Ion beam generated modes in the lower hybrid frequency range in a laboratory magnetoplasma

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The experiment is performed in the upgraded **LA**rge **P**lasma **D**evice (LAPD). The LAPD is a linear device, which produces a highly magnetized quiescent plasma. A schematic of the machine is shown in figure 1. The plasma is formed by a pulsed discharge between cathode and anode. The electron beam thus formed collisionally ionizes the fill gas (Helium). The discharge typically lasts for 10 - 15 ms, and is pulsed at 1 Hz. The plasma is highly reproducible. It is 18 m long, with a diameter of 50 cm, which is more than 100 ion larmor radii across at a background field of 1000 G. In the experiment typical electron densities and temperatures are on the order of 10^{12} cm^{-3} and 0.25 eV respectively. Magnetic fields were varied from 750 G to 1800 G.

A small vacuum chamber is bolted to the end of the LAPD. The chamber houses a 4 inch diameter lanthanum hexaboride (LaB_6 cathode)[1] which creates a pulsed discharge to an anode 6 inches away. A high density plasma is thus created in the small chamber and a series of grids, 8x8 cm large, extract and accelerate ions to high energies[2]. Ion beam energies range from 2 to 20 keV. The ion beam is space charge neutralized by electrons streaming from the LAPD into the beam chamber. The beam vacuum chamber can be angled with respect to the LAPD axis. The beam source itself is in the flaring magnetic field past the last magnetic field coils of the LAPD. As the ions stream into the high guide field in the LAPD their pitch angle increases as determined by the invariant $v_\perp^2/B_0$. Pitch angles in the LAPD vary from 0° (straight launch) to 40°. The plasma is diagnosed by a variety of probes, including a combined electric and magnetic field probe, pictured in figure 1, Langmuir probes and gridded energy analyzers.

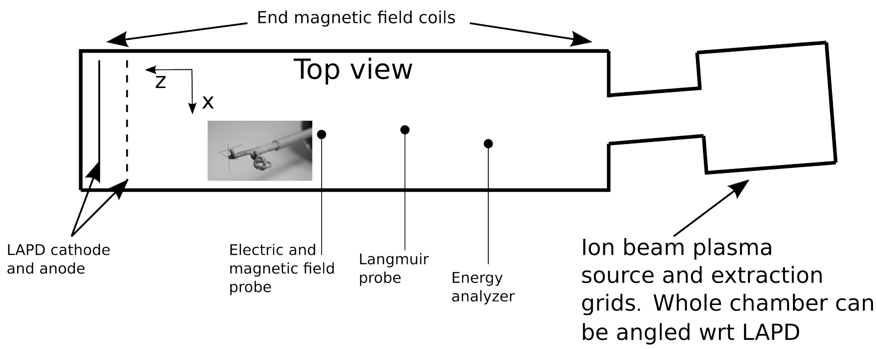

Figure 1: Schematic of the experiment

Figure 2 shows a typical time trace of one of the measured electric field components. The ion beam is turned on at t = 0 ms. Immediately afterwards the probe picks up some amount of electrical noise from the high voltage pulsing circuit. A few microseconds later a burst of waves passes the probe. This first burst consists both of waves above f_{ci}, possibly whistler waves, and waves below f_{ci} which were identified as shear Alfvén waves. After a few hundred microseconds the wave activity on the probe grows out of the noise and reaches a saturated level. In this stage shear Alfvén waves have been observed as well. This paper focuses on the higher frequency waves during this saturated stage. The electronics and probes used are sensitive in a range of 7 MHz - 200 MHz, which for our parameters corresponds to a frequency range starting at around 10 f_{ci} to several times the lower hybrid frequency, but well below the electron cyclotron frequency.

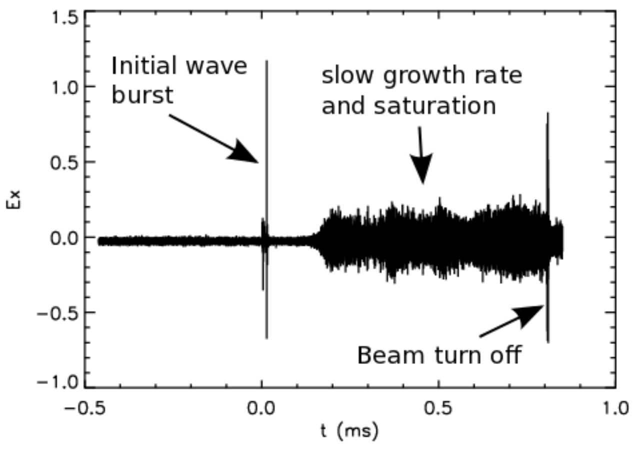

Figure 2: Typical time trace of E_x component

The spectrum for a Helium beam at 15 keV beam energy and 35° pitch angle, in a plasma of 10^{12} cm^{-3} electron density and 0.25 eV electron temperature with a 1500 G guide field is shown in figure 3. The spectrum is well above the noise level, is typically broadband with a peak at 20 - 30 MHz, and shows distinct peaks near ion cyclotron harmonics. For these parameters, the ion cyclotron frequency is 570 kHz and the lower hybrid frequency is 44 MHz. The waves are mostly electrostatic. The magnetic field components are barely above the noise level. The strongest magnetic field components oc-

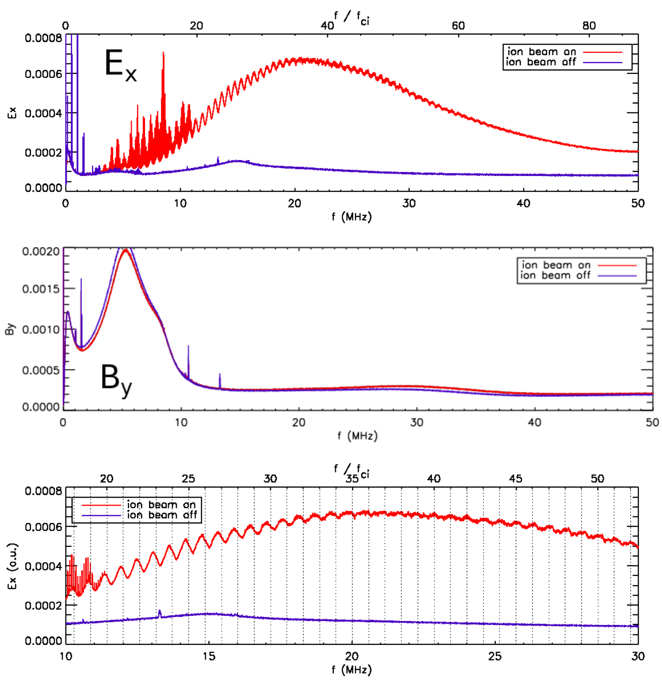

Figure 3: Typical spectra with zoom-in.

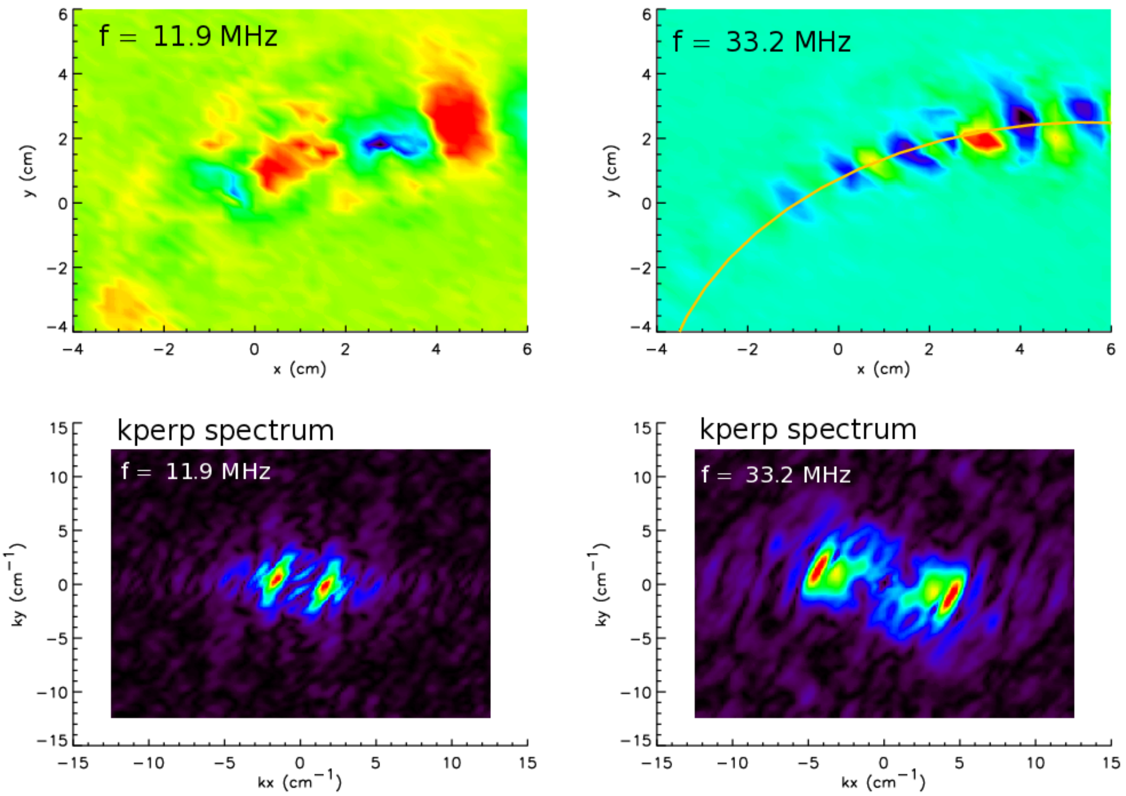

Figure 4: Mode structure obtained from cross correlation analysis at for two spectral peaks of figure 3, and perpendicular wave number spectrum for both modes.

cur for frequencies around 30 - 40 MHz, which is the frequency range above the peak in the broadband spectrum.

The mode structure of the waves was obtained by cross correlation analysis of a stationary probe 32 cm away axially from a moving probe. The moving probe measured the wave activity in a xy plane, 10 cm high by 10 cm wide. Figure 4 shows the amplitude of the wave multiplied by the sine of the cross phase at two different frequencies, 11.9 MHz and 33.2 MHz. Both frequencies correspond to one of the near-harmonic peaks in the spectrum of figure 3. A clear mode pattern can be identified in both cases, with higher perpendicular wave number at the higher frequency. Both modes seem to lie on the same curve. The yellow curve in figure 4(b) is a section of a circle with radius equal to the predicted gyro radius for a 15 keV He beam at 35 degree pitch angle in a 1500 G guide field. It is surmised that the modes exist on the beam path.

From the lower panels of figure 4 the dominant perpendicular wave number can be found. A similar analysis for all the peaks in the spectrum of figure 3 yields the measured dispersion relation of the perpendicular wave number versus frequency, plotted in figure 5.

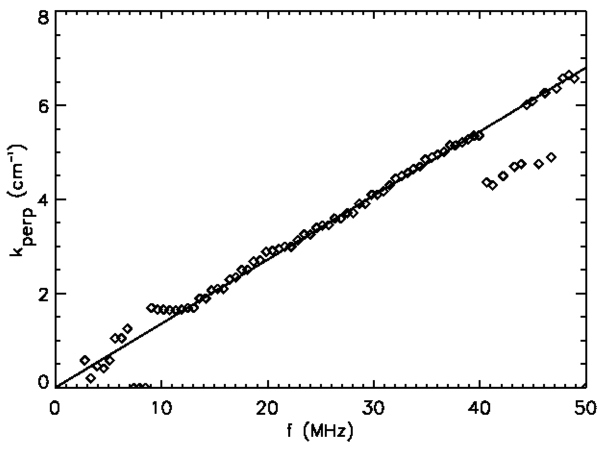

Figure 5: Measured dispersion relation of the perpendicular wave number versus frequency.

The measured dispersion shows a clear linear relationship between $k_\perp$ and frequency, indicating a constant perpendicular phase velocity for all modes. The fitted line corresponds the velocity of a 15 keV He beam with 33 degree pitch angle. The slope of the curve therefore agrees closely with a dispersion relation of the form $\omega \simeq k_\perp v_{beam,\perp}$. In cylindrical coordinates with $k_\perp = m/R$ and $v_{beam,\perp} = R\Omega$ we obtain $\omega - m\Omega = k_\parallel v_{beam,\parallel}$, where we have included the Doppler shift due to the parallel motion of the beam. This doppler shift moves the observed frequencies off the harmonics of the ion cyclotron frequency. From figure 3 one measures the frequency shift due to parallel Doppler shift to be on the order of 50 - 200 kHz, which indicates $k_\parallel \sim 0.005$ cm^{-1} and $\lambda_\parallel \sim 10$ m, on the order of the machine size. The ratio of perpendicular to parallel wave number $k_\perp/k_\parallel$ is on the order of 10^3, indicating near perpendicular phase velocities for the modes.

In conclusion, experiments involving the launch and propagation of a high energy ion beam in the LAPD at UCLA are underway and ongoing. Both low frequency waves at $f < f_{ci}$ and intermediate frequency waves at $f \lesssim f_{LH}$ are being studied. At frequencies $f \lesssim f_{LH}$ waves with spectra showing strong peaks near the ion cyclotron harmonics are observed. The wave dispersion is consistent with doppler shifted beam modes $\omega - m\Omega_i = k_\parallel v_{beam,\parallel}$. Further studies will focus on the dependence of the waves on various parameters, and comparisons will be made with theoretical models and simulations.

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References

[1] B. Van Compernolle, W. Gekelman, P. Pribyl and C. Cooper, *Wave and transport studies utilizing dense plasma filaments generated with a lanthanum hexaboride cathode*, Phys. Plasmas **18**, 123501 (2011)

[2] S. K. P. Tripathi, P. Pribyl, and W. Gekelman, *Development of a radio-frequency ion beam source for fast-ion studies on the large plasma device*, Rev. Sci. Instrum. **82**, 093501 (2011)