Experiment to Form and Characterize a Section of a Spherically Imploding Plasma Liner

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(AInvited Paper)

Abstract—We describe an experiment to form and characterize a section of a spherically imploding plasma liner by merging six supersonic plasma jets that are launched by newly designed contoured-gap coaxial plasma guns. This experiment is a prelude to forming a fully spherical imploding plasma liner using many dozens of plasma guns, as a standoff driver for plasma-jet-driven magneto-inertial fusion. The objectives of the six-jet experiments are to assess the evolution and scalings of liner Mach number and uniformity, which are important metrics for spherically imploding plasma liners to compress magnetized target plasmas to fusion conditions. This paper describes the design of the coaxial plasma guns, experimental characterization of the plasma jets, six-jet experimental setup and diagnostics, initial diagnostic data from three- and six-jet experiments, and the high-level objectives of associated numerical modeling.

Index Terms—Plasma applications, Plasmas

I. INTRODUCTION

Spherically imploding plasma liners formed by merging supersonic plasma jets are a proposed low-cost, high-shot-rate, standoff driver for plasma-jet-driven magneto-inertial fusion (PJMIF) [1]–[3]. Magneto-inertial fusion (MIF) [4]–[6] seeks to achieve fusion at ion densities intermediate between those of magnetic and inertial fusion, by combining attributes of both the latter approaches. The primary near-term objective of the Plasma Liner Experiment (PLX) [2], [7] is to demonstrate the formation of spherically imploding plasma liners by merging dozens of supersonic plasma jets, and to demonstrate their viability and scalability toward reactor-relevant energies and scales.

The PLX facility was built in 2010–2011 at Los Alamos National Laboratory (LANL) to study plasma-liner formation via merging supersonic plasma jets [2], [8]. From 2011–2014, PLX utilized parallel-plate mini-railguns [9]–[12], designed and built by HyperV Technologies Corp., in a series of experiments [7] to study single-jet propagation [13], two-jet oblique merging [14], [15], and two-jet head-on merging [16]. These experiments, with the aide of associated numerical modeling [14], [17], led to the following key results of relevance to the physics of plasma-liner formation: (1) confirmation of plasma-jet parameters, and characterization of their evolution and profiles, during approximately 1 m of jet propagation away from the railgun nozzle [13], (2) identification and characterization of collisional-plasma-shock formation between two obliquely merging plasma jets [14], [15], largely consistent with hydrodynamic oblique shock theory, and (3) the role of rising mean-charge-state $Z$ in keeping the dynamics between merging jets in a collisional regime (because of the $Z^{-4}$ dependence of the counterstreaming ion–ion mean free path) [16]. In parallel, additional theory and modeling efforts examined plasma-liner radial convergence and scalings in one dimension (1D) [18]–[22], and the effects of discrete jet merging on plasma-liner convergence in 3D [23]–[25].

Collectively, these prior studies set the stage for the present PLX-$\alpha$ project, which is named after the Accelerating Low-cost Plasma Heating and Assembly (ALPHA) program of the Advanced Research Projects Agency–Energy (ARPA-E) that sponsors the ongoing research. The primary objective of PLX-$\alpha$ by the end of the ALPHA program is to form and study a fully spherical imploding plasma liner with at least 36 and up to 60 merging plasma jets (Fig. 1) that are launched by newly designed coaxial plasma guns fabricated by HyperV Technologies Corp., which is now owned by new fusion startup HyperJet Fusion Corporation. Development of novel, $\beta > 1$ (where $\beta$ is the ratio of thermal-to-magnetic pressure) magnetized plasma targets [26] for PJMIF is at a nascent stage and discussed elsewhere [2], [27], [28]. In future experiments involving plasma-liner compression of magnetized plasma targets, we envision using a subset of the same coaxial guns (that form the liner) to form an inertially confined dense plasma target ($\sim 10^{18}$ cm$^{-3}$), and to potentially magnetize the target ($\beta > 1$, $\omega\tau \gtrsim 1$, where $\omega\tau$ is the Hall magnetization parameter) using laser beat-wave current drive [27], [28].

The remainder of this paper is organized as follows. Section II describes the design of the new PLX-$\alpha$ coaxial plasma guns and experimental data characterizing the plasma jets that they launch. Section III describes the motivation, experimental/diagnostic setups, and initial diagnostic results of three- and six-gun experiments (a predecessor to the spherical plasma-liner-formation experiments using 36–60 guns). Section IV provides a brief overview of the PLX-$\alpha$ numerical-modeling objectives. Finally, Sec. V provides a summary and description of future plans.
TABLE I
REQUIRED AND ACHIEVED ARGON PLASMA-JET PARAMETERS OF THE NEW PLX-α COAXIAL PLASMA GUNS. DETAILS REGARDING THE MEASUREMENT OF JET PARAMETERS ARE GIVEN IN SEC. II-C.

| Parameter   | Required  | Achieved       |
|-------------|-----------|----------------|
| Density     | \( \approx 2 \times 10^{16} \text{ cm}^{-3} \) | \( > 2 \times 10^{16} \text{ cm}^{-3} \) |
| Mass        | > 1 mg    | 0.47 ± 0.11 mg |
| Velocity    | \( \geq 50 \text{ km/s} \) | 52.5 ± 5.1 km/s |
| Length      | \( \leq 10 \text{ cm} \) | 16 ± 5.7 cm   |

II. PLX-α COAXIAL PLASMA GUNS

New contoured-gap coaxial plasma guns were designed and fabricated for the PLX-α project. The rationale for the contoured-gap coaxial-gun concept with pre-ionized mass injection for launching high-mass, high-density jets to \( > 50 \text{ km/s} \) was previously laid out in a series of seminal works [29]–[31]. The design of the new PLX-α coaxial guns was governed by the need to achieve particular plasma-jet performance parameters to meet requirements of the PLX-α project (see Sec. II-A), while establishing a basis for a gun design that could be further developed and scaled up to become fusion relevant.

A. Plasma-jet requirements

Plasma-jet requirements were determined largely based on the desire to build the lowest-cost experiment that would allow studies of plasma-liner formation and convergence in reactor-relevant physics limits inferred from the parameter regimes studied in [31]. These limits are: (1) plasma-jet merging occurs in the collisional limit, i.e., the jet interpenetration depth is small compared to the jet radius, (2) the plasma equation-of-state (EOS) has sufficient ionization and excitation states to provide a significant energy sink (including strong radiative losses) compared to the thermal energy of the jet, and (3) the plasma flow is strongly supersonic, i.e., the sonic Mach number \( M \equiv V_{\text{jet}}/C_s \geq 10 \), where \( V_{\text{jet}} \) is the directed jet speed and \( C_s \) the jet internal sound speed. Requirements (1) and (3) lead to minimum allowable jet density and velocity, respectively. Requirements (2) and (3) necessitate the use of heavier species such as Ar, Kr, or Xe, though we use lighter elements as well for establishing a scaling database. Table I summarizes the required and achieved plasma-jet parameters of the PLX-α guns. Further discussion of the achieved plasma-jet parameters is presented in Sec. II-C.

B. Coaxial-gun design

To fulfill these requirements, we exploited prior HyperV gun-development efforts that had already led to (1) linear railguns capable of achieving the plasma-jet parameters with regard to mass, density, and velocity [2], [10] and (2) coaxial guns with much lower current density that used ablative mass injection [31]. The new PLX-α guns essentially combine the plasma-jet performance and gaseous injection of the railguns with the coaxial electrode geometry of the coaxial guns.

Figure 2 shows a full-assembly drawing of the new PLX-α coaxial gun and its integrated pulsed-power module. We chose to mount the capacitors that drive the main gun-electrode discharge onto the back of each gun both to minimize inductance and to eliminate the complexity and cost of requiring many parallel transmission lines. Details of the electrodes (on the right side of the figure, hidden from view) are proprietary information of HyperJet Fusion Corporation. The contours on both the outer and inner electrode surfaces were designed based on a series of MACH2 [32] simulations that led to the desired, calculated plasma-jet parameters. The primary function of the contours is to eliminate the “blowby instability” [30], which must be avoided in order to accelerate high-mass jets.

The guns each have a fast gas valve (GV) mounted at the rear end of the inner electrode to minimize gas travel distance from the GV to the breech (i.e., the coaxial gap at the rear end

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**Fig. 1.** Illustration of the PLX-α experimental setup, which will ultimately have at least 36 and up to 60 (as shown) coaxial plasma guns mounted around a 2.74-m-diameter vacuum chamber. Shown are plasma guns with integrated capacitor banks and a spherically imploding plasma liner compressing a magnetized plasma target. The PLX-α project is focused on developing the plasma liner and is not addressing the plasma target.

**Fig. 2.** Illustration of the PLX-α coaxial gun with integrated pulsed-power components. See also Fig. 1.
of the gun) and also twenty tungsten “ignitor pins” (i.e., pre-ionizers, or PI) distributed uniformly in the azimuthal direction around the breech. The GVs are typically pressurized at up to 20 psig (for the three- and six-gun experiments described in Sec. III) using any gas or mixture available in a compressed-gas bottle (Ar has been our primary working gas, but we also use H₂, He, N₂, Ne, Kr, and Xe on PLX). Details of the GV and PI designs are proprietary information of HyperJet Fusion Corporation.

The gun firing sequence is as follows. All the capacitor banks are first charged to the desired voltages (see Secs. II-C and III-A for typical values). The GV is triggered first at \( t \approx -600 \mu s \) to fill the gun breech with neutral gas. Then the PI system is fired at \( t \approx -20 \mu s \) to ionize the gas fill, and finally the main gun bank is triggered (defined to be \( t = 0 \)) to accelerate the ionized plasma out of the coaxial gun. Gun performance can be tuned by varying the GV fill pressure, capacitor-bank voltages, and GV and PI trigger times.

C. Plasma-jet characterization

Experimental studies of single-plasma-jet performance were performed at HyperV Technologies in order to optimize jet performance, and to make progress toward meeting the requirements given in Table I. Jet reproducibility was assessed during this campaign, the gun fired correctly at the triggered time \( \approx -20 \mu s \) to ionize the gas fill, and finally the main gun bank is triggered (defined to be \( t = 0 \)) to accelerate the ionized plasma out of the coaxial gun. Gun performance can be tuned by varying the GV fill pressure, capacitor-bank voltages, and GV and PI trigger times.

III. PLX-α THREE- AND SIX-GUN EXPERIMENTS

The first phase of the PLX-α project, in addition to coaxial-gun development and testing at HyperV Technologies, also includes six-gun experiments at LANL (Fig. 4) in order to: (1) successfully operate six guns simultaneously as a demonstration of technical readiness to perform experiments using 36–60 guns for spherical plasma-liner formation, and (2) assess the effects of discrete jet merging on plasma-liner formation that could cause significant degradations from one-dimensional (1D) imploding-plasma-liner performance [3, 34]. These jet-merging effects include M-degradation due to: (1) successfully operate six guns simultaneously as a demonstration of technical readiness to perform experiments using 36–60 guns for spherical plasma-liner formation, and (2) assess the effects of discrete jet merging on plasma-liner formation that could cause significant degradations from one-dimensional (1D) imploding-plasma-liner performance [3, 34].

![Fig. 3. Interferometer (cm⁻²) and photodiode (arb.) signals vs. time (HyperV shot 201704251255) for transverse views across the plasma jet at various distances (as indicated in the legend) from the exit of the gun. The HyperV interferometer is a quadrature, heterodyne system using a 633-nm HeNe laser modulated at 110 MHz. The cart at the lower left holds the capacitors](Image 330x110 to 546x369)

![Fig. 4. Photograph (taken Jan. 31, 2017) of the PLX facility at LANL with six PLX-α coaxial guns mounted in a hexagonal pattern on a 2.74-m spherical vacuum chamber. The large port in the middle of the hexagon provides the launch positions of seven chords of a fiber-coupled, visible interferometer [see also Fig. 3(a)]. The cart at the lower left holds the capacitors](Image 66x108 to 282x265)
to shock heating and seeding of non-uniformities that could exacerbate deceleration-phase instabilities at the liner/target interface (in future, integrated liner-on-target experiments). The instabilities could lead to liner/target mix and reduce the overall effectiveness of plasma liners as a compression driver of magnetized plasma targets to fusion conditions.

A. Experimental and diagnostic setups

Figure 4 shows the six-gun configuration, i.e., a hexagonal arrangement with $24^\circ$ between adjacent guns. We can fire all six guns simultaneously or any arbitrary subset of them. We often fired two or three guns for better diagnostic access to and interpretation of plasma-shock evolution between adjacent merging jets.

Table II summarizes the specifications of the capacitor banks driving the six plasma guns. Each gun has an integrated capacitor bank (-5 kV, 575 µF, 7.2 kJ) driving the main electrode discharge. A separate capacitor bank (12 kV, 96 µF, 6.9 kJ) drives all six GV's of the six guns, and yet another separate capacitor bank (30 kV, 12 µF, 5.4 kJ) drives all six PI systems. A final capacitor bank (-30 kV, 6 µF, 2.7 kJ) drives the master-trigger (MT) system for all six guns. Typical operation on PLX has utilized -4.5 kV, 8.5 kV, 24 kV, and -28 kV for the gun-electrode, GV, PI, and MT banks, respectively.

All banks are switched by high-voltage, high-current spark-gap switches custom made by HyperV Technologies. Each 575-µF bank driving the gun electrodes consists of six separate sub-banks driven by six separate spark-gap switches. These switches (6 per gun, and 36 total for 6 guns) are triggered by the MT bank. The switches are pressurized to various static pressures with either Ar or Ar/N$_2$ (90%/10%) mixture (gun switches) or N$_2$ (GV, PI, and MT switches); the switch gases are purged for 15–30 s after each experimental shot. All switches are triggered by optically coupled signals that largely eliminate noise-induced misfires. Figure 5 shows sample electrical currents from the gun, GV, and PI banks for a three-gun experiment. Note the large imbalance for one of the GV currents; this is consistent with observed jet-to-jet imbalance leading to ongoing improvements in the GV design and power delivery, as discussed in Sec. III-B.4.

Diagnostics for the six-gun experiments are summarized in Table III. The twelve-chord, fiber-coupled, visible interferometer (using a 320-mW, 651-nm solid-state laser and upgraded from a previous eight-chord system [35], [36]) and broadband visible survey spectrometer have both been described in detail elsewhere [7], [13]. The survey-spectrometer detector (0.160 nm/pixel resolution at 510 nm) is now upgraded to a PI-MAX2 intensified charge-coupled-device (CCD) camera (1024 × 256 pixels, 16-bit dynamic range, typical exposure of 1–2 µs), and the collection optic has also been upgraded such that the diameter of the viewing chord at the positions of interest within the plasma is about 1 cm. Their setups (initially, using only seven of the twelve interferometer chords) are shown in Fig. 6(a). The high-resolution spectrometer is a 4-m
McPherson 2062DP, with 2400 mm\(^{-1}\) grating (1.52 pm/pixel at 480.6 nm), coupled to a Stanford Computer Optics 4 Quik E intensified-CCD camera (752 × 482 pixels, 10-bit dynamic range, typical exposure of 1 \(\mu\)s); plasma light is collected at a chamber window with two 2-in., 100-mm achromatic lenses [Fig. 6(b)] and transported to the spectrometer with a bifurcated 80 × 100-\(\mu\)m-core fiber bundle (so that two views can be recorded simultaneously). The diameter of the viewing chords at the positions of interest are about 1.5 cm. For the photodiode arrays, two channels of light are collected through 1-mm, 5/16-in.-deep pinholes near the end of each gun nozzle (Fig. 7), and transported through optical fibers (SH-4001) to a photodiode-array board that digitizes the signals at 100 MHz with 14-bit dynamic range. The light level received at the photodiode array board that digitizes the signals at 100 MHz with 14-bit dynamic range. The light level received at the photodiode array board that digitizes the signals at 100 MHz with 14-bit dynamic range. The light level received at the photodiode array board that digitizes the signals at 100 MHz with 14-bit dynamic range. The light level received at the photodiode array board that digitizes the signals at 100 MHz with 14-bit dynamic range.

### B. Initial diagnostic results

In this subsection, we present initial, sample results from key diagnostics from a series of three- and six-gun experiments; all shots reported here used argon. These were our first full experimental campaigns, and thus jet performance was not yet optimized. Furthermore, we operated well below peak powers/energies of our capacitor banks, as we were exploring parameter space and did not wish to push the limits of our systems yet.

1) **CCD-camera images**: Figure 8 shows time series of intensified-CCD camera images (from the single-frame DiCam Pro) from three- and six-gun experiments, showing the formation of “primary” shocks (due to merging of adjacent jets) and presumed “secondary” shocks (due to subsequent merging of the initial merged, shocked plasmas). Detailed prior diagnostic studies [14, 15] of plasma jets with similar densities and velocities showed, through quantitative diagnostic measurements and analyses, that what we are calling primary shocks is consistent with collisional oblique shocks forming along the merge plane of adjacent jets. Primary and secondary shocks were both also observed and studied in 3D hydrodynamic simulations [25].

2) **Photodiode arrays**: These provide measurements of \(V_{\text{jet}}\). Light is collected as shown in Fig. 7; a view dump eliminates pickup of stray light and reflections. Figure 9 shows sample photodiode and the inferred \(V_{\text{jet}}\) values. The latter are determined by dividing the distance (2 cm) by the time shift that maximizes the correlation between the two normalized photodiode signals from each gun. For the dataset presented in Sec. III-B, \(V_{\text{jet}}\) is generally in the range 30–45 km/s.

3) **Doppler spectroscopy**: This provides ion-temperature \(T_i\) measurements at the shock region between two merging plasma jets as depicted in Fig. 6(b). Figure 10(a) shows an example of the data from the CCD detector. Figures 10(b) and 10(c) show the data, instrumental-broadening profile, and the best fit to the data of a Gaussian convolved with the instrumental profile, for the secondary-shock and primary-
shock views, respectively. For the cases shown in Fig. 10, $T_1 = 6.0 \pm 0.13$ and $4.3 \pm 0.11$ eV at $t = 42 \mu s$ and $R = 20$ cm along the secondary and primary shock lines, respectively. Based on this time and viewing position, $T_1 = 6.0$ eV is likely indicative of $T_e$ of the secondary-shock plasma. We have also observed up to $T_i \sim 30$ eV (for argon) at the time ($t \approx 25$ $\mu$s) and spatial position ($R \approx 50$–60 cm) of the primary shock, but $T_i$ cools quickly (over $\sim 10$ $\mu$s) by equilibrating with electrons (full results on ion shock heating/dynamics for different gas species will be reported elsewhere). As discussed below in the survey-spectroscopy section, $T_e$ remains much colder throughout the primary and secondary shock-formation process.

Measurement of ion heating as an essential property of collisional plasma shocks [37] is an interesting study in its own right, which we are pursuing as part of a separate project on the experimental study of plasma shocks. Here, our interest in shock ion heating is to provide constraining data in order to properly assess its role in degrading the jet/liner interface. $M \sim C_s^{-1} \sim (T_e + T_i)^{-1/2}$. Because $T_e$ does not increase much throughout the jet-merging process [15], [16] (as well see survey-spectroscopy results below) due to strong thermal and radiative loss rates, ion heating dominates the $M$ degradation. The latter would lead to stronger liner spreading and is predicted to severely degrade the ability of the liner to suppress a magnetized target plasma to reactor-relevant fusion conditions [34]. Ongoing research using two-temperature ($2T$) hydrodynamic simulations (see Sec. IV-A) is investigating the role of ion shock heating on plasma-liner formation, convergence, and performance.

4) Multi-chord interferometry: Multi-chord interferometry is used to measure $\langle n_e \ell \rangle$ and to assess its variation across the spatial arc of the interferometer chords shown in Fig. 6(a). Figure 11(a) shows an example of $\langle n_e \ell \rangle$ for each of the seven chords vs. time. Figure 11(b) shows a comparison between $\langle n_e \ell \rangle$ ($t = 30 \mu s$, averaged over shots 1019–1032) and synthetic data from a 3D hydrodynamic simulation of the six-gun experiment (see Sec. IV-A for a description of the simulation). From the synthetic data, it can be seen that chords 1 and 5 are predicted to have the highest values of $\langle n_e \ell \rangle$, consistent with those chords intersecting the position of primary shocks [see Fig. 6(a)]. Similarly, chords 3 and 7 are predicted to have the lowest values of $\langle n_e \ell \rangle$, consistent with those chords intersecting the position of jets.

Two key, initial conclusions are drawn from the comparison between experimental and synthetic interferometry data: (1) very good agreement of the order-of-magnitude of $\langle n_e \ell \rangle$ gives us confidence in our knowledge of the jet parameters and leading-order accuracy of the simulations; and (2) poor agreement in the variation of $\langle n_e \ell \rangle$ vs. chord number is indicative of insufficient balance (in mass and/or velocity) among jets, and thus the symmetry seen in the synthetic data (e.g., between chords 1/5, 3/7, etc.) is not reproduced in the experiment. The lack of symmetry over a wide range of time is also apparent in Fig. 11(a). Numerical simulations of six-jet experiments that incorporate unbalanced jet velocities and/or trigger times are aiding our interpretation of these data (see Sec. IV-A for further discussion). In order to improve the jet-to-jet balance, we plan to upgrade our GVs and have also added the ability to fine tune (through variable resistances and inductances) the electrical characteristic of each of the six GV transmission lines. The new GVs (rev. 10) will provide higher precision and repeatability in the amount of mass injected. Varying the resistance/inductance of the GV transmission lines has already allowed us to tune the jet injected mass and velocity, as observed in the rise in chamber pressure after each shot, photodiode signals, and camera images.

5) Survey spectroscopy: By comparing survey-spectroscopy data with non-local-thermodynamic-equilibrium (non-LTE) PrismSPECT [38] spectral calculations that utilize $n_e$ values consistent with interferometry data, we are able to place bounds on $T_e$ and $\bar{\rho}$ of the observed plasma volume; this methodology was previously described in detail [13] and applied in multiple experimental configurations [13]–[16], [39]. Figure 12(a) shows an example of spectra from several viewing chords, showing that there is little variation over these chords. The chords intersect the jet-propagation axes at approximately 14.7 cm. Figure 12(b) shows an example of a comparison between data and spectral calculations, showing good agreement for a calculation that assumes $n_e = 10^{15}$ cm$^{-3}$ and $T_e = 1.6$ eV (for which $\bar{\rho} = 0.99$). On the other hand, for calculations assuming $T_e \leq 1.5$ eV or $T_e \geq 1.9$ eV, the agreement between the spectral data and PrismSPECT calculations becomes dramatically worse, implying that $1.5 < T_e < 1.9$ over a large spatial area and time range for the merging plasma jets.

IV. NUMERICAL MODELING

In this section, we provide a brief overview of the modeling research in support of the PLX-α project. However, detailed modeling results will be reported elsewhere.

A. Plasma-liner formation and convergence

We use two 3D hydrodynamic codes to simulate jet merging (two, three, and six guns) and spherical ($4\pi$) plasma-liner...
Fig. 8. Intensified-CCD camera images (10-ns exposure, logarithm of intensity, false color, cropped to 1280 × 850 pixels each) showing the evolution of (a)–(d) 3-gun (shots 1064, 1066, 1061, 1069) and (e)–(h) 6-gun experiments (shots 1007, 1038, 1041, 1043). As labelled in the 3-gun image sequence, primary shocks (b) form along the merge plane of adjacent jets, and (presumed) secondary shocks (d) form due to subsequent merging of the primary-shock plasmas.
formation and convergence (18–600 guns). The former are in support of our ongoing experiments (studying shock dynamics between merging jets and/or forming a section of a liner with six jets). The latter are to guide our preparation for planned $4\pi$ experiments over the next two years.

The two 3D codes being used are SPFMax [40], a smoothed-particle-hydrodynamic code, and FronTier [41], a hydrodynamic code with front tracking. As part of the PLX-$\alpha$ project, we have performed significant benchmarking of the codes against jet-merging experimental results, and we have added physics capabilities to the codes, including Braginskii thermal transport and viscosity [42], optically thin radiation loss, advanced equation-of-state (EOS) table lookup (using custom-generated non-LTE PROPACEOS tables [43] from Prism Computational Sciences), and $2T$ (i.e., separate $T_i$ and $T_e$ evolution) modeling.

SPFMax and FronTier have been used to simulate three- and six-jet merging to guide diagnostics setup, generate synthetic data [see Fig. 11(b)] for comparisons to the diagnostic data, and aid our understanding of the comparisons. For generating the synthetic data in Fig. 11(b), we ran SPFMax using the six-gun setup of Fig. 6(a) with the following initial argon-jet parameters: velocity of 35.8 km/s, $T_i = T_e = 2.5$ eV, ion density $n_i = 3.17 \times 10^{16}$ cm$^{-3}$, diameter of 8.5 cm, length of 10 cm, and leading edge of the jets at $R = 130$ cm. The simulation included non-LTE argon EOS, single-group opacity, $2T$, and ion and electron thermal conduction. To help understand the disagreement between the experimental and synthetic interferometry seen in Fig. 11(b), we ran six-jet FronTier simulations that included random variations among jet velocities (up to 10%) and/or trigger times (up to 1 $\mu$s); these results show that the symmetry of primary- and secondary-shock formation is indeed drastically degraded compared to the case with identical jet velocities/timings (further motivating our ongoing efforts to improve the jet-to-jet balance). We also plan to use VISRAD [43] to generate synthetic spectral data to compare with spectroscopy data.

The $4\pi$ simulations (with up to $N = 600$ jets) have focused on studies of liner uniformity and ram-pressure ($\rho v^2$) evolution as the liner forms and converges radially toward stagnation. For $N \leq 60$, the simulations directly inform planned PLX-$\alpha$ experiments, which aim to form $4\pi$ implosing liners with 36–60 jets and $\sim 100$–150 kJ of total liner kinetic energy, and predict peak $\rho v^2 \sim 50$ kbar. For $N > 60$, the simulations are assessing the jet and uniformity requirements to achieve fusion-relevant conditions, requiring total liner kinetic energy of $\gtrsim 30$ MJ and peak $\rho v^2 \gtrsim 150$ Mbar [3, 34].

B. Plasma-liner compression of a magnetized target

A separate modeling task is studying plasma-liner compression of a magnetized target in 1D and 2D, using the multi-fluid magnetohydrodynamic (MHD) code USim [45]. A major purpose of this task is to identify and optimize PJMIF configurations with energy gain, guided by the results of [3, 34]. New physics capabilities have also been added to USim as part of the PLX-$\alpha$ project, including optically thin radiation loss, non-LTE tabular EOS table lookup (also using PROPACEOS tables [43]), Braginskii viscosity [42], and $\alpha$-particle energy deposition based on the model implemented in [3]. A second important purpose of this task is to assess and understand the degradation of energy gain in going from 1D to 2D, and to examine the further degradation of energy gain when nonuniformities (based on the work described in Sec. [4-A] are imposed on the liner/target interface, which exacerbate Rayleigh-Taylor instabilities at the stagnating interface. Indeed, one specific objective of this task is to set requirements on the liner uniformity for PJMIF to remain viable as a fusion-energy concept.

V. SUMMARY AND PLANS

We have described an experiment to form and characterize a section of a spherically imploing plasma liner, as a development step toward PJMIF [1, 2]. This work is the first phase of the ARPA-E-sponsored PLX-$\alpha$ project, which
Fig. 10. (a) High-resolution-spectroscopy data (shot 1083, 1-µs exposure) showing two views of a singly ionized argon spectral line, corresponding to the $R = 20$-cm positions shown in Fig. 6(b). The vertical and horizontal axes represent the height of the spectrometer slit and wavelength, respectively. (b) Vertically integrated signal (arb.) vs. wavelength (centered at 480.602 nm) for the secondary-shock-line view ($T_i = 6.0 \pm 0.13$ eV) and (c) primary-shock-line view ($T_i = 4.3 \pm 0.11$ eV), from (a). The error quoted for $T_i$ is the curve-fitting error assuming Poisson weighting of the spectral data.

Fig. 11. (a) Line-integrated electron density $\langle n_e \ell \rangle$ vs. time (shot 1008) from multi-chord interferometry [based on the setup of Fig. 6(a)]. “Region of interest” refers to the approximate time duration when jets merge to form a liner section. (b) Data points are $\langle n_e \ell \rangle (t = 36 \mu s$, averaged over shots 1019–1032) vs. chord number; error bars are the standard deviation over the shot range. The bars are synthetic data from 3D SPFMX hydrodynamic simulations of the six-gun experiments (see Sec. IV-A).

This paper reports key early results from the PLX-α project: (1) design and operation of the new HyperV coaxial plasma guns and characterization of plasma-jet parameters, (2) completion of the PLX facility/diagnostic upgrades for six-gun experiments, (3) successful operation of up to six plasma guns and key diagnostics (photodiode arrays, fast imaging cameras, survey spectroscopy, hi-resolution spectroscopy, and multi-chord interferometry), and (4) diagnostic results showing that the key potentially deleterious physics issues associated with jet merging (e.g., ion shock heating leading to Mach-number degradation and the seeding of nonuniformities that may exacerbate deceleration-phase instabilities of the liner/target.
interface in future target-compression experiments) can now be studied in a serious manner; these studies are ongoing, and further details and conclusions will be reported elsewhere.

Ongoing three- and six-jet experiments are providing comprehensive datasets on ion shock heating for several plasma-jet species (H, He, N, Ne, Ar, Kr, Xe) and two different jet-merging angles. Upon installation of improved gas valves, which are expected to improve the jet-to-jet balance, we will then focus on obtaining more interferometry data to better assess the uniformity of the liner section formed by merging six jets [i.e., the setup shown in Fig. 6(a)]. Finally, we are incorporating a number of engineering improvements to the coaxial plasma guns to maximize both the assembly/operational efficiency and quality/quantity of experimental data for planned experiments with 36–60 guns to form 4π spherically imploding plasma liners (over the next two years). These experiments will provide critical data on the magnitude and evolution of liner nonuniformity and ram pressure during radial convergence, to allow continued technical assessment and development of the PJMIF concept.

ACKNOWLEDGMENTS

The authors thank R. Aragonez, R. Martinez (dec.), J. Vaughan, and M. Luna for valuable technical contributions, and Dr. G. Wurden for loaning numerous items of diagnostic hardware. Section III of this paper summarizes the invited talk by S. Hsu and posters by S. Langendorf and K. Yates that were presented at the International Conference on Plasma Science (ICOPS) in Atlantic City, NJ, May 22–25, 2017. This work was supported by the Advanced Research Projects Agency–Energy (ARPA-E) of the U.S. Department of Energy (DOE). We also acknowledge the DOE Office of Fusion Energy Sciences for sponsoring PLX construction and research (2009–2012) and plasma-gun development by HyperV Technologies Corp. (2005–2012).

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