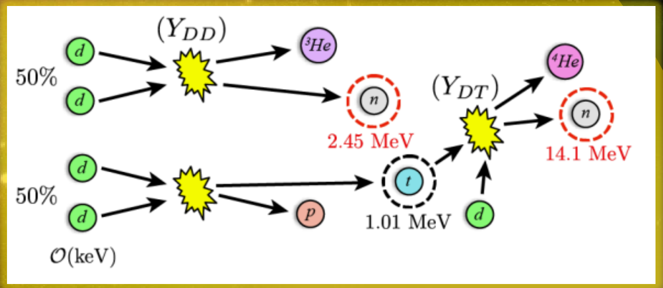
Gas-filled tubes pressurized with D_2 gas at 10 atm with traces of Ar and Kr

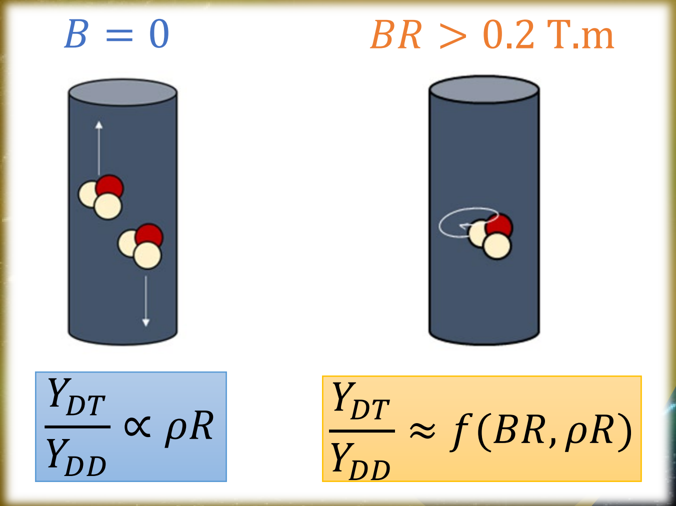
Two shot days on NIF in 2024 & 2025

- *Tubes of 4 mm diameter*
- *Core of 50-100 μm radius*
- *BR up to 0.9 T.m (compared to ~0.1 T.m on OMEGA)*

The larger implosions on NIF enables tritium trapping:

→ B-field strength and topology can be inferred using secondary neutron measurements





$B = 0$

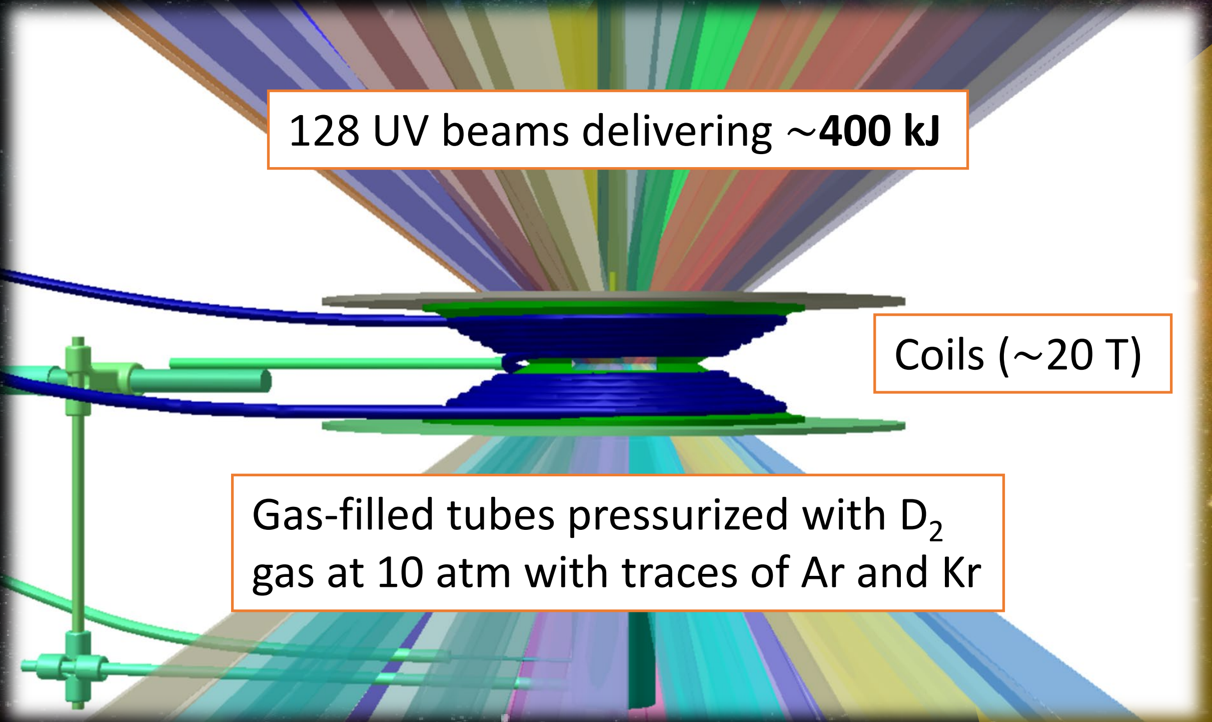
$BR > 0.2$ T.m

$$\frac{Y_{DT}}{Y_{DD}} \propto \rho R$$

$$\frac{Y_{DT}}{Y_{DD}} \approx f(BR, \rho R)$$

Discovery Science project on NIF

Quantifying extended-MHD effects and confinement properties of strongly magnetized cylindrical implosions



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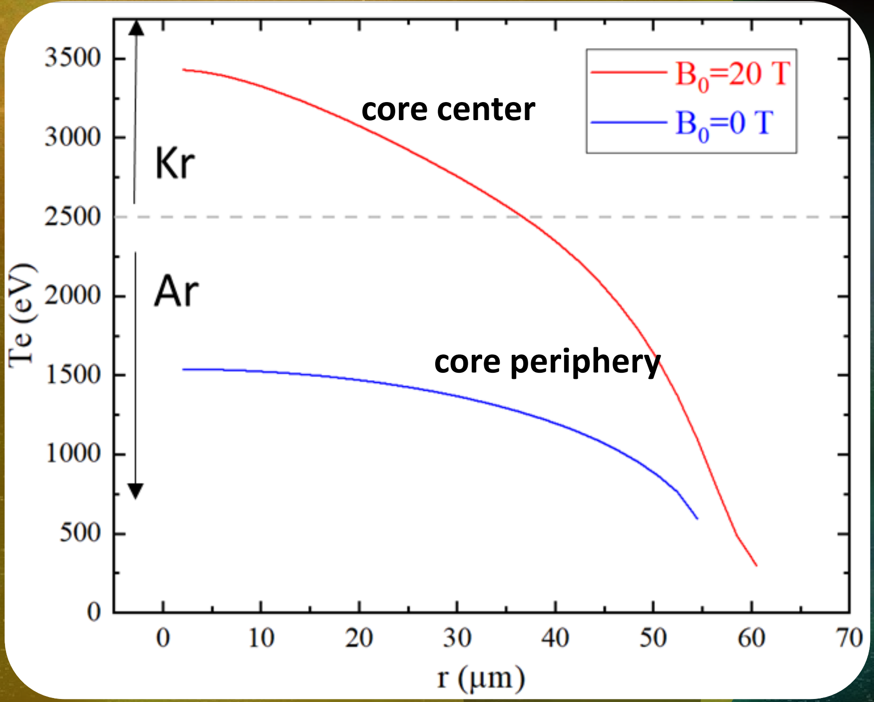
Dual dopant spectroscopy (Ar+Kr) allows to simultaneously infer temperature of the <u>core periphery</u> and <u>core center</u>:

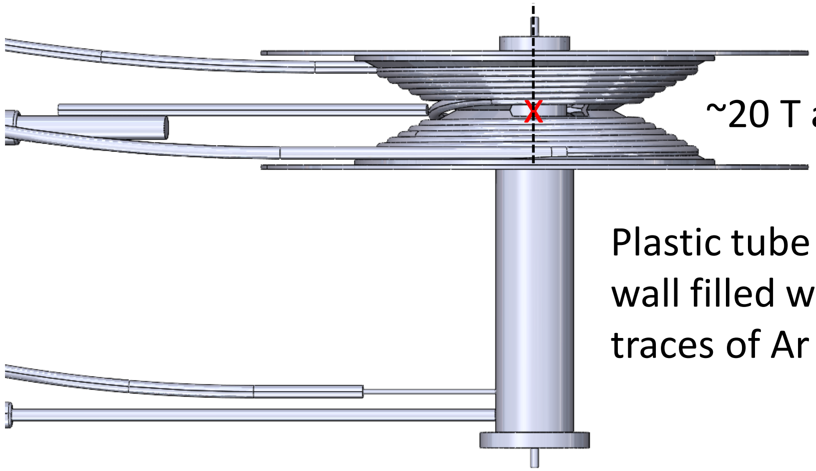
→ Fine characterization of magnetization effects



G. Pérez-Callejo *et al.*, *Physical Review E* ***106***, *035206 (2022) - LMJ*

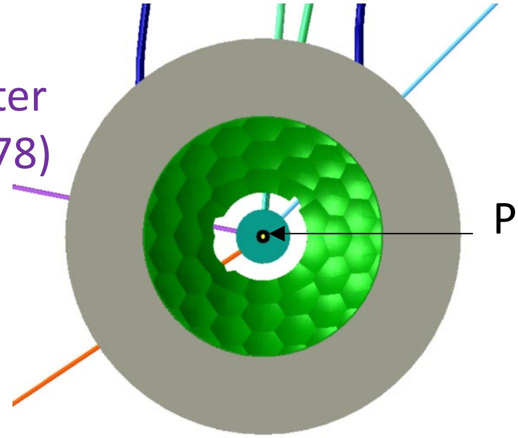
THE DESIGN OF MAGNETIZED CYLINDRICAL IMPLOSIONS ON NIF

Target and diagnostics



~20 T at TCC

Plastic tube with 50 µm-thick wall filled with 10 atm of D_2 and traces of Ar and Kr



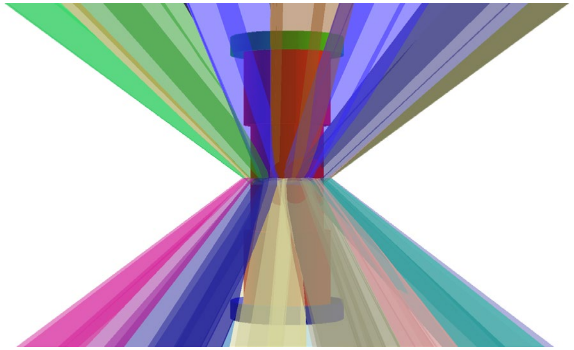
Ar spectrometer (NXS – 90-315)

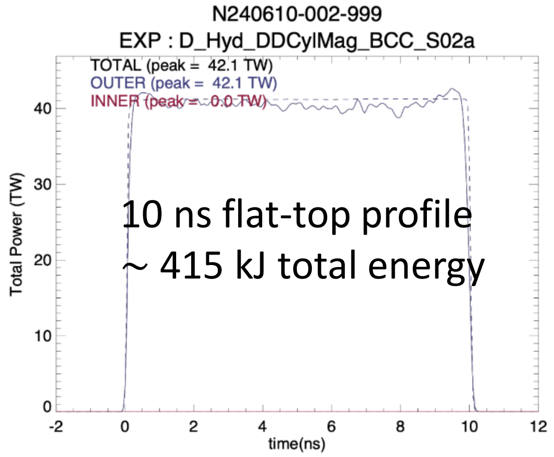
Kr spectrometer (dHIRES – 90-78)

Polar GXD (0-0)

Radial GXD (90-124)

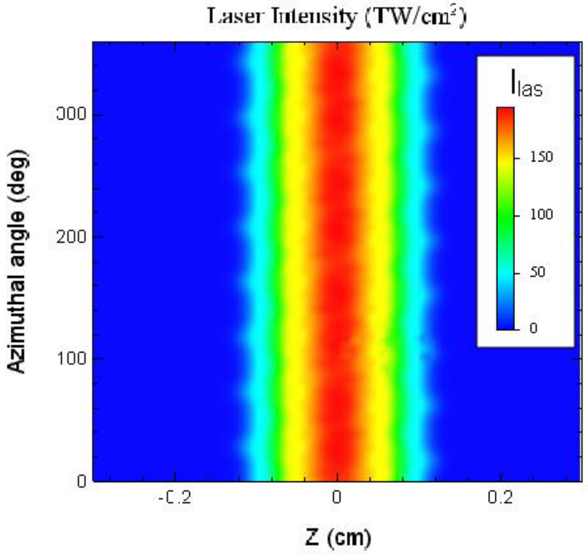
NIF illumination





10 ns flat-top profile

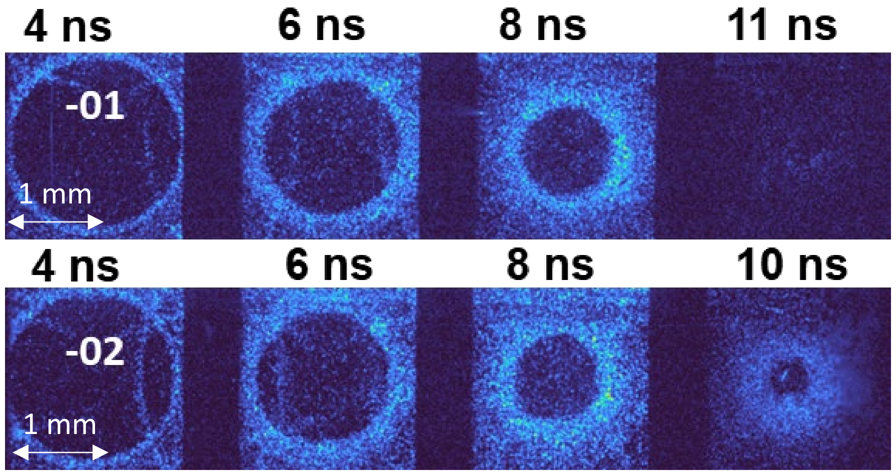
~ 415 kJ total energy

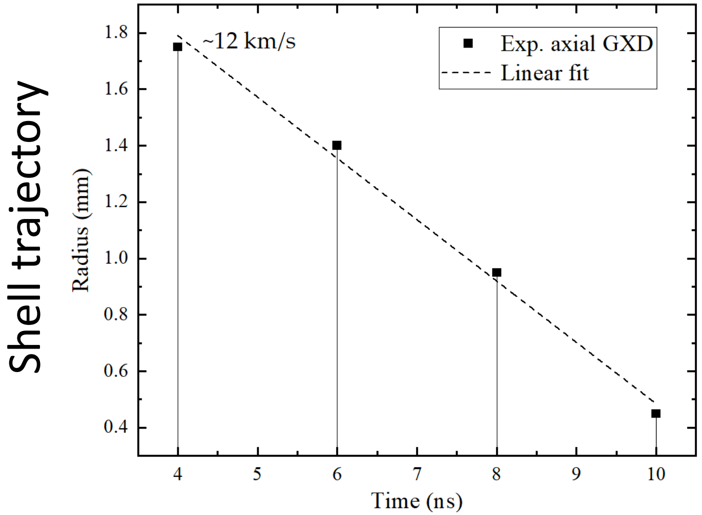


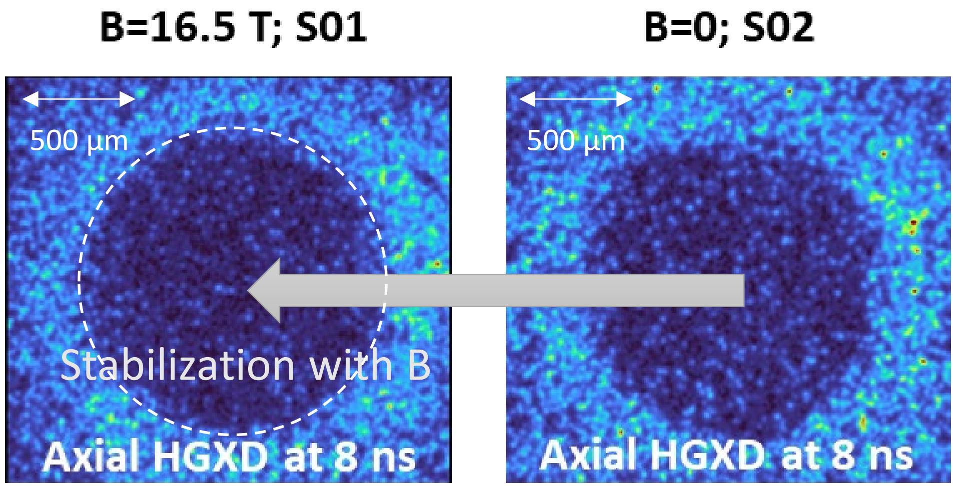
- 128 outer beams with quad-split drive (±45° and ±50°)
- Inherent mode-8 asymmetry due to NIF beams' geometry

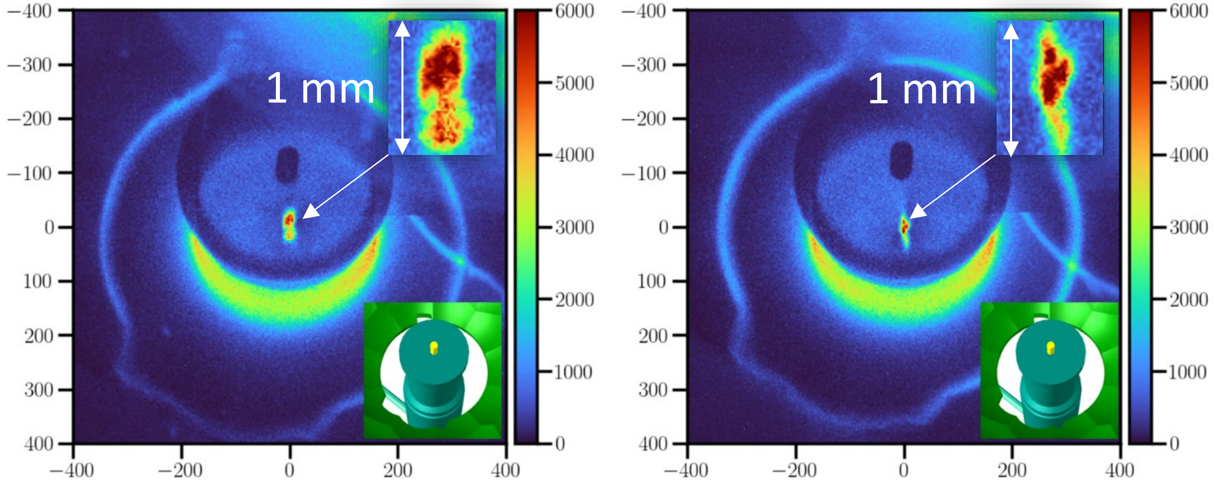
X-RAY IMAGING SHOWS A MORE UNIFORM IMPLOSION WITH APPLIED B-FIELD

Axial X-ray imaging (HGXD 0-0)

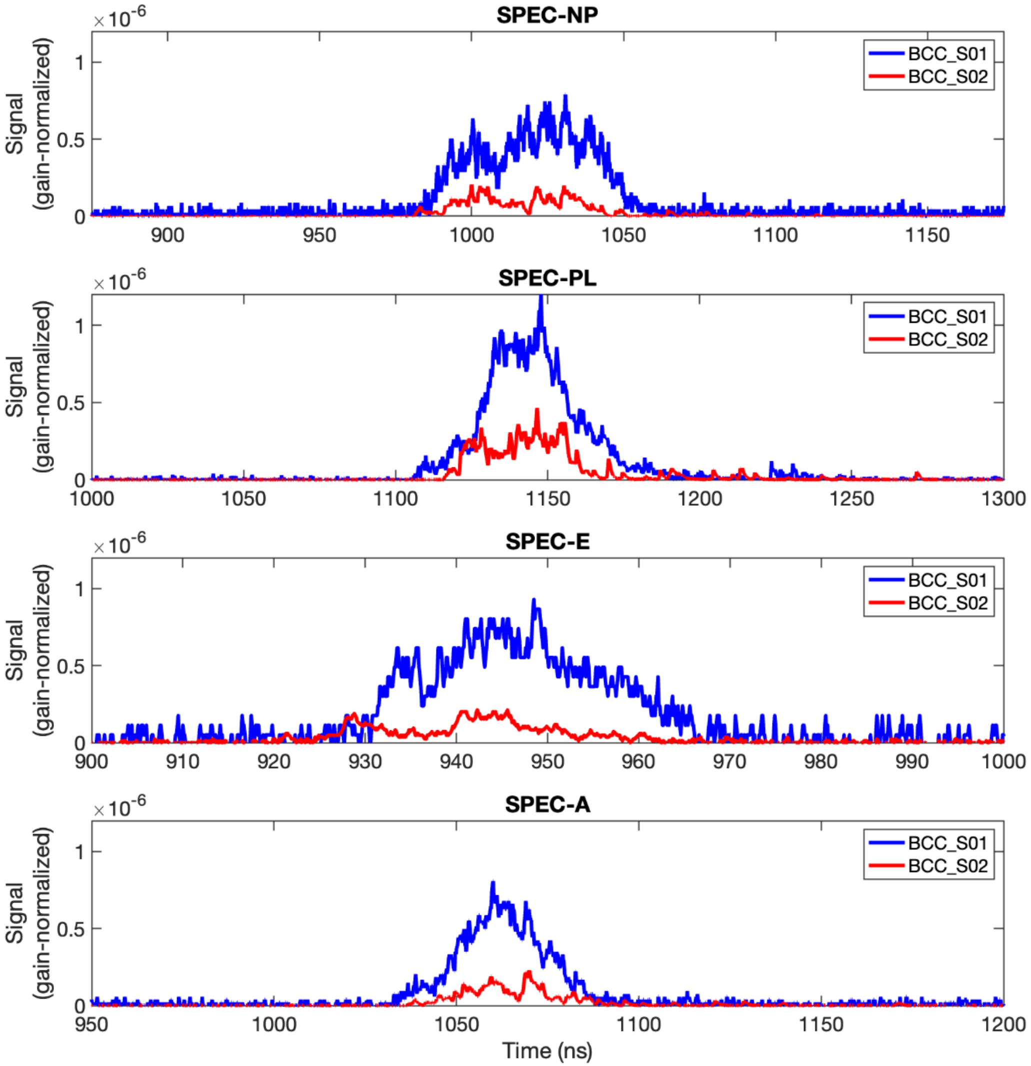








THE MAGNETIZED SHOT HAS ABOUT 3X HIGHER DD NEUTRON YIELD

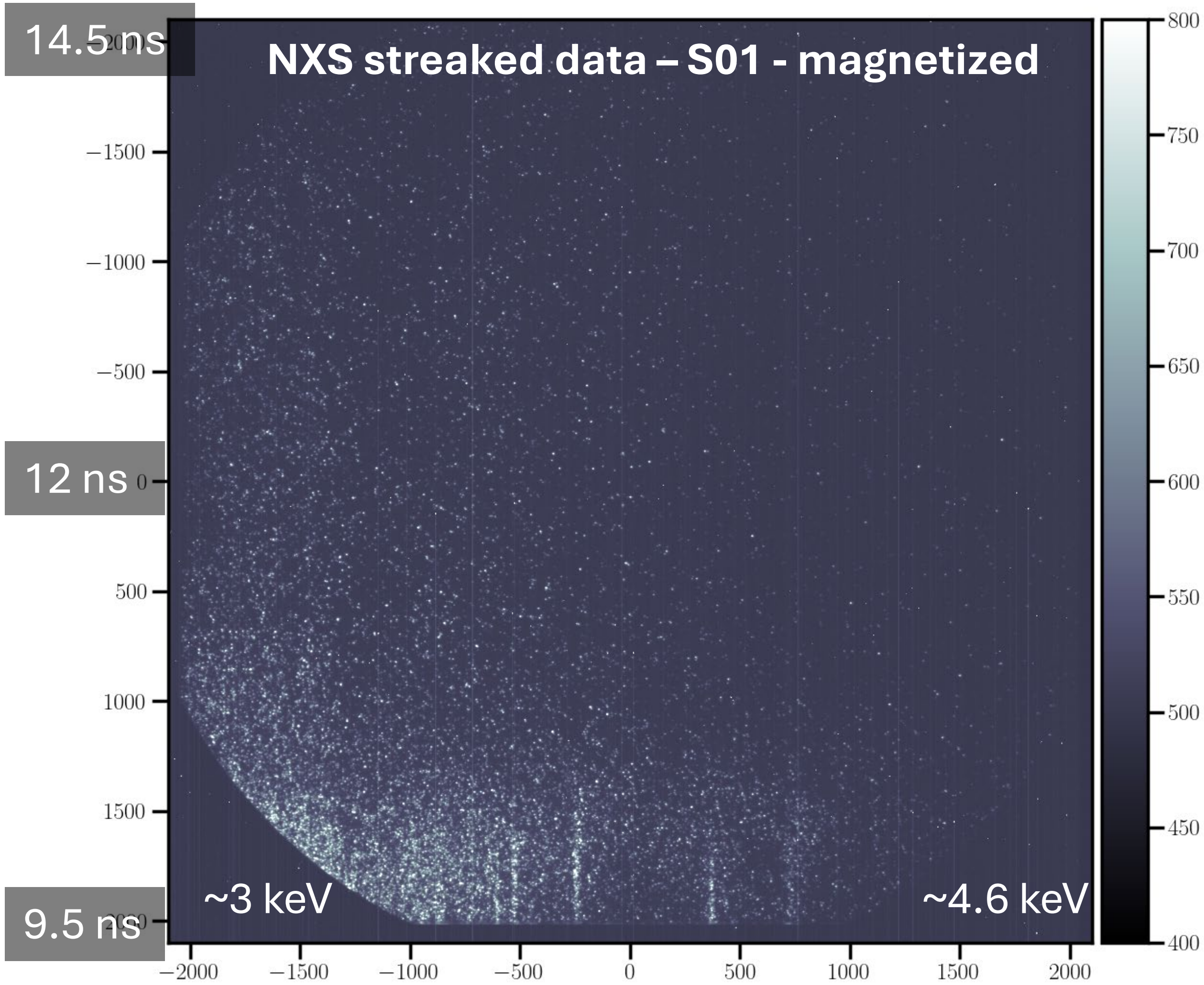


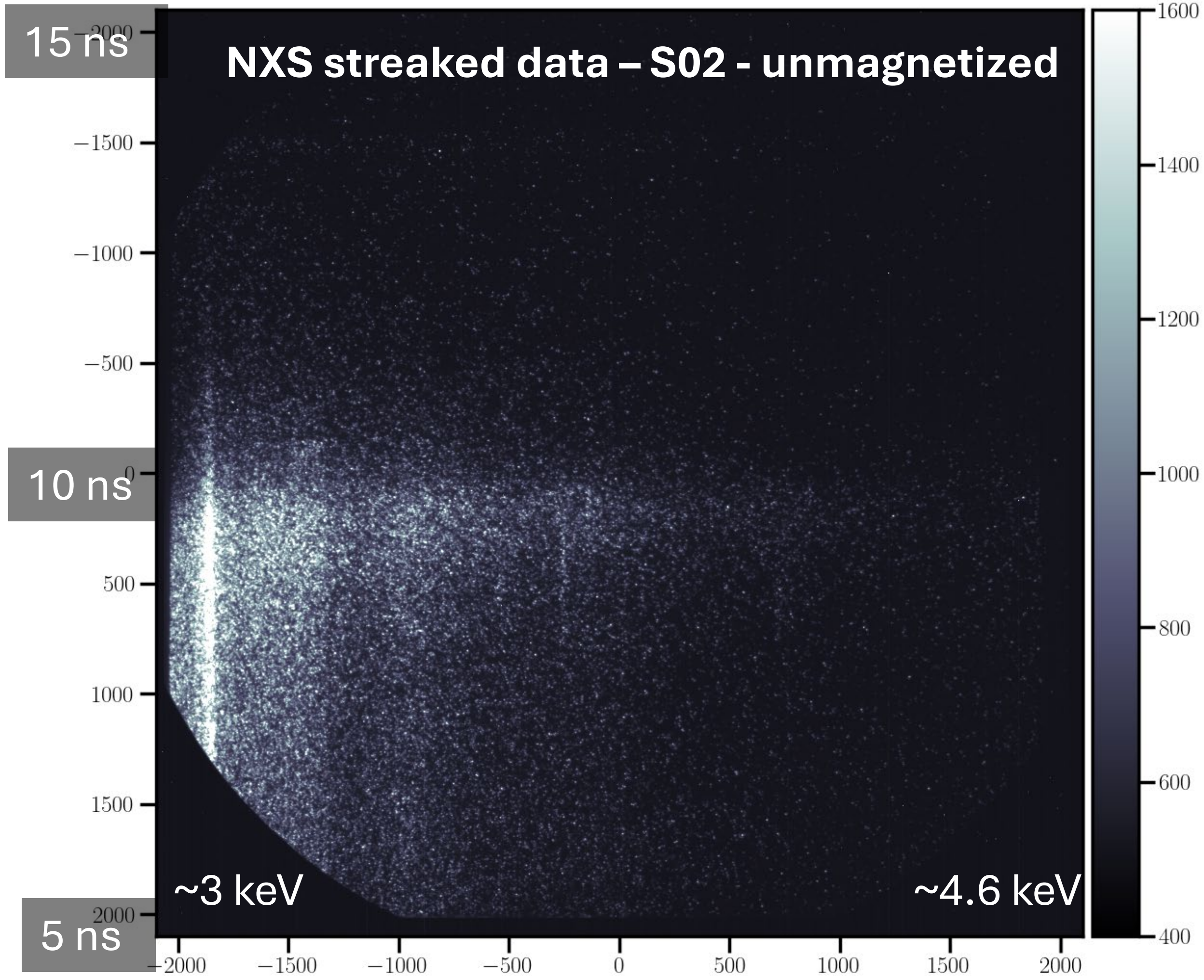
	θ	ϕ
NP	18°	303°
PL	63°	70°
E	90°	174°
A	116°	316°

- DD yield is of a few 10^9
- DD yield is about **3× higher** in S01 (magnetized) compared to S02 (unmagnetized)
- No DT neutrons detected

The increase in neutron yield likely originates from the stabilization of the implosion with applied B-field

The time-resolved emission data show stagnation around 9-10 ns, but the identification of Ar lines is difficult


NXS streaked data – S01 - magnetized


NXS streaked data – S02 - unmagnetized

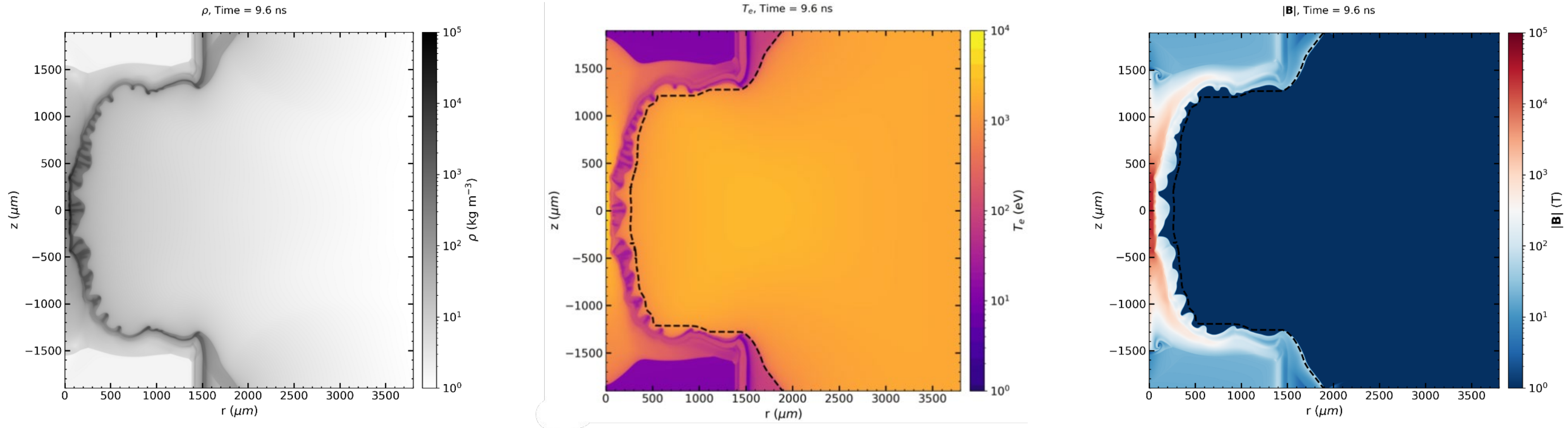
MHD SIMULATIONS PREDICT DISTINCT DIFFERENCES WITH B-FIELD BUT ALSO INSTABILITIES DURING COMPRESSION

Simulated with 2D GORGON, 10 ns drive, 3 kJ/beam, 4 mm initial OD

B_0 (T)	Y_{DD}	Y_{DT}	Te (burn avg., eV)	t_{bang} (ns)	ρR (mg/cm^2)	ρL (mg/cm^2)	BR (T.m)
0	2.8×10^{11}	4.2×10^{9}	1340	11.72	9	160-220	0
20	1.1×10^{12}	2.42×10^{11}	2170	11.68	7	100-260	0.9

$R_{\text{fuel}} / R_{\text{gyro,t}} \square 4$

Simulated with 2D CHIMERA, 10 ns drive, 3 kJ/beam, 4 mm initial OD, **including 3D ray tracing**



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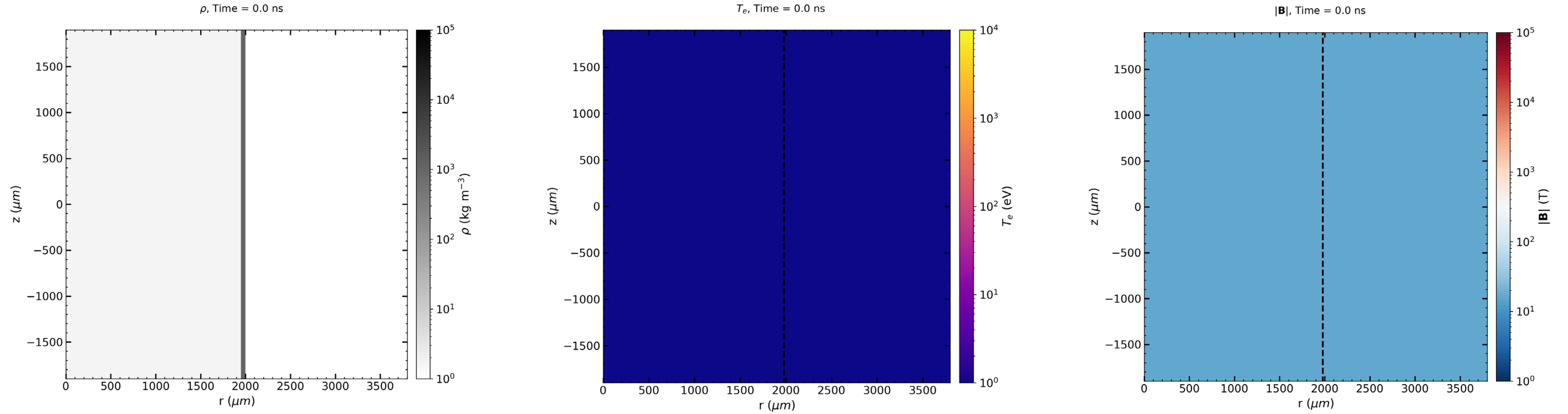
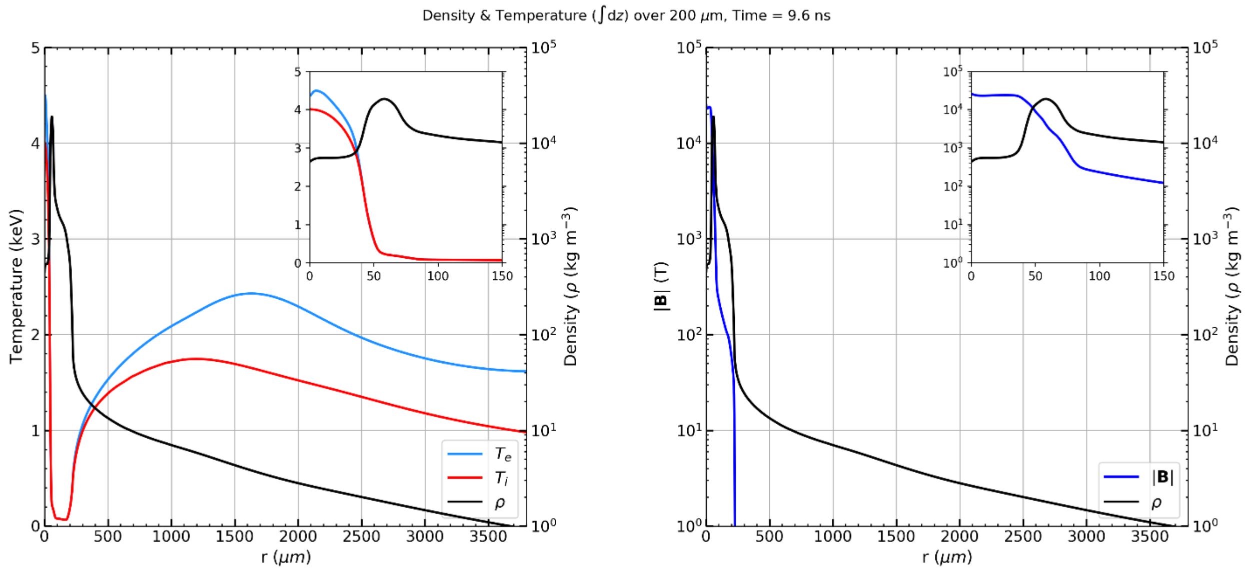


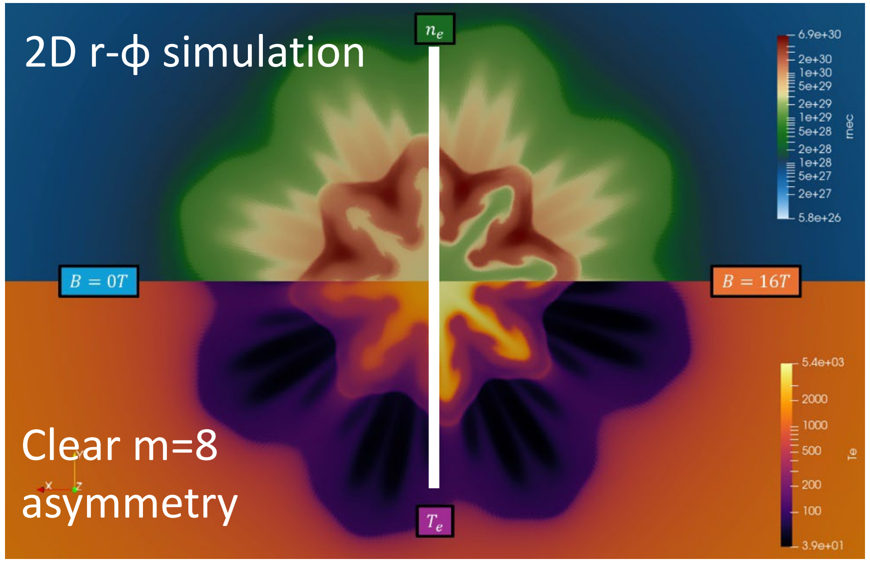
THE IMPACT OF DRIVE ASYMMETRIES IN THE SIMULATIONS



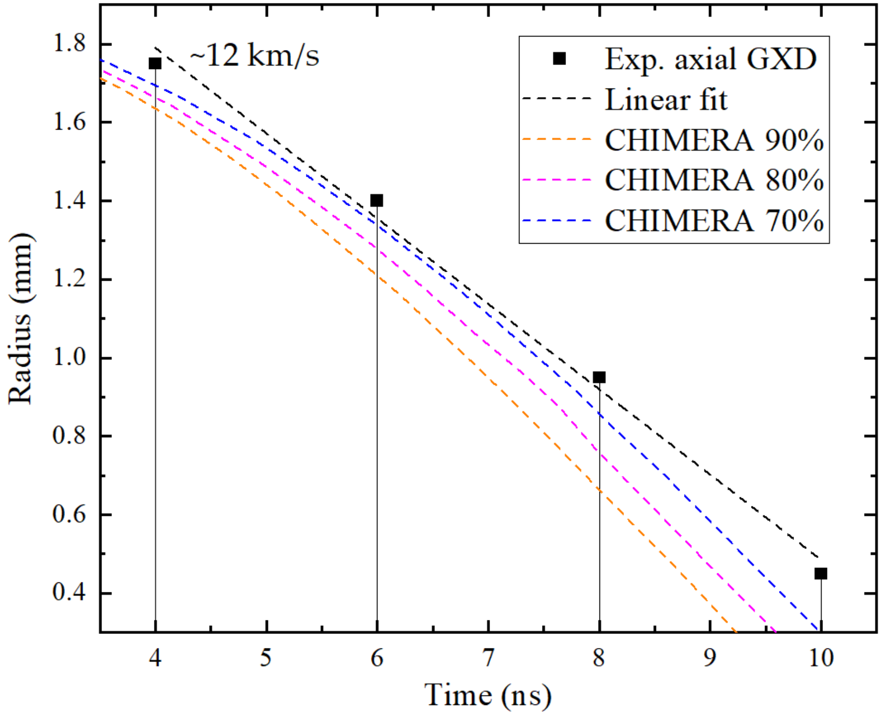
CHIMERA 98.9%

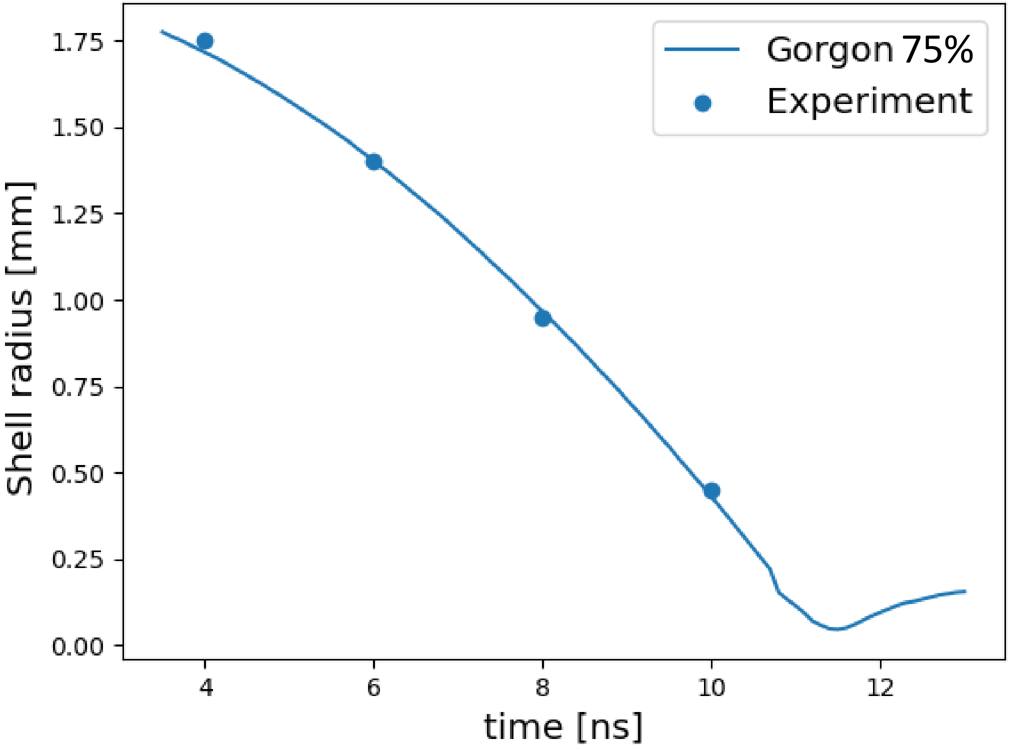
Metric	GORGON 75%	CHIMERA 90%	CHIMERA 80%	CHIMERA 70%
Bang Time	11.68 ns	10 ns	10.4 ns	12.62 ns
DD_n yield	2.4×10^{11}	1.1×10^{11}	4.3×10^{10}	3.7×10^{10}
DD burn avg. T_i	2.2 keV	2.3 keV	2 keV	2 keV

- When including 3D ray tracing (CHIMERA) at similar absorption:
  - The bang time and burn averaged T_i are not impacted significantly
  - The DD neutron yield is noticeably higher in GORGON compared to CHIMERA
- A 2D r-ϕ simulation shows a strong mode-8 asymmetry
- ➢ Drive azimuthal asymmetries are important to consider…



AN ABSORPTION OF ABOUT 70% PROVIDES A GOOD AGREEMENT WITH AXIAL X-RAY IMAGING MEASUREMENTS

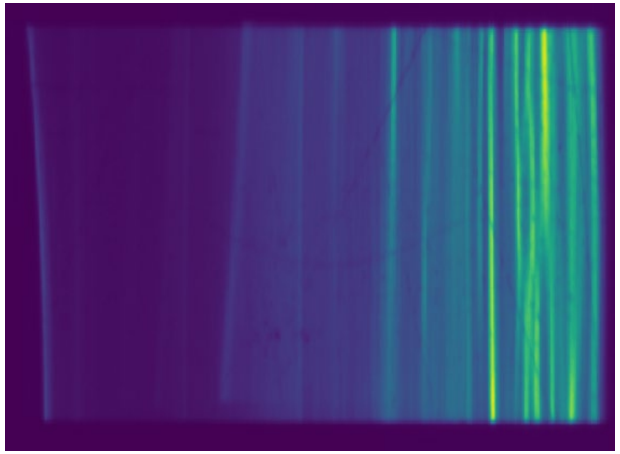




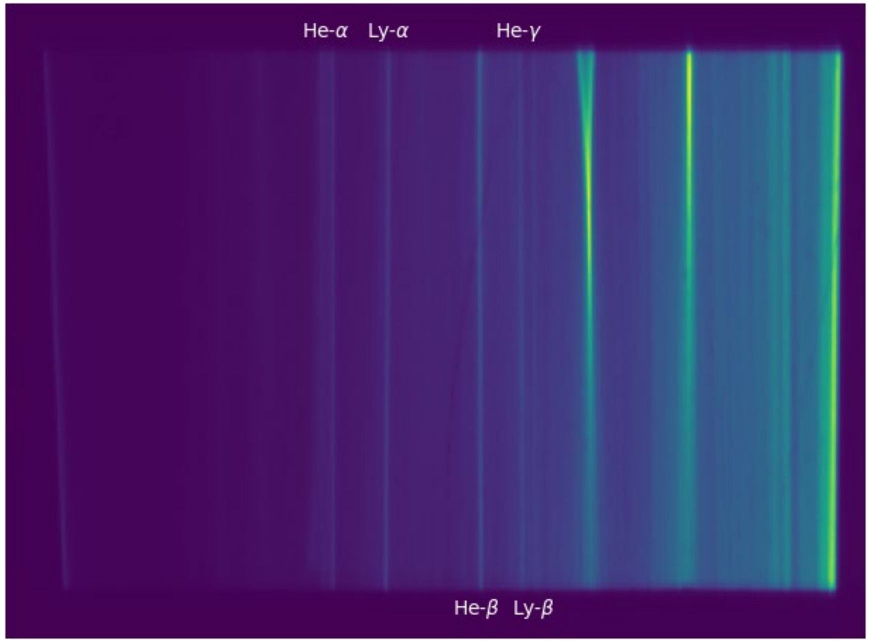
- The implosion velocity of ~12 km/s is consistent with simulations
- A better match is found with simulations at a reduced energy coupling of about 70%

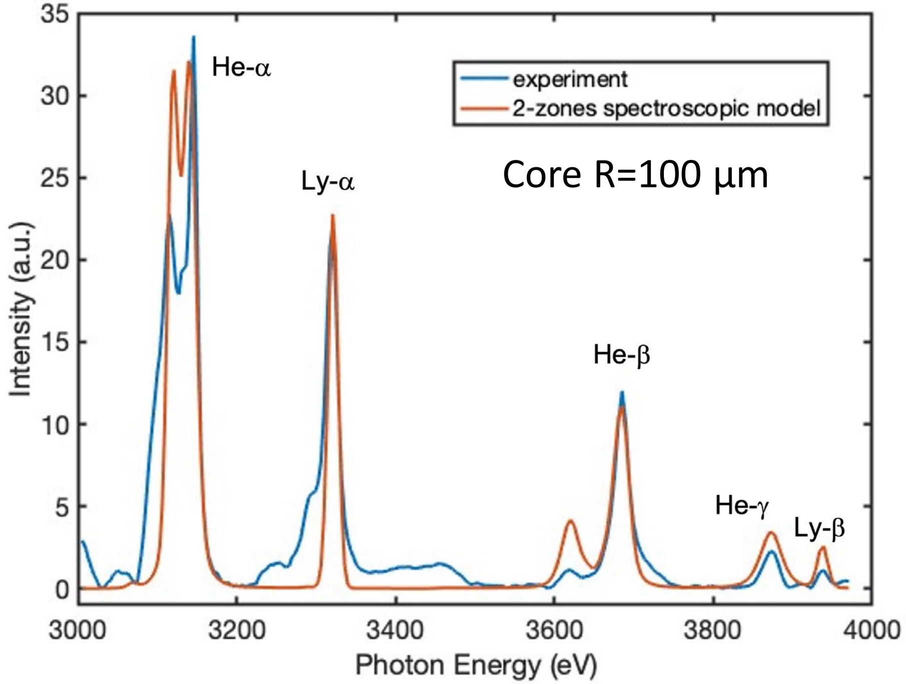
The Ar emission in the magnetized case indicates ~ 1.4 KeV core average temperatures

NXS Raw Image Plate (S02-unmagnetized)



NXS Raw Image Plate (S01-magnetized)

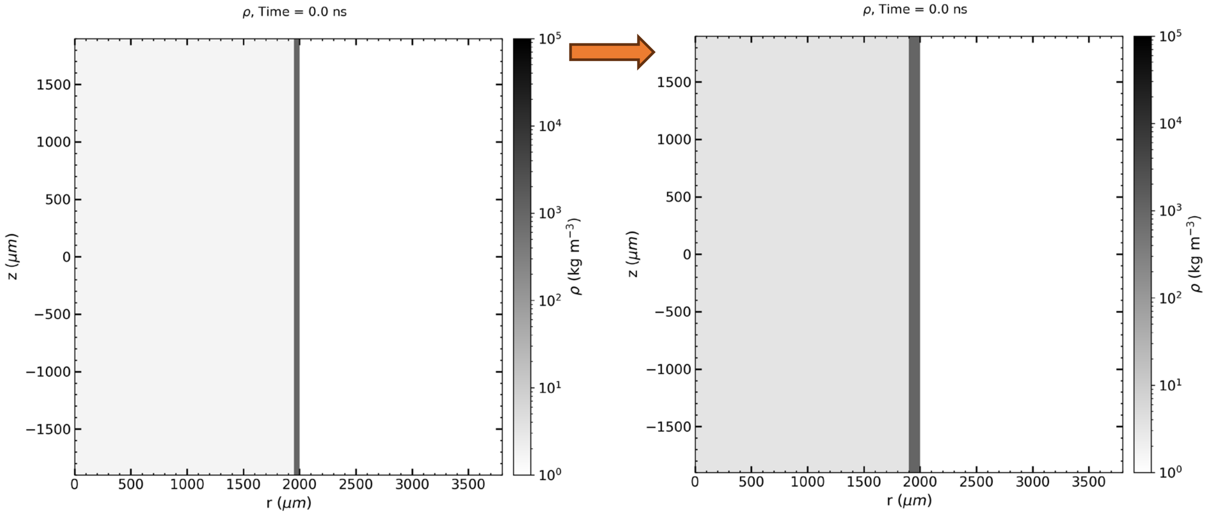




- In the magnetized shot, the average core temperature is estimated to be ~1.4 keV (colder than expected)
- In the unmagnetized shot, crystal defects are obscuring the Ar line emission

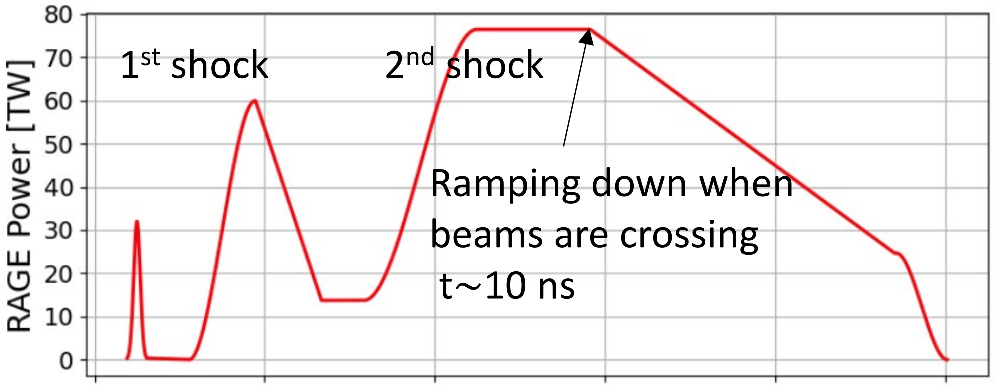
WE AIM TO STABILIZE THE IMPLOSIONS ON THE UPCOMING SHOTS

- Increase stability with thicker shell (50 µm → 100 µm) and higher fuel mass (10 atm → 20 atm).



- Bang time is reached later at ~15 ns
- DD yield is reduced from 10^{11} to $4\text{x}10^9$
- The thicker shell should be less prone to instabilities and shredding
- More stable implosion for a more robust match with simulations and comparisons with and without applied B-field

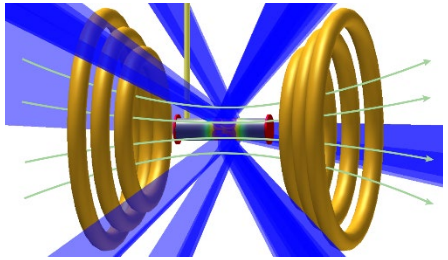
- Optimizing the pulse-shape (flat top → custom pulse shape)



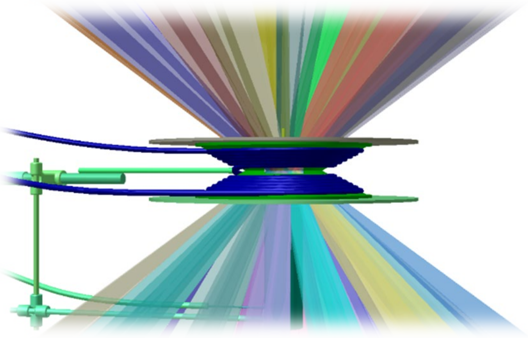
- Optimization runs performed by our LANL colleagues in xRAGE to increase yield while maintaining a stable implosion

SUMMARY

*Our project supported by DOE NNSA aims at **quantifying B-field compression and magnetization effects** in magnetized implosions.*



- We demonstrated the impact on core conditions of a **10-kT compressed B-field** in OMEGA experiments using **dopant spectroscopy**.
- We designed a **new NIF platform** to **magnetize larger cores** and trap tritium particles
  - **Secondary neutron measurements** are proposed to measure compressed B and its confinement properties
  - **Dual dopant spectroscopy** is proposed to infer magnetized heat transport



- The compression show **consistent evolution with simulations** with ~70% absorption, but **lower yield and temperature** measurements suggests **more unstable implosions**, even when including 3D ray tracing.
- **The magnetized implosion look more stable and had 3x higher yields.**
- We will use thicker shells and double the fuel mass to stabilize the implosions on the upcoming shot day.