Driving extreme magnetizations in compressed HED plasmas

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2nd LMJ-PETAL User Meeting
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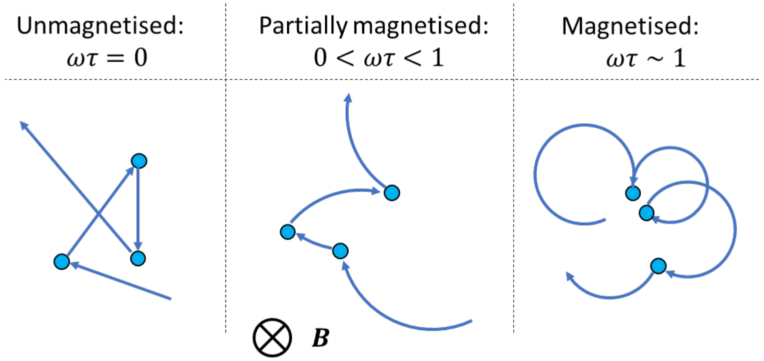
Electrons and alpha particles magnetization

Can magnetization further enhance fusion yields in ICF ?

Strong B-fields embedded in HED plasmas alter charged particles trajectories and change the way heat is transported

- Electron magnetization **reduces thermal conduction** losses from the hotspot

$$r_{Le} < R_{core} \quad \Longrightarrow \quad B > 10^3 - 10^4 \text{ T}$$



- Magnetic confinement of the α-particles enhances their collisionality within the hot spot, and **raises self-sustained fusion reactions yield**

$$r_{L\alpha} < R_{core} \quad \Longrightarrow \quad B > 10^4 - 10^5 \text{ T}$$

Hotspot self-heating condition :

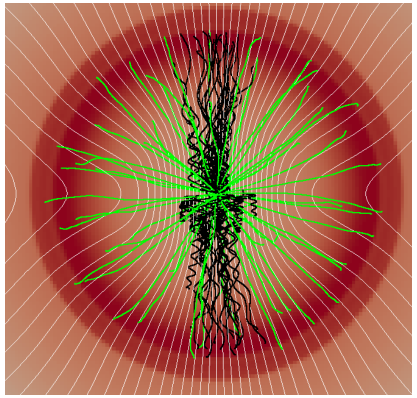
Enhanced α heating

Reduced thermal losses

$$\frac{dE}{dt} = P_\alpha + P_{pdV} - P_\kappa - P_{rad} > 0$$

Mechanical work

Radiation losses



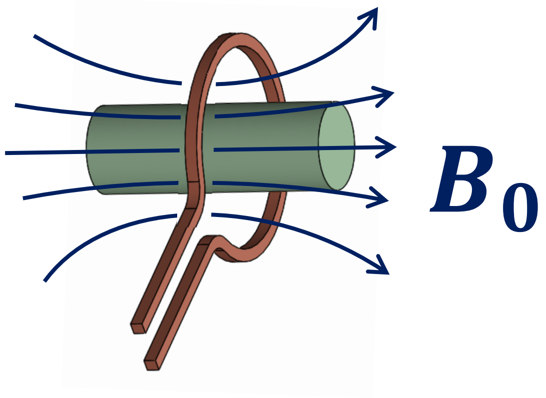
***Magnetized** and **unmagnetized** α-particles trajectories over the hot spot of an ICF imploded target*

Courtesy of Phil Maloney and Jerry Chittenden, ICLondon

In-flow B-field compression

Can seed B-fields of ~10 Tesla be amplified to ~10 kTesla ?

1) Soaking of seed B-field into the target



Resistive diffusion B-field advection

$$\frac{\partial \vec{B}}{\partial t} = -\vec{\nabla}\times \frac{\alpha_\parallel}{\mu_0 e^2 n_e^2}\vec{\nabla}\times\vec{B} + \vec{\nabla}\times\left(\vec{v}_B\times\vec{B}\right) + \cdots$$

Magnetic Reynolds number

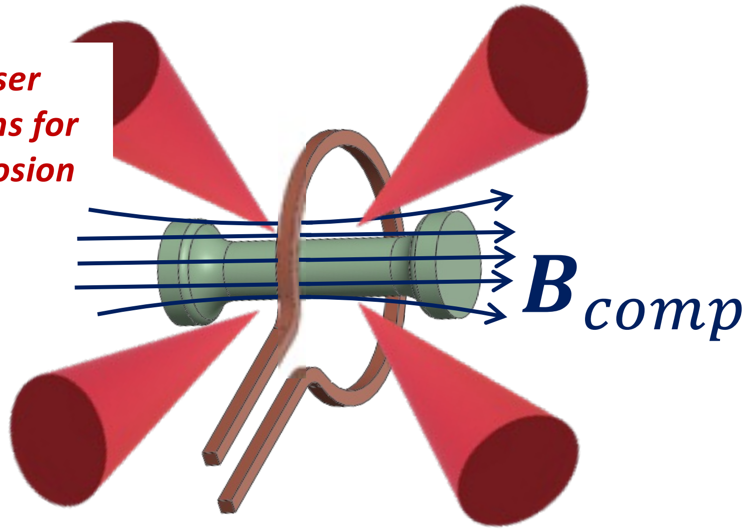
$$R_m = \frac{\tau_d}{\tau_i}$$

Magnetic diffusion time $\tau_d = \mu_0 R_0^2/\eta$

Implosion time $\tau_i = R_0/v_{imp}$

2) B-field amplified by advection with the imploding target

Laser beams for implosion



Frozen-in-flow B-field compression

$$\frac{B_{comp}}{B_0} = \left(\frac{R_0}{R}\right)^{2(1-1/R_m)} \xrightarrow[R_m \gg 1]{} \left(\frac{R_0}{R}\right)^2$$

B/B_0 ~500 previously demonstrated at OMEGA with 15 kJ laser drive

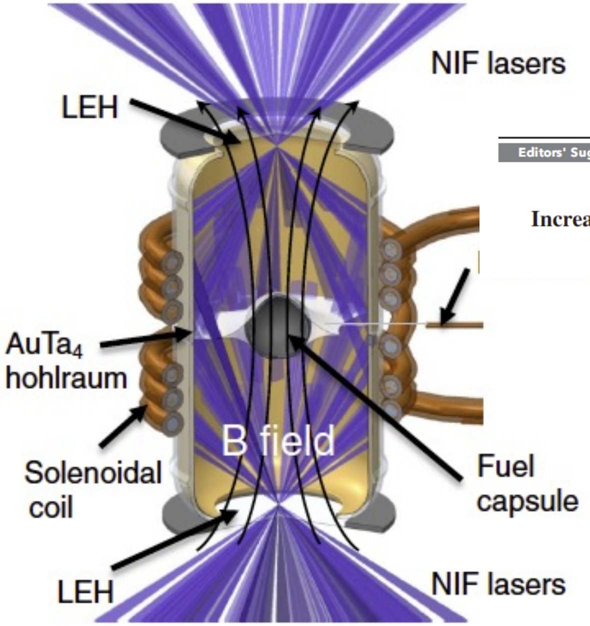
Hohenberger *et al.*, Phys. Plasmas **19**, 056306 (2012)

~ 30% losses could be due to resistive diffusion and axial plasma motion

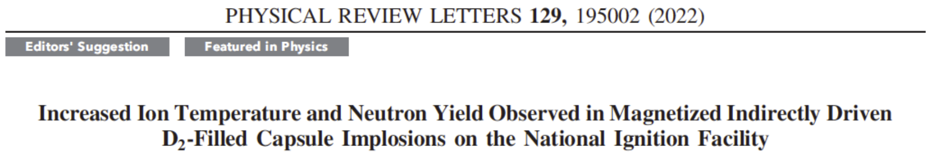
Other loss mechanisms may be linked to extended-MHD effects …

Magnetized inertial confinement fusion

Magnetic-field-assisted implosion and ignition explored at NIF and Omega



Magnetized Indirect Drive


PHYSICAL REVIEW LETTERS **129,** 195002 (2022)

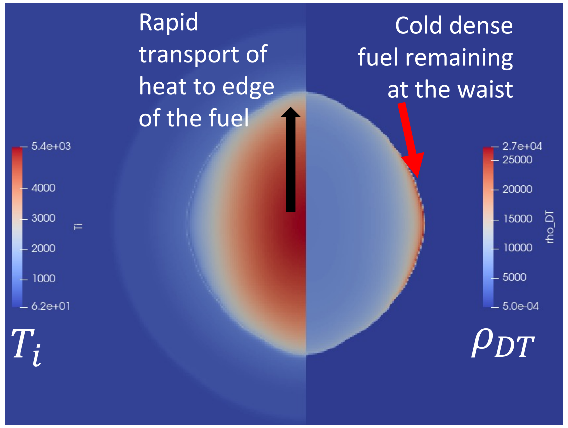
Editors' Suggestion Featured in Physics

Increased Ion Temperature and Neutron Yield Observed in Magnetized Indirectly Driven D_2-Filled Capsule Implosions on the National Ignition Facility

26 T seed B-field applied to a D_2-filled capsule indirectly driven at NIF:

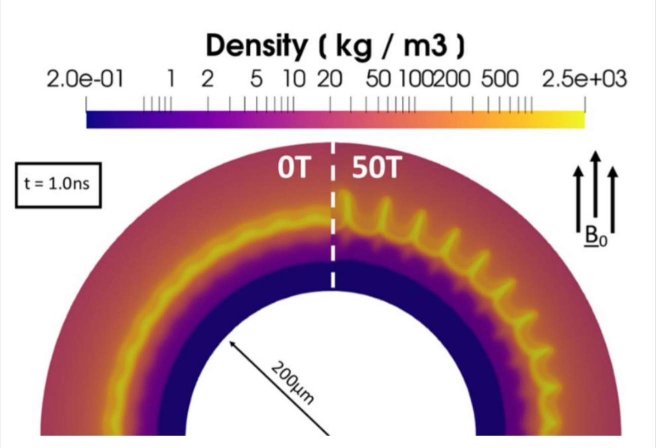
- 40% increase ion temperature T_i
- 3.2 times increase in neutron yield Y_{DD}

These experiments are inherently asymmetric, due to the applied B-field



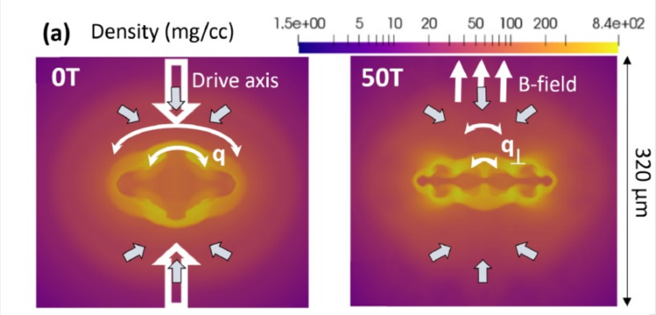
- *Enhanced conduction along the pole*
- *Increased shock velocity at the waist due to reduced electron pre-heat*

Magnetized Direct Drive



Walsh *et al.*, Nucl. Fus. **60**, 106006 (2022)

Extended-MHD sims :
Enhanced ablation surface RT instability growth at poles of the capsule



Bose *et al.*, PRL **128**, 195002 (2022)

Sims (and experiments) at OMEGA :
Drive on waist reduced by magnetised thermal conduction suppression, leading to flattened hotspot

Courtesy of J. Chittenden, S. O'Neil, P. Maloney, ICLondon

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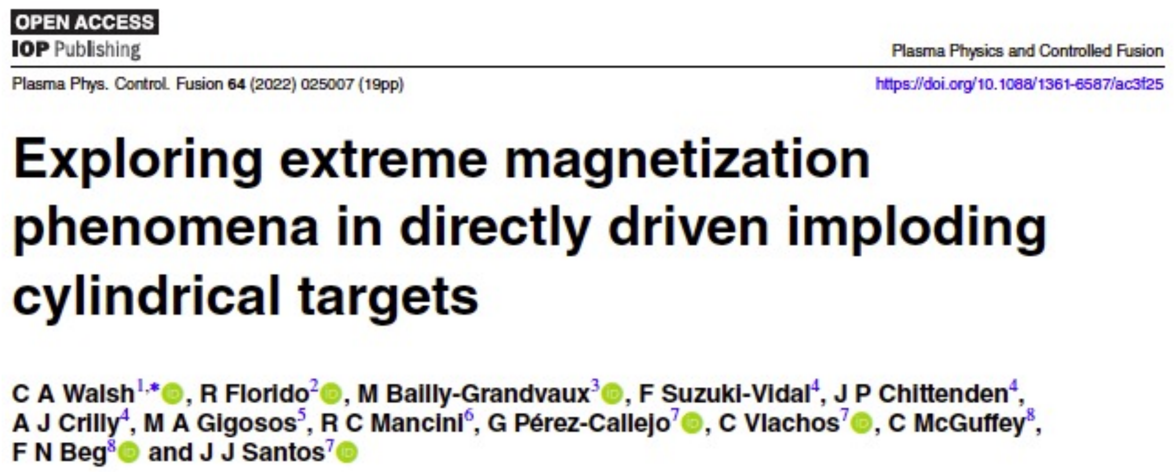
Cylindrical geometry ideally suited to interrogate MHD models



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Plasma Physics and Controlled Fusion

Plasma Phys. Control. Fusion **64** (2022) 025007 (19pp)

https://doi.org/10.1088/1361-6587/ac3f25

Exploring extreme magnetization phenomena in directly driven imploding cylindrical targets

C A Walsh[1,*], R Florido[2], M Bailly-Grandvaux[3], F Suzuki-Vidal[4], J P Chittenden[4], A J Crilly[4], M A Gigosos[5], R C Mancini[6], G Pérez-Callejo[7], C Vlachos[7], C McGuffey[8], F N Beg[8] and J J Santos[7]

Cylindrical geometry:

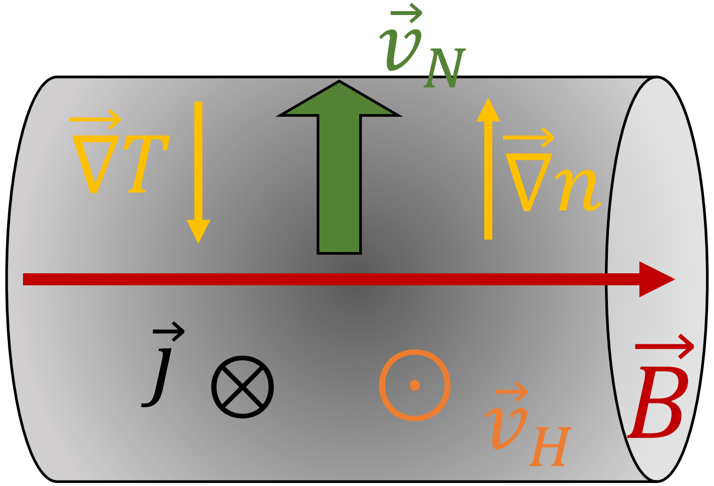
$\vec{B}$ ∥ **cylinder axis** and **target compressed radially**

→ **Less convoluted measurements of the magnetized heat transport and magnetic flux advection**

Resistive diffusion B-field advection

$$\frac{\partial \vec{B}}{\partial t} = -\vec{\nabla}\times\frac{\alpha_{\parallel}}{\mu_0 e^2 n_e^2}\vec{\nabla}\times\vec{B} + \vec{\nabla}\times\left(\vec{v}_B\times\vec{B}\right)$$

Nernst: moves $\vec{B}$ against $\vec{\nabla}T$



Hall: moves $\vec{B}$ against $\vec{j}$

Advection velocity :

$$\vec{v}_B = \vec{v}\ \underbrace{-\,\gamma_{\perp}\vec{\nabla}T_e}_{\substack{\text{Nernst}\\ \vec{v}_N}}\ \underbrace{-\,\gamma_{\wedge}\left(\vec{B}\times\vec{\nabla}T_e\right)}_{\text{Cross-gradient-Nernst}}\ \underbrace{-\,\frac{\vec{j}}{en_e}\left(1+\delta_{\perp}^{c}\right)+\frac{\delta_{\wedge}^{c}}{en_e}\left(\vec{j}\times\vec{B}\right)}_{\substack{\text{Hall terms}\\ \vec{v}_H}}$$

Experimental challenges:

- Characterize T_e, n_e, and $\vec{B}$
- Quantify **heat** and **magnetic flux transport**, and **B-field compressibility**

2D extended-MHD predictions for the core plasma conditions at OMEGA

Seed B-fields of 10-50 T are cylindrically-compressed to 8-30 kT with 14.5 kJ of laser drive

Extended-MHD 2D Gorgon simulations

laser heating

- Ray-tracing
- Inverse bremsstrahlung

thermal transport

- Anisotropic conduction
- Righi-Leduc

radiation transport

- Non-diffusive multi-group approx.

magnetic transport

- **Advection:**
  - Bulk plasma
  - Nernst + cross-gradient Nernst
- **Source terms:**
  - Bierman Battery
  - Sadler
- **Resistive diffusion**

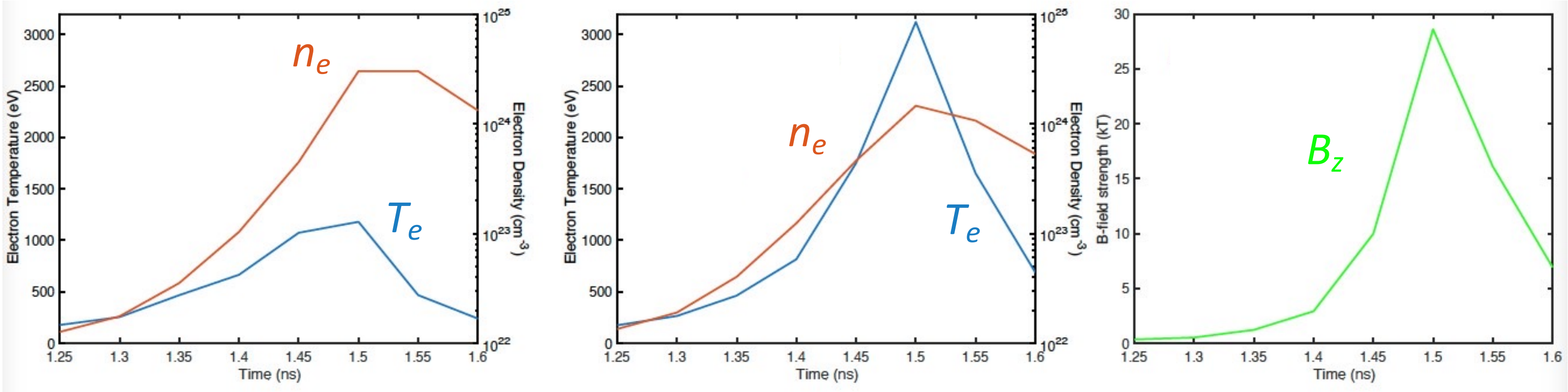
others

- Lorentz force
- Updated transport coefficients

Evolution of mass-averaged *core conditions*

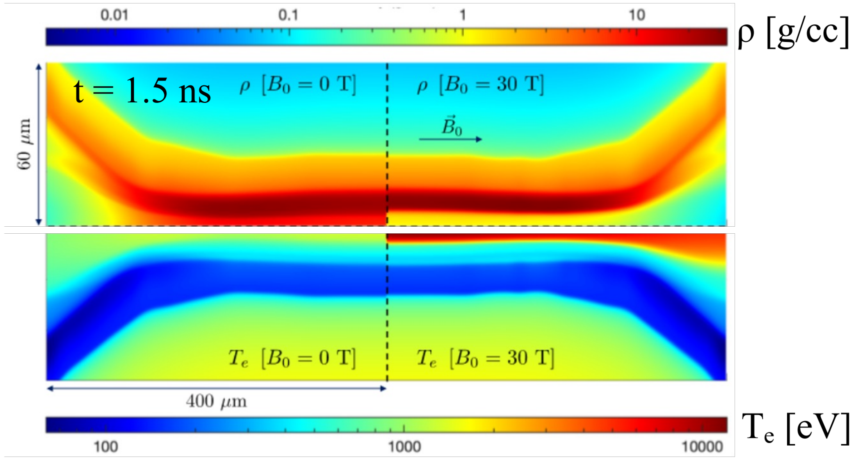
Unmagnetized implosion ($B_0 = 0$)

Magnetized implosion ($B_0 = 30$ T)



Plasma conditions at stagnation

Unmagnetized ($B_0 = 0$) *Magnetized ($B_0 = 30$ T)*



The **compressed >10 kT magnetic field** modifies plasma properties in the stagnated core:

- **Density** decreases from ~ 10 to ~ 5 g/cc
- **Temperature** increases from 1 to 3 keV

Walsh *et al.*, Plasma Phys. Control. Fusion **64**, 025007 (2022)

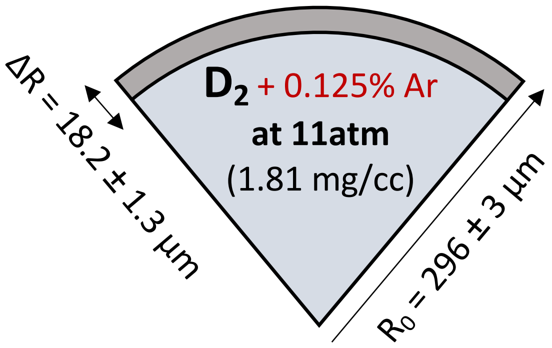
Magnetized cylindrical implosions at OMEGA

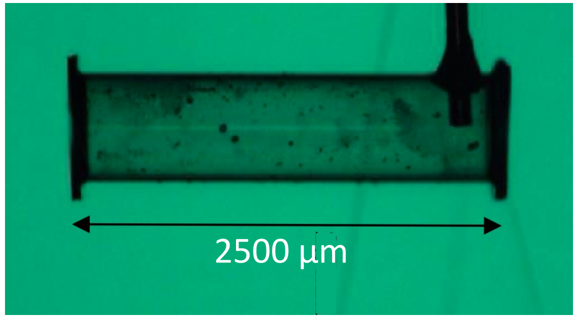
Platform setup at the OMEGA-60 laser facility

Cylindric plastic shells filled with D_2 at 11 atm
with 0.125% atomic concentration of Ar doping
for spectroscopic tracing

PI M. Bailly-Grandvaux (UCSD)

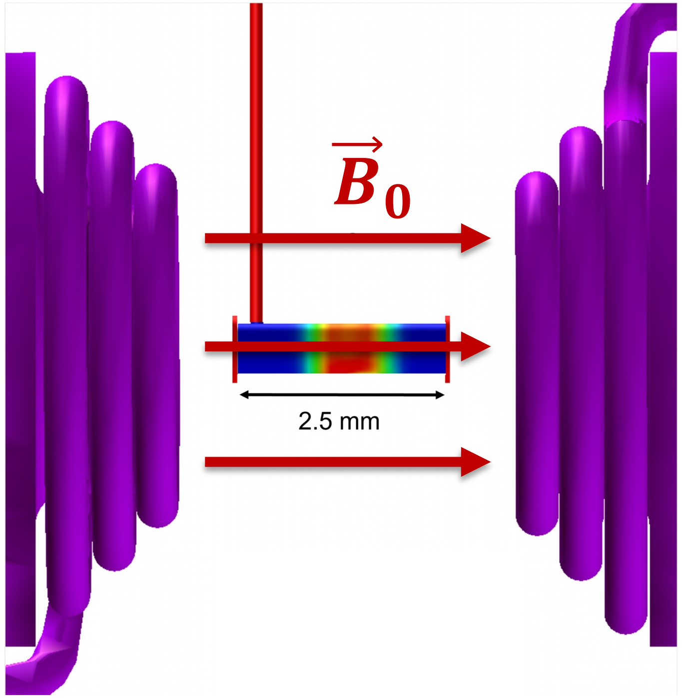
CH shell





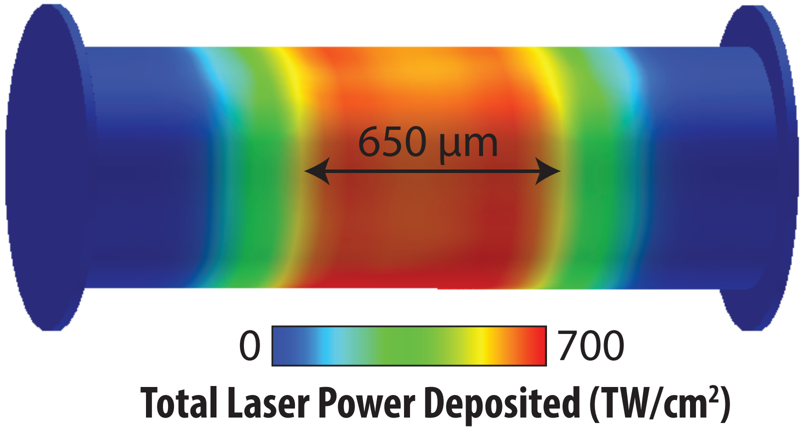
Seed B-field of B_0 = 30 T driven externally
by a capacitor bank discharge (~µs pulses)

MIFEDS: Gotchev *et al.* Rev. Sci. Inst. **80**, 043504 (2009)



Laser drive: 40 UV beams, 1.5 ns,
total energy of 14.5 kJ

> 5×10^{14} W/cm^2 fairly uniform across 650 µm

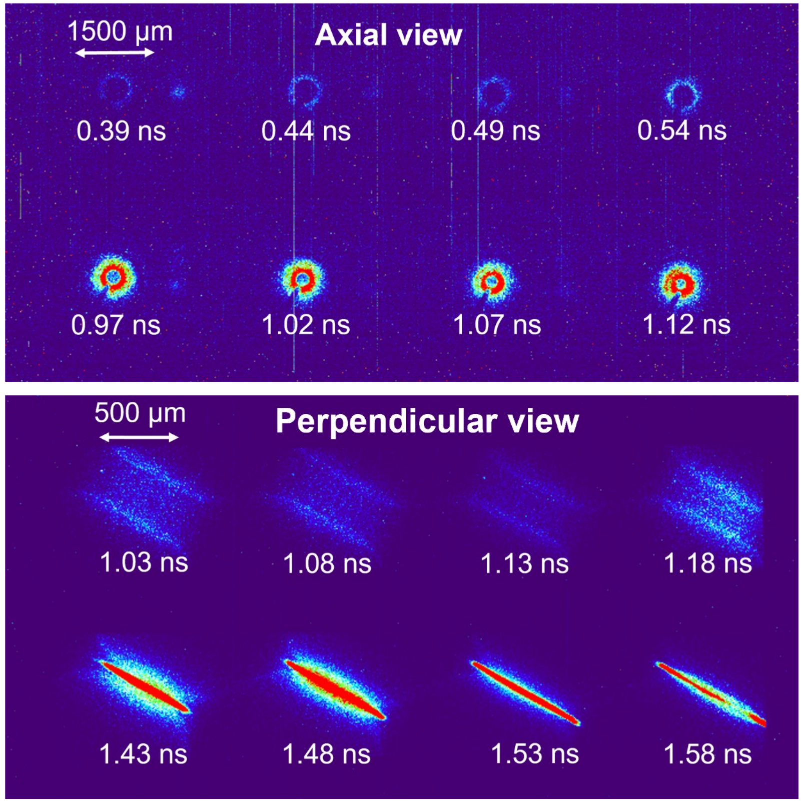


Standard laser drive of mini-MagLIF platform:
Hansen *et al.*, Phys. Plasmas **27**, 062703 (2020)

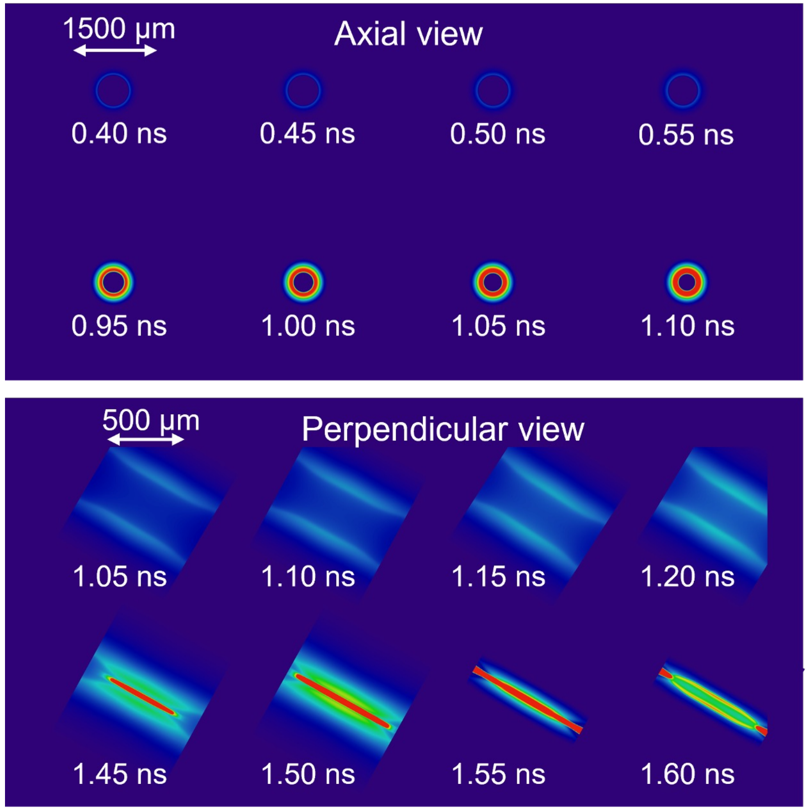
Implosion dynamics

X-ray pinhole framing cameras with two orthogonal views

Experimental data



Synthetic images : *MHD + Radiation transport + Instrument Response*



→ Radiation transport simulations reproduce major features of x-ray images

Two metrics to measure the progress of the imploding shell in the x-ray images:

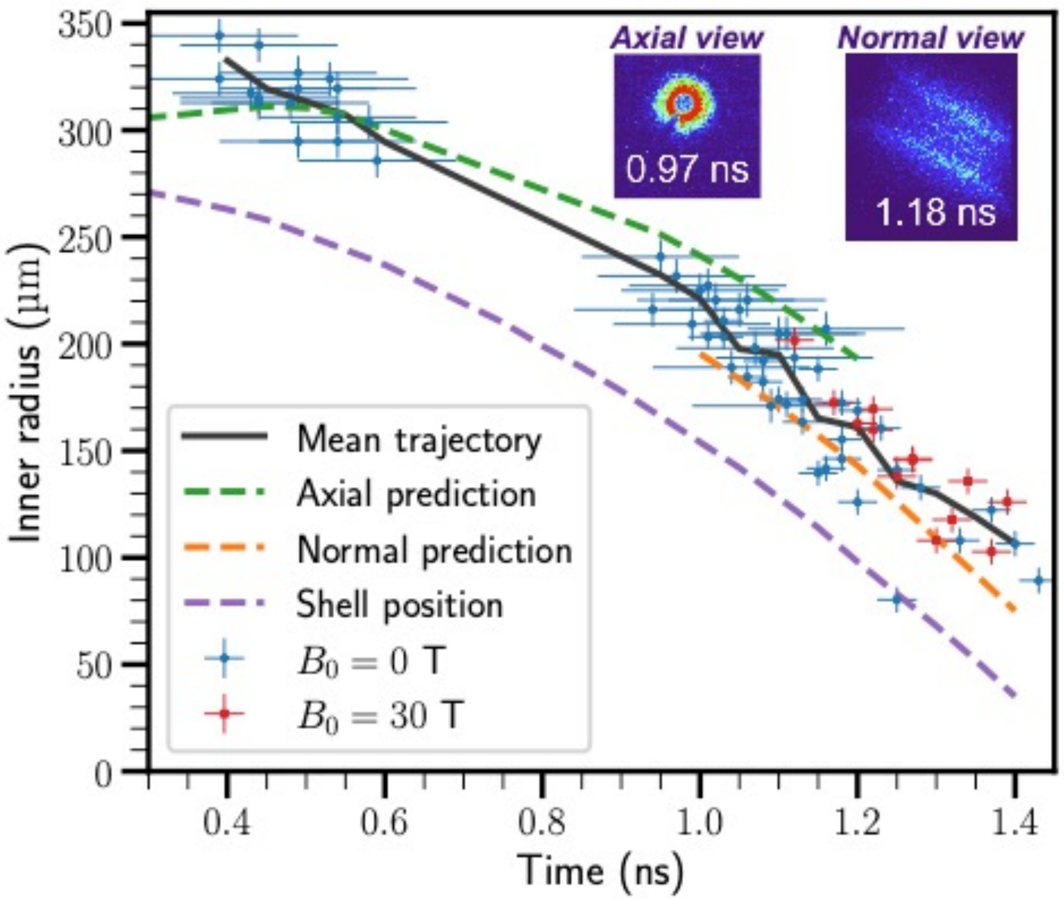
- **Shell separation** (early-times), at both axial and perpendicular views
- **Core thickness** (late-times) at perpendicular view

Pérez-Callejo *et al.*, Rev. Sci. Instrum. **93**, 113542 (2022)

Magnetized cylindrical implosions at OMEGA

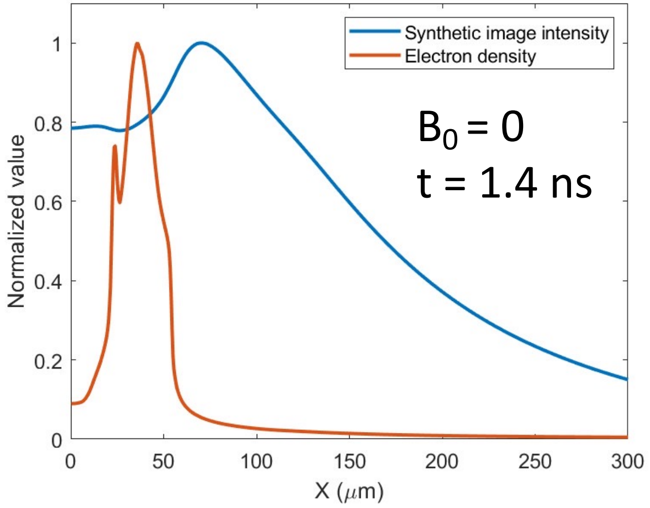
Implosion dynamics

Shell trajectory well-captured by MHD and radiation transport simulations up to 1.4 ns



Implosion accelerates at t ~ 1 ns,
increasing from 200 km/s to 280 km/s

The densest part of the shell partially absorbs the bremsstrahlung ⇒ peak signal <u>on the detector</u> does not correspond to the densest part of the plasma

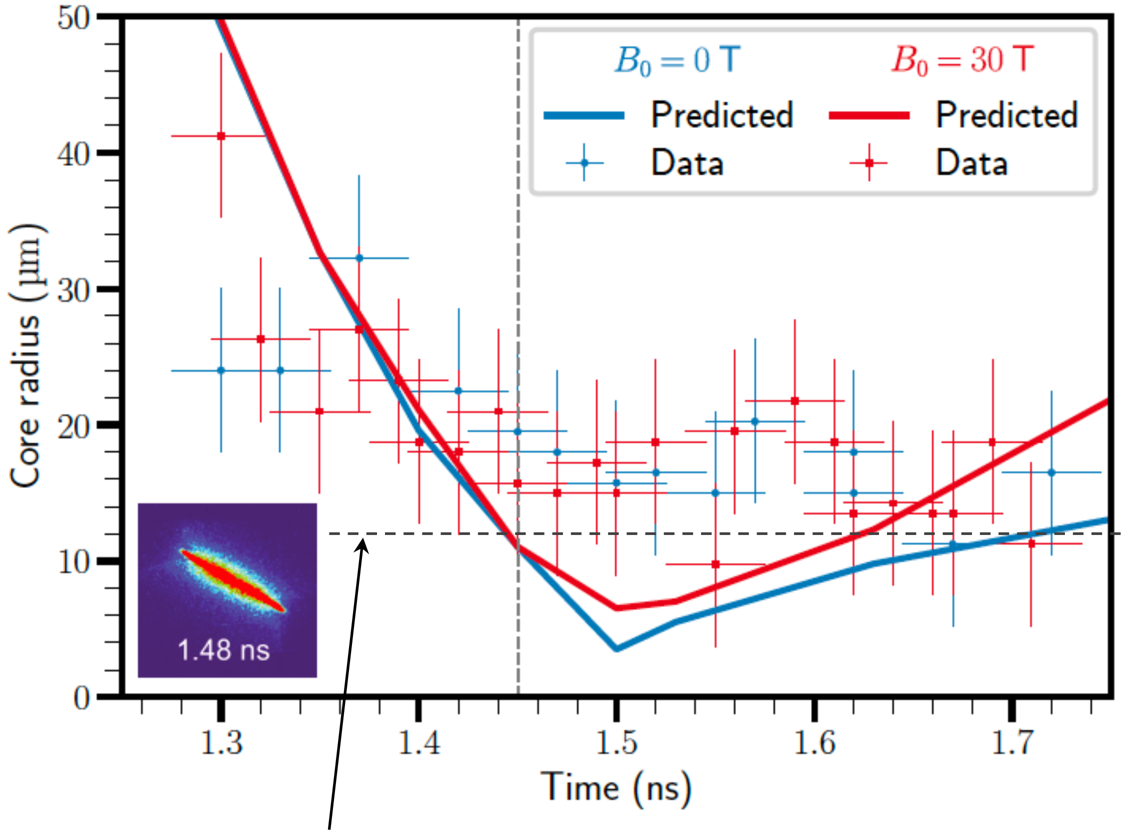


Pérez-Callejo *et al.*, Rev. Sci. Instrum. **93**, 113542 (2022)

Magnetized cylindrical implosions at OMEGA

Implosion dynamics

At stagnation, simulations deviate from experiments



12 μm instrument resolution
insufficient to resolve differences

Stagnation occurs at t ~ 1.5 ns and lasts ~ 200 ps

Similar compression with and w/o B-field

Despite higher T_e and P in the magnetized hot spot

Fuel compression reduced vs MHD predictions

Measured convergence ratio of R_0/R_f ~ 20 (vs ~ 40-60 in sims)

⇒ there are mechanisms, not yet included in the MHD sim, that reduce implosion performance
(e.g. hot electron pre-heat, ablator-fuel mixing, 2D vs 3D)

Similar discrepancy already reported in analogous cylindrical implosion experiments

J. Davies *et al.* PoP **26**, 022706 (2019)

Pérez-Callejo *et al.*, Rev. Sci. Instrum. **93**, 113542 (2022)

Spectral line shape and radiation transport coupled to MHD simulations

Variations in plasma conditions to be inferred from Ar K-shell line emission

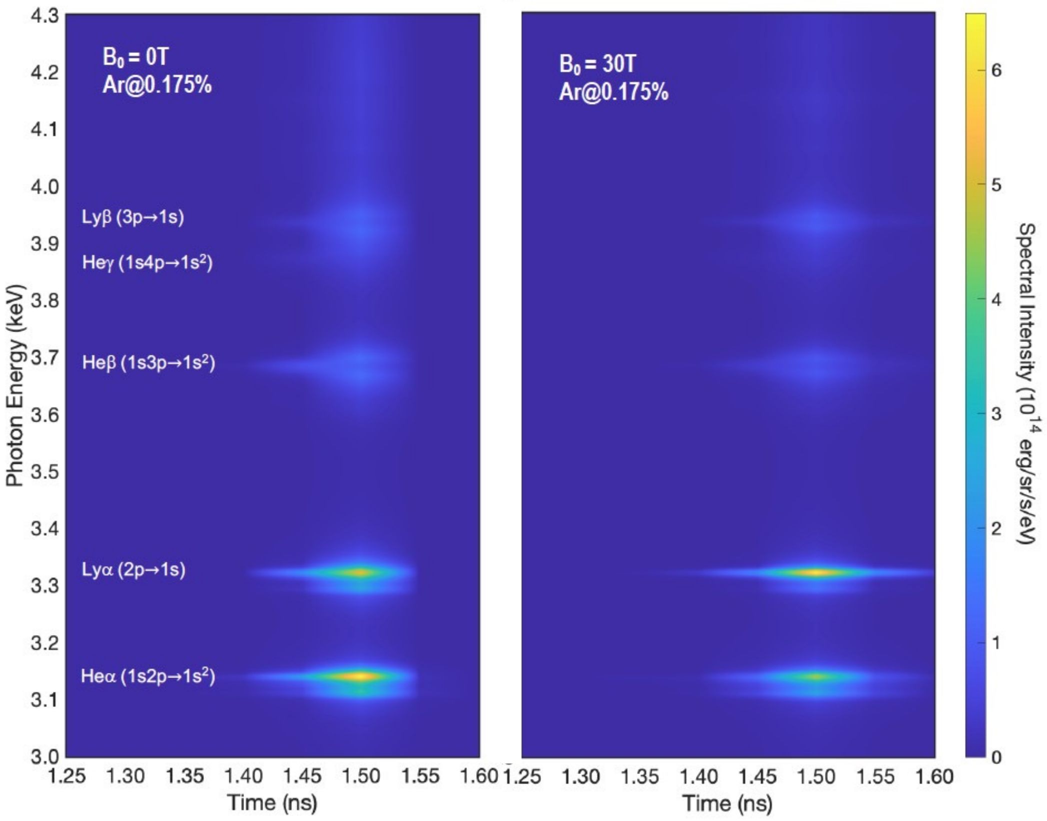
Targets:
D_2 gas at 11 atm (ρ = 1.81 mg cm^{-3})
0.125 % at. Ar dopant

Ar K-shell spectroscopy adapted to probe plasmas with :

- *electron densities* ~ 10^{23}-10^{24} cm^{-3}
- *temperatures* ~ *600 - 2500 eV*

Synthetic evolution of the Ar X-ray emission spectra

- *Emissivities, opacities and atomic level population distributions calculated with collisional radiative model ABAKO*[1]
- *Line shapes from MERL*[2]*, PPP-B*[3] *and DinMol*[4]



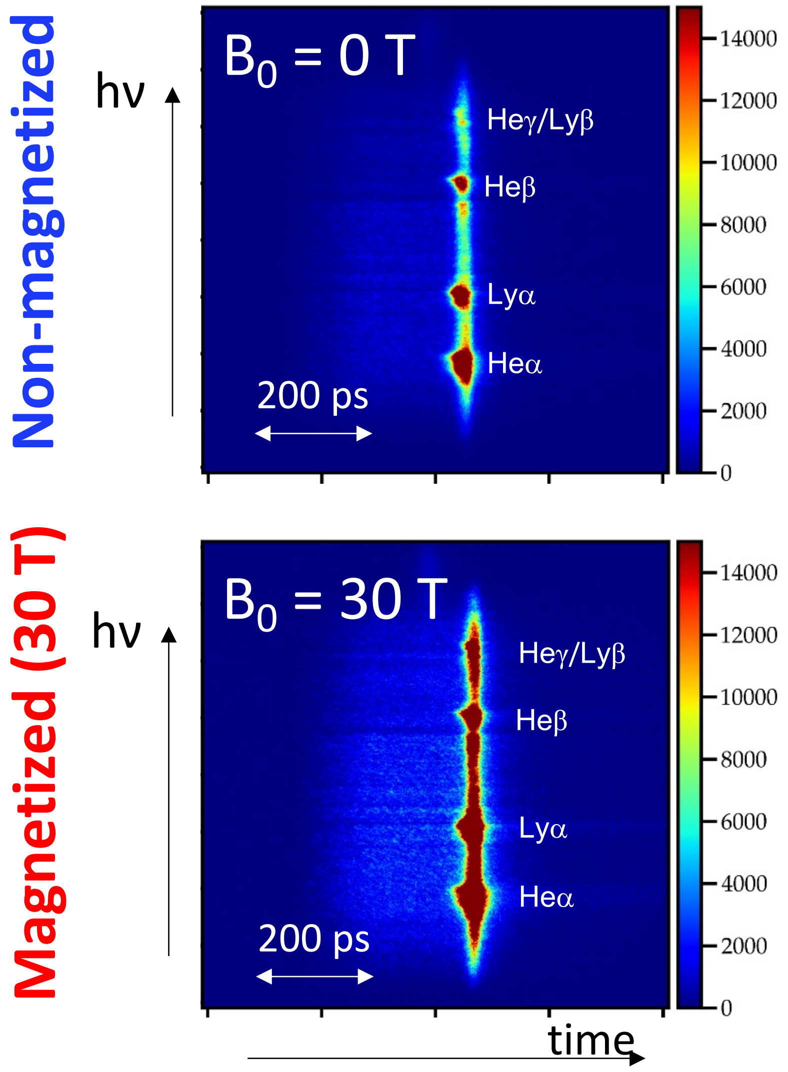
K-shell lines modified for magnetized implosion conditions

[1] Florido *et al.*, Phys. Rev. **E** 80, 056402 (2009)
[2] Mancini *et al.*, Comput. Phys. Commun. **63**, 314 (1991)
[3] Ferri *et al.*, Matter Rad. Extremes **7**, 015901 (2022)
[4] Gigosos et al., Atoms **9**, 9 (2021)

Walsh *et al.*, Plasma Phys. Control. Fusion **64**, 025007 (2022)

Magnetized cylindrical implosions at OMEGA

Experimental time-resolved argon K-shell emission



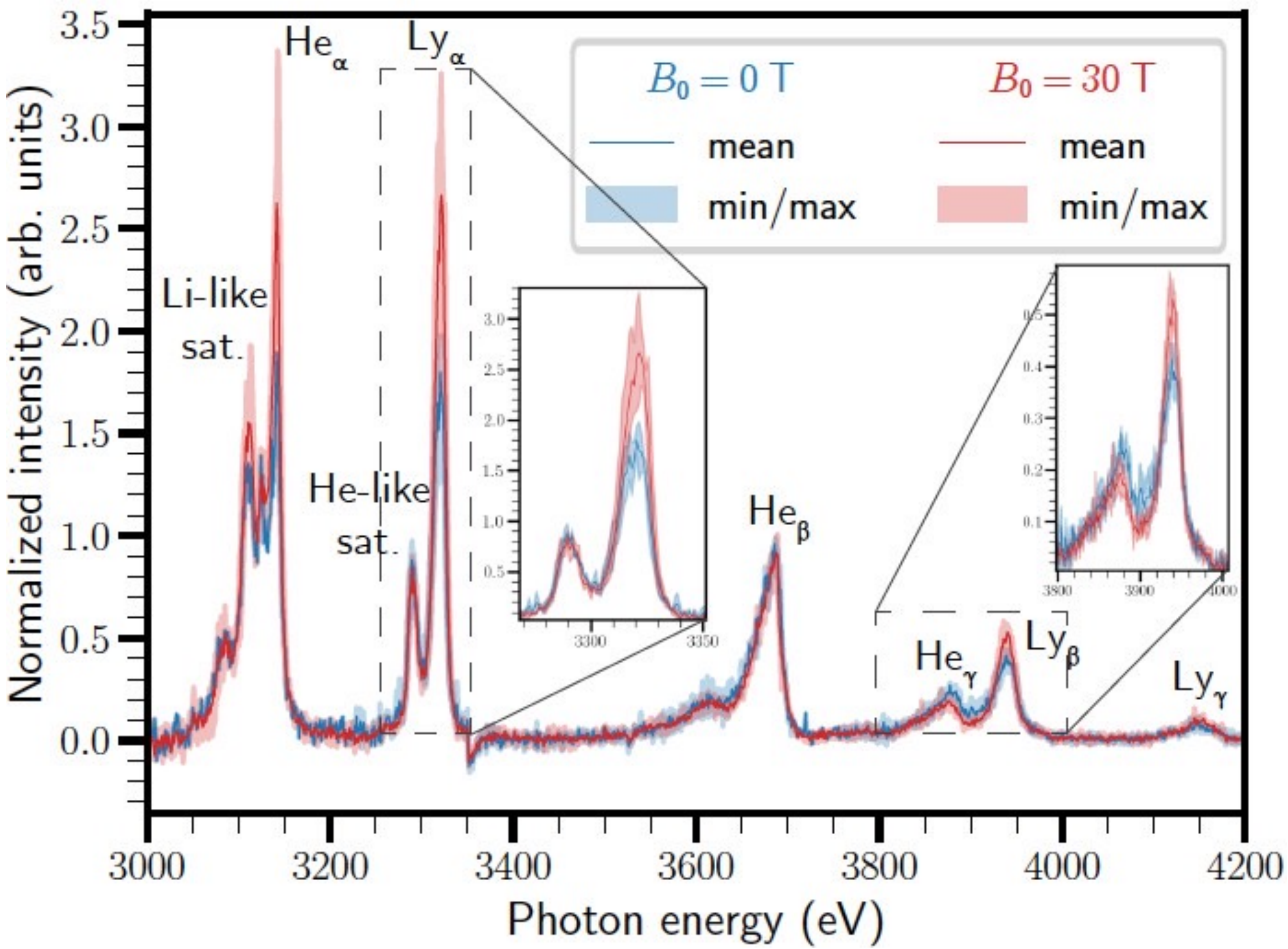
Data is saturated,

but Ar line emission concentrated over ~ 100ps when the target is maximally compressed

⇒ Time-integrated spectra are representative of core conditions

Time-integrated argon K-shell emission

Systematic changes observed between magnetized and unmagnetized spectra



Ar K-shell lines are reproducible for both magnetized and unmagnetized cases (over 6 shots - 4 with B-field, 2 w/o B-field)

Evidence for a **hotter magnetized core**:

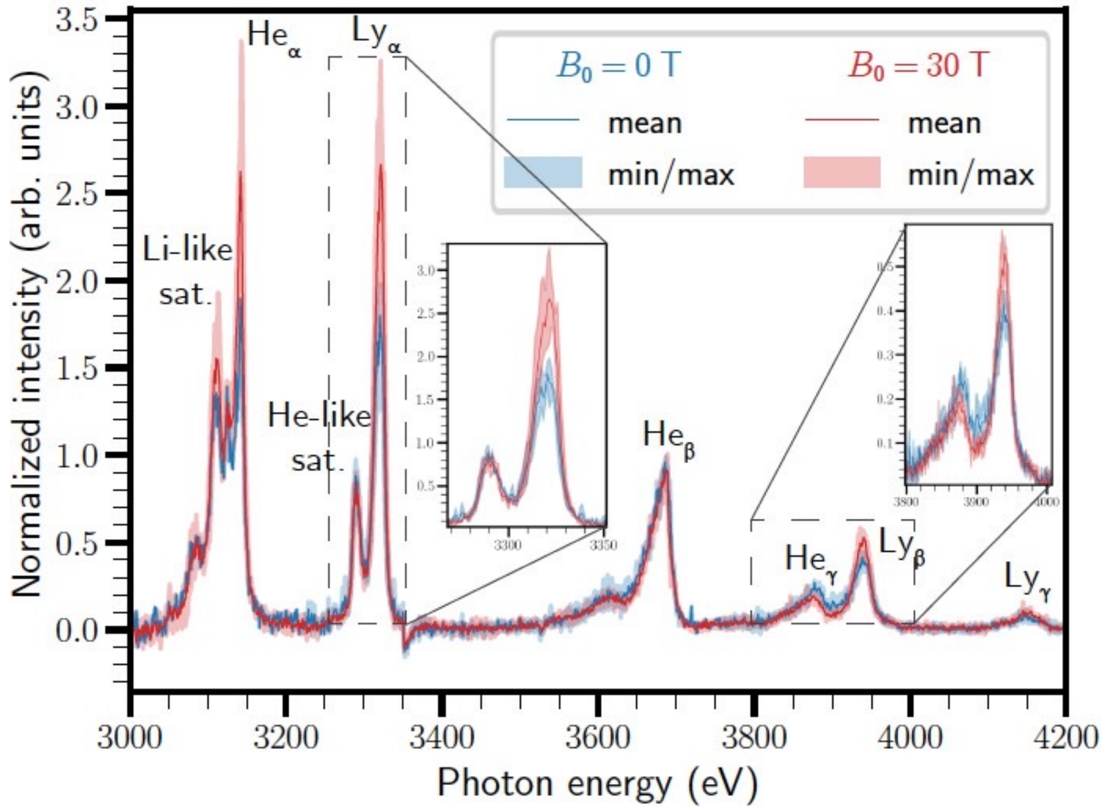
Lyβ/*Heβ* and *Lyα*/*He-like satellite* line intensity ratios higher for the magnetized case

⇒ H-like population increases in the magnetised case

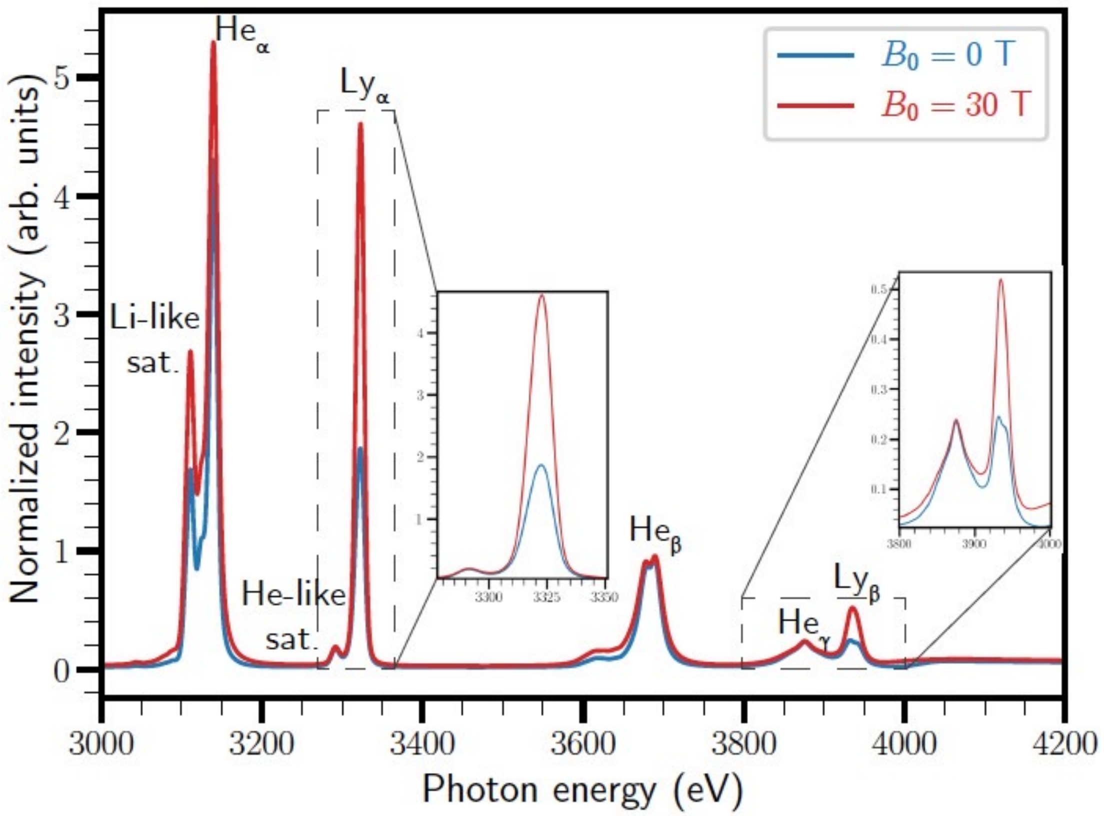
Time-integrated argon K-shell emission

Synthetic spectra ("forward" modelling) show good qualitative agreement with experiment

Experimental Ar K-shell emission spectra



Synthetic Ar emission spectra
for plasma conditions @ $R_0/R(t) = 20$



Agreement best when we use MHD simulation conditions 50ps before stagnation, when compression is the same as seen in the experiment, i.e $R_0/R(t) = 20$

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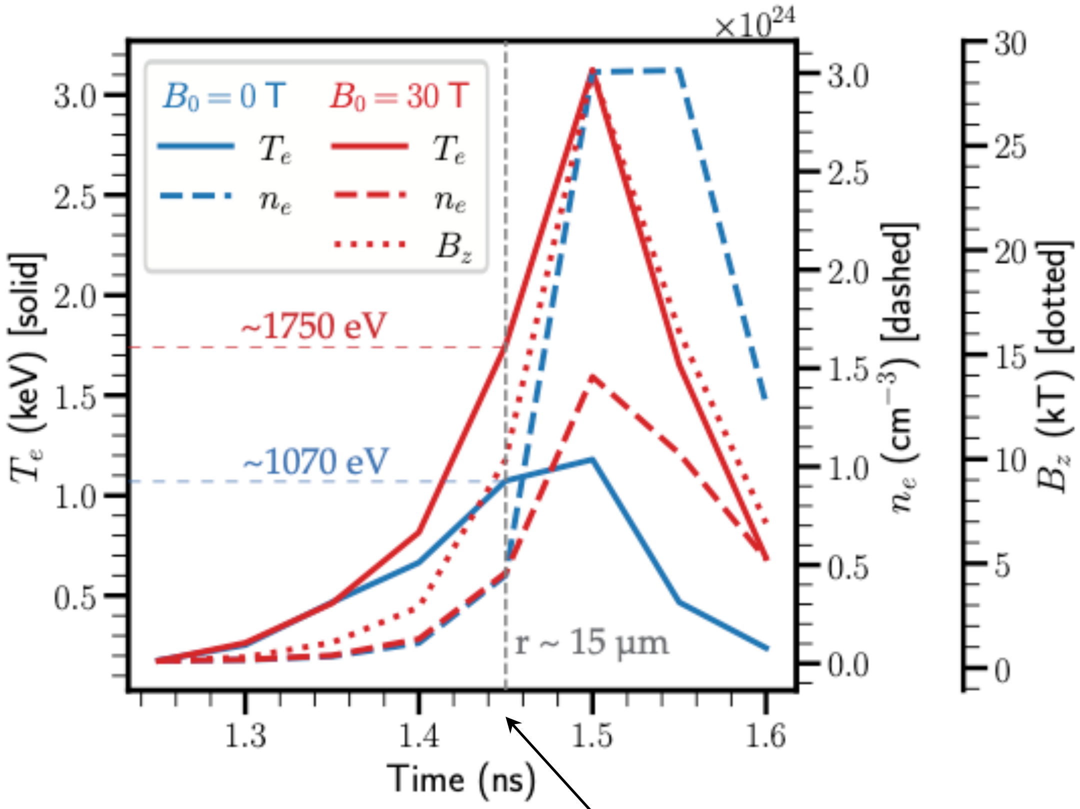
Reached plasma conditions at the OMEGA experiments



50 ps prior to stagnation :
R_0/R reaches 20 here,
consistent with exp. data

When magnetizing the implosions:

- **Compressed B-field reaches ~10 kT**
- **Hot spot temperature enhanced by ~70%**
  (from ~1 keV to ~1.7 keV)

Dopant K-shell spectroscopy appears robust to unravel magnetization effects in imploded plasmas

Next goals at OMEGA :

- obtain time-resolved Ar K-shell spectra
- use dual-dopant (Ar and Kr) as a spatially-resolved temperature gauge

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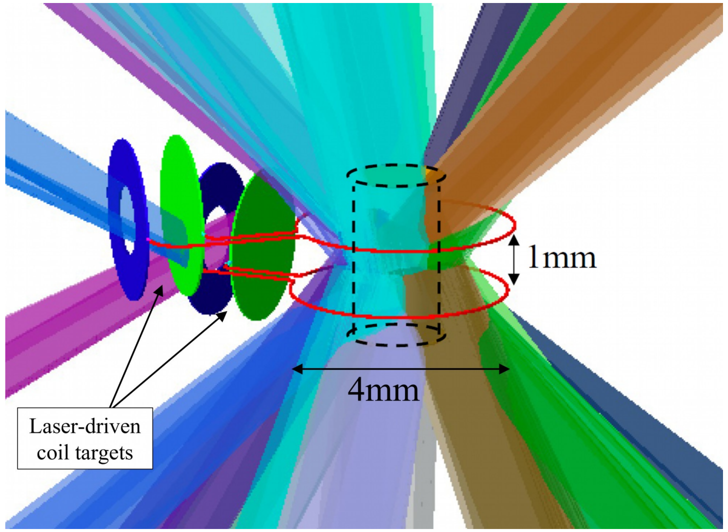
Moving the platform to larger scale facilities LMJ and NIF

About 300 kJ available (20x more than at OMEGA) for driving the implosions, crucial to reach the <u>self-sustained nuclear fusion</u>



Pérez-Callejo *et al.*, Phys. Rev. E **106**, 035206 (2022)

At LMJ :

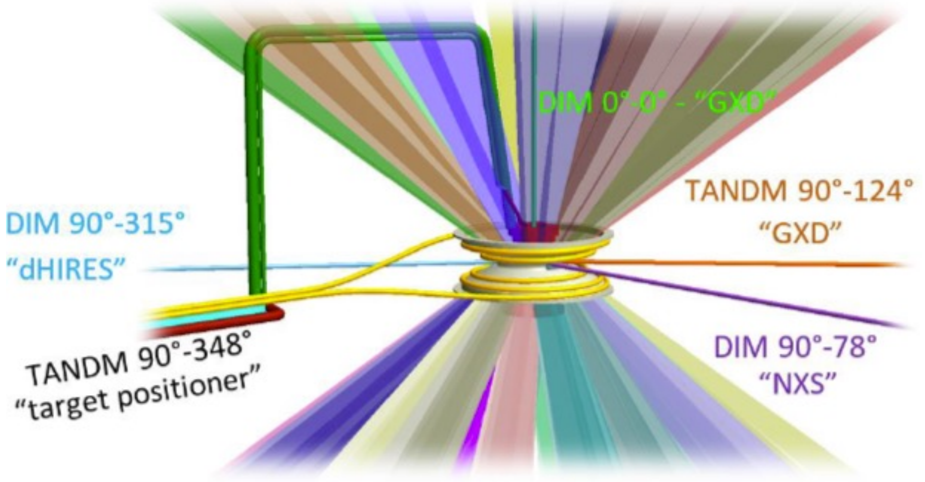
Granted experimental beam time for 2025-26, PI J.J. Santos

- Constrained to **B_0 = 5T** from laser driven-coils, we will aim at a higher compression
- Dual dopant spectroscopy to achieve an effective <u>spatial resolution of the core temperature</u>

At NIF :

Granted two shot days for FY2024 and FY2025, PI M. Bailly-Grandvaux

- **B_0 = 20T** from a pulsed power coil, possible to drive targets of larger radius, yielding significantly larger core radius (for the same R_0/R_f as at OMEGA)
- <u>Measurement of B-field compressibility</u> from angularly-resolved spectra of secondary neutrons



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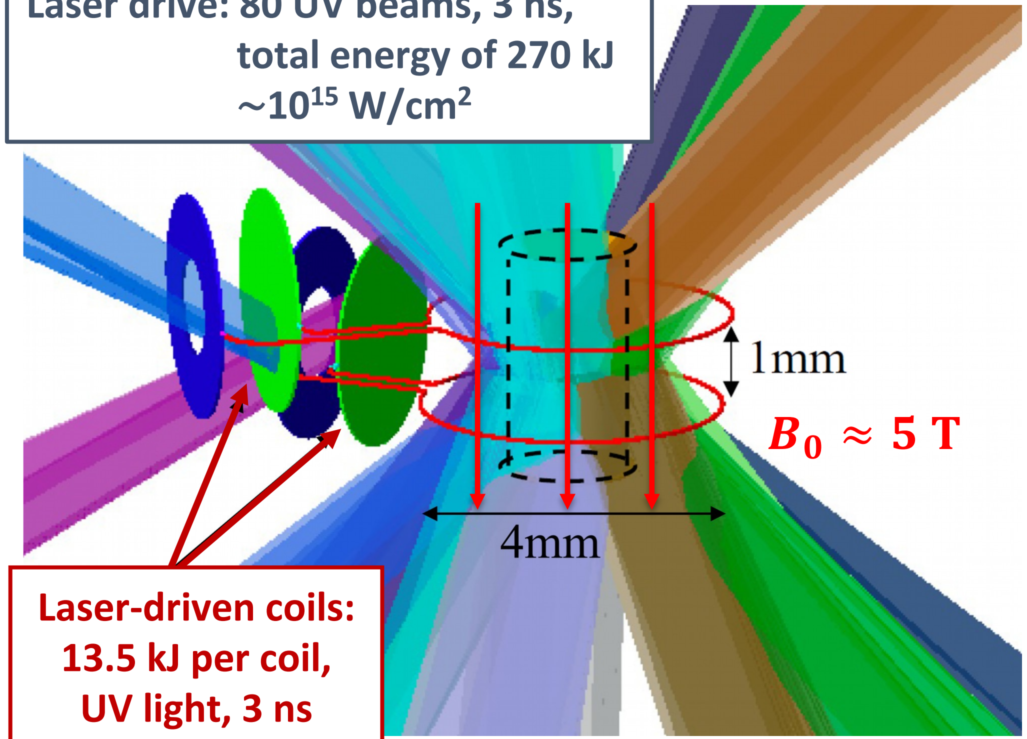
Magnetized cylindrical implosions at LMJ

Higher compression ratios allow to reach 10 kT out of a 5 T seed

**Laser drive: 80 UV beams, 3 ns,
total energy of 270 kJ
~10^{15} W/cm^2**



**Laser-driven coils:
13.5 kJ per coil,
UV light, 3 ns
~ 4×10^{15} W/cm^2**

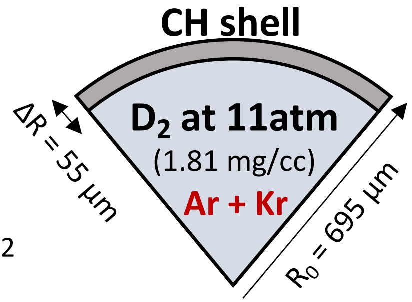
Pérez-Callejo *et al.*,
Phys. Rev. E **106**, 035206 (2022)

→ **10 kT can be reached departing from B_0 = 5 T**

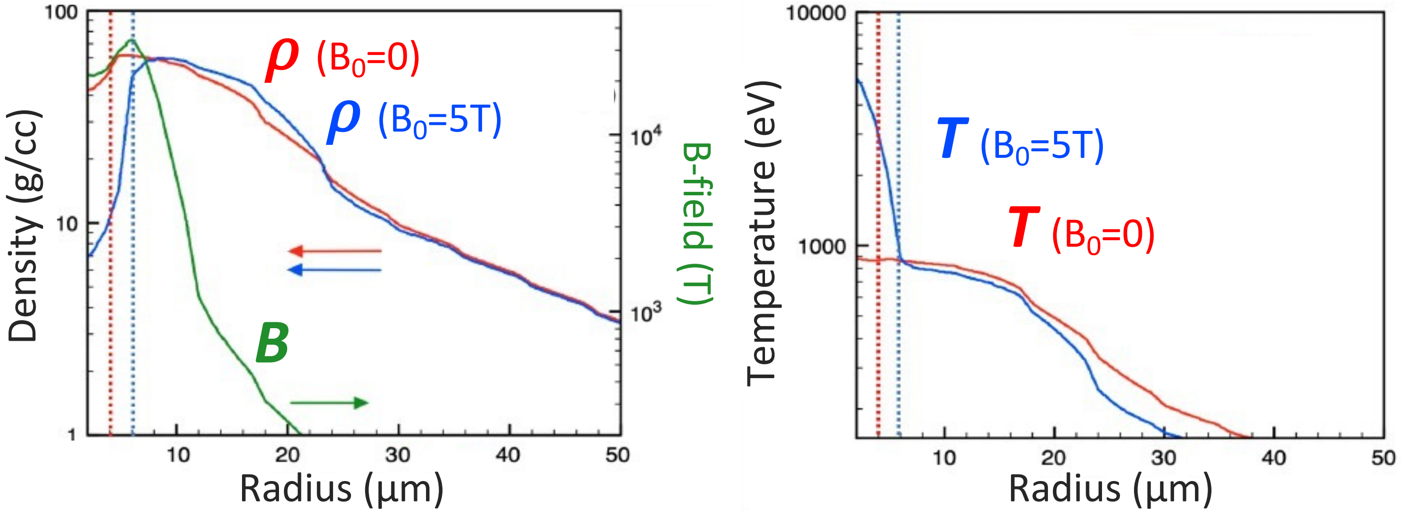
→ **Large range of temperatures in the core, up to >2.5 keV,** requires addition of Kr doping to probe hottest regions

LMJ setup compared to OMEGA :

- 20x more laser-drive energy
- 2.3x larger targets
  - → **Greater compression** $\frac{R_0}{R} \sim 100$
- Increase DD neutron yield from 10^8-10^9 to 10^{11}-10^{12}
  - → **Ion temperature measurements**
- No external pulsed power for B-field
  - → **Alternative use of laser-driven coils**



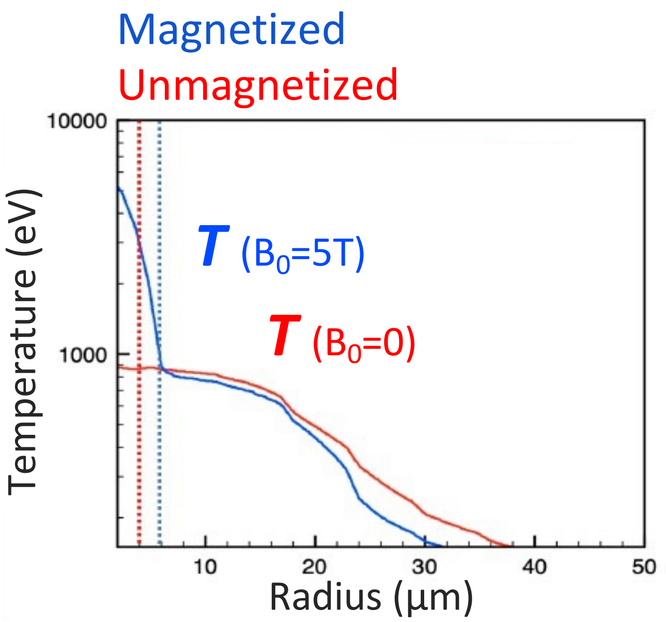
Extended-MHD predictions for the stagnated plasma (t = 3.5 ns)



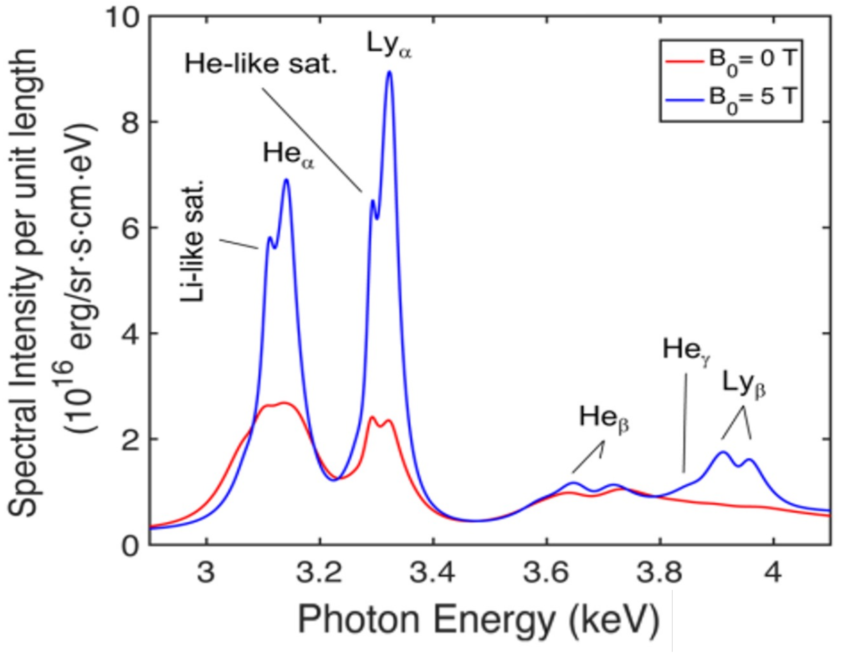
Magnetized cylindrical implosions at LMJ

Ar + Kr K-shell spectroscopy needed to "see" into the magnetized core

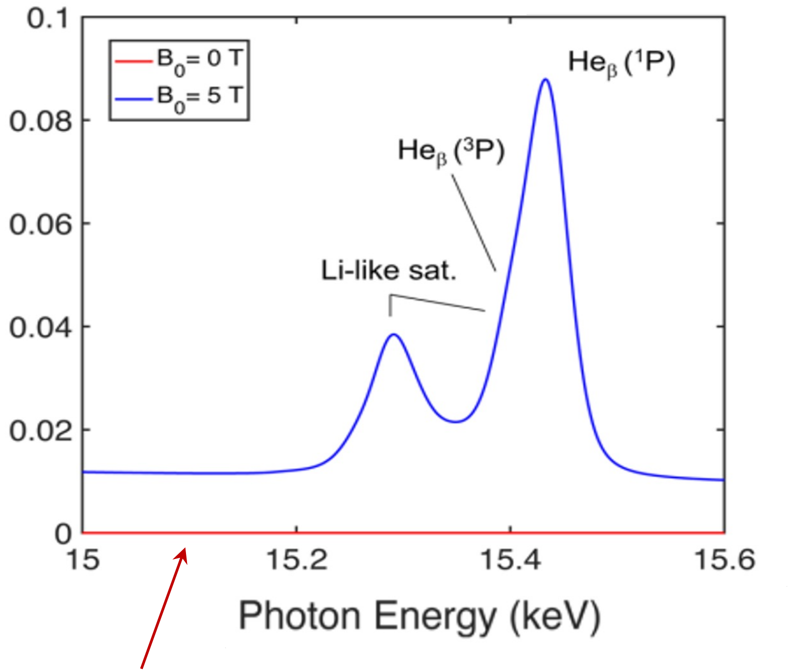
Measurable differences in Ar and Kr K-shell spectra with and w/o a seed B-field predicted by extended-MHD simulations coupled with radiation transport and instrumental broadening



Ar 0.3 % at concentration



Kr 0.01 % at concentration



No Kr K-shell emission expected in the non-magnetized case

Dual dopant works as a temperature gauge:
Scrutinize magnetization effects over two different regions of the hot spot, the edges for Ar (<2.5 keV) and the center for Kr (>2.5 keV)

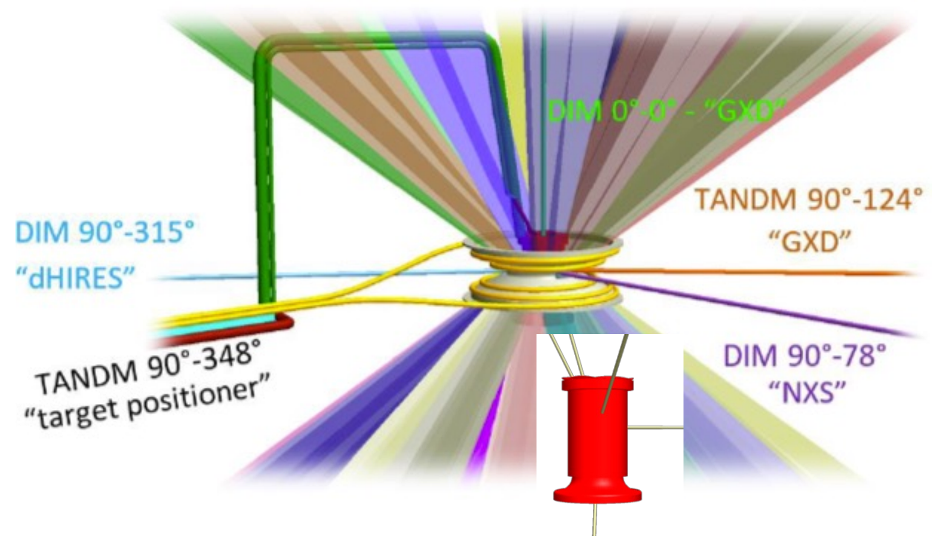
Goal: characterize $T_e(r)$

Pérez-Callejo *et al.*, Phys. Rev. E **106**, 035206 (2022)

Magnetized cylindrical implosions at NIF

Assess the B-field compressibility directly from experimental data

PI M. Bailly-Grandvaux (UCSD)



NIF setup :

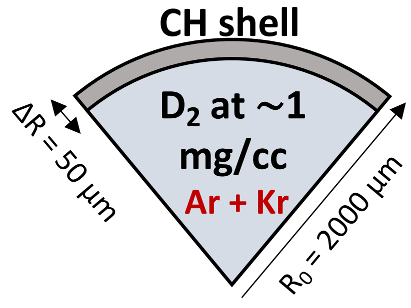
- Drive energy ~300 kJ (comparable to LMJ)
- MagNIF external power discharges :

  $R_0 = 2000\ \mu\mathrm{m} \ \rightarrow\ R_f \approx 100\ \mu\mathrm{m}$

  (instead of $R_f \approx 12 - 15\ \mu\mathrm{m}$ at OMEGA)

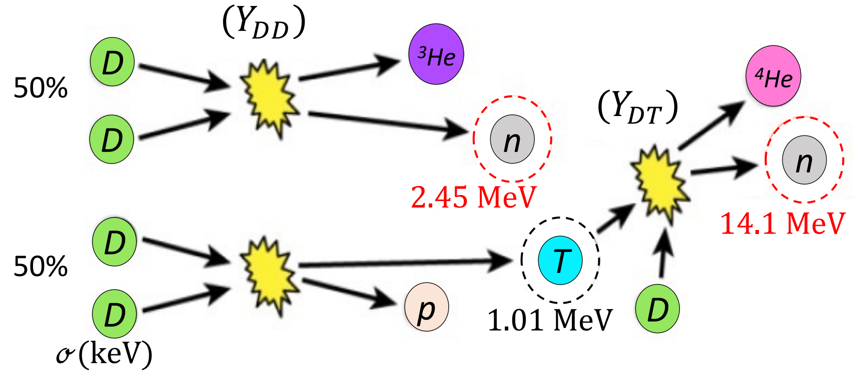
  $B_0 = 20\ \mathrm{T} \ \rightarrow\ B_f \approx 9\ \mathrm{kT}$
- DD neutron yield well beyond detection threshold

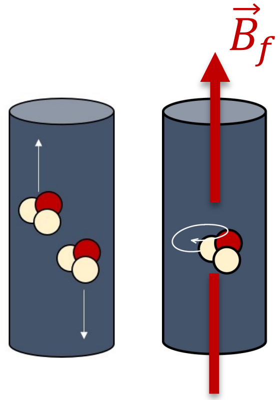
  $Y_{DD}|_{B_0=0} \approx 3\times10^{11}$ $\quad$ $Y_{DD}|_{B_0=20\mathrm{T}} \approx 10^{12}$



Measuring strength and topology of compressed B-field from angularly resolved ToF spectra of secondary neutrons

Schmitt *et al*., Phys. Rev. Lett. **113**, 155004 (2014)





Requirements:

- Magnetized core larger than Larmor radius of Tritons

  $B_f R_f \approx 0.9\ \mathrm{T.m} \ \Longrightarrow\ R_f \approx 4\rho_L$ for 1 MeV Tritons
- Secondary neutron yields beyond detection thresholds

  $\left.\frac{Y_{DT}}{Y_{DD}}\right|_{B_0=0} = f(\rho R) \approx 0.015$ $\quad$ $\left.\frac{Y_{DT}}{Y_{DD}}\right|_{B_0=20\mathrm{T}} = f(BR, \rho R) \approx 0.2$
- Radial areal mass $\rho_f R_f \sim 9\ \mathrm{mg/cm^2}$,

  enough high to change the Y_{DT}^n / Y_{DD}^n ratio, and

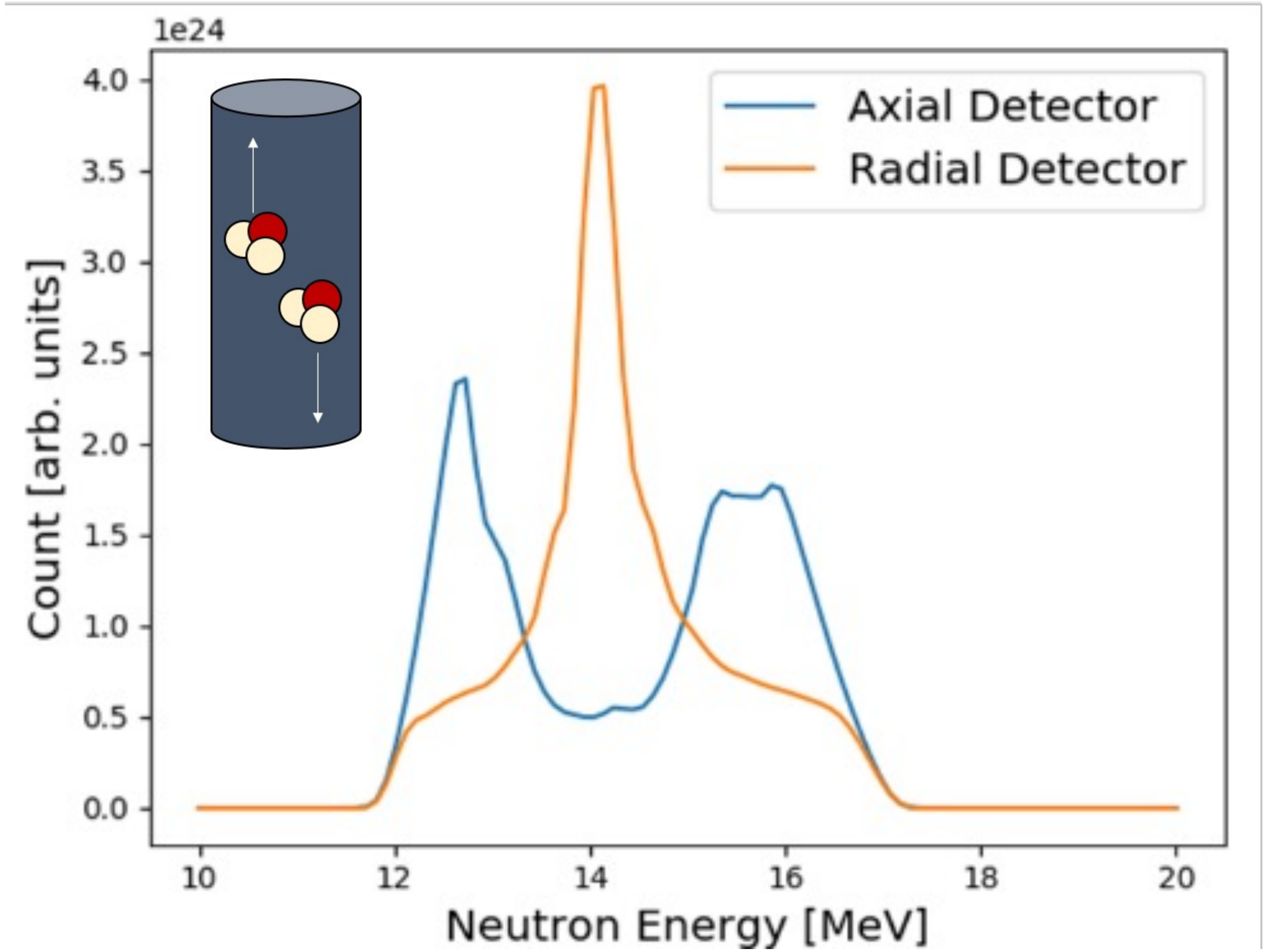
  enough low to not radially confine tritons on the ρR

Magnetized cylindrical implosions at NIF

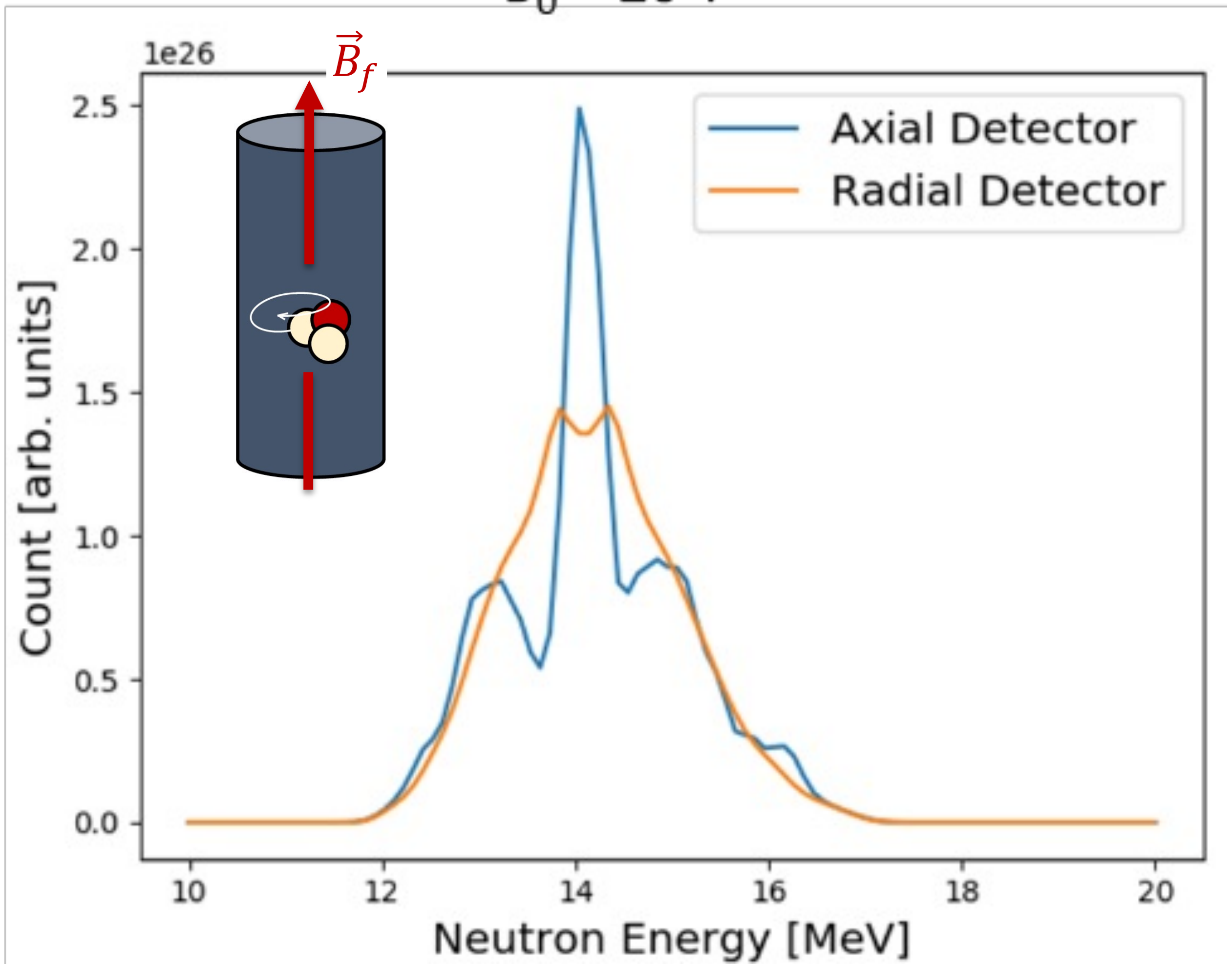
Quantify B-field amplification with secondary neutron yield

Calculated secondary neutron spectra for NIF conditions using PIC post-processing of extended-MHD simulations

$B_0 = 0$ T



$B_0 = 20$ T



Conclusions, for now…

What have we learned so far from the OMEGA experiments ?

- **Good agreement** found between MHD code and implosion dynamics up to t ~ 1.4 ns, though **factor ~2 discrepancy in hot spot radius** still to be explained

  Reduced implosion performance may be linked to target pre-heat caused by hot electrons, mixing of the ablator into the fuel, limitations of 2D versus 3D modeling, or azimuthal hydrodynamic instabilities … (?)

- **Clear and reproducible differences** between magnetized and unmagnetized Ar emission spectra

  Comparing time-integrated x-ray spectroscopic measurements with theory and "forward" simulations shows evidence of a hotter magnetized core by a factor 1.7

  This would be consistent with a compressed B-field of 10 kT, enough to impact on the electron magnetization and reduce radial energy losses from the core

Moving the platform to larger scale facilities LMJ and NIF (20x more laser energy drive) :

- Will explore both either **higher compressions**, at LMJ (with laser-driven coil B-field)**;** or **producing larger cores** (for same R_0/R_f as at OMEGA), at NIF
- **Ion temperature** characterized from primary neutron ToF spectra
- Dual dopant spectroscopy will allow to **characterize the core T_e with an effective spatial resolution**
- **B-field compressibility** directly assessed from secondary neutron ToF spectra

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Thank you !

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