

## **Electron Cyclotron Current Drive experiments in the FTU tokamak**

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### **Introduction**

Oblique injection of electron cyclotron (EC) waves with an angle with respect to the magnetic field allows to control the plasma core confinement and the magnetohydrodynamic (MHD) instabilities with highly localized EC current drive (ECCD) by changing the magnetic shear through the local re-shaping of the current density profile [1]. Experiments can be performed driving non-inductive EC current in the same direction of the plasma current (CO injection) and in the opposite one (COUNTER injection) on-/off-axis along the minor radius in order to locally reduce or increase the safety factor value  $q$ , respectively. The high flexibility of the Electron Cyclotron Resonance Heating (ECRH) system on FTU tokamak [2] allows to use four gyrotrons, independently steerable in the poloidal and toroidal plane, to locate the non-inductive current at the plasma centre and at off-axis positions.

The aim of the ECCD experiments in FTU was to explore the full range of injection parameters to assess the calculation models and the efficiency of the driven current at ITER relevant parameters, as plasma density and magnetic field. Significant effects on local tailoring of plasma current density have been observed and are reported in the present paper.

### **Experimental conditions**

In the experiments the EC power up to the full level of 1.6 MW were delivered by four gaussian beams, injected from the low field side, at 140 GHz ( $B_{\text{res}}=5$  T) in ordinary mode (OM) at the fundamental harmonic. Non-inductive current was generated in up-shifted scheme during the steady-state phase in a target plasma with  $I_p = 360$  kA with pulse length greater than 200 ms (4-5 times greater than the resistive time for FTU). Since the Doppler effect shifts the EC resonant location, the toroidal field has been varied (from 4.7 to 5.1 T) in order to keep the resonance layer in the same radial position (at the centre of plasma column) for all the 6 fixed toroidal angles used ( $\pm 10^\circ$ ,  $\pm 20^\circ$ ,  $\pm 30^\circ$ ), while the off-axis deposition was obtained by tilting poloidally the launching mirrors.

In order to maximize the ECCD efficiency, the line electron density was kept between  $0.5\text{--}0.7 \cdot 10^{20} \text{ m}^{-3}$ , while high EC power guaranteed enough electron temperature for full absorption. In this condition the  $Z_{\text{eff}}$  was between 2.3 and 3.6 while no suprathermal electrons were detected in all conditions. It is worth noting that, since a linear polarization was injected, a few percent of power has to be considered lost at large angles (about 15% at  $\pm 30^\circ$ ) being XM polarized. In our experiments Co-injection refers to positive angle and Counter- to negative one. Co/Counter EC current generation has been studied in the range  $0 \leq \rho = r/a \leq 0.3$  at six different toroidal launching angles ( $\pm 10^\circ$ ,  $\pm 20^\circ$  and  $\pm 30^\circ$ ).

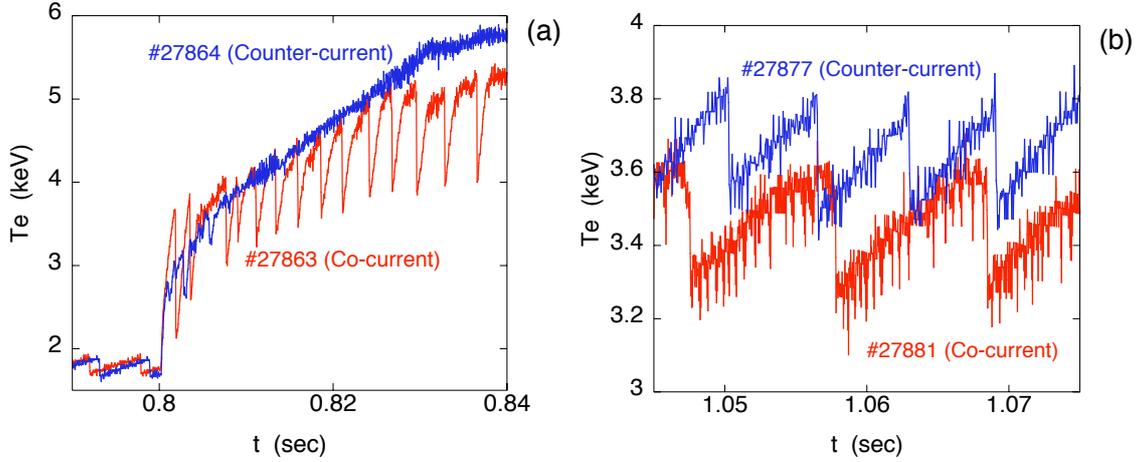
## Results

In Fig.1a the comparison of co/counter **on-axis** ECCD at full EC power (1.5 MW) and  $B_0=5.1 \text{ T}$  is presented, being  $\pm 10^\circ$  the toroidal angle,  $T_e \sim 5 \text{ keV}$ ,  $n_e = 1.1 \cdot 10^{20} \text{ m}^{-3}$  and  $R_{\text{ax}} = 99.5 \text{ cm}$  (#27863-#27864). The time evolution of  $T_e$ , from ECE polychromator, shows a stabilization effect on sawteeth activity with counter current while no suppression is seen in case of co-current. The co-current, added on-axis to the ohmic current, reducing the value of the safety factor  $q$ , is expected to maintain the ohmic instabilities, while the counter-current, increasing the  $q$  value and modifying the magnetic shear, should stabilize sawteeth activity. In Fig.1b the same comparison, still at  $\pm 10^\circ$  and  $B_0=5.1 \text{ T}$ , is made at lower EC power (1.1 MW) with an **off-axis** deposition ( $\rho \approx 0.2$ ,  $0 < r < 7 \text{ cm}$ ) near (inside) the  $q=1$ . In this case co-ECCD exhibits a longer sawteeth period ( $\approx 10 \text{ ms}$ ) than the counter-current ( $\approx 6 \text{ ms}$ ), as expected [3].

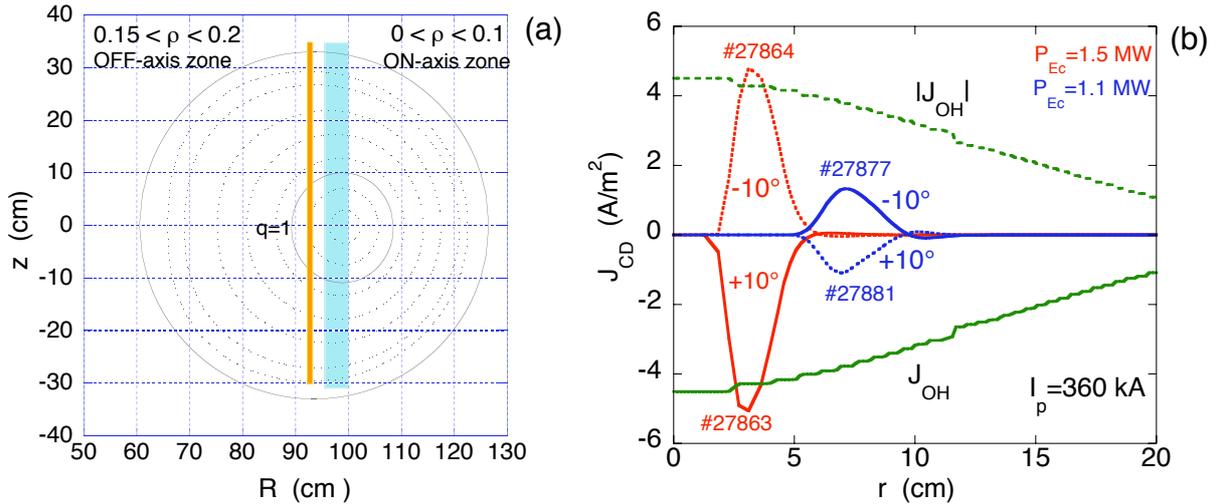
Evidence of suppression of sawteeth activity has been observed also in experiments for ITB formation with ECCD added to lower hybrid power. On-axis counter ECCD was seen to act favourably on the magnetic shear to form a barrier [4].

Theoretical linear calculations have been performed using the ECWGB beam tracing code [5] in which the EC current is given in the form of a modified thermoelectric effect [6]. The linear calculations seem adequate since the residual parallel electric field is less than 20% of the critical field for runaway electrons. Particle trapping effects are also included but they play a negligible role when the EC current is located within 1/3 of the minor radius as in FTU experiments, so that the CD efficiency is not reduced. For the on-/off-axis cases presented in Fig. 1, we sketch in Fig.2a the corresponding ECCD locations in the plasma poloidal section and in Fig.2b the calculated non-inductive current density profiles compared with the ohmic

term. The EC current density in the central region ( $0 < \rho < 0.1$ ) exceeds of about 15% the ohmic one, showing the possibility of a local modification of the plasma current profile.



**Fig.1:**  $T_e$  evolution at a radius near the plasma core for ON-axis Co (#27863) and Counter (#27864) ECCD (a), and near  $q=1$  for OFF-axis Co (#27881) and Counter (#27877) ECCD (b).

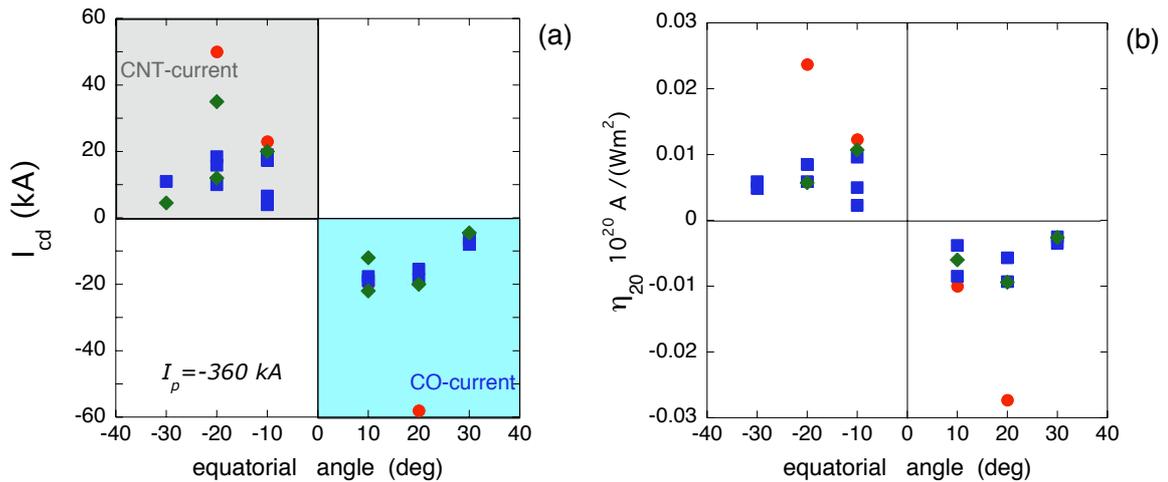


**Fig.2:** ECCD locations in the FTU plasma poloidal section (a), and EC calculated current density profiles and ohmic current density vs minor radius (b).

Two different methods are used to compute the total driven current from the experimental data. Since full ECCD has not been achieved in the experiments and a large residual inductive current remains during rf phase, in the first method (M1) the EC driven current is estimated as  $I_{ECCD} = I_p - I_{BS} - V/R$ , where  $I_{BS}$  is the bootstrap current,  $V$  the measured loop voltage and  $R$  the plasma resistance, computing the neoclassical resistivity from experimental  $T_e$  and  $Z_{eff}$  profiles. The second technique (M2) is based on the comparison of loop voltage variation in two different shots with co or counter ECCD. Assuming that the heating effects (i.e., plasma resistivity) are nearly identical in both cases, the non-inductive term is calculated from the

expression:  $I_{cd}=(I_p-I_{bs})(V_{cnt}-V_{co})/(V_{cnt}+V_{co})$ . It is worth stressing that errors in ECCD evaluation come from  $T_e$  and  $Z_{eff}$  profiles for the first method and from differences used for co/counter cases for the second in not identical shots.

In Fig. 3 we show the  $I_{CD}$  and the ECCD efficiency calculated by using the two methods discussed above and compared with the theoretical one (M3) versus the toroidal injection angles. A good agreement (within 10%) is found between the theoretical calculations and the second method M2. Larger discrepancies are obtained using the M1 method. Although the maximum value of the  $I_{cd}$  ( $\approx 20$  kA) was only 6% of  $I_p$ , local re-shaping of the plasma current density has been obtained. Stabilization of sawteeth activity has been achieved with on-axis counter-current and a correct response from off-axis co/counter behaviours has been observed. Full absorption has been obtained for ECCD located in the plasma centre with  $\pm 10^\circ$  and  $\pm 20^\circ$ . Partial single pass absorption ( $\approx 70\%$ ) has been found for  $\pm 30^\circ$  and  $\approx 85\%$  in case of off-axis deposition at  $\pm 10\%$ . It has to be noted that  $I_{CD} \approx 10\%$   $I_p$  could be obtained operating in cleaner plasma with  $Z_{eff} < 1.5$ .



**Fig.5:** Co/counter  $I_{cd}$  (a) and ECCD efficiency (b) from M1 (circle), M2 (diamond), M3 (square) vs toroidal injection angle for all considered shots.

### References

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