INVESTIGATION OF A COHERENT INSTABILITY WITH AN ION BEAM PROBE

Conference Paper

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Some of the most interesting plasma physics has come from studies of magnetoplasma instabilities. The primary diagnostic tool has generally been the Langmuir probe. However, there are some very serious drawbacks to this technique. Primarily, the Langmuir probe cannot supply detailed measurements everywhere in the plasma because it either perturbs the plasma or is destroyed by the plasma and because the measurements are difficult to interpret since magnetoplasma probe theory does not exist in closed form. In contrast to previous studies, we are engaged in the first study of an instability generated in a hollow cathode discharge using ion beam probing techniques developed at Rensselaer. This technique does not perturb or contaminate the plasma; it accesses any part of the plasma including the high energy density arc core, and most importantly, it provides accurate detailed measurements of plasma number density, electron temperature and space potential simultaneously. All measurements are made continuously with a spherical resolution volume of better than 0.1 cm^3 and time resolution of $10 \text{ } \mu\text{sec}$.

What will be presented in this paper is data from an experimental study using an IBP of a coherent instability at 70-80 KHz in a hollow cathode discharge in Helium. The data will be compared with three instability models -- the Kelvin Helmholtz, the Rayleigh Taylor, and the Drift mode.

Because of the newness of the technique, I will briefly describe the technique. My colleague, Bob Reinovsky, described ion beam probing in paper 2C4 on Wednesday. For those who heard it, this will refresh your memory. As seen on the first slide, we direct a +1 beam of alkali metal ions perpendicular to the magnetic confining field. We collect

+2 ions resulting from electron impact ionization. Because of the magnetic field, +2 ions are separated from +1 and more importantly, we "stare" at one small resolution volume whose size is about 0.1 cm^3 . We can move this small sample volume anywhere in the plasma cross section. By measuring the intensity of the beam, we measure the plasma density; by measuring the change in beam energy from one side of the plasma to the other, we measure the space potential. It is important to note that the ion beam probe is the only way to measure the space potential and density directly, accurately and simultaneously.

In order to investigate an instability, we must know DC parameters about the plasma. The second slide shows two isometric plots of DC density and space potential. The peak density is $2 \times 10^{14} / \text{cm}^3$; peak electron temperature is 8 eV and peak space potential is 50 V. From this data, we can get all the information on gradients in any direction. For example, from the space potential map, we get the electric field E in any direction by taking the appropriate derivative. This is the only way to directly obtain E .

Moving on to AC or fluctuating experimental data, we see on the third slide some typical data of fluctuating density and space potential at 75 KHz. On the right we see two oscillograms of the ion beam probe output of density and space potential taken from a spectrum analyzer. We see that we have a very coherent oscillation at about 75 KHz. When we scan along a diameter we obtain the radial plots seen on the left. The peak density fluctuations are about 10 percent of the DC density; the space potential fluctuations have a peak of 25 volts. Note the strong radial localization and the strong evidence of asymmetry.

This information can be cast in a different form by scanning the sample volume over the plasma cross section and making an RMS amplitude contour map as shown on slide 4. On the right, oscillograms from lines through the DC map show the AC fluctuations riding on top of the DC data. AC amplitude change as a function of position is clearly seen. The contour map shows the strong localization of the instability in the form of an incomplete ring. The oscillograms at the left show the change of density oscillation phase as a function of position. From this, we find that the oscillation approximates an $m = 1$ mode rotating in the electron diamagnetic direction. We have also measured $K_{\parallel}$, the parallel wave number, and it is small.

At this point, we know we have a fairly coherent oscillation; we know its frequency and its location. In order to compare it with theoretical models, we must know the fields and gradients that occur. One of the unique capabilities of the ion beam probe is that it can supply field and gradient information accurately and directly.

We have used this capability in obtaining the radial electric field which is seen on slide 5. Plotted are the RMS density fluctuation amplitude, the space potential and the radial electric field. The electric field has a striking reversal. This shows there are two counter-rotating fluids due to $\bar{\mathbf{E}} \times \bar{\mathbf{B}}$ rotation. There is maximum shear at this reversal, and at this reversal, we find maximum instability amplitude. This suggests the possibility of a Kelvin-Helmholtz mode.

In slide 6, we look at the density gradient. We again plot the instability amplitude for reference. Above it is a radial plot of the

radial density gradient. At the peak density gradient there is a peak in the instability amplitude. This suggests the possibility of a Drift wave.

We have looked at the electric field and the density gradient. From both, we can calculate an azimuthal velocity from both effects. From this we can calculate the shear in the azimuthal velocity V_θ in terms of ω_{ExB} and ω_{Di} . This is shown on slide 7 as a plot of total shear from both effects. There is a shear maximum at the instability maximum. It should be noted that the magnitude of the shear in $E \times B$ velocity is much larger than the diamagnetic shear.

We turn now to the evaluation of frequency to see the magnitude of both effects in predicting the instability frequency. This is shown on slide 8. Plotted is the instability fluctuating density amplitude, again given for reference, and a number of frequency plots as a function of radial position. The top horizontal line is the observed instability frequency; it is a constant as a function of radial position. Below this are two plots of ion diamagnetic frequency. The straight line is the ion diamagnetic frequency we would obtain if the DC density were fitted with a gaussian profile. The points are the diamagnetic frequencies obtained from the actual DC density profile. In either case, the ion diamagnetic frequency is still an order of magnitude lower than the instability frequency.

Moving to the top plot, we have the $E \times B$ rotation frequency as a function of radial position. From the field reversal, we have fluid rotation in the electron diamagnetic direction denoted by the dotted lines and fluid rotation in the ion diamagnetic direction denoted by the solid

line. The dotted line predicts the frequency and rotation direction seen experimentally, and this occurs in the region of instability maximum amplitude. More significantly, however, this is located in the region of maximum shear; the electric field is changing very rapidly in this region. The agreement is much stronger with the shearing flow rather than fortuitous frequency prediction.

Another important parameter is the phase of the density and space potential fluctuations. This is important because the theoretical models give predictions of the phase. To make sense both density and space potential phase measurements should be done simultaneously at the same point in the plasma. It should be noted that any phase measurements are extremely difficult to make. On slide 9, a radial plot of the phase shift of the density and space potential oscillations with respect to a reference are shown on the left. The open and closed points are for two data runs. In the region where the instability occurs we see a constant phase shift in density fluctuations; however, there is a sudden 180° phase shift from one side of the plasma to the other. This shows we have an $m = 1$ mode. The space potential fluctuation shows a rapid phase shift where the instability is located. These two facts -- a constant density phase shift and a rapid space potential shift -- indicate strong evidence of a Kelvin-Helmholtz instability. On the right is the relative phase shift between the density-space potential oscillations. This is obtained by subtracting the space potential phase from the density phase shown plotted on the left.

We have looked at the location of the instability, at the gradient and fields, at the predictions of frequency from the gradients and fields and at the phase of the density space potential oscillations. In the form of a summary, we will compare the data with three instability models. On slide 10, we show various characteristics and the agreement. To eliminate any model, we must have a definite no.

The first parameter listed is the parallel wave number. As mentioned earlier, this parameter is small and is found in agreement with all three models.

Looking at localization, we find experimentally that the localization is in a region of maximum shear. This is in agreement with the Kelvin-Helmholtz model although as we have seen, there is no evidence to rule out the other two models.

A look at mode number shows that with an experimental mode number of 1, we are in agreement with the three models.

The experimentally observed frequency is expressed in terms of maximum $E \times B$ rotation frequency ω_{em} . The Kelvin-Helmholtz model has a frequency requirement that is fulfilled experimentally. The other two still cannot be ruled out.

The rotation direction is in the electron diamagnetic direction. We cannot accurately compare with the models because we can pick the proper rotation depending upon which side of the shear interface we are on.

We have not measured growth rate but we think we know how. We cannot compare with the models.

The normalized density to space potential fluctuation ratio is experimentally very large and is predicted by the Kelvin Helmholtz model. The ratio is greater than unity for the Rayleigh-Taylor model and is not ruled out. However, the Drift mode ratio is less than unity, this fact eliminates the drift mode.

The local radial phase shift is between 140° - 250° experimentally. Looking at the various models we do not find a close correlation. However, as mentioned earlier, this measurement is extremely difficult to make. If we look at the change of the phase, the Kelvin-Helmholtz is in close agreement. We believe that there is a constant phase shift induced by the instrumentation. When this is taken into account the value of phase shift is within the predicted Kelvin-Helmholtz range.

Looking at the last entry, the normalized fluctuating space potential amplitude, we get a large number experimentally. This agrees with Kelvin-Helmholtz model. The Rayleigh-Taylor is eliminated as is the Drift Mode. This is important because it identifies the energy source of the instability.

We have investigated an instability in a magnetoplasma with an ion beam probe. Based on the detailed experimental data, we have eliminated the Rayleigh-Taylor and Drift waves as possible models, and we classify it as a Kelvin-Helmholtz mode.

Power Plot of Fluctuating Density and Space Potential