Electron Bernstein Waves Simulation in Helical Systems

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Following experimental results obtained in the CHS and the Heliotron-J devices concerning mode conversion into and heating with Electron Bernstein Waves (EBWs), numerical simulations have been carried out involving the ray-tracing, mode conversion and power deposition of EBWs for models of these experimental scenarios. EBWs-based heating has been confirmed for all the cases studied so far as measured by the experiment. Further investigation is being done to extend the range of the simulations and confirm more detailed issues like the power deposition location.

Keywords: ray tracing, electron Bernstein waves, mode conversion, ECRH, numerical simulations.

1 Introduction

Due to their electrostatic nature, Electron Bernstein Waves (EBWs) do not experience any density limit. This makes them particularly useful to interact with over-dense plasmas. However, the 'over-dense' condition is not only reached due to a very high plasma density. Propagation cutoffs depend also on the frequency of the wave and the local magnetic field, therefore they can occur also in low density-low field conditions. This makes EBWs a popular subject both in the tokamak and helical communities for their ability to overcome the density limits and deposit power in otherwise inaccessible regions of the plasma. The study of EBWs and their applications is a matter of particular interest in Japanese helical devices. Experimental campaigns involving research on EBWs have been carried out in the LHD and CHS experiments in NIFS as well as in the Heliotron-J in Kyoto University. In order to contrast these experimental results with the theory and to devise new experiments, numerical simulations of ray tracing, mode conversion and power deposition of EBWs are carried out with the aid of the ART ray-tracing code [1] and the bundle of codes COBE [2].

2 CHS - OXB

An increase of the plasma stored energy when ECH is switched on is observed in CHS for a comparatively over-dense plasma [3]. The core parameters are: n0 = 9.6 $10^{19}m^{-3}$, T0 = 0.4 keV, f0 = 54.5GHz, $B_0 = 1.9T$. The density for this shot would block propagation of the launched O-mode waves: cutoff density (f0 = 54.5GHz) = 3.8 $10^{19}m^{-3}$. The increase of stored energy is thought to be due to the absorption of EBW mode-converted from the launched O-mode wave (OXB) [see Fig. 1].

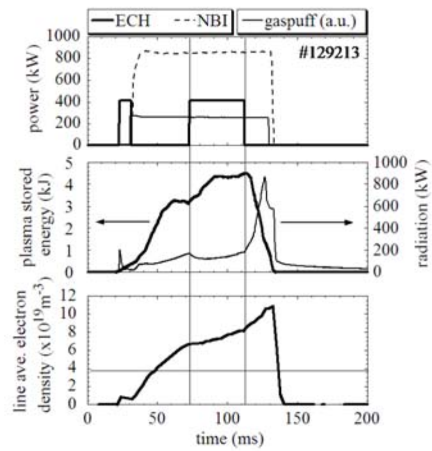

Fig. 1 Experimental data from the shot 129213. It can be seen an increase of the stored energy during the second ECRH injection.

An estimated profile of the neutral beam driven current has been used to calculate the VMEC equilibrium with the total measured current of -2.8kA. The evolution of the O-mode wave was simulated with the ART code. The numerical simulation show a clear OXB conversion in the evolution of the ray path. The power is absorbed between $s = 0.6 - 0.7$ beyond the O-cutoff ($s \sim 0.8$).

The OXB conversion can be identified from the evolution of the perpendicular refractive index and the CMA diagram. The O-mode wave propagates towards the core of the plasma. Near the O-cutoff region, it converts to X-mode ($N_\perp$ goes to 0). The X-mode wave propagates back until it reaches the Upper Hybrid Layer (UHL). In the UHL the X-mode is transformed to EBW (the $N_\perp$ increases drastically in a vertical line). Finally the B-mode wave propagates through the O-cutoff where it is finally fully absorbed (see Fig. 2).

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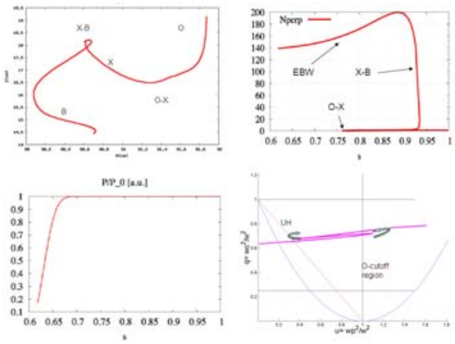

Fig. 2 Numerical results of the OXB simulation for CHS shot 129213. Ray path in R-Z coordinates (top left), $N_\perp$(top right), normalised power deposition profile (bottom left) and CMA diagram of the ray evolution (bottom right). profile

3 CHS - XB

An X-mode wave is launched from the top window and directed with a steerable mirror in the outer part of the torus (see Fig.3) [4]. The relevant parameters for the simulation are as follows: ECH power = 275kW, ECH frequency = 54.5GHz, polarisations = X-mode, NBI power = 845kW, Rax = 0.949m, Bax = 1.95T, plasma current = -11kA , β = 0.2. The magnetic geometry of CHS is such that the fundamental resonance reaches the magnetic axis but also appears in the outer region of the torus near the mirror. The rays were launched with a fixed vertical angle aiming at the fundamental resonance stripe (see Fig.4). A horizontal angle scan was carried out detecting an increase of the core electron temperature.

The simulations show that conversion is achieved when the wave is launched at towards the fundamental resonance region. However, the power is mainly absorbed away from the core of the plasma. Nevertheless, deposition nearer to the axis region is obtained for high horizontal and vertical angles. More simulations are on the way to simulate the ray's behaviour at wider horizontal angles > 20 *Deg*. The power deposition regions with respect to horizontal and vertical toroidal angles are displayed in Fig.5.

4 Heliotron J - XB

The plasma conditions in Heliotron-J provide a low single-pass absorption, therefore reflexion in the vacuum vessel is expected. The necessary conditions for an XB conversion are achieved if waves are launched in such a way that the reflexion takes place in the inner part of the torus' corner section [5]. The rays reflected in the vacuum vessel are modelled imposing the launching point in the inner part of the torus and launching towards the outer region. Horizontal and vertical scans have been carried out to investigate the XB conversion and the core deposition of Bern-

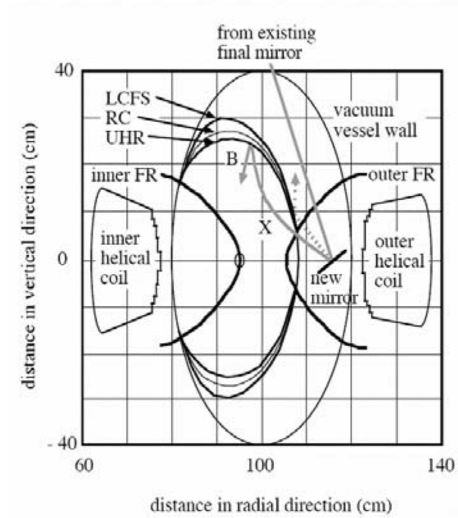

Fig. 3 CHS XB experiment launching scheme. The mirror is aimed at the region where the fundamental harmonic on the last flux surface.

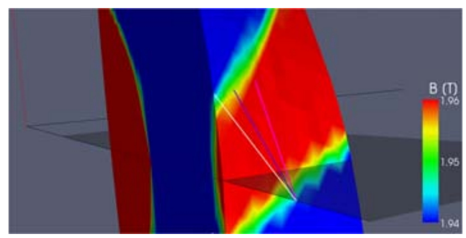

Fig. 4 CHS launching position and angles for the XB heating experiment. The scale of the magnetic field strength has been reduced in order to highlight the fundamental resonance stripe on the las magnetic surface.

stein waves. Figure 6 shows the ray-path of three sample rays directed respectively to clockwise, counter-clockwise and downwards launching conditions, all with satisfactory XB conversion. In Fig.7, the deposition location of the Bernstein-transformed waves is shown with respect to the horizontal launching angle. It is clear in this case that deposition takes place in the core region of the plasma as expected from the experimental results.

5 Conclusions

Helical devices with their complicated geometry offer a wide range of possibilities for mode conversion and power deposition. Ray tracing simulations for different mode-conversion scenarios leading to Bernstein wave heating in helical systems have been performed by means of the ART code.

OXB and XB simulations in CHS have been shown to be in agreement with experimental results. The OXB ray tracing calculations show a clear OXB conversion that justified the power deposition beyond the O-mode cutoff point. The XB simulations, show successful conversion

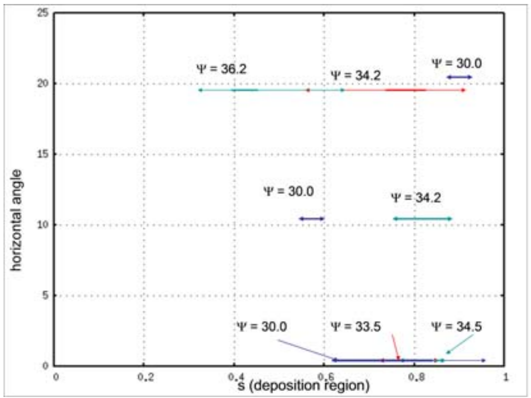

Fig. 5 Table indicating the power deposition region with respect to horizontal launching angle. The vertical angle of each simulation is also indicated. The thin lines represent partial X-mode absorption and the thick lines indicated Bernstein wave absorption.

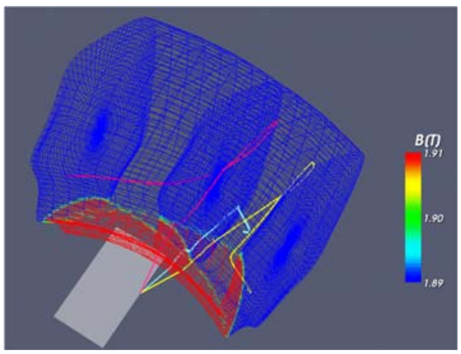

Fig. 6 Sample rays experiencing XB conversion when launched from the inner side of the torus simulating evolution after reflection in the inner wall. They represent reflections towards the clockwise, counter-clockwise and downwards directions. The scale of the magnetic field strength has been chosen to highlight the fundamental resonance region.

when the ray is directed towards the fundamental resonance stripe on the outer boundary and show that the power deposition region tends to towards the core as the horizontal angle is widened. In this last case more calculations are on the way for greater horizontal and vertical angles to better model the experimental results shown in [4].

In the Heliotron-J case, in order to model the trajectory of rays reflected on the vacuum vessel in the inner part of the torus after being injected from the outer region port, the launching point for the simulation has been imposed a few centimetres inwards from the inner boundary of the plasma in the corner region. Vertical and horizontal angular scans have been carried out with the ART code obtaining XB conversion in many cases. The deposition profiles show that the energy absorbed from these rays is deposited mainly in the core region in agreement with experimental measurements.

More simulations of EBW heating in Japanese helical

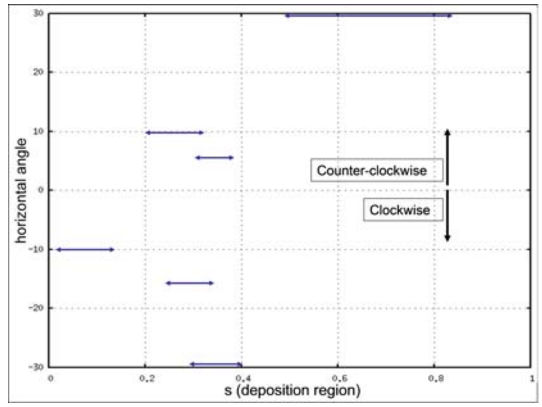

Fig. 7 Table indicating the power deposition region with respect to horizontal launching angle for the Heliotron-J XB conversion experiment.

systems are presently being performed.

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