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NON-INDUCTIVE CURRENT DRIVE WITH LOWER HYBRID AND ION BERNSTEIN WAVES IN PBX-M

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ABSTRACT. The synergistic behavior of a lower hybrid wave (LHW) and an ion Bernstein wave (IBW) on the PBX-M tokamak is experimentally analyzed using a 2-D hard X-ray (HXR) camera. The bremsstrahlung emission from suprathermal electrons, generated with lower hybrid current drive (LHCD), is enhanced during ion Bernstein waves injection. This enhancement is observed in limited regions of space suggesting the formation of localized current channels. The effects on plasma electrons, during combined application of these two type of waves are theoretically investigated on the basis of a quasilinear model. The numerical code solves, simultaneously, the 3-D (R, Z, Φ) toroidal wave equation for the electric field (in the WKBJ approximation) and the Fokker-Planck equation for the distribution function in two dimensions ($v_{||}$, $v_{\perp}$) with an added quasilinear diffusion coefficient. The beneficial effects of a combined utilization of both type of waves on the current drive are emphasized. The numerical results are compared with the experimental observations.

INTRODUCTION

The LHW+IBW experiment was performed in circular plasmas where we generally observe central LHCD. The aim of this experiment was to identify a possible way to localize part of the non-inductive additional current off-axis.

The main diagnostic used to detect variations of the electron distribution function is a 2-D HXR camera[1]. The camera measures the bremsstrahlung emission from fast electrons on the tail of the distribution function. Experimentally, when IBW is injected in a plasma during LHCD, there is a strong increase in the HXR emission with respect to the signal detected with LHW alone[2,3]. This increase appears to be predominantly localized off-axis. This phenomenology can be correlated with the Landau damping of the IBW power on the tail of the electron distribution function modified by LHCD. Due to the characteristic behavior of the IBW $n_{||}$ and parallel electric field $E_{||}$, this will result in a formation of spatially-localized current channels.

EXPERIMENTAL FINDINGS

To assess the impact of our radio frequency (RF) wave systems on the electron population, we use a measurement of the HXR emission from energetic electrons interacting with the waves via electron Landau-damping.

The HXR diagnostic is a pinhole camera providing a tangential view of the PBX-M plasma[1,2]. Our investigation is based on horizontal profiles obtained operating a cut of the HXR images along the mid-plane through the plasma center.

To assess the impact of IBW injection during LHCD, we refer to the time evolution of the spatial profile of the variable:

$$\Delta_{HX}(t) \equiv I_{HX}(t_{LH+IBW}) - I_{HX}(t_{LH})$$

where: $I_{HX}(t_{LH})$ is the vertical HXR intensity at a time frame just before the onset of IBW (i.e., when only LHW is present) and $I_{HX}(t_{LH+IBW})$ is the vertical HXR intensity at a time when both types of waves are present in the plasma. In this experiment, the data acquisition was programmed to have one HXR image every 5 ms. We refer to each image as a "time frame".

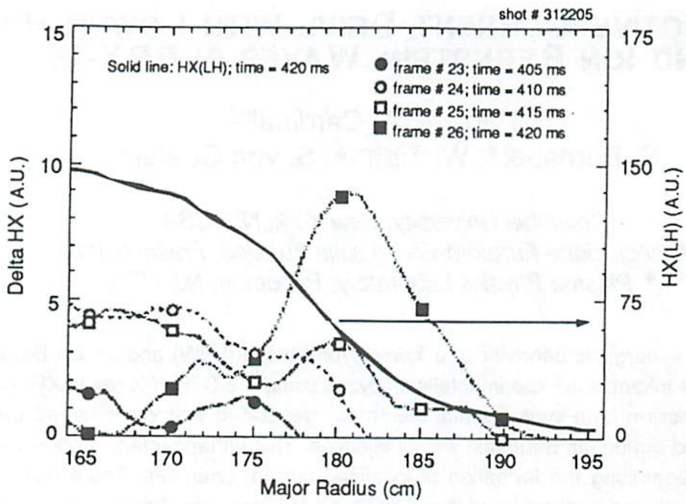

Figure 1

Plot of $\Delta_{HX}(t)$ vs. major radius for different time-frames for a PBX-M circular discharge

In Fig. 1 we show traces of $\Delta_{HX}(t)$ at different time frames for a typical circular PBX-M plasma. Since the IBW is triggered at 400 ms with a sharp ramp-up, so we can choose the reference LH-only time frame as: t_{LH} = 400 ms. At t = 410 ms (time-frame # 24), this centrally-peaked distortion extends up to R ≅ 182 cm. At t = 415 ms (time-frame # 25), a distinct peak begins to emerge around R ≅ 180 cm. At t = 415 ms (time-frame # 26), the peak is very well formed and represents the major part of the distortion in the HXR emission. The synergy between LHW and IBW appears to take place more efficiently in a region located off-axis as if the IBW electric field, interacting with the fast electrons located in that region of space, further accelerates them creating a current channel well-defined in space.

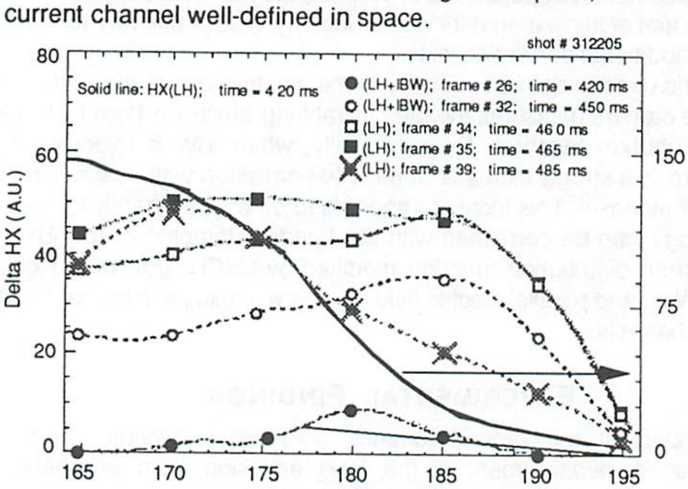

Figure 2

Plot of $\Delta_{HX}(t)$ vs. major radius for different time-frames for a PBX-M circular discharge

Following the evolution of the discharge, as in Fig. 2, we see the peak in $\Delta_{HX}(t)$ moving further out from its original position while it is growing in amplitude. This effect can be related to two different coexisting causes; first, a radial diffusion of the fast electrons population. This diffusion would help the extension of the suprathermal electron tail in the more peripheral regions enhancing the damping rate of the IBW low $n_{||}$ wave component. Second, a LHW "first-pass" damping on the tail of the distribution which has been extended in space and sustained by IBW. This can be seen as a non-linear loop interaction between LHW and IBW where the latter can help the former to be partially deposited off-axis. After IBW is turned off at t = 450 ms (frame # 32 in Fig 2.) the off-axis peak in $\Delta_{HX}(t)$ continues to rise for about 10-15 ms proving the fact that now LH alone is damping off-axis on a tail that is progressively disappearing. At this point, in fact, the profile starts relaxing towards its original shape while the variable $\Delta_{HX}(t)$ goes to zero. Here, LH waves no longer find enough fast electrons in the off-axis regions and they are required to reach the center to deposit their power (frame # 34, 35, 39 in Fig. 2).

The injection on IBW power on PBX-M is also correlated with a continuous influx of high Z impurities which results into a gradual peaking of the total radiated power profile[4]. This impurity influx also affects the fast electron bremsstrahlung emission. The result is a centrally peaked increase in the HXR signal. On the other hand, the region where the synergistic interaction between LH and IB waves appears to take place is located off-axis. Therefore, we can conclude that the described experimental observations cannot be explained as a result of an impurity influx since no impurity accumulation has been observed in any off-axis region[4].

The plasma parameters of a typical target plasma used in the LHW+IBW experiment on PBX-M are: I_p=120 kA, B_0= 1.89 T, $n_e(0)$ = 2.5 10^{13} cm^{-3}, $T_e(0)$ = 1.1 keV, R_{mag} = 164 cm, a = 32 cm, q(0) = 0.8, q(a) = 3.0.

The features of the IBW system are: ν_{IBW} = 43 MHz, $n_{||}$(range) = ±[2-16], $n_{||}$(peak) = ±9, P_{IBW} = 50 kW, Pulse Duration = 400-450 10^{-3} s.

While, the characteristics of the LH system are: ν_{LH} = 4.6 GHz, $n_{||}$(range) = [1.9-2.3], $n_{||}$(peak) = 2.1, P_{IBW} = 139 kW, Phase = 90°, Pulse Duration = 300-600 10^{-3} s

NUMERICAL RESULTS AND COMPARISON WITH THE EXPERIMENT

In our numerical model[5,6,7], we consider the interaction between LHW and IBW coupling a 3-D (R, Z, Φ) toroidal IBW+LHW ray-tracing algorithm with a 2-D ($v_{||}$, $v_\perp$) relativistic Fokker-Plank code. On each magnetic surface, the quasilinear distribution function is calculated as a result of the presence of both waves. This distribution function is used, after an integration over $v_\perp$, to calculate the power decrement and the non-inductive current density profile.

In previous studies, an analytical solution of the ray-tracing equations for IBW were obtained[8,9]. Following this formalism, we observe that the parallel wave number oscillates along the trajectory with a frequency that increases as the ray approaches the plasma center. Since the IBW electric field is proportional to $n_{||}^2$ we will have a resulting oscillating diffusion coefficient. Due to this oscillatory behavior, quasilinear modifications of the distribution function are localized in space.

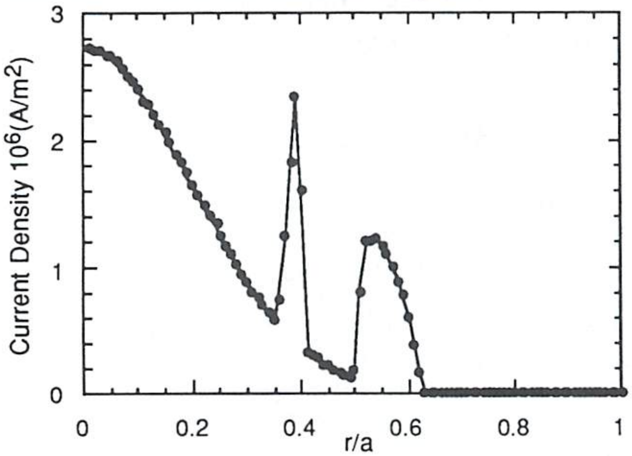

Figure 3
Simulated current density profile generated by IBW and LHW vs. normalized minor radius

The power damping and the current generation are also regulated by the oscillation of $n_{||}$. Fig. 3 shows the simulated non inductive current density profile generated by the presence of both waves. The peaks that we observe in Fig. 3 can be seen as current channels generated by IBW in localized regions of the space. Due to the limited spatial resolution of the HXR camera (± 5 cm), we are able to detect only the first oscillation.

For the specific case of the shown PBX-M plasma discharge, $n_{||}$ reaches its first maximum around x = 0.56 which corresponds to a radial location of R = 181.9 cm. In order to define a region of strong interaction, we can take the location of 0.5 $n_{||}$(peak) $R_{0.5}$ = [179.7 , 184.5] cm.

We can conclude that the location of the peak we observe from the analysis of the HXR images is consistent with the location of the region of strong interaction around the first maximum of the IBW $n_{//}(x)$ oscillation. Therefore, we can consider these experimental results as a direct prove that IB waves are coupled to the plasma, they propagate up to the region they deposit their power on the electron population enhancing the local LH current drive efficiency.

Conclusions

We presented a strong experimental confirmation of a synergistic interaction between LH and IB waves on PBX-M.

Using the HXR camera measurements, we reached the following conclusions: variations of the HXR emission profile, induced by IBW during LHCD, are predominantly observed off-axis. We refer to this result as the experimental proof of current channels formation with off-axis IBW deposition during LHCD.

During central LHCD, a portion of the LH power can be deposited off-axis with a "first pass" damping on the electron tail sustained by IBW. In turn, this will enhance the IBW power deposition in that region of space, creating a loop-type effect. The LHCD efficiency, in these off-axis regions, is enhanced by the extension of the electron tail during IBW injection.

Our theoretical investigation included the use of a toroidal 3-D LHW+IBW ray-tracing + 2-D Fokker-Planck numerical code. The results can be summarized as follows: due to the IBW $n_{||}$ oscillatory behavior, the IBW power is deposited in limited regions of space. When the IBW power is damped on a pre-existing electron tail (generated through LHCD), it generates localized current channels.

Considering a specific experimental PBX-M plasma discharge, we observed that the location of the first IBW $n_{||}$ maximum is consistent with the radial position of the region where we detect the highest distortion in the HXR emission.

Acknowledgments

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