ECCD Experiments in Heliotron J: Recent Results Regarding the Dependence on Magnetic Configuration and Wave Polarization

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(Received 17 March 2007 / Accepted 22 May 2007)

The electron cyclotron current drive (ECCD) is investigated in Heliotron J for two new magnetic configurations with ECRH heating located at the ripple top and the ripple bottom, respectively, using different incoming wave polarizations. The results are compared with the previous ECCD experiments, performed in the low, medium (standard) and high bumpiness configurations, where a sign reversal of the EC current is observed between the ripple top and the ripple bottom heating conditions. It is shown here that a similar behaviour is obtained in the new configurations. Positive currents are obtained when the ECR heating is located at the magnetic field minimum, whereas negative currents, but not higher in magnitude than the ones obtained in the previous experiments, appear with ripple top heating. The dependence of the ECCD on the polarization of the injected waves agrees with the expected behaviour.

Keywords: ECCD (electron cyclotron current drive), magnetic configuration, trapped particles, Heliotron J

DOI: 10.1585/pfr.2.030

ECCD experiments in Heliotron J [1] have been performed for low, medium and high bumpiness magnetic configurations ($\epsilon_b = 0.01, 0.06$ and 0.15 respectively, where $\epsilon_b \equiv B_{04}/B_{00}$ at $\rho = 0.67$). The magnetic field on-axis of these configurations is shown in Fig. 1, in which together with the bumpiness, the ratio between the toroidal coil A (TA) and the toroidal coil B (TB) is also used for labelling (TA:TB). A whole period of the device is represented.

The recent experiments presented in this communication have been done in the 5:4 and 6:1 configurations. Their magnetic field on-axis is also shown in Fig. 1. The 70 GHz ECRH power (up to 400 kW) is injected from the upper port of the straight Heliotron J section ($\phi = 0°$) with $N_{\|} = 0.44$, and thus, by changing the current ratio between both toroidal coils, it is possible to achieve strong changes in the ripple on-axis and very different EC-induced currents. In the density scan presented in [1], and carried out in the 5:1, 5:2 and 5:3 configurations, negative EC currents up to $I_{EC} \approx -4.6$ kA (in the 5:3 case) and positive currents up to $I_{EC} \approx +1.4$ kA (in the 5:1 case) were found for line average densities around $n_e \approx 0.3 \times 10^{19}$ m^{-3} and for the on-axis ECRH deposition. Those results were obtained with field reversal experiments. In this way, if the plasma density and temperature are not affected by the field reversal, it is possible to separate the bootstrap current from the

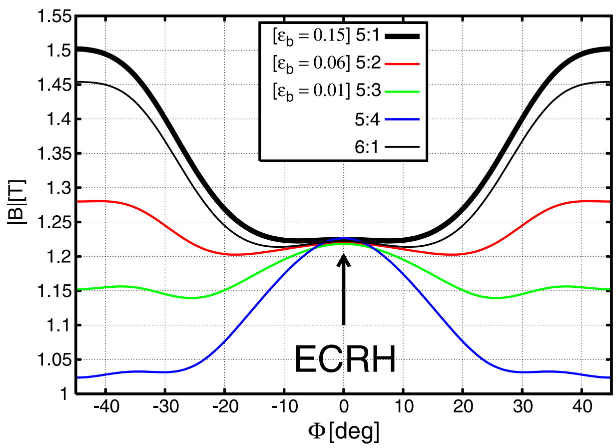

Fig. 1 Magnetic field on-axis of all the configurations used in the ECCD experiments.

ECCD contribution. The explanation for the change in the sign of the EC current relies on the strong change in the fraction of trapped particles between the ripple top (5:3) and the ripple bottom heating (5:1). In the first case, the current obtained is in agreement with the theoretically predicted direction when no trapped particles are considered (Fisch-Boozer process). In the second case, the ECRH heating turns the originally barely passing particles with the appropriate parallel velocity for resonant interaction

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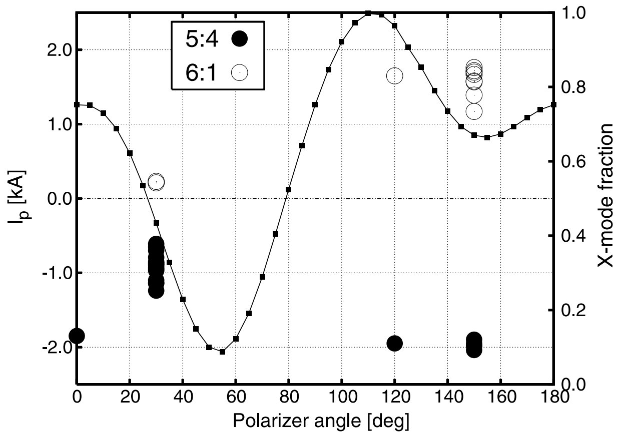

Fig. 2 Dependence of the total plasma current on the polarizer rotation angle and theoretical injected X-mode fraction in the 5:3 configuration (thin line with dots). Within the investigated values, the lower currents (either negative or positive) are observed when the fraction of power in the X-mode is around 0.3.

into trapped ones and a reversal of the sign of the current can be seen (Ohkawa process). The EC current measured in the 5:2 configuration had a negative sign and lower magnitude ($I_{EC} \approx -1.4$ kA for $n_e \approx 0.7 \times 10^{19}$ m^{-3}).

In principle, we thought that a configuration with even stronger ripple top heating could provide higher currents. This has been investigated using the 5:4 configuration for different positions of the polarizer rotation angle, and the results are presented in Fig. 2. The same figure shows the results for the 6:1 configuration. Note that since no field reversal experiments were performed in this case, the presented results refer to the total plasma current, where we expect a negligible bootstrap current contribution due to the low density conditions used in the experiments ($n_e \approx 0.4 \times 10^{19}$ m^{-3}). For the optimum orientation angle of the polarizer (see Fig. 2), negative plasma currents up to $I_p \approx -2$ kA have been obtained. We have also investigated the 6:1 configuration, which has a magnetic field on-axis close to the one of the 5:1 configuration, and similar EC currents are driven in both configurations. As expected from the previous results, again a sign reversal in the current is observed. However, for similar line average densities, currents higher than the ones obtained before could not be achieved. The observed sign reversal in the EC current values occurs when we go from ripple bottom heating (5:1, highest fraction of trapped particles on-axis) to gentle ripple bottom heating (5:2, low trapped particle population). Ripple top heating (5:3, no trapped particles) produces a higher negative current. Going further in the ripple top heating regime only by increasing the ripple itself (5:4) does not modify the fraction of trapped particles on-axis. The fact that the current is lower in magnitude in the 5:4 case than in the 5:3 case can be explained by taking into account an electron temperature decrease and the slight modification in $N_{\|}$ for the new configuration.

With respect to the drop in the temperature, only a few shots for each polarizer angle were carried out in the new configuration and no precise control of the wall conditions was achieved. Unfortunately, no reliable absolute temperature measurements that would have clarified this effect were available during the experiments.

Regarding the change in $N_{\|}$, the beam is launched with $N_{\|} = 0.44$ for the 5:2, 5:3 and 5:1 configurations, whereas $N_{\|} = 0.52$ is attained in the 5:4 configuration. For the 5:3 configuration, the magnetic field is set in such a way that the experimental power deposition is obtained on-axis. Due to the strong Doppler shift, the magnetic field on-axis must be reduced around 2 % with respect to the cold second harmonic resonance $\omega = 2\omega_c$. Changing $N_{\|}$ introduces a modification in the power deposition location which was not accounted for during the experiments. Considering the non-relativistic resonance condition, it can be seen that a further reduction to approximately 2.5 % is necessary if heating on-axis is desired (while heating the same zone of momentum space). Finally, the temperature reduction, due either to the worst wall conditioning or to the off-axis power deposition, is probably responsible for the current decrease. A detailed ray tracing calculation that takes into account the microscopic current drive efficiency (which increases with $N_{\|}$ but decreases at higher collisionalities, i.e., at lower temperatures) and the precise power deposition profile is needed to clarify the result.

The dependence of the EC driven current on the polarizer rotation angle seems to be in agreement with the theoretical calculation of the fraction of the injected power in the X-mode for the 5:3 configuration (see again Fig. 2). Moreover, the single pass absorption calculations obtained with the TRECE ray tracing code [2], for this configuration show a minimum absorption of around 50 degrees and a maximum one (96.3 %) of around 120 degrees. The accuracy of these calculations have been demonstrated using transmitted power measurements [3].

In summary, the ECCD dependence on magnetic configuration, presented in previous works, has now been investigated in two other configurations, one of them expanding the ripple structure on-axis to higher ripple top regimes. No higher negative currents have been observed, and the maximum ECCD efficiency is the one that was obtained previously in the 5:3 (low bumpiness) configuration. Moreover, for the investigated polarizer angles, the dependence of the current on the polarization of the injected waves is in agreement with the behaviour expected from the power absorption calculations.

This work was supported by NIFS/NINS under the NIFS Collaborative Research Program (NIFS04KUHL005) and under a project sponsored by the Formation of International Network for Scientific Collaborations.

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