Magnetization of inertial confinement implosions is a promising means of improving their performance, owing to the potential reduction of energy losses within the target and mitigation of hydrodynamic instabilities. In particular, cylindrical implosions are useful for studying the influence of a magnetic field due to their axial symmetry. Here we present results from magnetized cylindrical implosion experiments on the OMEGA-60 laser using a 40-beam, 14.5 kJ, 1.5 ns drive and an initial seed magnetic field of $B_0 = 24$ T along the axis of the targets. Implosions were characterized using time-resolved X-ray imaging from two orthogonal lines of sight. Measurements of shell implosion dynamics suggest there is no significant difference between the magnetized and non-magnetized cases, in line with Gorgon extended magnetohydrodynamic simulations. However, the location of the imploding shell - inferred from a peak in the bremsstrahlung X-ray emission profile - was systematically offset from the simulations. The experimental setup allowed us to follow the full implosion of the targets until stagnation, resulting in a convergence ratio of $\sim 20$ compared to the expected value of $\sim 50 - 60$ predicted by the simulations.

I. INTRODUCTION

The effect of an external magnetic field on Inertial Confinement Fusion (ICF) implosions[4,5] is a topic of ongoing interest in the Magnetized Liner Inertial Fusion (MagLIF)[4,6,7] indirect[4], and direct[4] drive communities. In laser-driven ICF, seed magnetic fields amplified by magnetic flux conservation during the implosion have the potential to increase fusion yields by relaxing the areal density requirement for ignition. The magnetic field (B-field) compressed within the target acts in addition to inertia to confine the hot spot, resulting in a hotter fuel[7]. This opens up the possibility of high-gain implosions with lower convergence ratios that are less susceptible to hydrodynamic instabilities. Magnetic fields can also effectively confine D-T ions and thermonuclear $\alpha$-particles[7], enhancing collisionality and fusion yield[7].

The interpretation of magnetized implosion experiments relies heavily on comparisons with magnetohydrodynamic (MHD) codes. These codes must account for extended-MHD effects to accurately model energy and magnetic flux transport mechanisms within the plasma[8]. To add confidence on their modelling capacity of more complicated scenarios of magnetized high-energy-density plasmas, the underlying physics requires to be benchmarked against experimental measurements in a simplified geometry and a priori easy-to-interpret regime. Characterizing the evolution of a cylindrical implosion and the compression of the fuel is fundamental to this benchmarking process.

In this work, we present X-ray imaging results from experiments with laser-driven, magnetized cylindrical implosions similar to the mini-MagLIF concept explored at the OMEGA laser facility[9]. We used two orthogonal X-ray framing cameras to obtain an axial and a radial view of the cylinder, mapping the whole implosion up to the point of stagnation. This platform is a simple testbed for exploring magnetized phenomena in HED plasmas, and the results presented here are a first step towards validating theoretical studies of this platform[9]. The paper is structured as follows: in Section II we describe the experimental setup, physical parameters and the imaging cameras that were used. Section III summarises our experimental results and compares them with numerical simulations performed with the Gorgon MHD code[10,11]. Finally, our conclusions are presented in Section IV.

II. EXPERIMENTAL SET-UP

The experiments (Figure 1) were conducted on the OMEGA-60 laser, using a 40-beam, 1.5 ns, 14.5 kJ, $3\omega$ laser drive to implode gas-filled cylindrical targets. The targets were 2.5 mm-long Parylene-N tubes with an outer radius of $296\pm3\mu m$ and a shell thickness of $18.2\pm1.3\mu m$. The cylinders were filled in-situ with $D_2$ gas at 11 atm ($\rho = 1.81\,\text{mg}\,\text{cm}^{-3}$) and their pressure was monitored through a transducer connected to the target stalk on the target holder. An argon dopant (atomic concentration...
FIG. 1. Overview of the experimental set up from VisRad (radial view). The red stalk connected to the gas cylinder corresponds to the target holder and gas-fill, whereas the purple coils indicate the position in which the MIFEDS are placed in the shots. The direction of the seed B-field ($B_0 = 24 \text{T}$) is shown schematically. The colorscale on the cylinder corresponds to the laser irradiation profile. When the MIFEDS are fielded, the axial line of sight (along the cylinder axis) is blocked.

A more comprehensive study of the results from these diagnostics will be presented in future publications.

The implosion dynamics were recorded with two orthogonal X-ray Framing Cameras - one oriented along the axial line of sight (view along the axis of the tube) and another along the radial line of sight (view of the tube from the side). Each X-Ray Framing Camera (XRFC) used a 4x4 pinhole array ($\phi = 10 \mu \text{m}$ pinhole diameter) coupled with a 4-strip microchannel plate (MCP) and an optical CCD, providing up to 16 images in each camera covering the whole duration of the implosion. The delay between the images within each strip was 50 ps for both lines of sight. The exposure time of each frame was 200 ps for the axial view, whereas the radial view had a 50 ps exposure. The magnifications were $M = 2$ and $M = 6$ respectively. The spatial resolution of each camera system is given by

$$\delta = \phi (1 + M^{-1}), \quad (1)$$

where $\phi$ is the pinhole size. Since our cameras operated with 10 $\mu \text{m}$-sized pinholes, the spatial resolutions are 15 and 12 $\mu \text{m}$ for the axial and radial views respectively. Other diagnostics included neutron diagnostics and X-ray spectroscopy of the argon dopant within the fuel. A more comprehensive study of the results from these diagnostics will be presented in future publications.

In the magnetized cases, a seed B-field of $B_0 = 24 \text{T}$ was applied along the axis of the cylinders by means of the MIFEDS pulsed-power device. In this case, the axial line of sight was blocked by the MIFEDS, and only a radial XRFC was used. In the experimental set-up shown in Figure 1 the colormap on the cylinder corresponds to the laser irradiation profile. The 40 driving beams lead to a nearly uniform irradiation region close to 700 TW cm$^{-2}$ on the central $\sim 650 \mu \text{m}$ length portion along the target (shown in red).

To model the implosions, we performed 2-dimensional extended-MHD simulations using the Gorgon code. Our results suggest that, while the implosion dynamics were independent of the B-field before 1.4 ns, there is a significant difference in the density of the compressed fuel, which translates in a difference in the compressed radius between the magnetized ($\sim 6 \mu \text{m}$) and the non-magnetized ($\sim 4 \mu \text{m}$) implosions. This is due to compression of the seed B-field, which is “frozen-in” to the imploding plasma and exceeds 10 kT at stagnation. Collisional energy losses are heavily reduced in this magnetized regime, increasing the temperature in the core and hence the thermal pressure. Magnetic pressure is also significant in the magnetized implosions, increasing core pressure and reducing the overall level of compression.
III. X-RAY IMAGING RESULTS

An example of XRFC data is shown in Figure 2 where the top half of the image shows 8 frames from the axial view and the bottom part corresponds to 8 frames from the radial view. X-ray emission is observed as early as ∼0.39 ns from the axial view, where \( t = 0 \) corresponds to the start of the laser drive.

Two different metrics were used to analyze these images: the separation between the two intensity peaks coming from the imploding shell and the width of the compressed core. These two metrics are not always available since core emission is negligible at early times but dominates over shell emission later in time (see Figure 2). The two metrics therefore provide information over two different periods of time and are not directly comparable. Figure 3 shows lineouts of the data in Figure 2 as examples of these two cases. The top panel is a profile from the axial view at 1.02 ns and the bottom panel is a profile from the radial view at 1.43 ns. At 1.02 ns, the width of the imploding shell is taken as the separation between the two bright peaks on each side of the core at 50% of the normalised pixel value. At 1.43 ns, the width of the core is taken as the Full Width at Half Maximum (FWHM) of the core emission. A compilation of measured shell and core radii from a total of 9 shots with (red points) and without (blue points) a seed B-field, using the two metrics described above, is shown in Figs. 3a-b respectively. The shell data was obtained from the 9 shots using a combination of both XRFC lines of sight, whereas the core measurements were obtained from 5 of the shots along the radial line of sight. No axial line of sight data was available at early times with a seed B-field, as the XRFC view was blocked by the MIFEDS coils. The vertical error bars correspond to the pixel size convolved with the resolution of the CCD. This translates to an error of ∼ ±6 µm for the radial view and ∼ ±9 µm for the axial view. The horizontal error bars are related to the exposure time from each XRFC. The shell and core radii with and without a seed B-field show no significant difference and, overall, the data is highly reproducible. Figure 4a shows the mean trajectory from all the data points. Linear behaviour observed between ∼0.4 and ∼ 1.1 ns was used to estimate a shell implosion velocity of \( 230 ± 10 \) km/s at early times. The implosion then accelerates from ∼ 1.1 ns onward, reaching a velocity of \( 330 ± 20 \) km/s. This is consistent with previous work.

The green line in Figure 4a corresponds to the trajectory of the shell as predicted from MHD simulations using Gorgon. In this case, we define the position of the shell as the point where the integrated bremsstrahlung emissivity is maximal. This is equivalent to maximizing the product \( n_e^2 T_e^{1/2} \), where \( n_e \) is the electron density and \( T_e \) is the electron temperature. We found that the point of maximum bremsstrahlung emission agrees with the position of the shell, owing to the strong dependence of the emission on the density of the plasma. It can be seen that, while the trajectory predicted by Gorgon (green line) follows the same trend as the mean trajectory inferred from the data (black line), there is a systematic offset between the two, with Gorgon predicting a smaller shell at all times. A preliminary analysis of the 2D simulations, including cylindrical radiation transfer, indicates that this difference is due to the fact that the bremsstrahlung emission is heavily absorbed in the densest parts of the shell - owing to a high free-free opacity - and therefore the position of peak brightness in the experimental data does not correspond to the position of peak bremsstrahlung emissivity. This analysis is currently under investigation and the results will be discussed in future publications.

Figure 4b shows measurements of the compressed cylinder radius. The convergence ratio (\( CR = R/R_0 \)) was estimated by taking the mean core radii in Figure 2 as \( R \sim 15 \) µm and the initial outer radius of the cylindrical target as \( R_0 \sim 300 \) µm resulting in a value of \( CR \sim 20 \). The green band in this figure corresponds to the value of the radii predicted by Gorgon, with its width corresponding to the difference between magnetized and non-magnetized implosions. Given that the measured core radius is limited by the spatial resolution of the XRFC, the simulated values are effectively impossible to measure, as the corresponding diameter lies below the 12 µm...
IV. CONCLUSIONS AND FUTURE WORK

We have measured the radial compression of 14.5 kJ laser-driven cylindrical implosions with and without an applied B-field of 24 T, combining x-ray images taken from axial and radial viewpoints.

Our results indicate that the implosion speeds up at ~1 ns, accelerating from 230 km/s to 330 km/s. Stagnation occurs at ~1.5 ns and lasts for ~200 ps. While this is consistent with the predictions from extended-MHD simulations, there is a systematic discrepancy between the predicted and inferred target radius at all times. Preliminary analysis seems to indicate that this is an effect of radiation transport within the imploding shell arising from the free-free absorption of radiation in the densest region of the plasma, which yields a discrepancy in the interpretation of the data.

A significant difference - unrelated to radiation transport effects - was also observed in the compressed radius, with MHD simulations predicting a ~2× smaller radius than experiment. This indicates there was a degradation mechanism limiting our implosion performance.

Future work includes doing a full radiation transport post-processing of the MHD simulations to directly compare experiments and simulations for the trajectory of the imploding shell. By doping the fuel with a small quantity of Ar, we may also be able to diagnose the temperature and density of the imploding core with X-ray spectroscopy. This will give us more information about possible sources of disagreement between simulation and experiment.
ACKNOWLEDGEMENTS

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreements No. 633053 and No. 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. The involved teams have operated within the framework of the Enabling Research Projects: AWP17-ENR-IFE-CEA-02 Towards a universal Stark-Zeeman code for spectroscopic diagnostics and for integration in transport codes and AWP21-ENR-IFE.01.CEA Advancing shock ignition for direct-drive inertial fusion.

This material is based upon work supported by the US National Nuclear Security Administration and National Laser Users’ Facility under Award No. DE-NA0003940, and by the US Department of Energy - Office of Science under Grant No. DE-SC0022250. The work has also been supported by the Research Grant No. CEI2020-FEI02 from the Consejería de Economía, Industria, Comercio y Conocimiento del Gobierno de Canarias; and by Research Grant No. PID2019-108764RB-100 from the Spanish Ministry of Science and Innovation.

This study has received financial support from the French State in the framework of the Investments for the Future programme IdEx université de Bordeaux / GPR LIGHT.

G.-P.C. acknowledges support from the Spanish Ministry of Science and Innovation through the Margarita Salas funding program. F.S.-V. acknowledges funding from The Royal Society (UK) through a University Research Fellowship. C.V. acknowledges the support from the LIGHT S&T Graduate Program (PIA3 Investment for the Future Program, ANR-17-EURE-0027).

Data availability: The data presented in this paper may be obtained from the authors upon reasonable request.

Conflicts of interest: The authors declare no conflicts of interest.

1. L. J. Perkins, D. D.-M. Ho, B. G. Logan, G. B. Zimmerman, M. A. Rhodes, D. J. Strozzi, D. T. Blackfield, and S. A. Hawkins, Physics of Plasmas 24, 062708 (2017). https://doi.org/10.1063/1.4985150
2. M. R. Gomez, S. A. Sflitz, A. B. Selkow, D. B. Sinars, K. D. Hahn, S. B. Hansen, E. C. Harding, P. F. Knapp, P. F. Schmit, C. A. Jennings, T. J. Awe, M. Geisel, D. C. Rovang, G. A. Chandler, G. W. Cooper, M. E. Cuneo, A. J. Harvey-Thompson, M. C. Herrmann, M. H. Hess, O. Johns, D. C. Lampa, M. R. Martin, R. D. McBride, K. J. Peterson, J. L. Porter, G. K. Robertson, G. A. Rochau, C. L. Ruiz, M. E. Savage, I. C. Smith, W. A. Stygar, and R. A. Vesey, Phys. Rev. Lett. 113, 155003 (2014)
3. J. D. Moody, A. Johnson, J. Javedani, E. Carroll, J. Fry, B. Kozioziemski, S. O. Kucheyev, B. G. Logan, B. B. Pollock, R. Sio, D. Strozzi, W. A. Stygar, V. Tang, and S. Winters, Physics of Plasmas 27, 112911 (2020)
4. O. V. Gotchev, J. P. Knauer, P. Y. Chang, N. W. Jang, M. J. Shoup, D. D. Meyerhofer, and R. Bettì, Review of Scientific Instruments 80, 106103 (2009)
5. C. A. Walsh, K. McGlinchey, J. K. Tong, B. D. Appelbe, A. Crilly, M. F. Zhang, and J. P. Chittenden, Physics of Plasmas 26, 022701 (2019). https://doi.org/10.1063/1.5085498
6. H. Sio, J. D. Moody, D. D. Ho, B. B. Pollock, C. A. Walsh, B. Lahmann, D. J. Strozzi, G. E. Kemp, W. W. Hsing, A. Crilly, J. P. Chittenden, and B. Appelbe, Review of Scientific Instruments 92, 043543 (2021). https://doi.org/10.1063/5.0043381
7. E. C. Hansen, J. R. Davies, D. H. Barnak, R. Bettì, E. M. Campbell, V. Y. Glebov, J. P. Knauer, L. S. Leal, J. L. Peebles, A. B. Selkow, and K. M. Woo, Physics of Plasmas 27, 062703 (2020). https://doi.org/10.1063/1.5144447
8. C. A. Walsh, J. P. Chittenden, D. W. Hill, and C. Ridgers, Physics of Plasmas 27, 021103 (2020) https://doi.org/10.1063/1.5124114
9. J. R. Davies, D. H. Barnak, R. Bettì, E. M. Campbell, P.-Y. Chang, A. B. Selkow, K. J. Peterson, D. B. Sinars, and M. R. Weis, Physics of Plasmas 24, 062701 (2017). https://doi.org/10.1063/1.4984779
10. C. Walsh, R. Florido, M. Bailly-Grandvaux, F. Suzuki-Vidal, J. P. Chittenden, A. Crilly, M. A. Gigosos, R. Mancini, G. Pérez-Caliejo, C. Vilachos, et al., Plasma Physics and Controlled Fusion 64, 025007 (2022).
11. A. Ciardi, S. V. Lebedev, A. Frank, E. G. Blackman, J. P. Chittenden, C. J. Jennings, D. J. AMPleford, S. N. Bland, S. C. Bott, J. Rapley, G. N. Hall, F. A. Suzuki-Vidal, A. Marocchino, T. Lery, and C. Stehle, Physics of Plasmas 14, 106103 (2007).
12. J. Chittenden, S. Lebedev, C. Jennings, S. Bland, and A. Ciardi, Plasma Physics and Controlled Fusion 46, B457 (2004).
13. C. Walsh, J. Chittenden, K. McGlinchey, N. Niasse, and B. Appelbe, Physical Review Letters 118, 155001 (2017).
14. E. C. Hansen, D. H. Barnak, P.-Y. Chang, R. Bettì, E. M. Campbell, J. R. Davies, J. P. Knauer, J. L. Peebles, S. P. Regan, and A. B. Selkow, Physics of Plasmas 25, 122701 (2018). https://doi.org/10.1063/1.5055776
15. S. Pikuz, T. Shellsokeno, and D. Hammer, Plasma Physics Reports 41, 291 (2015).
16. J. Davies, D. Barnak, R. Bettì, E. Campbell, V. Y. Glebov, E. Hansen, J. Knauer, J. Peebles, and A. Bettì, Physics of Plasmas 26, 022706 (2019).