Demonstration of Loss Cone Induced Quasi-Longitudinal (QL) Whistlers in Large Laboratory Plasma of LVPD

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Abstract

Turbulence of Quasi- Longitudinal (QL) nature is excited in LVPD when transverse magnetic field of Electron Energy Filter (EEF) is applied. The nature of turbulence changes from electrostatic to electromagnetic, in the energetic electrons rich belt region and have power residing in $3\,kHz < f \leq 30\,kHz$ and $40 kHz < f \leq 80\,kHz$ respectively. In later case, QL whistler of electromagnetic nature is excited by loss cone driven reflected electrons from the magnetic mirror, developed in the belt region. It propagates highly obliquely ($\theta = \tan^{-1}(k_\perp / k_\parallel) \approx 87^0$) with $k_\perp \sim 1.4\, cm^{-1}$ and $k_\parallel \sim 0.06 cm^{-1}$respectively. Noticeably, its wave polarization changes continuously with frequency. A good agreement is observed between the experimental observations and numerical results derived from the theoretical models[1-3]. We believe that this may probably be the first laboratory demonstration of QL whistlers[4].

I. Introduction

Whistler turbulence observed in earth's magnetosphere has free energy sources lying in energetic electrons, beams, anisotropies in temperature and distribution function, density gradients, loss cone etc. and is responsible for the precipitation of energetic electrons into the ionosphere. This has been observed that when pole bound electrons gets trapped in the earth's magnetic field and suffers loss cone instability, they results in the excitation of Quasi-Longitudinal (QL) whistlers at large oblique angles. Whistler turbulence is observed in Electron Magneto hydrodynamic (EMHD) plasma and EMHD turbulence is governed by length and time scales satisfying inequalities $\rho_{ce} << L_n << \rho_{ci}, d_i$ and $f_{ci} < f_{tur} < f_{ce}$, where, ρ_{ce}, ρ_{ci}, f_{ce}, f_{ci} are electron and ion gyro radii and frequencies, d_i is skin depth, f_{tur} is the turbulence frequency, L_n is density scale length. Extensive theoretical and experimental work on the EMHD plasma has been carried out for the excitation of driven modes by pressure gradients and energetic electrons both in in LVPD and other devices. But role of the loss cone in particular, has not been assessed in any of the large plasma devices such as LAPD, TRW and LVPD respectively.

II. Experimental System

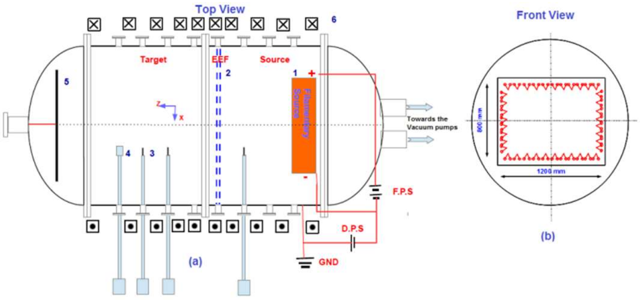

Figure 1: Schematic of the LVPD plasma system, (a) top view showing the locations for plasma source (1), EEF (2) and installed diagnostics (3-4) and (b) cross-sectional view showing the filament arrangement in rectangular periphery.

Schematic of the LVPD experimental arrangement is shown in figure 1. LVPD is a cylindrical vacuum chamber of dimension ($\phi = 2m$ and $L = 3m$). Radial plasma confinement is achieved by set of 10 solenoids, axially separated and can produce axial uniform magnetic field of $B_z \leq 150G$. Plasma source is a tungsten based multi-filamentary cathode with multi-cusp arrangement to minimize the plasma loss. In the experiment, axial field is fixed at 6.2G. In addition to this, an electron energy filter (EEF) is installed at the centre of the device to produce a strong transverse magnetic field ($B_{EEF} \sim 160G$) with respect to B_z. The EEF is a varying aspect ratio solenoid. Inactivated EEF provides electrostatic filtering while activated EEF allows formation of a strong magnetic mirror with ratio $R_M = B_{\max}/B_{\min} \sim 25.8$ at the radial location of $x = 60\ cm$. EEF divides LVPD plasma in three regions of Source, EEF and Target plasmas. Pulsed Argon plasma ($\Delta t_{discharge} = 9.2ms$) is produced at $P_{Ar} = 4.0 \times 10^{-4}\ mbar$ filled pressure. A discharge voltage of $-70V$ between cathode and the anode produces a discharge current $\sim 200A$. Investigations are carried out using conventional Langmuir and B-dot probes.

III. Results and Discussion

Activation of EEF has substantially modified the plasma conditions in LVPD. The resultant magnetic field ($B_z + B_{EEF}$) became asymmetric and induces an asymmetry in plasma profiles. Major observations are realized in the form of enhancement in plasma density and electron temperature in source plasma and sizeable reduction in plasma density and electron temperature by a factor of 8 and 2 respectively in target plasma. In this paper, we will limit ourselves to the source plasma characterization. Beside increase in plasma density and electron temperature, the plasma and floating potentials attain more negative values and exhibits pronounced peak in the line of sight of location of primary electron injection ($x = 60cm$) [4].

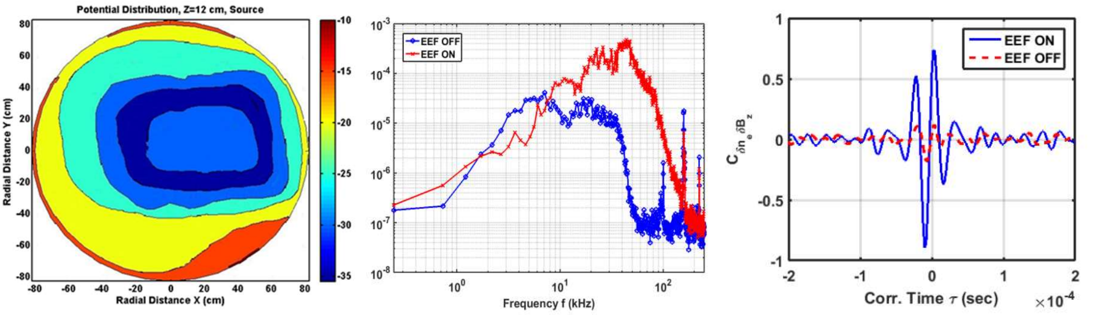

Figure 2: a) Asymmetric distribution of energetic electrons in the source plasma in $x - y$ plane. The blue color corresponds to the most energetic electrons present in a $3 - D$ belt like structure, obtained by picking the peak floating potential. b) power spectra of density fluctuations ($x = 60cm$), shows enhanced power and broadening of spectrum with EEF activation and c) cross section between plasma density and magnetic field fluctuations in the belt region with EEF OFF and ON conditions.

It is also observed that with EEF ON, the turbulence level in density fluctuations increases substantially. The peak floating potential, mimics presence of energetic electrons measured in $z - x$ plane indicates the formation of an asymmetric $3D$ belt like structure, rich with population of energetic electrons emanating out right from the filament locations to the EEF [Fig. 2a]. Interestingly, we have observed that the turbulence level is enhanced only in the right hand side of the energetic belt whereas it is suppressed in the left hand side of the belt [Fig. 2b]. Measurement for magnetic fluctuations in the region for EEF OFF case revealed that they attain values close to noise level in the location of energetic belt region but remains de-correlated with density fluctuations. They become significant when EEF is ON and fluctuations assume electromagnetic nature and strong negative correlation exists between δB_z and δn fluctuations [Fig. 2c]. The potential fluctuations do not change with EEF. This suggests the presence of an electrostatic mode in the region of belt for EEF OFF case but for EEF ON case, the same converts to an electromagnetic mode.

We have characterized further the electromagnetic mode for its identification and pin pointing the associated free energy source by considering role of pressure gradient, temperature gradient, energetic electrons and radial electric fields. As the density of the belt region shows an enhancement, we have also looked into the role of reflected particles from the possible magnetic mirror action at the EEF location ($x = 60cm$). The observations made are summarized as follows: 1) presence of significant magnetic fluctuations and strong out of phase correlation between the density and magnetic fluctuations, confirming electromagnetic nature, 2) $3-axis$ magnetic probe measurements confirms the right hand polarization of the wave; 3) the polarization is changing with frequency, 4) the turbulence is broadband $40kHz < f < 80kHz$, with $k_\perp$dominated $k_\parallel$ suggesting a highly obliquely propagating mode, $= \tan^{-1}\left(\frac{k_\perp}{k_\parallel}\right) \approx 87°$. The nature of the instability is identified as whistler, driven by the reflected electrons from the loss cone. We arrived to this conclusion after numerically estimating the mode frequency values due to a) pressure gradient, and b) electric field driven $E \times B$ driven turbulence and ruling them out. No anisotropy is observed in electron temperature. The growth of whistlers considering reflected particles in homogeneous plasmas using DGH [Dory-Guest-Harris] type of distribution for an obliquely propagating mode is estimated. We found that the typical growth time scales agree well with the experimental observations.

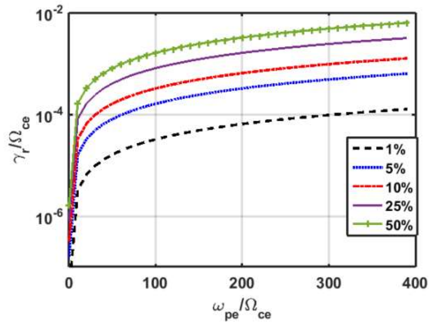

Fig. 3. Normalized growth rate for whistler wave instability due to the reflected particles in a loss cone configuration. The growth rate is estimated from the experimentally obtained parameters.

Figure 3 shows theoretically estimated growth rate values for the experimentally obtained values. Beyond $\frac{\omega_{pe}}{\Omega_{ce}} \sim 340$, the mode started approaching the saturation for different fraction of reflected particles. The reflected particle population has been controlled by changing the loss cone angle using variation in EEF magnetic field. This suggests that for EEF ON case, the excited mode is reflected electrons driven QL whistlers and for EEF OFF case it has electrostatic nature and is not in the purview of this paper.

References

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