Inferring Fuel Areal Density from Secondary Neutron Yields in Laser-Driven Magnetized Liner Inertial Fusion

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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. 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 of 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 <30. In MagLIF an 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, instead, a radially integrated axial magnetic field $BR \sim 0.6$ T·m is achieved. 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:

$$\begin{aligned} \mathrm{D}+\mathrm{D} &\longrightarrow \mathrm{T}(1.01\ \mathrm{MeV})+\mathrm{p}(3.02\ \mathrm{MeV}) \\ &\longrightarrow {}^{3}\mathrm{He}(0.82\ \mathrm{MeV})+\mathrm{n}(2.45\ \mathrm{MeV}), \end{aligned} \tag{1}$$

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. 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 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 approximately the same (currently 9 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.

The fuel areal density can be obtained approximately from

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

assuming a point or line source of tritium on the axis, and straight-line propagation of the tritium with no energy loss and no end losses. The result is only weakly dependent on the radial distribution of the tritium production. 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

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

For end losses to reduce the mean path length by less than 10% requires

$$\frac{L}{R} > 12, \tag{4}$$

where L is the length of the cylinder. For the magnetic field to cause a negligible increase in path length requires

$$BR \ll 0.25\ \mathrm{T \cdot m}. \tag{5}$$

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

Successful laser-driven MagLIF 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.

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 D–T yield $<2 \times 10^5$.

Type (number of shots)	ρR (mg/cm^2)	$\rho R_{\text{1-D}}$ (mg/cm^2)	$\rho R_{\text{2-D}}$ (mg/cm^2)	C_0	$C_{0,\text{1-D}}$	$C_{0,\text{2-D}}$
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

The fuel convergence ratio is of more interest in MagLIF than the areal density; 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 the fuel convergence ratio, as expected.

The inferred areal densities also provide a useful point of comparison with simulations. Areal densities from 1-D *LILAC*[3,4] and 2-D *HYDRA*[3,4,6] are included in Table I. 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 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 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.

This material is based upon work supported by the Department of Energy Advanced Research Projects Agency-Energy (ARPA-E) under Award Number DE-AR0000568, 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.

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