Numerical Simulation of magnetized jet creation using a hollow ring of laser beams

Y. Lu, P. Tzeferacos, E. Liang, R. K. Follett, L. Gao, A. Birkel, D. H. Froula, W. Fu, H. Ji, D. Lamb, C. K. Li, H. Sio, R. Petrasso, and M. Wei

1 Department of Physics and Astronomy, Rice University, Houston, Texas 77005, USA
2 Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico, 87545, USA
3 Department of Astronomy and Astrophysics, University of Chicago, Chicago, Illinois 60637, USA
4 Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA
5 Princeton Plasma Physics Laboratory, Princeton, New Jersey 08540, USA
6 Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Dated: February 6, 2022)

Three dimensional FLASH magneto-hydrodynamics (MHD) modeling is carried out to interpret the OMEGA laser experiments of strongly magnetized, highly collimated jets driven by a ring of 20 OMEGA beams. The predicted optical Thomson scattering spectra and proton images are in good agreement with a subset of the experimental data. Magnetic fields generated via the Biermann battery term are amplified at the boundary between the core and the surrounding of the jet. The simulation predicts multiple axially aligned magnetic flux ropes with alternating poloidal component.

Future applications of the hollow ring configuration in laboratory astrophysics are discussed.

I. INTRODUCTION

Supersonic, well collimated outflows are ubiquitous in many astrophysical systems, such as young stellar objects (YSO), active galactic nucleus (AGN) and gamma-ray bursts (GRB). Despite various astronomical observations, theoretical studies, and numerical modeling of astrophysical jets, many fundamental questions remain, e.g. launching mechanism, composition, morphology of the magnetic field and stability. Magnetic fields permeate the universe, but their origin is not fully understood, especially in astrophysical jets. A variety of ideas have been proposed in which seed magnetic fields could be created. However, this mechanism has only been demonstrated in the laboratory recently.

With advances in large laser facilities, scalable laboratory experiments to study astrophysical phenomena have become achievable. Over the years, experiments have been performed to study astrophysics utilizing high-intensity lasers at the OMEGA laser facility at the Laboratory for Laser Energetics (LLF), and the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory as well as laser facilities in other countries. Laboratory produced jets with proper dimensionless parameters may provide an alternative platform to study the jets of astrophysical scales.

A new way of launching high density and high temperature plasma jets using multiple intense laser beams is to utilize the hollow ring configuration as proposed by Fu et al. It was demonstrated in two dimensional numerical simulations that a bundle of laser beams of given individual intensity, duration and focal spot size, produces a supersonic jet of higher density, temperature and better collimation, if the beams are focused to form a circular ring pattern on a flat target instead of a single focal spot. The Biermann Battery \( (\nabla n_e \times \nabla T_e) \) term can generate and sustain strong toroidal fields downstream in the collimated jet outflow far from the target surface. Those simulations were carried out in two dimensional cylindrical geometry, where the intensity variation along the ring due to individual laser beams were neglected. Three dimensional simulations are necessary to understand the formation and evolution of the jet in the actual experiments.

The ring jet experiments were designed and carried out on OMEGA laser facility in 2015 and 2016. We used 20 OMEGA beams to simultaneously irradiate the target forming a ring pattern. Each beam delivers 500J energy in 1ns. In this paper, we aim to use three dimensional FLASH simulations to explain the observed jet parameters in the experiments. Using the MHD results, we can predict the diagnostics outcomes from first principles. In Sec. we describe the experiment design to produce laboratory jets on the OMEGA laser and the simulation methods to model the experiment. Simulation results are discussed in Sec. The validation against a subset of experimental data is discussed in Sec.

II. SIMULATION METHODS

A. Non-ideal magneto-hydrodynamics in FLASH code

The FLASH code is used to carry out the detailed physics simulations of our laser experiments to study the formation and dynamics of the jet and the origin of magnetic fields. FLASH is a publicly available, multi-physics, highly scalable parallel, finite-volume Eulerian code and framework whose capabilities include: adaptive mesh refinement (AMR), multiple hydrodynamic solvers, implicit solvers for diffusion using the HYPRE library and laser energy deposition. FLASH is capable of using multi-temperature equation of states and multi-group opacities. Magnetic field generation via the Biermann battery term has been implemented and stud-
Table I: Target characteristics used in the experiments and the simulations

| Composition (number fraction) | Density  | Laser target | Ring radius |
|------------------------------|----------|--------------|-------------|
| C(50%) H(50%)                | 1.04g/cc | 0, 400, 800, 1200µm |
| C(49%) H(49%) Fe(2%)         | 1.21g/cc | 800, 1200µm |

Figure 1: The illuminated area on the target by 20 OMEGA beams. The transverse section of the beams are circles, but the spots on the target surface are ellipses due to inclination. The incident angle is 59° for blue spot, 42° for green spot, and 21° for red spot. (a) \( d = 400\) µm ring radius; (b) \( d = 800\) µm ring radius; (c) \( d = 1200\) µm ring radius. The \( d = 0\) case is not shown.

Note that the red and green spots form a 5-fold symmetry and the blue spots form a 10-fold symmetry.

We use the same FLASH code units as in [4] to solve the three-temperature non-ideal MHD equations. A cartesian grid with \((256 \times 256 \times 512)\) zones is used to resolve a \((3\) mm \(\times 3\) mm \(\times 6\) mm) domain, corresponding to \(~11\) µm per cell width. The number of cells we use is sufficient to resolve the spatial distribution of all the quantities that the plasma diagnostics are able to resolve in the OMEGA experiments. We did test runs at different resolutions, and the simulation converge at a cell with of \(~11\) µm. The plasma has zero initial magnetic field. The laser target is modeled as a 3mm diameter and 0.5mm thick disk with the composition listed in Table I. To model the material properties of the CH and CH+ dopant targets, we utilize the opacity and EoS tables computed with PROPACEOS [23]. We use the equation of state of helium in the chamber with initial density equal to \(2 \times 10^{-7}\) g/cc, which should have been vacuum. The helium does not affect the simulation significantly, as the mass, momentum and energy budget in the modeled helium is much less than 1%. To suppress the magnetic field from numerical artefact, we turn off the Biermann battery term and use the largest allowed magnetic resistivity in the explicit solver for each time step in the regions with density lower than \(2 \times 10^{-5}\) g/cm³. The electron heat conduction is calculated using Braginskii model [24] in weak magnetic field limit.

To model the laser driven blowoffs, we use the spatial and temporal specifications of each of the twenty OMEGA driver beams. The 20 driver beams are turned on and turned off simultaneously with a 1ns pulse duration. Each delivers 500J of energy on a target flat-top. The radius of each beam is 125µm. The laser spots are arranged to form a ring pattern of radius \(d\), as shown in Figure 1. The target is 0.5mm thick to prevent the burn-through. The setup of the diagnostics is sketched in Figure 2 and discussed in the following subsections.

For convention, \(t = 0\) is the time for laser turn on. The \(z\) direction is perpendicular to the surface of the target plane. The jet is formed in the \(z > 0\) region. We also use cylindrical coordinates where \(r = 0\) is the central axis of the target. The target surface is located at \(z = 0\). Axial direction is along \(z\) axis. Toroidal or azimuthal direction is the \(\varphi\) direction in the cylindrical coordinate system. Target chamber center(TCC) is at \(x = y = r = 0, z = 0.25\) cm.

B. Optical Thomson scattering

Optical Thomson scattering [25, 26] is used to probe the electron/ion temperatures, electron density and flow velocity at TCC. We used one probe beam with 1ns pulse, 25 ~ 50J energy and 532nm wavelength(\(2\omega\)) as the backlighter. The intensity distribution of the probe beam is 70µm FWHM 2D gaussian.

We model the Thomson scattering spectrum using the 3D FLASH simulation results. The spatial profiles of
electron density, electron/ion temperature, flow velocity, and fraction of species are taken as the input for the spectroscopy code [27]. The heating by the probe beam is modeled by laser absorption. The dispersion relations for ion acoustic wave and electron plasma wave [27] are used to calculate the power output. The final power output is weight averaged by the spatial intensity distribution of the probe laser. The instrument broadening [28] is taken into account in the modeling spectrum.

The experimental data are also fitted using the model (see more results in Gao et al. 2018) to compare with the plasma quantities averaged (200µm) cube centered at TCC.

C. Proton radiography

Our OMEGA experiments used two types of proton sources to map out the magnetic fields (1) DD(3MeV) and D³He(14.7MeV) protons from fusion reaction driven by 24 OMEGA beams [29, 30]. The actual spectrum is typically an up-shifted symmetric gaussian distribution, FWHM = 320keV centered at 3.6MeV for DD protons, FWHM = 670keV centered at 15.3MeV for D³He protons. The emitting position of protons follows a 3D gaussian distribution with e-fold radius equal to 20µm, and the burn time is 150ps [30]; (2) Broadband protons up to 60MeV are driven by an OMEGA EP beam via Target Normal Sheath Acceleration (TNSA) mechanism [31]. The actual spectrum is typically an exponential distribution with effective temperature 3.79MeV for our copper backlighter target [32]. The initial position of protons at the source follows a 3D gaussian distribution with e-fold radius equal to 5µm [30], and the pulse duration is 1ps. For the DD and D³He protons, the source stands 1cm from TCC, while the image plate CR39 is located 17cm from TCC on the other side. For the TNSA protons, the source stands 0.8cm from TCC, while the radiochromic film pack is located 16.5cm from TCC on the other side.

The modeling for proton radiography is composed of (1) sampling for the source distributions mentioned above, (2) solving the trajectory of the protons, (3) recording the protons on the detector plane.

The deflection of protons in electromagnetic fields is calculated by solving the Newton-Lorentz equation

\[
\frac{d(m_p v)}{dt} = e(E + \frac{v}{c} \times B)
\]  (1)

In a typical MHD fluid, \( E \approx \frac{v_h}{c} B \), where \( v_h \) is the hydrodynamical velocity scale of the fluid. The ratio of electric force to magnetic force is \( \frac{E}{v_h B} \approx \frac{v}{c} \). For a proton with energy larger than \( \sim \) MeV, the proton speed \( v_p \) is much larger than \( v_h \), so we use electric field \( E = 0 \) approximation in the modeling. The energy lost is calculated throughout the proton motion from the NIST PSTAR table [33]. Protons lose significant amount of energy in the remaining solid target with density \( \sim 1g/cc \).

We assume that the detector for DD protons has uniform sensitivity for protons with \( E > 2 \) MeV, and that for D³He protons has uniform sensitivity for all protons with \( E > 14.4 \) MeV. The TNSA proton energy range that each film is primarily sensitive to is \( E > E_0 \), and the deposited energy per proton is proportional to \( (E - E_0)^{-1/2} \), while no energy is deposited for \( E < E_0 \). The characteristic energy \( E_0 \) is different for each pack in radiochromic film. Temporal smearing of TNSA protons images is neglected because the pulse duration is short. Temporal smearing of DD and D³He protons is calculated using the integral of the second order interpolation among successive images with 0.1ns intervals.

III. FLASH SIMULATION RESULTS

A. Hydrodynamics

The jet is formed by the merging of the plasma plumes produced by 20 individual OMEGA beams through a strong cylindrical shock. By using a large ring radius, the flows will not collide immediately while the lasers irradiate the target. For the collision at later time with more available room, the flows develop larger radial velocities which become more supersonic. Thus a stronger cylindrical shock is generated near the z axis. For the cylindrical shock, the surrounding is in the upstream and the central core is in the downstream. It is a hydrodynamic shock where the plasma \( \beta \) is much larger than unity. Figure 3 shows the time evolution of the jet for \( d = 800\mu m \) CH target simulation. The jet is supersonic and well collimated. The jets with different ring radius all travel several millimeters by \( t = 3ns \). The jet keeps traveling and expanding so that the length \( L \) and the radius \( R \) keep growing even after 3ns. The width and the length of the jet are much larger than the laser spot size(250µm), as shown in Table I.

The properties of the jet become more interesting as the ring radius \( d \) increases. Figure 4 shows the shape of the jet for different laser ring radii at \( t = 3ns \). Figure 5 shows the evolution of electron/ion temperature, electron density and flow velocity at TCC for different runs in the FLASH simulation. The quantities are calculated by averaging over a \( (200\mu m)^3 \) cubic around TCC(\( r = 0, z = 0.25cm \)). The peak electron/ion temperature on-axis is higher for larger ring radius. Comparing to the case where \( d = 0 \), the temperatures for \( d = 800\mu m \) or \( d = 1200\mu m \) are about one order of magnitude higher. The peak electron density is highest for \( d = 800\mu m \), which is one order of magnitude higher than the \( d = 0 \) case. The ratio \( L/R \) of the jet becomes larger(see Table I) as \( d \) gets larger. Large ring radius also reduces the opening angle of the jet. The flow velocity is hardly affected by increasing \( d \). These results are in good agreement with previous 2D cylindrical hydrodynamics simulations by Fu et al. [14] using 2D FLASH. The simulations in this work are in 3D cartesian geometry. The full details of the laser
configuration are taken into account. In 3D simulations, even though there is the azimuthal asymmetry of the laser intensity on the target as shown in Figure [1], the jet is still well collimated and has similar hydrodynamical properties as in the 2D cylindrical case. The azimuthal asymmetry level for electron density can exceed 10%, and the pattern of density distribution in z-slice resembles a “sun flower” as shown in Figure [7].

The jet for 2% Fe dopant shot is slightly different than the one without dopant, as shown in Figure [6]. The jet in a dopant shot radiate several times more than that in a non-dopant shot. But the radiative cooling time at \( t = 3 \text{ns} \) for the jet is much larger than nanosecond even in the dopant shot. Thus, the radiation cooling (see Table [V]) has little to do with the shape of the jet after it has grown to millimeter size. For an earlier time, however, cooling rate is large enough to play a role. As a result, the electron temperature at TCC for doped jets is always lower than that in the non-doped jets with the same ring radius \( d \). The reduction in electron temperature relaxes the cylindrical shock. Thus, more electrons flow into the core, which causes the jets in dopant shots to have higher electron density than the non-dopant ones. In both doped and non-doped case, the jets are always optically thin.

A list of on-axis plasma properties from a snapshot in FLASH simulation results is listed in Table III using the snapshot for \( d = 800 \text{\mu m} \) case at \( t = 3 \text{ns} \). Other relevant physical terms can be deduced from the scales and dimensionless numbers in Table III. The plasma in the jet is fully ionized, i.e. \( A = 6.5 \) and \( Z = 3.5 \) for non-doped shots, \( A = 7.49 \) and \( Z = 3.95 \) for doped shots. The optical Thomson scattering diagnostics are simulated and discussed in Sec. [V.A]. By including laser energy deposition from the probe beam, the hydrodynamical variables in a small region of around \((100 \text{\mu m})^3\) will change significantly. This effect is significant for the analysis of diagnostics, but not of the main interest in the dynamical evolution of the jet.

### Table II: Comparison of plasma properties for different ring radii and targets at \( t = 3 \text{ns} \) and \( r = 0, z = 2.5 \text{mm} \). The \( n_e, \rho, T_e, T_i \) and \( B \) are calculated by averaging over a \((200 \text{\mu m})^3\) cubic around TCC. The jet length \( L \) is the defined by the point on the \( z \) axis where electron density drops to \( 3 \times 10^{18} \text{cm}^{-3} \). The radius \( R \) is defined by reading the position in \( z = 2.5 \text{mm} \) plane where the density scale height \( |\nabla \log \rho|^{-1} \) reaches minimum. Columns 2 to 5 are for pure CH targets. Columns 6 and 7 are for 2% Fe dopant targets.

| Plasma property | \( d = 0 \) | \( d = 400 \text{\mu m} \) | \( d = 800 \text{\mu m} \) | \( d = 1200 \text{\mu m} \) | \( d = 800 \text{\mu m} \) | \( d = 1200 \text{\mu m} \) |
|-----------------|-------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Electron density \( n_e \) \((\text{cm}^{-3})\) | \( 1.7 \times 10^{20} \) | \( 1.2 \times 10^{20} \) | \( 2.0 \times 10^{20} \) | \( 1.5 \times 10^{20} \) | \( 2.7 \times 10^{20} \) | \( 1.6 \times 10^{20} \) |
| Electron temperature \( T_e \) \((\text{eV})\) | 81 | 2.1 \times 10^4 | 5.1 \times 10^4 | 1.0 \times 10^4 | 3.9 \times 10^4 | 8.5 \times 10^6 |
| Ion temperature \( T_i \) \((\text{eV})\) | 76 | 2.2 \times 10^4 | 5.7 \times 10^4 | 1.4 \times 10^4 | 5.9 \times 10^4 | 2.4 \times 10^4 |
| Magnetic field \( B \) \((\text{gauss})\) | 2.4 \times 10^4 | 1.4 \times 10^4 | 3.3 \times 10^4 | 3.1 \times 10^4 | 3.5 \times 10^4 | 3.7 \times 10^4 |
| Jet width \( R \) \((\text{cm})\) | > 0.15 | 0.091 | 0.049 | 0.039 | 0.047 | 0.042 |
| Jet length \( L \) \((\text{cm})\) | 0.46 | 0.52 | 0.54 | 0.53 | 0.55 | 0.50 |
| \( L/R \) | < 3.1 | 5.7 | 11 | 13.6 | 11.7 | 11.9 |

### B. Magnetic fields

Without any initial magnetic fields, the seed magnetic field is generated via the Biermann battery term caused by the beam heating. The azimuthal asymmetry in the system is significant for the generation of seed fields. In Table III, the Hall number \( \Omega_H \) is much larger than the Biermann number \( \Omega_B \). The Hall term is zero if \( B = 0 \), so it does not generate seed fields. Thus the Hall term \((-\Omega \nabla \times \nabla T_e \times B / 4e\sigma n_e)\) is negligible in our system. Biermann battery term is the only source term in the generalized Ohm’s law that we calculate in FLASH simulation. Magnetic resistivity is also included in the computation. However, due to large magnetic Reynolds number, magnetic reconnection can hardly happen until later on in the MHD picture.

The generation and evolution of the axial dominant magnetic field is demonstrated in Figure [7]. Because of the radial temperature gradient (see Figure [7a]) and the azimuthal density gradient (see Figure [7b]), the Biermann battery term \((-\Omega \nabla \times \nabla T_e \times B / 4e\sigma n_e)\) is mainly in axial direction. Toroidal dominated magnetic fields are only generated near the surface of the target, where there is little azimuthal density gradient but large axial density gradient. At a millimeter above the target surface, the magnetic field is generated in the surrounding (the ring near \( r \approx 0.08 \text{cm} \) in Figure [7c]) and advected into the core (the central part of Figure [7d]). The shock amplifies the axial magnetic field by a factor of ~4 due to the flux conservation as the plasma flows from the surrounding to the core. The cylindrical shock makes the magnetic field highly concentrated as shown in Figure [7e]. Because the gradient of density alternates several times azimuthally, the generated axial field also alternates. The 5-fold symmetry in the field comes from the 5-fold symmetry in arranging the laser spots as shown in Figure [1]. The symmetry is slightly broken in the simulation due to the cubic cells and finite resolution. By using a larger ring of laser spots, the magnetic energy is more concentrated in the core of the jet as shown in Figure [9] and [10].
Table III: Simulated plasma properties for case $d = 800 \mu m$, $t = 3$ns at $z = 2.5$mm in non-dopant run. All quantities are in cgs units except temperatures expressed in eV. The length scale is $L$ approximately the width of the jet at $z = 2.5$mm, which is $L \approx 1$mm. The $n_e$, $\rho$, $T_e$ and $T_i$ at $r = 0$ are calculated by averaging over a $(200\mu m)^3$ cubic around TCC. The $n_e$, $\rho$, $T_e$ and $T_i$ at $r = 1$mm are calculated by averaging over a $200\mu m$ high and $200\mu m$ thick ring around $r = 1$mm, $z = 2.5$mm. $B$ is calculated using the root of mean square in the same cubic. The variation of $n_e$ is $\Delta n_e = \sqrt{n_e^2 - \bar{n}_e^2}$, similar for other variables.

| Plasma property                  | Formula                                      | Value at $r = 0$          | Value at $r = 1$mm          |
|---------------------------------|----------------------------------------------|---------------------------|-----------------------------|
| Electron density $n_e$ $(\text{cm}^{-3})$ | $\cdots$                                 | $2.0 \times 10^{20}$     | $3.0 \times 10^{20}$       |
| $\Delta n_e$ $(\text{cm}^{-3})$    | $\cdots$                                 | $1.5 \times 10^{19}$     | $4.1 \times 10^{18}$       |
| Mass density $\rho$ $(g/cm^3)$    | $\cdots$                                 | $6.3 \times 10^{-4}$     | $1.1 \times 10^{-4}$       |
| $\Delta \rho$ $(g/cm^3)$         | $\cdots$                                 | $4.7 \times 10^{-7}$     | $1.3 \times 10^{-5}$       |
| Electron temperature $T_e$ (eV)  | $\cdots$                                 | $5.1 \times 10^{4}$      | $3.9 \times 10^{4}$        |
| $\Delta T_e$ (eV)                | $\cdots$                                 | $1.2$                     | $1.4$                      |
| Ion temperature $T_i$ (eV)       | $\cdots$                                 | $5.7 \times 10^{4}$      | $1.8 \times 10^{4}$        |
| $\Delta T_i$ (eV)                | $\cdots$                                 | $1.2 \times 10^{4}$      | $1.7$                      |
| Magnetic field $B$ (gauss)       | $\cdots$                                 | $3.3 \times 10^{5}$      | $4.6 \times 10^{4}$        |
| $\Delta B$ (gauss)               | $\cdots$                                 | $1.5 \times 10^{5}$      | $3.0 \times 10^{4}$        |
| Average ionization $Z$           | $\cdots$                                 | $3.5$                     | $3.5$                      |
| Average atomic weight $A$        | $\cdots$                                 | $6.5$                     | $6.5$                      |
| Flow velocity $u \approx u_i$ $(\text{cm}/s)$ | $\cdots$                                 | $1.1 \times 10^8$        | $1.1 \times 10^8$          |
| $\Delta u$(cm/s)                | $\cdots$                                 | $3.2 \times 10^6$        | $3.2 \times 10^6$          |
| Perpendicular velocity $\sqrt{u_x^2 + u_y^2}$ $(\text{cm}/s)$ | $\cdots$                                 | $2.7 \times 10^6$        | $1.5 \times 10^6$          |
| Sound speed $c_s$ (cm/s)         | $9.8 \times 10^5[I_{\text{el}}^{1/2} + 1.67 T_i^{1/2}]^{1/2}$ | $2.0 \times 10^7$        | $1.6 \times 10^7$          |
| Mach number $M$                  | $u/c_s$                                    | $5.5$                     | $6.8$                      |
| Electron plasma frequency(rad/s) | $5.6 \times 10^4 n_{e,0}^{1/2}$            | $7.9 \times 10^{14}$     | $3.1 \times 10^{14}$       |
| Coulomb logarithm $\ln \Lambda$ | $23.5 - \ln(n_{e,0}^{1/2} T_{e,0}^{-3/4})^{-1} - [10^{-5} + (\ln T_e - 2)^2/16]^{1/2}$ | $6.9$                     | $7.5$                      |
| Electron thermal velocity $v_{Te}$(cm/s) | $4.2 \times 10^4 T_{e,0}^{1/2}$          | $9.5 \times 10^8$        | $8.3 \times 10^8$          |
| Electron collision rate $\nu_e$(1/s) | $2.9 \times 10^{-6} n_{e,0} \ln \Lambda T_{e,0}^{-3/2}$ | $3.5 \times 10^{11}$     | $8.5 \times 10^{10}$       |
| Electron-ionic collision rate $\nu_{ei}$(1/s) | $3.2 \times 10^{-9} Z A^{-1} n_{e,0} \ln \Lambda T_{e,0}^{-3/2}$ | $2.1 \times 10^8$        | $5.1 \times 10^7$          |
| Electron mean free path $l_e$(cm) | $v_{Te}/\nu_e$                            | $2.7 \times 10^{-3}$     | $9.8 \times 10^{-3}$       |
| Electron gyro-frequency $\omega_{ce}$(rad/s) | $1.7 \times 10^6 B$                       | $5.6 \times 10^{12}$     | $7.8 \times 10^{14}$       |
| Electron gyroradius $r_{re}$(cm) | $2.4 T_{e,0}^{1/2} B^{-1}$                | $1.6 \times 10^{-4}$     | $7.0 \times 10^{-4}$       |
| Ion thermal velocity $v_{Ti}$(cm/s) | $9.8 \times 10^4 A^{-1/2} T_{i,0}^{1/2}$  | $9.2 \times 10^6$        | $2.9 \times 10^6$          |
| Ion collision rate $\nu_i$(1/s) | $4.8 \times 10^{-8} Z A^{-1/2} n_{e,0} \ln \Lambda T_{i,0}^{-3/2}$ | $8.2 \times 10^{10}$     | $1.8 \times 10^{14}$       |
| Ion mean free path $l_i$(cm) | $v_{Ti}/\nu_i$                            | $1.1 \times 10^{-4}$     | $1.6 \times 10^{-8}$       |
| Ion gyro-frequency $\omega_{ci}$(rad/s) | $9.6 \times 10^6 Z B / A$                    | $1.7 \times 10^9$        | $2.4 \times 10^9$          |
| Ion gyroradius $r_{ri}$(cm) | $1.0 \times 10^4 A^{1/2} T_{i,0}^{1/2} B^{-1}$ | $5.3 \times 10^{-3}$     | $2.1 \times 10^{-2}$       |
| Plasma $\beta$                  | $\frac{2.4 \times 10^{-10} n_{e,0} (T_{e,0} + T_{i,0})}{\mu_0 n_{e,0}^2 T_{e,0}^{1/2} B^{-1}}$ | $75$                     | $3.8 \times 10^2$          |
| Kinetic energy/Thermal energy    | $\frac{\frac{1}{2} m v^2}{\frac{1}{2} m c^2 T_i}$ | $12$                     | $18$                       |
| Reynolds number $Rm$             | $uL/\eta \left( \eta = 3.2 \times 10^5 \frac{\kappa \ln \Lambda}{T_{e,0}^{1/2}} \right)$ | $1.6 \times 10^4$        | $1.0 \times 10^4$          |
| Magnetic Reynolds number $Re$    | $uL/\nu \left( \nu = 1.9 \times 10^{-19} \frac{\kappa \ln \Lambda}{A^{1/2} Z^2 n_{e,0} \ln \Lambda} \right)$ | $1.1 \times 10^4$        | $3.3 \times 10^4$          |
| Biermann number $Bi$             | $\frac{u_{ci} B}{ck_0 T_e}$                | $71$                     | $13$                       |
| Hall number $\Omega_H$          | $\frac{u_{ci} B}{ck_0 T_e R_e}$             | $1.3 \times 10^4$        | $1.4 \times 10^4$          |

The magnetic field is mostly axial near the $z$ axis and mostly toroidal near the surface of the target, as shown in Figure 7(f) and Figure 8. The width and the length of the field bundles grow with the jet. The maximum field strength reaches several hundred kilo-gauss. The maximum magnitude of magnetic field at $t = 3.6$ns increases with the radius $d$ of the laser ring, as shown in Figure 10. This is consistent with the 2D cylindrical simulation. However, the full three dimensional simulation predicts a magnetic field axial polarized and much stronger than those in the two dimensional cylindrical simulation. In the 2D cylindrical simulation, the laser intensity is azimuthally uniform, thus the Biermann battery term only has the toroidal component.
Table IV: Radiation properties of the jet at TCC for \(d = 800\mu m\) ring radius. The temperature and density are in Table II.

| Plasma property                              | Formula                                      | Value               |
|----------------------------------------------|----------------------------------------------|---------------------|
| Planck opacity \(\kappa_P (cm^2/g)\) for CH target | from PROPACEOS                               | \(1.8 \times 10^{-2}\) |
| Optical depth \(\tau\) for CH target         | \(\kappa_P \rho L\)                         | \(1.1 \times 10^{-6}\) |
| Cooling rate (1/s) for CH target             | \(0.72AZ^{-1}\kappa_P T_e^2\)              | \(3.2 \times 10^7\) |
| Planck opacity \(\kappa_P (cm^2/g)\) for 2% Fe dopant target | from PROPACEOS                               | \(3.9 \times 10^{-1}\) |
| Optical depth \(\tau\) for 2% Fe dopant target | \(\kappa_P \rho L\)                         | \(4.4 \times 10^{-6}\) |
| Cooling rate (1/s) for 2% Fe dopant target   | \(0.72AZ^{-1}\kappa_P T_e^2\)              | \(3.2 \times 10^7\) |

IV. DIAGNOSTICS MODELING AND COMPARISON TO EXPERIMENTS

A. Optical Thomson scattering spectrum

Although we can fit the optical Thomson-scattering spectrum using the theoretical spectrum to infer the temperatures, density, and flow velocity, the gradient of these quantities near TCC can affect the spectrum and mislead the interpretation. As shown in Table III, the variation of some quantities can exceed 10% and thus significantly alters the spectrum. Moreover, the \(2\omega\) probe beam can potentially heat the plasma near TCC. In our simulation, the heating effect and all the gradients are taken into account. Instead of directly comparing the deduced quantities with those predicted in Figure 5, we compare the synthetic spectrum with the data for experiment spectrum in Figure 11.

Figure 11(a) and (b) shows that the heating from the TS probe has a significant impact on the measured spectra. Although the energy in the probe beam (25 ∼ 50J) is low compared to the drive beams, the 70µm diameter focal spot results in an intensity of \(10^{15}\) W/cm². FLASH simulations are performed with and without the probe beam to study the impact of probe-beam heating. The locations of the TS peaks in the simulated spectra that included the probe beam are in much better agreement with the measured spectra. The effect is more pronounced for smaller ring radii because the electron temperature is lower, which leads to higher collisional absorption.

The background of the measured EPW spectrum comes from the bremsstrahlung radiation, which is not calculated in the simulation. The bremsstrahlung shape is apparent when the electron density is larger than \(\sim 10^{20}\) cm⁻³.

The agreement for IAW spectrum is excellent for \(d = 0\) when the heating is included, as shown in the first plot in Figure 11(a). However, for finite \(d\), the simulation always underestimates the width of the broadened line. The depth of the valley in the middle of the shape is corrected by including the heating effect, which can be explained by the increasing of the electron temperature from probe heating. The under-predicted width of the IAW spectrum indicates the under-predicted ion temperature. Because ions are not directly heated by the probe beam, we...
Figure 4: Three-slice plots for electron density at $x = 0$, $y = 0$ and $z = 0.01\text{cm}$ planes at $t = 3\text{ns}$ for four different ring radii $d$ in FLASH simulations. The unit is $\text{cm}^{-3}$. The scale is as same as Figure 5. The targets are CH. (a) $d = 0$, (b) $d = 400\mu\text{m}$, (c) $d = 800\mu\text{m}$, (d) $d = 1200\mu\text{m}$. Figure (c) here is as same as Figure 3(d).

also compare the ion temperature from fitting the IAW spectrum and the $(200\mu\text{m})^3$ averaged value in FLASH simulations in Figure 12.

One may argue that the reason for underestimating the IAW line width is the inaccuracy of the RAGE-like (it is so named because it is identical to the method implemented in the radiation hydrodynamics code RAGE\cite{34}) energy apportion in our modeling. The RAGE-like approach apportions the work term among the ions, electrons, and radiation field in proportion to the partial pressures of these components. It is physically accurate in smooth flow, but does not distribute internal energy correctly among the ions, electrons, and radiation field at shocks. For the finite $d$ case, strong and multiple shocks are presented. There are the shocks between the plumes generated by neighboring beams and the cylindrical shock surrounding the core. The core is usually a secondary downstream. The ion heating exists at all shocks, but is not calculated accurately using the RAGE-like approach. The electron temperature should be significantly overestimated if the energy apportion between electrons and ions is inaccurate. However, the comparison between the measured IAW spectrum and the synthetic spectrum with probe heating does not suggest any significant overestimation of electron temperature. The reason for this might be the usage of electron heat conduction in FLASH simulation, which mitigates the inaccuracy of energy apportion. The extra part of the ion thermal energy measured by IAW spectrum can only come from part of the kinetic energy in the axial bulk motion of the flow, since multiple shocks already convert the kinetic energy of radial and toroidal bulk motion into thermal energy, and the magnetic energy is little comparing to the thermal energy and the kinetic energy. For example, 10% of the bulk kinetic energy density at $t = 3\text{ns}$ and $z = 2.5\text{mm}$ corresponds to $k_BT_i = 0.1 \times \frac{m_u a^2}{2} \approx 2\text{keV}$. It is likely that the

Figure 5: The evolution of plasma variables at TCC for the six different runs in FLASH simulation. Four sub-figures share the time axis and legends. The quantities are calculated by averaging over a $(200\mu\text{m})^3$ cubic around TCC.
turbulence is developed from the flow velocity difference between the plumes generated from different laser spots due the laser intensity difference between these spots. The plasma has high Reynolds number, as shown in Table III. The kinetic energy in turbulent motion does not have to be dissipated into heat to make the IAW spectrum broader, as long as a significant amount of turbulent kinetic energy is cascaded down to a scale below the resolution of Thomason scattering, i.e., $\sim 100\mu$m. We will study the turbulence effect in a future work.

\section{Proton radiography}

The proton images are smeared by a few factors (1) Spatial smearing: the finite size of the proton source, which is $\sim 45\mu$m for the fusion protons and $\sim 5\mu$m for the TNSA protons; (2) Temporal smearing: the pulse duration of the proton source, which is $\sim 150$ps for fusion protons and 1ps for TNSA protons. The pulse duration $\Delta t$ causes the smearing at length scale $\Delta l \sim v\Delta t$, where $v$ is the characteristic speed of the plasma. For fusion protons, $\Delta l_x \sim 160\mu m$, $\Delta l_{x,y} \sim 13\mu m$, using the velocities in Table III. For TNSA protons with $E = 10$MeV, $\Delta l_x \sim 1\mu m$, $\Delta l_{x,y} \sim 0.15\mu m$; (3) Spectrum smearing: the energy variation $\Delta E$ of the source proton. Derived from Eq(16) in Graziani et. al.\cite{35}, the variation of deflection angle cause by $\Delta E$ is $\frac{\Delta E}{E}$ times the deflection angle. If there is only spectrum smearing, assuming the proton is shifted by $200\mu$m(=which is typical) seen in the TCC frame, it is expected that the $10.2$MeV TNSA protons with $\frac{\Delta E}{E} = \frac{3.79MeV}{2} = 1.895MeV$ resolve magnetic field at $\sim 20\mu m$, DD protons with $\frac{\Delta E}{E} = \frac{0.32MeV}{2} = 0.16MeV$ resolve magnetic field at $\sim 11\mu m$, and D$^3$He protons with $\frac{\Delta E}{E} = \frac{0.67MeV}{2×14.7MeV} = 0.04MeV$ resolve magnetic field at $\sim 5\mu m$. The energy gain or lost from the electric field is estimated to be less than 0.1MeV, which is negligible compare to the $\Delta E$ of the beam itself. Overall, our FLASH simulation is able to resolve a smaller spatial scale than the experiment.

The simulation of images predicts the features observed in the experimental data. To the lowest order the light and dark patterns correspond to the averaged MHD current($\nabla \times B$) projected along the light of sight\cite{35}. The alternating axial field filaments result in several vertical dark and bright strips. The curved horizontal strip close to the surface of the target is produced by the large loop of surface toroidal field. Figure 13 shows the comparison between the simulation synthetic and experimental D$^3$He proton images. Figure 14 shows the comparison between the simulation synthetic and experimental $10.2$MeV TNSA proton image. Figure 15 shows examples of the proton images for $d = 400\mu m$ and $d = 1200\mu m$ case. The good qualitative agreement between the synthetic images and the ones from experiment on the general trend of large scale features suggests that the magnetic field structures we predict using FLASH simulation are consistent with the structures in the experiments.

Nernst effect can affect the evolution of magnetic field\cite{36,37}. This might be the reason why there are some disagreements in small scale structure and sizes between the experimental data and the synthetic images. In Table III the product of the electron gyro-frequency $\omega_{ce}$ and electron collision time $\tau_e (= 1/\nu_e)$ is $\omega_{ce}\tau_e \sim 15$ at $r = 0$ and $\omega_{ce}\tau_e \sim 9$ at $r = 1$nm. The value $\omega_{ce}\tau_e > 1$ indicates that Nernst effect is important for our experiments. The MHD model with Nernst term will be implemented in FLASH in the future. We will make detail qualitative comparison in a future study with Nernst term included.
Figure 7: Slice plot of several quantities at $z = 0.1 \text{cm}$ for $t = 1.6 \text{ns}$. These figures demonstrate the generation and evolution of the axial dominant magnetic field with alternating polarity and 5-fold symmetry (a) Electron temperature(eV). The pattern is concentric circles. (b) Electron density($\text{cm}^{-3}$). The “sunflower-like” pattern has 5-fold symmetry due to the laser pattern. The symmetry is slightly broken due to finite number of cells in the simulation (c) $z$ component of Biermann battery term $\frac{\varepsilon}{4\pi} \nabla \times \nabla n_e = \frac{cE}{\pi} \nabla T_e \times \nabla n_e \text{ (kG/s)}$ (d) $z$ component of advection term $\nabla \times (v \times B) \text{ (kG/s)}$ (e) $z$ component of magnetic field(kG) (f) $\phi$ component of the magnetic field(kG).

V. CONCLUSIONS AND DISCUSSIONS

The FLASH simulation results were validated against a subset of experimental data from the OMEGA experiments. The creation of the jets and strong magnetic fields using the ring laser pattern is explained. 3D simulations reproduce some features in previous 2D cylindrical results[14, 15]. However, many new features emerges in 3D, e.g. the “sunflower” density pattern and the alternating para-axial magnetic field bundles. Some questions still remain, e.g. the under-prediction in the line width of IAW spectrum in Figure[11]. An accurate modeling for the magnetic fields requires implementation of Nernst effect in FLASH code. Simulations using higher resolutions are also desired. The XRFC modeling will be discussed in a future study.

The geometry of magnetic fields in our jets may be different from the generally believed models in many astrophysical context, e.g. the magnetic field of the jet along the axis of an accreting black hole[35], where the toroidal field supposedly dominates. However, much can still be learned about the magnetic effect on jet collimation, stability and structure in the laboratory. The characteristics of the magnetized jet can be well controlled by tuning the ring radius and increasing number of beams. By varying the hollow ring radius, laser and target properties, we can achieve a large dynamic range for the jet parameters, thus creating a highly versatile laboratory platform for laser-based astrophysics. By using the jets we created, shocks and shear flows can be studied with
Figure 8: Sample magnetic field lines (color scale unit: kG) for $d = 800$ cm, CH target. (a) at $t=1.6$ ns (b) at $t=3.6$ ns. The field far way from the target is mainly axial and the field close to the target is toroidal.

Figure 9: Three slice plot for magnetic field amplitude (unit: kG) at $x = 0$, $y = 0$ and $z = 0.1$ cm for different laser ring radius $d$ at $t = 1.6$ ns. The disk slice is at $z = 0.1$ cm with $0.3$ mm diameter. (a) $d = 0$ (b) $d = 400 \mu$m (c) $d = 800 \mu$m (d) $d = 1200 \mu$m

jet-jet collisions.

The hollow ring laser platform is also ideally suited to scale up to NIF with 192 beams and more energy per beam, creating centimeter-sized magnetized jets. The jets produced with the NIF platform will have several distinctive properties from OMEGA experiments, but are of key importance for astrophysical jet modeling. The higher temperature, density, flow velocity, and magnetic field will lead to large dimensionless parameters. A turbulence regime is possible. The longer pulse on NIF can sustain the jet for longer time, so that the radiative cooling for doped targets become significant and useful to make the aspect ratio larger. The aspect ratio can become large enough ($\gg 10$) that the stability study can become more relevant to astrophysics. The physical parameters of the jet can be tuned in such ways that various collisionless and collisional regimes of the plasma can be accessed. The dimensionless parameters for astrophysical jets may be better realized in the large scale jets of NIF. Magnetic field geometry may be tuned by increasing the number of beams.

VI. ACKNOWLEDGMENT

This research is supported by DOE grant DE-NA0002721. The research and materials incorporated in this work were partially developed at the National Laser Users' Facility at the University of Rochester's Laboratory for Laser Energetics (LLE), with financial support from the U.S. Department of Energy (DOE) under Cooperative Agreement DE-NA0001944. This work used the Extreme Science and Engineering Discovery Environment (XSEDE[39]), which is supported by National Science Foundation (NSF) grant number ACI-1548562. This research used resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. Additional simulations were performed at the Argonne Leadership Computing Facility.
Figure 10: Three slice plot for magnetic field amplitude (unit: kG) at $x = 0$, $y = 0$ and $z = 0.25$ cm for different laser ring radius $d$ at $t = 3.6$ ns. The disk slice is at $z = 0.25$ cm with 0.3 mm diameter. (a) $d = 0$ (b) $d = 400$ µm (c) $d = 800$ µm (d) $d = 1200$ µm.

and with Los Alamos National Laboratory institutional computing. YL and EL acknowledge partial support by LANL-LDRD during the writing of this paper. We also acknowledge the valuable discussions with Hui Li.

[1] S. Hirose, Y. Uchida, K. Shibata, and R. Matsumoto, Publications of the Astronomical Society of Japan 49, 193 (1997)

[2] A. Ferrari, Annual Review of Astronomy and Astrophysics 36, 539 (1998)

[3] R. Sari, T. Piran, and J. P. Halpern, The Astrophysical Journal 519, L17 (1999)

[4] P. Tzeferacos, A. Rigby, A. Bott, A. R. Bell, R. Bingham, A. Casner, F. Cattaneo, E. M. Churazov, J. Emig, N. Flocke, F. Fiuza, C. B. Forest, J. Foster, C. Graziani, J. Katz, M. Koenig, C.-K. Li, J. Meinecke, R. Petrasco, H.-S. Park, B. A. Remington, J. S. Ross, D. Ryu, D. Ryutov, K. Weide, T. G. White, B. Reville, F. Miniati, A. A. Schekochihin, D. H. Froula, G. Gregori, and D. Q. Lamb, Physics of Plasmas 24, 041404 (2017)

[5] P. Tzeferacos, A. Rigby, A. F. A. Bott, A. R. Bell, R. Bingham, A. Casner, F. Cattaneo, E. M. Churazov, J. Emig, F. Fiuza, C. B. Forest, J. Foster, C. Graziani, J. Katz, M. Koenig, C.-K. Li, J. Meinecke, R. Petrasco, H.-S. Park, B. A. Remington, J. S. Ross, D. Ryu, D. Ryutov, T. G. White, B. Reville, F. Miniati, A. A. Schekochihin, D. Q. Lamb, D. H. Froula, and G. Gregori, Nature Communications 9 (2018), 10.1038/s41467-018-02953-2

[6] B. A. Remington, Plasma Physics and Controlled Fusion 47, A191 (2005)

[7] J. M. Foster, B. H. Wilde, P. A. Rosen, R. J. R. Williams, B. E. Blue, R. F. Coker, R. P. Drake, A. Frank, P. A. Keiter, A. M. Khokhlov, J. P. Knauer, and T. S. Perry, The Astrophysical Journal 634, L77 (2005)

[8] A. Ciardi, S. V. Lebedev, A. Frank, E. G. Blackman, J. P. Chittenden, C. J. Jennings, D. J. Ampleford, S. N. Bland, S. C. Bott, J. Rapley, G. N. Hall, F. A. Suzuki-Vidal, A. Marocchino, T. Lery, and C. Stehle, Physics of Plasmas 14, 056501 (2007)

[9] A. Ciardi, S. V. Lebedev, A. Frank, F. Suzuki-Vidal, G. N. Hall, S. N. Bland, A. Harvey-Thompson, E. G. Blackman, and M. Camenzind, The Astrophysical Journal 691, L147 (2009)

[10] S. V. Lebedev, D. Ampleford, A. Ciardi, S. N. Bland, J. P. Chittenden, M. G. Haines, A. Frank, E. G. Blackman, and A. Cunningham, The Astrophysical Journal 616, 988 (2004)

[11] S. V. Lebedev, A. Ciardi, D. J. Ampleford, S. N. Bland, S. C. Bott, J. P. Chittenden, G. N. Hall, J. Rapley, C. Jennings, M. Sherlock, A. Frank, and E. G. Blackman, Plasma Physics and Controlled Fusion 47, B465 (2005)

[12] S. V. Lebedev, J. P. Chittenden, F. N. Beg, S. N. Bland, A. Ciardi, D. Ampleford, S. Hughes, M. G. Haines, A. Frank, E. G. Blackman, and T. Gardiner, The Astrophysical Journal 564, 113 (2002)
Figure 11: Comparison between the synthetic optical Thomson-scattering spectra based on FLASH simulations and the experimental data. The red solid line is the experimental data, the blue dotted line is the synthetic spectrum without probe beam heating, and the black dashed line is the synthetic spectrum with probe beam heating. (a) EPW spectrum at 3.6ns. (b) IAW spectrum at 3.9ns.

Figure 12: The data for ion temperature from fitting the IAW spectrum and the \((200 \mu m)^3\) averaged value in FLASH simulations, both at TCC .

[13] B. A. Remington, R. P. Drake, and D. D. Ryutov, Reviews of Modern Physics 78, 755 (2006).
[14] W. Fu, E. P. Liang, M. Fatenejad, D. Q. Lamb, M. Grosskopf, H.-S. Park, B. Remington, and A. Spitkovsky, High Energy Density Physics 9, 336 (2013).
[15] W. Fu, E. P. Liang, P. Tzeferacos, and D. Q. Lamb, High Energy Density Physics 17, 42 (2015).
[16] L. Biermann, Zeitschrift Naturforschung Teil A 5, 65 (1950).
[17] T. Boehly, D. Brown, R. Craxton, R. Keck, J. Knauer, J. Kelly, T. Kessler, S. Kumpan, S. Loucks, S. Letzing, F. Marshall, R. McCrorry, S. Morse, W. Sela, J. Soures, and C. Verdon, Optics Communications 133, 495 (1997).
[18] L. Gao et. al. to be submitted.
[19] B. Fryxell, K. Olson, P. Ricker, F. X. Timmes, M. Zingale, D. Q. Lamb, P. MacNeice, R. Rosner, J. W. Truran, and H. Tufo, The Astrophysical Journal Supplement Series 131, 273 (2000).
[20] FLASH4 is available at https://flash.uchicago.edu/.
[21] A. Dubey, K. Antypas, M. K. Ganapathy, L. B. Reid, K. Riley, D. Sheeler, A. Siegel, and K. Weide, Parallel Computing 35, 512 (2009).
[22] C. Graziani, P. Tzeferacos, D. Lee, D. Q. Lamb, K. Weide, M. Fatenejad, and J. Miller, The Astrophysical Journal 802, 43 (2015).
[23] PROPACEOS is available at http://www.prism-cs.com.
[24] S. I. Braginskii, Reviews of Plasma Physics 1, 205 (1965).
[25] D. H. Froula, J. S. Ross, L. Divol, and S. H. Glenser, Review of Scientific Instruments 77, 10E522 (2006).
[26] D. Froula, P. Davis, L. Divol, J. Ross, N. Mezzan, D. Price, S. Glenser, and C. Rousseaux, Physical Review Letters 95 (2005), 10.1103/physrevlett.95.195005.
[27] J. Sheffield, D. Froula, S. H. Glenser, and J. N. C. Luhmann, Plasma Scattering of Electromagnetic Radiation: Theory and Measurement Techniques (Academic Press, 2010).
Figure 13: Comparison of synthetic proton image with data recorded on CR39 for 14.7MeV protons. The color scales are the same for all images. The ring radius is $d = 800\mu m$. The target is CH without dopant. (a) synthetic image at $t = 1.6\text{ns}$, the corresponding three-slice plot of the field is in Figure 9(c). (b) experiment image at $t = 1.6\text{ns}$ (c) synthetic image at $t = 3.6\text{ns}$, the corresponding three-slice plot of the field is in Figure 10(c). (d) experiment image at $t = 3.6\text{ns}$. The CR39 image plate is $10cm \times 10cm$. On the plot, magnification is taken into account and the scale listed is in the plasma frame. In (a) and (b), upward is the $+z$ direction. In (c) and (d), upright is the $+z$ direction. The void region in below in (a) and (b), and bottom left corner in (c) and (d) is the target, which block the protons.

[33] The PSTAR table is available at [https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html](https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html)

[34] M. Gittings, R. Weaver, M. Clover, T. Betlach, N. Byrne, R. Coker, E. Dendy, R. Hueckstaedt, K. New, W. R. Oakes, D. Ranta, and R. Stefan, Computational Science & Discovery **1**, 015005 (2008).

[35] C. Graziani, P. Tzeferacos, D. Q. Lamb, and C. Li, Review of Scientific Instruments **88**, 123507 (2017).

[36] L. Gao, P. Nilson, I. Igumenshchev, M. Haines, D. Froula, R. Betti, and D. Meyerhofer, Physical Review Letters **114** (2015), 10.1103/physrevlett.114.215003

[37] L. Lancia, B. Albertazzi, C. Boniface, A. Grisollet, R. Riquier, F. Chaland, K.-C. L. Thanh, P. Melor, P. Antici, S. Buffechoux, S. Chen, D. Doria, M. Nakatsutsumi, C. Peth, M. Swantusch, M. Stadlbauer, L. Palumbo, M. Borghesi, O. Willi, H. Pépin, and J. Fuchs, Physical Review Letters **113** (2014), 10.1103/physrevlett.113.235001

Figure 14: Comparison of synthetic proton image with data recorded on radiochromic film for 10.2MeV protons. The color scales are the same for two images. The ring radius is $d = 800\mu m$. The target is CH without dopant. (a) three-slice plot at $x = 0, y = 0, z = 0.1cm$, magnetic field strength(kG) plot at $t = 1.9\text{ns}$ (b) synthetic image at $t = 1.9\text{ns}$ (c) experiment image at $t = 1.9\text{ns}$ from H4 pack. The image plate is a disk of 10cm. The scale and orientation is as same as Figure 13(a) and (b).

[38] K. Beckwith, J. F. Hawley, and J. H. Krolik, The Astrophysical Journal **678**, 1180 (2008)

[39] J. Towns, T. Cockerill, M. Dahan, I. Foster, K. Gaither, A. Grimshaw, V. Hazlewood, S. Lathrop, D. Lifka, G. D. Peterson, R. Roskies, J. R. Scott, and N. Wilkens-Diehr, Computing in Science & Engineering **16**, 62 (2014)
Figure 15: (a) three-slice at $x = 0, y = 0, z = 0.1$ cm, magnetic field strength (kG) plot at $t = 1.8$ ns for $d = 400$ µm (b) synthetic 3MeV proton image at $t = 1.8$ ns for $d = 400$ µm (c) experiment 3MeV proton image at $t = 1.9$ ns for $d = 400$ µm (c) three-slice at $x = 0, y = 0, z = 0.1$ cm, magnetic field strength (kG) plot at $t = 2.3$ ns for $d = 120$ µm (d) synthetic 14.7MeV proton image at $t = 2.3$ ns for $d = 1200$ µm (e) experiment 14.7MeV proton image image at $t = 2.3$ ns for $d = 1200$ µm. The scale and orientation of the image are as same as Figure 13(a) and (b). The color scales are the same for all images.