A Laboratory Astrophysical Jet Validation Test of the Radiation Hydrodynamics Capabilities of the FLASH Code

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The potential for laser-produced plasmas to yield fundamental insights into high energy density physics (HEDP) and deliver other useful applications can sometimes be frustrated by uncertainties in modeling the properties and behavior of these plasmas using radiation-hydrodynamics codes. In an effort to overcome this and to corroborate the accuracy of the HEDP capabilities that have been added to the publicly available FLASH radiation-hydrodynamics code, we present detailed code-to-code comparisons between FLASH and the HYDRA code developed at Lawrence Livermore National Laboratory using previously published HYDRA simulations from Grava et al. 2008. That study describes a laser experiment that produced a jet-like feature that the authors compare to astrophysical jets. Importantly, the Grava et al. 2008 experiment included detailed x-ray interferometric measurements of electron number densities. Despite radically different methods for treating the computational mesh, and different equation of state and opacity models, the FLASH results greatly resemble the results from HYDRA and, most importantly, the experimental measurements of electron density. Having validated the FLASH code in this way, we use the code to further investigate and understand the formation of the jet seen in the Grava et al. (2008) experiment and discuss its relation to the Wan et al. (1997) experiment at the NOVA laser.

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I. INTRODUCTION

The potential for laser experiments to yield fundamental insights into High-Energy-Density Physics (HEDP) is in many ways limited by the sophistication and accuracy of current-generation “three-temperature” (3T\textsuperscript{1}) radiation-hydrodynamics codes that simulate the heating, conduction and radiation of laser-irradiated fluids. In deconstructing the results from ultra-high intensity, short-pulse laser experiments, for example, Particle-In-Cell (PIC) simulations of the ultra-intense pulse interaction with the target may depend sensitively on radiation-hydrodynamics simulations of the heating and ionizing effect of stray “pre-pulse” laser energy in the nanoseconds before the arrival of the main pulse. It is not always possible to use interferometric instruments to measure electron number densities in the “pre-plasma” created by this pre-pulse, as the target geometry may not permit probe beams to access the pre-plasma, e.g., in cone targets as in Ref.\textsuperscript{1}, so the pre-plasma properties must be predicted using a radiation-hydrodynamics code. The uncertainties in these simulations may frustrate efforts to gain a better understanding of ion acceleration or electron transport that could prove to be valuable for a variety of applications, such as radiation therapy, x-ray generation, or the activation and detection of fissile materials.

Another important use of these codes is in modeling inertial confinement fusion experiments at laser facilities like Omega and the National Ignition Facility (NIF) \cite{2,3}. Rosen et al. \cite{4} describe some of the subtleties encountered in understanding indirect-drive experiments and a 2012 panel report by Lamb & Marinak et al. \cite{6} outlines a number of remaining uncertainties in simulating ignition-relevant experiments at NIF. Lamb & Marinak et al. \cite{6} emphasize the need for code-to-code comparisons and validation in a wider effort to reproduce the diagnostics of NIF implosions. Although there have been some recent investigations with other codes \cite{7,8}, the HYDRA code \cite{9,10}, developed at Lawrence Livermore National Laboratory (LLNL), is frequently used for radiation-hydrodynamics modeling of these experiments.

Uncertainties and inaccuracies in radiation-hydrodynamics modeling can also frustrate the design and interpretation of experiments to investigate fundamental plasma properties (e.g., opacities, equation

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\textsuperscript{1} We use the term “three-temperature” (or “3T”) to denote the approximation that electrons and ions move together as a single fluid but with two different temperatures, and that this fluid can emit or absorb radiation. In the 3T simulations presented in this paper, each cell has an electron temperature, an ion temperature, and radiation energy densities in a number of photon energy bins.
of state, hydrodynamic instabilities) at HEDP-relevant densities and temperatures [12–14]. Both Omega and NIF, among other facilities, have completed a number of experiments in this category, and will continue to do so in the future [15, 16].

With these concerns in mind, and in an effort to confirm the accuracy of the HEDP capabilities of the FLASH radiation-hydrodynamics code [17–19], we compare the predictions of FLASH to previously-published results from nanosecond laser irradiation of an Aluminum target and previously published modeling of this experiment using the HYDRA code [20]. FLASH is a finite-volume Eulerian code that operates on a block-structured mesh using Adaptive Mesh Refinement (AMR) [21], whereas the HYDRA code uses an Arbitrary-Lagrangian-Eulerian (ALE) scheme to determine the computational grid [22–24], which can deform and stretch in response to the movement and heating of the fluid. In other respects the codes are very similar in that they use a tabulated Equation of State (EOS) and make many of the same assumptions regarding laser propagation and absorption as well as various aspects of the hydrodynamics. The simulations in this paper were performed with FLASH 4-beta [25] with an added Lee-More conductivity and thermal equilibration model [26]. The Lee-More model became part of the publicly available version of the code starting with FLASH 4.2.2 [27].

We show results for an experiment in which a target consisting of an Al slab with a mm-long triangular groove is irradiated by a rectangular laser beam. The results of this experiment, which is translationally invariant along the groove and so is a test of plasma expansion in 2D Cartesian geometry, were modeled with HYDRA simulations in Grava et al. 2008 [20], hereafter referred to as GRAVA. They investigated this problem for its resemblance to astrophysical jets where radiative cooling plays an important dynamical role, and as a miniature version of similarly-motivated experiments at the Nova laser by Wan et al. [28] (hereafter WAN) and [29]. The experiment was performed at Colorado State University and, importantly, GRAVA present x-ray interferometric measurements of electron density in the blowoff plasma. GRAVA conducted these measurements with a few-ns cadence using soft x-rays with a wavelength of 46.9 nm. This implies a critical density of $5 \times 10^{23}$ cm$^{-3}$; however, taking into account instrumental resolution and other details, the largest measurable electron density is reported to be $5 \times 10^{30}$ cm$^{-3}$.

GRAVA pursued the experiment as a scaled version of astrophysical radiative shocks, explaining that the radiative energy loss timescale in the problem, $\tau_{\text{rad}}$, is comparable to hydrodynamic expansion timescale, $\tau_{\text{hydro}}$. They were also motivated by the fact that similar, earlier NOVA experiments produced puzzling results, raising the question whether radiation-hydrodynamics codes might be inadequate to model the experiment and collisionless Particle-In-Cell (PIC) codes might be needed instead [WAN]. GRAVA and later work by the same collaboration [31, 32] showed that radiation-hydrodynamic codes are able to model this kind of experiment, and for a variety of different target elements.

### II. COMPARISON TO GRAVA ET AL. 2008

In this section, we describe code-to-code comparisons between FLASH and HYDRA for an experiment that was carried out at Colorado State University and modeled using HYDRA (GRAVA). The GRAVA study is unique in both the quality of the experimental data that was collected and the sophistication of the radiation-hydrodynamics modeling that was done. In the experiment, an Al target with a V-shaped groove was irradiated by a rectangular laser beam striking the target perpendicularly to its face. The intensity of the laser beam had a Gaussian cross section with a FWHM of 360 $\mu$m.

#### A. Non-Radiative Results: Electron Number Density

GRAVA presents the results of HYDRA simulations with and without multi-group radiation diffusion to demonstrate the importance of radiation on their simulation results. We use GRAVA's non-radiative HYDRA simulations as the starting point for our comparison, since it removes any dependence on the opacity model. We performed FLASH simulations using the PROPACEOS EOS model [30] which included physics from the so-called QEOS model [35] for near-solid-density
interactions. Figure 1 compares the results of the FLASH simulation and the HYDRA simulation, which also used QEOS in its tabulated EOS. The comparison shows that the results of the two simulations agree qualitatively. Specifically, there are no important features in the FLASH simulations that are not in the HYDRA simulations, and vice versa; and many of the contours from the simulations bear a remarkable resemblance to each other.

B. Results including Radiation: Electron Number Density

Radiating plasmas can be compressed to higher densities than non-radiating plasmas because the loss of energy cools the plasma, lowering the pressure. This is evident in comparing Figs. 1 and 2. Fig. 1 shows the spatial distribution of the electron number density at four different times for HYDRA and FLASH simulations without radiation transport and Fig. 2 shows the same information for HYDRA and FLASH simulations with radiation transport. Also shown in Fig. 2 is the spatial distribution of the electron number density from experimental measurements (left panel). In both figures the ablating plasma is colliding with itself at 1.1 ns, creating a relatively thin jet of high density, high temperature Al extending from center of the groove in the target. In Fig. 1 the jet expands due to the high pressure, thus creating the double horn feature seen there at later times. However in Fig. 2 the jet stays compressed for longer so that...
at 4.6 ns the width of the jet is only modestly larger. Only by 9.7 ns has ablation from the diagonal walls of the target lessened enough that the pressure can broaden the jet and produce the double horn structure in the density similar to what is seen in Fig. 1. For a more extreme example of the effect of radiation in this problem see the Cu or Mo results in [32].

Despite the possibility of important differences arising from the implementation of flux-limited, multi-group diffusion and/or the opacity models used, the FLASH and HYDRA radiative results shown in Fig. 2 agree about as well as do the non-radiative results shown in Fig. 1. Importantly, both codes agree well with the experimental data.

To provide a quantitative comparison, we compare in Fig. 3 the width of the jet as a function of time as measured in the experiment and given by the FLASH and HYDRA simulations. As the width of the jet, we take the distance between the most steeply rising features in the electron density along a line perpendicular to the laser axis centered at (0,0). This definition is convenient for measuring the jet width from the figures in GRAVA, since a line perpendicular to the laser axis that is centered at (0,0). This definition is convenient for measuring the jet width from the figures in GRAVA, since the point of steepest rise is simply where the electron number density contours are closest together. We assign to the HYDRA results in Fig. 3 an error bar of width ± 2.5 μm, which is the typical distance between the two closest contours. We measure the width of the jet derived from the interferometric measurements in the same way. As our estimate of the error bars for the interferometric jet width, we take roughly half the distance between the fringes (±7.5 μm), except at 1.1 ns when the jet is still forming. The true resolution of the interferometric data may be slightly finer than indicated in Fig. 3 although, in principle, a slight misalignment of the laser on target would be an additional source of uncertainty [32]. The width of the jet in the FLASH simulations can be inferred in a precise way using the above definition and at a large number of times.

Fig. 3 shows that the width of the jet as a function of time that is given by the HYDRA simulation is somewhat closer to the experimental width derived from the interferometry than that given by the FLASH simulation, which slightly under predicts the width of the jet at 4.6 ns and after. The reason for this is unclear. Interestingly, FLASH and HYDRA both over predict the width of the jet at the first measurement at 1.1 ns.

C. Results including Radiation: Electron Temperature and Mean Ionization State

Fig. 4 compares the electron temperatures in FLASH and HYDRA at the same times reported in Figs. 1 & 2. In comparing these results, it is important to note that the interface between the expanding Al plasma and the He is visible at 1.1 ns and 2.6 ns. The Z contours in Fig. 4 show that at this boundary the plasma goes from a region where Al is significantly ionized to a region where Z can at most be equal to two. As a result, the narrow region of closely spaced contours corresponding to this transition moves steadily away from the target; by 4.6 ns the transition has left the grid. Fig. 4 indicates that at 1.1 ns the He temperatures rightward of the interface are somewhat higher in the FLASH simulation than in the HYDRA simulation. This difference could stem from a difference in how key physical processes are handled in this very low density region, including the non-equilibrium (i.e. \( T_{\text{ele}} \neq T_{\text{ion}} \)) nature of the shock. More prosaically, the He density assumed but not reported in GRAVA may simply be higher than what we assumed for the FLASH simulation (which was \( \rho = 5 \cdot 10^{-7} \text{ g/cm}^3 \)).

In the expanding Al plasma leftward of this Al/He interface, the results of the FLASH and HYDRA simulations are again qualitatively similar, with \( T_{\text{ele}} \) being slightly higher at 1.1 ns in the FLASH simulation than in the HYDRA simulation. The plasma is slightly more ionized in the FLASH simulation than in the HYDRA simulation, due to some combination of this slightly higher \( T_{\text{ele}} \) and possible differences between the EOS models. The \( Z \) contours in Fig. 4 are consistent with an overall difference of \( \Delta Z \sim 1 \) between the results of the two simulations. A closer look at the FLASH output at 1.1 ns reveals that this is true for the highest ionization state as well, and we find some regions where \( Z \sim 11 \). Both FLASH and HYDRA simulations agree that the mean ionization state never reaches \( Z \sim 12 \), which would require much higher temperatures. GRAVA states that the highest mean ionization state in their HYDRA simulation is \( Z \sim 10 \), and that this result is confirmed by the absence of signatures of more-highly-ionized charge...
FIG. 4: Comparing electron temperatures in radiation-hydrodynamics simulations from HYDRA (left column) to results from FLASH (right column); the FLASH simulation uses PROPACEOS opacity and EOS data. Contours for the mean ionization state, \( \bar{Z} \), are over plotted. HYDRA panels are adapted with permission from Fig. 6 in GRAVA with permission (copyrighted by the American Physical Society).

states in extreme UV spectroscopy.

The contours of \( \bar{Z} \) can be used as another measure of the width of the jet versus time to quantify the level of agreement in Fig. 4. Aluminum ablating from the walls expands and collides with plasma flowing outward on axis, creating peaks in \( T_{\text{ele}} \) and \( \bar{Z} \) just above and below the axis of the laser beam instead of on axis. This produces the double-horned features in \( T_{\text{ele}} \) and \( \bar{Z} \) seen in Fig. 4 prior to 5 ns. The distance between the peaks in \( \bar{Z} \) can be measured on a line perpendicular to the laser axis centered at (0,0). The FLASH measurements (green points) come from the \( \bar{Z} \) contours in Fig. 4, which are derived from GRAVA Measurements from the FLASH simulation (solid blue line) are presented at finely spaced intervals in time.

FIG. 5: A quantitative comparison of jet width versus time as measured from the distance between the peaks in the mean ionization state (\( \bar{Z} \)) on a line perpendicular to the laser axis that is centered on (0,0). The HYDRA measurements (green points) come from the \( \bar{Z} \) contours in Fig. 4, which are derived from GRAVA Measurements from the FLASH simulation (solid blue line) are presented at finely spaced intervals in time.

D. Results including Radiation: Total Pressure

Fig. 6 compares the total plasma pressure at early times in the FLASH and HYDRA simulations with radiation. While FLASH and HYDRA use EOS models that are related to or are the same as the QEOS model constructed by More et al. [33], the implementations are clearly somewhat different. In HYDRA the total pressure at solid density, i.e. well into the target, is vanishingly small, as one expects for a cold solid. FLASH uses the
III. FORMATION AND PROPERTIES OF THE JET IN THE GRAVA EXPERIMENT

The GRAVA experiment had two objectives: (1) to obtain data that would make possible an important additional validation test of radiative hydrodynamics codes in the wake of the apparent failure of LASNEX simulations to reproduce a similar experiment done using the Nova laser [34] and (2) to create a jet analogous to astrophysics jets, following Stone et al. [29]. Having validated FLASH for the GRAVA experiment, we now use FLASH simulations to better understand the formation and properties of the jet. We focus on early times (≤ 1.1 ns) and to inform our discussion we use comparisons between (1) the FLASH simulations of this experiment presented earlier in Sec. II (2) a FLASH simulation involving a flat Al target irradiated by the same rectangular laser beam used in the GRAVA experiment, and (3) a FLASH simulation using the same laser beam with a V-shaped groove but with the inner ±75 µm section of the target removed. This latter configuration resembles an earlier experiment done by WAN in which two slabs with a gap between them were oriented perpendicular to each other and irradiated by beams of the NOVA laser. GRAVA cites this experiment as an important motivation for their work.

A number of questions arise in drawing parallels between the self-colliding, ablating plasma in GRAVA and astrophysical jets. While in both the astrophysical and laboratory context the radiative cooling timescale may be similar in magnitude to the hydrodynamic expansion timescale (and therefore the adiabatic cooling timescale), how similar are these situations in other respects? Here we address three specific questions about the formation and properties of the jets seen in the laser experiments whose answers enable us to compare them with astrophysical jets:

1. What determines the physical conditions (e.g., the density, temperature, and velocity) in the core of the jet?

2. Is the collimating effect of the plasma ablating from the angular sides of the groove due to thermal pressure, i.e., the internal energy of the ablating plasma, or ram pressure, i.e., the component of the momentum of the ablating plasma perpendicular to the mid-plane of the experiment?

3. Does the collimation of the flow by the plasma ablating from the angular sides of the groove and the entrainment of this plasma in the resulting jet increase or decrease the velocity of the jet?
FIG. 7: Lineouts along the laser axis of the component of the velocity parallel to the laser axis at various times. The thick solid lines show results from the FLASH simulation of a V-shaped groove target described in Sec. §II. These thick solid lines become dotted lines at the point where the cell material is mostly very low density He instead of Al. Thin solid lines (which become dashed lines at the Al/He transition) show the same measurements from a simulation where a flat target of the same material is irradiated with the GRAVA laser pulse.

FIG. 8: Lineouts along the laser axis of the component of the velocity parallel to the laser axis at various times. The thick solid lines show measurements from the FLASH simulation of a V-shaped groove target described in Sec. II. These thick solid lines become dotted lines at the Al/He transition. Thin solid lines (which likewise become dashed lines at the Al/He transition) show the same measurements from a simulation where, similar to the target geometry of WAN, a large gap of material is missing from the center of the V-shaped groove. This target is irradiated by the GRAVA laser pulse.

A. What determines the physical conditions in the core of the jet?

Figures 3 and 5 show that the width of the jet at early times (≤1.1 ns) is similar to the width of the rounded region at the center of the V-shaped groove which is relatively flat and relatively perpendicular to the laser beam illuminating the target. The incident laser beam has a Gaussian cross section with a FWHM of 360 µm which implies that most of the laser energy is deposited within ±100 µm of the laser axis. Accordingly, the intensity of the laser beam will be much greater on the relatively flat portion in the middle of the V-shaped groove than on the sides of the groove. In this way, the interaction near the center of the groove resembles the simple case of an Al slab (i.e. flat) target. If the physical mechanism producing the jet is the same in for both the V-shaped groove and slab target then one would expect that the velocity at various locations along the core of the jet should be similar in the two cases.

To investigate this possibility, we compared lineouts of the velocity along the mid-plane for the two problems at five relatively early times; i.e., ≤1.1 ns. These are shown in Fig. 7. Ignoring the very high (v_z ≥ 350 km/s) velocities of very low density gas and focusing on v_z ≤ 350 km/s, the velocity profiles for the two problems agree closely at all five times, supporting our conjecture that the mechanism producing them is the same. The differences seen between the two simulations at very high velocities (v_z ≥ 350 km/s) are at very low densities and near or
approaching the transition from cells that are mostly Al to cells that are mostly very low-density He. This transition is marked by a change in line type from thick solid to dotted lines for the V-shaped target or from thin solid to dashed lines for the flat target. Because the He serves only as an approximation to vacuum conditions, the results near this very low-density interface are not relevant to the questions we are concerned with in this section.

We also compared the lineouts of the velocity along the mid-plane for the Al target with a V-shaped groove to a target consisting of two Al slabs oriented perpendicular to each other with a gap between them, similar to the WAN experiment. This comparison allows us to contrast the properties of the jet produced by a V-shaped groove that has a relatively flat portion near the mid-plane and one that does not. Figure 3 shows the results of the simulation for the V-shaped groove target and that for the WAN-like target. As in Fig. 7 the change from a solid line to a dotted or dashed line indicates the transition from mostly Al to mostly He. Focusing on the thin and thick solid lines that correspond to Al target material, the two velocity profiles differ greatly. The absence of a relatively flat portion of the target near the mid-plane means that formation of the jet is delayed until the plasma ablating from the sloping sides of the target has had time to meet at the mid-plane. Furthermore, the velocity profile of the jet is much shallower and its maximum velocity is much smaller. These results provide further support for the hypothesis that the physical mechanism producing the jet in GRAVA is the same as in the slab problem.

Figure 2 compares lineouts of the density along the mid-plane for the V-shaped groove target (thick solid lines) and a flat Al slab target (thin solid lines), while Fig. 10 compares the same measurement from the V-shaped groove target simulation (thick solid lines) to results from a target consisting of two Al slabs oriented perpendicularly to each other with a gap between them (thin solid lines), similar to the WAN experiment. As in Figs. 7 and 8 these lines become dotted or dashed when the cells are mostly He instead of Al.

Clearly, ablation from the sloping sides of the V-shaped groove confines the flow, as discussed by WAN and GRAVA, greatly increasing the density in the jet relative to the density in the case of the flat Al slab target, where the flow can expand laterally as well as away from the surface of the target. Collimation of the flow by the plasma ablating from the sloping sides of the V-shaped groove in GRAVA raises the question of whether the collimation is due primarily to thermal pressure or to ram pressure. We now address this question.

B. Is the collimating effect of the plasma ablating from the angular sides of the groove due to thermal pressure or ram pressure?

To address this question, we calculate the ratio of the specific kinetic energy,

$$e_{\text{kin}} = \frac{1}{2}|\vec{v}|^2$$  \hspace{1cm} (1)

to the total specific internal energy,

$$e_{\text{int}} = e_{\text{ele}} + e_{\text{ion}}.$$  \hspace{1cm} (2)

If $e_{\text{kin}}/e_{\text{int}} \gg 1$, the kinetic energy of the ablation flow is dominant. On the other hand, if $e_{\text{kin}}/e_{\text{int}} \ll 1$, the internal energy due to the temperature of the plasma is dominant.

Figure 11 shows the ratio $e_{\text{kin}}/e_{\text{int}}$ throughout the computational domain at six different times for the V-shaped groove target, while Fig. 12 shows the same quantity at the same times for the target comprised of two slabs oriented perpendicularly to each other with a gap in between, similar to the WAN experiment. Figure 13 compares the these measurements at 1.1 ns to measurements from the simulation of a flat Al slab target, In Figs. 11-13 we see a similar behavior: even at very early times, in the plasma very near the target, the internal energy of the plasma dominates the kinetic energy of the bulk flow away from the target, but further out the kinetic energy of the bulk flow dominates the internal energy. Once the laser turns off, the region where the kinetic energy of the bulk flow dominates the gas internal energy begins to grow substantially larger.

Examining the properties of the ablation flow as it approaches the mid-plane, we see that the internal energy of the plasma dominates at distances $< 50 \mu m$ from the target, but the kinetic energy of the bulk flow dominates at all larger distances. This indicates that the collimation of the jet is due primarily to ram pressure except very near the target, where it is due primarily to thermal pressure of the hot plasma.

The plasma in the jet is heated when the plasma ablating from the sloping sides of the target in both the GRAVA and the WAN-like experiments collides in the center, converting kinetic energy to thermal energy. This process is simplest in the 28 target and this collision produces a low ratio of $e_{\text{kin}}/e_{\text{int}}$ along the center.

The GRAVA target simulation shown in Fig. 11 has a more complex structure to $e_{\text{kin}}/e_{\text{int}}$ than the other cases. Material from the target collides in the center, but there is also material originating from the middle of the V-shaped groove that is moving rapidly away from the target. The result is a complex lateral structure within the jet in which $e_{\text{kin}}/e_{\text{int}}$ is large in the core of the jet and small at its edges, and large again in the ablating plasma above and below the jet. This is the origin of the double-horn structure evident at very late times in the electron density, which can be seen in Figs. 14 and in the ionization state, which can be seen in Figs. 15.
While the complex lateral structure of the jet in these experiments is comparable to astrophysical jets, it differs in that the ratio $e_{\text{kin}}/e_{\text{int}}$ in astrophysical jets is expected to be large in the core of the jet and progressively smaller values further away from the jet axis with $e_{\text{kin}}/e_{\text{int}} \to 0$ in the ambient medium [e.g. 35].

C. Does the ablation from the angular sides of the groove increase or decrease the velocity of the jet?

We are now in a position to address whether the ablating plasma from the angular sides of the groove in the target increases or decreases the velocity of the jet. A key piece of information is that the velocity of the jet is much smaller in the WAN-like experiment in which the target is two Al slabs oriented perpendicular to each other with a gap in between than in the GRAVA experiment in which the target is an Al slab with a V-shaped groove in it. We can now understand the reason why from the answer we obtained to the previous question. The energy density of the ablating plasma is dominated by its bulk kinetic energy by the time it approaches the mid-plane, except at very small distances ($< 50 \, \mu m$) from the target. The component of the momentum of the ablating plasma that is perpendicular to the mid-plane will go into heating the jet, while the component parallel to the mid-plane will add to the velocity of the jet. However, because the laser intensity is much lower away from the mid-plane, due both to the profile of the laser beam and the slanted angle of the surface of the groove, the specific internal energy (i.e., the internal energy per gram)
FIG. 11: Plotting the ratio of $e_{\text{kin}}/e_{\text{int}}$ at various times for the FLASH simulation of the V-shaped groove described in Sec. II. The original target location is shown with a white line. The transition from mostly Al to mostly He cells is indicated with a solid black line in each panel.

generated by the component of the momentum of the ablating plasma when the ablating plasma collides with the jet, and the specific component of the momentum of the accreting plasma parallel to the mid-plane (i.e., the momentum per unit mass) are both smaller than in the jet flow itself, which is generated by the most intense part of the laser beam illuminating the nearly flat part of the groove near the mid-plane. This suggests that the entrainment in the jet of the plasma ablating from the sloping sides of the groove will decrease slightly the velocity of the jet compared to the velocity along the mid-plane of the freely expanding plasma in the case of a slab target. This expectation is consistent with the results shown in Figure 11.

IV. CONCLUSIONS AND SUMMARY

We compared the results of FLASH hydrodynamic simulations to previously-published experimental results and HYDRA simulations for the irradiation of a mm-long V-shaped groove cut into an Al target GRAVA. Importantly, these experiments, conducted at Colorado State University, included soft x-ray interferometric measurements of the electron density in the Al blowoff plasma as a powerful validation test. We performed these FLASH simulations without the exact same EOS and opacity models that were used in the previously published HYDRA simulations. Instead we used a commercially available PROPACEOS EOS and opacity model [30] that included QEOS physics for near-solid-density fluids [33].

In all cases the FLASH results greatly resemble the results from HYDRA and, most importantly, the experimental measurements of electron density. This includes the properties of the underdense Al blowoff plasma, which matters most for the use of these codes in calculating pre-plasma properties as initial conditions for PIC simulations of ultra-intense, short-pulse laser-matter interactions (e.g., [4]). This result is encouraging for the wider HEDP community since FLASH is a “user” code that is freely available to the academic community. It is also encouraging because FLASH uses a finite-volume Adaptive Mesh Refinement (AMR) scheme that makes it
FIG. 13: Plotting the ratio of $e_{\text{kin}}/e_{\text{int}}$ at 1.1 ns for three different FLASH simulations: (Top) the V-shaped groove simulation described in Sec. II, (middle) results from a V-shaped groove with a gap as in [WAN] (bottom) results from a FLASH simulation of a flat target that is likewise irradiated by the [GRAVA] laser pulse. In each plot the original target location is shown with a thick white line. The transition from mostly Al to mostly He cells is indicated with a solid black line in each panel.

Having validated the FLASH simulations for the Al target with a V-shaped groove, we used these and other FLASH simulations to better understand the formation and properties of the jet in the experiment. We show that the velocity of the jet is produced primarily by the heating of the target in the relatively flat region of the V-shaped groove at the mid-plane, as in standard slab targets. We show that the jet is collimated primarily by the ram pressure of the plasma that ablates from the sloping sides of the groove. Further, we find that the interaction of the plasma ablation from the sloping sides of the groove with the jet produces the observed complex lateral structure in it, a structure that is comparable to astrophysical jets but differs significantly from them, quantitatively. Finally, we show that the entrainment in the jet of the plasma ablation from the sloping sides of the groove slightly decreases the velocity in the jet compared to the velocity along the mid-plane of the freely expanding plasma in the case of a slab target.

In this work we validated the FLASH code for a specific, previously-published experiment on laser-irradiated Al plasmas. Similarly high-quality interferometric data also exists for C, Cu and Mo [31, 32], which can be used in future efforts to validate the HEDP capabilities in FLASH.

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