Enhanced diamagnetic perturbations and electric currents observed downstream of the high power helicon

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The high power helicon (HPH) is capable of producing a high density plasma ($10^{17} - 10^{18}$ m$^{-3}$) and directed ion energies greater than 20 eV that continue to increase tens of centimeters downstream of the thruster. In order to understand the coupling mechanism between the helicon antenna and the plasma outside the immediate source region, measurements were made in the plasma plume downstream from the thruster of the propagating wave magnetic field and the perturbation of the axial bulk field using a type ‘R’ helicon antenna. This magnetic field perturbation (AB) peaks at more than 15 G in strength downstream of the plasma source, and is 3–5 times larger than those previously reported from HPH. Taking the curl of this measured magnetic perturbation and assuming azimuthal symmetry suggests that this magnetic field is generated by a (predominantly) azimuthal current ring with a current density on the order of tens of kA m$^{-2}$. At this current density the diamagnetic field is intense enough to cancel out the $B_0$ axial magnetic field near the source region. The presence of the diamagnetic current is important as it demonstrates modification of the vacuum fields well beyond the source region and signifies the presence of a high density, collimated plasma stream. This diamagnetic current also modifies the propagation of the helicon wave, which facilitates a better understanding of coupling between the helicon wave and the resultant plasma acceleration. © 2011 American Institute of Physics. [doi:10.1063/1.3574753]

I. INTRODUCTION

Helicon experiments have successfully produced high density plasma ($>10^{18}$ m$^{-3}$) over a wide range of parameters, including background magnetic field strengths, RF input powers, operating frequencies, and neutral densities. This has led to the development of helicon systems for in-space propulsion concepts, double-layer experiments, and to study the effect of dense plasmas on background magnetic fields. Helicon plasma sources require a base magnetic field to propagate the helicon wave along and limit the movement of electrons across the source region due to the oscillating antenna fields. The relationship between the energy density of this imposed magnetic field and the energy density of the plasma is part of what determines the evolution of the plasma and is commonly represented by Eq. (1) the plasma thermal beta, $\beta_{\text{thermal}}$

$$\beta_{\text{thermal}} = \frac{nkT_e}{\frac{B^2}{2\mu_0}},$$

the ratio of the plasma thermal pressure to the magnetic pressure, as determined by the plasma density and electron temperature and the external magnetic field strength. For cases of high beta plasmas it is expected that the plasma pressure will act to deform the external magnetic field instead of following the magnetic field lines. A high beta plasma with a large gradient in plasma pressure is expected to exhibit a large diamagnetic effect, with the magnetic field being pushed out from the dense region and creating a region of low local magnetic field.

The effects of high beta plasmas on their surrounding magnetic fields have been demonstrated in the laboratory environment with limited success. An experiment by Stenzel et al. conducted in a uniform background axial field ($B_0 = 5$ G, $n_e \leq 8 \times 10^{11}$ cm$^{-3}$, $kT_e \leq 5$ eV) was able to cancel the base field for a plasma thermal beta ratio of 5 but not for $\beta_{\text{thermal}} = 1$ as would be expected. Even though $\beta_{\text{thermal}}$ exceeded unity for more than 150 $\mu$s in the afterglow of the discharge, the magnetic field returned to $\sim 5$ G much faster than was expected based on diffusion of the field into the plasma. The rise in the base field was correlated in time with the loss of the high energy tail of electrons ($kT_e \sim 50$ eV) that were responsible for light production in the discharge and not with the bulk thermal electron population providing the plasma pressure used to estimate $\beta_{\text{thermal}}$. An experiment conducted by Banerjee et al. under similar conditions reported that even with $\beta_{\text{thermal}} \sim 10$ their base magnetic field was not entirely cancelled on axis.

A more recent experiment was performed by Corr et al. with a helicon source firing into a dipole field along the axis. Their results indicated a 2% decrease along the axis of the 34 G base field for $\beta_{\text{thermal}} = 2$ or a total field change of $< 1$ G. Their magnetic field strength was high enough to magnetize the ions in the plasma plume, unlike the case of Stenzel et al., and they also concluded that the lack of a strong diamagnetic signal was the result of the field rapidly diffusing into the plasma.
In the early work on the high power helicon (HPH) experiment, Ziemba et al.\textsuperscript{1} also measured a perturbation of the base magnetic field downstream of the source. It developed as the plasma flowed downstream and lasted for a few hundred microseconds. It was a few gauss in strength on the axis and was diamagnetic, similar to what was measured by Stenzel\textsuperscript{6} and Corr.\textsuperscript{5}

Another parameter that is important for the evolution of the plasma and external magnetic field downstream of the source is Eq. (2) the square of the Alfvén mach number,\textsuperscript{7}

\[
M_a^2 = \frac{V_a^2}{V_a} = \frac{n_i m_i V_a^2}{\frac{B^2}{\mu_0}},
\]

the ratio of the plasma velocity to the Alfvén speed, which is proportional to the ratio of the directed kinetic energy density along the thruster axis to the magnetic pressure. Optimal performance of the thruster requires that \( M_a \gg \beta_{\text{thermal}} \) (i.e., more directed energy than thermal energy) and \( M_a \gg 1 \) the plasma is super-Alfvénic so that plasma is able to escape the source without significant return flow.

Early estimates of the plasma velocity downstream of the HPH by Ziemba et al.\textsuperscript{1} using the time of flight between Langmuir probes revealed that the plasma was accelerating downstream of the source, with the bulk of the plasma traveling at 4 km/s within the first 15 cm but traveling at 7 km/s by the time it was 70 cm downstream. It was uncertain at the time whether this acceleration was due to the formation of a double-layer similar to that seen by Charles,\textsuperscript{10} or if it could be the result of the helicon wave continuing to couple energy into the plasma downstream of the source region. Measurements of the directed ion energies (>20 eV) by Prager\textsuperscript{10} with a retarding field energy analyzer (RFEA) similar to that of Conway et al.\textsuperscript{11} that could be moved downstream and the earlier time of flight estimates by Ziemba\textsuperscript{1} both indicated that the Alfvén mach number was greater than unity within 10–20 cm of the source region along the thruster axis. In order to characterize the helicon wave downstream of the plasma source and determine if it could be responsible for the downstream plasma acceleration, Prager et al.\textsuperscript{12} measured the magnetic component of the helicon wave downstream of the source with an integrated B-dot coil near the frequency of the antenna (~560 kHz). Estimates of the wavelength (~30 cm) closely matched what was expected given the length of the half-wave antenna (15 cm).

In this work the HPH system was modified with a new antenna similar to the ‘R’ antenna used in Light et al.\textsuperscript{13} to increase the coupling to the driven wave measured by Prager et al.\textsuperscript{12} and determine what effect that would have on the downstream plasma parameters such as density, \( \beta_{\text{thermal}} \), and \( M_a \). This resulted in a significantly larger diamagnetic decrease in the magnetic field than was previously observed, with the peak of the perturbation greater than 15 G, and an extended region along the axis where the field was 100% excluded from the plasma. This result is important as it demonstrates that the helicon can produce significant magnetic perturbations well away from the source region, which has potential consequences for long distance beam/plasma interactions. One consequence of the diamagnetic cavity is that the propagating wave field could not propagate into it, which limits deposition of the energy into the plasma.

This paper presents measurements of the perturbation to the base magnetic field of the HPH system, as well as an estimate of the oscillating wave magnetic field strength and an estimate of the azimuthal diamagnetic current. Section II describes the HPH system and the plasma diagnostics that were used. Section III details the measurements of the magnetic field perturbation along the axis with time and compares them to measurements of the plasma density and the wave magnetic field. Section IV then presents axial, radial, and azimuthal \( \Delta B \) measurements with a 2D cut across the source axis. The downstream current density is estimated using these data and is shown to peak at greater than 20 kA m\textsuperscript{-2}. Section V will discuss the properties of the diamagnetic perturbation and suggest some conclusions and future work to be performed.

II. EXPERIMENTAL SETUP

The HPH experiment has been conducted in the large vacuum chamber at the University of Washington Advanced Propulsion Laboratory. The experimental apparatus for HPH has been described previously\textsuperscript{1,7,10,12} and will be summarized here. The chamber is cylindrical and is roughly 1.4 m in diameter and 2.5 m long, with the plasma source mounted on one end and probe access from the sides as well as on a movable track along the top of the chamber. A turbo-molecular pump is used to maintain a low neutral vacuum base pressure (typically 1–3 \times 10\textsuperscript{-6} Torr). To inject neutral gas into the plasma source a 0.25 in. ceramic feed-through is extended into the source from the rear of the chamber (as shown in Fig. 1) and is connected through a puff valve to a pressurized (20 PSI) Ar line. The puff valve is opened for 3–7 ms to

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure1.png}
\caption{(Color online) Side view of high power helicon test chamber with diagnostics. Measurements of position are made relative to the front of the quartz antenna along the centerline.}
\end{figure}
allow the neutral gas to expand into the helicon source and bring the neutral argon density in the source to $\geq 10^{20}$ m$^{-3}$ (before ionization begins) while keeping the neutral density low downstream.

The base magnetic field of the experiment is provided by a set of six electromagnetic coils, each 15 cm in diameter, inside the vacuum chamber that produce a dipole-like magnetic field surrounding the plasma source that is 400 G in the center of the coils on the axis. Plasma is formed near the center of the coils where the field strength is high and only weakly divergent, and then flows downstream into the weaker dipole field that is more divergent.

The plasma source antenna and power supply for the HPH experiment are similar to those used in previous experiments\cite{1,7,10,12} but have been modified with the intention of increasing the coupling between the antenna and the driven plasma wave. The helicon wave is driven at 560 kHz, a frequency that is well above the ion cyclotron frequency and well below the electron cyclotron frequency\cite{12} for the magnetic field provided by the base field dipole. The antenna is a half-wave helical antenna wrapped around a quartz tube (15 cm long and 7 cm in diameter), similar to the ‘R’ antenna used in Light et al.\cite{13} The radio-frequency (RF) power supply is typically operated for 200 $\mu$s and generates a peak plasma density in the source of $\sim 10^{20}$ m$^{-3}$. The bulk of the plasma produced flows downstream over the next 100 $\mu$s with the downstream probes making measurements out to 60 cm from the source antenna. The short operation time allows the experiment to approximate spacelike conditions downstream for a brief time before the plasma has filled the conducting chamber and collision rate with neutrals becomes significant.

Changes to the magnetic field are measured with a set of B-dot coils that are inserted into the downstream plasma. These probes use a coil of fine copper wire to generate a voltage across the output leads proportional to the change in the magnetic field through the coil based on those described in Hutchinson\cite{14}

$$V = NA \frac{\partial B}{\partial t}. \quad (3)$$

Integrating this voltage over time gives the changes in the magnetic field from when the measurement began. The voltage is also filtered using a low-pass resistor-capacitor (RC) filter to remove most of the antenna noise. The first of the magnetic field probes used was a coil of 25 turns of copper wire covered in Torr Seal to protect it from the plasma and formed a ring 2 cm in diameter that was placed so that the ring normal was aligned with the axis of the plasma source. This diagnostic was inserted from the rear of the chamber to positions from 7 to 60 cm downstream of the source, measuring changes to the axial magnetic field at that position.

A second set of magnetic field probes was made to study the radial profile of the magnetic field perturbation in finer detail near the plasma source axis. This probe contained seven, three-axis B-dot probes with coils of 25 turns and 2 cm in diameter embedded in a nylon rod and covered in Torr Seal. This array was hung from a movable track along the top of the chamber and lowered down into the plasma flow so that the center of the array was on the plasma source axis. The movable track system allowed measurements to be axially downstream of the source from $\sim$10 to 60 cm in 2 cm increments.

Each coil of each probe was calibrated using a commercial Bell Gauss meter before being put under vacuum, and the axial field probes were calibrated against the $B_0$ magnetic field coils to confirm the direction and strength of the magnetic perturbation relative to the base magnetic field. The wave magnetic field generated by the source antenna was measured downstream along the source axis with a smaller, 0.25 in., three-axis B-dot probe that was previously described in Prager et al.\cite{12}

Electron density flowing downstream was measured with an asymmetric planar probe based on those described in Hutchinson\cite{14}, with a flat ion collecting disk 7 mm in diameter and a stinger 8 mm long, and 1 mm wide for collecting electrons. A hardware RC filter of 1.5 $\mu$s screened out the noise picked up in the wires from the RF antenna.

### III. AXIAL DIAMAGNETIC FIELD PERTURBATION AND THE HELICON WAVE

The base magnetic field of HPH falls off like a dipole field and drops in magnitude from hundreds of gauss near the exit of the source down to the terrestrial field strength within 1.5 m of the source. This was done to simulate spacelike conditions where it is not feasible to maintain a uniform field far downstream of the spacecraft.

The planar probe indicated a flowing plasma population similar to that seen in Prager et al.,\cite{10} with the peak density decreasing as the probe is moved further from the source. The antenna was shut off at 200 $\mu$s, and the decrease in the downstream density is delayed by the time it takes the plasma to flow downstream at the bulk plasma speed. This plasma density is shown as function of time in Fig. 2 for axial locations at 15, 30, and 45 cm (with time relative to the antenna activation). These density data are compared with the measurement of the perturbation to the bulk magnetic field along the axis at the same location. Prior to the arrival of plasma at the downstream locations there is no change in the bulk magnetic field. Within $\sim$10 $\mu$s of the plasma density increase the B-dot detects a diamagnetic change in the bulk axial magnetic field at that same position.

The diamagnetic perturbation increases over a period of $\sim$30 $\mu$s at each of the downstream locations in Fig. 2 and builds to a peak value of 8–12 G. At each position, the $\Delta B$ begins to fall with time after 110 $\mu$s and decreases to $\sim$2 G which is more typical of earlier measurements.\cite{1} This suggests the perturbation is decreasing with time either because the population of particles carrying the diamagnetic current are propagating away or being damped out (independently of the bulk population measured by the planar probe) or because the effect is being damped out by plasma increasingly interacting with the chamber wall.

At 200 $\mu$s the antenna is shut off and at each point downstream in Fig. 2 the magnetic perturbation decays away in less than 10 $\mu$s, even though the density measurements indicate that source plasma is still flowing downstream from...
the helicon for more than 10 μs after shutoff. This is similar to the results of Stenzel et al.\textsuperscript{8} in which their diamagnetic perturbation disappeared within 100 μs of their source being shut down, even though the measured plasma pressure still indicated a $\beta_{\text{thermal}} > 1$. This indicates that part of the diamagnetic perturbation late in time is being driven by the source antenna, and is strongly damped out as soon as the source is shut off.

Previous experiments with a low background field of ~5 G indicated that a high plasma pressure ($\beta_{\text{thermal}} > 1$) was

FIG. 2. The axial component of the measured magnetic perturbation (Gauss) is shown in the dashed line along with the electron density profile shown in the solid line at the same location. The direction of the $\Delta B$ was diamagnetic, decreasing the total magnetic field.\textsuperscript{6}

FIG. 3. The axial magnetic perturbation $\Delta B$ downstream of the source is shown as the solid line for six separate times. The axial component of base field is plotted as a dashed line to show the comparative strengths, but the two fields are opposite in direction (diagramatic).\textsuperscript{7}
capable of canceling out most of the axial magnetic field, while the work of Corr et al. used a significantly higher background field of ~34 G that could not be cancelled out with their helicon source. In these results from HPH it was observed that once the axial field strength had decreased to <15 G the peak of the diamagnetic perturbation was approximately the same magnitude as the base magnetic field. Figure 3 shows the axial magnetic perturbation plotted as a function of axial distance for six characteristic times throughout the plasma shot. For comparison the axial component of the base magnetic field is plotted on the same scale, but the ΔB is diamagnetic so that the two fields have opposite signs.

Early in time at t = 75 μs [Fig. 3(a)] the perturbation is only ~4 G and is restricted to near the source antenna. The diamagnetic perturbation builds in strength and reaches a peak value of >15 G on axis at 110 μs [Fig. 3(c)], between 20 and 30 cm downstream of the plasma source. The perturbation falls off in intensity farther downstream in Fig. 3(c), but beginning at ~25 cm downstream the perturbation is comparable to the base magnetic field. The magnitude of the perturbation roughly follows the fall in strength of the axial base magnetic field downstream of the peak. In time the peak of the perturbation shifts further downstream, decreasing in magnitude with the base magnetic field as shown in Figs. 3(d) and 3(e) and canceling the axial field downstream of the peak. By the time of antenna turnoff at 200 μs, the magnetic perturbation has become a more uniform ~2 G field along the axis, which is still large enough to cancel the base magnetic field at 50 cm downstream. This large diamagnetic perturbation of the field (>15 G) is significantly higher than what was measured with previous versions of HPH or reported in other helicon sources. This indicates that from 110 μs and later in time there is an extended region along the axis downstream where the magnetic field has been fully expelled from the axis and the total magnetic field (local field) is ~0.

A smaller three-axis magnetic field probe was used to observe waves propagating downstream of the source similar to those of Prager et al. The temporal and spatial evolution of the wave magnetic field is directly tied to the evolution of the total axial magnetic field, as shown for six times in Fig. 4. The external base magnetic field provided by the dipole magnets and the diamagnetic perturbation to the axial field are combined to form a total axial field represented by a dashed curve.

As the oscillating wave magnetic field propagates downstream with the plasma it is initially bound by the edge of

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**FIG. 4.** Comparison of the wave magnetic field magnitude (solid line) to the total axial magnetic field magnitude (dashed line) downstream of the source at six times. Downstream of the source the wave magnetic field driven by the antenna is comparable to the axial magnetic field.
the plasma, but as the total field begins to drop when the external magnetic field is expelled from the axis the wave magnetic field is clearly being bound on the right-hand side by the drop in axial magnetic field as seen in Fig. 4(c). The wave magnetic field decreases in magnitude following the axial magnetic field, dropping from $\sim 2 \text{ G} 25 \text{ cm downstream in Fig. 4(b)}$ to $\sim 0 \text{ G}$ at the same position in Fig. 4(c).

Later in time in Figs. 4(d) and 4(e) the point at which the axial magnetic field drops to zero has moved farther downstream, and the wave magnetic field has propagated farther downstream as well, still following the decrease in the axial magnetic field. This is good evidence that the external magnetic field is being 100% expelled from this region near the axis because the helicon wave requires a base magnetic field to propagate, the lack of the helicon wave suggests that the local field strength is $\sim 0$. Beginning at 150 $\mu$s it is possible that the wave field is beginning to penetrate into the region at a lower magnitude, perhaps because the diamagnetic effect has begun to damp away and it is no longer completely expelling the field.

The ratio of the wave magnetic field to the total axial field in Fig. 4 is significant because most helicon sources are thought to produce a linear plasma wave, with the wave magnetic field being a small perturbation of the total field. In the case of the HPH, the plasma wave being produced by the source is a nonlinear perturbation of the wave field, being perhaps $> 10 \text{ G}$ in the source region (compared to 400 G peak base field), and 4 G downstream of the source when the total axial field has dropped to $\sim 4 \text{ G}$. This region where the wave magnetic field is the same magnitude as the total field could be part of the explanation why the peak in the diamagnetic perturbation occurs so far downstream of the source, because the diamagnetic effect is at least partially driven by the antenna late in time.

IV. 2D SPATIAL VARIATIONS OF MAGNETIC FIELD AND ESTIMATED CURRENT DENSITY

To study how the perturbation of the base field changes near the axis in finer detail, an array of seven, three-axis B-dot was used. This probe array was described in Sec. II and produced a 2D data set that is $\sim 50 \text{ cm}$ long and $\sim 12 \text{ cm}$ wide in a vertical plane along the axis of the thruster. The z component of the B-dot array was used to measure the axial component of the diamagnetic field perturbation and $\Delta B_z$ is shown as a function of position for four separate times in Fig. 5. The scales on the plots are distorted due to the probe being able to move a much farther distance axially downstream than the radial width of the probe array.

Early in time at $t = 100 \mu$s in Fig. 5(a) the diamagnetic perturbation is restricted to near the antenna source, peaking at 15 cm downstream and not extending more than a few centimeters off the thruster axis. In Fig. 5(b) at $t = 125 \mu$s, the perturbation has propagated farther downstream and peaks at $\sim 25 \text{ cm}$, and extends further from the axis as the base magnetic dipole field diverges from the axis. The magnetic perturbation has already expanded beyond the edge of the probe array, with the $\Delta B_z > 5 \text{ G}$ at 6 cm away from the axis. The diamagnetic perturbation appears roughly symmetric and is centered on the source axis, with the magnitude

![Image of Fig. 5](https://example.com/fig5.png)

**Fig. 5.** (Color online) The $\Delta B_z$ component of the magnetic perturbation downstream of the source at four times, with the z axis is aligned with the thruster axis. This effectively axial perturbation to the field is antiparallel to the axial component of the base field in each frame. The $\Delta B_z$ is the largest component, and the color scale for this figure covers a larger range than the others.
falling off radially as the axial component of the external dipole field decreases.

This evolution in time is similar to the results of the axial probe (Fig. 3) in the previous section: a diamagnetic perturbation is built up downstream and propagates away from the source, with the peak of the $\Delta B_z$ roughly equal to the base magnetic field strength, leading to a cancellation of the field as the peak moves past it and expelling the external field. Figure 5 indicates that the magnetic perturbation described in Sec. III is not just limited to near the source axis but is part of a large diamagnetic effect over an extended region downstream of the source. If the decrease in axial magnetic field near the axis was due to flux being pushed outward by the diamagnetic effect as was thought in Ziemba et al., 1 it would appear in the data set as an increase of the base magnetic field on the radial edge of the $\Delta B_z$ or further downstream of the source. There is no indication of an enhanced axial field in the bulk B-dot array results near the axis in Fig. 5. It is possible that the increase in flux would only be measurable tens of centimeters off the axis as was seen previously, 1 which would put it too far off axis to measure with this probe array centered on the axis.

The y axis of the B-dot array is oriented vertical to the ground and perpendicular to the thruster axis, so that the y axis gives effectively the radial component of the magnetic perturbation, taking into account the change in sign across the axis. The $\Delta B_y$ component of the magnetic perturbation is shown as a function of position for four separate times in Fig. 6. Early in time in Fig. 6(a), $\Delta B_y$ is limited to within 15 cm of the source antenna and peaks, a few centimeters off the axis. The sign of the $\Delta B_y$ is opposed to the y component of the base magnetic field, pointing radially inward toward the axis while the diverging dipole base field is pointed away from the axis, indicating that this is a diamagnetic perturbation as well. This suggests that early in time and near the source, the region in which the external field is entirely expelled is extending a radially off axis for at least a small distance.

Even though the base magnetic field coils provide a symmetric field with a radial component point away from the axis, there is an additional field component due to the Earth’s magnetic field. At the latitude where these data were taken the Earth’s magnetic field is $\sim 0.5$ G vertically downward, and part of the asymmetry is likely due to the magnetic perturbation opposing the total magnetic field: the dipole magnets and Earth’s field together. The addition of the Earth’s field by itself is not enough to explain the asymmetry, but since the magnetic perturbation has expanded beyond the limits of the probe this suggests that the probe array is only sampling part of a larger region of $\Delta B_y$.

The x axis of the B-dot array is pointed horizontally to the left looking along the z axis and gives effectively the azimuthal component of the magnetic perturbation around the axis, after accounting for the change in sign. The $\Delta B_x$ component of the magnetic perturbation is shown as a function of position for four separate times in Fig. 7. For each of the four times, the $\Delta B_x$ is mostly positive (to the left) above the source axis and negative (to the right) below the axis, making this (effectively) azimuthal perturbation of the magnetic field left-handed around the source axis. For the vertical cut measured along the axis by the B-dot array, both the base magnetic field dipole and the Earth’s magnetic field only

FIG. 6. (Color online) The $\Delta B_y$ component of the magnetic perturbation downstream of the source at four times, with the y-axis being vertical. This (effectively) radial component of the magnetic perturbation is initially diamagnetic and points towards the thruster axis, but late in time becomes uniformly upward. Note that the color scale for $\Delta B_y$ has a smaller range than the dominant $\Delta B_z$. 

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have significant components in the axial and radial direction (the y axis and z axis). There should not be any external base magnetic field component along the x axis, in the azimuthal direction, so the magnetic perturbation $\Delta B_x$ is not diamagnetic and is instead an increase in the magnetic field in that direction. Early in time in Fig. 7(a) the $\Delta B_x$ is restricted to near the source antenna, but there is an asymmetry in the magnitude, with the perturbation above the axis peaking at ~$5$ G and the perturbation below the axis peaking at half of that. Each region has expanded to be roughly the same size, but is more diffuse below the axis and peaked above it. In Fig. 7(b) at $t = 125 \mu s$, the $\Delta B_x$ has expanded beyond the edge of the probe array on both sides, with the peak of the perturbation above the axis being on or near the edge of the probe array.

The three axes of the B-dot array taken together suggest that the magnetic perturbation is a macroscopic effect that begins near the source region and expands downstream and radially away from the source building up to a peak value. Then the perturbation propagates downstream off the edge of the probe array as well as expanding radially away from the axis beyond where the probe can measure. Near the time when the antenna has turned off there is an extended region downstream with a magnetic perturbation $\geq 1$ G and near the source the perturbation is still $\geq 5$ G until the antenna is turned off, at which point the magnetic perturbation disappears within tens of microseconds. The $\Delta B_z$ diamagnetic perturbation is the dominant term, building to a peak $>15$ G more than 1 antenna length away from the source. The $\Delta B_y$ term was in some cases diamagnetic but was also asymmetric later in time above the axis. The $\Delta B_x$ term was not diamagnetic because there was no base magnetic field in the x direction along the axis of the probe array. This suggests that the dominant effect is an azimuthal diamagnetic current to generate the large diamagnetic $\Delta B_z$ and smaller axial and radial currents to generate the other two components of $\Delta B$.

The volume of plasma downstream of the source has only been partially measured with the diagnostics available, but with some assumptions of symmetry an estimate of the currents produced can be developed. The first assumption that must be made is that the plasma plume and the magnetic perturbation are azimuthally symmetric. This allows the 2D cut from the bulk B-dot array to be sufficient information to determine the downstream current density. Previous measurements of the plasma density with Langmuir probes support this, indicating a mostly symmetric plasma plume downstream. While the dominant $\Delta B_z$ component is symmetric across the axis, the smaller $\Delta B_x$ and $\Delta B_y$ components are not symmetric across the axis. To estimate how severe the deviation from azimuthal symmetry is, we must look at each component of the current density.
From the differential form of the Maxwell–Ampère equation
\[ \nabla \times \mathbf{B} = \mu_0 \left( -\frac{\partial \mathbf{D}}{\partial t} + \mathbf{J} \right). \tag{4} \]

The magnetic perturbation we measure is present for longer than 100 μs, and the dominant axial component of the \( \Delta \mathbf{B} \) suggests that the curl of the magnetic field perturbation is predominantly in the azimuthal direction around the plasma axis. This makes it unlikely that there are azimuthal displacement fields building up for the bulk of the plasma shot time. So if we assume that displacement fields are small, then
\[ \nabla \times \mathbf{B} = \mu_0 \mathbf{J}. \tag{5} \]

The spatial resolution in the magnetic field perturbation measurements is limited to 2 cm over an area that is 12 cm wide by 52 cm long, and because the curl of the magnetic perturbation depends on the partial derivatives, the estimates of the current density are further limited. In the Cartesian coordinates used in the lab measurements
\[ \nabla \times \mathbf{B} = \left( \frac{\partial B_z}{\partial y} - \frac{\partial B_y}{\partial z} \right) \mathbf{x} + \left( \frac{\partial B_x}{\partial z} - \frac{\partial B_z}{\partial x} \right) \mathbf{y} + \left( \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \right) \mathbf{z}. \tag{6} \]

The partial derivatives with respect to \( y \) and \( z \) can be read from the B-dot array results, only the derivatives with respect to \( x \) are absent. The \( \partial B_z/\partial x \) in the second term of Eq. (6) can be assumed to be small because of the observed symmetry of the \( \Delta B_z \). Only the \( \partial B_y/\partial x \) in the third term of Eq. (6) can still complicate the assumption of azimuthal symmetry, with the upward pointing \( \Delta B_y \) dominating the whole array late in time. However, even though the \( \partial B_y/\partial x \) term may not be small, we still expect \( \partial B_x/\partial y \) to be dominant in the third term of Eq. (6). This is because late in time the \( \Delta B_y \) is only \( \sim 1 \) G in magnitude over the array while the \( \Delta B_z \) term varies from 4 to \( \sim 2 \) G and should yield a larger derivative. Therefore if we are assuming azimuthal symmetry and that the vertical \( yz \) plane that the probe measured is typical of any cut across the plasma, we expect it to be accurate with the possible exception of a correction to the current density in the \( z \) direction along the axis.

The \( x \) component of the curl represents an azimuthal current around the source axis and is shown as a function of position for four separate times in Fig. 8. The (effectively) azimuthal current is left-handed about the thruster axis, in the same direction as the azimuthal magnetic perturbation. The current peaks \( 2–3 \) cm off the source axis and is \( \sim 20 \) kA m\(^{-2}\) in magnitude. The high current density is the result of the sharp radial decrease of the \( \Delta B_z \) away from the source axis, suggesting a current source that is restricted to a few square centimeters near the axis.

Early in time in Fig. 8(a), the region with azimuthal current has extended roughly 1 antenna length (15 cm) downstream. The current density peak reaches \( \sim 20 \) kA m\(^{-2}\) at \( 2–3 \) cm from the axis and has decreased to \( 5 \) kA m\(^{-2}\) at the edge of the probe array, suggesting that the effect does not

![FIG. 8. (Color online) Estimated \( J_x \) current density downstream of the source at four times. The (effectively) azimuthal current is oriented left-handed about the axis, such that the field that would be induced by this current has its normal antiparallel to the base magnetic field, resulting in the axial diamagnetic field.](image-url)
extend much farther beyond the edge of the array. At $t = 125 \mu s$ in Fig. 8(b), the $J_x$ region has expanded to 30 cm downstream and radially off the edges of the probe array, but the peak of the $J_x$ remains within 4 cm of the axis and $>15$ kA m$^{-2}$. In Fig. 8(c) the peak of the current density has decreased to $\sim 10$ kA m$^{-2}$ and is peaked near the helicon source rather than 1–2 antenna lengths downstream. The current drive region extends downstream but has grown more diffuse. By the time of antenna turnoff in Fig. 8(d), the peak in the $J_x$ current density is beyond the inner edge of the probe array toward the source, while the downstream region has a $J_x$ that is $1–10$ kA m$^{-2}$ over the extent of the B-dot probe array.

The azimuthal current is consistent with the kind of diamagnetic current we would expect to find in a high beta plasma plume with a radial gradient in plasma pressure. However, late in time the azimuthal current is peaked near the source region and damps out immediately after the antenna is shut off. This suggests that at least part of the diamagnetic current we measure is being driven by the antenna, although it could only be important for the lower current density observed after 150 $\mu s$, while the peaked azimuthal current observed before 150 $\mu s$ could be predominantly a pressure driven diamagnetic current.

V. DISCUSSION AND SUMMARY

The modification of the HPH plasma source to use an antenna similar to the ‘R’ antenna used in Light et al. to drive the helicon wave downstream in place of the antenna previously used was effective in increasing the measured wave field magnitude downstream. This change was also correlated with a large increase in the magnetic perturbation measured downstream of the HPH source antenna to more than 15 G at the peak, which is larger by a factor of 3–5 than those previously reported. The perturbation is predominantly diamagnetic to the base field, but has an additional azimuthal component.

Previous experiments had been able to show complete expulsion of the base field for high plasma $\beta_{\text{thermal}}$ (Ref. 8) when the base field is on the order of $\sim 5$ G, but had difficulty driving large enough magnetic perturbations to cancel out a larger field of $\sim 34$ G (Ref. 5) even when the plasma pressure was high enough for $\beta_{\text{thermal}} > 1$. The presented results from HPH show that downstream of the source where the base magnetic field drops below 15 G on axis, the induced $\Delta B$ is able to cancel out the guide magnetic field along the axis as it propagates downstream. This produces a region along the axis where the external magnetic field is entirely expelled from the center. Estimates of the magnetic field component of the plasma wave downstream indicate that the wave field is roughly 10 G near the exit of the helicon source and is large enough to equal the axial base magnetic field 25–30 cm downstream of the source, the same location where the large $\Delta B$ was measured. The wave magnetic field decreases in strength following the axial component of the base magnetic field and is near zero beyond this point when the diamagnetic perturbation is canceling the base field. When the antenna is shut off and the wave magnetic field drops to zero, the magnetic perturbation drops to zero as well.

The magnetic perturbation was shown to be a three-dimensional effect with each component ($\Delta B_x, \Delta B_y, \Delta B_z$) ranging from several gauss in magnitude to more than 15 G. These components indicate a $\Delta B$ forms initially near the source and then propagates downstream, building to a peak and canceling the base magnetic field as it both moves away from the source and expands radially away from the axis beyond the limits of the probe. Taking the curl of the magnetic perturbation to estimate the current in a method similar to that used for space plasmas and previous experiments indicates a predominately azimuthal diamagnetic current that is left-handed around the source axis.

The source antenna operates at a frequency above the ion cyclotron frequency so that the ions are not significantly perturbed by the wave fields, while the frequency is well enough below the electron cyclotron frequency that the electrons should see a uniform perturbing wave field over their whole gyro-orbit. Downstream of the source, $f_{ce}/f_{ei} \geq 10$ for the first 50 cm, so the electrons are still mostly magnetized, and the measured wave magnetic field is comparable to the total magnetic field where the large $\Delta B$ is measured. Because the observed plasma wave being driven by the antenna rotates in a right-handed fashion around the axis with time, and if the electrons are still magnetized they will be driven in a right-handed fashion around the axis as well. With the ions being relatively stationary, this should result in a left-handed current around the axis and a magnetic field perturbation antiparallel to the base field. The measured $\Delta B$ that is antiparallel to the base field and disappears as the antenna is shut off is strong evidence that the antenna is driving a left-handed current in the plasma downstream at positions where the wave magnetic field is comparable in magnitude to the total magnetic field.

An important point to consider is how electron collisions downstream of the source can act to limit or damp out any electron currents driven by the rotating wave field. Downstream of HPH the electron density is $\sim 10^{18}$ m$^{-3}$ while the electron temperature is $\sim 10$ eV. This puts the electron–neutral collision rate $<10^4$ s$^{-1}$ but gives an electron–ion Coulomb collision rate of $\sim 9 \times 10^2$ s$^{-1}$. This is larger than the antenna frequency of $\sim 6 \times 10^8$ s$^{-1}$, but is in the same order of magnitude. This suggests that the bulk of the electrons will undergo a coulomb collision before the wave field can make a full rotation around the axis, and any wave driven current will be strongly damped. This could be part of the reason why the $\Delta B$ dissipates so quickly after the antenna is shut off. Because the more energetic electrons in the distribution have fewer coulomb collisions than the bulk, they could make a full rotation around the axis and may carry the majority of the driven current as a result. This is similar to what was observed in Stenzel et al., where the magnetic perturbation decayed away with the loss of the energetic tail ($\sim 50$ eV) electrons. In many typical helicon experiments the $f_{ce}/f_{ei} \geq 10$ and $f_{en} \sim 10^7$ s$^{-1}$, which is on the order of the typical helicon antenna frequency of 14 MHz. This could be part of the reason why large magnetic perturbations have not been previously seen in other helicon experiments, the
electron motion is strongly damped out by collisions with neutrals.

The current density estimated downstream peaks at $>20$ kA m$^{-2}$ and is several kiloamps per meter squared over an extended region downstream. With the present system the total current driven downstream is on the scale of tens to hundreds of amps, but only part of the downstream region has been measured with the B-dot array. The region near the axis where the field was expelled from the axis and piled up at the edge could benefit from this in terms of additional collimation, as the magnetic pressure at the boundary is balancing out the particle pressure in the core as it expands downstream. Additionally, if the current driven region could be extended downstream for longer distances, this could result in a plasma beam confined to its own magnetic field disconnected from the source magnetic field and able to propagate for significant distances with a high plasma density. The output plasma is super-Alfvenic along the axis, suggesting that perturbations to the magnetic field by the dense plasma could be carried a significant distance downstream of the source when operated in a larger vacuum chamber or in space where interaction with the wall would not occur so quickly. In progress toward this goal, the HPH experiment has been working to increase the power output of the antenna to increase the downstream currents. There have also been some initial results which indicate that altering the strength and shape of the magnetic field downstream of the source region can extend the current drive region and result in a denser beam with a higher bulk velocity. These results will be presented in a subsequent paper.

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