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EC Heating and Current Drive studies during current ramp-up in Tore-Supra

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Introduction

Experiments aimed at tailoring the plasma current profile by heating and current drive during the ramp-up phase of a discharge have been carried out in most Tokamak devices, using all the available heating and CD systems from Neutral Beam Injection (NBI) to Lower Hybrid Current Drive (LHCD), Ion Cyclotron Resonance Heating (ICRH) and Electron Cyclotron Resonance Heating (ECRH). The ultimate objective of such experiments is the production of enhanced central confinement with flat or reversed magnetic shear. In Tore-Supra, encouraging results were already obtained with a combination of LHCD, ICRH and FWEH [1,2] before a major vessel refurbishment. Recently, these studies have been resumed and given a new impetus by the installation of a highly flexible, although power limited, 118 GHz Electron Cyclotron Heating and Current Drive (ECH/CD) system [3].

Experimental Setup and Results

In this paper we shall present the results obtained in Tore-Supra by ECCD injection early in the initial current ramp-up phase, in a scenario similar to those developed in most tokamaks in order to tailor the current profile. In our case, an extensive set of predictive simulations carried out before the experiments with the CRONOS transport code [4] had indicated that a variety of current profiles, from monotonic to deeply hollow, could be obtained by varying the current ramp rate and the ECCD deposition profile. In particular, the modelling had suggested that flat or weakly reversed q profiles would be produced by a fast ramp with the addition of off-axis co-ECCD, while the same current ramp plus on-axis counter-ECCD was the most promising route towards a more deeply reversed q profile.

The time evolution of a typical discharge with on-axis counter-ECCD is shown in fig. 1. An MHD stable I_{PLA} ramp-up rate of ~0.7 MA/s was selected, reaching 1.1 MA in flat-top, with B_{TOR} = 3.86 T to obtain the most central ECH deposition. During the ramp-up phase, the density is low, increasing up to $\overline{n}_e$ ~ 2-2.5x 10^{19} m^{-3} on the flat-top, corresponding to ~ 30% of the Greenwall density limit. ECH is typically applied at ~0.7 MW, 2 gyrotrons, from 0.5s into the current ramp, when $I_{PLA} \approx 0.5$ MA. One of the aims of these experiments was to study the confinement with zero or reversed shear core conditions: ICRH has therefore been applied, in on-axis (H)D scenario and so far at moderate power levels ~1-2 MW, in some of the discharges before the I_{PLA} flat-top is reached.

The discharges with on-axis counter-ECCD show high central temperature, up to 10 keV, and strong gradients, dT_e/dR up to 40 keV/m at ρ ~ 0.25 (fig. 2). Interestingly, a series of core temperature collapses are also observed throughout the high temperature phase, reminiscent of what is seen during electron heated deeply reversed shear discharges in other devices [5,6]. This is an indication that, as predicted by the CRONOS code simulations, the combination of ECCD and a fast current ramp could indeed generate reversed shear conditions in the plasma core. The peaked pressure profiles are maintained with increasing density, into the current flat-top and once ICRH is added to ECCD for ~0.5s, or 5 x τ_E. The foot of the steep ∇T_e region moves inwards with time (fig. 3) and, eventually, the high temperature phase is terminated by an internal collapse, which is not accompanied by any obvious MHD activity, followed by the appearance of regular sawtooth activity. The time evolution of the electron temperature suggests that the high gradient feature is not due purely to the ECH central power deposition but it is rather an indication that trasport is decreased in a narrow radial zone, linked to the evolution of the current profile. Indeed it is interesting to note (fig. 3) that the ρ^*_{Te} measure is above the JET criterion for identification of Internal Transport Barriers (ITB) [7]. Another observation is the presence in the core measurements of reflectrometry spectra of unusual features, with frequency ~10 kHz, which could be bursts of TAE modes. One has to note here that on other machines, e.g. JET, similar bursts of TAE modes (“cascades”) have been observed in reversed shear scenarios and correlated with the passage of the q profile through q_{min}=rational surfaces.Different results were obtained with other ECCD scenarios. The “pure” off axis ECCD scenario did not produce either T_e relaxations or steep T_e, even with added ICRH (fig. 2). Finally, in the “mixed” scenario, on-axis counter and off-axis co-ECCD, no sawtooth-like T_e relaxations were observed and ∇T_e was not as steep as in the pure on-axis case, consistent with less power being deposited in the core.

Numerical Modelling

The CRONOS transport code has also been used for interpretative modelling of these current tailoring experiments with ECCD. So far, out of the three ECCD scenarios and the purely ohmic current rise, only the “pure” on-axis counter-ECCD has been satisfactory modelled, i.e. for this case the code results are consistent with the measurements of line integrated Faraday rotation angles, neutron rate and stored energy. The modelling indicates that reversed q profiles are produced and the observed steep ∇T_e is located in the negative shear region (fig. 4), but the current diffusion is relatively fast and the s<0 region shrinks until the q=1 surface is reached. It is interesting to note that, even if the direct EC driven current is neglected, the calculated q profile is reversed, thus implying that the dominant role of the EC is heating rather than current drive. The code also seems to indicate that the bootstrap current, being driven at the location of the high ∇T_e , is counteracting the negative EC driven current, possibly accelerating the relaxation towards a monotonic current profile. Cronos shows that the electron transport in the core is lower during the high temperature phase than during the subsequent sawtoothing phase.

A microstability analysis has also been carried out with the electrostatic linear gyrokinetic code KINEZERO [8], again for the on-axis counter-ECCD scenario. The Electron and Ion Temperature Gradient modes seems to be essentially stable throughout the ECRH and ECRH+ICRH phases. On the other hand, the Trapped Electron Modes (TEMs) are dominant and appear to be stabilised in the core by the negative magnetic shear.

Conclusions

ECCD has been successfully used for current profile tailoring during the current ramp-up in Tore-Supra. Different ECCD scenarios have been compared: with counter-ECCD on axis, high core electron temperatures and steep gradients have been observed, which are maintained for some time on the current flat-top and with the addition of ICRF (H)D heating. There are strong experimental indications that a negative magnetic shear region is produced in the core, confirmed by interpretative modelling with the CRONOS code.

It is planned to continue these interesting and promising experiments, in particular to assess the ion transport taking advantage of the new CX ion temperature measurements and to exploit ECCD as a flexible tool for studies of advanced scenarios with strongly or weakly reversed shear.

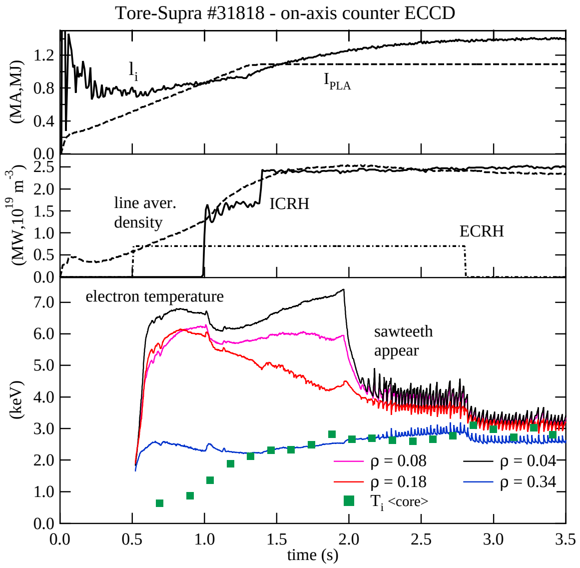

figure 1: time evolution of plasma parameters for a discharge with on-axis counter-ECCD and ICRH

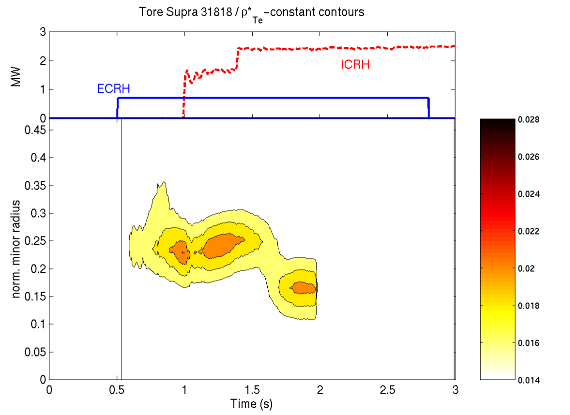

figure 3 : contours of ρ^*_{Te} for a discharge with on-axis counter-ECCD + ICRH

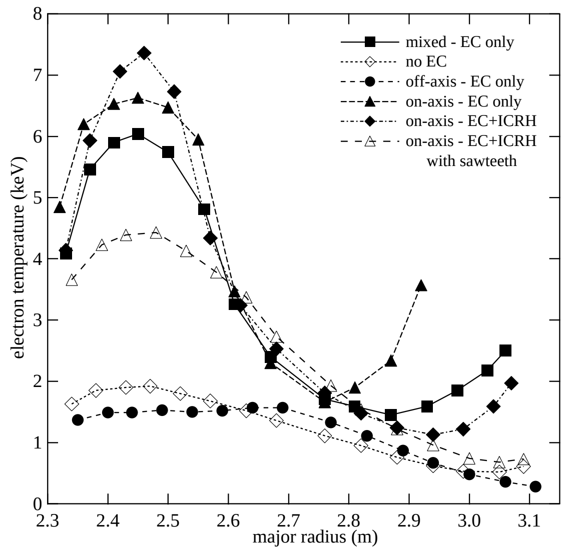

figure 2: electron temperature profiles, measured by ECE, for different ECCD scenarios

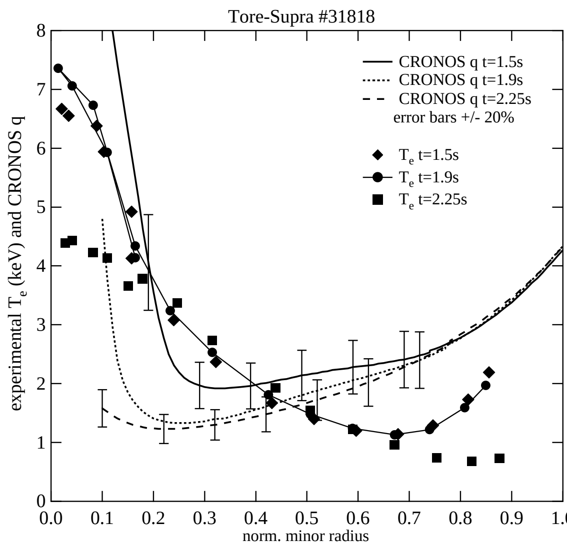

figure 4: measured electron temperature profiles and computed q profiles for a discharge with on-axis counter-ECCD and ICRH

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