Final Report
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Studies of Flows in Plasmas

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a). Formation of field aligned density structure.

Plasma flows and transport, associated with the formation of magnetic field-aligned density structures, have been investigated. A field-aligned density structure is created by applying a voltage bias to an electrode embedded within, an otherwise, uniform background Helium plasma. The general layout of the experiment is shown in Figure 1. Using a transistor switch and capacitor bank, a positive voltage pulse is applied to the electrode during the steady state portion of a 10ms plasma discharge. The pulse length is typically 1 to 3 ms in duration and the bias is 85 V referenced to the chamber wall. The electrode is a rectangular, 1.85 cm by 17.7 cm, copper plate, 0.15 cm thick. It is oriented so that the axial magnetic field vector lies in the plane of the copper plate.

The application of the voltage pulse results in the formation of a 'current sheet' of electrons. At the axial location of the electrode, the current sheet is less than one helium ion gyroradius in thickness, while at a distance of 6 m along the magnetic field, it is 4 cm thick (full width at half-height of a current profile). The current sheet broadens due to cross-field diffusion caused by electron-ion Coulomb collisions. A localized planar flow of ions, parallel to the background field and in the same direction as the electron flow, is observed within the electron current sheet. The ion flow measurements are made using a double-sided planar Langmuir probe (2-faced Mach probe) biased to collect ion saturation current. A two-dimensional representation of the measured flow is shown in Figure 2(a). Red represents a flow of ions directed out of the page (in the same direction as B_0) at a Mach speed of .45, and violet represents zero flow. The peak value of the parallel flow at Mach number, $M=v_{flow}/c_s=0.45$ is near the ion thermal velocity of the background plasma. Typical LAPD ion temperatures during the discharge (as measured with a Fabry-Perot interferometer) are $T_i \approx 0.7 - 1.0$ eV. Further work is necessary to confirm these flow measurements by using Laser Induced Fluorescence[1] (LIF) in an argon plasma. Additionally, as shown in Figure 2(b), the bias pulse produces a cross-field flow due to ExB drifts. Since the electric field is asymmetric about x=0 the cross-field flow has a reverse shear.

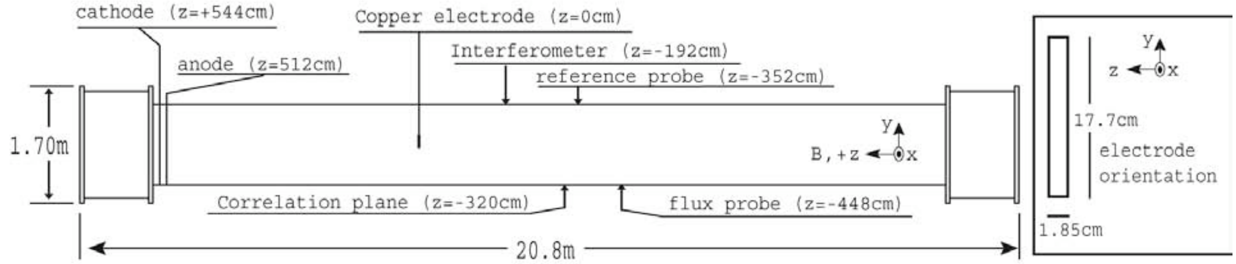


Figure 1. Schematic layout of the device and axial locations of biased plate electrode and various measurements. The orientation of the plate is also shown as an inset to the right; the thickness of the plate (in the x-direction) is 0.15cm, which is 0.6 helium gyroradii at 750 Gauss.

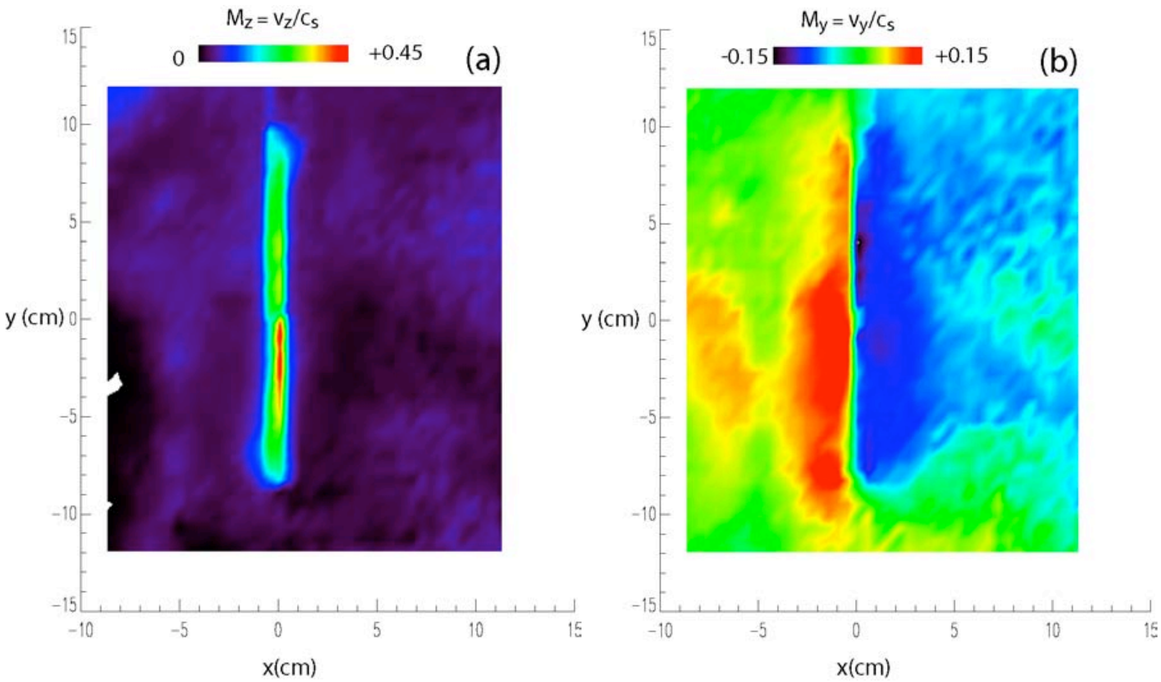


Figure 2. Mach probe measurements of ion flow (a) parallel to the magnetic field, and (b) in the y-direction. The flow in the x-direction could not be measured with this setup. The axial location of the data planes is -320cm from the electrode, and the magnetic field is directed out of the page.

The continued application of the bias leads to a fifty percent, field-aligned depression of plasma density, possibly due to lower-hybrid wave heating[2] of the ions and a depletion of electrons due to the current sheet. A consequence of the density depletion is the spontaneous growth of drift-Alfvén waves, which subsequently drive a cross-field particle flux to relax the gradient. The drift-Alfvén waves grow in the regions of cross-field gradients in plasma pressure. Detailed measurements of the mode structure obtained using a two-probe correlation method are shown in Figure 3. In addition, a linear array of probe tips is used

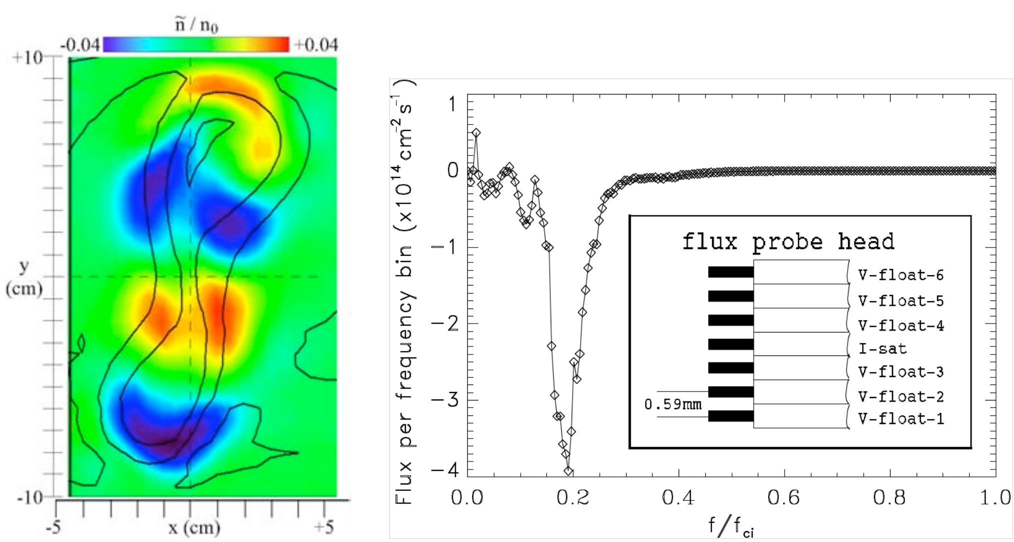


Figure 3 (left) Mode structure, at $f=0.16f_{ci}$, of density fluctuations due to drift-Alfvén waves in color and density contours as black lines. (right) Inset of particle flux array and measured inward going particle flux as a function of frequency measured in the density gradient at y=0, x=1.25cm.

to measure density and potential fluctuations from which the ExB particle flux is derived. The probe array also allows a reliable, multi-point calculation of the perpendicular wavenumber for each plasma discharge. The frequency-integrated particle flux of $5.5\text{x}10^{15}\text{cm}^{-2}\text{s}^{-1}$ obtained from this diagnostic is in rough agreement with the flux necessary to account for the observed filling in of the density depression at x=0, which is $2.2\ \text{x}10^{15}\text{cm}^{-2}\text{s}^{-1}$.

A manuscript reporting the details of the observed parallel and perpendicular flows, as well as the rapid formation of the density cavity, has been published in the Physics of Plasmas[3]. A second manuscript dealing with the parameter scaling of the fluctuation-driven particle flux, and a comparison of the measured dispersion relation to existing kinetic theory[4] has been published as well.

b). Imaging the plasma column with Laser induced Fluorescence

The density structures produced in the biased electrode experiment have been investigated in Argon plasmas using LIF (Laser Induced Fluorescence). LIF was done with a pulsed dye laser (SIRAH laser). The laser pulse is stretched to 100 ns. The laser is set to the 611.66nm Ar II transition ($\left(3d^1\right)^2 G_{9/2} \rightarrow \left(4p^1\right)^2 F^0_{7/2}$). The laser system is housed in a clean room adjacent to the LAPD device and laser light is transported to the LAPD plasma via an optical fiber. A cylindrical lens is used to change the laser beam into a sheet of light 20 cm wide and 0.5 cm thick. The laser intensity is set high to intentionally power broaden the line[5]. A laser line is saturated when the optical pumping rate equals the spontaneous emission rate plus the collisional transition rate of the upper level (the latter term is negligible at our density). When the laser intensity exceeds the saturation value, the wings of the spectral line continue to grow but the center does not. The line width is broadened and measurement of the line profile will give an artificially high temperature. However, all the ions in the laser beam will contribute to the signal so this is a good technique for measuring the density of ions in the $\left(3d^1\right)^2 G_{9/2}$ state. The LIF signal (which decays at 460.96nm to the $\left(4s^1\right)^2 F^0_{7/2}$ state) is very strong and can be easily photographed with a fast CCD camera as shown in figure 4.

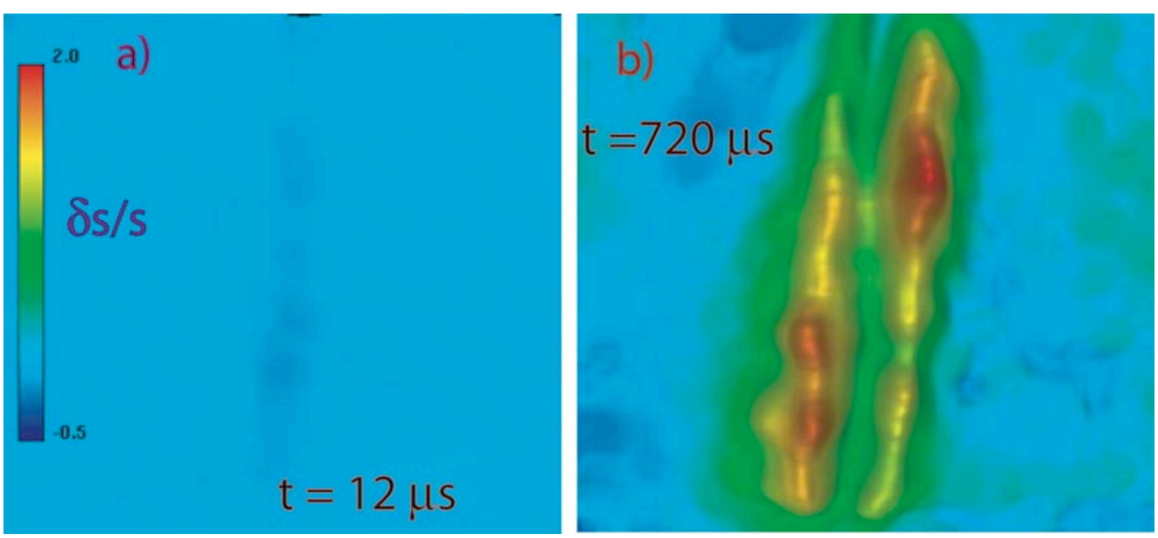


Figure 4. Shown is the Ar II LIF signal (S) from a sheet of laser light perpendicular to the device axis and cutting through the current channel. a) Taken 12 μs after the current sheet is initiated showing a faint signal in the center of the channel indicating the formation of the density depression. b) LIF signal at a much later time. Ridges of higher density are seen at the edge of the narrow sheet. The area illuminated in this photograph is 20 by 20 cm.

The intensity of the received signal depends on the laser intensity as well as the number of LIF target ions. The threshold energy of the $\left(3d^1\right)^2 G_{9/2}$ state is 15.8 eV above the ground state of Ar II. The DC discharge voltage is 53 volts, and the bias voltage to the grid is +85 volts. There are ample fast electrons to populate the target state. The number of Ar II ions in the $\left(3d^1\right)^2 G_{9/2}$ state is heavily dependent on the population of fast electrons. Significant electron heating in the current channel or on its edge may be responsible for the large ridges as well as an enhanced signal within the density depression associated with the current sheet. The power broadened LIF data, coupled to the density measurement may ultimately be a diagnostic for fast electrons. In future experiments, LIF, in a non-power broadened mode, will be used to measure the ion distribution for an independent measurement of flow. Planar LIF has been used successfully by other researchers to measure properties of large amplitude drift waves in a small Tokamak[6]. The LIF measurements in this experiment were obtained by Brett Jacobs, a full time graduate student.

c). Creating localized cross-field plasma flows.

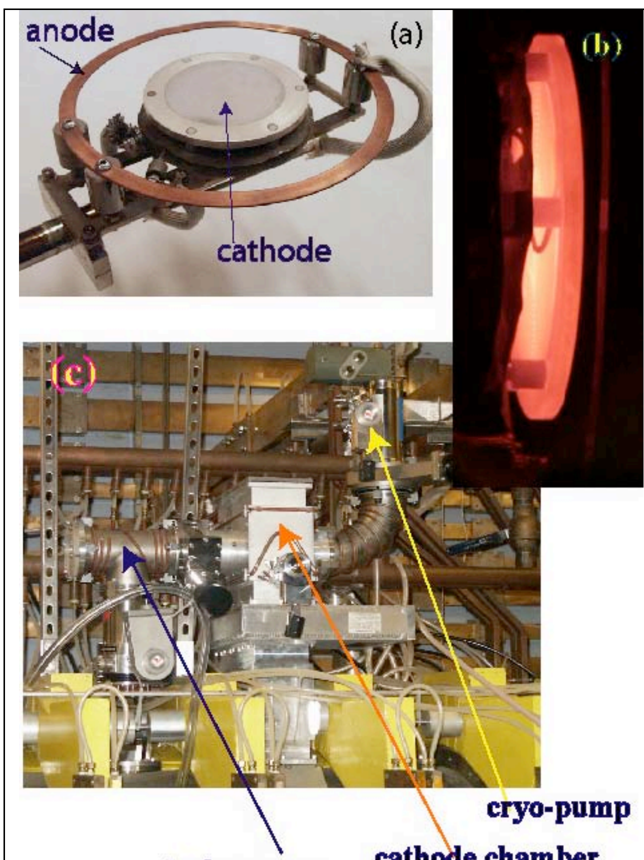


Figure 5. (a) Photograph of a 10 cm diameter Ni cathode with an embedded heater. The heater is made of thermal coaxial cable and is brazed into a recessed area in back of the cathode. Also shown is a circular anode with the same surface area of the cathode. The power and bias connectors shown in the diagram are fed through a one inch vacuum feedthrough also constructed for this experiment. (b) The cathode in the LAPD device at emission temperature. (c) Hardware support for the small cathode. Since the cathode had to be chemically converted without disturbing ongoing experiments, it was mounted in water cooled flange on top of the device. A small turbo and cryopump were used for the conversion. When conversion is complete a gate valve (square object above the magnets) is opened and the cathode placed in the LAPD.

A discharge source consisting of a small cathode with accompanying ring anode has been developed and tested. This source is designed to spin up the plasma column through J x B forces. A photograph of the cathode and ring anode source is shown in figure 5 (a). A 500 Amp, 250 volt, transistor-based pulser was constructed to power the cathode/anode system. The cathode is coated with a Barium tri-carbonate coating that must be chemically converted into Barium Oxide by heating. The chemical conversion is accomplished, before insertion of the cathode into the main plasma chamber, in a separate, secondary chamber constructed explicitly for this purpose. The conversion chamber is shown mounted on the LAPD in Figure 5 (c).

Initial experiments indicated that, when the cathode is biased with respect to the ring anode, only small cross-field currents (on the order of one Ampere) are produced and, thus, only small azimuthal flows occur. It appears that the anode surface area perpendicular to the background field is not large enough to produce significant cross-field currents. The anode has been redesigned as a short cylinder with a significantly larger area perpendicular to the magnetic field. A full time graduate student, Eric Lawrence, is working on this project.

d). Modeling the effect of flows on shear Alfvén waves.

Under previous support, funding was available for theoretical investigations into the effects of plasma flow on the propagation of shear Alfvén waves. The propagation of Alfvén waves through regions where a transverse plasma flow exists relative to the wave source is a topic of interest to various space and laboratory studies. The basic shear Alfvén wave current pattern is current loops in which the electrons carry current along the field lines and ions carry current across the field lines. These current loops propagate away from a small source in an expanding conical pattern[7]. Cross-field plasma flows have an effect on these current patterns. An example of the magnetic field pattern of an Alfvén shear wave, with and without flow, is shown in figure 6.

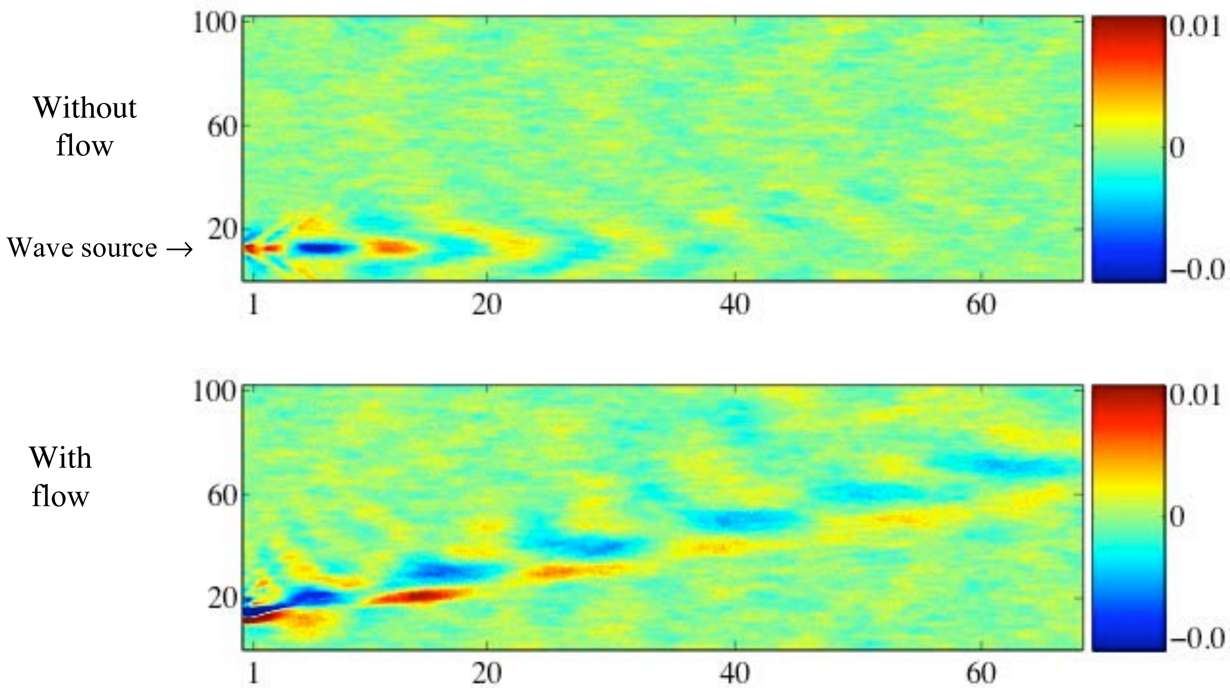


Figure 6. Contours of transverse magnetic field of shear Alfvén waves launched from a source on the left hand boundary. Upper panel is without plasma drift and the lower panel is with a drift in the positive x-direction such that the perpendicular Doppler shift exceeds the wave frequency.

The vertical x-axis is scaled to the electron skin depth, the horizontal z-axis is scaled to the ion inertial length.

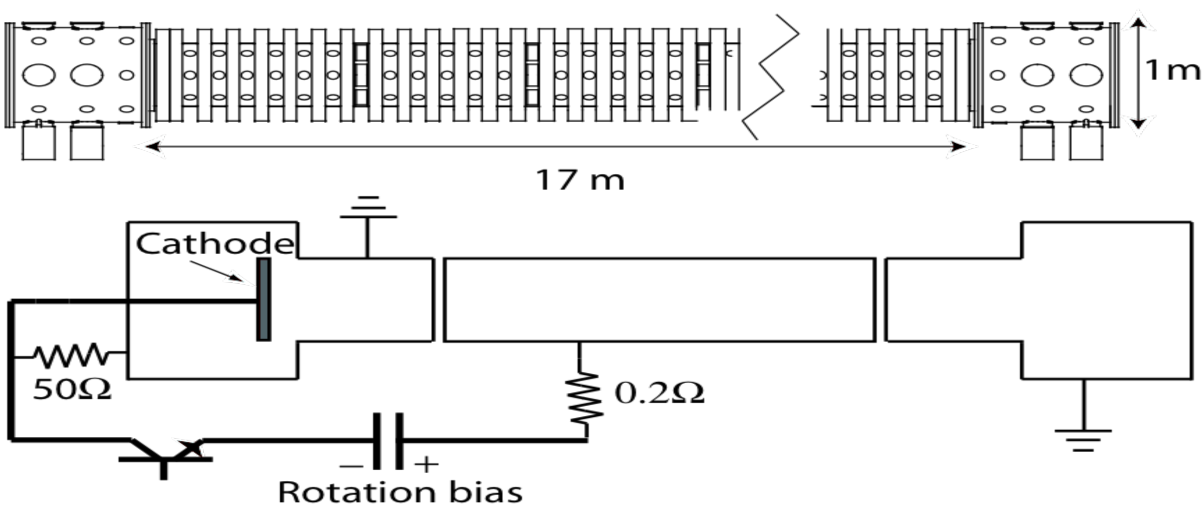
In the inertial regime, where the Alfvén speed (V_A) is much larger than the electron thermal velocity (V_{te}), a transverse flow above a critical speed gives rise to filamentation of currents associated with shear waves. The phenomenon arises from the competition between induction and electron inertia and is absent in MHD descriptions. In the kinetic regime ($V_A \sim V_{te}$) the wave-particle interaction increases the complexity of this competition. To explore this important regime, a parallel electromagnetic particle-in-cell code, PARSEC, is used. The effects of finite ion gyroradius (kinetic ion effects) and resonant electron damping (kinetic electron effects) are independently investigated. The major findings are:

1) Finite ion gyroradius effects give rise to secondary, banded-structures that accompany the convection induced by the flow on the primary shear-wave cone. This bifurcation of the wave pattern is due to dispersion effects.

2) The electron Landau damping experienced by shear-wave cones launched in a resistive plasma $V_{te} \sim V_A$ can be cancelled by the flow. This results in collimated propagating structures as shown in figure 6. This work has also been the subject of talks and invited papers[8].

Plasma Edge Rotation Experiments: J. Maggs, T. Carter, D. Pace.

The edge rotation of Tokomak plasmas has become an important topic in that shear flow associated with rotation suppresses instabilities and can lead to smaller radial particle transport. In this series of experiments the plasma source, an oxide coated cathode, was biased negatively with respect to the chamber wall using a transistor switch. The bias voltage is applied after the 17 long, plasma column has been created. A schematic of the bias arrangement is shown in figure 4.



This experiment was performed towards the end of the cathode lifetime and plasma column was asymmetric (it is usually round). When the bias voltage is applied there is a profound difference in the plasma column as seen in figure (5). Figure 5a is a picture ($\delta T = 1\ \mu s$) taken though the end port of the machine when there is no bias (rotation). The picture is light integrated over the length of the plasma column. Figure 5b was taken when a 100 Volt bias was applied

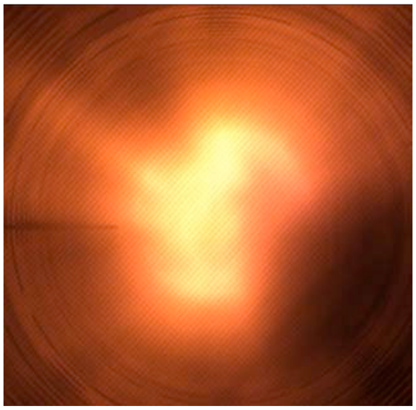


Figure 5a) Vbias = 0.0

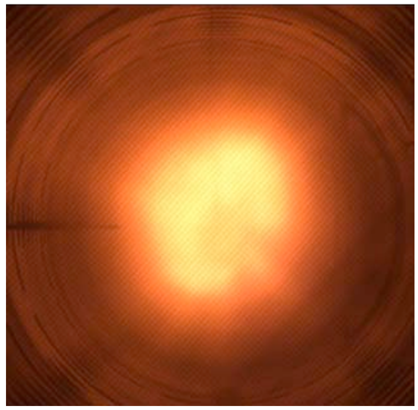
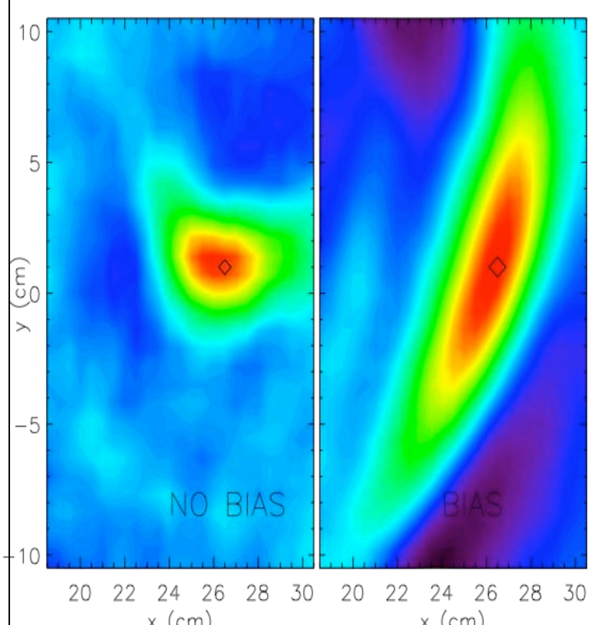


Figure 5b) Vbias = 150 V (250 A)

The plasma flow was measured with Mach probes and existed in a 20 cm diameter annulus around the plasma column and was consistent with a radial electric field of 100 V/m. The gradient scale length steepens when the electric field is present. The measured suppression of radial particle flux was also consistent with the plasma profile steepening.

Figure 4 Density Correlation Functions a) without bias and with a 200 Volt bias. Blue signifies no correlation.



Density correlations were performed using a fixed probe at the location shown by a diamond. The fixed probe was located one meter downstream from the plane that movable probe traveled and acquired correlations at 1200 spatial positions. The center of the plasma column is at (x,y) = (0,0). In the biased case (Fig 4b) the correlation is markedly different. It is sheared along the flow direction; the azimuthal correlations are clearly much greater. The radial extent of the correlations are slightly smaller. For bias voltages above 200 Volts a second set of coherent fluctuations is observed and the radial transport reverses to become inward. These experiments have been published Phys. Plasmas[9].

We feel that these experiments will have a significant impact on the community interested in edge transport.

Theory/simulation Activities

Extensive particle-in-cell simulations have been performed of the effect of cross-field plasma flows on the propagation properties of shear Alfvén waves of small transverse scale. This is a topic of general interest to space and laboratory situations in which ambient flows are present and convect current systems associated with Alfvén waves that have been excited at remote locations. Some environments in which related issues are encountered include: the auroral ionosphere, the solar wind, fusion devices operating in H-mode, and edge-plasma divertors. The topic deals with the broader issue of structure formation in magnetized plasmas and has the potential to develop into a sensitive diagnostic tool of plasma flows.

In this funding period our effort has concentrated in the development of a robust, state-of-the-art, parallel PIC computer code. It is capable of handling the difficulties of cross-field flow simultaneously with the excitation of Alfvén waves, while minimizing spurious effects arising from numerical boundaries. A successful algorithm for wave absorption has been developed that makes the finite system behave practically as if it were infinite in extent. Because the phenomena deals with extremely low-frequencies, and electron and ion dynamics are followed exactly and self-consistently, the code needs to run for extended periods in powerful computers. In these studies we have been taking advantage of the Dawson Cluster recently completed at UCLA. This unique, 512-processor computer is made available for this study to the co-PI (Prof. G. Morales) because he is also co-PI on the NSF Major Research Instrumentation Award (MRI) that funded the construction of the cluster. Over the next year the full availability of the cluster will permit extensive surveys that will shed new insight into a variety of flow effects.

The preliminary results of our flow simulations have confirmed the general predictions of the earlier theoretical study by Drozdenko and Morales[10]. When the scaled flow parameter $p=k_{\perp}U/\omega$ reaches a value close to unity, the propagation cones characteristic of inertial shear waves undergo a substantial distortion. In here $k_{\perp}$ is the effective perpendicular wave number (in the absence of flow) of the signal at frequency ω. U is the magnitude of the flow velocity. In the process, a filamentary current system develops whose cross- field scale becomes extremely small. The simulations have uncovered several new kinetic effects that arise at these smaller scales and which are not contained in the earlier fluid analysis. On-going analytical and computational studies are presently exploring the role of finite ion Larmor radius, electron acceleration and nonlinear modifications. The results have been reported at the 46th annual meeting of the Division of Plasma Physics of the American Physical Society[11] and at the Fall meeting of the American Geophysical Union[12]A long article describing the results is under preparation.

The following figures show results of the PIC simulations that contrast the spatial pattern in the absence of flow (Fig. 6) to that obtained for a flow parameter p=0.8 (Fig. 7) for a shear wave whose frequency is 0.2 of the ion-cyclotron frequency.

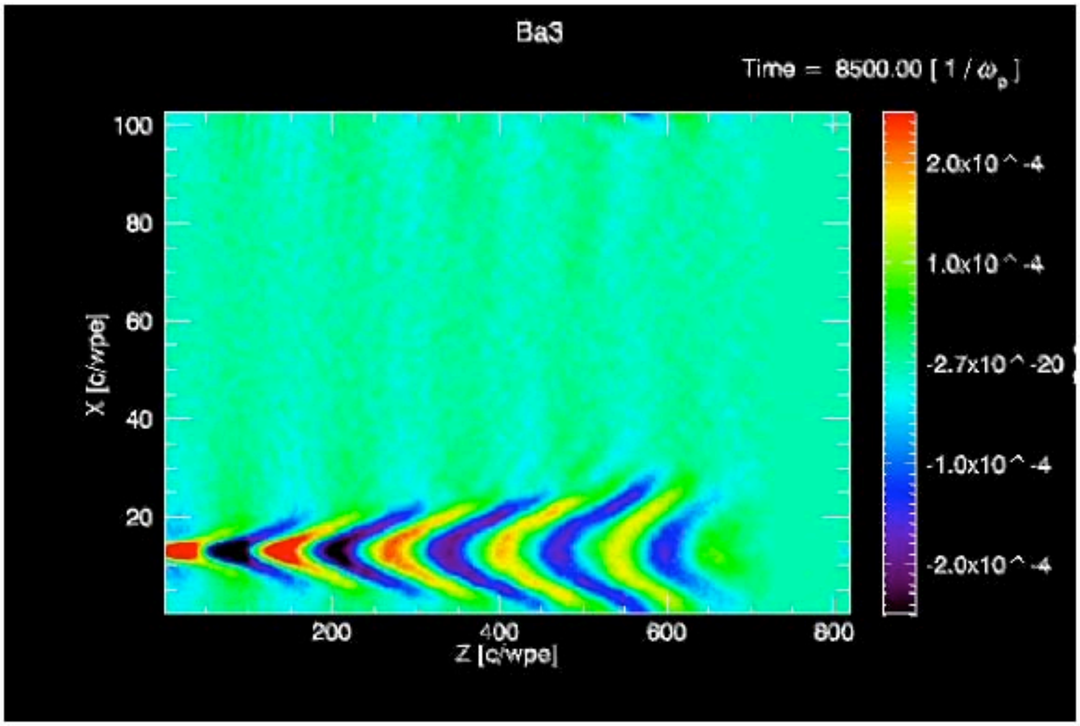


Fig. 6. Instantaneous spatial pattern of shear-wave magnetic field in the absence of flow

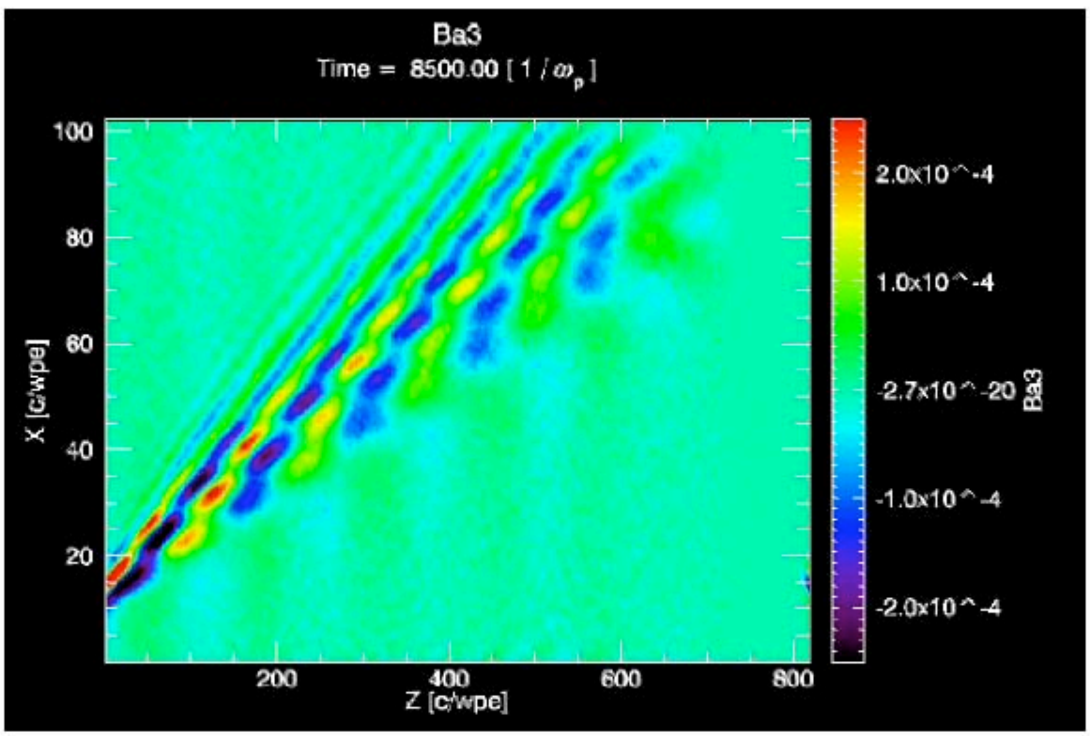


Fig. 7. Instantaneous spatial pattern of shear-wave magnetic field with scaled flow p=0.8

In figures A and B the confinement magnetic field points to the right in the horizontal direction (z). The shear wave is excited at the left boundary (z=0) and in the absence of flow (Fig. 6) it spreads across the field (x-direction) according to the inertial cone angle. The color scale represents the value of the component of the wave magnetic field out of the page (i.e., δB_y). Red corresponds to large positive values and deep blue to large negative values. Note that the oblique magnetic-field patterns shown in Fig. 7 imply that very narrow current filaments are formed by the flow. This is a consequence of finite electron inertia not contained in MHD descriptions

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