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Experimental investigations of ablation stream interaction dynamics in tungsten wire arrays: Interpenetration, magnetic field advection, and ion deflection

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Experiments have been carried out to investigate the collisional dynamics of ablation streams produced by cylindrical wire array z-pinch. A combination of laser interferometric imaging, Thomson scattering, and Faraday rotation imaging has been used to make a range of measurements of the temporal evolution of various plasma and flow parameters. This paper presents a summary of previously published data, drawing together a range of different measurements in order to give an overview of the key results. The paper focuses mainly on the results of experiments with tungsten wire arrays. Early interferometric imaging measurements are reviewed, then more recent Thomson scattering measurements are discussed; these measurements provided the first direct evidence of ablation stream interpenetration in a wire array experiment. Combining the data from these experiments gives a view of the temporal evolution of the tungsten stream collisional dynamics. In the final part of the paper, we present new experimental measurements made using an imaging Faraday rotation diagnostic. These experiments investigated the structure of magnetic fields near the array axis directly; the presence of a magnetic field has previously been inferred based on Thomson scattering measurements of ion deflection near the array axis. Although the Thomson and Faraday measurements are not in full quantitative agreement, the Faraday data do qualitatively support the conjecture that the observed deflections are induced by a static toroidal magnetic field, which has been advected to the array axis by the ablation streams. It is likely that detailed modeling will be needed in order to fully understand the dynamics observed in the experiment. *Published by AIP Publishing.*

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I. INTRODUCTION

In this paper, we present a review of a series of experimental campaigns which investigated the collisional dynamics of radially convergent plasma ablation streams¹ produced by cylindrical wire array z-pinch in the early phase of the current drive.^{2–5} These experiments were conducted on the 1.4 MA, 240 ns Magpie pulsed power driver at Imperial College London,⁶ and diagnosed using a range of techniques, including laser interferometric imaging, optical Thomson scattering (TS), and Faraday rotation imaging.⁷ The range of quantitative measurements resulting from this work is highly suitable as a source for the benchmarking of computer codes designed to model complex plasma physics problems involving flow

interpenetration, magnetic field advection, and the atomic physics of high Z, multi-fluid plasmas.

The physics of interpenetrating plasmas is currently an area of broad interest in research fields such as inertial confinement fusion, high energy density physics, and laboratory astrophysics.⁸ Experiments have been carried out at a range of facilities in order to investigate the physics of interpenetrating plasma flows. The collisions of expansion flows launched from laser-irradiated targets have been used to investigate the formation of current filaments⁹ driven by the Weibel¹⁰ instability in collisionless, interpenetrating plasma interactions, with the aim of observing the formation of collisionless shocks.¹¹ Interpenetration phenomena have also been investigated on larger spatial scales using railgun-launched plasma jets.^{12,13} The velocity, density, temporal and spatial scales of the flows produced by wire array experiments ($\sim 10^5 \text{ ms}^{-1}$, $\sim 10^{18} \text{ cm}^{-3}$, $\sim 100 \text{ ns}$, $\sim 1 \text{ cm}$) fall in-between those produced in laser driven experiments ($\sim 10^6 \text{ ms}^{-1}$, $\sim 10^{19} \text{ cm}^{-3}$, $\sim 1 \text{ ns}$, $\sim 1 \text{ mm}$)¹¹ and those produced in railgun driven experiments ($\sim 10^5 \text{ ms}^{-1}$, $\sim 10^{16} \text{ cm}^{-3}$, $50 \mu\text{s}$, $\sim 1 \text{ m}$).¹³ What sets the wire array driven experiments apart is that the plasma streams are

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magnetized at launch and that the magnetic Reynolds numbers of the flows are large ($Re_m \sim 20$), i.e., the embedded magnetic field tends to be advected with the flows, providing an opportunity to study the interactions of magnetized, interpenetrating plasma flows.

The remainder of the paper is organized as follows: In Section II, we review previously published interferometry measurements. These measurements illustrate the differences in the ablation stream interaction dynamics observed when the wire material is changed from aluminum to tungsten. Further interferometric measurements are then used to infer the time variation of the collisional scale length for the stream interactions, and to infer that collisional interactions are ion–ion in nature. In Section III, we review previously published Thomson scattering measurements of ablation stream interpenetration, ion heating and axial deflection, and the temporal evolution of the flow interactions. These data also support the conclusions made in Section II about the nature of the dominant collisional process. Possible kinetic effects due to magnetization of the ions in these plasmas are also discussed briefly. Finally, Section IV presents data from new Faraday rotation imaging experiments; while these data do show a magnetic field structure of the form implied by the Thomson scattering data, the strength of this field appears to be smaller than needed to fully explain the observed ion deflections.

II. INTERFEROMETRIC EVIDENCE OF CHANGES IN COLLISIONAL DYNAMICS

A series of experiments were carried out in order to investigate ablation stream interaction dynamics using an

interferometric imaging diagnostic;^{2,3,7,14} in these experiments, a probe laser was aligned along the axis of the array in order to measure the axially integrated, radially and azimuthally resolved (“end-on”) free electron density distribution ($\int n_e dz$) of the plasma. Aluminum and tungsten wire arrays were investigated; previous calculations^{15–17} had indicated that while the ablation streams produced by aluminum arrays should mostly interact collisionally, those produced by tungsten arrays should remain collisionless for a significant portion of the experiment.

Figures 1(a) and 1(b) show examples of raw end-on interferograms from a pair of 32-wire array experiments. Both of these images were captured 140 ns into the 240 ns Magpie current pulse; the only change made between the two experiments was the wire material, aluminum in (a) and tungsten in (b). The obvious differences in the appearances of the raw interferograms recorded in these experiments are indicative of the differences in the ablation stream interaction dynamics. The dense, sharply distorted fringe shifts seen in the aluminum data contrast sharply with the smoothly varying fringe shifts observed in the tungsten data.

The $\int n_e dz$ maps shown in Figures 1(c) and 1(d) were produced via quantitative analysis of the interferograms above each image. The aluminum density map² (c) is clearly dominated by a dense pattern of oblique shocks. These shocks are formed by successive collisions between the radially convergent ablation streams emanating from each wire core (positions indicated by red spots); the shocks act to steer and compress the flows towards the axis of the array. These shock-dominated dynamics are characteristic of supersonic,

FIG. 1. Contrasting electron density distributions seen in 32-wire aluminum (a) and tungsten (b) z-pinches. Both images were captured at ~ 140 ns into the 240 ns Magpie current pulse. Quantitative analysis of (a) and (b) results in $\int n_e dz$ maps (c) and (d), respectively. Reproduced with permission from Swadling *et al.*, Phys. Plasma **20**, 022705 (2013). Copyright 2013 American Institute of Physics; Swadling *et al.*, Phys. Plasma **20**, 062706 (2013). Copyright 2013 AIP Publishing LLC.

radially convergent compressible flows in the fully collisional limit. In contrast, the tungsten $\int n_e dz$ map³ (Figure 1(d)) varies very smoothly; at large radius, modulations in the electron density corresponding to the individual ablation streams are evident; however closer to the axis, these modulations rapidly relax. The $\int n_e dz$ distribution immediately about the axis appears azimuthally isotropic, with little evidence of any remaining azimuthal modulation. The absence of shock structures in the data suggests that the ablation streams are not fully collisional, i.e., they must be interpenetrating over some significant scale length.

Similar structures are seen even in experiments using arrays with significantly fewer wires. Figure 2 shows interferometry data from an 8-wire tungsten array experiment. At large radius, the ablation streams are well defined and focused, but nearer to the axis they appear to spread or scatter, forming an isotropic density distribution similar to that seen in the 32-wire experiments.

The broad, smooth distribution of plasma seen near the axis in the tungsten data is interesting. Previous estimates^{16,17} of collisional mean free paths for these experiments have indicated that while each ablation stream should be self-collisional, the approach velocity between counter propagating Tungsten ablation streams has to be large enough that they should interpenetrate without significant collisional interaction. Although interferometric imaging is sensitive only to the free electron density of the plasma, the mass discrepancy between the ions and the electrons means that the ion component of the plasma carries the vast majority of the momentum; over the spatial scales resolvable in our experiment, the free electron distribution is forced by the constraints of quasi-neutrality ($\lambda_{De} \sim \mu\text{m}$) to reflect the underlying ion density distribution. The rapid formation of this broad distribution of free electrons near the axis therefore indicates that the ions making up the incoming ablation streams must be undergoing significant transverse scattering as they approach the axis of the array.

Two types of classical collisional interaction can affect the incoming ions, electron-ion collisions, and ion-ion collisions. In this regime, electron-ion collisions will tend to produce a drag-like effect; the directed kinetic energy of each ion will be deposited into the electron population as thermal energy and the ions will gradually slow down without undergoing significant deflection from their initial paths. This lack

of individual deflections will correspond to minimal spreading of the overall incoming stream. Individual ion-ion collisions on the other hand involve significant transfers of energy and momentum between particles. These types of collision will induce significant scattering of the incoming ions, leading to an increased ion temperature, and an apparent spreading of the flow as its Mach number falls. Our observations of a smooth distribution of plasma near the array axis are consistent with scattering of the ion streams, implying that ion-ion collisions are dominant.

Thomson scattering measurements, which will be discussed in Section III, indicate that the full-width half-max (FWHM) of this region (the “interaction region”) is controlled to some extent by the collisional scale length for the ablation stream interactions. A time series of end-on interferometric imaging measurements of 8-wire tungsten arrays have been captured between 77 and 160 ns, and were presented in Ref. 5. The FWHM of the “interaction region” and peak electron density on axis were extracted from these data and are plotted in Figure 2(b). These data suggest that the mean free path for the tungsten ablation stream collisions decreases with time, consistent with the increasing density of plasma measured on axis. The width of the interaction region falls rapidly and monotonically from $\sim 4\text{ mm}$ at 120 ns to $\sim 1\text{ mm}$ at 160 ns. These measurements appear in line with previous observations of the evolution of this region using extreme ultra-violet/soft x-ray self-emission imaging diagnostics.^{16,18}

III. THOMSON SCATTERING INVESTIGATIONS

Additional information on ablation stream dynamics in the “interaction region” (labeled in Figure 3(b)) was obtained via Thomson scattering (TS) measurements.^{4,5} Measurements of the TS ion feature provided detailed information about the structure and evolution of the ion velocity distribution near the wire array axis, and provide direct evidence for flow interpenetration over the width of the “interaction region” identified in the interferometry measurements. These data support the argument made in Section II that the width of the “interaction region” may be used as a measure of the collisional scale length of the flows. Measurements in our experiments were limited to the ion-feature of the TS spectrum, as the electron-feature could not be resolved above the background self-emission produced by the experiment.

FIG. 2. (a) An example of a $\int n_e dz$ distribution from an 8-wire tungsten array at $\sim 140\text{ ns}$, showing the azimuthally smoothed region near the axis. (b) Temporal evolution of the full-width half-max of the interaction region and peak n_e on axis. Reproduced with permission from Swadling *et al.*, Phys. Plasma **20**, 062706 (2013). Copyright 2013 AIP Publishing LLC; Swadling *et al.*, Phys. Plasma **22**, 072706 (2015). Copyright 2015 AIP Publishing LLC.

FIG. 3. Thomson scattering experimental setup. (a) Side view of rotated array configuration. (b) End-on view of plasma illustrating the flow configuration. (c) TS diagnostic layout. (d) scattering geometry. Reproduced with permission from Swadling *et al.*, Phys. Plasma **22**, 072706 (2015). Copyright 2015 AIP Publishing LLC.

The TS probing and collection geometry used in the experiments is described in detail in Refs. 4 and 7; diagrams are provided in Figure 3. This geometry is designed to allow simultaneous measurements of two orthogonal components of the ion velocity distribution. These components are aligned parallel to the axial ($\hat{z}$) and radial ($\hat{r}$) vectors of the overall wire array geometry, respectively. Simultaneous measurements of two orthogonal components of the ion velocity distribution allow the ion velocity vectors to be reconstructed in 2D, while also providing two separate measurements of the ion temperature.

In order to collect scattered light along the vectors indicated in Figure 3(c), the wire array load was rotated 90° with respect to the axis of the pulsed power drive electrodes;¹⁹ a simplified diagram of this arrangement is provided in Figure 3(a). An end-on cartoon of the flow geometry is provided in (b), the diagnostic layout is shown in (c), and the scattering geometry is indicated in (d). Scattered light is collected using a pair of linear fiber optic arrays; initial experiments used arrays consisting of seven equally spaced 200 μm $\varnothing$ fibers,

while in later experiments, these were replaced with arrays consisting of 14, 100 μm $\varnothing$ fibers. Light is imaged from the experiment onto the ends of the fibers using lenses, and the fibers then couple it into the input slit of a gated imaging spectrometer (0.5 m, 2400 l/mm, 0.5–0.35 Å). Careful alignment ensures that the two fiber arrays collect scattered light from coincident scattering volumes. These volumes are spaced evenly, radially, and axially, across the “interaction region.”

A. Interpenetration, deflection, and heating

Figure 4(a) is a raw TS spectrogram recorded 120 ns after current start in an 8-wire tungsten wire array experiment. Simultaneously measured end-on interferometry data are presented in Figure 4(b); the small red circles near the axis in this image indicate the radial positions of the TS scattering volumes. Spectral profiles extracted from the TS spectrogram are plotted in Figure 4(c) in black from each collection volume, alongside calculated TS fits in red and an un-shifted calibration measurement in blue. The fits are calculated using the multi-species, non-relativistic, Maxwellian TS form factor $S(\omega, k)$.²⁰ Figure 4(d) shows plots of the variation of the fitting parameters used to calculate these fits against radial position.

The details of the methods used to construct and calculate the fitted spectra are discussed in detail in Refs. 4, 7, and 21. In brief, two spectra are recorded from each scattering volume: one sensitive to the radial component of the ion velocity distribution and one sensitive to the axial component. Each of these pairs of spectra is fitted simultaneously using the constraint that they must be constructed from the same ensemble of ion populations; for the data presented in Figure 4, each volume was modeled using two interpenetrating ion populations. The majority of the plasma parameters (e.g., T_e , T_i , n_i , $\bar{Z}$) of the two populations are shared between the two fits; however, each fit is sensitive to a separate orthogonal component of the bulk flow velocity, so this parameter is unconstrained between the two fits. This model assumes that the two ion-populations are thermal. For the initial incoming streams, this is reasonable, as the intra-stream collisional scale lengths are small ($\sim 50 \mu\text{m}$); however, at the higher end of the temperature range of interest, the collision lengths can become quite long ($\sim 1 \text{ mm}$). At these higher “temperatures,” the ion velocity distributions may become non-thermal, however this is difficult to diagnose; the possible effects of non-thermal distributions are discussed in Section III C; however, for the present analysis, the effective ion temperatures are based on the assumption that all of the ion populations have thermal distribution functions. This should be a good approximation at least for the incoming portions of the streams.

The parameters of the two populations, mainly their ion temperatures, densities, radial and axial velocities were varied to produce the best possible simultaneous fit for both spectra. The radial variations of the parameters used to model the two ion-populations are plotted in Figure 4(d) using solid and open triangles, respectively; the pointing direction of these triangles indicates the direction of radial propagation for each population. The uppermost plot shows

FIG. 4. Thomson scattering measurements of stream interpenetration in 8-wire tungsten arrays. (a) Raw TS spectrogram, (b) end-on interferograms with TS volumes indicated by red circles. (c) Extracted TS spectra (black), fits (red), unscattered probe (blue). (d) Radial variation of fitting parameters for two population fit. Reproduced with permission from Swadling *et al.*, Phys. Rev. Lett. **113**, 035003 (2014). Copyright 2014 American Physical Society.

the variations in the radial velocity; the two populations are clearly interpenetrating, with the radial velocity of each decreasing reasonably monotonically across the width of the “interaction region.” The lower plot in Figure 4(d) shows the variation of the ion-temperatures for the two populations; this parameter increases approximately linearly with distance

of propagation across the interaction region; both populations start at ~ 2 keV and reach ~ 20 keV at the array axis. The middle plot shows the variations in axial velocity of the two ion populations. This plot indicates that the ion populations close to the array axis have acquired a significant axial velocity component. This axial velocity is not present in the

incoming populations at large radius and is reduced for the populations that have already passed through the array axis.

The models used in this analysis are very much simplified with respect to the true experimental situation. In particular, for the modeling presented in Ref. 4, the fits are limited to just two independent plasma populations (Ref. 5 contains examples of fits using the complete set of four populations). If the fit to the radially sensitive spectra was the only measurement of the ion temperature, then we might expect some overestimate, particularly near the array axis; however the simultaneous fit to the axially sensitive spectrum at the array axis, where symmetry implies that all of the ion populations should have the same temperature and velocity component, indicates that our measurement of the trend of the effective ion temperature of the plasma should be reasonably accurate. It is possible, however, that the true thermal temperature of the plasma is lower and that the measured effective temperature is enhanced by the presence of a non-thermal distribution function. This will be discussed in more detail in Section III C.

The observed slowing and heating of the ion populations indicates that the ablation streams are not entirely collisionless; some mechanism is slowing and heating the ions. These observations further support the conclusion drawn in Section II that ion–ion collisions must be dominant. Only ion–ion collisions could produce the observed ion heating. The kinetic energy of the incoming ions is ~ 25 keV, comparable to the ion temperature measured at the array axis. This means that almost all of the incoming ion kinetic energy must be thermalized to produce the observed ion heating. At the array axis, the ion thermal velocity becomes comparable to the directed bulk velocity of the stream; the flow Mach number has transitioned smoothly from ~ 4 to 5 in the incoming stream to ~ 1 on axis. The falling Mach number is consistent with the observed spreading of the flows and with the formation of the smooth “interaction region” near the axis. If ion–electron collisions are dominant, the kinetic energy of the ions would be deposited into the electron population as heat. This thermal energy could then be rapidly radiated away; ion deceleration would occur but would not be accompanied by significant ion heating (see Ref. 5 for further details of this argument).

The increased axial velocity of the ablation streams observed for the populations near the array axis indicates that the streams must be undergoing some sort of deflection or acceleration as they approach the array axis. This deflection may be explained as being the result of a Lorentz $F = q\vec{B} \times \vec{v}$ force acting on the ions as they propagate across the “interaction region.” A cartoon of this deflection geometry is provided in Figure 5; it should be noted that this cartoon does not represent the path of an individual ion, but instead is representative of the deflection of the bulk ion population. Ions approaching the axis have a thermal spread of velocities, which implies a spread of gyro-radii; however the ion population is, at least initially, highly self collisional (ion–ion collision length, $\lambda_{ii}(2 \text{ keV}) \sim 100 \mu\text{m}$),²² so the individual ions will not follow and complete these individual orbits. Instead, the slight deflections induced by the field will sum to produce a resultant deflection of the overall ion population

FIG. 5. Cartoon of magnetic deflection geometry.

velocity vector. This is inherently a complex problem; however, the simplified model sketched in Figure 5 should help to provide a reasonable estimate of the required field strength (Since the λ_{ii} of the plasma scales with T_i^2 , kinetic effects in the ion velocity distributions become more important as T_i rises; see Section III C for discussion). To date, all measurements of this axial velocity component have shown it directed towards the anode end of the array, i.e., in the opposite direction to the electric field produced by the generator. The direction of the deflection is, however, consistent with that which would be induced due to deflections by a toroidal magnetic field pointing in the same direction as the global field of the array. Furthermore, the axial velocity component is reduced in the streams that have already passed through the array axis. This is again consistent with magnetic deflection, as the direction of the Lorentz force will reverse after the ions have passed the array axis (see Figure 5). Experiments have now been performed in order to try to measure this field directly; these new results are presented and discussed in Section IV.

B. Temporal evolution of interpenetration dynamics

Further Thomson scattering measurements were carried out in order to look in more detail at the temporal evolution of the ablation stream collisional interactions. These data are presented, analyzed, and discussed in detail in Ref. 5; here, we present a brief review of the main results. TS spectra were recorded at 100, 140, and 150 ns. The raw TS spectrograms captured in these experiments are shown in Figure 6.

A cursory inspection of the three spectrograms in Figure 6 reveals that the structure of the scattered spectrum changes significantly over the temporal range of the measurements. The most recognizable of the three spectra is shown in Figure 6(b), which was recorded at 140 ns, and appears qualitatively similar to the spectrum measured at 120 ns (see Figure 4(a)). Analysis of this spectrum revealed similar evidence of stream interpenetration, stagnation, and a deflection consistent with the presence of a toroidal magnetic field on axis.⁵

The structure of the spectrum measured at 100 ns (Figure 6(a)) is quite different from the spectra at 120 and 140 ns. The radially sensitive scattered spectrum (the top

FIG. 6. Raw data from most recent TS-diagnosed interpenetration experiments. Reproduced with permission from Swadling *et al.*, Phys. Plasma **22**, 072706 (2015). Copyright 2015 AIP Publishing LLC.

half of the spectrogram) is very broad and structured differently compared to the later spectra. While this might seem to suggest that the ion temperature is higher at this time, an analysis⁵ using the simultaneous fit methods similar to those described in Section III A reveals that the apparent width of this spectrum is in fact due to the superposition of scattered spectra from multiple, cross-propagating, largely non-interacting, and relatively cold ablation streams.

The spectrum measured at 150 ns (Figure 6(c)) is also very different; at large radius, it is much narrower than those recorded at earlier times, indicating that the ion temperature has fallen significantly. The streams appear to propagate without interaction, and then to undergo a shock-like transition to lower velocity and higher temperature. The data then show a central column of warmer plasma that is undergoing compression. There is no evidence of significant flow interpenetration, suggesting that the flow interactions have now transitioned to a collisional regime. The reduced temperature of the plasma is consistent with an increasing rate of ion–electron thermal equilibration, driven by the increasing density of the plasma, both in the streams and near to the array axis. Cooling of the ions reduces the thermal pressure of the plasma near the axis, while the increasing density and therefore decreasing ion–ion mean free path of the streams lead to an overall compression of the plasma near the axis to smaller radius and higher density. This interpretation is consistent with previous observations using other diagnostic techniques.¹⁶

The axial deflection of the ablation streams seen in the 120 ns TS measurement is reproduced in both the 100 and 140 ns TS measurements; however, no effect is seen in the

measurement at 150 ns. The 100 and 140 ns spectra both show an increasing deflection of the flows towards the anode end of the array as they approach the axis, followed by a deflection back towards radial propagation as they depart from the axis, consistent with the magnetic deflection model (Figure 5) introduced at the end of Section III A. These dynamics will be discussed further in Section IV, where we present the first direct measurements of the magnetic field structure near the array axis.

Analysis of the complete TS dataset allows us to look at how the interactions of the plasma streams evolve over time. Plots of the key flow parameters are shown in Figure 7. The overall story is easily seen from these plots: (a) shows the evolution of the parameters of the ion populations measured at the array axis, while (b) shows the same for the parameters measured for the incoming flow populations. The radial velocity (green +) measured at the array axis clearly falls with time. This is consistent both with the increasing collisionality of the streams and with the decreasing incoming flow velocity seen with time. The radial velocity on axis falls to zero at 150 ns, consistent with the view that the flows are no longer interpenetrating. The axial velocity (blue *) at the axis initially increases. This is consistent with an increasing magnetic field around the axis, driven by the increasing drive current, and also reflecting the fact that more fields will have been advected to the axis at later time. The axial velocity falls off rapidly at 150 ns; this may simply be due to greater collisionality at later times, but may also reflect a collapse of the static magnetic field structure. Finally, the ion temperature (red x) on axis initially rises, again in line with

FIG. 7. Temporal evolution of flow parameters as measured via fits to Thomson scattering spectra. (a) Parameters of ion populations at the array axis. (b) Parameters of incoming streams. Reproduced with permission from Swadling *et al.*, Phys. Plasma **22**, 072706 (2015). Copyright 2015 AIP Publishing LLC.

increasing collisionality between the ablation streams, before falling rapidly around 140–150 ns. This fall in temperature is consistent with the onset of rapid ion–electron equilibration and loss of the accrued ion thermal energy via radiative cooling.

C. Kinetic effects due to ion magnetization

Any temperature measurement that is sensitive directly to the velocity distribution of the plasma has the potential to be disturbed by the presence either of non-thermal distribution functions or of meso-scale modulations in the fluid motion of the plasma within the observed volume. A good example of this is seen in the exaggerated stagnation temperatures of Z-pinch plasmas measured through spectroscopic measurements of the Doppler broadening of emission lines.^{23,24} In this case, without careful consideration, the meso-scale hydro-motion of the plasma at stagnation would lead to an overestimation of the microscopic ion temperature. In the case of the present experiments, we are concerned over the effects of non-Maxwellian ion distribution functions. In particular, as the ion temperature increases, the ion populations become less and less self-collisional; at the higher end of the measured range of effective T_i , this implies that the ion velocity distributions may become quite non-Maxwellian. Magnetization of the individual ions will lead to orbital motions that will cause TS measurements of the

velocity distribution in directions perpendicular to the magnetic field to produce an overestimate of the ion temperature.

The magnitude of the magnetic field expected near the edge of the “interaction region” ($B \sim 10 \text{ T}$) suggests an ion gyro-frequency in this region of $\omega_{ci} \sim \frac{10^4 Z B}{A} \sim 5 \times 10^8 \text{ rad s}^{-1}$. This corresponds to a characteristic time required for an ion to turn around of $\frac{\pi}{\omega_{ci}} \sim 6 \text{ ns}$, quite quick compared to the $\sim 100 \text{ ns}$ overall experimental timescale. The strength of the magnetic field will vary with radius from the array axis and should be expected to fall to zero at the array axis. Magnetization effects are therefore expected to be strongest at the edge of the “interaction region.” At ion temperatures greater than $\sim 15 \text{ keV}$, ω_{ci} exceeds ν_{ii} , the ion–ion collision frequency. This is the threshold over which we might expect to see a significantly enhanced effective temperature due to ion magnetization. For the incoming flows, the temperatures are low enough that the internal collisionality of the streams is likely to keep their distribution functions reasonably thermal, and the ion stream will tend to deflect as a whole. At the array axis, the absence of a strong magnetic field suggests that the temperature is also likely to be largely thermal, with perhaps a little enhancement of the measured effective ion temperature. At the ion-temperatures at which the streams leave the axis however, internal collisions are greatly suppressed and it should be expected that the ions will become magnetized.

This effect may help to explain the particularly high temperatures observed in the stagnated populations seen at large radius (previously,⁴ it was suggested that the energy mismatch might be due to the observed trend in the launch velocity of the streams, which is seen to decrease with time). It is possible that these populations have not stagnated at all but are instead magnetically trapped in the region near the edge of the interaction region. The data currently available do not provide conclusive evidence for these effects; however, future Thomson scattering measurement of the azimuthal components of the ion velocity distribution could help to clarify the situation, as magnetization effects should not be observed in the direction parallel to the field.

IV. MAGNETIC FIELD MEASUREMENTS

The Thomson scattering data presented in Section III showed a significant deflection of the ions towards the anode end of the array as they approach the array axis. It has been proposed^{4,5} that this deflection may be due to the presence of an advected and accreted, static, toroidal magnetic field embedded in the plasma surrounding the array axis (see Figure 5 for diagram). This field is frozen into the magnetized electron population of the plasma within the “interaction region” and prevented from pinching towards the array axis by the supporting thermal pressure of the high temperature ions ($\beta > 1$). The presence of this field requires the resistivity of the plasma to be low enough to inhibit rapid field diffusion towards the array axis and eventual magnetic flux annihilation. Estimates suggest that this requirement is met at least for the time period where the deflection is observed.⁴

New Faraday rotation imaging experiments have now been conducted in order to investigate the presence of this field more directly. The experimental setup used to make

these measurements is similar to that shown in Figure 3(a). A tungsten wire array is mounted perpendicular to the drive electrodes¹⁹ and diagnosed simultaneously using an “end-on” interferometric imaging diagnostic and a “side-on” Faraday rotation diagnostic; details of the design of both of these diagnostics may be found in Ref. 7. In the experiments reported here, the polarization analyzers for the two polarimetry channels were set $\pm 3^\circ$ either side of the extinction angle. This offset was selected in order to maximize the differential sensitivity of the polarimeter over the expected range of the Faraday rotation measurement ($-3^\circ:3^\circ$). The measurement was carried out at 125 ns, comparable to the timing of the Thomson scattering measurement of ion deflection presented in Section III A, and previously in Ref. 4.

The raw polarimetry images recorded by the Faraday diagnostic were analyzed using the technique described in Ref. 7; the resulting map of the rotation angle (α) is shown in Figure 9. The wire array used in this experiment consisted of eight tungsten wires. The diagnostic view is side-on to the array, and the array is aligned to provide a clear view of the plasma near the array axis; the four columns evident in each Faraday image correspond to a pair of two aligned wire cores. Qualitatively, the image is divided down the axis with positive rotation angles on one side and negative rotation angles on the other; this is as expected for a toroidal magnetic field topology and compares well with the cartoon view of the field structure shown in Figure 5. The color scale used in Figure 9 ranges from -0.5° to 0.5° , illustrating the weakness of the Faraday effect. This small signal leads to a low signal to noise ratio for the measurement; however, since the magnetic field structure does not appear to vary significantly in the axial direction, an axially averaged mean rotation angle, shown in the lower half of Figure 9, may be used to assess overall trends. Looking at the axially averaged rotation, the angle in the main region of interest for this measurement, within a radius of 2 mm of the array axis, varies only between -0.1° and 0.1° . The overall mean data are reasonably anti-symmetric about the array axis, again in keeping with expectations for this cylindrically symmetric system.

Extraction of the magnetic field distribution from a side-on Faraday rotation measurement presents a number of challenges; the Faraday effect is sensitive to both the magnetic field and to the free electron density of the plasma. Direct side-on interferometric measurements of the free electron density are not possible, as the high density wire cores block the probe beam, cutting through the interference fringes and making it impossible to assess a “zero shift” for the fringes in the interior region of the array. This problem is overcome by carrying out a simultaneous “end-on” electron density measurement. The cylindrical symmetry of the experiment makes this measurement particularly useful, as it gives a direct measurement of the axially averaged, radial electron density distribution of the central plasma column without the need for Abel inversion. The electron density map extracted from the end-on interferograms captured in this experiment is presented in Figure 8(a). A radial profile of the central plasma column is shown in (b) by the blue dashed line. The shape of the density profile is well approximated using a Gaussian distribution, plotted by a solid red line.

FIG. 8. (a) End-on, axially averaged electron density distribution measured simultaneously to Faraday data presented in Figure 9. (b) Radial electron density profiles. Blue dashed line shows profile taken across the array axis (red arrow in (a) shows profile path), red line shows Gaussian fit.

$$n_e \sim n_{e0} e^{-\frac{r^2}{2w^2}},$$

where $n_{e0} = 1.1 \times 10^{18} \text{ cm}^{-3}$ and $w = 1.2 \text{ mm}$. Inspection of the density plot shown in Figure 8(a) allows an assessment of the range over which there is a reasonably clear view of the central plasma column. In the region between the two white dashed lines, the view of this column is almost entirely unobstructed by the incoming ablation streams, and therefore the Faraday rotation measured in this region should be due only to the magnetic field embedded in the column itself. In order to aid reference, this region of unobscured view is also indicated in the plots in Figures 9 and 10.

The large amount of noise in the mean Faraday rotation profile means that it is difficult to use Abel inversion techniques to directly extract the radial dependence of the magnetic field strength near the axis. Instead, the approach taken is to attempt to fit the observed rotation profile using a plausible, modeled magnetic field distribution. The model is based on a number of strong assumptions; however, it is useful in that it gives an estimate of the likely strength of the field near the axis.

Starting with the assumption that the current density near the array axis is uniform ($j(r) \equiv j_0$). The magnetic field that corresponds to this current density distribution is calculated

$$\vec{B}_\phi(r) = \frac{\mu_0}{r} \int_0^r r' j(r') dr' = \frac{\mu_0 j_0}{2} r.$$

The differential Faraday rotation per unit optical path ($\vec{\gamma}$) through the magnetized plasma column is given [radians m^{-1}]

FIG. 9. Upper half, analyzed side-on Faraday rotation imaging data, lower half, axially averaged rotation angle taken from side-on Faraday image. This measurement was taken 125 ns after current start.

$$\frac{d\alpha(r)}{dy} = v(\lambda) n_e(r) \vec{B}_\phi(r) \cdot \hat{y} = v(\lambda) n_e(r) |\vec{B}_\phi(r)| \frac{x}{r},$$

$$v(\lambda) = \frac{e^3 \lambda^2}{8\pi^2 \mu_0 m_e^2 c^3} = 2.62 \times 10^{-13} \lambda^2 [SI].$$

An Abel transform of this function gives the rotation angle seen when probing the cylindrically symmetric density and magnetic field structure from the side.

FIG. 10. Fitting of Faraday rotation data. This plot shows the axially averaged rotation angle $\alpha(x)$ near the axis, taken from Figure 9, plotted with a set of fits calculated using a range of values for the current density near the array axis. The magnetic field quoted for each fit corresponds to the magnetic field at a 2.5 mm radius, approximately the edge of the density distribution shown in Figure 8.

$$\alpha(x) = \int_{-\infty}^{\infty} \frac{d\alpha}{dy} dy = 2 \int_x^{\infty} \frac{d\alpha}{dy} \frac{r dr}{\sqrt{r^2 - x^2}},$$

$$\alpha(x) = 2 \int_x^{\infty} \left[v(\lambda) n_e(r) |\vec{B}_\phi(r)| \frac{x}{r} \right] \frac{r dr}{\sqrt{r^2 - x^2}},$$

$$\alpha(x) = 2v(\lambda)x \int_x^{\infty} \frac{|\vec{B}_\phi(r)| n_e(r)}{\sqrt{r^2 - x^2}} dr.$$

Inserting functions for $n_e(r)$, $\vec{B}_\phi(r)$,

$$\alpha(x) = v(\lambda) n_{e0} j_0 \mu_0 x \int_x^{\infty} \frac{r e^{-\frac{r^2}{2w^2}}}{\sqrt{r^2 - x^2}} dr.$$

The above equation was used to fit the experimentally measured rotation angle; the current density j_0 was adjusted in order to produce the best possible fit for the central region. The results of this fitting process are presented in Figure 10. The best fit for the measured rotation angle was found at a current density of $j_0 = 4.5 \text{ kA mm}^{-2}$. This current density corresponds to a magnetic field of $B = 7 \text{ T}$ at $r = 2.5 \text{ mm}$, with the field linearly decreasing towards zero at the axis. The range of fitting values shown in Figure 10 gives some idea of the experimental uncertainty—these represent an upper limit of the uncertainty as they were fitted to encapsulate the $\lambda \sim 0.5 \text{ mm}$ noise. This noise arose from fringing in the experimental images and should not be interpreted as data.

This result qualitatively confirms our interpretation of the observed ion deflection as being due to toroidal magnetic field, but the value of the magnetic field estimated from the polarimetry is smaller than expected. Analysis of ion deflections measured with Thomson scattering indicates that the plasma near the axis should be characterized by a mean $B\bar{Z}$ of $\sim 110 \text{ T}$. Estimates of the average ionization based on the observed collisional mean free path have suggested that the average ionization cannot be much higher than $\bar{Z} \sim 11$. Combining these estimates, we find that the average magnetic field required near the array axis needs to be $B \sim 10 \text{ T}$. On the other hand, fitting of the Faraday rotation data using the constant current density model presented in the preceding three paragraphs leads to a linearly increasing magnetic field, starting at $B = 0$ on axis, and increases linearly with radius to reach $B \sim 7 \text{ T}$ at $r = 2.5 \text{ mm}$. This magnetic field structure suggests an average magnetic field strength in the “interaction region” where the deflections take place of only $\bar{B} \sim 3.5 \text{ T}$, almost a factor of three smaller than we require for consistency with our TS measurements. One possibility is that the actual magnetic field (current distribution) has a more complicated structure than is assumed in the above estimates.

V. CONCLUSIONS

A comprehensive range of experimental measurements of tungsten ablation streams interaction dynamics have been made over a wide range of experimental times, using a variety of different diagnostics. The interpenetration of tungsten ablation streams has been observed directly, and the temporal evolution of the interpenetration dynamics has been investigated through measurements of the changing plasma

flow parameters. The temporal evolution of the inter-stream stagnation length has been measured both using interferometry and Thomson scattering, while flux advection and magnetic field accrual have been observed both through Thomson scattering measurements (indirectly) and through Faraday rotation imaging measurements.

The data that have been produced in these experiments are highly quantitative, and represent an excellent potential source for code verification and model validation exercises. A complex range of physics will be required in order to accurately reproduce the measured ion stream interpenetration dynamics, magnetic field advection, and atomic physics behavior. The plasmas are characterized by a high atomic number, which will make accurate modeling of radiation, ionization, and recombination rates challenging, particularly given the multi-fluid nature of the problem.

Disagreement remains between the magnetic field estimate from the Faraday rotation measurements and the field implied by the Thomson scattering measurements. There is still a long way to go in order to fully understand these experiments. Accurate computational modeling of the experiment, using the diverse range of physics discussed in the previous paragraph will be essential in order to properly understand all of the observed phenomena.

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