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ABSTRACT

A LaB\textsubscript{6} thermionic emitter of annular shape is used in the Large Plasma Device at the University of California, Los Angeles to create off-axis heating conditions for various transport studies. Since the emitter is biased relative to a distant anode, which is many collision lengths away, the entire magnetized plasma develops a self-consistent, potential structure that simultaneously generates transverse and axial flows with shear. This study uses swept Langmuir probe techniques and Mach probes to map the flow patterns and their dependence on bias and plasma parameters. By implementing additional biasing configurations, it is possible to control the magnitude of the flows and their shear strength. The experimental measurements, including the self-consistent currents, are compared to predictions of a model that incorporates the boundary conditions associated with thermionic injection, combined with a Braginskii transport code for the electron temperature.

I. INTRODUCTION

There is a long history to the topic of currents drawn from a heated cathode that emits electrons, i.e., thermionic emission. An extensive literature exists on the subject, pre-dating the seminal work of Richardson leading to the 1928 Nobel prize in physics. For plasma researchers, often interested in using the thermionic process to generate energetic beams or to create neutral plasmas by ionization, the phenomenon is intrinsically linked to the problem of space-charge limited flow, commonly referred to as the Child-Langmuir law. In the one-dimensional limit, for injection into a vacuum (i.e., a diode), this law predicts that the thermionic current increases as the 3/2 power of the voltage applied with respect to an anode that is not too distant from the injector. As the distance to the anode increases, the finite size of the cathode becomes relevant. For two-dimensional (2D) geometry, particle simulations by Luginsland et al., and a simple theory by Lau, have demonstrated that the 2D rearrangement of the equipotential profiles allows the extracted current to exceed the Child-Langmuir limit as the distance to the anode is increased. Further 2D simulations by Kumar and Biswas have addressed the time-dependent behavior encountered for large injection currents. They also find that, on average, the transmitted currents can exceed the Child-Langmuir limit.

The space-charge limit is also modified if the thermionic cathode is in contact with a nominally neutral plasma. The significant additional process in this case is the partial cancelation of the injected negative charge by the flow of ions from the bulk of the plasma. The interplay between thermionic and ion currents led to the concept of emissive probes, which are extensively used to measure plasma potential, but whose detailed operation is still the subject of research. Emissive probes were used by Intrator et al. to map the extended potential structures created by a hot cathode immersed in an unmagnetized, triple plasma machine, under conditions that could be approximated as being collisionless. Two observations by Intrator et al. of relevance to the present study are that the global potential structure of the device can be altered by thermionic injection, and that the underlying processes are three-dimensional.

An application of thermionic emission that has not received much attention is the generation of plasma flows corresponding to the $E \times B$ velocity driven by global potential structures of the type mapped by Intrator et al., but in a magnetized plasma. A notable example is the work by Taylor et al., in which electron-emissive injectors inside a tokamak are used to generate plasma rotations that induce H-modes. Another is the experiment by
Moon et al.\textsuperscript{12} in which control of the space potential gradient is achieved, in a linear device, by the superposition of thermionic electrons on plasmas created by electron cyclotron resonance.

The present study involves an experimental arrangement in which thermionic emission induces global flows in a large, magnetized plasma. In addition to the various processes mentioned previously (finite cathode size, ion flow, magnetization, 3D) in the results reported here the distance between the cathode and the anode is more than a thousand collision-lengths; thus, the anode and the injector are connected by a global current system. The parameters of the experiment are such that the Ohmic current induces significant plasma heating without ionization.

A LaB$_6$ thermionic emitter of annular shape is used in the Large Plasma Device (LAPD) at the University of California, Los Angeles (UCLA)\textsuperscript{16} to create off-axis heating conditions for various transport studies.\textsuperscript{17,18} Since the emitter is biased relative to a distant anode (15 m apart), the entire magnetized plasma develops a self-consistent, potential structure that simultaneously generates transverse and axial flows with shear. Swept Langmuir probe techniques and Mach probes are used to map the three-dimensional flow patterns and their dependence on bias and plasma parameters. Integration of the signals obtained by B-dot probes provides a measurement of the self-consistent currents. By implementing additional biasing configurations, it is possible to control the magnitude of the flows and their shear strength. The experimental measurements are compared to predictions of a new model described in a separate, companion paper by Poulos.\textsuperscript{19} The model calculates the spatial dependence of the plasma potential incorporating the boundary conditions associated with thermionic injection. The model is combined with a Braginskii transport code to calculate the electron temperature self-consistently. The details of the model and additional theoretical considerations in support of the experimental results are reported in the companion paper. It is found that the analysis and modeling provides an excellent, quantitative description of the electron physics measured in the experiment. But a quantitative explanation for the global, field-aligned ion flow has not yet been achieved.

The manuscript is organized as follows. Section II describes the experimental arrangement and measurement techniques. Section III provides a theoretical overview useful in understanding the comparisons made of the model predictions to experimental results. Results of measurements and modeling of the model are presented in Sec. IV. Conclusions are given in Sec. V.

II. EXPERIMENTAL SETUP

The experiment is performed on the upgraded Large Plasma Device (LAPD)\textsuperscript{16} operated by the Basic Plasma Science Facility (BaPSF) at the University of California, Los Angeles (UCLA). A schematic, not to scale, is shown in Fig. 1(a). The LAPD is a cylindrical device, with an axial magnetic field that confines a quiescent plasma column 18 m long and 60 cm in diameter. The plasma is created from collisional ionization of He gas by 70 eV electrons of a large area low-voltage electron beam, produced by the application of a positive voltage between a barium oxide (BaO) coated cathode and a mesh anode 50 cm away. The electron beam heats the plasma to electron temperatures in the range of 5 eV. The active phase lasts for 12 ms and is repeated every second (1 Hz pulse rate). The magnetic field in this experiment is uniform and is set to 1000 G.

In the experiment, a second cathode\textsuperscript{20} is introduced on the opposite side of the LAPD vacuum vessel. The cathode’s emissive surface is ring-shaped and made out of lanthanum hexaboride (LaB$_6$). LaB$_6$ is a refractory ceramic material and is stable in vacuum. It has a low work function, in the range of 2.67–2.91 eV (Refs. 21, 22 and references therein), and one of the highest electron emissivities known when heated to its operating temperature in the range of 1500 °C. The geometry of the ring-shaped thermionic emitter is achieved by masking off an 8 cm diameter LaB$_6$ disk with carbon plates to leave a ring of exposed LaB$_6$ with 4 cm inner diameter and 6 cm outer diameter, as shown in Fig. 1(b). When the LaB$_6$ disk is biased with respect to an axially distant anode 15 m away, electrons are emitted from the LaB$_6$ in the form of a hollow cylindrical “ring.” The discharge voltage applied between the LaB$_6$ cathode and the distant anode is kept below the ionization potential for the helium fill gas, i.e., \( \leq 25\) V. The self-consistent current system produces a hollow, cylindrical high pressure region embedded in the background cold plasma, as shown in Fig. 1(c) which shows a 2D cut of the ion saturation current profile \( I_{sat} \sim n_e \sqrt{Te} \) across the plasma column. Associated with the application of discharge bias between the cathode and anode is a substantial modification of the radial
plasma potential profile, which creates large-scale $E \times B$ flows peaking near the high pressure ring. These potential profiles and their relation to the emissive boundary are the main focus of the paper.

The cathode has been modified slightly from the original design in the work of Van Compernolle et al.\textsuperscript{26} in order to have control over the boundary conditions at the cathode. The inner and outer masks have been electrically isolated from each other and also isolated from the LaB$_6$ disk by ceramic spacers, slightly visible as the white material in Fig. 1(b). Both masks can be biased separately from the LaB$_6$ disk. Figure 1(a) shows schematically the connections to the masks and LaB$_6$. Each is biased with respect to the main LAPD anode through a gated transistor switch. The current to each mask and to the LaB$_6$ is monitored with Pearson current monitors. The sum of these three measured currents is the total current emitted by the cathode assembly. A fourth current monitor measures the current collected by the anode. The current measured on the anode current monitor equals the total current emitted by the cathode assembly, indicating all the current is accounted for and no current goes through the vessel wall. The location of the current monitors is schematically shown in Fig. 1(a). The current traces and the bias voltages of each component are digitized as standard practice in the experiment. It should be noted that the discharge voltage quoted in this paper is the voltage difference measured between the respective cathode component and the anode. These voltages differ from the voltage on the capacitor bank connected to the transistor switch since there is some voltage drop in the long electrical connectors running to the cathode and anode. Previous reported results\textsuperscript{17,18} used the capacitor bank voltage as the discharge voltage. This paper reports the actual anode-cathode voltage difference because this is used as a direct input to the modeling without the need to account for the electronics of the transistor switch or the resistive drop across the leads to the anode and cathode.

The present experiment is performed during the afterglow phase, after the active phase of the LAPD discharge is terminated. In the afterglow phase, the 70 eV beam from the BaO cathode is turned off, and the electron temperature falls below 0.5eV within 100 ms while the plasma density decreases on a time scale of tens of milliseconds. The time evolution of the electron density, $n_e$, and temperature, $T_e$, in the afterglow phase are shown in Fig. 2 in the absence of heating by the LaB$_6$ source. The shaded regions indicate the time during which the LaB$_6$ thermionic emitter is active, i.e., biased negative with respect to the anode. Panel (c) shows the typical temporal evolution of the discharge voltage and discharge current of the LaB$_6$ source when it is active. The majority of the results presented here focus on the plasma properties 1 ms after the LaB$_6$ bias is turned on, indicated by the dotted line in Fig. 2. This is a time after the initial transients have decayed and before any major pressure-driven instability develops. Instabilities occurring in the experiment are discussed elsewhere.\textsuperscript{17,18} In the subsequent sections, the start of the heating pulse is taken as $t = 0$ and the axial location of the LaB$_6$ cathode as $z = 0$. The heating pulse typically lasts for 10–20 ms.

The properties of the LAPD plasmas are sampled with probes through vacuum ports spaced every 32 cm along the axial direction ($z$-axis) of the cylindrical vacuum chamber. Probes are inserted into the vacuum chamber through ball valves \textsuperscript{23} which allow for 3D movement. Probes are mounted on an external probe drive system and can be moved to a prescribed position with sub-millimeter accuracy. The data acquisition system is fully automated; it controls the digitizers and the probe drive system. Typically, a probe moves through a series of user defined $(x, y, z)$ transverse positions at a fixed axial position, $z$. At each position, data from several plasma pulses are acquired and stored, before moving to the next position. Since the LAPD plasma is highly reproducible, an ensemble measurement of the plasma parameters can thus be obtained. The main set of probe diagnostics in this experiment sample the plasma potential, electron temperature, and density. Information about these quantities is obtained from the I-V characteristic of a swept Langmuir probe. These diagnostics are complemented by six-faced Mach probes as described in the paper by Gunn et al.\textsuperscript{24} to obtain the velocity profiles. Magnetic field measurements with 3-axis pick-up loops are used to obtain the radial profile of parallel current.

**III. THEORETICAL MODEL**

An iterative procedure is used to calculate the spatial dependence of the plasma potential and plasma currents in terms of the externally applied bias and surface temperature of the emissive cathode-surface. This is done in two steps: first the potential is determined,\textsuperscript{19} and second, this potential is used via a
Braginskii transport code\textsuperscript{25} to obtain the associated currents, resulting Ohmic heating term, and the electron temperature. The updated electron temperature and corresponding plasma conductivity feeds back into the calculation of the plasma potential. The procedure is initialized with the plasma parameter values measured prior to applying the bias to the cathode. Attaining a solution that can be compared to experimental measurements requires a few iterations. The system is assumed to be azimuthally symmetric.

A detailed description of the model used in this manuscript and additional supporting details are provided in a companion paper.\textsuperscript{19} Here, only a brief summary of the important details is given. The model for the plasma potential is outlined in Sec. III A. The Braginskii code calculation of the electron temperature is discussed in Sec. III B, and the feedback of the temperature increase on the plasma potential model is shown in Sec. III C.

### A. Plasma potential model

The model seeks the global shape of the plasma potential in terms of the externally applied bias and surface–temperature of the emissive cathode–surface. This is accomplished by partitioning the plasma into three regions: the cathode–sheath, the bulk of the plasma, and the anode sheath. The electric potentials for each region are solved in parallel and matched at the interfaces between the sheaths and plasma.

In the bulk of the plasma, the steady-state perpendicular and parallel currents are expressed in terms of the plasma potential $\phi$ via Ohm’s law

$$j_\perp = -\sigma_\perp \nabla_\perp \phi, \quad j_\parallel = -\sigma_\parallel \nabla_\parallel \phi.$$  \hfill (1)

For a partially ionized and strongly magnetized plasma, such as for the afterglow conditions considered here, the dominant contribution to the perpendicular conductivity $\sigma_\perp$ is due to collisions between ions and neutrals

$$\sigma_\perp = 2.13 \frac{e^2 n_{\text{in}}}{M \Omega^2},$$  \hfill (2)

and the parallel conductivity $\sigma_\parallel$ results from Coulomb collisions between electrons and ions

$$\sigma_\parallel = 1.96 \frac{e^2 n_e}{m}.$$  \hfill (3)

where spatial variation of the electrical conductivities is assumed negligible, and $\sigma_\parallel$ is evaluated in an averaged sense, as discussed in Sec. III C.

At the axial boundaries of the machine, the matching condition for the sheath–plasma interface

$$\nabla_\parallel \phi = -\frac{1}{\sigma_\parallel} \left[ j_\parallel (1 - e^{\psi_{\text{sheath}}}) + j_{\text{enh}} \right],$$  \hfill (4)

equations to the plasma potential in the absence of the thermionic emission, and $\psi_{\text{sheath}} \equiv \phi_{\text{plasma}} - \phi_{\text{wall}}$ is the potential-drop across the sheath. The ion saturation current, $j_\parallel \equiv e n_{\text{enc}}$, is set by the ion-sound speed, $c_s \equiv \sqrt{T_e/M}$, at the sheath–plasma interface.

In the absence of virtual cathode formation, the thermionic-electron current density $j_{\text{enh}}$ is assumed to obey Richardson’s law

$$j_{\text{enh}} = C_n T_e^3 \exp \left( -\frac{e \psi_{\text{sheath}}}{T_e} \right),$$  \hfill (6)

where $T_e$ is the surface-temperature of the emissive cathode, $\psi_{\text{sheath}}$ is the work-function of the material, and $C_n$ is a material-dependent constant.

For large thermionic current compared with the ion saturation current, the space-charge carried by the plasma-ions may be insufficient to cancel with the space-charge of the thermionic-electrons, and the result is the formation of a virtual cathode, a minimum in the sheath-potential, which limits the total thermionic current. Solving the one-dimensional Poisson’s equation in the sheath region under the constraint of monotonicity\textsuperscript{19} yields a threshold condition for virtual cathode formation

$$j_{\text{enh}} \leq \frac{e \psi_{\text{sheath}}}{T_e} + \sqrt{1 + 2 \psi_{\text{sheath}} - 2 \frac{e \psi_{\text{sheath}}}{T_e}}.$$  \hfill (7)

where $\psi_{\text{sheath}} \equiv e \phi_{\text{sheath}}/T_e$ is the scaled potential-drop across the sheath. In the situation where Eq. (7) is violated, the thermionic current-density for the matching condition in Eq. (5) is replaced with its critical value.

Evaluation of Eq. (4) subject to the matching condition (5) with constraint (7) yields the global shape of the plasma-potential for a given externally applied bias and cathode temperature.

### B. Ohmic heating

The plasma potential model is combined with a Braginskii code\textsuperscript{21} which previously modeled the source-term in the equation of electron heat-balance as an ideal heat-source with uniform power density, which had to be postulated. Here, the new addition to the Braginskii code is the self-consistent calculation of the steady-state current-system sourced from emissive-sheath boundaries,\textsuperscript{26} i.e., the result of the plasma potential...
model. The Ohmic heating induced from the global current-system in the plasma replaces the ideal heat-source in the equation of heat-balance, allowing the increase in temperature to be self-consistently calculated from

\[ \frac{3}{2} n \frac{dT_e}{dt} = \nabla_\parallel (\kappa_\parallel \nabla T_e) + \nabla_\perp (\kappa_\perp \nabla_\perp T_e) + Q_J, \tag{8} \]

where the parallel and perpendicular thermal conductivities are as given by Braginskii

\[ \kappa_\parallel = 3.16 \frac{nT_e r_e}{m}, \tag{9} \]

and

\[ \kappa_\perp = 4.66 \frac{nT_e}{m \Omega_e^2 r_e}. \tag{10} \]

The heat-source \( Q_J \) accounts for the local increase in temperature due to Joule-heating

\[ Q_J = \sigma_\parallel (\nabla_\parallel \phi)^2. \tag{11} \]

For the experimental regime considered here, the potential-drop across the cathode-sheath is much smaller than the resistive-drop across the plasma, which implies that primary heating from collisions with the injected electrons is negligible. Thus, heating of the plasma is modelled as entirely Ohmic.

C. Feedback from heating

The feedback from electron heating into the plasma potential model is important in evaluating the boundary condition at the cathode [Eq. (5)], and to a lesser extent in solving for the potential in Eq. (4). The increased electron temperature near the cathode determines the parallel conductivity used when matching the current in the plasma to the current in the cathode sheath in Eq. (5). The accurate modeling of the total current with applied bias depends on the implementation of this feedback. A self-consistent cathode-spot model may be used, or, alternatively, it may be numerically obtained from a Braginskii transport code, as is done here. It has been verified that for the conditions of relevance to the present experiment the two methods yield indistinguishable results.

While the Braginskii code returns \( T_e \) as a function of radial and axial position, the electrical conductivity in Eq. (4) is assumed uniform. An axial averaging scheme is used to self-consistently update its value based on the instantaneous temperature calculated from the transport code. To consistently define the averaged temperature, it is helpful to consider a collection of resistors in series between anode and cathode. The resistance of each resistor depends on the local temperature to the negative 3/2-power, and summation yields the total resistance. These considerations motivate the following axial averaging procedure for calculating the averaged temperature

\[ \langle T_e \rangle = \left[ \frac{1}{T_e} \int_0^z dz \frac{1}{T_e^2} \right]^{-2/3}. \tag{12} \]

The averaging procedure is performed on the field line at the center of the ring-cathode \( r = 2.5 \text{ cm} \), corresponding to the radial location where the parallel current is the largest.

Note that for the experimental regime considered here, the electron temperature increases are modest and occur only in the near-cathode region of the device. Thus, the feedback of the self-consistently calculated electron temperature is a second-order correction to the plasma model results, but nevertheless ensures a closer agreement with the experimental data.

IV. EXPERIMENTAL RESULTS AND MODEL PREDICTIONS

A. Model input parameters

The input parameters to the model are LaB\(_6\) cathode temperature \( T_{\text{LaB}6} \), LaB\(_6\) work function, material-dependent Richardson constant \( C_m \), neutral density \( n_0 \), ion temperature \( T_i \), ion mass \( M \), magnetic field \( B_0 \), electron density \( n_e \), electron temperature \( T_e \), applied bias potential \( V_b \), geometry of the ring-cathode, and geometry of the LAPD (length and radius). The parameters with the greatest uncertainty are the neutral density, the ion temperature, both of which enter in the ion-neutral collision frequency in Eq. (2), and the LaB\(_6\) cathode temperature.

The background density, at \( 4 \times 10^{11} \text{ cm}^{-3} \), and the background electron temperature at 0.2 eV are obtained from measurements just prior to the turn-on of the ring-source. Note that the electron temperature is updated self-consistently in the model, as explained in Secs. III B and III C. The background magnetic field, applied bias potential, ring-cathode geometry, and LAPD geometry are all known to a high degree of precision.

The ion temperature in the LAPD during the discharge was not measured explicitly in this experiment, but it has been measured in other experiments under similar discharge parameters. During the LAPD discharge, the typical ion temperature is 1 eV, and then decays in the afterglow. The ion temperature in the model is 0.5 eV.

The model assumes a constant neutral density throughout the device, which is a reasonable approximation in the afterglow plasma, when the ionization fraction drops below the 10% range. The neutral pressure in LAPD is measured with ion gauges. The gauge pressure reported in the central section of the LAPD was 2.4 \( \times \) 10\(^{-5}\) Torr; adjusting for the gauge sensitivity to helium (gas correction factor of 0.18) leads to helium pressure of 1.33 \( \times \) 10\(^{-4}\) Torr, which in turn leads to a neutral density of \( 4 \times 10^{12} \text{ cm}^{-3} \), using the ideal gas law and assuming the neutrals are at room temperature. Further confidence in the neutral density is that the LAPD during the main discharge phase is typically about 50% ionized. Densities measured with Langmuir probes, and calibrated with interferometers, are near \( 2 \times 10^{12} \text{ cm}^{-3} \) during the main discharge phase and agree with the 50% ionization. In the afterglow of the LAPD discharge, when the ring-experiment is performed, the plasma density drops steadily, and the neutral density rises to near the value of \( 4 \times 10^{12} \text{ cm}^{-3} \). For the model, the neutral density was chosen as \( 4 \times 10^{12} \text{ cm}^{-3} \). The sensitivity of the model on the ion-neutral collision frequency and, thus, implicitly on the neutral density and the ion temperature are discussed in Sec. V.
The surface temperature of the LaB$_6$ is determined using an Omegascope OS3750, an infrared pyrometer, from a distance of 6 m away. The long distance makes an accurate reading of the 1 cm wide LaB$_6$ ring difficult. The maximum temperature recorded for a given LaB$_6$ heater power is retained as $T_s$ for that heating power. A local hot spot on the cathode, however, could throw off the reading of $T_s$. The optimum value of the work function of the LaB$_6$ ring that results in the best agreement with the data is 2.9 eV, which is higher than the typical value of 2.67–2.91 eV. The discrepancy most likely lies in the uncertainty of the measured surface temperature. If the measured temperatures, however, are consistently higher than actual temperatures by about 50°C, then the model predictions would match the experiment using a work function of 2.9 eV, in line with the established value for this quantity.

It is important to stress from the outset that one set of input parameters is chosen for all the comparisons presented in the manuscript. This set of input parameters, and more specifically the value of the neutral density, the ion temperature, and the LaB$_6$ work function, is chosen to optimize the model prediction to one case of experimental conditions, as discussed further in Sec. V, and is then kept fixed while the cathode bias voltage and the cathode temperature are varied.

**B. Emissive vs non-emissive behavior**

The difference of having a thermionic boundary condition compared to a cold-sheath boundary condition is investigated by varying the input power to the heater of the LaB$_6$ cathode assembly. During the power scan, both masks and LaB$_6$ emitter are tied together electrically; all the elements are biased using the same discharge pulser. Figure 3 shows the currents flowing through the different components as the LaB$_6$ surface temperature $T_s$ is varied following the change in heater power. The cathode is biased to –12 V with respect to the anode. The LaB$_6$ discharge pulser is turned on 2 ms after the end of the LAPD BaO cathode discharge, and stays on for 20 ms. The data shown in Fig. 3 are a snapshot at $t = 1$ ms, i.e., 1 ms after the LaB$_6$ discharge pulser is triggered. The currents are normalized to the total current at the lowest value of $T_s$, which is close to the ion saturation current for the cold cathode. The term “cold” in this case refers to non-emissive. While the currents flowing through the inner and outer carbon masks remain approximately constant throughout the temperature scan, the LaB$_6$ current shows a clear transition from non-emissive at the lower $T_s$ to emissive at the higher $T_s$. The saturation in the emitted current is reached for a temperature $T_s$ around 1500°C, which is defined here as the critical temperature $T_c$. The horizontal axis is normalized to $T_c$. For $T_s < T_c$, the LaB$_6$ current is essentially constant and in saturation. As discussed in Secs. III and IV of the companion paper, there are two factors that lead to the saturation of total current as the surface temperature is increased and the externally applied bias is held fixed: (1) the total current cannot exceed the externally applied bias divided by the plasma resistance; (2) thermionic current values violating Eq. (7) form a virtual cathode, which limits the total current to the critical value. For the externally applied bias of –12 V, the critical temperatures for these two different limiting factors nearly coincide. Regardless, the predicted saturation is essentially identical for both limiting factors. As the temperature is reduced below $T_c$, there is a rapid change in the LaB$_6$ emission current which is a consequence of the exponential dependence of the thermionic current on the surface temperature, as in Eq. (6). For $T_s \ll T_c$, the thermionic current is essentially zero. The current collected by the LaB$_6$ ring is then comprised of ion saturation current to the cathode due to the large negative bias (compared to the electron temperature) of the cathode with respect to the anode. In the rest of the paper, the cathode is held at constant temperature in the emissive regime; this operating point is indicated by the circle in Fig. 3. The predicted dependence of the LaB$_6$ current by the model outlined in Sec. III is shown as the solid red line in Fig. 3, and is in good agreement with the data.

Figure 4 shows the radial profiles of the corresponding plasma potential at an axial position $z = 2.56$ m associated with the temperature scan. Dashed lines are the experimentally measured profiles. Solid lines are the model predictions. Radii are normalized to the ion sound speed prior to the LaB$_6$ discharge pulse; potentials are normalized to the pre-turn-on value of $T_s$. The vertical dashed lines at $r = 2$ cm and $r = 3$ cm indicate the position of field lines connected to the edges of the LaB$_6$ ring. The outer mask extends from $r = 3$ cm to $r = 7$ cm. The radial profiles shown here and throughout the paper are not azimuthally averaged, but instead correspond to the radial profiles along one azimuthal angle, chosen to be the least perturbative by insertion of the probe. The overall shape of the radial profiles can be described as a “hockey stick.” Far from the cathode assembly ($r > 10$ cm), the plasma potential asymptotes to a fixed value. This value corresponds to the value of the flat plasma potential profile measured before the ring-shaped LaB$_6$ source is turned on (similar to 0 V case shown later in Fig. 6). Near $r = 0$ cm, the plasma potential dips by several volts, a
At low LaB₆ temperatures, i.e., Tₛ < Tₑ, the potential profile does not vary with Tₑ. The profile changes smoothly from a minimum at r = 0 cm to its ambient value, i.e., the value far from the cathode where plasma parameters are essentially unperturbed by the ring-experiment. Since both the carbon masks and the LaB₆ are then non-emissive, there is no signature of the LaB₆ ring. The steepest change in plasma potential occurs near r = 7 cm which is at the edge of the applied bias. The E × B flow peaks, therefore, on field lines connected to the edge of the cathode assembly. As the temperature Tₛ is raised, the LaB₆ ring becomes emissive, resulting in a smaller sheath voltage drop at the LaB₆ compared to at the carbon plates. A large fraction of the applied bias then appears as a potential drop across the plasma. The plasma potential profiles on field lines connected to the LaB₆ are lowered. The minimum of the profile now occurs on field lines connected to the LaB₆ ring. The largest change in potential happens near the outer edge of the ring. Note that the slope of the plasma potential is opposite for r < 2 cm compared to r > 2 cm, meaning that the E × B flow is oppositely directed on the inside of the ring compared to the outside. For Tₛ > Tₑ, the potential profiles do not vary with Tₑ as the LaB₆ emission has saturated. Figure 4 shows that the presence of the emissive surface causes a much larger radial potential drop and stronger E × B flows compared to the non-emissive case, indicating that emissive surfaces are a good choice of boundary material to manipulate flows in a magnetized plasma.

C. Dependence on bias voltage

A complementary scan of the applied bias Vₑ at fixed Tₛ is performed to elucidate the underlying physics. The LaB₆ temperature is held fixed at Tₛ = 1730 °C, which is in the saturated state as indicated by the circle in Fig. 3. For this Vₑ scan, the masks and the LaB₆ are tied together. The bias voltage is varied from 0 V to 16 V. The results for higher voltages are not presented since under such conditions the onset of instabilities in the plasma is nearly immediate after the turn-on of the LaB₆ discharge pulsers.

For a cathode temperature of Tₛ = 1730 °C, with an externally applied bias of less than 16 V, the thermionic current density is well into the virtual cathode regime, where the value of the thermionic current density is irrelevant to the behavior of the system as long as it remains above the critical value. As discussed in detail in Sec. VI of Poulos, the self-consistent increase in plasma temperature with increasing applied bias introduces a non-linearity to the Ohmic behavior of the plasma due the temperature dependence of the parallel conductivity. An increase in applied voltage across the plasma increases the temperature, which, in turn, feeds back on the current via the change in plasma resistance.

The dashed lines in Fig. 5 indicate the measured currents flowing through the various elements as the applied bias is varied. The solid line is the model prediction for the LaB₆ current. The currents are normalized to the total current collected by the cathode when it is non-emissive, as in Fig. 3. The LaB₆ currents and mask currents all increase with applied bias. Note that the LaB₆ current increases faster than linearly with Vₑ, the latter
initially expected from the model, if the electron temperature is independent of the bias voltage. However, in the actual experiment as the bias voltage increases, the Ohmic power input increases and thus the temperature rises, as determined by collisional transport. This increase in $T_e$ with increased $V_b$ is responsible for the faster than linear rise in LaB$_6$ current. The specific non-linearity associated with the self-consistent increase in temperature was obtained. Similarly the currents to the masks show a slight increase with applied bias since $T_e$ is changing with applied bias.

The radial profiles of plasma potential for different values of the bias voltage $V_b$ are shown in Fig. 6. The dashed lines are the experimentally measured profiles; solid lines are the model predictions. At 0 V of applied bias, the profile is flat and identical to the pre-turn-on profile. As the bias is increased, the potential profile evolves into the “hockey-stick” shape. The potential drop increases slightly faster than linear with $V_b$, as discussed for Fig. 5. The model predictions are again seen to be in excellent agreement with the measured profiles. Note that increasing $V_b$ at this fixed $T_e$ has a similar effect on the plasma potential profile shape as increasing $T_e$ for fixed $V_b$ as in Fig. 4. As $V_b$ is increased, the minimum in the profile moves from $r = 0$ cm to $r = 2$ cm, and as a result, the oppositely directed flow on the inside of the ring appears and becomes stronger with increasing $V_b$. The result is a flow profile with a strongly sheared flow. The qualitatively similar behavior of Figs. 4 and 6 results because the voltage drop across the plasma increases both with $T_e$ and with $V_b$ as shown in Fig. 4 of the companion paper by Poulos.

D. Spatial dependence of plasma properties

The results previously presented focused on the radial dependence of the plasma potential at fixed axial location $z$. In this subsection, the combined axial and radial variation of the plasma potential and flows are examined. The results shown in this section have the LaB$_6$ ring and both masks biased to the same potential as in Secs. IVB and IVC. The bias voltage $V_b$ is $-12$ V, and $T_e = 1730$ °C.

Figure 7 displays the radial profile of the plasma potential at four axial locations. Dashed lines are the experimental results; solid lines show the model predictions. The plasma potential is seen to exhibit a rapid axial variation close to the cathode. The minimum plasma potential on the profile scales nearly linearly with distance from the cathode. It is seen from Fig. 7 that the model predictions are in excellent agreement also with respect to the axial dependence.

Measured radial profiles of plasma potential, of the type shown in Fig. 7, are used to calculate the expected $E \times B$ flow velocities; the results are displayed as the colored solid curves in Fig. 8. These velocities are compared in Fig. 8 to direct measurements of the perpendicular Mach number $M_\perp$, corresponding to the colored dashed lines. The Mach numbers are obtained with a Gunestrup probe, consisting of 6 collecting faces, each 60° apart, and attached to a 3 mm diameter ceramic cylinder with its axis along a direction perpendicular to the machine axis, i.e., the $x$-axis. The Mach probe, therefore, is able to measure both the parallel and the perpendicular components of the plasma flow velocity. These are given by

$$\frac{1}{b} \ln R = M_\parallel \cot \alpha,$$

with $R = I_{sat1}/I_{sat2}$, the ratio of the ion saturation currents collected by two probe faces 180° apart, and at an angle $\alpha$ with respect to the magnetic field ($\alpha = 90°$ for a probe face with its normal along the magnetic field). $b$ is a constant given by

$$b = 2 \left[ 1 + 0.14 \cosh \left( M_\parallel/0.862 \right) \right].$$

![FIG. 6. Radial profiles of plasma potential for a range of bias voltages $V_b$ at $z = 2.55$ m and for $T_e = 1730$ °C. Dashed lines are the experimental measurements, solid lines are the model predictions. The vertical dashed lines indicate the location of the emissive ring. Note the use of dual display on the axis, in absolute numbers and in scaled form, with radius scaled to the ion sound gyroradius and plasma potential to the ambient electron temperature.](image)

![FIG. 7. Radial profile of the plasma potential at different axial locations, for $T_e = 1730$ °C and $V_b = -12$ V. Colored dashed lines are experimental results and colored solid curves are model predictions. The discrete symbols indicate uncertainties in the measurements. The vertical dashed lines indicate the location of the emissive ring. Note the use of dual display on the axis, in absolute numbers and in scaled form, with radius scaled to the ion sound gyroradius and plasma potential to the ambient electron temperature.](image)
The Mach probe was moved along a radial line through the center of the ring (equatorial cut). As such, the measured perpendicular component of the flow velocity corresponds to the azimuthal component, and can be directly compared to the prediction for the azimuthal component by calculating the $E/C_2 B$ velocity from plasma potential profiles of the type shown in Fig. 7. As a caveat, the data for Figs. 7 and 8 were obtained during two experimental campaigns several months apart in which the background plasma densities were slightly different. Qualitatively the main features observed are consistent between the Mach profiles and the $E/C_2 B$ profiles. It is possible that the major deviations may be a consequence of the resolution of the Mach probe.

Near the cathode, at $z = 2.56$ m, the largest azimuthal flow velocity develops just outside the ring. On the inside of the ring, a weak oppositely directed flow is seen. This counter-rotating flow is not observed far from the cathode, at $z = 4.5$ m and $z = 6.4$ m where the flows are weaker and less sheared. Peak values of the perpendicular flow velocity in the device are less than one-half the sound speed, but are likely higher at positions closer to the cathode. An interesting pattern that emerges from these measurements is that the oppositely directed rotations on the inside of the ring are limited to locations close to the cathode. The counter-rotating flows on the inside of the ring reverse direction within a few meters from the cathode. In contrast, the large azimuthal flows outside of the ring span the whole length of the plasma column.

In addition to the external currents measured by the Pearson current monitors as in Figs. 3 and 5, it is possible to deduce the parallel current density flowing within the plasma by measuring the magnetic field due to the injected current from the LaB$_6$ cathode, i.e., using Ampere’s law

$$J_z(x, y) = \frac{c}{4\pi} \nabla \times B_z(x, y).$$

The magnetic field is measured with a pick-up probe that consists of three orthogonal coils of 3 mm diameter and 50 turns of wire on each coil. The probe is moved on a radial line along the $x$-coordinate through the center of the ring $r = 0$. The measured $B_z$ component of the probe then corresponds to the azimuthal $B_\theta$ component. Assuming azimuthal symmetry, $J_z(r)$ is obtained from

$$J_z(r) = \frac{c}{4\pi} \frac{\partial}{\partial r} (r B_\theta).$$

Through a separate 2D measurement of the magnetic field, it has been confirmed that this procedure with the assumption of azimuthal symmetry yields the same $J_z(r)$ as Eq. (15) does.

Figure 9(a) shows the deduced radial profiles of $J_z$ at three axial positions. Current densities are normalized to the ion sound gyroradius.
saturation current density for the background plasma. Near the cathode at \( z = 0.64 \) m, the parallel electron current density peaks on field lines connected to the LaB\(_6\) cathode as expected. Further away, the current density spreads out radially because of the small but non-zero perpendicular conductivity. Far from the cathode at \( z > 6 \) m, the current density profile becomes peaked on the geometric center, and not on the ring. The model predictions for the parallel current density, shown as the colored solid curves in Fig. 9(b), are in good agreement with the measurements within the ring region, but differ slightly outside the region of emission.

The model predictions for the axial profiles of the parallel current density on the ring at \( r = 2.5 \) cm and in the center at \( r = 0 \) cm are displayed as the colored solid curves in Fig. 9(b). The axial profile is normalized to the ion skin depth \( \delta_i = \sqrt{\pi \sigma_i} \). Axial profiles are difficult to extract in the experiment because of the absence of an axial probe drive in LAPD. Axial information is limited to data taken at selected axial positions. In Fig. 9(b), the model predictions for the axial current density, shown as the colored solid curves in Fig. 9(b), are in good agreement with the measured values. This display clearly shows how the current density is rearranged from a ring-shaped profile to a profile with the largest current density at \( r = 0 \) cm. In absolute terms, the largest current densities are near the cathode on field lines connected to the ring region. These current densities are large enough to do substantial heating of the background plasma.

Figure 10(a) displays the radial profiles of electron temperature for two different axial positions. The main source of heating is Ohmic heating by the current injected from the ring-shaped cathode. A separate source of heating is the thermalization through Coulomb collisions of the injected electrons accelerated in the cathode sheath. The potential drop across the cathode sheath being on the order of 1 V for our typical conditions is, however, too small for this to be a significant source of heating.

The transport code results presented are obtained with only the Ohmic heating by the parallel electron current. Effectively this heat source is limited to one or two meters in front of the cathode where \( J_z \) is substantial on the field lines connected to the LaB\(_6\) ring. This heat source then raises the temperature of the cold, afterglow plasma through parallel and perpendicular heat conduction. It is no surprise that the radial \( T_e \) profile at \( z = 0.64 \) m in Fig. 10(a) nearly coincides with the current density profile of Fig. 9(a). The experimental measured profiles of \( T_e \) agree well with the transport code. The only discrepancy is inside the ring where the experiment reports higher \( T_e \) values than the transport code predicts. This is shown more clearly in Fig. 10(b) which has the axial \( T_e \) profile from the transport code with the measured values overplotted. While the transport code does an excellent job of reproducing the heating of the ring-shaped hot filament, it fails to capture the elevated electron temperature near \( r = 0 \) cm. It is not yet understood what transport mechanisms or source of heating is the cause for this discrepancy.

The measured plasma density, shown in Fig. 11, is similarly peaked on field lines connected to the LaB\(_6\) ring. Dashed colored curves show the profiles 300 \( \mu \)s before the voltage is applied to the LaB\(_6\) ring. Solid colored curves show the profiles at \( t = 1 \) ms.

The observed increase in density on those field lines after the voltage is applied is not expected to arise from pure heating conditions at these small voltage levels, and relatively small temperature increase is achieved. The density increase is conjectured to be a consequence of a change in axial flow because the calculated increases due to any residual ionization are far smaller than the values observed. It should be noted that before the LaB\(_6\) source is turned on, the cold, afterglow plasma density streams out to the boundaries of the machine at the sound speed, including a flow towards the LaB\(_6\) source, as shown later in Fig. 12. After the discharge voltage is applied, however, a new axial flow is set up opposite to this ambient, afterglow outflow.

![Figure 10](image-url)
In a sense, this effect acts as a plug, thereby locally increasing the density. Additional contributions to the density enhancement can result from cross-field pinching due to the ion drag force associated with neutral collisions and also from the ion polarization-drift due to the rapid turn-on of the accelerating voltage. A separate possibility is that a local background density enhancement at a different azimuthal angle than the radial cut in Fig. 11 gets swept up in the strong azimuthal flow at turn-on and is distributed azimuthally symmetrically.

Radial profiles of the parallel Mach number are shown in Fig. 12. Both the profiles at \( t = 1 \) ms and at \( t = -100 \) \( \mu \)s are shown. Before the LaB\(_6\) discharge pulse is applied, the plasma flows in the \(-z\) direction at a fraction of the sound speed, with the fastest flow near the cathode. At \( t = 1 \) ms, however, the plasma is flowing in the opposite direction, away from the cathode, in most places. The strongest flows are observed at \( r = 0 \) cm.

### E. Varying mask bias and flow control

The effect of biasing the carbon masks separately from the LaB\(_6\) ring is examined in this section. Three different scenarios are reported on: (a) biasing the inner mask separately and floating the outer mask, (b) biasing the outer mask separately and leaving the inner mask floating, and (c) biasing the inner mask and outer mask the same. For each scenario, the discharge bias for the LaB\(_6\) ring is kept fixed, while the bias to the respective masks is varied in a range around the fixed LaB\(_6\) bias.

The resulting plasma potential profiles for the scenarios (a) and (b) are reported in Figs. 13(a) and 13(b), respectively. The ratio \( V_m/V_b \) is the ratio of the applied mask bias to the applied LaB\(_6\) bias. It is clear by comparing panels (a) and (b) that the different...
mask bias has an effect on the plasma potential profile on field lines connected to the biased mask, while the rest of the plasma potential profile remains essentially the same as in the case where the LaB₆ and masks are all biased together. As \( V_{m}/V_b \) is lowered, the mask bias is essentially biased less and less negative, which raises the potential on the respective field lines. When biasing the inner mask only as in panel (a), the consequence is that the oppositely directed flow on the inside of the ring is strongly enhanced, as is the flow shear near \( r \leq 2 \) cm. Biasing the outer mask only as in panel (b) has less of an effect on the plasma potential profile, but it does increase the flow and the flow shear substantially just outside the ring.

A more detailed \( V_{m}/V_b \) scan with both masks tied together electrically is shown in Fig. 14. Panel (a) displays the potential profiles, panel (b) the calculated \( E \times B \) profiles, and panel (c) the flow shear profiles, where the flow shear is defined as

\[
\gamma_s = \frac{\partial}{\partial r} \left( \frac{v_{th}}{c} \right). \tag{17}
\]

and normalized to the ion cyclotron frequency \( \Omega_i \). Changes in the plasma potential profiles are evident both on field lines connected to both masks, as well as on field lines connected to the LaB₆ ring, even though its potential is kept fixed. Biasing the masks to a potential more negative than the LaB₆ bias, i.e., \( V_{m}/V_b > 1 \), has little to no effect on the potential and flow profiles. The flow profiles are affected most on the inside of the ring where one can vary the flow from near zero to a substantial fraction of the sound speed. On the outside of the ring the shape of the flow profile is affected, but the magnitude of the flow remains about the same. Perhaps the more significant change as \( V_{m}/V_b \) is varied occurs in the shear profile. Both on the ring-filament and on the outside of the ring the extrema in the flow shear can reach double the magnitude compared to the standard scenario where all masks and LaB₆ are biased together.

Choosing which mask(s) to bias provides control over the flow and shear profile, with the possibility of increasing the shear in one area but not in another. Furthermore, varying the ratio \( V_{m}/V_b \) yields a fine control knob over how much the flow and shear profile are changed which has a major effect on the instability observed in the experiment.

V. DISCUSSION AND CONCLUSIONS

In light of the remarkable agreement between model and experimental results, it is worth discussing the sensitivity of the model results on the chosen input parameters, and the validity of the assumptions. As mentioned in Sec. IVA, there is some uncertainty in the neutral density and the ion temperature, both of which only enter in the model through the ion-neutral collision frequency, \( \nu_{in} \sim n_{in} \sqrt{T_i} \), in the definition of the cross-field conductivity \( \sigma_z \). The dependence on both parameters is weak in the model since the dimensionless parameter of importance is \( \sqrt{\gamma_i/\sigma_z} \), which follows from the scaling of Eq. (4). Therefore, the ion temperature appears as \( T_i^{1/4} \) and the neutral density as \( n_{in}^{1/2} \). To illustrate the dependence of the model results on the neutral density and ion temperature, the plasma potential profiles of Fig. 7 are displayed in Fig. 15 together with the model predictions for a range of ion-neutral collision frequencies, within a factor of 4 around the value used throughout the paper. Model predictions for larger ion-neutral collision frequencies are shaded gray; predictions for lower values are shaded blue. The line at the intersection of the blue and gray shaded regions is the model prediction for the value of the ion-neutral collision frequency used in the model.
frequency used throughout the paper. The full range of model solutions in the shaded regions spans a large section of parameter space: a factor of 4 in neutral density, and a factor of 16 in ion temperatures. The model solutions deviate by less than 30% around the center solution, confirming that the model sensitivity on the neutral density and ion temperature is rather weak. The chosen value for the ion-neutral collision frequency used throughout the paper represents the best fit to the experimental data. A similar sensitivity study was performed to find the optimal value for the work function of the LaB₆ disk. A lower or higher work function shifts the model prediction for Fig. 3 to the left or right, respectively. The optimal value of 3.0 eV is chosen as the best fit to the data. It is important to stress here that while the parameters are chosen to fit a particular case as in Fig. 15, the model can predict a wide range of cases (for varying discharge voltages, LaB₆ temperatures, axial positions) with the same input parameters, which is a strong confirmation that the model is indeed a good representation of the experiment.

Aside from the input parameters chosen, there are some simplifying assumptions to the model. The model assumes azimuthal symmetry. While no experiment is truly fully azimuthally symmetric, the assumption of azimuthal symmetry is good for the ring-cathode experiment. The small non-azimuthal symmetry that appears in Fig. 1(c), for example, is to a significant degree caused by the probe and is not intrinsic to the plasma. Such an interference arises because the probes are normally inserted from the right-hand side (when looking into the figure displayed) and thus the probe and the support shaft cut across the ring profile to access the region associated with the top, left-hand side of the figure. The azimuthal flow of the plasma is in the counter-clockwise direction in this picture. Therefore, when the probe tip is at the top left hand side, the flowing plasma is partially blocked by the probe shaft and results in a slight depression in the probe signal. Overall, the system can be considered to be azimuthally symmetric to a practically significant degree, as verified by stationary probes that are inserted from the left-hand side. The small natural asymmetries due to construction and alignment errors are partially mitigated by the strong azimuthal flow which tends to smooth out any azimuthal asymmetry.

This investigation has explored the effects produced by thermionic injection at the boundary of a magnetized plasma in which the distance between the cathode injector and the accelerating anode is much larger than the mean free-path for Coulomb collisions. It has been documented that in such an environment the thermionic process causes a global rearrangement of the plasma potential structure, even under conditions when no additional ionization occurs. The electric field associated with the potential structure is observed to drive Ohmic currents that increase the electron temperature, and also induces plasma flows. By using swept Langmuir probes, Mach probes, and B-dot loops, these features have been measured for a wide range of cathode temperatures and accelerating voltages. A detailed comparison has been made to predictions of a new transport/thermionic model presented by Poulos in a companion paper. It is found that all the features associated with electron dynamics, i.e., plasma potential, electron temperature, Ohmic currents, and \( \mathbf{E} \times \mathbf{B} \) drifts, including their dependencies on cathode temperature, can be quantitatively described by the model within the experimental uncertainties. A surprising and challenging finding that deserves future investigation is that the observed parallel ion flows cannot be explained in terms of the same classical processes that successfully predict the electron behavior. It is suggestive that some form of nonlocal transport regulates the ion behavior.

For the particular annular cathode arrangement used in the study, it has been found that the three-dimensional structure of the plasma potential results in \( \mathbf{E} \times \mathbf{B} \) flows, within the hollow region, that rotate in the opposite direction to those in the outer portion of the structure. But the oppositely directed rotation has a finite axial extent, as measured from the cathode. The consequence is that a region of strong flow-shear exists on the inner gradient of the pressure profile generated by the ring cathode. This finding explains the previously reported observations that the inner gradient remains quiescent while the outer gradient can be strongly unstable, leading to avalanche events.

The support structure of the annular cathode has been electrically configured so that the separate elements can be individually biased while achieving net thermionic injection. It has been demonstrated that such an arrangement allows for independent control of the flow and shear profiles while generating a localized pressure profile. Such a configuration provides a useful environment for studies of plasma turbulence in sheared flows.

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