Laser-driven magnetized liner inertial fusion

J. R. Davies[1], D. H. Barnak[1], R. Betti[1], E. M. Campbell[1], P.-Y. Chang[1,2], ,

A. B. Sefkow[1], K. J. Peterson[3], D. B. Sinars[3], and M. R. Weis[3]

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

[2]Institute of Space and Plasma Sciences, National Cheng Kung University,

Tainan City 701, Taiwan

[3]Sandia National Laboratories, Albuquerque, New Mexico 87185, USA

A laser-driven, magnetized liner inertial fusion (MagLIF) experiment is designed for the OMEGA Laser System by scaling down the Z point design to provide the first experimental data on MagLIF scaling. OMEGA delivers roughly 1000× less energy than Z, so target linear dimensions are reduced by factors of ~10. MIFEDS (magneto-inertial fusion electrical discharge system) could provide an axial magnetic field of 10 T. Two-dimensional hydrocode modeling indicates that a single OMEGA beam can preheat the fuel to a mean temperature of ~200 eV, limited by mix caused by heat flow into the wall. One-dimensional magnetohydrodynamic (MHD) modeling is used to determine the pulse duration and fuel density that optimize neutron yield at a fuel convergence ratio of roughly 25 or less, matching the Z point design, for a range of shell thicknesses. A relatively thinner shell, giving a higher implosion velocity, is required to give adequate fuel heating on OMEGA compared to Z because of the increase in thermal losses in smaller targets. Two-dimensional MHD modeling of the point design gives roughly a 50% reduction in compressed density, temperature, and magnetic field from 1-D because of end

losses. Scaling up the OMEGA point design to the MJ laser energy available on the NIF (National Ignition Facility) gives a 500-fold increase in neutron yield in 1-D modeling.

I. INTRODUCTION

Magnetized liner inertial fusion (MagLIF) is an inertial confinement fusion (ICF) scheme that uses magnetized preheated fuel to allow cylindrical compressions with lower implosion velocities and lower convergence ratios than conventional ICF.[1]

An axial magnetic field lowers electron thermal conductivity, allowing a near-adiabatic compression at an implosion velocity ~100 km/s, limited by ion thermal conductivity, lower than the ≥300 km/s required for conventional ICF. The compressed magnetic field can confine alpha particles from deuterium–tritium (DT) fusion or T from deuterium–deuterium (D_2) fusion, if the radially integrated magnetic field $BR \geq 0.6$ T m (Larmor radius less than fuel radius). Therefore, with $BR \geq 0.6$ T m, radial areal density $\rho R > 0.3$ g/cm^2 is not required for self-heating in DT,[2] allowing cylindrical compressions that achieve lower ρR than comparable spherical compressions and reducing the minimum convergence ratio. Axial areal density, on the other hand, must be high enough to stop alphas in DT, setting a minimum compressed fuel density for a given length.

The ion temperature required for self-heating of a magnetized DT cylinder at low ρR has been calculated[2] to be ~7 keV—higher than the 4.5 keV required for unmagnetized DT at $\rho R >$ 0.3 g/cm^2. The lower fuel densities and higher temperatures of MagLIF compared to conventional ICF mean that bremsstrahlung is not a major loss mechanism, provided that high-*Z* material does not mix with the fuel; instead, ion thermal conduction dominates.[1,2]

Preheating to ~100 eV is required to achieve 7 keV with a subadiabatic, cylindrical compression reaching a fuel convergence ratio of no more than 30, which is required to limit instability growth and mix.

The confinement time required to ensure adequate fuel burnup is provided by the inertia of the target, as in conventional ICF.

MagLIF was proposed as a pulsed-power scheme, using a laser for preheating.[1] A point design based on 1-D magnetohydrodynamic (MHD) modeling was given for parameters considered to be within reach of Sandia's Z machine, consisting of a 5-mm-long beryllium cylinder with an outer radius of 3.48 mm and a thickness of 0.58 mm, in a 30-T axial magnetic field, filled with 3 mg/cm^3 of DT, preheated to 250 eV, and compressed by a 27-MA pulse with a 100-ns rise time. The shell's aspect ratio (outer radius divided by thickness) was chosen to be 6 based on 2-D MHD modeling that showed shell breakup for higher shell aspect ratios. The convergence ratio was chosen to be 25 to limit magneto-Rayleigh–Taylor instability growth during compression, which set the required fuel density. The 1-D modeling gave an implosion velocity of 70 km/s, a peak ion temperature of 8 keV, a peak BR of 1.6 T m, and a fusion yield of 0.5 MJ/cm (50% of the energy coupled to the target).

MagLIF experiments were carried out on Z using slightly longer and thinner targets than the original point design—7.5 mm long with an outer radius of 2.79 mm and a thickness of 0.465 mm, giving the same shell aspect ratio of 6. The fuel was D_2, not DT, at significantly lower densities, typically 0.7 mg/cm^3, because windows that were thin enough to transmit the laser could not hold 2.4 mg/cm^3 of D_2 (equivalent to 3 mg/cm^3 of DT in number density) at room temperature. The axial magnetic field reached only 10 T because a solenoid providing 30 T would have completely obscured the side view of the target. The targets were driven by a lower current of 19 MA, because of the higher inductance of the targets and coupling inefficiencies, which may be improved in the future. The fuel was preheated using 2.5 kJ from the Z-Beamlet laser, which was expected[3] to achieve a mean preheat temperature of around 100 eV. Neutron-averaged ion temperatures of up to 2.5 keV, *BR* of at least 0.4 T m, and D_2 neutron yields up to 3.2×10^{12} were obtained.[4,5]

Two-dimensional MHD modeling of these experiments[3] had predicted a neutron-averaged ion temperature of 3.2 keV, *BR* of 0.53 T m, and a D_2 neutron yield of 6.1×10^{13}. The principal candidate for the lower temperatures and yields achieved in the experiments is lower laser coupling to the fuel; the experimental results can be reproduced if the laser energy coupled to the gas is reduced by a factor of ~6 (Refs. 3, 6, and 7). Off-line experiments have shown lower-than-predicted window transmission.

A variation on MagLIF that gives higher gains on systems larger than Z has been proposed using a layer of DT ice on the inside of the liner;[6,8] an "ice burner" rather than a "gas burner," which in conventional ICF would be described as moving from volume ignition to hot-spot ignition. Two-dimensional MHD calculations have predicted that target gain (fusion yield divided by energy coupled to the target) can exceed 100 at a current of 60 MA, which might be achieved by the next-generation Z machine.[9] Experimental confirmation of the accuracy of these calculations would be required, however, before starting a project of this scale, which is difficult to obtain from experiments on a single facility with a limited range of practical operating parameters.

Magnetized cylindrical compressions were carried out on the OMEGA Laser System before MagLIF was proposed,[10] using the MIFEDS (magneto-inertial fusion electrical discharge system) field generator,[11] which has since been updated.[12] The only element of MagLIF that was missing from these experiments was preheating. A laser-driven version of MagLIF on OMEGA was therefore considered as a natural extension of this work.

The energy delivered to a target by the OMEGA laser is roughly 1000× lower than delivered by Z, therefore the linear dimensions of an OMEGA MagLIF target would have to be ~10× smaller than a Z target. Such a mini-MagLIF experiment on OMEGA would provide the first experimental test of MagLIF scaling. OMEGA would also provide a higher repetition rate and better diagnostic access than available on Z, facilitating the study of the basic physics of MagLIF. In particular, the axial magnetic field could be probed with protons on OMEGA,[10] which is not possible on Z because of the large azimuthal magnetic field from the pulsed-power compression.

Here we describe a point design for laser-driven MagLIF experiments on OMEGA based on scaling down the point design for Z. First, in Sec. II, we use basic scaling and practical considerations to choose a target outer radius, a range of possible shell thicknesses, practical goals for implosion velocity and convergence ratio, and an estimate of the required preheat. In Sec. III, we use 2-D hydrocode modeling to determine a reasonable value for the preheat temperature to be used in subsequent 1-D modeling, along with the stand-off distance of the laser entrance window from the compressed region to be used in the first experiments. With the axial magnetic field, outer radius, and preheat temperature fixed, we use 1-D MHD modeling in Sec. IV to determine the laser pulse duration and fuel density that optimize neutron yield at a convergence ratio of roughly 25 or less, as chosen for the Z point design, for the shell thicknesses selected. In Sec. V we explore the effect of varying preheat temperature and axial magnetic field in the point design. We finish consideration of the point design in Sec. VI with simplified 2-D modeling to determine the magnitude of end losses. We then consider scaling up the point design to over a MJ of laser energy in Sec. VII, corresponding to the energy available on the NIF (National Ignition Facility). Finally, in Sec. VIII, we present our conclusions, including an outline of the planned experiments.

II. BASIC SCALING CONSIDERATIONS AND INITIAL DESIGN CHOICES

The objective of the point design is to match key intrinsic parameters of the Z point design or experiments as closely as possible, certainly within a factor of 2, with the emphasis on matching the point design where possible. Several key parameters are listed in Table I.

A number of key extrinsic parameters cannot be matched by smaller targets, which will lead to inferior performance. The value of BR will be smaller because the magnetic field cannot be significantly higher, therefore confinement of charged fusion products (T for D_2 fusion, alphas for DT) cannot be obtained on OMEGA; the Larmor radius of these fusion products cannot be scaled down. Thermal losses will be greater because surface area to volume ratio and temperature gradient both vary as $1/r$, whereas implosion time at a fixed implosion velocity varies as r, where r is fuel radius, therefore the final fuel temperature on OMEGA will be lower. We will estimate the temperature scaling with size in Sec. II.B. For the same reasons, loss of axial magnetic field from the hot fuel to the cold shell because of the Nernst effect will be greater,[1,13] which can be thought of as convection of magnetic field with electron heat flow.[14] Resistive dissipation of the magnetic field will also be higher in smaller targets. The scaling of magnetic field loss with target size will be considered in Sec. II.C.

A. Drive energy, target dimensions, and magnetic field

Obtaining the same energy density (kinetic and internal) will require scaling target volume with energy coupled to the target. Only 40 of OMEGA's 60 beams can be used to compress a cylindrical target because the remaining 20 beams will have grazing angles of incidence that cause an excessive amount of energy to miss the target. With 40 beams, the maximum energy on target, with SSD (smoothing by spectral dispersion), is 18 kJ (roughly 10% more energy is available without SSD). This is only achieved, however, for a 1-ns square-shaped pulse, but the pulse duration should be longer than 1 ns because the aim is to achieve an implosion velocity of the order of 100 km/s, instead of the usual 300 km/s or more. Longer pulses result in lower laser energies because the frequency-conversion efficiency goes down with decreasing power. A key objective of the 1-D modeling (Sec. IV) is to determine the best compromise between pulse duration and laser energy. The net coupling efficiency (laser absorption times hydroefficiency of the ablatively driven implosion) will certainly be less than 10%, so it is reasonable to assume that ~1 kJ can be coupled to kinetic energy of the unablated shell. The Z designs[1,3] couple around 0.5 MJ to the targets, so the volume of the OMEGA targets should be *at least* 500× lower, corresponding to a factor of at least 8 in linear dimensions. Scaling down from the Z point design by a factor of 8 gives a 0.435-mm outer radius, a 0.625-mm-long target, and from the Z experiments a 0.35-mm-outer-radius, 0.94-mm-long target.

The spot size of OMEGA beams is determined by the phase plates and must match the size of the target: if the spots are too large, an excessive amount of energy will miss the target; if they are too small, the separation of the laser spots will lead to nonuniform drive. Manufacturing phase plates is an expensive and time-consuming process, so initial experiments must make use of existing phase plates. There are sets of 40 phase plates matched to ~0.15-mm-, 0.3-mm-, and 0.43-mm-outer-radius targets; we chose 0.3 mm—11.6× smaller than the Z point design and 9.33× smaller than used in Z experiments. The selected phase plates, called SG2's, give a roughly Gaussian intensity profile with a full width at half maximum in intensity of ~0.289 mm.

For the laser pulse shape we will use a square-shaped pulse, even though Z uses a ramped pulse, for three reasons: (1) It gives maximum energy on target; (2) experience shows that code predictions for square-shaped pulses (higher adiabat) are closer to experiment than for shaped pulses (lower adiabat); and (3) it simplifies the design process since it removes the need for pulse-shape optimization, which would have to be refined experimentally. It will not be possible to achieve an accurate, scaled-down reproduction of the 100-ns ramped drive of Z because the maximum-possible pulse duration on OMEGA is 4 ns. However, the time taken from when the shell starts to implode to peak convergence is roughly 40 ns on Z, which when scaled down by a factor of 10, gives 4 ns, so it should be possible to get close to this number, given a much greater initial acceleration of the target.

The shell aspect ratio of the Z point design and experiments was 6, determined to be the maximum-acceptable value from 2-D MHD modeling because of feedthrough of the magneto-Rayleigh–Taylor (RT) instability from the outer surface, which would give a 50-μm-thick shell for OMEGA. In OMEGA experiments shell aspect ratios of 20 or more are typically used, which is acceptable because ablation stabilizes the RT instability. We will therefore model shell aspect ratios of up to 15 because this gives a 20-μm-thick shell as used in previous magnetized OMEGA compressions.[10]

The compressed length of the targets will depend on how far the laser spots can be spread out along the cylinder while maintaining uniform drive, which is a complex problem. The laser beams enter at two different angles; the 40 beams are arranged in rings of 10 at angles of ±31.15° (ring 3) and ±8.75° (ring 4) to the target normal, as illustrated in Fig. 1. Oblique incidence will increase the spot size along the target surface, will cause the axial position of the beams on the target surface to change as the target implodes, and will lead to beams refracting in the coronal plasma before the critical surface. Furthermore, nonlocal thermal transport and cross-beam energy transfer (CBET) have both been found to be important to determining laser absorption in OMEGA targets and are difficult to model accurately. Therefore, we will rely on the first experiments to optimize beam pointing. Our first guess is that ring 3 should be fully overlapped at the center to compensate for their lower on-target intensity and lower effective critical density, and ring 4 should be separated to drive the ends, which should be able to uniformly compress a region roughly 0.6 mm long. We will assume that the uniformly driven length will be from 0.5 to 0.7 mm long.

Z targets are made of beryllium (1.85 g/cm^3 Be) because they must be good electrical conductors while still cold, and a low atomic number is desirable to reduce the impact of any mixing with the fuel. Electrical conductivity is not an issue for laser drive, so OMEGA targets will be made of parylene-N plastic, which contains only carbon and hydrogen (1.11 g/cm^3 CH), because it is cheaper and safer to handle than beryllium. The lower density of the target will lead to a faster implosion velocity on OMEGA than Z for the same shell aspect ratio. A nonconducting target also has the advantages of faster and more complete axial magnetic-field penetration.

Table II summarizes the target dimensions chosen for the OMEGA point design and those used in the Z point design and experiments.

MIFEDS coils that can accommodate a 0.3-mm-outer-radius target and clear the ring 3 beams, when crossed to overlap completely at the target outer surface, have been designed and are shown in Fig. 1. They provide ~10 T at the center of the target, with a slightly higher field toward the ends, as shown in Fig. 2. We will assume a uniform 10-T field in our calculations.

B. Thermal losses, implosion velocity, fuel density, and preheat

A key element of MagLIF is reducing radial thermal losses from the fuel using an axial magnetic field. The reduction in thermal conductivity perpendicular to a magnetic field is determined by the Hall parameter χ, given by the ratio of cyclotron frequency to collision frequency, or equivalently the mean free path to Larmor radius at the thermal velocity. For a straight, uniform magnetic field, which we expect to be the case for MagLIF, electron thermal conductivity perpendicular to the field in a hydrogenic (Z = 1) plasma falls as $\kappa/\kappa_0 \to 1.47/\chi^2$ for $\chi \gg 1$ (Braginskii conductivity),[15] where κ_0 is the unmagnetized thermal conductivity. Magnetic-field curvature and nonuniformity lead to a slower reduction in thermal conductivity with increasing Hall parameter. Thermal conductivity across disordered field lines is predicted to fall as $\kappa/\kappa_0 \to 0.6/\chi$ for $\chi \gg 1$ (Bohm conductivity),[16] and for intermediate cases powers of χ between 1 and 2 have been obtained experimentally, theoretically, and empirically.[16–18]

The electron Hall parameter in a hydrogen (Z = 1) plasma is roughly

$$\chi_\mathrm{e} \approx 0.24\left(\frac{A}{2}\right)\left(\frac{\rho}{2.4\ \mathrm{mg/cm^3}}\right)^{-1}\left(\frac{B}{10\ \mathrm{T}}\right)\left(\frac{T}{200\ \mathrm{eV}}\right)^{3/2}, \qquad (1)$$

where A is average ion mass number, ρ is mass density, B is magnetic field, T is temperature, and $\ln\Lambda = 10$ has been used. We have considered a fuel density of 2.4 mg/cm^3 of D_2 because it corresponds to the number density chosen for the Z point design, a magnetic field of 10 T because it can be provided by MIFEDS, and a temperature of 200 eV because this is a reasonable value for the preheat temperature, just short of the 250 eV chosen for the Z point design. In the absence of resistivity and the Nernst term, B/ρ is constant in a cylindrical compression and the Hall parameter changes only with temperature; with this simplification, for our example parameters used in Eq. (1) $\chi_e > 1$ at $T > 524$ eV, for Z parameters this temperature is roughly 250 eV.

The ion Hall parameter in a hydrogen (Z = 1) plasma can be written in terms of the electron Hall parameter as

$$\chi_i = \frac{\chi_e}{30.2 A^{1/2}}. \tag{2}$$

Ions would not be magnetized for our example parameters until the temperature exceeds 6 keV, and for Z parameters only at temperatures above 3 keV, which have not been achieved in Z experiments. In general, ion thermal conductivity in MagLIF will be only significantly reduced close to ignition. Magnetizing ions from the outset would require an initial axial magnetic field of ~ kT, which would lead to magnetic pressure preventing compression, so it would not be useful even if it could be generated.

The significant disparity between electron and ion Hall parameters means that increasing the electron Hall parameter will have little effect on thermal losses once electron thermal conductivity (κ_e) drops below ion thermal conductivity (κ_i), which can be written as

$$\kappa_i = \frac{\kappa_e}{24.9 A^{1/2}}. \quad (3)$$

For Braginskii thermal conductivity[15] $\kappa_e < \kappa_i$ when $\chi_e > 6.4$ in a deuterium plasma; only when the ions are magnetized at $\chi_e > 43$ will total thermal conductivity (electron plus ion) start to fall significantly again. The change in total thermal conductivity with electron Hall parameter in a deuterium plasma for the Braginskii and Bohm models is illustrated in Fig. 3. It can be seen that total thermal conductivity changes very little between electron Hall parameters of about 6 and 20 and is similar for both models. Therefore, it is not essential for OMEGA experiments to closely match the Hall parameter of the Z point design or experiments to be in the same thermal-transport regime; achieving an electron Hall parameter above 6 before thermal losses become significant should give the same behavior whether the magnetic-field lines remain straight or become strongly perturbed.

To estimate the scaling of thermal losses from the fuel we will assume that only ion thermal conductivity is important and that it is unmagnetized. Estimating the order of magnitude of the temperature gradient ∇T to be T/r, where r is the fuel's outer radius, and treating ions and electrons as ideal gases at the same temperatures, energy balance per unit length of the fuel including thermal losses and work done in compression gives

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(3neT\pi r^2\right) \sim -K_0 T^{5/2}\frac{T}{r}2\pi r - 2neT\frac{\mathrm{d}}{\mathrm{d}t}\left(\pi r^2\right), \tag{4}$$

where T is temperature in eV, K_0 is an approximately constant term from ion thermal conductivity, given by $125/\sqrt{A}\,\mathrm{W\,m^{-1}eV^{-7/2}}$ for $\ln\Lambda = 10$, and n is electron and ion number density ($\mathrm{m^{-3}}$). Note that Eq. (4) gives only an estimate for some form of representative fuel temperature as a function of the fuel's outer radius; it is not an exact result, it could be described as a zero-dimensional (0-D) model. Assuming a constant implosion velocity $v = -\mathrm{d}r/\mathrm{d}t$ (m/s), we can obtain

$$\frac{T}{T_\mathrm{c}} = \frac{0.7^{2/5}C^{4/3}}{\left[C^{7/3} - 1 + 0.7\left(T_\mathrm{c}/T_0\right)^{5/2}\right]^{2/5}}, \tag{5}$$

where T_0 is preheat temperature, $C = r_0/r$ is fuel convergence ratio, and T_c is the value of T_0 at which thermal loss equals work done by compression:

$$T_\mathrm{c} = \left(\frac{2en_0 r_0 v}{K_0}\right)^{2/5} \approx 1.6\left(\sqrt{\frac{2}{A}}\frac{\rho_0}{2.4\ \mathrm{mg/cm^3}}\frac{r_0}{0.3\ \mathrm{mm}}\frac{v}{140\ \mathrm{km/s}}\right)^{2/5}\ \mathrm{keV}. \tag{6}$$

For small convergence ratios, Eq. (5) gives

$$T \approx T_0 C^{(4/3)\left[1-\left(T_0/T_\mathrm{c}\right)^{5/2}\right]}, \quad C - 1 = 1, \tag{7}$$

which reproduces the adiabatic result $T = T_0 C^{4/3}$ for T_0 □ The final temperatures of interest for MagLIF are greater than T_c, so thermal losses will be significant; therefore we can expect significantly lower temperatures on OMEGA than on Z. For large convergence ratios Eq. (5) gives

$$
\begin{aligned}
T &\to 0.7^{2/7} C^{2/5} T_c, \\
C^{7/3} \; ? & \;\; 0.7\left(T_c/T_0\right)^{5/2} - 1 \\
&\propto \left(C \rho_0 r_0 v\right)^{2/5},
\end{aligned}
\tag{8}
$$

which is exact for $T_0 = T_c$, is approached from below for $T_0 < T_c$, which is the regime of interest, and is approached from above for $T_0 > T_c$, following an initial fall in temperature. Equation (8) should be an adequate approximation for the scaling of the final temperature in MagLIF.

Equation (8) indicates that reducing target radius by a factor of 10 while maintaining the same convergence ratio, fuel density, and implosion velocity will reduce the final temperature by a factor of 2.5, which would be too much. To limit the reduction in temperature to less than a factor of 2, the product of convergence ratio, fuel density, and implosion velocity will have to be increased by a factor of at least 1.75. We believe that the best approach is to increase implosion velocity by a factor of around 2, by increasing shell aspect ratio, while maintaining fuel density and convergence ratio close to the Z point design values. The convergence ratio should not be increased because it would increase the risk of shell breakup and mix. The fuel density should not be increased because higher densities will require a higher magnetic field to magnetize the electrons and a thicker laser entrance window to hold the pressure and will present issues for preheat laser propagation in the fuel.

An interesting feature of Eq. (8) is that it is independent of preheat temperature T_0, indicating that there is a preheat threshold for a given convergence ratio, above which the final temperature does not increase significantly. The preheat temperature required to reach 90% of the limiting value given by Eq. (8) is

$$T_0 > 1.47 \frac{T_c}{C^{14/15}} \sim 120 \left(\sqrt{\frac{2}{A}} \frac{\rho_0}{2.4\ \mathrm{mg/cm^3}} \frac{r_0}{0.3\ \mathrm{mm}} \frac{v}{140\ \mathrm{km/s}} \right)^{2/5} \left(\frac{C}{25} \right)^{-14/15} \mathrm{eV}, \tag{9}$$

which indicates that preheating as high as 200 eV should not be necessary on OMEGA. For the Z point design, Eq. (9) gives 230 eV, close to the 250 eV that was chosen.

The final temperature estimate for sufficient preheat is

$$T \sim 5.1 \left(\sqrt{\frac{2}{A}} \frac{\rho}{2.4\ \mathrm{mg/cm^3}} \frac{r_0}{0.3\ \mathrm{mm}} \frac{v}{140\ \mathrm{km/s}} \frac{C}{25} \right)^{2/5} \mathrm{keV}, \tag{10}$$

which gives 10 keV for the Z point design, higher than the peak ion temperature of 8 keV, and 6.5 keV for Z experiments, had there been sufficient preheat; 1-D modeling of these experiments with adequate preheat[3] gave a peak ion temperature of ~5 keV. These results are remarkably close for a simple order-of-magnitude estimate, roughly 30% higher than the peak values from 1-D modeling. Furthermore, using a limiting value and neglecting electron thermal conduction would be expected to overestimate the temperature. Based on these results, a peak temperature of 3.6 keV should be achievable on OMEGA.

C. Magnetic-field loss from the fuel

Magnetic field will be lost from the fuel because of diffusion and the Nernst term, both of which will be greater for smaller-radius targets.

To estimate the scaling of magnetic-field loss to diffusion, we will estimate the associated energy dissipation to ohmic heating. The current density j induced in the plasma as the magnetic field is compressed is concentrated in a peak near the edge; as an order-of-magnitude estimate we will use $j \sim \left(C^2 - 1\right) B_0 / \Delta r,$ assuming a small loss in field compression, and $\Delta r \sim \sqrt{\eta t / \mu_0} / C,$ the conventional diffusion length reduced by compression. The rate of energy dissipation per unit length is $\sim \eta j^2 2\pi \left(r_0 / C\right) \Delta r,$ where η is resistivity. Using the Spitzer resistivity and the large convergence ratio limits from our simple model, this can be integrated to give the energy dissipated per unit length. Taking the square root of the ratio of this energy dissipation to the magnetic-field energy per unit length in the absence of losses, $C^4 B_0^2 \pi \left(r_0 / C\right)^2 / 2\mu_0,$ gives an estimate for the fraction of field lost:

$$f_B \sim 0.5 \left(\sqrt{\frac{2}{A}} \frac{\rho_0}{2.4\ \mathrm{mg/cm^3}} \right)^{-3/20} \left(\frac{r_0}{0.3\ \mathrm{mm}} \frac{v}{140\ \mathrm{km/s}} \right)^{-2/5} \left(\frac{C}{25} \right)^{7/20}. \tag{11}$$

Equation (11) indicates that field loss to diffusion will be significant and has the same scaling with radius and implosion velocity as thermal loss to conduction but is less sensitive to fuel density; therefore increasing implosion velocity is also the obvious means to reducing field losses. For the Z point design Eq. (11) gives $f_B \sim 0.26$ and a flux loss of 25% is reported without including the Nernst term.[1] Although the fraction of the magnetic field remaining decreases with convergence ratio, the total field will still increase with convergence, just more slowly than the lossless C^2 result.

The Nernst term is an electrothermal effect arising from the $v \times B$ force on electrons carrying heat flow down the temperature gradient that generates an electric field perpendicular to both the magnetic field and the temperature gradient. It leads to a velocity-like term in the magnetic-field–evolution equation that can be written as[14]

$$v_{\mathrm{N}} \approx \frac{q_{\perp}}{2.5nkT}, \tag{12}$$

where $q_{\perp}$ is the electron heat flux perpendicular to the magnetic field. Nernst convection of the magnetic field can be interpreted as field being frozen to conduction electrons rather than to the plasma as a whole, which can be ascribed to their lower collision frequency. In MagLIF, the Nernst velocity will be directed out of the hot fuel and into the cold shell, so it will act to reduce the net implosion velocity seen by the magnetic field. If the temperature gradient varies as $1/r$, the Nernst velocity will be roughly a factor of 10 higher on OMEGA than on Z, a change that can be partially compensated for by increasing implosion velocity. The situation is not so straightforward, however, because Nernst velocity is sensitive to electron magnetization, which changes the scaling, so we cannot obtain a simple estimate of the magnetic-field loss.

To evaluate the relative importance of the Nernst term, we will use a dimensionless number v/v_N, a "Nernst number;" high values indicate a negligible reduction in magnetic-field compression, and a value less than 1 indicates that the magnetic field will fall rather than being compressed with the fuel. Crudely speaking, the reduction in magnetic-field compression should be $\sim(1-v_\mathrm{N}/v)^2$. Using $\nabla T \sim T/r$ and the temperature from Eq. (5), we can write

$$\frac{v}{v_\mathrm{N}} \sim \frac{0.072}{\sqrt{A}} \frac{C^{7/3}-1+0.7\left(T_\mathrm{c}/T_0\right)^{5/2}}{C^{7/3}} \frac{1}{f\left(\chi_\mathrm{e}\right)}, \tag{13}$$

where $f\left(\chi_\mathrm{e}\right) \geq 1$ gives the reduction in electron thermal conductivity perpendicular to the magnetic field.

Initially electrons are not magnetized for the parameters we have considered, $f\left(\chi_\mathrm{e}\right) \sim 1$, giving

$$\frac{v}{v_\mathrm{N}} \sim 7\left(\frac{2}{A} \frac{\rho}{2.4\ \mathrm{mg/cm^3}} \frac{r_0}{0.3\ \mathrm{mm}} \frac{v}{140\ \mathrm{km/s}}\right)\left(\frac{T_0}{200\ \mathrm{eV}}\right)^{-5/2}, \tag{14}$$

which gives 20 for the Z point design and 460 for Z experiments, so we would expect to see a noticeable loss in magnetic-field compression right from the outset on OMEGA—a much more modest loss for the Z point design and practically none at all for Z experiments.

For the 10-T axial magnetic field used in Z experiments and available with MIFEDS, electron heat flow is not magnetized until partway through compression, whereas for the 30 T of the Z point design, electron heat flow is magnetized as soon as the temperature increases. While electron heat flow is unmagnetized, the Nernst number will decrease as the target is compressed. To estimate the minimum value of the Nernst number, we will use the temperature at which $\chi_e = 1$, lossless field compression $B = C^2 B_0$, and estimate convergence ratio from the adiabatic result $C = (T/T_0)^{3/4}$, giving

$$\frac{v}{v_N} \sim 1.5 \left(\frac{2}{A} \frac{\rho_0}{2.4 \text{ mg/cm}^3} \right)^{-1/6} \left(\frac{r_0}{0.3 \text{ mm}} \frac{v}{140 \text{ km/s}} \right) \left(\frac{T_0}{200 \text{ eV}} \right)^{-3/4} \left(\frac{B_0}{10\, T} \right)^{7/6}, \tag{15}$$

indicating a significant loss of magnetic-field compression. For Z experiments the value is roughly 40; 1-D modeling of these experiments[7] found that the Nernst term was not significant at preheat levels that matched measured neutron yields.

For strongly magnetized electron heat flow, using Eq. (5) for the temperature, lossless field compression $B = C^2 B_0$, and Braginskii's thermal conductivity gives

$$\frac{v}{v_N} \sim 23 \left(\frac{2}{A} \right)^{9/10} \left(\frac{\rho_0}{2.4 \text{ mg/cm}^3} \right)^{-4/5} \left(\frac{r_0}{0.3 \text{ mm}} \frac{v}{140 \text{ km/s}} \frac{C}{25} \right)^{6/5} \left(\frac{B_0}{10 \text{ T}} \right)^{2}, \tag{16}$$

so toward the end, the loss of magnetic-field compression should become small on OMEGA and be negligible for the Z point design.

By modeling the Z point design with and without the Nernst term,[1] the Nernst term was found to increase the optimum axial magnetic field from 10 T to 30 T, and even at 30 T the Nernst term increased the flux loss from 25% to 45%. According to our estimates the higher axial magnetic field was required to ensure electrons were magnetized from the start of the compression, avoiding the initial fall in the Nernst number, but this would require an ~40-T axial magnetic field on OMEGA, which is not currently available, although plans for a system to reach such fields does exist. The effect of the Nernst term could be reduced at 10 T by lowering fuel density, which increases the electron Hall parameter, and only preheating to the threshold value [Eq. (9)] since increased preheat gives a lower Nernst number while electrons are not magnetized [Eqs. (14) and (15)]. This will be evaluated in the 1-D modeling of Secs. IV and V.

According to these estimates, the increase in magnetic-field loss to the Nernst term should be the most pronounced of the changes as we move to smaller targets.

III. PREHEAT MODELING, PREHEAT TEMPERATURE, WINDOW STANDOFF, AND TIMING

Laser preheating by inverse bremsstrahlung in the context of MagLIF was considered as part of the Z point design using analytic and 2-D hydrocode models with ray tracing.[1] Parametric instabilities could also occur during laser preheating and are largely undesirable because they can cause backscattering, sidescattering, and energy transfer to a small population of electrons, which would lead to inadequate fuel preheat and could lead to mix by ablating parts of the target. This is a complex area that we will not deal with here; instead we will use a simple rule of thumb that provided the laser beam is sufficiently smooth, parametric instabilities should not be an issue if fuel density is less than one-tenth of critical density. For the 351-nm wavelength (λ) of the OMEGA laser, one-tenth critical density corresponds to 2.7 mg/cm^3 D_2; for the 527 nm of the Z beamlet laser, it corresponds to 1.2 mg/cm^3 D_2.

Electron temperature related to inverse bremsstrahlung heating scales as $(nI\lambda^2 t)^{2/5}$, assuming a fixed number density n and neglecting thermal conduction and radiation. Intensity multiplied by time (It) is energy per unit area, so if preheat temperature, fuel number density, and laser wavelength remain the same, the laser energy required for preheating will vary as the square of the radius, so it should be roughly 100× lower on OMEGA than Z. The laser energy required for preheating varies with area rather than volume because the heated length, which is proportional to $n^{-7/5}(It)^{3/5}\lambda^{-4/5}$, does not change, meaning that preheating becomes less efficient at smaller scales, but axial uniformity becomes less of an issue. The preheating time should scale linearly with radius, so it will be roughly 10× lower on OMEGA than Z, giving a laser intensity that is 10× higher.

Two-dimensional hydrocode modeling for the Z point design showed that the desired 250-eV preheating of 3 mg/cm^3 of DT (equivalent to 2.4 mg/cm^3 of D_2 in number density n) could be provided by a 500-nm-wavelength laser delivering 8 kJ in 10 ns with a 1-mm-radius spot, giving a power of 0.8 TW and an intensity of 2.5×10^{13} W/cm^2. On OMEGA (351-nm wavelength), this scales to a laser energy of 120 J in 1 ns with a 100-μm-radius spot, giving a power of 0.12 TW and an intensity of 3.8×10^{14} W/cm^2, well within the capabilities of a single beam. To illustrate the inefficiency of the preheating at OMEGA scale, the energy required to heat a 0.3-mm-radius cylinder of 2.4 mg/cm^3 of D_2 to 200 eV (electrons and ions) is only 20 J/mm.

The pulse shape for the OMEGA preheating beam must be the same as the compression beams because independent pulse shaping is only possible on one of the three legs of the OMEGA laser and beams from all three legs are required for compression. Therefore, the preheat beam will have a square pulse shape with a duration certainly greater than 1 ns. The relative timing of the preheat beam with respect to the compression beams and the energy in the preheat beam can be varied independently of the compression beams.

The smallest available phase plate that gives a sufficiently smooth beam profile has a radial intensity profile that can be adequately fitted by $\exp\left\{-\left[\left(r/126.8\ \mu\mathrm{m}\right)^2\right]^{1.195}\right\}$, which is larger than the 100 μm obtained by scaling from the Z point design, but smaller phase plates have been found to give inadequate beam smoothing. For a power of 0.12 TW the peak intensity with this phase plate would be 2.3×10^{14} W/cm^2, a power of 0.2 TW is required to reach 3.8×10^{14} W/cm^2.

The thickness of the laser entrance window and the energy required to burn through it are critical issues that were not considered in the Z point design. Targets for preheating experiments on OMEGA have been built and tested, and it was found that a 1.84-μm-thick polyimide ($C_{15}H_5N_3O_2$, 1.44 g/cm^3) film could hold 2.4 mg/cm^3 of D_2 at room temperature and that it absorbed no more than 60 J of laser energy. Z experiments also use polyimide film, down to 1.5 μm thick for 0.7 mg/cm^3 of D_2 at room temperature. Entrance window material will blow into the target, so there must be a standoff between the entrance window and the region to be compressed. Another potential issue with the window is that x rays emitted before burnthrough could ionize the inner surface of the shell, causing wall blow-in and mix.

To more accurately determine the preheat temperature, the preheating time, and the standoff required between window and compression region for the OMEGA point design, we have used the 2-D hydrocode *DRACO*. A series of preheat experiments have been carried out on OMEGA and OMEGA EP,[19] and initial results indicate that hydrocode modeling with ray tracing and inverse bremsstrahlung heating does an adequate job of modeling the preheating. (Further details of these experiments will be published elsewhere.)

DRACO was used in Eulerian mode,[13] which uses spherical geometry, so a large offset from the origin was used to give almost cylindrical geometry, with 12-group radiation transport; opacity tables from collisional, radiative equilibrium calculations; *SESAME* equations of state; and a flux limit of 0.06. To prevent the shell from expanding under its own pressure, cells identified as solid were prevented from moving until their average electron and ion temperature exceeded 0.06 eV (melting point) or the pressure of a neighboring, nonsolid cell exceeded their pressure. In the interest of obtaining a conservative preheat temperature and reducing run times, we did not consider the magnetic field, which would be expected to slightly reduce electron heat flow from the center, possibly slowing wall heating.

The power indicated by scaling from the Z point design results is roughly 0.12 TW, which is the maximum power of a single beam for a 2.5-ns square-shaped pulse. Higher powers are possible with shorter pulses; for example, 0.18 TW is the maximum power for a 2-ns pulse duration. It may be advantageous to use a lower power, so we will also consider 0.09 TW. The actual pulse duration does not matter here because wall blow-in becomes too great before 2 ns, so laser power was ramped up linearly over 0.1 ns, then held constant.

The OMEGA targets, as illustrated in Fig. 1, will be long enough to be inserted through the coils and will have a fill tube attached to the back, so the back wall will be very far from the entrance. Therefore in *DRACO* we considered only 1.8 mm of target with an open boundary at the back, which was chosen based largely on memory constraints; however, a standoff distance of more than 1.8 mm would place very stringent requirements on the angle of the target to the preheat beam. The inner radius of the shell varies with the shell thickness if the outer radius is fixed. To be on the conservative side we considered just the lower inner radius of 250 μm, which will increase the effect of wall plasma blow-in.

Fuel densities from the 0.7 mg/cm^3 used in most of the Z experiments to the 2.4 mg/cm^3 of the Z point design were considered, with 1.5 mg/cm^3 used as an intermediate value.

The principal issue of concern is plasma blow-in from the window and walls; to quantify this we calculated the fraction of the original fuel volume that remained free of window and wall plasma. The axial variation of this "clean area" and the mean temperature of the fuel at key times for the intermediate fuel density (1.5 mg/cm^3) and intermediate laser power (0.12-TW) case is shown in Fig. 4; the other fuel densities and laser powers showed similar behavior. The position of the window can be clearly seen from the sudden drop in clean area and increase in temperature. Ahead of the window, the clean area begins to fall even before the laser burns through the window, which occurs just after 0.4 ns in this case, as a result of the walls being heated by thermal conduction near the window and by x rays emitted by the window farther down the target. The mean temperature ahead of the window, once the laser has burned through it, is relatively uniform over the 1.8 mm considered, as expected.

Wall blow-in is the limiting factor in determining preheating time, standoff distance, and preheat temperature in the cases considered. In the 2-D hydrocode, wall blow-in leads principally to compression of the fuel and not to mix, but in 3-D with a rough inner surface it is likely to lead to mix, which could create a problem. We set a somewhat arbitrary lower limit on clean area of 0.9 to estimate preheat temperatures, preheating times, and standoff distances. Lowering this limit to just over 0.8 had little effect on the temperature that could be reached, but it significantly reduced the required standoff distance to the region just ahead of the window plasma, so lower standoff distances might be practical. Increasing this limit led to a rapid fall in the preheat temperature, so it does represent a reasonable compromise value.

For the case shown in Fig. 4, the latest time at which a clean area of about 0.9 exists is 1.3 ns, over most of the region beyond 1.2 mm from the entrance, at which point the mean temperature has reached about 190 eV. At 1.75 ns the clean area has decreased significantly and is increasing only slowly with distance, while the mean temperature ahead of the window plasma has increased only slightly to just over 200 eV. The same analysis was repeated for each case and the times, standoff distances, and mean temperatures obtained are given in Table III.

The preheat temperatures meet our estimated requirement [Eq. (9)] for all cases, based on the fall in predicted preheat threshold with fuel density. Fuel density is the dominant factor in determining preheat temperature because it increases both the heating rate and the preheating time, as increasing density lowers thermal diffusivity and increases fuel pressure, which slows wall blow-in.

The preheat temperature increases slowly with increasing laser power but more slowly at higher densities; doubling the laser power increases the temperature by 18% at 0.7 mg/cm^3 and only 8% at 2.4 mg/cm^3. Two disadvantages of increasing laser power are a decrease in preheat time and an increase in the window standoff distance. Therefore, it might be advantageous to use less-than-maximum laser power to decrease the precision of the timing required between preheat and compression beams and to reduce the standoff distance since this will cause only a small reduction in preheat temperature.

The radial temperature and density profiles across the middle of the clean region at 1.3 ns for the 1.5-mg/cm^3 and 0.12-TW case are shown in Fig. 5, which is representative of the general behavior at other densities and powers.

The temperature profiles are significantly broader than the laser intensity profile because of thermal conduction. According to the calculations for the Z point design, heating a smaller radius region leads to higher gain and lower preheat energy, but this is not possible at OMEGA scale because the electron thermal diffusion time

$$t_{\mathrm{dif}} \sim 1.6\left(\frac{2}{A}\frac{\rho}{2.4\ \mathrm{mg/cm^3}}\right)\left(\frac{T}{400\ \mathrm{eV}}\right)^{-5/2}\left(\frac{r}{0.3\ \mathrm{mm}}\right)^{2}\mathrm{ns}, \tag{17}$$

using twice the expected temperature because initially only electrons are heated, is of the same order as the preheating time, ignoring magnetization. At OMEGA scale it is not possible to heat the center of the gas to the required temperature without rapidly ionizing the wall; thermal conduction into the wall is the key limiting factor for preheating. For the Z point design, Eq. (17) gives 92 ns, so shock propagation from the heated gas into the wall is the limiting factor, not thermal conduction.

The electron temperature in Fig. 5 is just over twice the ion temperature near the center because the electron–ion equilibration time

$$t_{\mathrm{ei}} \approx 0.68\left(\frac{A}{2}\right)\left(\frac{\rho}{2.4\ \mathrm{mg/cm^3}}\right)^{-1}\left(\frac{T}{400\ \mathrm{eV}}\right)\mathrm{ns} \tag{18}$$

is not much less than the preheating time. Electron–ion equilibration during preheat starts to become an issue at scales smaller than Z, particularly for lower densities and higher temperatures.

The fuel density profile is modified by the preheating. The fuel density in the central portion in Fig. 5 has dropped from 1.5 mg/cm^3 to ~1 mg/cm^3 as the heated plasma expands, and the density in a small region near the edge has roughly doubled. The implosion velocity of the wall, resulting from the laser drive, will be far greater than this initial motion of the fuel and wall, so it should have a small effect on the final results.

IV. ONE-DIMENSIONAL MODELING, PULSE DURATION, SHELL THICKNESS, AND FUEL DENSITY

The 1-D MHD code *LILAC*[13] was used to determine the laser pulse duration and fuel density that maximize neutron yield while maintaining a convergence ratio of roughly 25 or less, as chosen for the Z point design, for 20-, 30-, 40-, and 50-μm-thick shells, a 10-T initial axial magnetic field, and 200-eV preheat. *LILAC* was run using six-group radiation transport, tabulated opacities, *SESAME* equations of state, and a flux limit of 0.06, which was also applied to the Nernst term.[13]

We expect a 1-D code to overestimate the neutron yield by at least a factor of 10, even if perfect target and laser conditions could be achieved, because yield is sensitive to temperature and density, both of which will be somewhat overestimated in 1-D because of the lack of axial flow and axial transport. We expect the optimum values of laser pulse duration and fuel density obtained to be reasonably accurate, however, and 1-D calculations allow a rapid exploration of a wide parameter space.

Setting fuel temperature to 200 eV leads to a steep temperature gradient from the fuel to the shell that depends on grid spacing, which is unphysical and leads to numerical issues with the Nernst term. Therefore, we chose a simple, arbitrary function that transitions continuously from a nearly constant value over most of the fuel to a constant value in the shell and whose gradient transitions continuously to zero in the shell:

$$T = T_0 \cos^2\left[\frac{\pi}{2}\left(\frac{r}{R}\right)^4\right] + T_1, \qquad r \le R(\text{fuel}) \tag{19}$$

$$= T_1, \qquad r > R(\text{shell}), \tag{20}$$

where r is radial coordinate and R is fuel's outer radius. T_0 was set to 292 eV and T_1 to 0.025 eV (room temperature) to give a mean fuel temperature of 200 eV.

Ideally, the laser would drive the shell throughout the compression; for a 140-km/s implosion velocity and 0.3-mm radius, the compression time should be about 2 ns; adding an initial phase before compression starts will increase this to about 2.5 ns. However, as the pulse length is increased beyond 1 ns, the energy on target falls almost exponentially because of the nonlinear nature of the frequency conversion, so a shorter pulse may be ideal. The maximum energy per beam (with SSD on) that has been measured for a series of square-shaped–pulse durations is given in Table IV. We limited the pulse durations used to these tested values.

LILAC uses 2-D ray tracing in cylindrical geometry, with parallel rays incident onto the side of the target, so the angles of the beams to the axis are not considered, which will overestimate the drive. Therefore, we used the peak, azimuthally averaged intensity on the initial target surface from a single ring of ten near-normal beams (8.75°, ring 4) to specify the laser drive in *LILAC* because the drive from these beams should not be significantly overestimated. The ring-4 beams will be used to drive the ends of the target and will overlap the wings of the

31.15° beams (ring 3), which should compensate the expected, small loss in drive from ring 4. The ring-3 beams will be overlapped at the center to give an intensity greater than or equal to the total intensity where the ring-4 beams are pointed in order to give uniform drive; the exact spacing of the rings required to maximize the uniformly driven length will be determined in the first experiments. The calculated effective drive intensity on the initial target surface is given in Table IV.

The key results are summarized in Table V. As expected, the peak ion temperatures are all significantly lower than the 8 keV reported from 1-D modeling of the Z point design,[1] but the 20-μm-thick shell is within a factor of 2. The predicted neutron-averaged ion temperatures and neutron yields for the 40- and 50-μm-thick shells are getting too low to allow an accurate measurement with the neutron diagnostics available on OMEGA, so we will use a shell thickness of 30 μm or less.

Figure 6 shows the neutron yields and convergence ratios obtained from the scan of pulse duration and fuel density for a 30-μm-thick shell; other shell thicknesses showed similar behavior. The neutron yield is highest for the lowest fuel density considered, but the convergence ratio is well above the objective of 25; however, increasing fuel density to lower convergence ratio does not significantly reduce the neutron yield.

Figure 7 shows absorbed laser power, fuel radius, and mean fuel ion temperature as functions of time for the 30-μm-thick shell, which can be compared to the results for the Z point design given in Fig. 4 of Ref. 1. The drive for the OMEGA point design (absorbed laser power) flattens out roughly halfway through the pulse, whereas the drive for the Z point design (current) rises almost throughout the compression. For the Z point design preheating was applied at a fixed rate some time after the start of the drive and shortly before the fuel started to compress, instead of being imposed as an initial condition, but the shorter time scale and sharp rise in drive on OMEGA does not require delayed preheating to avoid loss of fuel temperature prior to compression, which is seen in the Z point design.

The ion temperature, density, and magnetic-field profiles in the fuel at peak neutron rate for a 30-μm shell are shown in Fig. 8, with and without the Nernst term included, which can be compared to the results for the Z point design given in Fig. 5 of Ref. 1. The profiles are similar for both point designs, except for our magnetic field that included the Nernst term, which is considerably lower than without the Nernst term throughout the fuel, whereas in the Z point design it is unaffected by the Nernst term near the center and reduced to a somewhat lesser degree near the edge. The Nernst term lowers the magnetic field at the center in our case because convergence of the initial shock on-axis produced a narrow peak in temperature on-axis; the ramped drive of the Z point design will give a much weaker shock, so the temperature gradient near the center was probably negligible throughout. Once the temperature profile has relaxed to the shape seen in Fig. 5, the Nernst term lowers the implosion velocity seen by the magnetic field over all but the center of the fuel; the steeper temperature gradient of the OMEGA point design (Sec. II.C) and the lower axial magnetic field lead to this effect being far greater than in the Z point design, and most of the field is lost from the fuel. The dramatic loss of magnetic field resulting from the Nernst term is not a major issue because it is the field at the fuel–shell interface that matters for reducing heat loss from the fuel; this is actually marginally higher with the Nernst term included. The Nernst term does lower BR, but this could never be high enough to confine charged fusion products at the OMEGA scale.

Flux loss by the time of peak neutron rate was roughly 85%. For the Z point design a 70% flux loss is reported when a 10-T axial magnetic field was also used, decreasing to 45% at

30 T because of reduction of the Nernst term. Without the Nernst term, we obtained a 39% flux loss and for the Z point design a 25% flux loss was reported,[1] in remarkably good agreement with the estimate of Eq. (11).

V. PREHEAT AND MAGNETIC-FIELD SCANS

In the previous section preheat temperature and axial magnetic field were fixed at approximately the highest values we believe can be currently achieved on OMEGA. Here we will look at the effect of varying both of these parameters for a 30-μm-thick shell, from zero to well above current capabilities, although the ability to generate higher magnetic fields should be available in the future.

The effects of preheat on yield for selected axial magnetic fields are shown in Fig. 9, and the effect of axial magnetic field on yield, ion temperature, implosion velocity, and convergence ratio for no preheat and 200 eV preheat are shown in Fig. 10.

The dependence of yield on preheat temperature, with an axial magnetic field, shows good agreement with the estimated 120-eV threshold [Eq. (9)], with a slight fall at higher values. The same behavior was seen in 1-D modeling of Z experiments,[7] where the fall was found to be caused by the Nernst term, as expected, because of the increase in electron heat flux this causes while electrons are not strongly magnetized [Eqs. (14) and (15)]. Without magnetization there is little change in yield with preheat; for unmagnetized electron thermal conductivity, the predicted threshold temperature is only 29 eV [Eq. (9)].

The change in yield between 100 eV and 400 eV is not significant, so the choice of 200 eV for the 1-D modeling was not critical; in addition, the exact preheating achieved in experiments should be critical, provided it exceeds 100 eV. On the other hand, for unmagnetized targets the convergence ratio does decrease significantly with increased preheat, which might result in better performance because of reduced perturbation growth and mix.

Yield and temperature increase with magnetic field because energy loss to electron thermal conduction is reduced. With preheating, yield and temperature continue to increase up to 30 T, although the rate of increase starts to fall beyond 20 T. Without preheat there is an optimum magnetic field of 15 T because magnetic pressure becomes significant (see Fig. 11) as a result of the high convergence ratio. With preheating, magnetic pressure remains negligible at 30 T; however, providing more than 30 T would be a major technical challenge.

Increasing magnetic field should reduce the loss of magnetic-field compression because of the Nernst term (Sec. II.C). Figure 12 shows that flux conservation in the fuel at peak neutron rate does increase with axial magnetic field; it roughly doubles from 15.6% to 32.1% as the axial magnetic field is increased from 10 T to 30 T for 200-eV preheat. Flux conservation for the Z point design showed a similar increase from 30% to 55% as the axial magnetic field was increased from 10 T to 30 T—roughly twice that of the OMEGA point design because of the smaller temperature gradient—as expected from the scaling given in Eq. (11). Figure 12 also shows that flux conservation is significantly higher without preheat, which is a result of a significant reduction in the Nernst term due to the lower fuel temperature.

Increasing axial magnetic field decreases both convergence ratio and implosion velocity; therefore, the ideal point design parameters will change. With the perspective of eventually achieving a 30-T capability, we repeated the point design process for 30 T, the results of which are shown in Table VI. The optimum pulse durations are unchanged. The fuel densities that maximized neutron yields increased and the convergence ratios decreased to the point that only for the 20-μm shell was fuel density increased to maintain a convergence ratio of approximately

25; for the thicker shells, the convergence ratio is now closer to 20 (for a 20-μm shell, 1.5 mg/cm^3 was the optimum density, giving a neutron yield of 3.03 × 10^{11} mm^{-1}, but a convergence ratio of 30.9).

VI. TWO-DIMENSIONAL MODELING OF THE POINT DESIGN, END LOSSES, AND ABSOLUTE NEUTRON YIELDS

A key concern with cylindrical compressions is end losses of mass because of axial flow, of heat resulting from axial flow and axial thermal conduction, and of magnetic field caused by axial flow, including the Nernst velocity, and axial diffusion. Slutz *et al.*[1] give an approximate expression for end losses based on an analytic solution for a rarefaction wave. Assuming flow out of both ends over the full radius of the fuel, this gives

$$\frac{\mathrm{d}}{\mathrm{d}t}(\ln N) = -2\left(\frac{3}{4}\right)^4 \frac{c_\mathrm{s}}{L}, \tag{21}$$

where N is total particle number in the length L and c_s is adiabatic ion sound speed $\sqrt{5kT/3m_\mathrm{i}}$. With the temperature from Eq. (5), the solution to Eq. (21) is long and includes a hypergeometric function, but for preheat levels of interest and a final temperature close to the limiting value, it simplifies to

$$\frac{N}{N} \approx \exp\left[-6\left(\frac{3}{4}\right)^4 \frac{r_0}{L}\frac{c_\mathrm{s}(T_0)}{L}\right], \quad C^{7/3} \Box \quad \left(\frac{T_{-}}{T_0}\right)^{5/2} \quad \left(\frac{T_{-}}{T_0}\right)^{5/2} \Box \tag{22}$$

where c_s (T_0) is the adiabatic ion sound speed at the initial temperature. Note that there is a limited margin to lower end losses by reducing the initial temperature because it must exceed the approximate threshold value given by Eq. (9) for this to be an adequate approximation. For our example parameters and taking L = 0.5 mm, Eq. (22) gives 64% mass loss; heat and field losses should be slightly higher.

To evaluate end losses in more detail, 2-D modeling was carried out with *HYDRA*[20] for the pulse durations and fuel densities determined by the 1-D *LILAC* modeling, considering only 20- and 30-μm-thick shells since only these gave adequate yields and temperatures in *LILAC*, for just a 10-T initial axial magnetic field.

HYDRA was run with 35-group radiation transport, tabulated LTE (local thermodynamic equilibrium) opacities and LTE equations of state (LEOS), Epperlein–Haines transport coefficients[15] with a Lee–More degeneracy correction, except for the resistivity of D_2, which used QLMD (quantum Lee–More–Desjarlais),[21] and a flux limit of 0.05. The Nernst term was not available in *HYDRA* at the time. To ensure an accurate 2-D to 1-D comparison, the results were compared to 1-D results from *HYDRA*, not *LILAC*. The implosion velocities and convergence ratios from 1-D *HYDRA* were within 10% of the results from *LILAC*, despite the differences in radiation transport, equations of state, thermal conductivities, and resistivities. Flux conservation at peak neutron rate matched the 60% that was obtained in *LILAC* when the Nernst term was not included.

The issue of laser pointing was not considered; instead normal incidence rays and a super-Gaussian axial intensity profile were used, with a full width at 95% intensity of 0.5 mm—a conservative estimate for the length of the region we expect to drive with adequate uniformity. The peak intensity was set to the same value used in *LILAC* (Table IV). As can be seen from the density plot shown in Fig. 13, this led to uniform compression of the shell over a region close to 0.5 mm long.

The preheat laser was modeled in 2-D rather than applying preheating as an initial condition as in *LILAC*. The *DRACO* results given in Sec. III indicate that for a 1.5-ns pulse duration and a fuel density of 2.4 mg/cm^3, an energy of 180 J will give a mean temperature of 219 eV by the end of the pulse and require a standoff distance of the window from the compression region of 1 mm. To reduce the length of the target that needed to be included in *HYDRA*, the window was not modeled. *DRACO* showed the preheat laser passing through the gas at around 0.5 ns, so a 1-ns, 120-J preheat beam was used in *HYDRA* to approximate a 1.5-ns, 180-J beam after burning through the window. The preheat beam was timed to finish as the shell started to compress, which corresponded to the full pulse being fired 1.17 ns before the start of the compression beams for a 20-μm-thick shell and 1 ns for a 30-μm-thick shell. A limited scan of preheat beam timing was carried out and indicated that this was the optimum timing, as expected from previous results for Z (Ref. 3). The far end of the target was also left open in *HYDRA*, so the target only had to be 1 mm long.

The electron and ion temperature profiles in the fuel obtained at the end of the preheating for 2.4 mg/cm^3 of D_2 (30-μm shell) are shown in Fig. 14; the results for 2.7 mg/cm^3 (20-μm shell) were very similar. The mean ion temperature in the central 0.5-mm-long region was just under 200 eV and fairly uniform, similar to the preheat imposed in *LILAC*, but the electron temperature was up to a factor of 5 higher than the ion temperature, whereas *LILAC* used equal electron and ion temperatures initially. In 2-D, however, a significant fraction of the additional electron heating was lost to axial heat flow, and at peak neutron rate, ion temperature exceeded electron temperature.

The key results from the 1-D and 2-D *HYDRA* runs are compared in Table VII. End losses in terms of mass and heat are roughly 50% for 30-μm-thick shells and roughly 40% for 20-μm-thick shells; Eq. (22) gives 60% and 55%, respectively, assuming 200-eV preheat. The combined effect of the loss in temperature and density leads to a 53-fold reduction in neutron yield for the 30-μm-thick shells and a 14-fold reduction for 20-μm-thick shells, based on the 1-D neutron yield for the 0.5-mm-long region of the shell that is being uniformly driven. If we were to consider some effective neutron-emitting length from the 2-D results, the comparison to 1-D would be more favorable because, by whatever measure, the core is shorter than the compressed region of the shell.

Axial profiles of area-averaged fuel density and temperature at peak neutron rate, as fractions of the 1-D results (see Fig. 15) show considerable axial gradients; only density remains roughly constant across the central 0.4 mm, with a slight dip in the center caused by the central peak in the temperature. These profiles show that heat loss is slightly greater than mass loss, as would be expected from the combined effects of axial flow and thermal conduction; this is not seen in the neutron-averaged ion temperature because it is strongly weighted by temperature. The overall heat loss from the central 0.5 mm is 58% for 30-μm-thick shells and 49% for 20-μm-thick shells, and the mass loss is 53% for 30 μm and 43% for 20 μm. The axial asymmetries arise from the axial gradients in the preheat temperature (see Fig. 14), and from the flows to which this leads, and differ for 30-μm and 20-μm targets because of the different implosion times.

Axial profiles of the radially integrated magnetic field (*BR*) at peak neutron rate, as fractions of the 1-D results (see Fig. 16) show similar behavior to the density profiles in Fig. 15, but with a slightly greater reduction in moving from 1-D to 2-D because of axial magnetic diffusion, which also leads to a more-uniform profile near the center. The overall loss in the radially integrated magnetic field over the central 0.5 mm in moving from 1-D to 2-D is 56% for the 30-μm-thick shells and 48% for the 20-μm-thick shells, indicating that end losses can be as significant for the magnetic field as radial diffusion, which led to a roughly 40% loss. A similar trend would also be expected for loss related to the Nernst term, which was not included. The magnitude of *BR* is, as expected, far too low to give measurable confinement of charged fusion products, but it is sufficient to give measurable deflections in proton radiography.

Neutron yields of about 10^9 or greater are required to be able to determine a neutron-averaged ion temperature on OMEGA, so 20-μm-thick shells should give adequate yields. Neutron yields as low as 10^5 can be measured on OMEGA, but with significant uncertainties.

One of the key objectives of the 1-D modeling was to match the convergence ratio of the Z point design, and the convergence ratios do not change significantly in 2-D. The implosion velocity is also only slightly lower in 2-D than 1-D, the reduction being caused by axial heat flow in the corona leading to lower drive pressure.

VII. SCALING UP TO MJ LASER ENERGY

The NIF Laser System can deliver up to 1.9 MJ of laser energy, so the potential of laser-driven MagLIF on the NIF is an obvious question, particularly as magnetization of NIF targets is being considered.[22] The NIF has roughly 10× less energy available than Z, so this would still be a smaller-scale MagLIF target, representing another step in understanding MagLIF scaling and the capability of laser-driven MagLIF.

To give an idea of the potential of laser-driven MagLIF on the NIF, and to see how laser-driven MagLIF scales, we followed an approach similar to Nora *et al.*:[23] increasing total drive energy in 1-D modeling of the 30-μm-thick shells by a factor f of up to 100, reaching roughly 1.6 MJ, while increasing all linear dimensions and laser pulse duration by factors of $f^{1/3}$ to keep laser intensity, laser energy per unit shell mass, shell aspect ratio, and fuel aspect ratio constant, maintaining 2.4 mg/cm^3 D_2 fuel density, 10-T axial magnetic field, and 200-eV preheat. The projected magnetic-field–generation capability for the NIF is up to 70 T using a solenoid, so 30 T should be possible with a pair of multi-turn coils; therefore we will also consider scaling up at 30 T.

We will not consider the practical details of magnetization, preheating, phase plates, laser energy variation with pulse duration, laser pointing, and laser absorption on the NIF. The principal issue with laser-driven MagLIF on the NIF would be the preheating beam, which would require diverting a NIF beam into a new beam port or, ideally, adding a new beam.

In the absence of changes in thermal losses and magnetic-field losses, implosion velocity, convergence ratio, final fuel temperature, and pressure should remain the same, leading to an $f^{4/3}$ increase in total yield (f in volume, $f^{1/3}$ in confinement time). We expect lower thermal losses as size increases, however, thereby increasing the temperature, which will lead to a lower convergence ratio and to a slightly lower implosion velocity, which will lower the final fuel pressure. We also expect lower magnetic-field losses as size increases, which will further contribute to an increase in temperature. If temperature scales as indicated by Eq. (8) and the increase in temperature does not lead to a reduction of implosion velocity and therefore final pressure, final temperature should scale as $f^{1/9}$ and convergence ratio as $f^{-1/18}$, leading to an $f^{5/3}$ scaling of total yield, assuming fusion reactivity $\langle \sigma v \rangle \propto T^4$, which is an adequate approximation for D_2 fusion at 2 to 3 keV, and assuming that confinement time decreases as $T^{-1/2}$ because of the increase in expansion velocity.

The scaling of total yield, neutron-averaged ion temperature, implosion velocity, and convergence ratio with scaling factor *f*, the increase in compression laser energy, is shown in Fig. 17, along with power law fits where these are adequate.

Total yield increases as $f^{1.4}$ at both 10 and 30 T, between the $f^{4/3}$ expected for fixed temperature and convergence ratio and the $f^{5/3}$ expected for temperature scaling according to Eq. (8) with fixed implosion velocity and final pressure. Temperature does increase roughly as $f^{1/9}$ at 30 T, at least initially, and slightly slower at 10 T, but there is a fall in implosion velocity, which leads to a fall in final pressure, so the fall in convergence ratio is faster than $f^{-1/18}$. The increase in total yield with scale factor is the same at 30 T as 10 T despite the faster increase in temperature and marginally slower fall in convergence ratio because the increase in fusion reactivity with temperature is slower for the higher temperatures reached at 30 T.

The significant drop in convergence ratio at $f = 100$—16 at 10 T and 14 at 30 T—indicates that the ideal parameters for laser-driven MagLIF on the NIF will differ from those given by this simple scaling, but determining them is beyond the scope of this work.

Increasing target size should reduce flux loss from the fuel caused by the Nernst term and resistive diffusion. Figure 18 shows that flux conservation increases with *f*; at 10 T, flux conservation more than doubles from 15% at $f = 1$ to 34% at $f = 100$; at 30 T it increases somewhat less, from 34% to 49%, just short of the 55% of the Z point design.

A key MagLIF parameter that is proportional to size is the radially integrated magnetic field in the fuel *BR*, which determines radial confinement of charged fusion products. The value of BR is shown as a function of f in Fig. 19. The values at $f = 100$ are still short of the 0.6 T m required for self-heating[2] and the 0.4 T m inferred from Z experiments,[5] even at 30 T, but they are high enough at 30 T to give a measurable increase in DT yield from D_2 fuel.[5] As a result magnetic confinement of fusion products could be studied on the NIF, which is a crucial aspect of magnetized inertial fusion.

VIII. CONCLUSIONS

A laser-driven equivalent of MagLIF experiments on Z is being developed on the OMEGA Laser System using a target roughly 10× smaller in linear dimensions. OMEGA experiments will provide the first experimental data on MagLIF scaling and a higher shot rate with better diagnostic access than Z.

The smaller OMEGA targets will not achieve magnetic confinement of charged fusion products because of the lower value of BR, and will suffer from greater thermal losses and a greater reduction in magnetic-field compression caused by resistive diffusion and the Nernst term.

We presented the point design process for laser-driven MagLIF on OMEGA, which led to the choice of a 0.3-mm-outer-radius, ≤ 30-μm-thick plastic (CH) shell, filled with up to 2.7 mg/cm^3 of D_2, with a 10-T axial magnetic field provided by MIFEDS,[12] preheated by a single OMEGA beam delivering 180 J in 1.5 ns and compressed by 40 OMEGA beams delivering a maximum energy of 15.8 kJ in 1.5 ns. The OMEGA target was designed to achieve an implosion velocity just over twice that used on Z, partially compensating for greater thermal and field losses, and a convergence ratio close to 25, as chosen for the Z point design. Two-dimensional modeling indicates that end losses of mass, heat, and magnetic field will be of the order of 50%. For a 20-μm-thick shell the 2-D modeling predicts a neutron yield of 1.45×10^9 and a neutron-averaged ion temperature of 1.85 keV, which would be measurable with existing neutron diagnostics on OMEGA.

The experimental campaign has already begun. To date we have carried out experiments on just preheating to determine the temperature achieved, experiments on compression of unmagnetized targets without preheat to optimize beam pointing and measure implosion velocities, and a few integrated shots. The results are being analyzed and will be published elsewhere.

Laser-driven MagLIF experiments could eventually be carried out on the NIF, but the drive energy would still be 10× lower than MagLIF experiments on Z. One-dimensional modeling indicated that the NIF could achieve at least 500× the neutron yield of OMEGA. With a 30-T initial axial magnetic field, it should also be possible to achieve measurable magnetic confinement of charged fusion products on the NIF.

Laser-driven MagLIF experiments could potentially be carried out at an even smaller scale on the Gekko (Japan), Shenguang (China), Orion (UK), and Vulcan (UK) laser systems.

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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. M. M. Basko, A. J. Kemp, and J. Meyer-ter-Vehn, Nucl. Fusion **40**, 59 (2000).
3. 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).
4. 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).
5. 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).
6. S. A. Slutz, W. A. Stygar, M. R. Gomez, K. J. Peterson, A. B. Sefkow, D. B. Sinars, R. A. Vesey, E. M. Campbell, and R. Betti, Phys. Plasmas **23**, 022702 (2016).
7. R. D. McBride, S. A. Slutz, R. A. Vesey, M. R. Gomez, A. B. Sefkow, S. B. Hansen, P. F. Knapp, P. F. Schmit, M. Geissel, A. J. Harvey-Thompson, C. A. Jennings, E. C. Harding, T. J. Awe, D. C. Rovang, K. D. Hahn, M. R. Martin, K. R. Cochrane, K. J.

Peterson, G. A. Rochau, J. L. Porter, W. A. Stygar, E. M. Campbell, C. W. Nakhleh, M. C. Herrmann, M. E. Cuneo, and D. B. Sinars, Phys. Plasmas **23**, 012705 (2016).

8. S. A. Slutz and R. A. Vesey, Phys. Rev. Lett. **108**, 025003 (2012).

9. W. A. Stygar, T. J. Awe, J. E. Bailey, N. L. Bennett, E. W. Breden, E. M. Campbell, R. E. Clark, R. A. Cooper, M. E. Cuneo, J. B. Ennis, D. L. Fehl, T. C. Genoni, M. R. Gomez, G. W. Greiser, F. R. Gruner, M. C. Herrmann, B. T. Hutsel, C. A. Jennings, D. O. Jobe, B. M. Jones, M. C. Jones, P. A. Jones, P. F. Knapp, J. S. Lash, K. R. LeChien, J. J. Leckbee, R. J. Leeper, S. A. Lewis, F. W. Long, D. J. Lucero, E. A. Madrid, M. R. Martin, M. K. Matzen, M. G. Mazarakis, R. D. McBride, G. R. McKee, C. L. Miller, J. K. Moore, C. B. Mostrom, T. D. Mulville, K. J. Peterson, J. L. Porter, D. B. Reisman, G. A. Rochau, G. E. Rochau, D. V. Rose, D. C. Rovang, M. E. Savage, M. E. Sceiford, P. F. Schmit, R. F. Schneider, J. Schwarz, A. B. Sefkow, D. B. Sinars, S. A. Slutz, R. B. Spielman, B. S. Stoltzfus, C. Thoma, R. A. Vesey, P. E. Wakeland, D. R. Welch, M. L. Wisher, and J. R. Woodworth, Phys. Rev. ST Accel. Beams **18**, 110401 (2015).

10. O. V. Gotchev, P. Y. Chang, J. P. Knauer, D. D. Meyerhofer, O. Polomarov, J. Frenje, C. K. Li, M. J.-E. Manuel, R. D. Petrasso, J. R. Rygg, F. H. Séguin, and R. Betti, Phys. Rev. Lett. **103**, 215004 (2009); J. P. Knauer, O. V. Gotchev, P. Y. Chang, D. D. Meyerhofer, O. Polomarov, R. Betti, J. A. Frenje, C. K. Li, M. J.-E. Manuel, R. D. Petrasso, J. R. Rygg, and F. H. Séguin, Phys. Plasmas **17**, 056318 (2010).

11. O. V. Gotchev, J. P. Knauer, P. Y. Chang, N. W. Jang, M. J. Shoup III, D. D. Meyerhofer, and R. Betti, Rev. Sci. Instrum. **80**, 043504 (2009).

12. G. Fiksel, A. Agliata, D. Barnak, G. Brent, P.-Y. Chang, L. Folnsbee, G. Gates, D. Hasset, D. Lonobile, J. Magoon, D. Mastrosimone, M. J. Shoup, and R. Betti, Rev. Sci. Instrum. **86**, 016105 (2015).

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

14. M. G. Haines, Plasma Phys. Control. Fusion **28**, 1705 (1986).

15. E. M. Epperlein and M. G. Haines, Phys. Fluids **29**, 1029 (1986).

16. A. R. Bell, in *Laser Plasma Interactions 5: Inertial Confinement Fusion*, edited by M. B. Hooper, The Forty Fifth Scottish Universities Summer School in Physics (Taylor & Francis, New York, 1995), p. 139.

17. J.-Y. Hsu, K. Wu, S. K. Agarwal, and C.-M. Ryu, Phys. Plasmas **20**, 062302 (2013).

18. A. R. Bell, F. N. Beg, Z. Chang, A. E. Dangor, C. N. Danson, C. B. Edwards, A. P. Fews, M. H. R. Hutchinson, S. Luan, P. Lee, P. A. Norreys, R. A. Smith, P. F. Taday, and F. Zhou, Phys. Rev. E **48**, 2087 (1993).

19. A. J. Harvey-Thompson, A. B. Sefkow, T. N. Nagayama, M. S. Wei, E. M. Campbell, G. Fiksel, P.-Y. Chang, J. R. Davies, D. H. Barnak, V. Y. Glebov, P. Fitzsimmons, J. Fooks, and B. E. Blue, Phys. Plasmas **22**, 122708 (2015).

20. 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).

21. M. P. Desjarlais, Contrib. Plasma Phys. **41**, 267 (2001); M. P. Desjarlais, J. D. Kress, and L. A. Collins, Phys. Rev. E **66**, 025401 (2002).

22. L. J. Perkins, B. G. Logan, G. B. Zimmerman, and C. J. Werner, Phys. Plasmas **20**, 072708 (2013).

23. R. Nora, R. Betti, K. S. Anderson, A. Shvydky, A. Bose, K. M. Woo, A. R. Christopherson, J. A. Marozas, T. J. B. Collins, P. B. Radha, S. X. Hu, R. Epstein, F. J. Marshall, R. L. McCrory, T. C. Sangster, and D. D. Meyerhofer, Phys. Plasmas **21**, 056316 (2014).

FIGURE CAPTIONS

FIG. 1. Design drawing of the OMEGA laser-driven MagLIF scheme showing the coils, which are connected to MIFEDS; the entire target; target holder; fill tube, which will be connected to a pressure transducer; the preheat beam; and only two compression beams, from each ring for clarity.

FIG. 2. Axial magnetic field along the axis of the target for the initial coil design with the positions of the target (dark shaded area) and coils indicated (wire by red circles and plastic support by light shading). The dashed lines indicate the region that should be compressed.

FIG. 3. Change in total thermal conductivity (electron plus ion) perpendicular to a magnetic field with electron Hall parameter in a deuterium plasma given by the Braginskii[15] and Bohm[16] models, using $1/\left[1+(5/3)\chi\right]$ as an approximation for Bohm inhibition.

FIG. 4. (a) Fractional area of fuel free of window or wall plasma and (b) mean fuel temperature as functions of distance from the laser entrance window for a fuel density of 1.5 mg/cm^3 and a laser power of 0.12 TW at selected times.

FIG. 5. (a) Radial temperature and (b) density profiles across the middle of the clean region (1.5 mm from the laser entrance window) at 1.3 ns for a fuel density of 1.5 mg/cm^3 and a laser power of 0.12 TW.

FIG. 6. (a) Neutron yield and (b) convergence ratio versus fuel density for three sample pulse durations for a 30-μm-thick shell.

FIG. 7. Absorbed laser power, position of the outer surface of the fuel, and mean fuel ion temperature as functions of time for a 30-μm-thick shell with a fuel density of 2.4 mg/cm^3 driven by a 1.5-ns pulse. The straight line indicates how implosion velocity was defined, and the dot indicates the time of peak neutron rate used to define fuel convergence ratio.

FIG. 8. Ion temperature, density, and magnetic-field profiles in the fuel for the 30-μm-thick shell at peak neutron rate. The dashed lines give the results without the Nernst term included. The ion temperature is normalized to 3.40 keV, the density to 3.44 g/cm^3, and the magnetic field to 5.82 kT.

FIG. 9. Neutron yield versus preheat temperature for 0-, 10-, and 20-T axial magnetic fields for a 30-μm-thick shell.

FIG. 10. Yield, neutron-averaged ion temperature, implosion velocity, and convergence ratio as functions of axial magnetic field for no preheat and 200-eV preheat for a 30-μm-thick shell.

FIG. 11. Volume-averaged magnetic pressure divided by volume-averaged thermal pressure in the fuel at peak neutron rate as a function of axial magnetic field for no preheat and 200-eV preheat for a 30-μm-thick shell.

FIG. 12. Percentage of the magnetic flux retained in the fuel at peak neutron rate as a function of axial magnetic field for no preheat and 200-eV preheat for a 30-μm-thick shell.

FIG. 13. Density given by the 2-D *HYDRA* run for a 30-μm-thick shell at peak neutron rate.

FIG. 14. (a) Area-averaged electron and ion temperatures and (b) radial profiles of the electron and ion temperatures across the center of the target in the fuel at the end of the preheat beam from 2-D *HYDRA* for the 30-μm-thick shell case.

FIG. 15. (a) Area-averaged densities and (b) electron and ion temperatures at peak neutron rate from 2-D *HYDRA* as fractions of the 1-D results.

FIG. 16. Radially integrated axial magnetic fields in the fuel at peak neutron rate from 2-D *HYDRA* as fractions of the 1-D results, which were 0.038 T m for the 20-μm-thick shell and 0.042 T m for 30-μm-thick shell.

FIG. 17. The increase in total yield, neutron-averaged ion temperature, implosion velocity, and convergence ratio with energy scale factor f, including power law fits where appropriate, from 1-D *LILAC* MHD.

FIG. 18. Percentage of the magnetic flux conserved in the fuel at peak neutron rate as a function of energy scale factor f for axial magnetic fields of 10 and 30 T from 1-D *LILAC* MHD.

FIG. 19. Radially integrated magnetic field *BR* in the fuel at peak neutron rate as a function of energy scale factor *f* for axial magnetic fields of 10 and 30 T from 1-D *LILAC* MHD.

TABLES

Table I. Some key intrinsic parameters of the Z point design and Z experiments that should be matched as closely as possible by the OMEGA point design. The preheat temperature for the experiments is the mean value required to reproduce experimental results with a 2-D MHD code.[5,6]

Parameter	Z point design	Z experiments
Preheat temperature (eV)	250	~20
Fuel density (mg/cm^3)	3 (DT)	0.7 (D_2)
Axial magnetic field (T)	30	7 to 10
Implosion velocity (km/s)	70	≈70
Fuel convergence ratio	25	≈40
Peak temperature (keV)	8	≈3

Table II. Target dimensions for the Z point design, Z experiments, and those chosen for the OMEGA point design. Shell aspect ratio is the outer radius divided by shell thickness; fuel aspect ratio is length divided by inner radius. Larger values should give a better performance, but a large shell aspect ratio may lead to shell breakup during compression and a large fuel aspect ratio to loss of drive.

Target parameter	Z point design	Z experiments	OMEGA
Outer radius (mm)	3.48	2.79	0.3
Shell thickness (mm)	0.58	0.465	0.02 to 0.05
Length (mm)	5	7.5	0.5 to 0.7
Shell aspect ratio	6	6	6 to 15
Fuel aspect ratio	1.72	3.23	1.79 to 2.80

Table III. Preheating results from *DRACO* for a range of D_2 fuel densities (ρ) and laser powers (P) giving the mean temperature achieved before the fractional clean area goes below 0.9 and the times t and distances s from the laser entrance window at which this occurs.

ρ (mg/cm^3)	P (TW)	T (eV)	t (ns)	s (mm)
0.7	0.09	112	1.00	1.34
0.7	0.12	118	0.90	1.61
0.7	0.18	132	0.75	1.67
1.5	0.09	177	1.50	1.20
1.5	0.12	187	1.30	1.21
1.5	0.18	198	1.05	1.62
2.4	0.09	213	1.65	1.01
2.4	0.12	219	1.50	1.04
2.4	0.18	231	1.25	1.38

Table IV. Maximum energy on target per beam measured on OMEGA for square-shaped pulses of different durations, with SSD on, and the effective drive given by the peak, azimuthally averaged intensity on the target surface calculated for a single ring 4 (ten beams).

Pulse duration (ns)	1.0	1.5	1.8	2.0	2.5	2.7	3.0
Maximum beam energy (J)	450	395	380	360	295	270	260
Effective drive (10^{14} W/cm^2)	7.69	4.49	3.60	3.08	2.02	1.71	1.48

Table V. Pulse duration and fuel density that optimize neutron yield with a 10-T axial magnetic field and 200-eV preheat while maintaining a fuel convergence ratio of approximately 25 for each shell thickness with the neutron yields, peak ion temperatures, neutron-averaged ion temperatures, mean fuel implosion velocities, and fuel convergence ratios obtained from 1-D *LILAC* MHD.

Shell thickness (μm)	20	30	40	50
Pulse duration (ns)	1.5	1.5	1.8	1.8
Fuel density (mg/cm^3)	2.7	2.4	1.5	1.5
Neutron yield (10^{10} mm^{-1})	12.4	3.26	0.709	0.151
Peak ion temperature (keV)	4.27	2.85	2.34	1.72
Neutron-averaged ion temperature (keV)	3.36	2.28	1.82	1.34
Implosion velocity (km/s)	188	154	128	113
Fuel convergence ratio	27.3	25.5	24.6	22.8

Table VI. Pulse duration and fuel density that optimize neutron yield with a 30-T axial magnetic field and 200-eV preheat while maintaining a fuel convergence ratio of ~25 or less for each shell thickness with the neutron yields, peak ion temperatures, neutron-averaged ion temperatures, implosion velocities, and fuel convergence ratios obtained from 1-D *LILAC* MHD.

Shell thickness (μm)	20	30	40	50
Pulse duration (ns)	1.5	1.5	1.8	1.8
Fuel density (mg/cm^3)	2.0	2.4	2.0	1.5
Neutron yield (10^{10} mm^{-1})	27.3	9.26	2.62	0.888
Peak ion temperature (keV)	10.8	5.26	3.75	3.05
Neutron avgerage ion temperature (keV)	5.91	3.38	2.54	2.11
Implosion velocity (km/s)	196	158	128	114
Fuel convergence ratio	25.9	20.9	18.7	19.9

Table VII. Comparison of 1-D *HYDRA* results with 2-D *HYDRA* results for the point design. The numbers in parenthesis give the percentage of the 1-D result. The 1-D neutron yields assume a length of 0.5 mm. The convergence ratio in 2-D is obtained at the center. The compressed fuel density in 2-D is the average over 0.5 mm.

Shell thickness (μm)	20	20	30	30
Number of dimensions	1	2	1	2
Neutron yield (10^9)	17.0	1.22 (7.2%)	12	0.224 (1.9%)
Peak ion temperature (keV)	3.46	2.22 (64%)	3.11	1.52 (49%)
Neutron average ion temperature (keV)	2.54	1.73(68%)	2.30	1.27 (55%)
Implosion velocity (km/s)	205	168 (82%)	163	139 (85%)
Fuel convergence ratio	26.2	25.6 (98%)	27.3	26.5 (97%)
Compressed fuel density (g/cm^3)	1.81	1.03 (57%)	1.80	0.85 (47%)