Inferring fuel areal density from secondary neutron yields in laser-driven magnetized liner inertial fusion

J. R. Davies,[a] D. H. Barnak, R. Betti, E. M. Campbell, V. Yu. Glebov, E. C. Hansen, J. P. Knauer, J. L. Peebles, and A. B. Sefkow,

Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA

[a]jdav@lle.rochester.edu

A technique to infer the areal density ρR of compressed deuterium (D) in cylindrical implosions from the ratio of secondary D–T (deuterium–tritium) neutrons to primary D–D neutrons is described and evaluated. For ρR to be proportional to the ratio of D–T to D–D yield, the increase in the D–T fusion cross section with collisional slowing of the tritium must be small, requiring $\rho R = 15 T_{\mathrm{keV}}^{3/2}$ mg/cm^2, where T_{keV} is the electron temperature in keV. The technique is applied to results from laser-driven magnetized liner inertial fusion (MagLIF) targets on OMEGA, where ρR is certainly less than 4 mg/cm^2. OMEGA MagLIF targets do not achieve a sufficiently high, radially integrated, axial magnetic field BR to confine the tritium, as occurs in Z MagLIF targets, because they are ~10× smaller in radius. The inferred areal densities show that fuel convergence is reduced by preheating, by an applied axial magnetic field, and by increasing the initial fuel density, which are key features of the MagLIF scheme. The results are compared to 1-D and 2-D magnetohydrodynamic simulations for nominal laser and target parameters, which predict areal densities 2× to 3× higher than the measurements.

I. INTRODUCTION

Laser-driven magnetized liner inertial fusion (MagLIF[1]) experiments are being carried out on the OMEGA laser[2–6] to study scaling by providing data from targets ~10× smaller in linear dimensions than those used on the Z pulsed-power machine[7–9] at Sandia National Laboratories, which is currently the only other facility carrying out integrated MagLIF experiments.

One of the key initial design criteria in the development of MagLIF[1] was to find a means to achieve fusion conditions in a cylindrical implosion at a convergence ratio less than 30. It is well-known that high-convergence implosions are very sensitive to small departures from symmetry in the drive and targets, making them impractical. By preheating to ~100 eV, temperatures up to 9 keV can be achieved in an adiabatic, cylindrical compression with a convergence ratio of less than 30. The axial magnetic field reduces electron thermal conduction from the fuel into the liner during compression, making it possible to achieve a near-adiabatic compression at a lower implosion velocity. With the compressed axial magnetic field, alpha particles can be confined from deuterium–tritium (D–T) fusion without reaching a radial areal density of $\rho R \sim 0.6$ g/cm^2 if a radially integrated axial magnetic field $BR \sim 0.6$ T m is achieved instead. The initial gas density is limited to a few mg/cm^3, whereas the initial magnetic field could readily reach 30 T, so $BR \sim 0.6$ T m can be achieved at a lower convergence ratio than $\rho R \sim 0.6$ g/cm^2.

In experiments on Z, the radially integrated axial magnetic field in the compressed deuterium fuel was inferred to be ~0.4 T m from the ratio of secondary D–T fusion neutrons to primary D–D fusion neutrons.[9] The D–D fusion reaction has two equally probable branches:

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}\left(1.01\ \mathrm{MeV}\right) + \mathrm{p}\left(3.02\ \mathrm{MeV}\right) \tag{1}$$

$$^{3}\mathrm{He}\left(0.82\ \mathrm{MeV}\right) + \mathrm{n}\left(2.45\ \mathrm{MeV}\right), \tag{2}$$

where the kinetic energies given in parentheses are in the center of the momentum frame. The tritium may go on to fuse with the deuterium, producing secondary 14.5-MeV neutrons. Obviously, the longer the path length of the tritium in the deuterium, and the higher the density of the deuterium, the greater the probability of D–T fusion. Calculations indicated that for the Z experiments, the increase in path length of the tritium resulting from the compressed axial magnetic field was a major contributor to the secondary D–T yield.[9] The BR = 0.4 T m that was inferred means that a 1-MeV tritium has a Larmor radius of 0.63R, where R is the radius of the fuel. The tritium produced in D–D fusion is a good surrogate for the alpha particles produced in D–T fusion because they have similar Larmor radii.

The BR in MagLIF targets on OMEGA will be at least ~10× lower than on Z because the radius is 10× smaller and the initial axial magnetic field is the same (currently 10 T, but values up to 30 T can be achieved). Therefore, magnetic confinement of charged fusion products cannot be achieved on OMEGA. As a result, the secondary D–T yield from D_2 fuel is determined by the radial areal density ρR of the compressed fuel.[10] While not an important

metric for MagLIF, fuel areal density does provide useful information on the convergence ratio of the fuel, which cannot be determined from the x-ray imaging diagnostics available on OMEGA[4] because they do not have sufficient spatial resolution for a compressed fuel that should be <10 μm in radius. D–T neutron yields, just above the detection threshold of 2×10^5, have been measured on the majority of laser-driven MagLIF shots. Here we describe how these measurements have been used to infer the fuel areal density and compare the inferred areal densities to 1-D and 2-D simulations.

II. INFERRING DEUTERIUM AREAL DENSITY IN A CYLINDER FROM THE SECONDARY NEUTRON YIELD

Secondary yield ratios have been used to infer the fuel areal density ρR in spherical implosions[10] when the areal density was less than roughly 3 mg/cm^2. For typical fuel temperatures of ~keV, the thermal energy spread of the tritium produced and the deuterium ions it encounters is negligible, so the tritium can be considered to have an energy of 1 MeV and the deuterium to be effectively at rest. If the tritium loses no significant amount of energy in the compressed fuel, the cross section for D–T fusion σ is effectively a constant. The 14.5-MeV DT neutrons will be emitted almost isotropically with only a small shift in energy resulting from the motion of the tritium because of their much greater speed. The number of tritium ions produced is equal to the number of D_2 neutrons produced Y_{DD}, which readily leads to

$$\langle \rho s \rangle = \frac{m_D}{\sigma} \frac{Y_{DT}}{Y_{DD}}, \tag{3}$$

where ρs is the areal density of the deuterium averaged over the path lengths s of all the tritium ions produced and m_D is deuterium mass. According to the fit of Bosch and Hale,[11] the fusion cross section for 1-MeV tritium incident on deuterium at rest (0.4-MeV center of momentum energy) is 413 mb (1 mb = 10^{-31} m^2). The fit given in the plasma formulary,[12] based on an older calculation discussed by Bosch and Hale, gives 352 mb. A number of fits have been published since Bosch and Hale's work,[13] but those we have seen consider only lower energies, around the peak in the D–T fusion cross section. The decay in the D–T fusion cross section at energies around 1 MeV is not of particular interest in thermonuclear fusion.

For a spherical target, ρs will be approximately equal to the fuel areal density ρR, provided that the mean path length of the tritium is greater than the fuel radius, with some dependence on the radial distribution of the D–D fusion. It may not be immediately obvious that this is also true for the cylindrical targets used in MagLIF because some tritium will travel almost parallel to the axis, giving a path length closer to the length of the cylinder. To demonstrate that the length of the cylinder is not a significant factor, consider an isotropic source of particles on the axis of an infinitely long cylinder of radius R. For a cylinder that is infinitely long, the axial distribution of the particles is irrelevant. The mean path length to the edge of the cylinder for straight-line propagation is given by integrating $R/\sin\theta$, where θ is the angle to the axis over a uniform distribution in solid angle, which varies as $\sin\theta$, canceling the divergent $1/\sin\theta$ term from the path length and giving simply

$$\langle s \rangle = \frac{1}{4\pi} \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\pi} \frac{R}{\sin\theta} \sin\theta \mathrm{d}\theta \mathrm{d}\phi = \frac{\pi}{2} R. \tag{4}$$

The mean path length for an isotropic source on the axis of an infinitely long cylinder is only 1.571R because no particle travels precisely along the axis, and the decreasing area covered by angles getting closer to the axis exactly cancels the increase in path length in calculating the mean.

It is also possible, although more involved, to obtain an expression for the mean path length of an isotropic source at a position r in an infinitely long cylinder:

$$\langle s \rangle = \mathrm{E}\left(r/R\right) R, \tag{5}$$

where E is the elliptic integral of the first kind [note that by some definitions this would be E(r^2/R^2)]. Equation (5) is plotted in Fig. 1. The minimum path length is for a source on the edge of the cylinder and is equal to the radius R, only 36% shorter than the mean path length for a source on the axis, because although some particles go directly outward others must cross the diameter of the cylinder.

Using Eq. (5), the mean path length for a uniform radial distribution of particles can be calculated numerically, giving 1.416R. We expect the radial distribution of tritium produced in MagLIF targets to be somewhere between a delta function on the axis and a uniform radial distribution, so the mean path length should lie somewhere between 1.571R and 1.416R, a relatively small variation.

In a cylinder of finite length the mean path length is reduced by end losses. For a uniform distribution along the axis of a cylinder of length L, having two integrals in θ, for those leaving the ends and those leaving the edge, then integrating over a uniform axial distribution, give

$$\langle s \rangle = R\left[\frac{\pi}{2} - \arctan\frac{R}{L} - \frac{R}{4L}\ln\left(1+\frac{L^2}{R^2}\right) + \frac{L}{4R}\ln\left(1+\frac{R^2}{L^2}\right)\right]$$
$$\approx \frac{\pi}{2}R\left(1-\frac{R}{\pi L}\ln\frac{L}{R}\right), L \;?\; R. \tag{6}$$

In compressed MagLIF targets on OMEGA, the value of L/R for the compressed fuel is at least 50, giving a reduction in mean path length from the result for an infinitely long cylinder of less than 2.5%.

We have neglected any change in energy of the tritium and any deviation from a straight-line path. We will now demonstrate that these effects are certainly negligible in OMEGA laser-driven MagLIF experiments.

The energy of the tritium can be changed by electric fields and collisions. The electrostatic potential across the compressed fuel should not be much more than the change in electron temperature, which is certainly much less than 1 MeV in our case. Collisional energy loss will be dominated by collisions with electrons, which at the temperatures of interest (>1 keV) will have a mean speed significantly higher than that of the tritium, so the relative velocity in collisions will be dominated by the electron thermal velocity, giving the mean rate of energy loss to be[14]

$$\frac{\mathrm{d}E}{\mathrm{d}s} \approx -\frac{Dv}{6\sqrt{2\pi}v_{\mathrm{th}}^3}, \tag{7}$$

where E is kinetic energy of the tritium,

$$D = \frac{ne^4 \ln\Lambda}{2\pi\varepsilon_0^2}, \tag{8}$$

n is electron's and deuterium's number density, $\ln\Lambda$ is the Coulomb logarithm (which is where stopping models differ), v is speed of the tritium, and

$$v_{\mathrm{th}} = \sqrt{\frac{kT_{\mathrm{e}}}{m_{\mathrm{e}}}} \tag{9}$$

is electron thermal velocity. Assuming that the change in energy and the resulting change in fusion cross section are small along the path length s, we can then neglect the change in fusion cross section if

$$\frac{\Delta\sigma}{\sigma_0} \approx \frac{1}{\sigma_0}\left|\frac{\mathrm{d}\sigma}{\mathrm{d}E}\frac{\mathrm{d}E}{\mathrm{d}s}s\right| = 1. \tag{10}$$

Using Bosch and Hale's fit for the D–T fusion cross section and ln $\Lambda = 12$ gives the condition for the increase in fusion cross section with decreasing energy to be negligible as

$$\rho s = 14.5 T_{\mathrm{keV}}^{3/2}\ \mathrm{mg/cm^2}. \tag{11}$$

Using the fit from the plasma formulary[12] changes the above number to 15.2 mg/cm^2. The highest areal density we expect for a compression-only shot is about 4 mg/cm^2. Equation (7), with ln $\Lambda = 12$, gives the range of the tritium in deuterium at 2 keV to be 7.5 g/cm^2, much greater than the limit imposed by Eq. (11).

We could use the Taylor expansion of Eq. (10) to obtain a quadratic expression for the areal density, which has been used for spherical implosions.[10] This requires, however, a suitably averaged electron temperature, which we have not measured, among other parameters that add to the uncertainty of the method. Therefore, we do not consider the yield ratio method to be useful once higher-order corrections are needed.

The path length of the tritium through the fuel can be increased by the magnetic field and collisions. We have already noted that the increase in path length caused by the magnetic field will be small for OMEGA MagLIF targets. To illustrate this, if we start with an axial magnetic field of $B_0 = 10$ T and a fuel radius of $R_0 = 0.27$ mm and achieve lossless field compression so that $B = C^2 \mathrm{B}_0$, where $C = R_0/R$ is the fuel convergence ratio, then the ratio of tritium Larmor radius to fuel radius R is $93/C$, which is greater than 1, and in practice we expect greater than 50% magnetic flux loss.[3] Collisional scattering will be dominated by collisions with deuterium ions, which at the temperatures of interest will have a much lower mean speed

than the tritium, giving the increase in mean-squared scattering angle θ along the path length s to be[14]

$$\frac{\mathrm{d}\left\langle \theta^2 \right\rangle}{\mathrm{d}s} \approx \frac{D}{m_T^2 v^4}. \tag{12}$$

The value of $\ln\Lambda$ in the parameter D [Eq. (8)] is different for angular scattering and for drag, but, for, an order of magnitude estimate, the difference can be ignored. By comparing Eqs. (7) and (12), one can see that if collisional energy loss is negligible, collisional scattering is certainly negligible; scattering becomes significant only near the end of a particle's trajectory.

Angular scattering can be significantly increased by the presence of high-Z impurities in the fuel because it scales as Z^2. The range of the tritium is so much greater than the areal densities achieved in OMEGA MagLIF targets, however, that this is unlikely to be an issue. For example, if the fuel were to become pure carbon, the mean stopping distance of the tritium would be reduced by approximately $\sqrt{6}$, giving 3.1 g/cm^2 for an electron temperature of 2 keV and $\ln \Lambda = 12$, still considerably greater than the limit imposed by Eq. (11). Of course, if the fuel were to become pure carbon, there would be no neutron emission.

The time evolution of the fuel has also been neglected, which should be a reasonable assumption because the expected duration of neutron emission is less than the time over which the fuel density evolves.

Based on the above considerations, we have inferred a neutron-averaged fuel areal density ρR from measured yield ratios using the mean path length of an isotropic source on the

axis of an infinitely long cylinder, the D–T fusion cross section from Bosch and Hale,[11] and ignored any change in energy and deviation from a straight-line path. We consider that uncertainties caused by the actual radial distribution of the neutrons, the distribution of the fuel density, end losses, tritium energy loss, deviation from a straight-line path, and the D–T fusion cross section amount to an error of no more than ±20%, with the cross section being the dominant source of uncertainty.

The final expression we have used is

$$\rho R = 5.18 \pm 1.04 \frac{Y_{\mathrm{DT}}}{Y_{\mathrm{DD}}} \mathrm{g/cm^2}. \tag{13}$$

For the increase in D–T fusion cross section caused by collisional slowing of the tritium to be negligible, and for angular scattering to be negligible, requires

$$\rho R = 14.5 T_{\mathrm{keV}}^{3/2} \mathrm{\ mg/cm^2}. \tag{14}$$

For end losses to reduce the mean path length by less than 10%, based on Eq. (6), requires

$$\frac{L}{R} > 12. \tag{15}$$

For the magnetic field to cause a negligible increase in the mean path length requires

$$BR = 0.25\ \mathrm{T \cdot m}. \tag{16}$$

All of these conditions are comfortably satisfied in laser-driven MagLIF experiments on OMEGA.

III. RESULTS

A typical laser-driven MagLIF experiment on OMEGA uses a 0.58-mm-outer-diam, 20-μm-thick parylene-N cylinder (CH 1.1 g/cm^3), filled with 1.8 mg/cm^3 of deuterium, a 9-T initial axial magnetic field, 14.5 kJ of laser energy in 1.5 ns to compress the cylinder, and 180 J of laser energy in 1.5 ns to preheat the deuterium, starting 1 ns before the compression beams.[2]

These current baseline experimental parameters differ from the initial point design.[3] The point design used an outer diameter of 0.6 mm, but the target-fabrication technique of vapor deposition on a mandrel lent itself to a fixed inner diameter, and an outer diameter of 0.6 mm was chosen for 30-μm-thick shells. The thinnest shell considered in the point design was 20 μm thick and was selected because in initial compression-only experiments,[4,6] it was the only shell thickness that gave neutron yields high enough to obtain two reliable measurements of neutron-averaged ion temperature and a measurement of secondary yield. In the point design, a fuel density of 2.7 mg/cm^3 was chosen for 20-μm-thick shells to give a fuel convergence ratio of 25, but in initial experiments too many targets failed to hold gas at this pressure, so the density was reduced to 1.8 mg/cm^3, which should increase the convergence ratio. The 9-T axial magnetic field is close to the 10 T used in the point design, and the 180 J in

the preheat beam does, according to simulations,[5] preheat the gas to a mean temperature of about 200 eV, as used in the point design.

X-ray framing-camera measurements of self-emission indicate that, for this setup, the shell implodes at a mean velocity of 200±4 km/s over a region 0.6 mm in length during the laser pulse,[6] regardless of preheating and magnetization. The implosion velocity predicted by the 1-D point design simulations[3] for a 20-μm-thick-shell was 188 km/s, slightly lower than this measured value because a conservative estimate for the effective laser intensity on target was used.

Primary D–D neutron yields for this setup were considered by Barnak *et al.*[2] Since this publication, two measurements of yield for magnetized shots without preheat and some further repeats have been obtained. Currently, the mean D–D neutron yield for compression-only shots is $(1.14\pm0.21) \times 10^9$, for preheated shots without magnetic field it is $(1.38\pm0.22) \times 10^9$, for magnetized shots without preheat it is $(1.76\pm0.13) \times 10^9$, and for integrated shots it is $(1.61\pm0.04) \times 10^9$. Here we will concentrate on the areal densities inferred from secondary- to primary-yield ratios. A table of results from all successful shots so far using this setup is given in the Appendix.

Successful shots have been taken with all four combinations of preheat on/off and axial magnetic field on/off for 1.8 mg/cm^3 of deuterium and for compression-only and compression with field for 1.2 mg/cm^3 of deuterium. The inferred areal density by type of shot is given in Table I. Where two measurements of yield ratio are available, the error-weighted mean value and standard error are given. For the integrated shot at 1.8 mg/cm^3 and the two compression-only shots at 1.2 mg/cm^3, D–T yields were below the detection threshold of about 2×10^5, so

only an upper limit on the areal density can be given. In some cases, yields lower than 2×10^5 can be determined, but 2×10^5 is required to be certain that the measurement is greater than three standard errors above the typical noise level. The principle source of error when determining ρR is from the D–T yields because the highest values are only just above the detection threshold.

The areal density of the fuel is not an important figure of merit for MagLIF, as it is in conventional inertial confinement fusion, because retention of charged fusion products in the fuel is meant to be achieved by BR, and inertial confinement by the areal density of the shell (liner).[1]

The fuel convergence ratio is of more interest; both the initial Z point design[1] and the OMEGA point design[3] set out to achieve a convergence ratio of 25. If the fuel density profile remains uniform and there are no end losses, the fuel convergence ratio is $\rho R/(\rho R)_0$, which we will refer to as C_0, our zeroth-order estimate of a neutron-averaged fuel convergence, the values of which are given in Table I. When fuel density peaks at the edge, which is to be expected, C_0 will underestimate the convergence ratio; if fuel density peaks at the center, C_0 will overestimate the convergence ratio. End losses, which are to be expected, will result in C_0 underestimating the convergence ratio. Therefore, we expect C_0 to be somewhat lower than the actual convergence ratio C.

Even if the actual convergence ratio is as high as $2C_0$, the integrated shot has achieved a convergence ratio <26, meeting our initial point design objective, despite the lower fuel density.

In any case, the values of C_0 should provide an indication of how the fuel convergence ratio is modified by preheating, magnetization, and fuel density, which are important aspects of MagLIF. The results indicate that preheating, magnetization, and increasing fuel density reduce fuel convergence ratio, as expected. The results also show that although the primary D–D neutron yield for the integrated shot[2] is not higher than for the magnetized shots, as was expected,[3] this yield is being achieved with a lower convergence.

The inferred areal densities also provide a useful point of comparison with simulations. Areal densities from 1-D *LILAC*[3,4,15] and 2-D *HYDRA*[3,4,6,16] are included in Table I. The typical laser and target parameters given above were used in the simulations. *LILAC* was run using six-group radiation transport, tabulated opacities, *SESAME* equations of state, a thermal flux limit of 0.06, and a Nernst flux limit[15] of 0.06. The laser power per unit length was set at half the actual value to match the measured x-ray implosion velocity near the center,[4] a result of the oblique angle of incidence of the beams driving the center, which is not considered in *LILAC*. Preheating was treated using a fixed initial temperature profile with a mean value of 200 eV (Ref. 3). *HYDRA* was run using 35-group radiation transport, tabulated local thermodynamic equilibrium (LTE) opacities, LTE equations of state, a thermal flux limit of 0.09, and no flux limit on the Nernst term. The simulations were initialized with 200 cells in the axial direction spanning 2 mm, with a feathered grid achieving a maximum resolution of 5 μm at the center, 100 radial cells in the fuel, 60 in the shell, and 20 in the vacuum region, spanning 3.5 mm, with a feathered grid achieving a maximum resolution of 0.1 μm at the outer edge of the shell. The arbitrary Lagrangian–Eulerian scheme was maintained Lagrangian long enough to ensure at least 20 cells in the fuel at peak convergence, which was found to be sufficient for

the areal-density predictions to converge, but not for the D–D neutron yield predictions to converge for the higher convergence, nonpreheated cases. The power in the beams driving the ends of the targets was reduced by two-thirds in order to match the measured x-ray implosion velocity along the length of the target.[6] The preheating laser beam was simulated in *HYDRA*. The laser entrance window and part of the front end of the target were not included, so the preheat beam energy and duration were reduced by 25% to account for window absorption, based on measurements of window reflection and transmission.[5] The final mean temperature was just under 200 eV, but the electron temperature was higher than the ion temperature and there was a slight axial gradient, unlike *LILAC*. The areal densities were determined at the time of peak neutron emission rate in the codes. The areal density from *LILAC* is simply the integral of the fuel density from the origin outward, in effect assuming that D–D fusion is peaked on axis. The areal density from *HYDRA* was calculated by averaging over an isotropic distribution of straight-line trajectories from the positions where the D–D neutrons were generated. In effect, a yield ratio was calculated based on straight-line propagation of the tritium using a fixed cross section for D–T fusion, which should be an adequate approximation given that the mean free path of 1-MeV tritium is much greater than the size of the targets in the simulations.

The ratios of measured to simulated values are given in Table II. The simulations overestimate the areal densities for all except the magnetized 1.2-mg/cm^3 shots, where agreement is good, although the 2-D simulations are toward the upper end of the error bar. The difference between the simulations and measurements is slightly greater for the increase in areal density C_0 because the actual initial densities were slightly higher than the nominal values to allow for some loss of pressure between filling and shot time, so C_0 is probably a better

parameter for comparison. The simulations give values of C_0 that are 2× to 3× higher than the measurements, excluding the 1.2-mg/cm^3 results. The simulations would be expected to overestimate the areal density because the growth of nonuniformities from the laser beams and targets, which are not considered, will break up the compressed fuel. In 1-D and 2-D the imploding shell must converge on the axis and will stop only once the pressure in the fuel becomes high enough. In 3-D, opposing elements of the shell can miss the axis and not compress the fuel to such a high pressure. The growth of nonuniformities is expected to be greater the higher the convergence, and the discrepancies between the measured and simulated areal densities are greater at higher values, excluding the 1.2-mg/cm^3 results.

It is possible that the agreement between measurements and simulations for magnetized 1.2-mg/cm^3 shots is just a matter of chance, with the actual value lying at the lower end indicated by the experimental uncertainty, particularly as the D–T yields in these shots are at the very lowest detectable levels.

The 2-D simulations might be expected to give consistently lower areal densities than 1-D because of end losses, but for the magnetized shots and the compression-only shots at 1.2 mg/cm^3, the areal densities are higher in 2-D than 1-D. The reason for this is that the 2-D simulations predict higher areal densities at the ends than at the center, for all except the preheated, no-magnetic-field case, which acts to increase the average areal density, as shown in Fig. 2. End loss is not the only 2-D effect in these simulations.

The fuel convergence ratios can be obtained from the simulations and provide an indication as to how accurately the increase in areal density C_0 might represent the actual convergence ratio C. The values are given in Table III, along with values of C/C_0. The

convergence ratio from *HYDRA* was calculated using an average over the length where the D_2 neutron emission rate exceeded 90% of maximum, which was from 0.46 to 0.54 mm long.

It is notable that for magnetized shots, without preheat, the convergence ratios in both 1-D and 2-D are significantly higher than the increase in areal density. For other types of shots, C/C_0 is not significantly greater than 1 in 1-D and is around 1.3 in 2-D. In the magnetized shots the compressed fuel density is strongly peaked at the edge, increasing C/C_0, whereas in other types of shots, there is a much less pronounced increase in fuel density near the edge, as shown in Fig. 3. Without preheat, the compressed magnetic field forms a pronounced peak at the center because the Nernst velocity ($\propto \nabla T_e$) during the initial shock convergence enhances field compression,[15] whereas with preheat the Nernst effect acts to lower magnetic field compression and leads to a relatively flat magnetic-field profile in the fuel.[3] The peak in magnetic field leads to a peak in temperature, which in turn leads to a dip in density. Therefore, the decrease in convergence caused by magnetization would appear to be less than indicated by the change in areal density, indicating that in the experiments magnetization has had significantly less effect on convergence than preheat. If the value of C/C_0 from 2-D simulations is accurate, the convergence ratio of the integrated shot is <19.

IV. CONCLUSIONS

We have derived an expression to determine the neutron-averaged radial areal density ρR of deuterium compressed in cylindrical targets from the ratio of secondary DT neutrons to primary D–D neutrons, given by Eq. (13). The conditions for this to be valid are expressed by Eqs. (14)–(16). This work is an extension of previous results for spherical targets[10] to

cylindrical targets, with an additional consideration for magnetization. The areal densities achieved in spherical implosions on OMEGA are typically too high for this method to be useful, but it is useful for laser-driven MagLIF experiments on OMEGA.[2–6] The principle limitation of this method is the low DT yield, which is inevitable when operating at a sufficiently low ρR for this method to be adequate.

The areal density of the compressed fuel, while not an important metric for MagLIF, does give a good indication of the fuel convergence ratio, which is an important parameter in MagLIF designs that cannot be measured by the x-ray imaging diagnostics available on OMEGA because they do not have sufficient spatial resolution. The values of ρR inferred from laser-driven MagLIF experiments on OMEGA indicate that preheating to ~200 eV, applying a 9-T axial magnetic field, and increasing the fuel density from 1.2 to 1.8 mg/cm^3 all significantly reduce fuel convergence, as expected. The convergence ratio of the integrated shot is certainly less than the objective of the point design of 25, despite the use of a lower fuel density than originally intended based on 1-D simulations (1.8 mg/cm^3 in place of 2.7 mg/cm^3).[3] Achieving a lower convergence because of imperfect compression was not the goal, however, so lowering convergence with a higher fuel density and a higher initial magnetic field, and hopefully achieving results closer to simulations, will still be pursued. Although the integrated shot did not achieve a higher D–D neutron yield than the magnetized shots without preheat, it did attain a comparable yield with a lower convergence ratio, demonstrating that the combination of magnetization and preheat does provide a route to higher yield at lower convergence ratio—one of the basic objectives of the MagLIF scheme.[1] Increasing the axial

magnetic field should lead to higher yields from integrated shots than from magnetized shots without preheat.[3]

One- and two-dimensional simulations, for nominal laser and target parameters, predict areal densities that are a factor of 2 to 3 higher than the measurements, with the difference being greater at a higher predicted convergence, as would be expected, with the exception of magnetized, no-preheat 1.2-mg/cm^3 shots. The simulations show that magnetization causes a greater drop in areal density than in convergence ratio because it leads to a density profile strongly peaked at the edge. If magnetization is causing such a density profile in the experiments, it is having less of an impact on convergence than preheating.

The areal density diagnostic described here will be applied to future laser-driven MagLIF shots that will include higher magnetic fields (up to ~30 T), a scan of preheat energies, and higher fuel densities. The simulations will be extended to 3-D, using laser and target parameters as close as possible to the as-shot values, and the effects of cross-beam energy transfer and nonlocal thermal transport will be taken into consideration.

ACKNOWLEDGMENT

This material is based upon work supported by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000568, the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

This report was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees,

makes any warranty, express 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 U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

Appendix A: Results from individual shots

Table A-I summarizes the conditions, neutron yields, and inferred areal densities for all of the shots considered in this article.

REFERENCES

1. S. A. Slutz, M. C. Herrmann, R. A. Vesey, A. B. Sefkow, D. B. Sinars, D. C. Rovang, K. J. Peterson, and M. E. Cuneo, Phys. Plasmas **17**, 056303 (2010).
2. D. H. Barnak, J. R. Davies, R. Betti, M. J. Bonino, E. M. Campbell, V. Yu. Glebov, D. R. Harding, J. P. Knauer, S. P. Regan, A. B. Sefkow, A. J. Harvey-Thompson, K. J. Peterson, D. B. Sinars, S. A. Slutz, M. R. Weis, and P.-Y. Chang, Phys. Plasmas **24**, 056310 (2017).
3. J. R. Davies, D. H. Barnak, R. Betti, E. M. Campbell, P.-Y. Chang, A. B. Sefkow, K. J. Peterson, D. B. Sinars, and M. R. Weis, Phys. Plasmas **24**, 062701 (2017).

4. E. C. Hansen, D. H. Barnak, R. Betti, E. M. Campbell, P.-Y. Chang, J. R. Davies, V. Yu. Glebov, J. P. Knauer, J. Peebles, S. P. Regan, and A. B. Sefkow, Plasma Phys. Control. Fusion **60**, 054014 (2018).

5. J. R. Davies, R. E. Bahr, D. H. Barnak, R. Betti, M. J. Bonino, E. M. Campbell, E. C. Hansen, D. R. Harding, J. L. Peebles, A. B. Sefkow, W. Seka, P.-Y. Chang, M. Geissel, and A. J. Harvey-Thompson, Phys. Plasmas **25**, 062704 (2018).

6. E. C. Hansen, D. H. Barnak, P.-Y. Chang, R. Betti, E. M. Campbell, J. R. Davies, J. P. Knauer, J. L. Peebles, S. P. Regan, and A. B. Sefkow, "Optimization of Laser-Driven Cylindrical Implosions on the OMEGA Laser," to be published in Physics of Plasmas.

7. A. B. Sefkow, S. A. Slutz, J. M. Koning, M. M. Marinak, K. J. Peterson, D. B. Sinars, and R. A. Vesey, Phys. Plasmas **21**, 072711 (2014).

8. M. R. Gomez, S. A. Slutz, A. B. Sefkow, 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. Geissel, 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. Lamppa, 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).

9. P. F. Schmit, P. F. Knapp, S. B. Hansen, M. R. Gomez, K. D. Hahn, D. B. Sinars, K. J. Peterson, S. A. Slutz, A. B. Sefkow, T. J. Awe, E. Harding, C. A. Jennings, G. A. Chandler, G. W. Cooper, M. E. Cuneo, M. Geissel, A. J. Harvey-Thompson, M. C. Herrmann, M. H. Hess, O. Johns, D. C. Lamppa, M. R. Martin, R. D. McBride, J. L. Porter, G. K. Robertson, G. A. Rochau, D. C. Rovang, C. L. Ruiz, M. E. Savage, I. C. Smith, W. A. Stygar, and R. A. Vesey, Phys. Rev. Lett. **113**, 155004 (2014).

10. E. G. Gamaliĭ, S. Yu. Gus'kov, O. N. Krokhin, and V. B. Rozanov, JETP Lett. **21**, 70 (1975); H. Azechi, N. Miyanaga, R. O. Stapf, K. Itoga, H. Nakaishi, M. Yamanaka, H. Shiraga, R. Tsuji, S. Ido, K. Nishihara, Y. Izawa, T. Yamanaka, and C. Yamanaka, Appl. Phys. Lett. **49**, 555 (1986); M. D. Cable and S. P. Hatchett, J. Appl. Phys. **62**, 2233 (1987); S. Kurebayashi, J. A. Frenje, F. H. Séguin, J. R. Rygg, C. K. Li, R. D. Petrasso, V. Yu. Glebov, J. A. Delettrez, T. C. Sangster, D. D. Meyerhofer, C. Stoeckl, J. M. Soures, P. A. Amendt, S. P. Hatchett, and R. E. Turner, Phys. Plasmas **12**, 032703 (2005).

11. H. S. Bosch and G. M. Hale, Nucl. Fusion **32**, 611 (1992); **33**, 1919(E) (1993).

12. J. D. Huba, *NRL Plasma Formulary*, Naval Research Laboratory, Washington, DC, Report NRL/PU/6790/16-614 (2016).

13. Z. L. Xing, M. W. Qing, and L. Bin, Nucl. Fusion **48**, 125003 (2008); T. Koohrokhi, A. M. Izadpanah, and S. K. Hosseini, J. Fusion Energ. **35**, 816 (2016).

14. L. Spitzer, *Physics of Fully Ionized Gases* (Interscience Publishers, New York, 1956).

15. J. R. Davies, R. Betti, P.-Y. Chang, and G. Fiksel, Phys. Plasmas **22**, 112703 (2015).

16. M. M. Marinak, R. E. Tipton, O. L. Landen, T. J. Murphy, P. Amendt, S. W. Haan, S. P. Hatchett, C. J. Keane, R. McEachern, and R. Wallace, Phys. Plasmas **3**, 2070 (1996); M. M. Marinak, G. D. Kerbel, N. A. Gentile, O. Jones, D. Munro, S. Pollaine, T. R. Dittrich, and S. W. Haan, Phys. Plasmas **8**, 2275 (2001).

Figure Captions

FIG. 1. Mean path length of an isotropic source of particles at radius r in an infinitely long cylinder of radius R, propagating in straight lines.

FIG. 2. The increase in areal densities $C_0 = \rho R/(\rho R)_0$ at peak neutron emission rate as a function of axial position from 2-D *HYDRA* simulations. Results for an initial D_2 density of (a) 1.8 mg/cm^3 and (b) 1.2 mg/cm^3. The mean values reported in the tables are indicated by horizontal lines.

FIG. 3. Radial profiles of fuel density through the center at peak neutron emission rate from 2-D *HYDRA* simulations. Results for an initial D_2 density of (a) 1.8 mg/cm^3 and (b) 1.2 mg/cm^3.

TABLE I. Areal density ρR and the increase in areal density $C_0 = \rho R/(\rho R)_0$ inferred from measured secondary- to primary-yield ratios by shot type and obtained from 1-D *LILAC* and 2-D *HYDRA* simulations for nominal laser and target parameters. For the integrated shot and the compression-only shots at 1.2 mg/cm^3, the upper limit is based on a DT yield $<2 \times 10^5$.

Type (number of shots)	ρR (mg/cm^2)	$\rho R_{1\text{-D}}$ (mg/cm^2)	$\rho R_{2\text{-D}}$ (mg/cm^2)	C_0	$C_{0,1\text{-D}}$	$C_{0,2\text{-D}}$
Compression-only 1.8 mg/cm^3 (2)	1.2±0.4	3.8	3.3	22±7	77	68
Preheated 1.8 mg/cm^3 (2)	0.98±0.39	2.2	1.7	19±8	46	35
Magnetized 1.8 mg/cm^3 (2)	0.67±0.08	1.7	1.9	13±2	34	39
Integrated 1.8 mg/cm^3 (1)	<0.64	1.6	1.4	<13	32	29
Compression-only 1.2 mg/cm^3 (2)	<2.7	2.2	3.4	<82	70	100
Magnetized 1.2 mg/cm^3 (2)	1.2±0.3	1.2	1.5	37±8	37	46

TABLE II. The ratio of areal densities inferred from measurements to those from 1-D and 2-D simulations.

Type	$\rho R/\rho R_{1\text{-D}}$	$\rho R/\rho R_{2\text{-D}}$	$C_0/C_{0,1\text{-D}}$	$C_0/C_{0,2\text{-D}}$
Compression-only 1.8 mg/cm^3	0.30±0.10	0.35±0.11	0.29±0.09	0.33±0.1
Preheated 1.8 mg/cm^3	0.45±0.18	0.58±0.23	0.42±0.17	0.55±0.22
Magnetized 1.8 mg/cm^3	0.39±0.05	0.36±0.04	0.38±0.05	0.34±0.04
Integrated 1.8 mg/cm^3	<0.40	<0.45	<0.40	<0.44
Compression-only 1.2 mg/cm^3	<1.2	<0.80	<1.2	<0.79
Magnetized 1.2 mg/cm^3	1.0±0.2	0.81±0.17	1.0±0.2	0.80±0.17

TABLE III. Fuel convergence ratios C and C/C_0, where C_0 is the increase in areal density, from 1-D and 2-D simulations.

Type	$C_{1\text{-D}}$	$C_{2\text{-D}}$	$C_{1\text{-D}}/C_{0,1\text{-D}}$	$C_{2\text{-D}}/C_{0,2\text{-D}}$
Compression-only 1.8 mg/cm^3	78	87	1.01	1.28
Preheated 1.8 mg/cm^3	46	45	1.00	1.30
Magnetized 1.8 mg/cm^3	52	66	1.53	1.69
Integrated 1.8 mg/cm^3	34	43	1.06	1.48
Compression-only 1.2 mg/cm^3	70	130	1.00	1.21
Magnetized 1.2 mg/cm^3	59	89	1.59	1.92

TABLE A-I. OMEGA shot number, initial deuterium fuel density ρ_0, initial axial magnetic field B_0, energy in the preheat beam E_{pre}, total energy in the compression beams E_{com}, D–D neutron yield Y_{DD}, D–T neutron yield Y_{DT}, secondary- to primary-yield ratio Y_{DT}/Y_{DD}, inferred compressed fuel areal density ρR, and increase in areal density $C_0 = \rho R/(\rho R)_0$. An upper limit is given where there was no detectable DT signal.

Shot	OD (μm)	ρ_0 (mg/cm^3)	B_0 (T)	E_{pre} (J)	E_{com} (kJ)	Y_{DD} ($\times10^8$)	Y_{DT} ($\times10^5$)	Y_{DT}/Y_{DD} ($\times10^{-4}$)	ρR (mg/cm^2)	C_0
82955	581	1.93	0	0	13.9	7.89±0.16	2.32±0.47	2.94±0.60	1.52±0.43	28.7±8.2
82956	581	1.91	0	0	13.6	11.9±0.16	0.54±0.23	0.45±0.19	0.23±0.11	4.5±2.1*
84313	588	1.82	9	172	14.6	16.1±0.43	<2	<1.24	<0.64	<12.7
84315	587	1.83	0	173	14.6	13.3±0.41	3.53±0.58	2.65±0.44	1.37±0.36	27.0±7.0
84316	586	1.83	0	0	14.7	8.72±0.28	<2	<2.29	<1.18	<23.4*
84318	584	1.85	0	174	15.0	16.2±0.43	2.57±0.50	1.59±0.31	0.82±0.23	16.1±4.5
85561	584	1.86	9	0	14.6	18.5±0.54	2.22±0.46	1.20±0.25	0.62±0.18	12.1±3.5
85562	585	1.88	9	0	15.0	16.7±0.36	2.41±0.48	1.44±0.29	0.74±0.21	14.3±4.1
85563	585	1.86	0	0	14.8	11.1±0.28	2.11±0.45	1.90±0.41	0.98±0.29	19.1±5.6
85564	583	1.21	9	0	14.8	5.04±0.16	1.05±0.32	2.08±0.64	1.07±0.39	32.2±11.8
85566	584	1.20	0	0	14.8	3.8±0.14	<2	<5.26	<2.71	<82.2
85567	582	1.20	9	0	15.0	6.24±0.19	1.73±0.41	2.77±0.66	1.43±0.45	43.3±13.5
86427	581	1.20	0	0	14.1	3.44±0.12	<2	<5.81	<3.00	<91.0
86435	579	1.83	0	180	14.2	12.0±0.30	<2	<1.67	<0.86	<17.2*
90365	580	1.82	0	0	15.0	13.9±0.49	1.06±0.32	0.76±0.23	0.39±0.14	7.9±2.9*

*Values not included in Table I because of low D–T yields