RESULTS ON ELECTRON CYCLOTRON CURRENT DRIVE IN RTP

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Abstract

Second harmonic ECCD in RTP is obtained through oblique injection of 110 GHz waves. ECCD improvement has been obtained by way of injecting elliptically polarized waves, making the available rf power up to 30% more effective. Hollow density profiles have been observed with counter-drive in the center. Observed efficiencies do not surpass the level of linear calculations.

Introduction and Experimental set-up

Non-inductive current drive and control of the current profile are supposed vital issues for steady-state tokamaks and for many of the advanced operation concepts. ECCD, based on selective heating of electrons moving in one toroidal direction [1], is one of the mechanisms for this. In tokamaks it can be generated by injecting rf beams which strongly couple to the plasma and which have a component parallel to the magnetic field [2]. The maximum drive will occur if the wave is completely damped before the EC (cold) resonance is reached. In many machines this can be achieved by launching waves into the plasma that couple to the 2^{nd} harmonic X-mode. Oblique injection requires a proper elliptical polarization of the injected beam.

The RTP tokamak (R_0 = 0.72 m, a_{lim} = 0.165 m, $B_T \leq 2.5$ T, $I_p \leq 150$ kA, iron core, boronized SS first wall, and carbon limiters) is equipped with a 110 GHz, 200 ms, 500 kW gyrotron (Gycom) for 2^{nd} harmonic ECRH and ECCD. The rf power is transmitted quasi-optically as a linearly polarized Gaussian beam. It is launched via an adjustable mirror at LFS: the center is 0.08 m below the equatorial plane and at 0.23 m from the plasma center in major radius direction. A universal polarizer [3], consisting of two grooved mirrors, has recently been installed in the transmission line. The launched waves usually get absorbed in the plasma core, at the low field side of the cold resonance position. The diameter of the rf beam there is a few cm. So, the power deposition is very localized.

Linear theory [1] predicts the scaling I_{cd} (:) $P_{rf} \cdot T_e / (R_0 \cdot n_e \cdot (Z_{eff} + 5))$ and so guides to experiments at low densities and full rf power for generation of the highest EC driven currents. The RTP experiments have been performed in the density range $\langle n_e \rangle = (1 - 2) \cdot 10^{19}$ m^{-3} to have the best combination of low density and sufficient absorption. In standard operation an injected power level of 300 kW during 150 to 200 ms, and a plasma current I_p = 60 kA are used. Hydrogen is the working gas in the ECCD experiments; density, $\langle n_e \rangle$, and plasma current, I_p, have been feedback controlled. A recent system extension largely increases RTP's control possibilities [4]. Now, by regulating the output of the gyrotron, feedback control of the plasma temperature and of various other experimental parameters has become possible. These features will be exploited in next current drive experiments.

If a beam is launched with non-proper polarization, only part of the injected power couples to the 2X-mode. The rest gets lost for current drive. The injection angle with respect to the magnetic field, θ, is one of the variables the fitting polarization depends on. Figure 1 shows for RTP type of parameters which part of the injected power couples to the 2X-mode for different degrees of elliptical polarization, $P = iE_{vert} / E_{hor}$. For linear polarization, the fraction is seen to fall rather sharply: at ± 30° off-perpendicular injection 65% is effective, see Fig. 1a. Thus, a polarizer will effect quite an improvement. Though for each injection angle a matching value of *P* should be chosen to fully exploit the available gyrotron power, this will not be critical in practice. A considerable overall performance enhancement could already be obtained in RTP even with only one appropriate degree of polarization - both left- and right-handed of course - which for our purposes should be in the interval 1.5 to 3, see Fig. 1b. The polarizer in RTP is not restricted to this and provides in a practical way the needed ellipticities, from linear to circular.

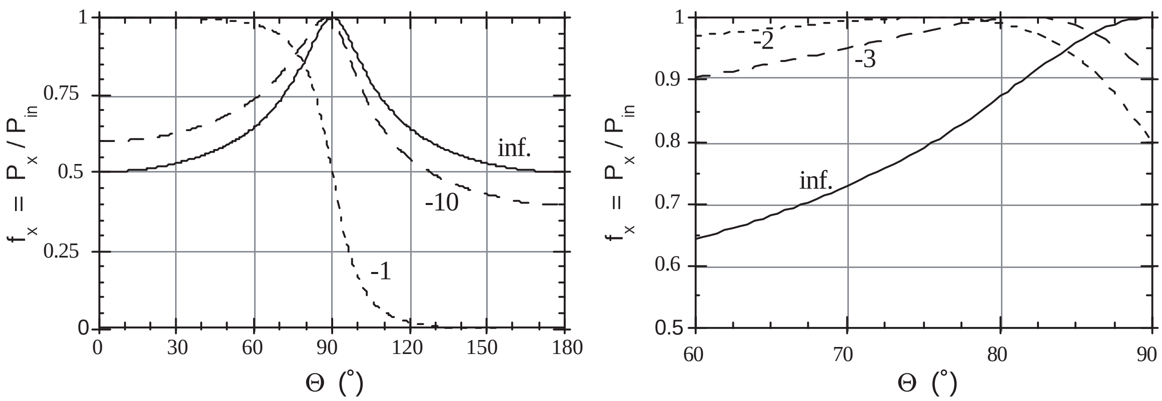


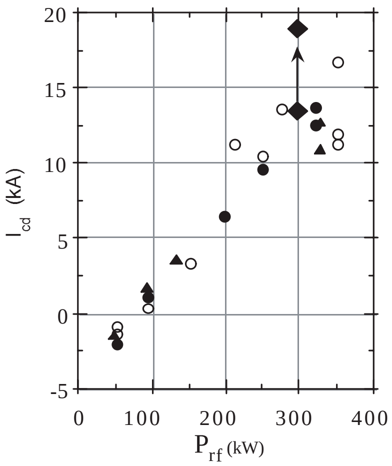
Fig. 1. Fraction of injected power coupling to 2X-mode, for various degrees of $P = iE_{vert} / E_{hor}$
Fig. 1a P = -1 (circular), -10, and inf (linear) Fig. 1b P = -3, -2, and inf

The determination of I_{cd} is difficult. The rf power both heats and drives current. The current drive in RTP is not large enough to carry all of I_p, and a residual loop voltage is observed. Unfortunately, RTP has no method available to determine the EC current directly and we are driven back to a succedaneum: the drive I_{cd} is estimated from a comparison of the residual loop voltages during co-drive (V_{co}) and counter-drive (V_{cntr}) [2]. This method - doubtful for our case - relates for zero bootstrap current: $I_{cd} / I_p = (V_{cntr} - V_{co}) / (V_{cntr} + V_{co})$.

Results

Best ECCD results have been obtained with $\langle n_e \rangle = (1.1 \pm 0.2) \times 10^{19} m^{-3}$ and with ±17.5° off-perpendicular injection angles, and magnetic fields in the range 1.97± 0.05 T. The efficiency - usually expressed in $\langle n_e \rangle \cdot R \cdot I_{cd}/P_{rf}$ - for 2nd harmonic ECCD by linearly polarized waves appeared $(0.05 \pm 0.015) \times 10^{19}$ A/Wm^2 [5]. A higher efficiency is a desirable goal. A numerical doubling could be obtained without doing additional experiments by simply replacing the average density over the plasma cross-section, $\langle n_e \rangle$, by the density at the location of the current drive, $n_e(0)$. A real improvement of over 30% has been reached in standard 60 kA plasmas through the injection of elliptically polarized waves (as was expected from Fig. 1).

The mentioned current scaling formula hints that P_{rf} will rule the magnitude of the driven current for optimum machine setting (aside from its effect on T_e). This is illustrated in Fig. 2, which shows the increase in I_{cd} with P_{rf} for linear polarization. The available gyrotron power was restricted to 350 kW and the polarization of the launched EC beam was linear. For P_{rf} > 175 kW and conditions close to optimal the efficiency I_{cd}/P_{rf} is around 0.045 A/W. At lower power the efficiency decreases, partly as a result of lower plasma temperatures. For P_{rf} < 100 kW no, or even a negative, current was driven. Effectively the ECCD responds on P_{rf} as if there is a threshold power of 100 kW. Above this level, ECH produces 0.06 A/W. The reason for the threshold is not known at this moment, unwanted gyrotron modes could be a cause. The data clearly hold out the prospect of higher currents if more power could be absorbed. Elliptical polarization increased the driven current with 30% as compared with linear polarization. Two points in Fig. 2 (fat diamonds) illustrate the amelioration; the lower point was obtained with linear polarization (coupling 75% to 2X-mode), the upper point with an ellipticity 2 (coupling >99%).



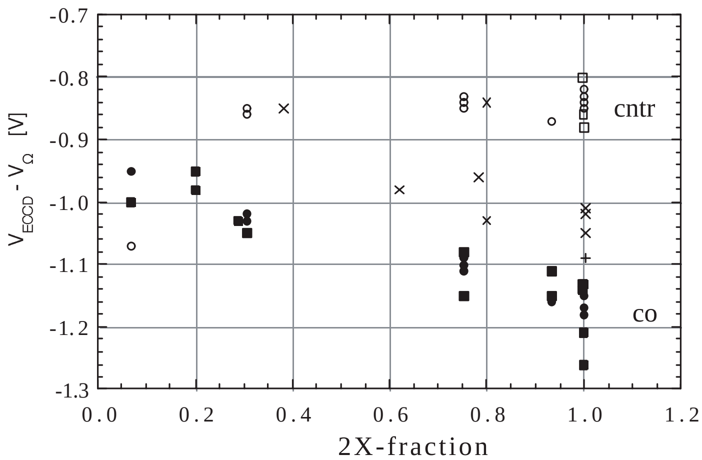


Figure 2. (left) I_{ECCD} as a function of the rf power for linear polarization of the injected waves. The diamonds show the improvement that is obtained by proper polarization of the waves.

Figure 3. (right) The loop voltage decrement during co- (filled squares and circles) or counter-drive (open squares and symbols) and heating (x's and +'s) as function of 2nd X-mode fraction .

The focused rf beam produces very localized current drive, and simple considerations show that for the fractions driven at I_p = 40 - 60 kA current density profiles will be very different for co- and counter-drive. The result is a strong q-profile modification. Though the magnitudes and profiles of I_{cd} are not really known, the RTP discharges show many signatures of modified q-profiles. For example, sawteeth are generated during ECCD in a high-q(a) discharge, revealing that the central q(0) is driven below 1, whereas in a low-q(a) plasma, the small sawteeth present in the Ohmic phase explode during co-drive, and become stabilized during counter-drive. In moderate-q discharges we often observe large amplitude (20% modulation) usual relaxation time (1 ms) sawteeth with co-drive. These show different and more virulent MHD behaviour with counter drive: large-amplitude, 5 ms sawteeth terminating with a sharp spike before the collapse [4, 5]. The counter-intuitive observation that temperature profiles can be broader for co-drive than for counter-drive also indicates a strong q-profile modification through ECCD. The mentioned effects have been observed for both normal and reversed I_p, and B_T.

As mentioned above, I_{cd} is inferred from residual loop voltages. Polarizer experiments with full gyrotron power and injection of different degrees of ellipticity with both left- and right handed rotation - thus coupling different 2X-mode fractions at the same rf input power - showed a voltage drop increasing with coupled power for heating and co-drive. With counter drive the voltage (drop) stays more or less constant (Fig. 3). Strong profile modifications are observed (Fig.4). Note the spiky temperature profile and the hollow density profile for strong counter-drive.

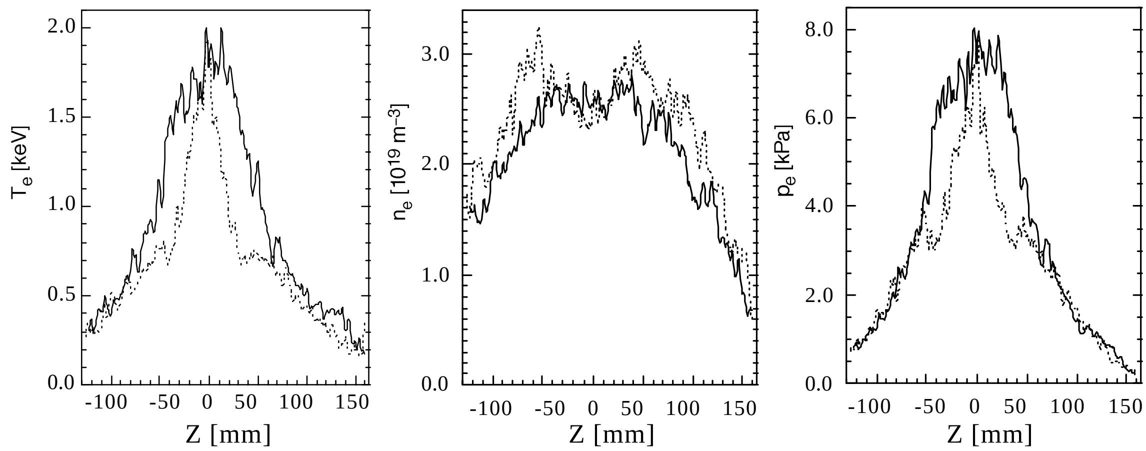


Figure 4. Plasma profiles during co- (full curves) and counter-drive (dotted curves).

Linear Fokker-Planck calculations for 25° off-perpendicular injection in a plasma with parabolic density profile and $n_e(0) = 2.0 \times 10^{19} m^{-3}$ predict maximum driven currents around 15 kA for $T_e(0) = 1.5$ keV, and around 40 kA for $T_e(0) = 3$ keV for 300 kW injected power, values corresponding fairly well to the experimental results, albeit in a different B-window (1.85-1.95 T). Due to the high power density, quasi-linear effects are very large for the pertinent parameter regime and should give rise to a strong increase (up to a factor of 2) of the predicted current. This non-linear improvement has still not been observed.

From the differences in co- and counter-drive profiles we discreetly conclude that the experiments are in the non-linear regime and that observed non-linear efficiencies do not really surpass the level of linear calculations.

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