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An Extremely Large Beta Laboratory Plasma

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Introduction

Large beta ($\beta \sim 1 - 10^3$) plasma is characteristic of stellar terrestrial environment[1]. In cases where the ambient magnetic field B is very low (0.1-0.3 G), as in solar wind, the Larmor radii of particles become comparable with characteristic scale lengths, invoking kinetic effects in dynamics having wave frequency $\omega < \omega_{ce}$ which covers both MHD and EMHD perturbations. For example, finite electron Larmor radius (FELR) invokes gyrokinetic effects that modify conventional dispersion of EMHD waves through the significance of $k_{\|}r_{Le} \sim \omega/\omega_{ce} \sim \delta B/B$. Large β plasma has implications in near-earth plasma as well. Here, laboratory experiments[2,3,4] on ionospheric plasma reveal a controversy between the behavior of antenna-excited and spontaneously excited EMHD structures. Observations on the former show that a null point is required for invoking nonlinearity, while the spontaneously excited EMHD turbulence indicates nonlinearity even in presence of a finite B. Resolution of this paradox requires experiments at large β condition as in both the cases, a significant fraction of the experimental volume has very high ($\sim 10^2$) β values.

Investigation of such a plasma requires simulation of high β conditions in a large laboratory device in a manner that enables controlled experiments, devoid of boundary effects. Very high β conditions are difficult to realize in a laboratory by conventional methods. This is because, a finite B is required to produce and confine a high density ($\sim 10^{18}$ m^{-3}) plasma, setting an upper limit to the attainable value of β. We have set up an arrangement in the large volume plasma device (LVPD) that enables transition of the relatively low β plasma once produced, to high β, by tailoring the existing B to required value over time scales << the plasma confinement time. The plasma thus produced with $\beta \sim 10^3$, termed the extremely large beta (ELB) plasma, shows evidences of FELR effects that modifies the diamagnetism. Further, the response of the ELB plasma to electromagnetic perturbations is also different, as presented in this report.

Experimental Setup and Procedure

The schematic of the set up is shown in Fig.1. Details on production of the LVPD plasma is given elsewhere[5]. The ELB plasma is produced in two steps: (i) The production of plasma in LVPD by conventional method and (ii) Cancellation of B during the mainglow or afterglow of the discharge depending on the requirement. Cancellation of B_x, B_y and B_z is achieved with the help of three Helmholtz coils. Square coils fed by dc current, installed outside the chamber are used for B_x and B_y compensation where as the circular B_z compensation coil, fed by pulsed current, is installed inside. Experiments in vacuum have shown that using this set up a volume of 80 x 90 x 100 cm^3 is obtained inside the device within which B < 100 mG. The diagnostics consist of Langmuir, magnetic and emissive

Fig. 1(a)

Schematic of the experimental setup

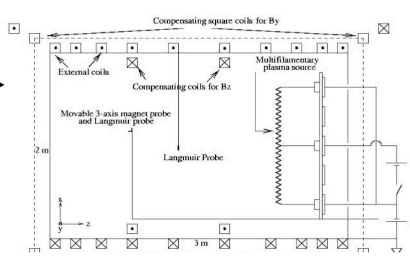
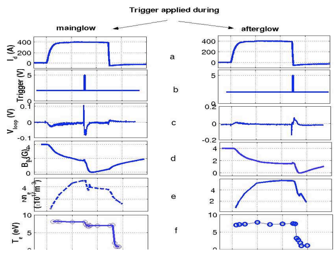


Fig. 1(b)

Typical LVPD Discharge



Probes. The data are acquired using a 16 channel VXI system.

The typical LVPD discharge and temporal sequence of the field compensation are depicted in Fig.1(b) that shows I_d (a), trigger to the B_z compensation coil (b), magnetic probe signal (c) showing the flux change due to diamagnetism, the net B_z in the plasma (d), n_e (e) and T_e (f) when the trigger is applied (i) at ~ 3 ms and (ii) at ~ 5 ms. Upon application of the compensation trigger, B_z reduces and attains a plateau at about ~ 500 μs after the trigger, corresponding to the formation of ELB regime. Once formed, the ELB state is sustained for about 200 μs.

Results:

Diamagnetism : The diamagnetic behavior of the mainglow plasma during its transition to ELB state has been studied by examining the radial profiles of $P=nkT_e$, V_p and B_z at different instances. These profiles are plotted in Fig.2 ((b), (c) and (d)) for three temporal points indicated in Fig.2(a). These temporal points correspond to (i) 500 μs prior to, (ii) 250 μs after and (iii) 500 μs after the application of the Helmholtz pulse. In all three cases, our

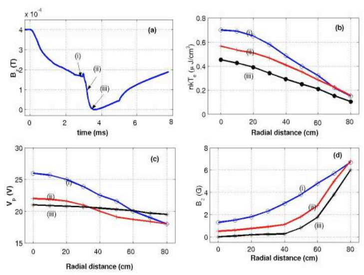


Fig. 2

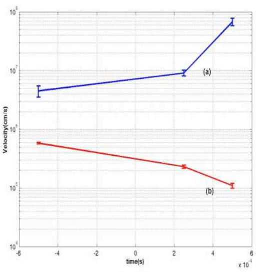


Fig. 3(a)

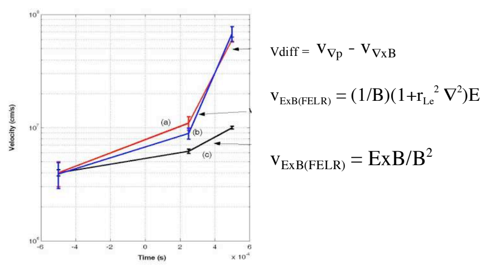


Fig. 3(b)

examination of energy balance reveals that the diamagnetism shows deviation compared to predictions based purely on pressure balance as in MHD. As per conditions in MHD, the observed azimuthal velocity, $v_{\nabla xB} = (1/n\ e\mu)\ (\delta B_z/\delta r)$ should equal the pressure driven drift velocity $v_{\nabla P} = (\nabla P \times B/(neB^2)$. We observe that $v_{\nabla xB}$ in all three cases is significantly less compared to $v_{\nabla P}$. This deviation from MHD prediction is due to the E x B drifts that result in azimuthal electron current, marking the EMHD nature of the plasma.

There is however a marked difference between the natures of E x B drift as the plasma undergoes transition from relatively low to very high values of β. This is understood from a close look at the velocities $v_{\nabla P}$, and $v_{\nabla xB}$ and v_{ExB} estimated from the gradients in P, B and V_p shown in Fig.3. Figure 3 (a) shows the estimated velocity $v_{\nabla xB}$ at the three instants depicted above, along with $v_{\nabla P}$. Shown in Fig. 3(b) is the difference v_{diff} between the observed $v_{\nabla P}$ and $v_{\nabla xB}$ corresponding to the three instances along with the ExB drift velocities. At point (i) v_{ExB} estimated as ExB/B^2 matches well with v_{diff}. With the approach of ELB lasma the deviation of $v_{\nabla xB}$ from $v_{\nabla xB}$ becomes increasingly prominent and v_{ExB} estimated in the above manner ceases to account for the observed v_{diff} . One important change of the ELB plasma compared to the typical discharge is the significant increase of r_{Le} from about 2 cm to 30 cm. The contribution from FELR effects is assessed by applying a correction to the v_{ExB} by using the relation $\mathbf{v_{ExB(FELR)} = (1/B)(1+r_{Le}^2\ \nabla^2)E}$. As can be seen from Fig. 3(b), the FELR corrected E×B velocity values provide a good account of the observed velocity deviation. This observation gives indications that electron Larmour radius manifest its significant role by accentuating the E×B effects in case of the ELB plasma. By reducing the field gradients significantly, this characteristic is responsible for the enhanced field uniformity of the ELB plasma.

<u>Response to electromagnetic perturbations</u>: The ELB plasma shows characteristic difference with respect to its response towards excitation of linear and nonlinear e.m. perturbations of frequency 0.1 - 4 MHz in the afterglow plasma. Fig.4 (a) shows the difference in dispersion and Fig. 4(b) shows polarization between the linear modes excited in

Fig. 4(a)

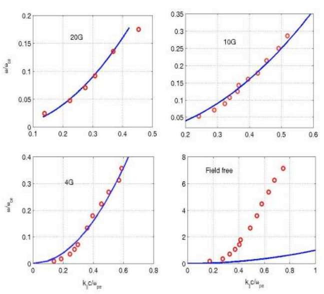
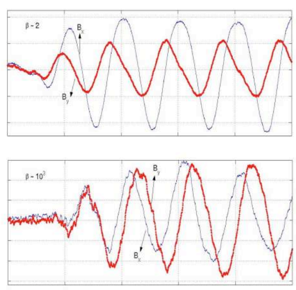


Fig. 4(b)



low and high β conditions. The ω vs $k_{||}$ dependence in case of the low β plasma shows a good agreement of the experimental points to the theoretical dispersion relation (solid curves) for cold plasmas for plane whistler waves propagating along $B_{z,dc}$ (B_z=4G,10G,20G as shown in figure) given by $k^2c^2/\omega^2 = 1-\omega_p^2/(\omega\ (\omega-\omega_{ce}))$. In the ELB state, the experimental data do not agree with the theoretical curve obtained for the local ambient B_z = 250 mG. As shown in this figure, the waves excited in low and high β conditions show opposite polarization. Our preliminary investigations on nonlinear EMHD structures has also revealed difference in their propagation characteristis. The role of kinetic effects in modifying the behaviour of linear and nonlinear EMHD perturbations is presently being analyzed and will form the subject of discussion for our future article.

<u>Conclusions</u>

An extremely large beta (ELB) ($\beta \sim 10^3$) plasma is produced over a large volume in LVPD by compensating the confining magnetic field of plasma once produced. The major parametric difference of ELB plasma compared to the relatively low β plasma is the large value of electron larmour radius, about 30 cm, comparable with the field and density scale lengths.

In the ELB state, evidence of FELR effects is obtained by the accentuated E×B current, causes modification of the plasma diamagnetism. Experimental evidences are also obtained for different response of the ELB plasma to linear and nonlinear e.m. perturbations as compared to the low β counterpart. These observations are significant, directing us towards further exploration on kinetic effects of the ELB plasma.

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