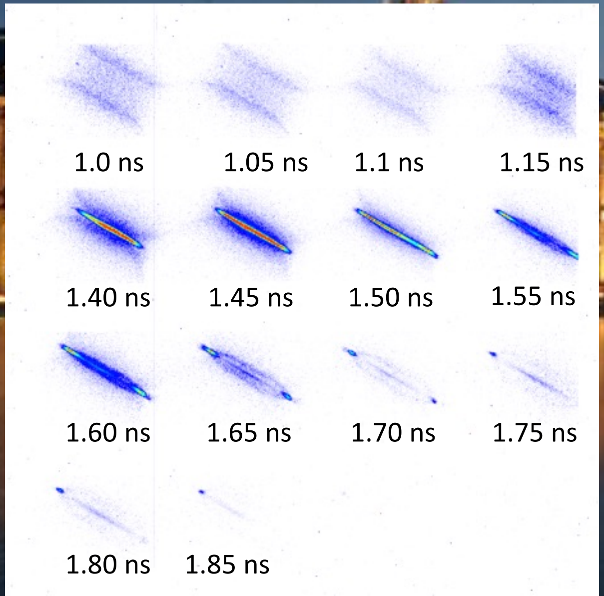
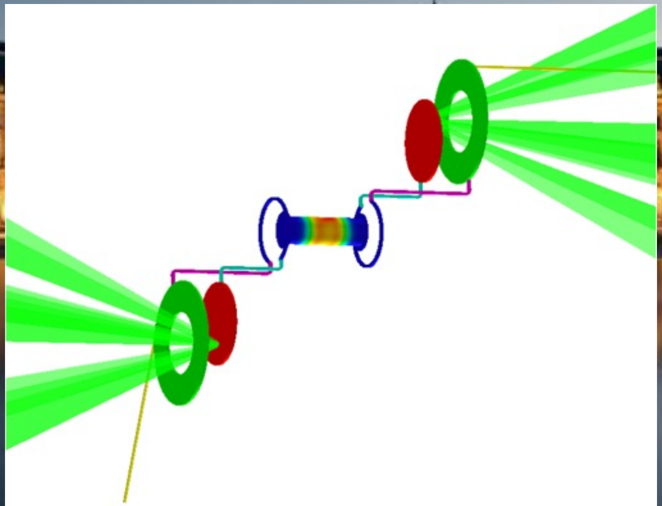
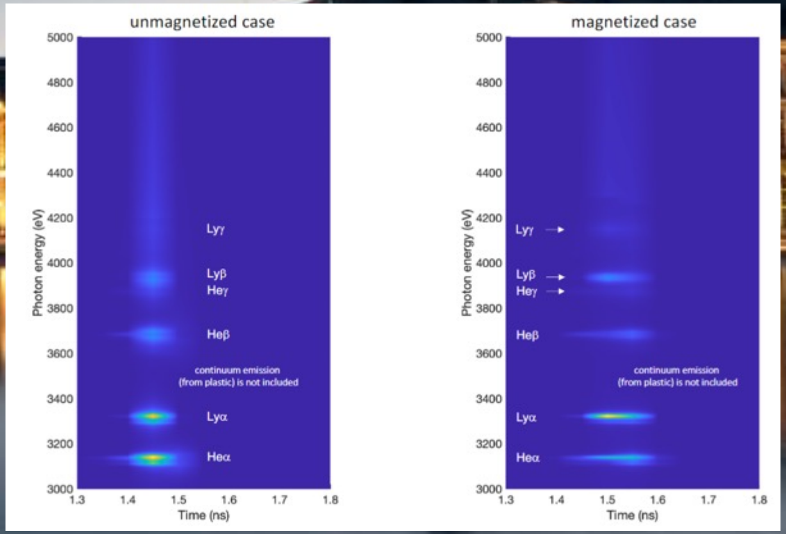
Driving strongly magnetized HED plasmas at Omega

G. Pérez-Callejo – CELIA, Université de Bordeaux – CEA – CNRS







Forum ILP

27 September – 1 October 2021

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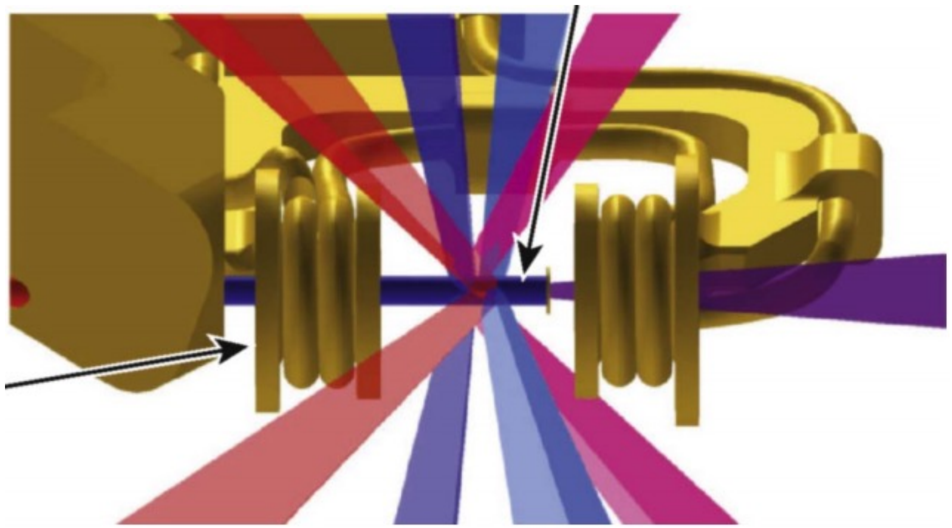
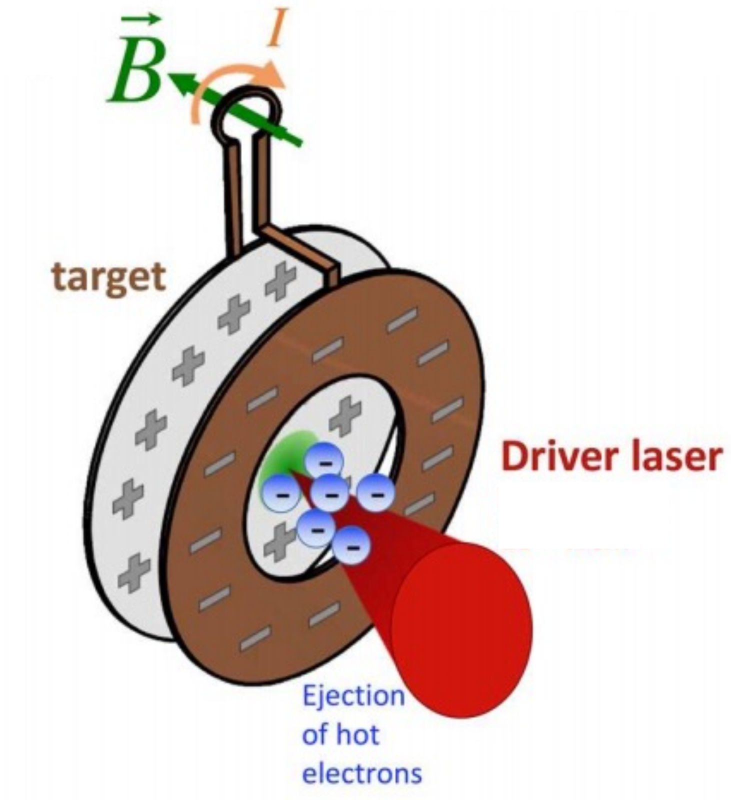
Magnetic drive: 2 main methods

Externally driven coils



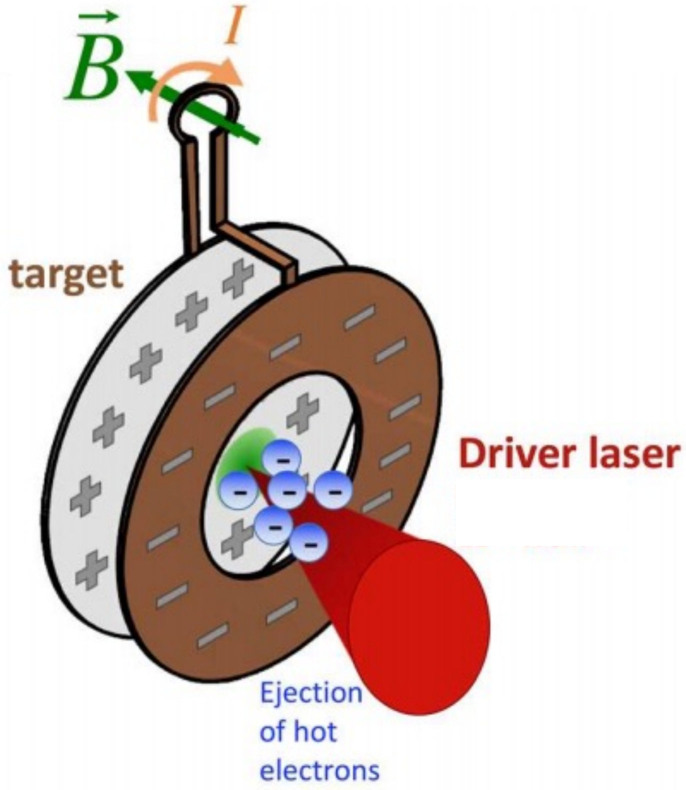
This image corresponds to the MIFEDS platform used in mini MagLIF experiments

Laser-driven Coils

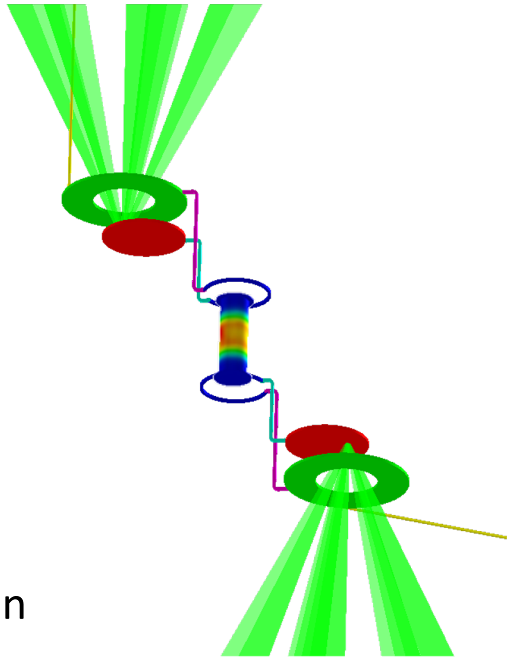


Laser-driven coil targets

Laser-driven B Coils

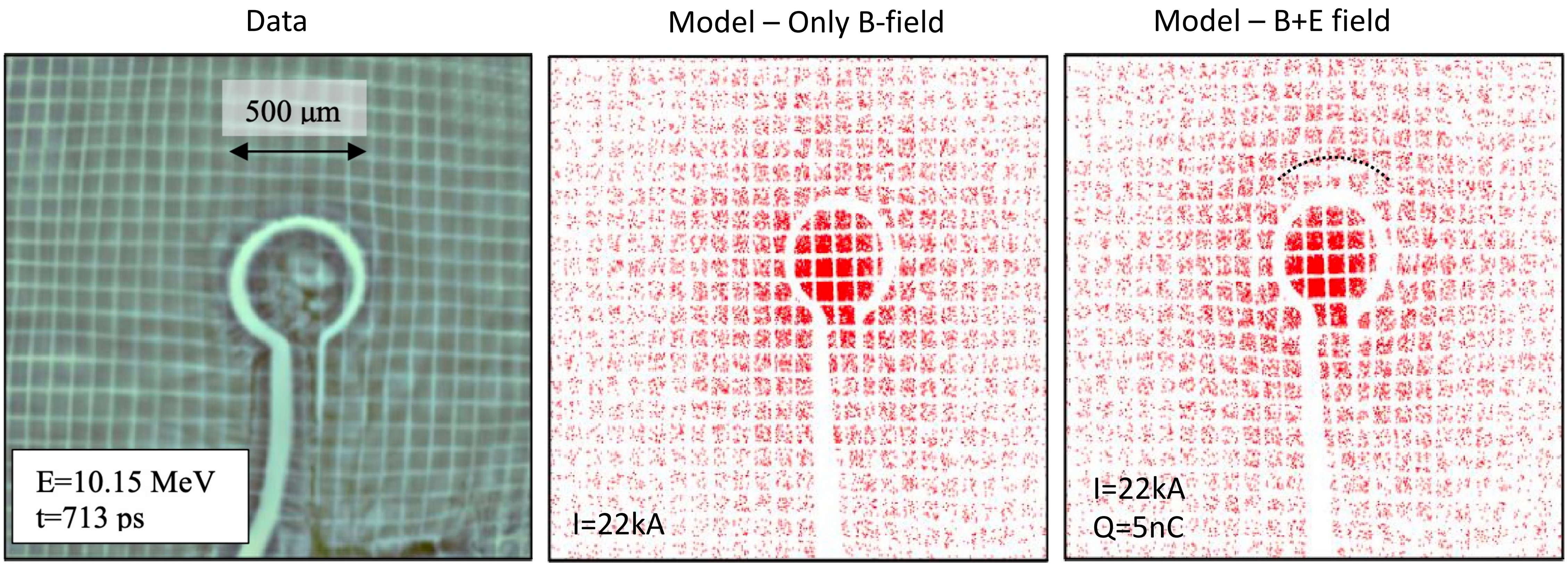


- Laser ejects electrons from the backplate
  - The backplate acquires a positive charge
- The laser-generated plasma closes the circuit between the two plates
- A current loops through the circuit
- The coil concentrates the magnetic field lines.
- Possible to mount two in quasi-Helmholtz configuration



These targets have been characterized at LULI

Results from May 2021 → 10^{15} Wcm^{-2}, as obtainable at OMEGA or LMJ



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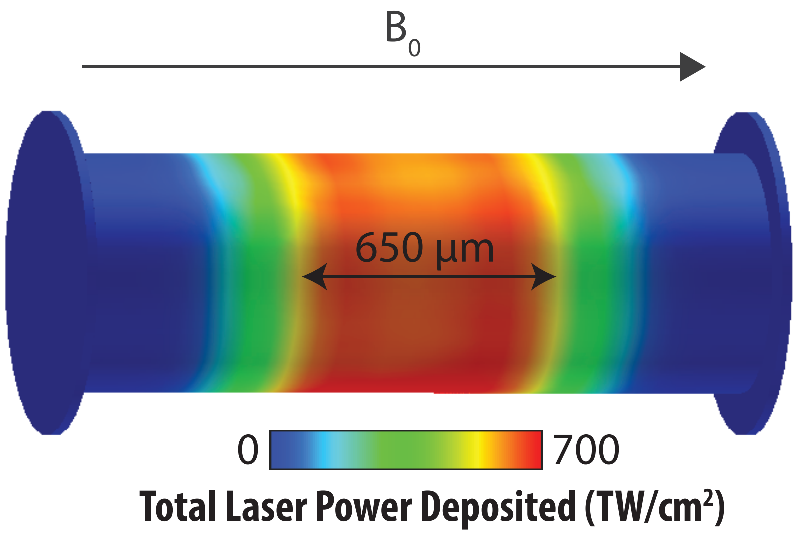
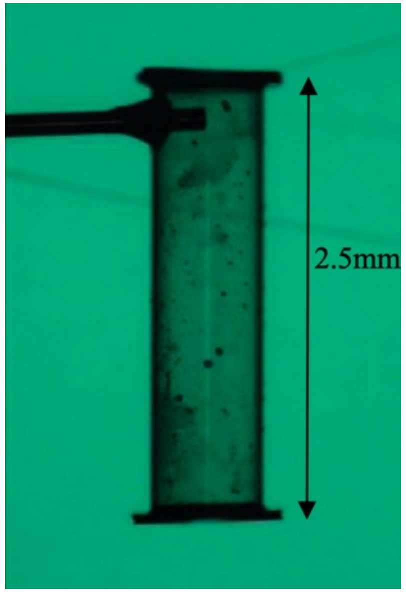
Cylindrical implosions at OMEGA



- Design for standard cylindrical implosion at OMEGA (Hansen *et al.* 2018)
- 40 beams on target (14.5 kJ)
- Cylindrical plastic shells with 11atm D_2 fill
- Magnetic field generated by laser-driven coils (day 1) and MIFEDS (day 2)



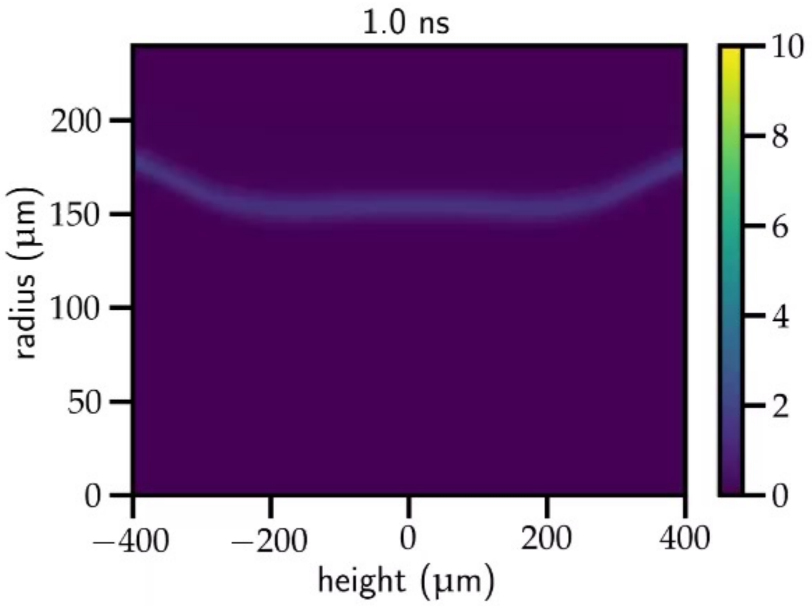
Hydrodynamic simulations with Gorgon – 50T

B-field amplification with target compression

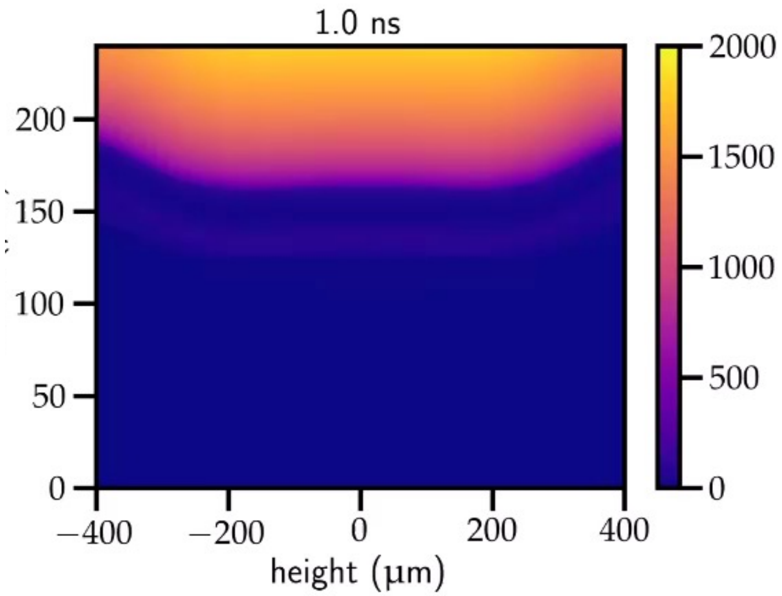
Magnetic flux is conserved (frozen-in-flow) →

$$\left.\begin{aligned}\Phi_0 &= B_0 r_0^2 = 50\,T \cdot (280\mu m)^2 \\ \Phi_1 &= B_1 r_1^2 \sim 40kT \cdot (10\mu m)^2\end{aligned}\right\} \Gamma = \frac{\Phi_0}{\Phi_1} \sim 1$$

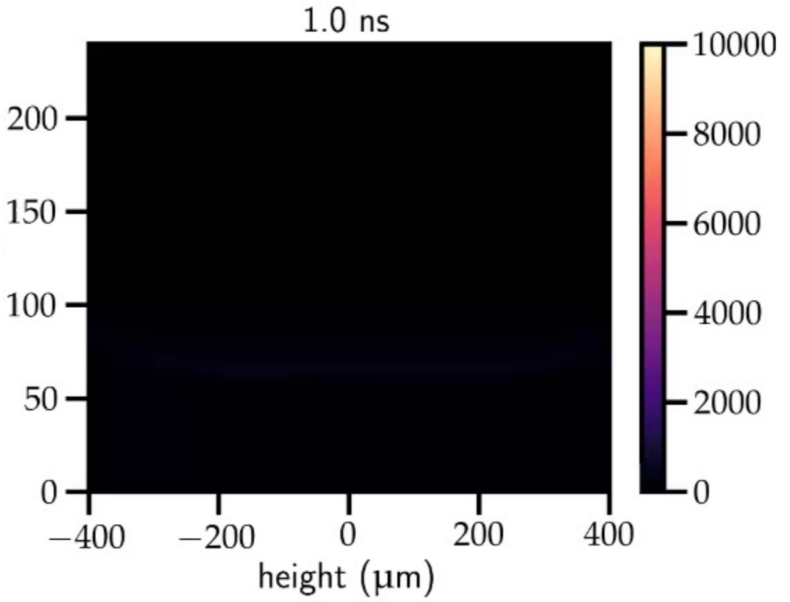
ρ (g/cm³)



T_e (eV)



B_z (T)



Expected effect of the B-field

As the magnetic field is compressed with the plasma:

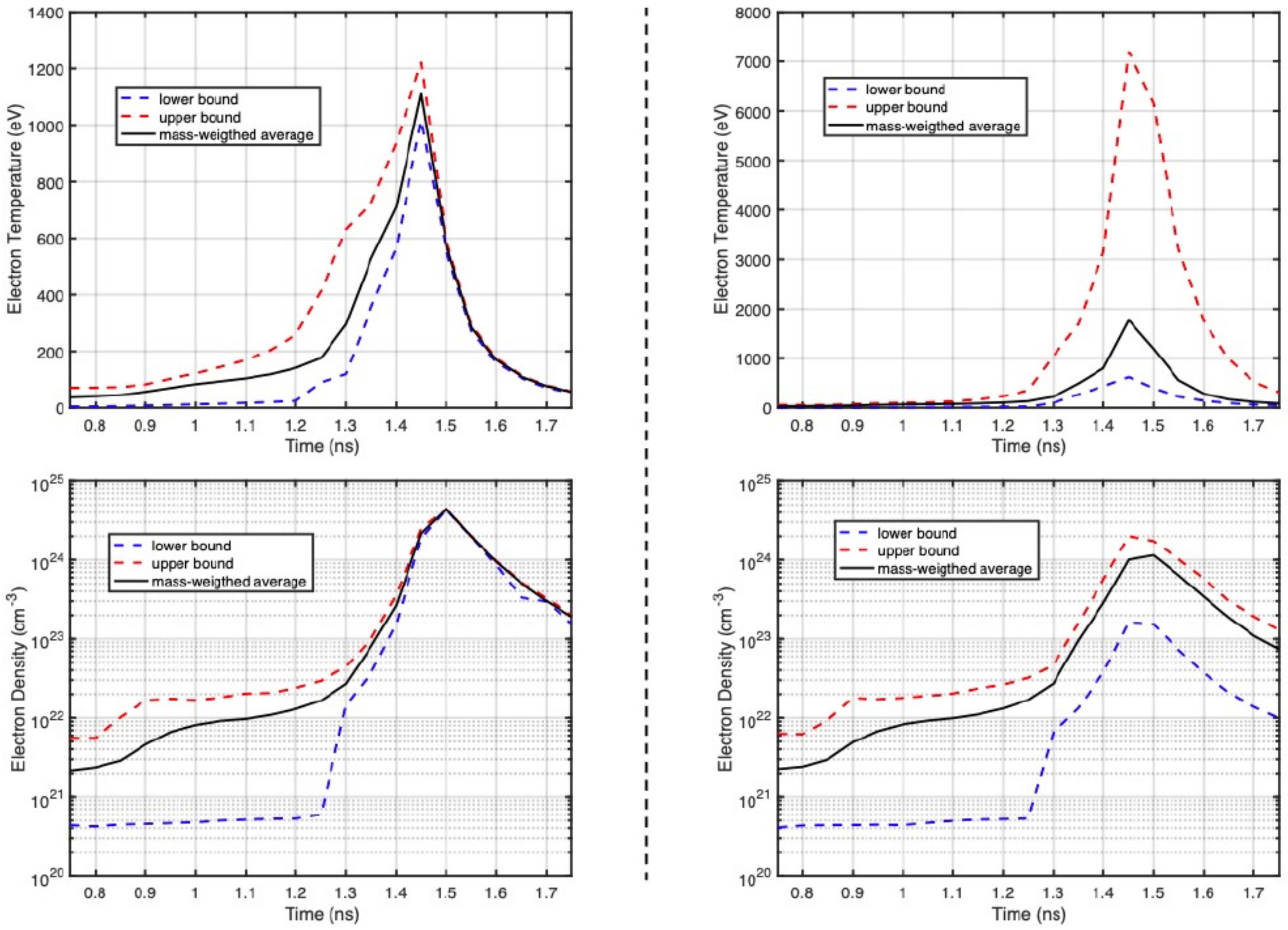
1. Electron conduction is magnetized → Collisional energy losses decrease → Temperature increases
2. Magnetic pressure builds up → Total pressure in the core increases faster → Lower density at peak compression
3. Increase the number of nuclear reactions → Increase of neutron yield
4. In DT fusion, confinement of α particles → Increase fusion yield further

MHD simulations summary (Gorgon)

	Applied Field	tbang	Burn av. Ti	Burn av. Density	Relative (n) yield
1D	0T	1.45 ns	1860 eV	4740 kg/m^3	1
1D	50T	1.47 ns	3320 eV	1570 kg/m^3	1.69
2D	0T	1.48 ns	1450 eV	1880 kg/m^3	1 (~10^9)
2D	50T	1.49 ns	2090 eV	620 kg/m^3	1.14

Include extended-MHD effects (magnetized heat transport, Biermann battery, Nernst effect)

Hydrodynamic evolution



- Electron conduction is magnetized
- Magnetic pressure becomes comparable to thermal pressure
  - Increased maximum temperature
  - Reduced core density
- The magnetic field introduces significant gradients
- These effects can be diagnosed with X-ray spectroscopy

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Main diagnostic – X ray spectroscopy

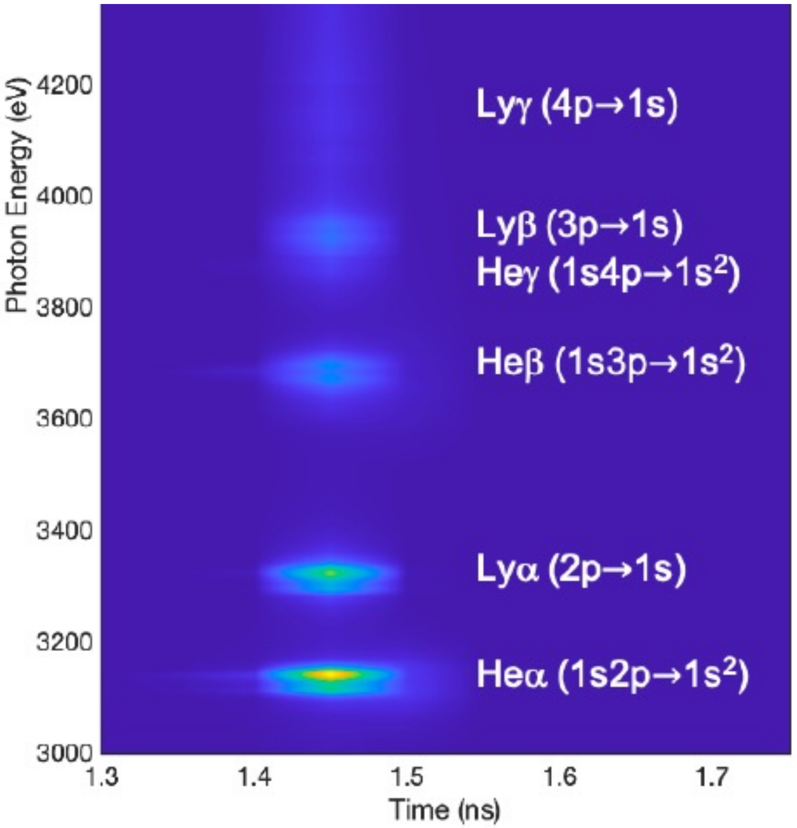
Using Ar as a dopant in the D_2 fuel (0.3% atomic)

Temperature increase and density reduction have an effect on the line emission:

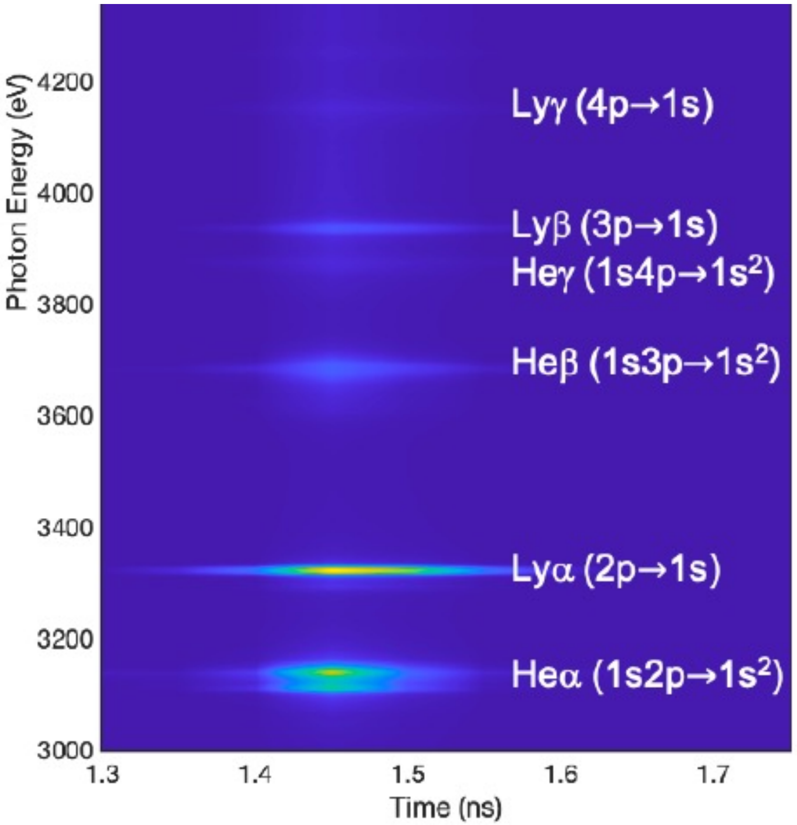
- Change in the line ratios
- Change in the line shape

Time-evolution changes

Non-magnetized



Magnetized



Spectra obtained using ABAKO and MERL

Synthetic streaked spectra

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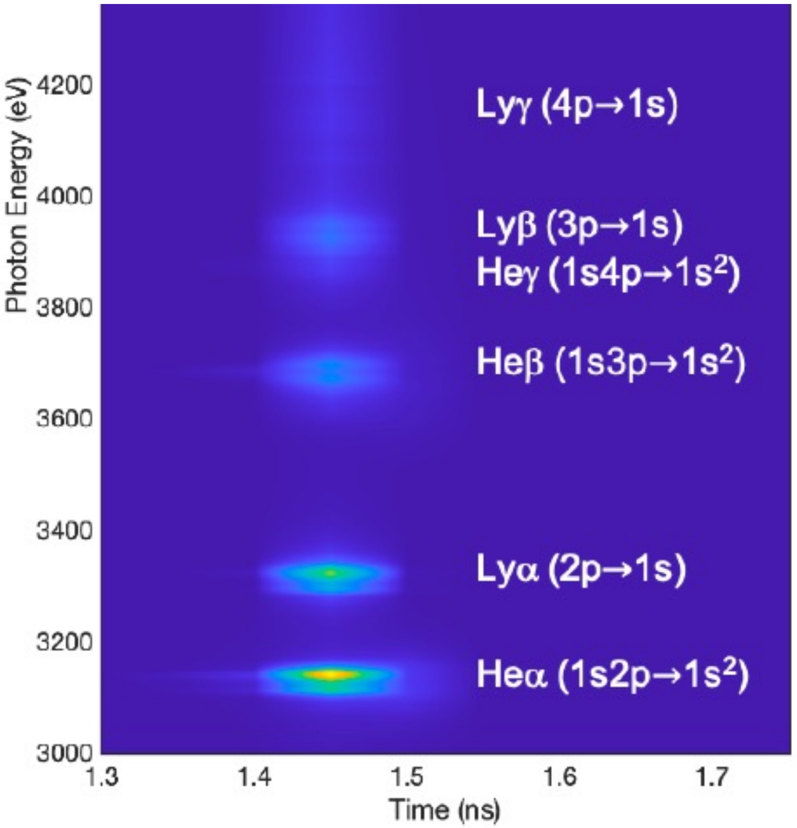
Main diagnostic – X ray spectroscopy

Magnetization effects:

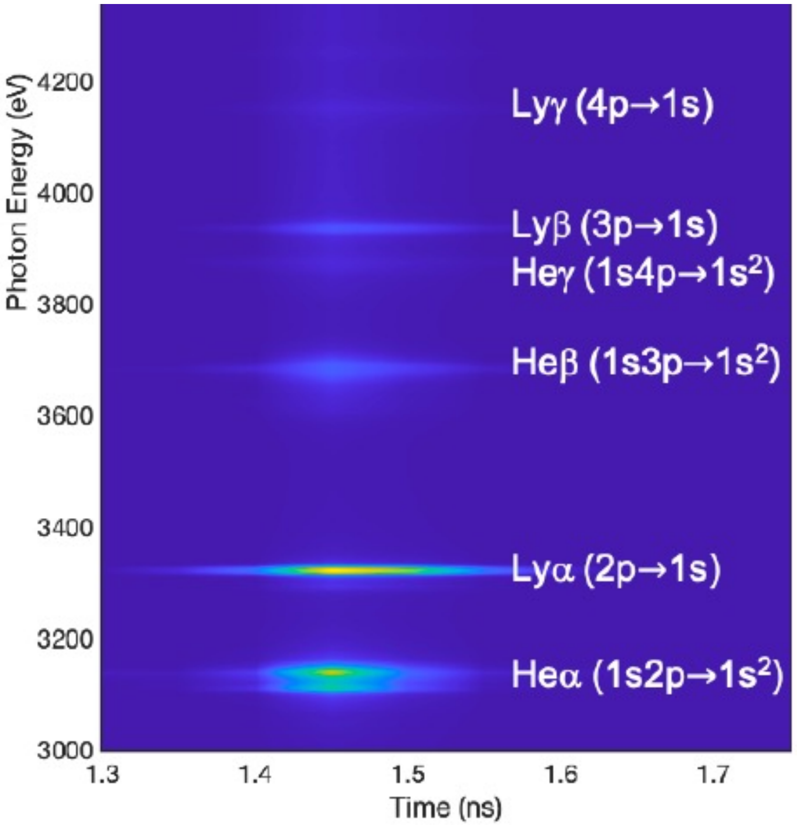
- Narrower lines
- Balance shifts to higher energies

These effects are enhanced by the gradients that appear by the action of the magnetic field.

Non-magnetized



Magnetized



Synthetic streaked spectra

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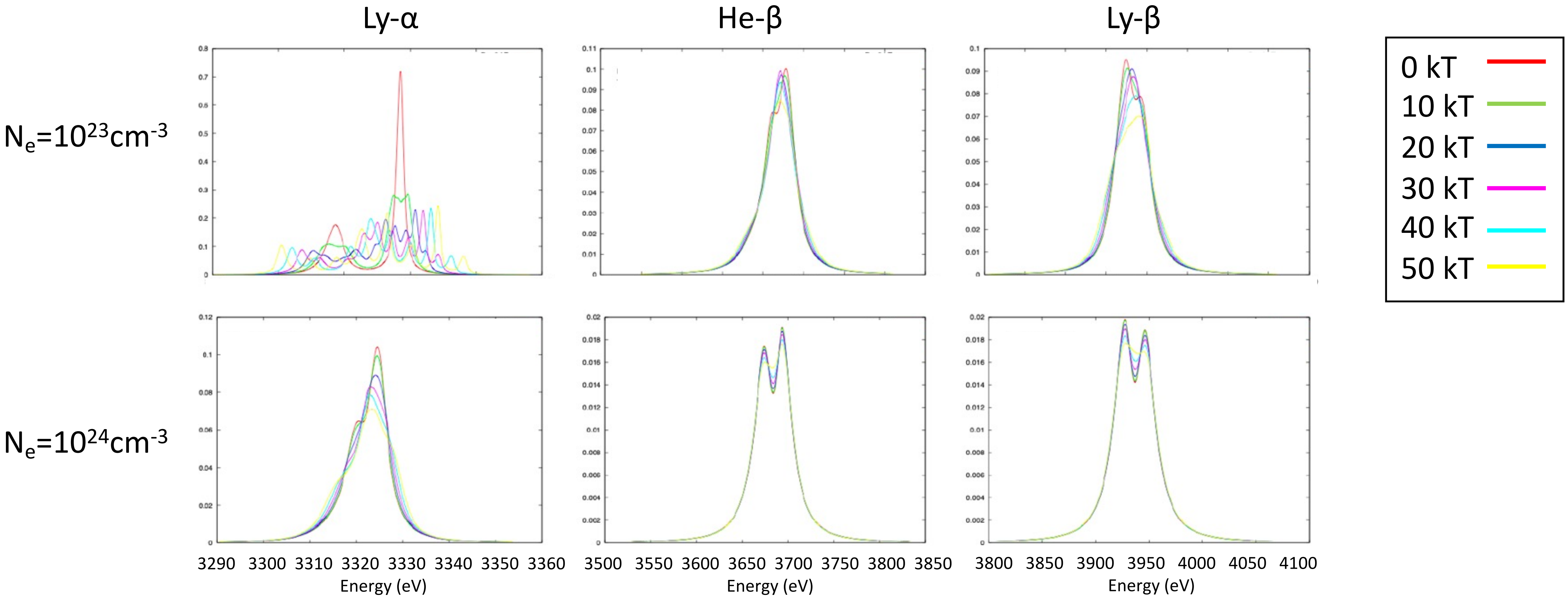
Zeeman splitting results

Despite the >10kT magnetic fields, Zeeman spectroscopy is not applicable owing to the high density of the implosion.



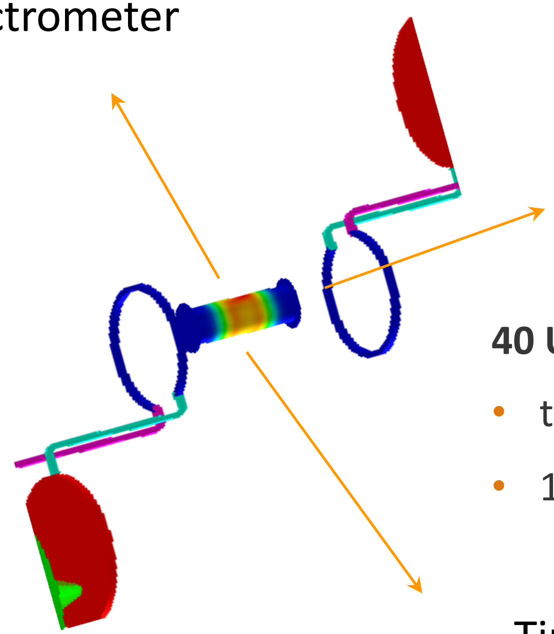
Experimental set-up – Laser driven coils

Time-integrated
X-ray spectrometer

Time-resolved
X-ray imaging

5 UV beams / CCT

- total energy ~2 kJ
- 1.5 ns square pulse
- I_0~8×10^{15} W/cm^2



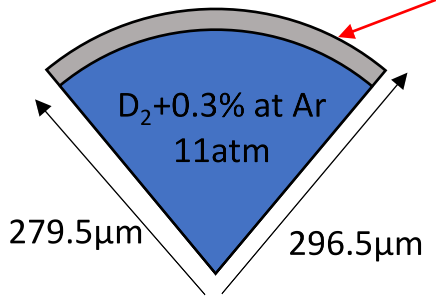
40 UV beams

- total energy ~14.5 kJ
- 1.5 ns square pulse

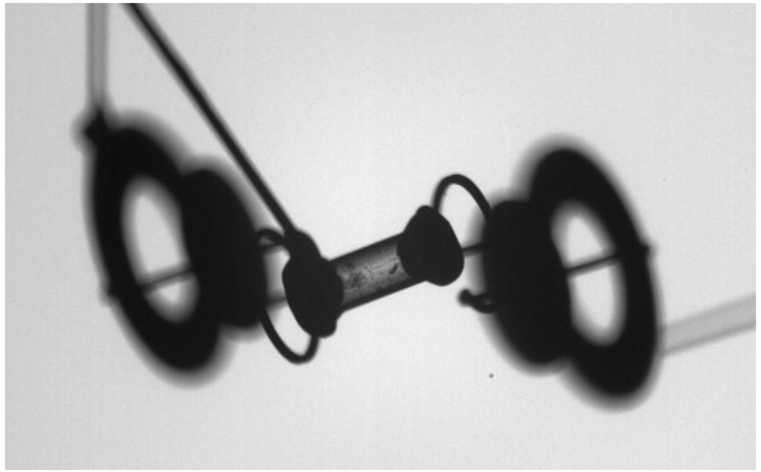
Time-resolved
X-ray spectrometer

Plastic shell

17µm thick shell



In reality shell thickness was ~19µm instead.

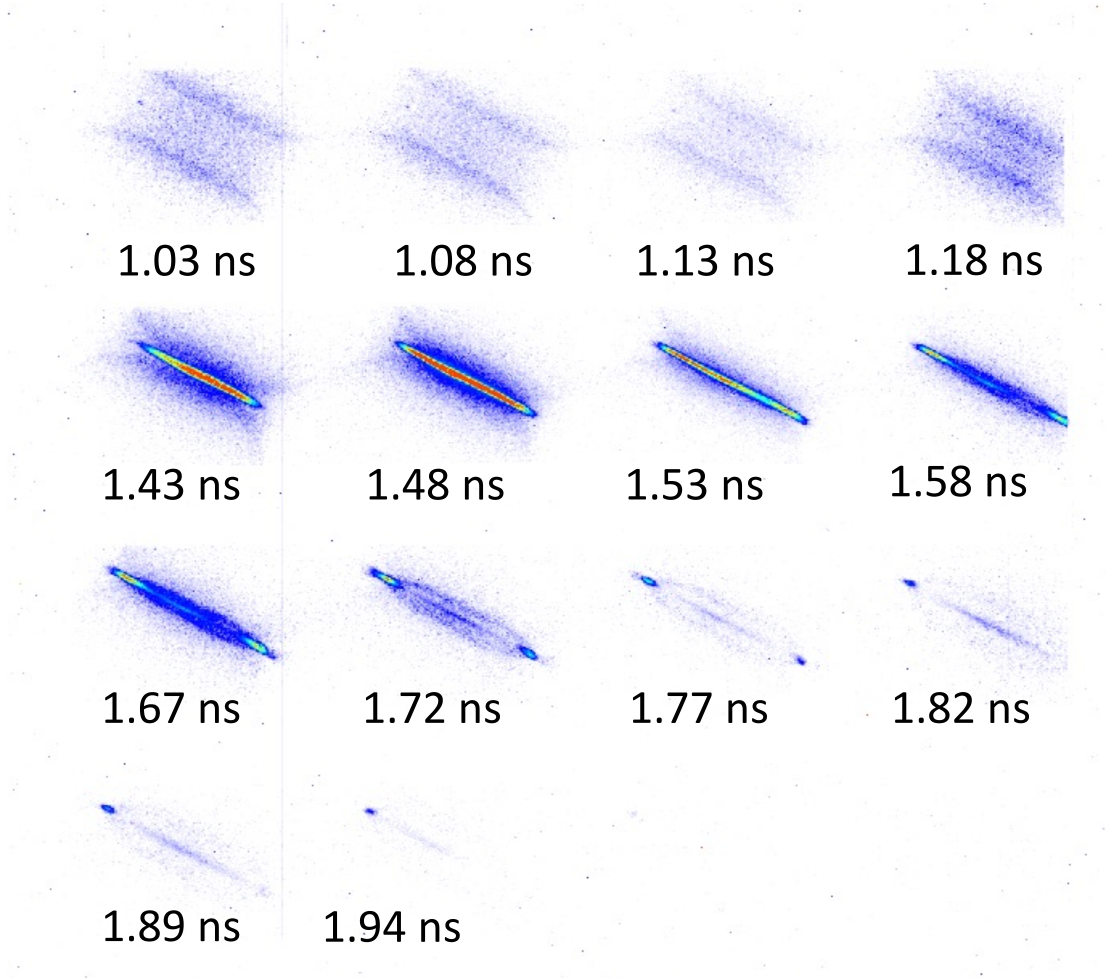


X-Ray Pinhole Camera data

Maximum compression is reached at 1.4-1.5 ns.

- This is in good agreement with hydrodynamic simulations using Gorgon and FLASH.
- However, the compression was much lower than predicted (minimum diameter of 30µm vs 10µm predicted) → Difference in shell thickness?

No significant difference between magnetized and unmagnetized implosions.



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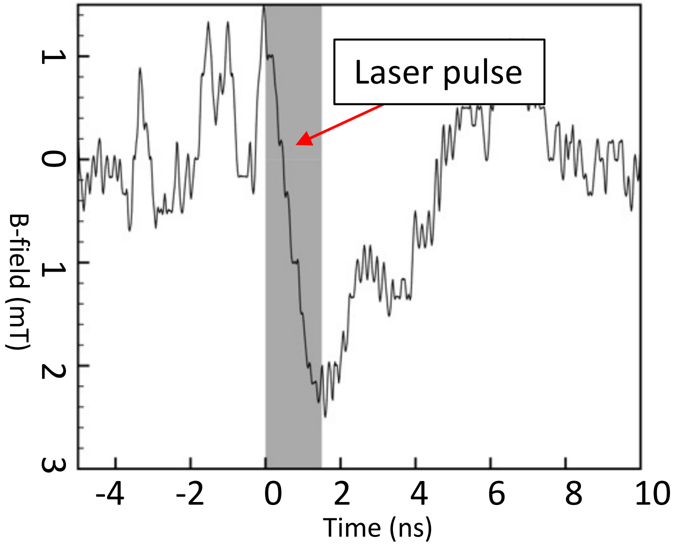
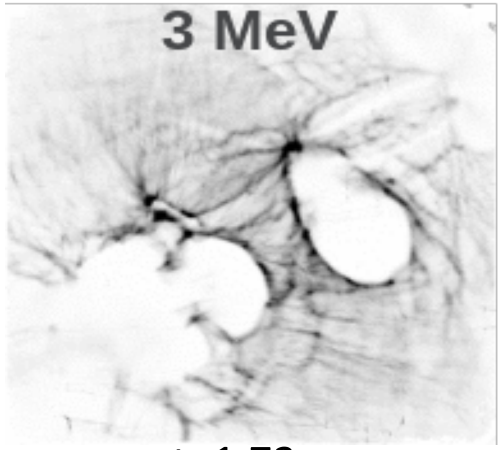
Performance of coils was not ideal

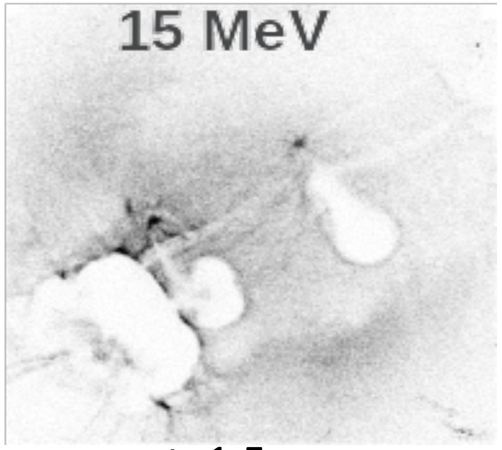
- Time evolution of B-field characterized using B-dot probes
  - Field increases while the laser is on



- B-field characterized using proton radiography.
  - Peak was found to be ~6T
- To increase B-field, laser-driven coils were replaced by MIFEDS for second shot day (24T)



t=1.73ns



t=1.5ns

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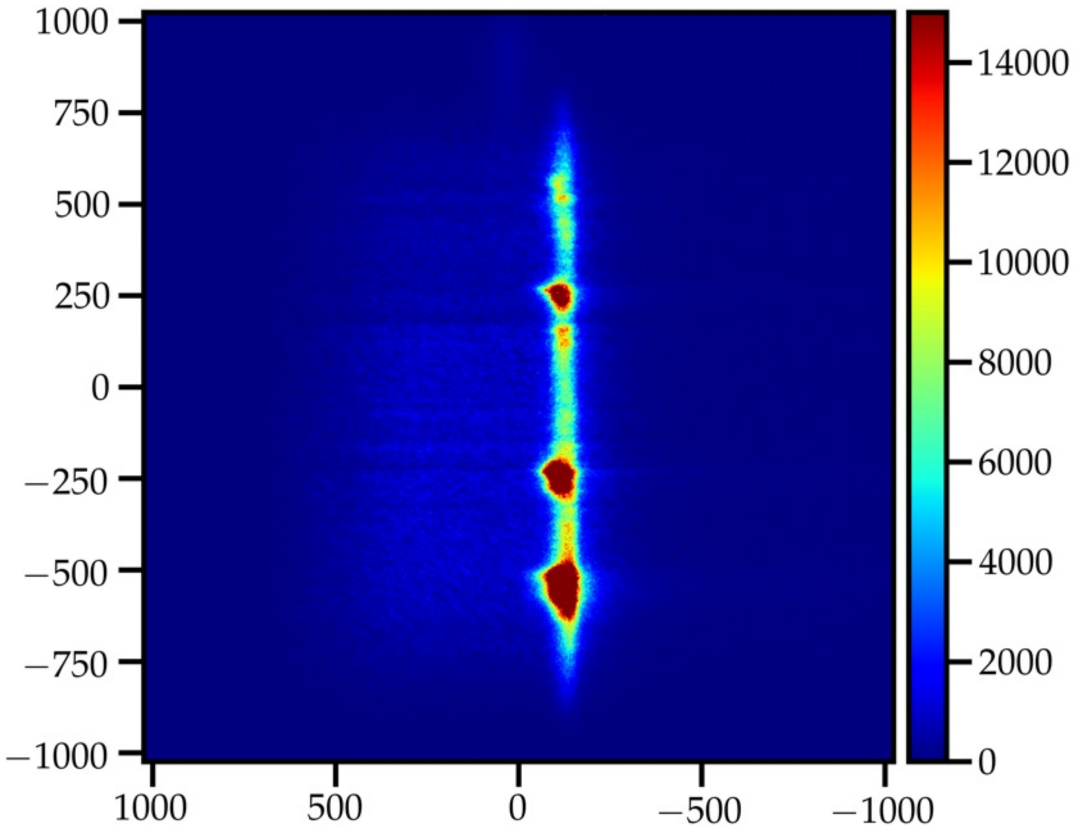
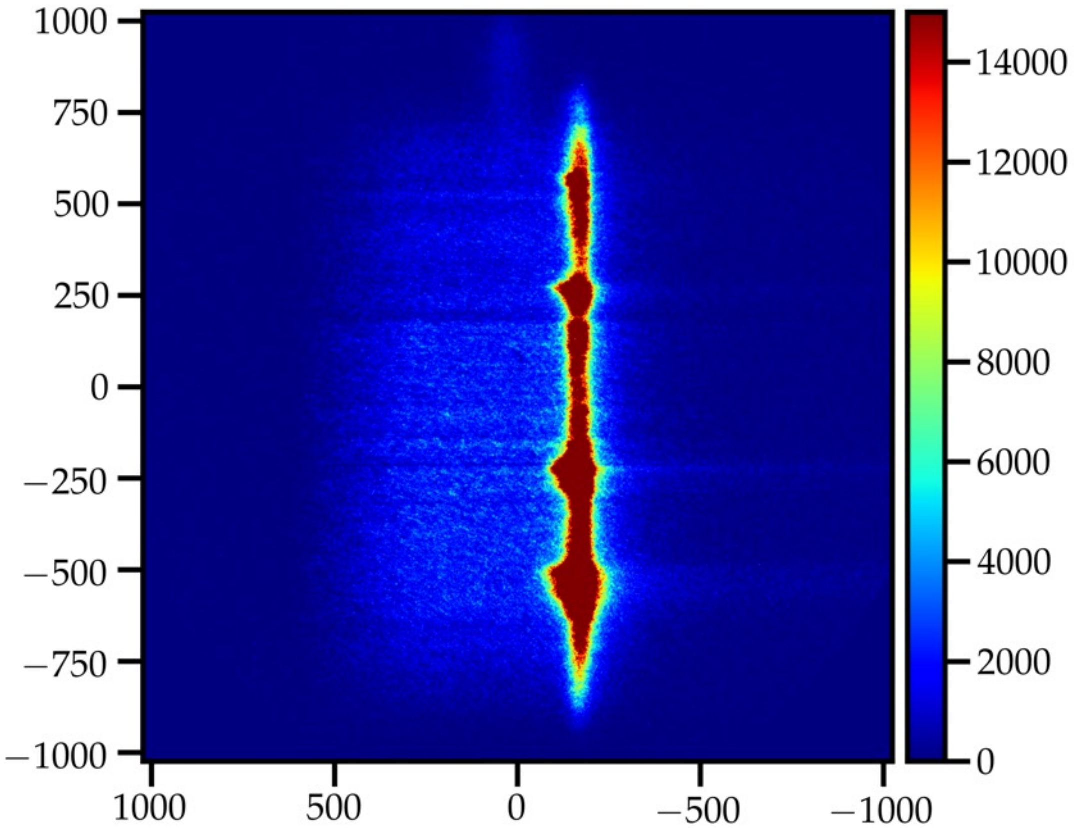
Time-resolved spectrometer

From second shot day → Using MIFEDS

Non-magnetized



Magnetized (24T)



Sweeping time=4ns

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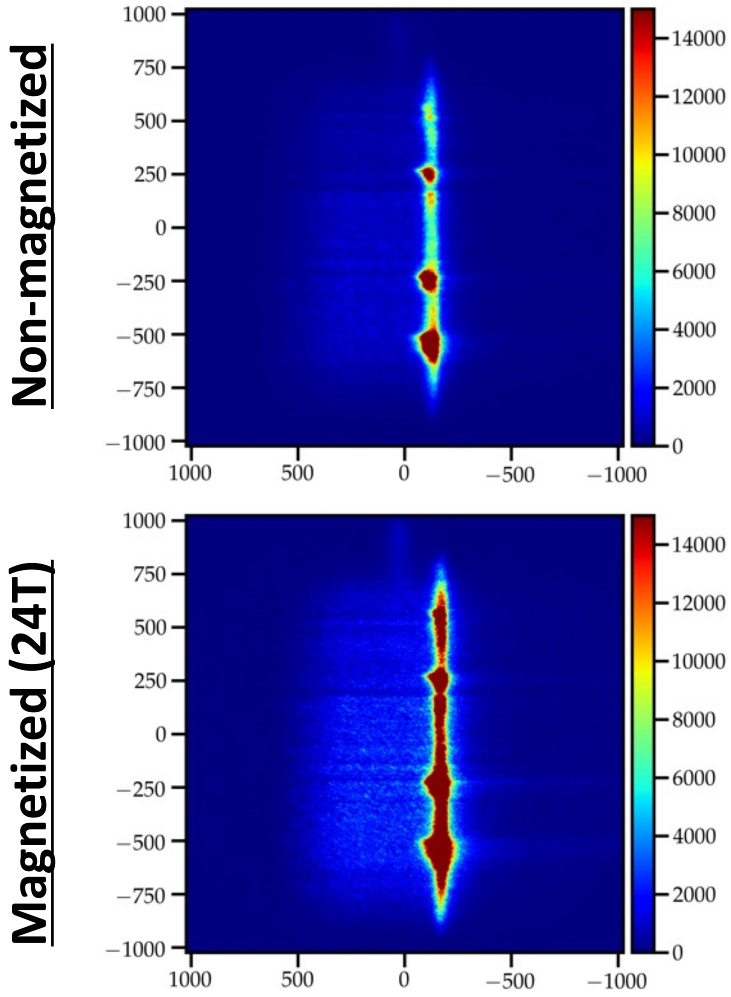
Time-resolved spectrometer



- Time-integrated emission is representative of peak compression
- Conditions pre- and post- peak compression can be obtained
- Streaked spectra can help us characterize conditions before and after peak compression → Saturation during peak compression
- Magnetized case seems to be significantly brighter across the whole spectrum

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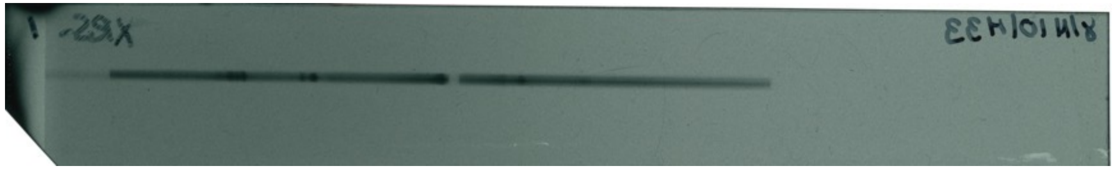
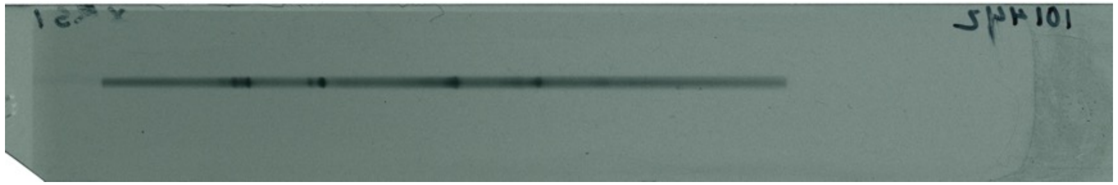
Time-integrated spectrometer

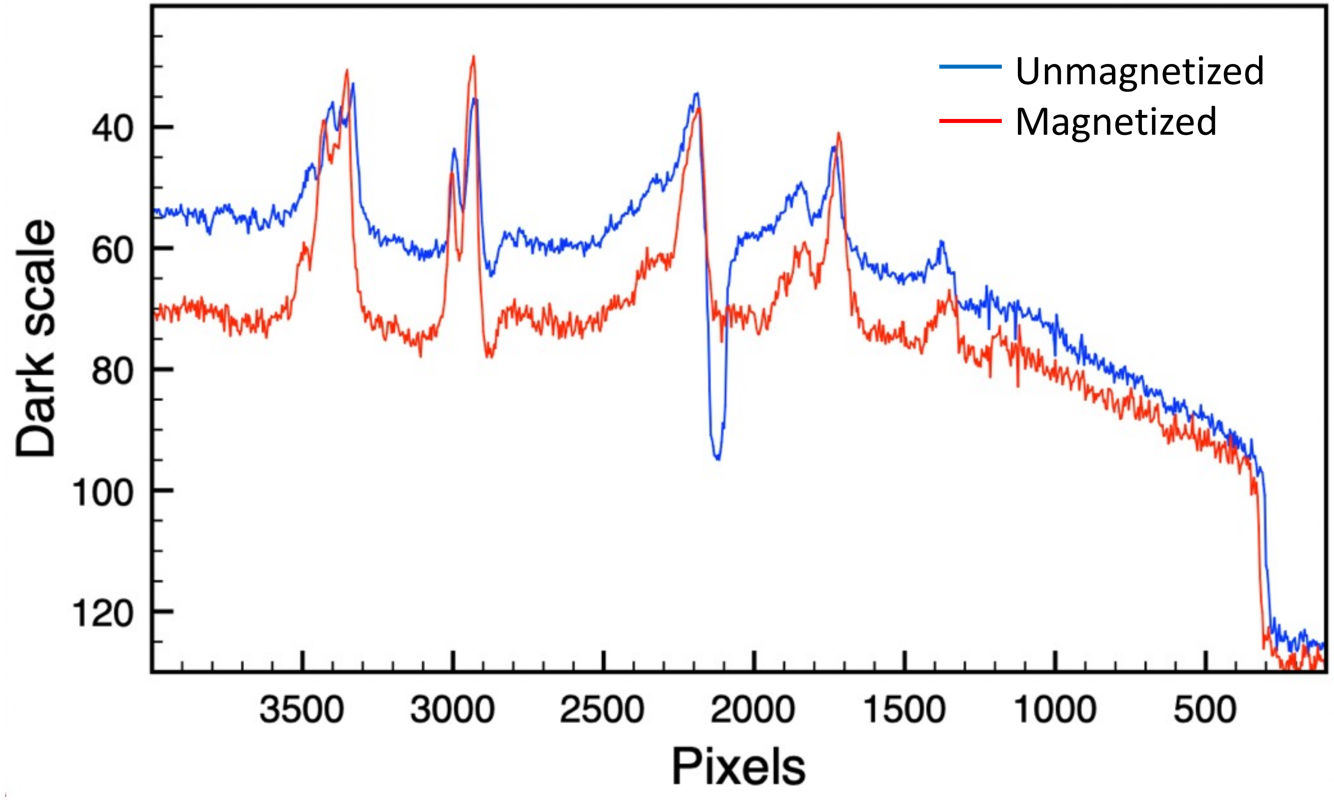
Unmagnetized



Magnetized



Photon energy



Film data is still being processed

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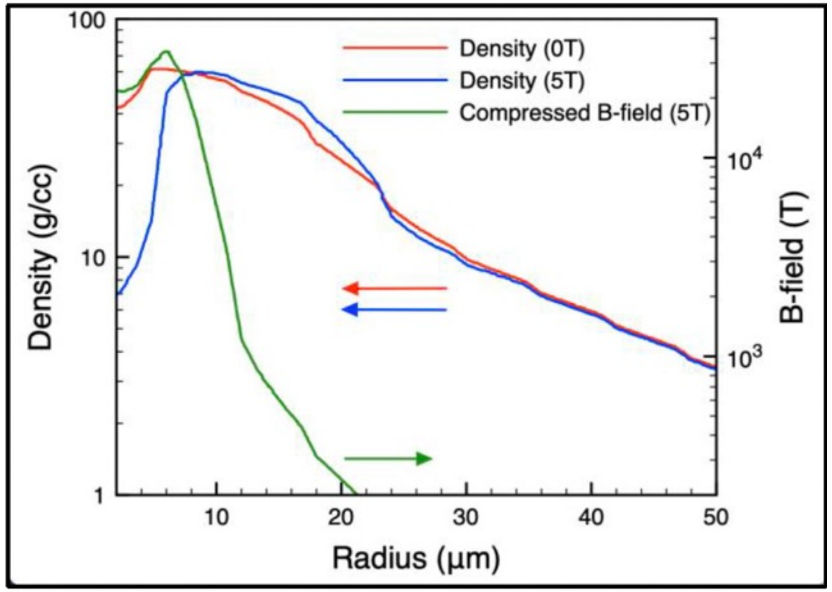
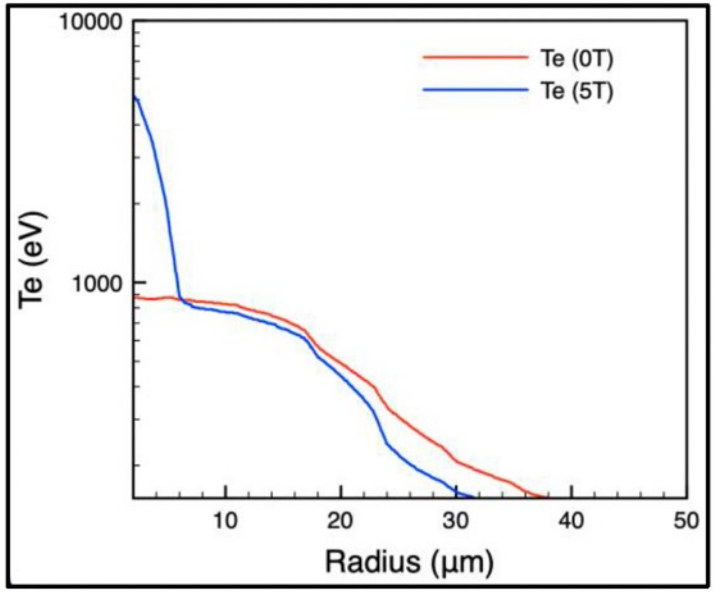
Conclusions

- We carried out the first experiment that includes an implosion and laser-driven coils
  - Coils B-field rises for the duration of the laser pulse
  - The specific geometry of OMEGA imposes a boil geometry that limits the seed B-field
  - The compressing power of the laser was below our expectations → Compressed core
- The experiment was repeated using MIFEDS (B_0 = 24T)
- Ar (dopant) emission spectroscopy is used for diagnosing the plasma conditions
  - There seem to be indications of the B-field affecting the brightness of the spectra
    - Data currently being analyzed
  - Time-integrated emission representative of peak compression
  - Streaked emission can be used to infer conditions prior and after peak compression

Future work

- Scaling up the platform for bigger lasers → More compressing power
  - We submitted a proposal for LMJ – Accepted last week





100s of kJ of energy → Greater compression

This translates in higher B-fields

Lower requirements for seed B-field

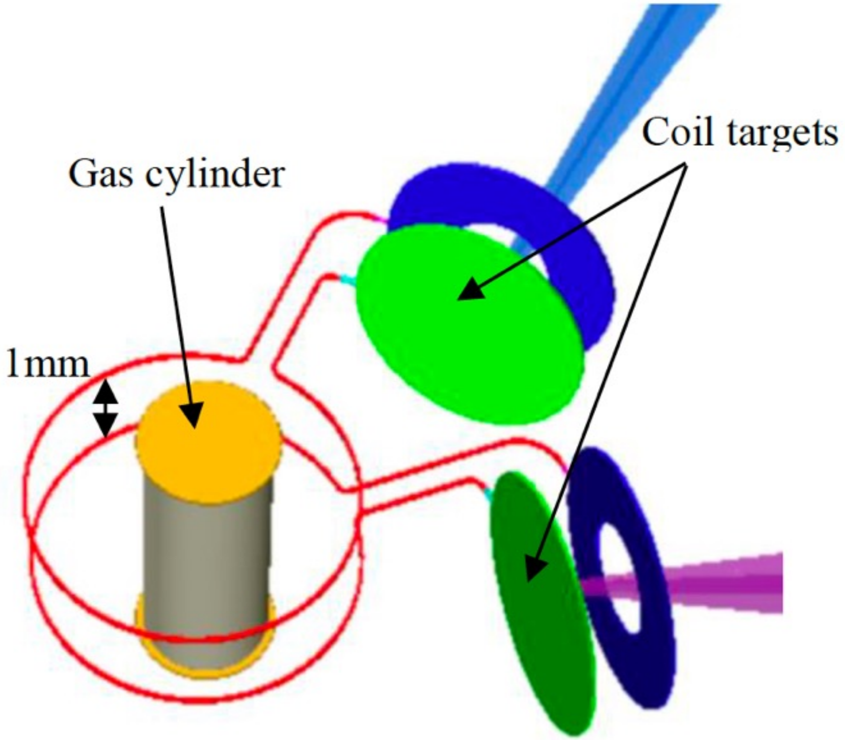
Access to an unexplored MHD regime

Validation of X-ray spectroscopy as diagnostic

Future work

By tuning target, laser and different set-up parameters, this new magnetization regime allows for:

- Studying the relative importance of different transport mechanisms
- Investigating Hall physics in HED
- Improving modelling of laser-plasma interaction with magnetic fields
- Mitigating hydrodynamic instabilities
- Enhancing the yield in nuclear fusion



CELIA

Thank you for your attention

Any questions?