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Quantification of suprathermal current drive on FTU

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Introduction

The radiofrequency non-inductive current drive (CD) is expected to have two major roles in the future large tokamaks: to contribute (together with bootstrap) in driving plasma current for the steady state operation and to control the current profile for MHD stabilization and shear shaping. The most widely used systems for these purposes are lower hybrid waves (for their high efficiency) and electron cyclotron waves (for the strong localization). The simultaneous injection of these two waves and the possible beneficial synergetic interaction have been studied theoretically and experimentally in the past, and recently verified experimentally on FTU [1,2], as proofs of principle without a quantification of CD performances, and on Tore Supra [3] with a more clear effect. The aim of the presented work is to give an experimentally quantification of the overall CD efficiency on FTU when both the waves are used to drive current, extending possibilities and interest in using EC wave to generate significant amount of non–inductive current drive.

Suprathermal Electron Cyclotron Current Drive (SECCD) occurs when the EC wave is absorbed by fast electrons, here generated and sustained by LHCD. The resonant electrons of the tail gain energy (mainly in the perpendicular direction) and reduce their collisionality, thus giving rise to a current due to the asymmetry of the distribution. This mechanism has a strong CD efficiency because involves directly electrons with high parallel momentum. As described by theory, the EC interaction can occur if the fast electron cyclotron frequency (reduced by the way of the relativistic factor γ) equals the Doppler shifted wave frequency, this depending on the local magnetic field, the launching toroidal angle (i.e., $N_{||}^{EC}$) and on the electron velocity. The interaction is defined up-shifted if the resonant absorption takes place in region locate at magnetic field lower than the cold resonant one B_R (in this case the $N_{||}^{EC}$ must be positive with respect to the $v_{//}$ sign: co-injection) or down-shifted if the interaction magnetic field is higher than B_R and $N_{||}^{EC} \le 0$ (counter injection) [4].

Experimental apparatus

Experiments were carried out on FTU, a compact circular tokamak (a=0.3 m; Ro = 0.935 m) with a wide operating magnetic field range (4 – 8 T), at plasma current 500 kA or 360 kA and at a moderate line averaged density (0.6 – 0.8 10^{20} m^{-3}). In the experiments, up to 1.5 MW, 8 GHz, Lower Hybrid waves, with launched $n_{\|}^{LH}$ in the range 1.52 – 2.15, are injected to generate the fast electron population, while the EC waves are launched by means of a set of 4 fully steerable mirrors fed by 4 gyrotrons (140 GHz, 0.5 MW, 0.5 s) in O-mode polarization, or in X-mode for a minor set of pulses, varying toroidal launching angle φ from –30° to 20°. The used scheme was the down shifted, with B_0 =7 T at the centre of the vacuum chamber and the *cold* resonance (5 T) well outside the plasma. Some attempts have been done also in the up-shifted scheme (B_0 < 5T) but, apart the proof a principle [1, 5], a quantification of the SECCD on FTU seems to be problematic since the fast electron EC resonance (4.5 – 4.8 T) is located close to *cold* one, so that a partial overlap of the absorption of thermal electrons with non-thermal ones occurs. As a consequence the path of the wave in presence of fast electrons is too short before being definitely absorbed by thermal ones.

The driven current has been determined using the formula:

$$I_{cd} = I_p \left(1 - \frac{V_{l\_cd}}{V_{l\_oh}} \frac{< T_e^{3/2} >_{cd}}{< T_e^{3/2} >_{oh}} \frac{Z_{eff\,oh}}{Z_{eff\,cd}} \right)$$

which gives the I_{cd} term from the loop voltage reduction, compensated of the resistive change induced by Z_{eff} and by volume averaged temperature ($<T_e^{3/2}>$) variations. The main features of the suprathermal interaction were observed using a 15 chords FEB camera (8 energy levels) [6] while the absorbed power was estimated from sniffer calibrated probes [7], measuring the 140 GHz circulating power.

Results

On a partially (at least 70% of the current) LHCD sustained plasma up to 1.1 MW of O-mode EC power produced an increase of driven current (up to full CD condition) followed by a clear increase in electron temperature (Te). Since there is no way to distinguish the part of I_{cd} due to LHCD or to SECCD, being the interaction fully synergic, to calculate the current drive efficiency, we use $\eta_{cd} = \left(R\bar{n}_e I_{cd} \right)/(P_{LH} + P_{EC}) \cdot (Z_{eff} + 5)/6$, where bootstrap current has been neglected. The resulting η_{cd} is presented in fig.1, where is compared with the LHCD FTU Data Base [5]. The global efficiency of SECCD+LHCD goes from 0.17 to 0.25 $10^{20} AW^{-1}m^{-2}$ and seems to scale with volume averaged electron temperature as the data from pure LHCD. The EC absorbed power (estimated from sniffer probes) is from 30% to 55%, with a small dependence on the launched φ, in agreement with theory. No significant variation of η_{cd} is found with φ, at least outside of the error bars. This can be interpreted considering that all the injected power (also after multiple reflection due to the partial first pass absorption) can be absorbed only by fast electron at an angle anyway efficient in driving current. The SECCD is always accompanied with an increase in Hard-X counts in the higher energy domain (>90 keV) as reported in Fig.2, indicating a clear increase of electron population in the higher energy range of the tail. If we consider this energy increment vs φ the expected theoretical picture is founded again, with a more efficient interaction for φ = –20° and poor interaction for +20°. The major effect on FEB emission can be related to the first pass interaction, when the wave has a still defined $N_{\parallel}^{EC}$, before losing directivity after the first reflection on the vessel. Inverted profile of FEB data shows a wider emission profile during the SECCD in a wide energy range (40-200KeV) confirming the modification to the current profile (see Fig.3). With SECCD, at line averaged density below 0.7 $10^{20}m^{-3}$, a clear increase of central T_e is observed with a moderate electron ITB (see Fig.4). Stronger ITBs have been obtained in transient experiment during the ramp up of the current (up to 800kA), at least until the quenching of fast electron tail, due to the density raise, strongly reduces the EC absorbed power [8]. Experiments with X-mode polarization has suffered for the presence of cut-off in the vessel port. Increasing central B_0 (up to 7.8 T) allowed to a reduced power level (0.4 MW) to be transmitted and coupled to the fast electron as expected by theory, but no CD estimation can be done at this level of power.

Conclusion

The co-injection of EC and LHCD waves, with the aim to drive current in down shifted scheme has been explored in FTU, demonstrating the possibilities for EC waves to reach current drive efficiency similar to those of LHCD if used in presence of fast resonating electron. The EC waves absorption is coherent with what expected from theory. The perpendicular energy distribution of electron population is modified by EC with an increase of electron density at high energy.

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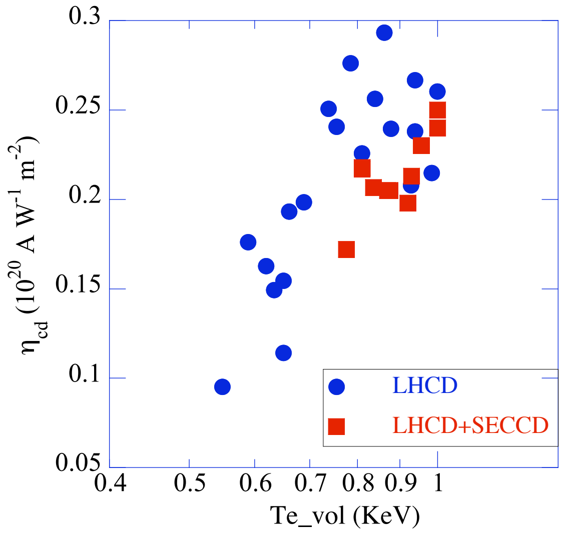

Fig. 1. FTU Current Drive Data Base vs volume averaged T_e. For SECCD data LHCD and EC power are in the range 0.7 – 1.2 MW.

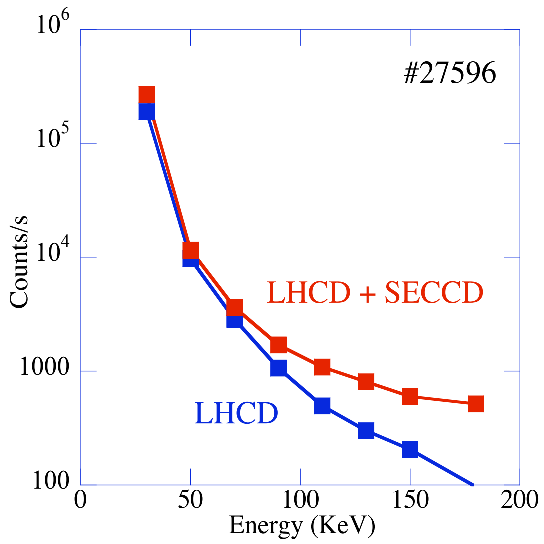

Fig. 2. Hard-X spectral density vs energy, integrated on central viewing chord. SECCD increase electrons energy while the LHCD spectra shape maintains before and after EC injection.

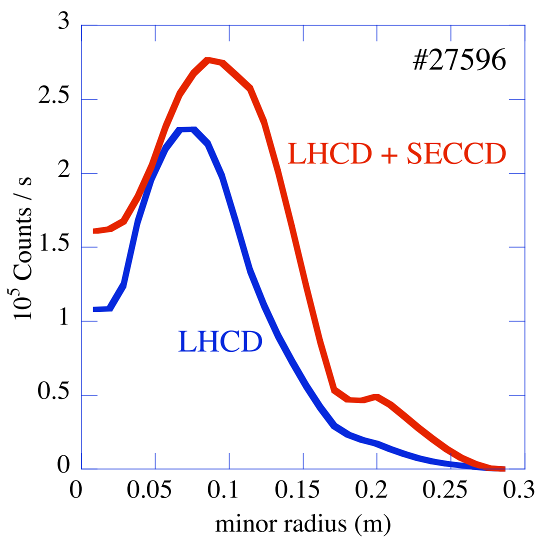

Fig. 2. Hard-X emission profile vs minor radius for energy 40 – 200 KeV. Ip = 500kA, $n_e = 0.75\ 10^{20} m^{-3}$, $P_{LH} = 1$ MW and $P_{EC} = 1.15$ MW, $N_{\|}^{EC} = 0$.

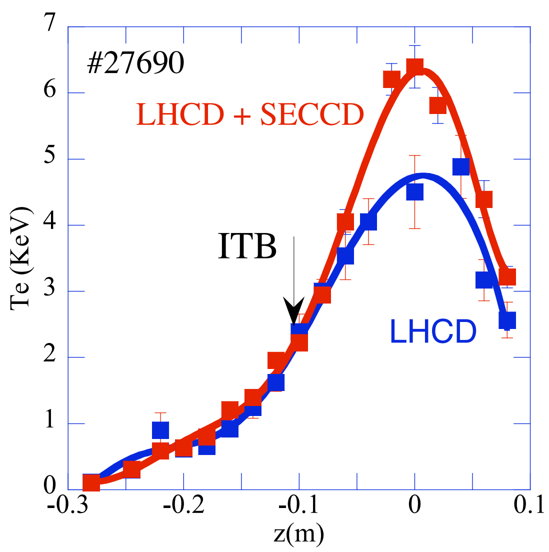

Fig. 4. Comparison of T_e profile, with SECCD an ITB is formed at r/a=0.3. Ip=500kA, n_e=0.6 $10^{20} m^{-3}$ with PLH = 1.1MW and PEC = 0.8MW, $N_{\|}^{EC}$ = - 0.5