Thermal transport and global energy confinement during ECRH at 140 GHz, on steady-state discharges of FTU tokamak

A.Bruschi[1], C.Sozzi[1], A.Airoldi[1], L.Bertalot[2], G.Bracco[2], S.Cirant[1], B.Esposito[2], L.Gabellieri[2], G.Granucci[1], H.Kroegler[2], S.Nowak[1], D.Pacella[2], A.Simonetto[1], V.Zanza[2], M.Zerbini[2], FTU Group[2], IFP/ECRH Group[1]

[1]*Istituto di Fisica del Plasma, Associazione EURATOM/ENEA/CNR sulla Fusione, via Cozzi 53, 20125 Milano, Italy*
[2]*Centro Ricerche Energia, Associazione EURATOM/ENEA/CNR sulla Fusione, C.P.65, 00044 Frascati, Rome, Italy*

1.Introduction.

A number of shots of the Frascati Tokamak Upgrade with 800 kW of electron cyclotron heating at 140 Ghz, fundamental resonance for the O-Mode at 5T [1], were dedicated to the suppression of the sawtooth instability.   It was achieved exploiting the very narrow power deposition profile obtained with the launching system [2] in particular when the resonant surface is moved away from the plasma center (B0=5.5T, $r_{RES}/a=0.15$) the power deposition profile FWHM is less than 2 cm. In this case a strong heating in an off-axis position causes a proper shaping of the electron temperature and current density profiles, modifying the q-factor and the local shear of the magnetic field in the plasma core region[3].

The full sawteeth suppression has been obtained for a few shots at low current (400 kA) and high density (above $6\ 10^{19}\ m^{-3}$, line averaged density), in which the central temperature during the 0.2 s of E.C. pulse shows no signs of the usual variation. In this case all the quantities relevant to the plasma power balance reach a stationary state, allowing a plain analysis of the transport and in particular of the energy confinement time. The higher electron density at which the shots were performed (peak electron density of $1.9\ 10^{20}\ m^{-3}$, cutoff density for O-Mode ECRH at 140 GHz is $2.4\ 10^{20}\ m^{-3}$) lets the ions play a decisive role in the balance, through the electron-to-ion energy exchange (Fig.1).
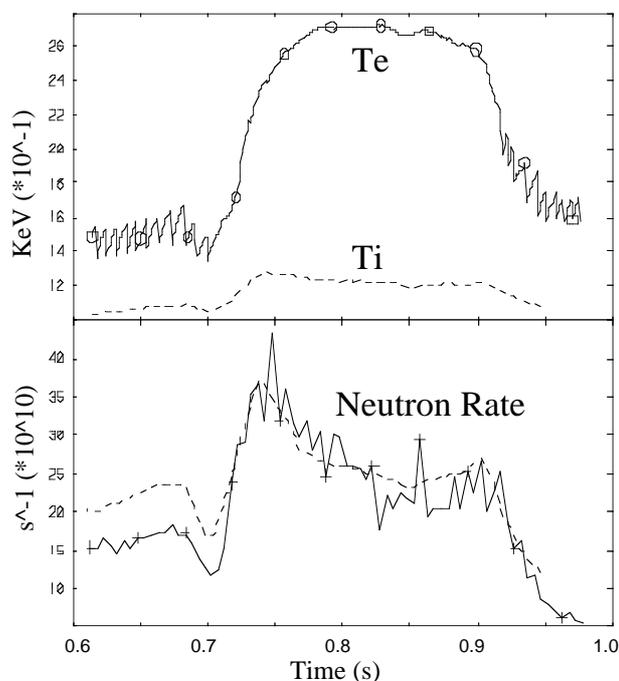

Fig.1: Top: time traces of central electron (from ECE) and ion temperature (from the code); bottom: measured (full line) and computed (dashed line) neutron rate for shot 15477 during ECRH.

2. Power Balance Simulations

The analysis has been performed with the transport code EVITA, in the interpretative version, which solves the time-dependent magnetic field diffusion equation (assuming neoclassical resistivity) and the electron and ion energy balance equations linearised each time step and integrated by a finite difference method. The analysis is carried out with input data given by the experimental geometry (from equilibrium reconstruction), electron density from a 5-channels DCN interferometer, temperature profiles from ECE Michelson, total radiated power from bolometric measurements and plasma current. A constant multiplication factor on the ion neoclassical conductivity is varied in order to reproduce the experimental neutron rate. A cross-check of measured to computed loop-voltage is made for consistency. In most of the cases an "anomaly" on the neoclassical ion transport in the range 1.5-3 is enough to fit the data.

3. Energy Confinement Time

An estimate of the energy confinement time follows from the run of the code. For this particular set of discharges, the result is compared with the current principal scaling laws worked out for ITER[4,5,6] and a more optimistic one in high density conditions[7]. The results show a general agreement with the L-mode scalings, with a scattering of data around a $\tau_E/\tau_{E,SCALING}$ value of 1.2 with respect to $\tau_{th,ITER(96)}$, $\tau_{E,ITER(89-P)}$, and 0.95 with respect to the Lackner-Gottardi scaling (Fig.2) . If $\tau_E/\tau_{E,SCALING}$ is plotted against the total input power, a slight dependence is found, showing, in the examined discharges, a confinement time higher with respect to the ITER(96) scaling law predictions and in a better agreement with the ITER 89-P and Lackner-Gottardi (Fig.3).
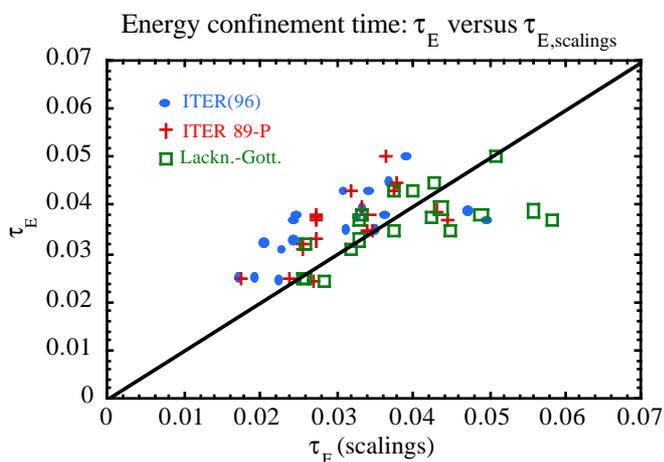

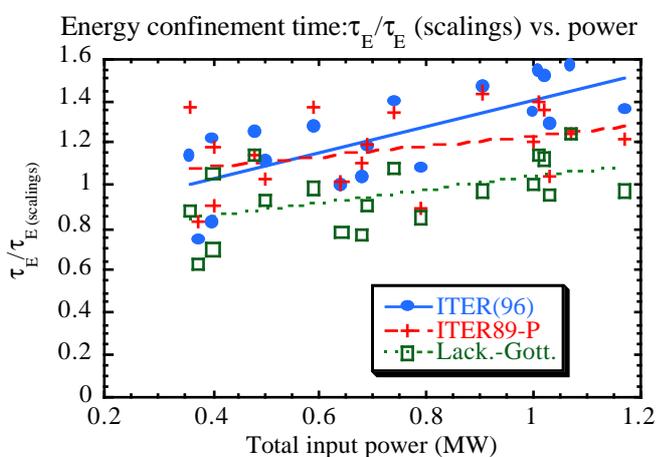*Fig.2 Comparison of the energy confinement times experimental and obtained from scaling laws.*

Fig.3 Ratio of τ_E to τ_E from scalings, plotted versus total input power (ohmic+ECRH).

4. Power to the Ionic Population

For the considered set of discharges the ECRH power deposition profile used by the code EVITA is computed by a Ray-tracing Code[8] linked to the equilibrium reconstruction of magnetic surfaces and density profiles from experimental data. Due to the narrowness of the heated region, the resulting electron temperature profiles are rather flat from the center to the resonant region, where also the electron thermal diffusivity remains flat, staying below 0.5 m^2/s, and show steep gradients on the outside. The electron-ion energy exchange depends strongly on the local parameters (density, difference from electron to ion temperature) and shows a certain variability from shot to shot. The resulting fraction of the additional EC power transferred from electrons to ions via collisions is estimated in about 10% of the power injected (at 800 kW).

5. Effect of Density on Electron Temperature Profiles

At densities above 6 10^{19} m^{-3} (line average) hollow T$_e$ profiles appear to be created and mantained in steady-state (Fig.4). This is clearly seen from the code analysis when considering the electron power balance in the center (Fig.5).

At the switch on of the EC power, in the central region, not interested by EC wave absorption, the power density that heats the electron population (ohmic - radiative losses - power transferred to ions) drops below zero, due to the diminished ohmic power input and increased radiative losses.

A positive T$_e$ gradient (hollow profile) must then be established to recover the energy losses and assure a stationary state with negative input in the electronic population. Decisive in the balance is the power transferred to the ions which, especially at high density, equals or exceeds the ohmic contribution.

In Fig.5 the net power density heating the electronic population is plotted against the total power input (ohmic+ECRH). Two subset are singled out: low and high densities (less or more than 6 10^{19} m^{-3}), to show the density role in the balance.
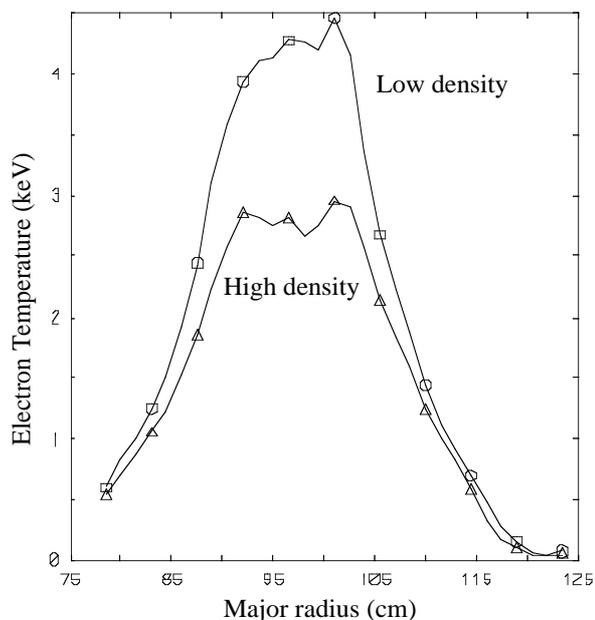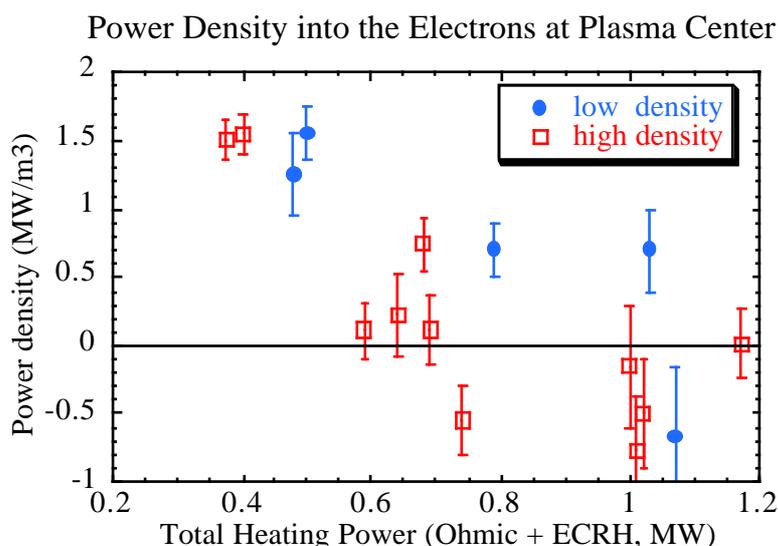

Fig.4 Typical steady-state electron temperature profiles during ECRH. (from ECE).

Fig.5 Power density into the electrons at plasma center, reaching negative balance at high powers and densities; the error bars reflect the confidence in the balance, mainly due to the error in the estimate of the radiated power density.

6. Conclusions

The application of 800kW of ECRH power in a particular off-axis position causes visible effects on the electron temperature profile shape and in the current profile as demonstrated by the suppression of the sawteeth instability. Ions participate in the task, at sufficiently high densities, draining power from electrons and cooling the plasma center.

The exploitation of this effect at higher EC powers and densities is now under study, with the aim to obtain a hollow steady-state electron temperature profile and possibly a reversed shear configuration, in addition with or even without current drive methods.

References

[1] C.Sozzi et al., "High Power System for ECRH at 140GHz, 2MW, 0.5s on FTU Tokamak" 13th Topical Conf."Applications of RF power to Plasmas"- Apr. 12-14,1999 - Annapolis,Maryland.
[2] Simonetto A. et al."Low and medium power tests on 4 beams launching optics for the 1.6MW ECRH experiment at 140Ghz on the FTUtokamak", Proc. 23rd Int. Conference on Infrared and Millimeter Waves, Colchester, UK, 7-11 September 1998 - pg 122-123, Eds. T.J. Parker, S.R.P.Smith.
[3] S.Cirant et al.,"Transport and MHD Studies at High Te In FTU Tokamak", This Conference.
[4] P.Yushmanov et al., Nucl.Fusion 30,No.10 (1990), p.1999.
[5] T.Takizuka et al., Fusion Energy 1996, Vol.2, p.795, IAEA (1997)
[6] S.M.Kaye et al.,Nucl.Fusion.37,No.9 (1997)
[7] K.Lackner, N.A.O.Gottardi, Nucl.Fusion 30, No.4 (1990), p.767.
[8] S.Cirant, S.Nowak and A.Orefice, J. Plasma Physics, 53, 345 (1995).