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Role of Plasma Edge in the Direct Launch Ion Bernstein Wave Experiment in TFTR*

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ABSTRACT. Two types of direct IBW launching, EPW ⇒ IBW and CESICW ⇒ IBW are investigated using two numerical codes, Full Hot Plasma Ray-Tracing Code and SEMAL Full Wave Slab Code, for the TFTR direct launch IBW experimental parameters. The measured density profiles (by microwave reflectometry) in TFTR appear to be satisfactory for IBW launching while the observed stored energy rise compared to the expected value (ray tracing + TRANSP) indicates only up to 50% of launched power is reaching the plasma core. Possible causes of IBW inefficiency are also discussed.

INTRODUCTION

An Ion Bernstein Wave (IBW) antenna[1] has been installed in Tokamak Fusion Test Reactor (TFTR) to test a concept of generating sheared flow[2] in order to trigger an internal transport barrier formation utilizing the direct launch IBW. This experiment is motivated by the Core High Confinement Mode (CH-Mode) observed during application of IBW in the Princeton Beta Experiment-Modified (PBX-M).[3,4] Based on the model estimate, the required IBW power to induce sufficient sheared flow for the case of the tritium harmonic heating is predicted to be about 1 - 2 MW. Since the IBW antenna is designed to handle 1- 2 MW, it is particularly important to maximize the IBW launching efficiency for the core deposition. In order to launch IBW, it is necessary to first couple to cold plasma waves with a sufficient Poynting flux since IBW itself contains a very little Poynting flux that it is difficult to couple directly. There are two cold plasma waves which can couple directly to IBW, namely, electron plasma waves (EPW) and cold electrostatic ion cyclotron waves (CESICW). We term the two types of direct IBW launching as EPW ⇒ IBW and CESICW ⇒ IBW. Two types of IBW launching are investigated using the full hot plasma IBW ray tracing code[5] and the full wave slab code, SEMAL.[6]

IBW EXCITATION VIA EPW AND CESICW

The physics description of IBW launching via EPW and CESICW is previously reported (Sec. II-B of Ref. 5). It should be noted that all waves involved (i.e., IBW, EPW, and CESICW) are backward propagating waves (v_g anti-prallel to v_{ph}) which permits a relatively smooth mode-transformation process (continuous transition) to occur between these waves. The lesser known wave, CESICW, exists for $\Omega_H > \omega > \omega_{ii}$ and, in the cold plasma electrostatic limit, the wave dispersion can be written as

$$k_\perp^2 \left(1 + \frac{\omega_{pH}^2}{(\Omega_H^2 - \omega^2)} - \sum_{i \neq H} \frac{\omega_{pi}^2}{(\omega^2 - \Omega_i^2)}\right) \; - \; k^2 \left(\frac{\omega_{pe}^2}{\omega^2}\right) \; = \; 0,$$

The CESICW exhibits a perpendicular resonance at the ion-ion hybrid resonance frequency ω_{ii}. The external launching of CESICW has been previously demonstrated in the L-4 device.[7] Due to the finite-Larmor-radius effect, CESICW mode-transforms into IBW at ω_{ii}, provided that the CESICW do not suffer reflections due to the Alfven wave cut-off. Since the low $n_\parallel$ part of the spectrum tends to encounter the cut-off, the toroidally phased antenna would be advantageous for this mode of launching. The launching of IBW via CESICW is attractive since the coupling is relatively density insensitive and the edge density can be much higher than the EPW $\Rightarrow$ IBW case, though there is a dependence on hydrogen concentrations and magnetic field values.

FULL HOT PLASMA RAY TRACING CODE RESULTS

To study the wave launching physics, a full hot plasma IBW ray tracing code including up to fifty ion cyclotron harmonics was used for this study.[5] In Fig. 1(a) the possible edge density profiles are shown. These profiles are consistent with the measured reflectometry values within the error bars which makes the exact determination of the profile shape in the low density range of 10^{11}cm^{-3} difficult. The following three profiles are considered: Profile I $\propto \Delta x$; Profile II $\propto \Delta x^{1.5}$, and Profile III $\propto \Delta x^2$ where Δx is the distance from the plasma edge. There is a small edge density pedestal of 5×10^{10}cm^{-3} assumed to represent a plasma sheath at the surface of the antenna. The edge ion and electron temperature profiles are assumed to be 50 eV at the edge which then ramp up to 300 eV at R = 355 cm. In Fig. 1(b), the calculated perpendicular wave number is shown as a function of position for three profiles. The wave numbers are continuous as expected. In Fig. 1(c), the corresponding WKB parameter, $(\partial k_\perp / \partial r) / k_\perp^2$. is plotted. The wave reflections tend to occur when the WKB parameter goes much above 1. The WKB value for the linear profile goes above one near the very edge of the plasma suggesting some reflection from the edge. However, the wave reflection near the very edge may not be so serious since the reflected wave is likely to come back to the antenna which can be tuned out by the high Q antenna circuit. The WKB parameter stays below one for higher exponent profiles, Profiles II and III. The Profile III may be what one might expect from the rf ponderomotive consideration. As can be seen from the figure, no further reflection is expected for all profiles once EPW propagates a few centimeters in to the plasma and becomes IBW. Therefore, the measured density profiles in TFTR appears to be in the range of relatively good wave launching conditions.

For the CESICW launching, even a more challenging linear ramp density profile with larger edge pedestal of $2 \times 10^{11}\text{cm}^{-3}$ is quite acceptable as shown in Fig. 2. For this case, the wave number stays relatively constant and the WKB parameter is very low everywhere. In addition to the WKB consideration, the antenna's ability to launch power can be characterized by the wave power flow parameter at the plasma edge which is a product of wave perpendicular group velocity and wave energy density. In Fig. 3, the power flow parameter is plotted (a) for EPW $\Rightarrow$ IBW as in Fig. 1 and (b) for CESICW $\Rightarrow$ IBW as in Fig. 2. The power flow parameter at the edge is considerably larger for CESICW case since the allowable coupling edge density is larger. The CESICW $\Rightarrow$ IBW launching therefore should be particularly effective in this regime.

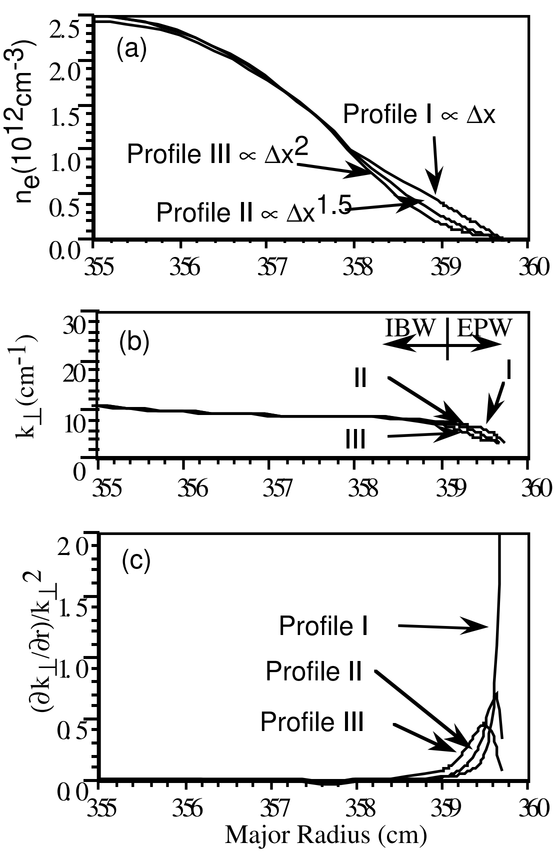

Fig. 1. EPW $\Rightarrow$ IBW launching case. f = 76 MHz, B_{TF} = 3.3 T (at R=275cm), $n_{\wedge}$ = 5, N_H= 15 %, N_D = 45%, and N_C= 40%. (a) Density profiles, (b) corresponding perpendicular wave numbers, and (c) WKB parameters.

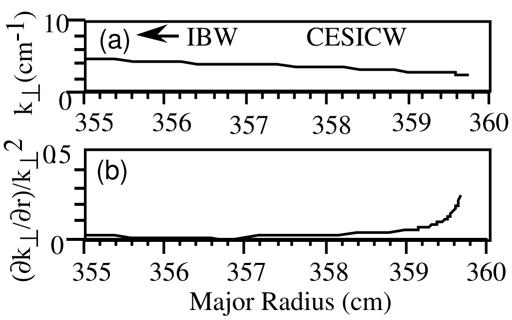

Fig. 2. CESICW $\Rightarrow$ IBW launching case. f = 51 MHz, B_{TF} = 4.5T (at R=275cm) (a) $k_\perp(\text{cm}^{-1})$, and (b) WKB parameters.

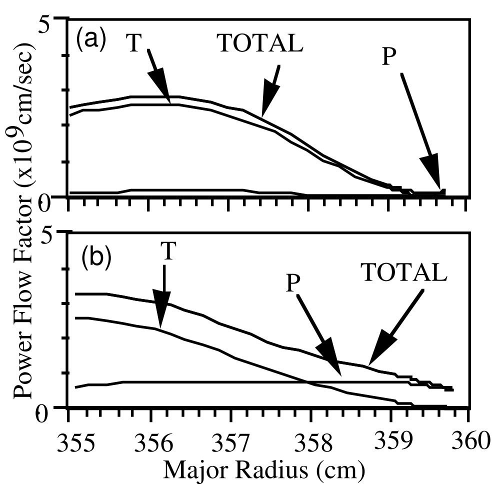

Fig. 3. Power Flow Factors. (a) EPW $\Rightarrow$ IBW, Fig. 1, Profile II. (b) CESICW $\Rightarrow$ IBW, Fig. 2.

FULL WAVE SLAB CODE, SEMAL RESULT

The physics of IBW wave launching has also been investigated with the full wave kinetic slab code, SEMAL.[6] This code is useful for the coupling problem where the local plasma variation is significant yet the geometry is such that the slab approximation is reasonable. The SEMAL code essentially validated the full hot plasma ray-tracing code results. This agreement is largely due to the short wavelength nature of the waves which makes the WKB approximation (and therefore the ray tracing calculation) satisfied in most parameter. In particular, the SEMAL analysis confirmed the existence of a launching window near $B_T \approx 4.8$ T with the hydrogen minority fraction of 10-15% for $n_\parallel \approx 2$-6. The spectrum $n_\parallel < 2$ tend to encounter the Alfvén cut-off and strong Landau damping is expected for $n_\parallel > 8$.

CONCLUSIONS AND DISCUSSIONS

Two typed of direct IBW launching, EPW $\Rightarrow$ IBW and CESICW $\Rightarrow$ IBW are investigated using two numerical codes, Full Hot Plasma IBW Ray-Tracing Code and SEMAL Full Wave Code, for the TFTR directed launch IBW experimental parameters. EPW $\Rightarrow$ IBW is relatively sensitive to the edge plasma density profile. In general, an exponentiating profile is good for wave launching while linearly ramping profile can cause some radial reflections. CESICW $\Rightarrow$ IBW is relatively insensitive to the edge density profile while there is some dependence on hydrogen minority concentration and magnetic field value. Both launching scenarios tend to have a "clipping" effect of low $n_\parallel$ spectrum due to reflections and accessibility related problems. The measured density profiles (by microwave reflectometry) in TFTR appear generally to be satisfactory for IBW launching. However, the observed stored energy suggests IBW wave core power deposition may be inefficient (< 50%).[8] Possible cause of IBW inefficiency is under investigation. There was however no active parametric instability activities throught out the experiment. Since the TFTR antenna was not toroidally phased due to the available port access, there is a significant low $n_\parallel$ spectrum component (e.g., $n_\parallel < 2$) which may not penetrate into the plasma core. The poloidal phasing $(0, 0, \pi, \pi)$ which should not itself alter the IBW coupling physics showed a smaller (about half) loading resistance and better stored energy increase compared to the unphased case (0, 0, 0, 0) suggesting a presence of "parasitic loading."[9,10] A damage to IBW antenna Faraday shield which was found during the operation may also contributed to the cause of inefficiency. It should be noted that a poloidal sheared flow generated by IBW has been indeed measured by the Poloidal CHERS on TFTR in accordance with theoretical expectation.[8]

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