# Electron Cyclotron Heating experiments during the current ramp-up in FTU.

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**Introduction**. An experimental campaign with Electron Cyclotron Resonance Heating (ECRH) [1] during the current ramp-up has been performed in FTU with the purpose of studying the core energy transport in sawtooth-free plasmas. In the early phase of the discharge, before the onset of sawteeth, a variety of shapes of the current density profile are produced, depending mainly on the plasma start-up characteristics (gas pre-filling, light and heavy impurity content). The onset of sawtooth activity has been delayed significantly by controlling the current profile modification induced by localized ECRH. Up to 800 kW of radio frequency power at 140 GHz, corresponding to 5T fundamental electron cyclotron frequency, was injected from the low field side. Polarization was ordinary with perpendicular launch. High temperatures (12-13 keV) have been obtained with central deposition; the electron-ion coupling is very weak in these conditions, so that electron heat transport can be studied accurately. No evidence of electron suprathermal population (energetic tail) has been detected, but at high temperature and low plasma density experimental indication of a low energy ($E \sim E_{th}$) distortion of the Maxwellian distribution has been found. The analysis of MHD free phases has shown that the central electron thermal diffusivity is comparable with the Ohmic one ($0.2 \div 0.4$ m$^2$/s), even at high temperature and high temperature gradient, both with monotonic and with reversed q profiles.  Simulation with the mixed Bohm-gyroBohm [2] model has shown that the central temperature can be predicted only by neglecting the gyroBohm term.

**Revisiting temperature measurements**. Electron temperature on FTU is measured by Thomson scattering (TS) and electron cyclotron emission. The first one has been designed to work at relatively low temperature, so that it is affected by significant error bars at temperature $T_e > 10$ keV.

At high central temperature, the ECE temperature profiles show a hump at the low field side (i.e. low frequencies) due to the relativistic down shifted emission from central electrons that is not reabsorbed by the plasma periphery. Simulations of ECE spectra with the measured central temperature (~13.5 keV) predict a very high hump at low frequency (six times the measured

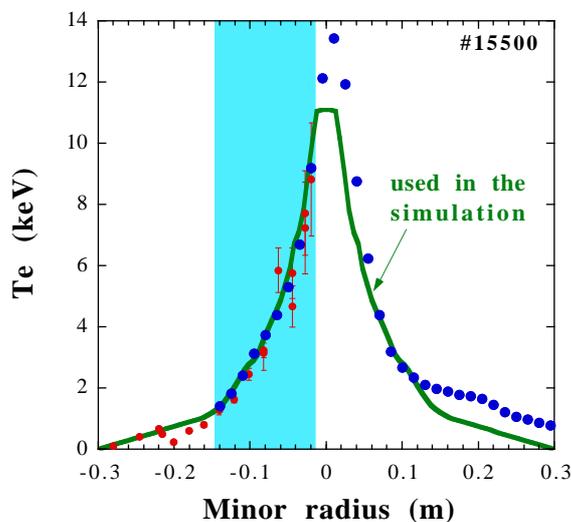one) and a higher emission at third and fourth harmonic. The spectrum, not including the second harmonic central emission, can be reproduced with a peak temperature of about 11 keV. Recently, it has been pointed out [3,4] that in presence of high ECRH power density, similar discrepancies between the second harmonic and other parts of the ECE spectrum can arise, due to a distortion in the electron distribution function at low energy. The distribution function, calculated using a high poloidal resolution Fokker-Planck code, has an isotropic non-Maxwellian population, with energy dependent slope temperature peaked between 10 and 20 keV. This distortion also affects TS temperature by a smaller amount. The amplitude

**Fig.1** *Temperature profiles from ECE(o) and TS(•), compared with the interpolation used in the power balance. Shaded area indicates the ECE temperature measurements used in the interpolation.*

of this effect depends on several parameters, as plasma density ($n_e$), ECRH power (P), temperature and $N_{//}$ wave spectrum, and each experimental case must be analyzed separately. For fixed conditions (central deposition and perpendicular launching), the following scalings have been found for the difference between the apparent temperature and the minimum slope temperature: $\Delta T_{ECE} \sim (P/n_e^2)^{1.5}$, $\Delta T_{TS} \sim P/n_e^2$.

This non-Maxwellian contribution to the ECE is important only in the ECRH deposition region, that for central deposition is just in a small region at plasma axis. As it does not affect the evolution of the global confinement and of the diffusivity at larger radii we have considered it as an error band on the center quantities. Within this frame, we still can get a good temperature measurement from the high field side of the ECE second harmonic, not affected by the relativistic down shift, from few centimeters from the center to half plasma radius where the overlap with the third harmonic takes place. The central temperature has been reduced in order to take account of the non-Maxwellian effect, and the external part of the profile has been obtained by a linear interpolation, according with the TS data (fig 1). We are confident that such a profile provides a good basis for the evolution of the local and global energy confinement, as the estimated loop voltage is in good agreement with the experimental value, using $Z_{eff}$ from visible bremsstrahlung.

**Power balance analysis.** The power balance analysis has been carried out by the EVITA code, which allows both interpretative and predictive time-dependent analysis. The code solves the diffusion equation for the poloidal magnetic field and for the ion temperature, using the geometry obtained by the equilibrium reconstruction. Input and output data are interfaced with the FTU database for direct comparison with experimental results. The input data are: a) the ECE temperature profile, b) 5 chords DCN interferometer for plasma density, c) visible bremsstrahlung for $Z_{eff}$, d) 12 chords bolometer for radiation losses, e) the ECRH deposition profile from ray-tracing. Neutron yield is used to adjust the anomaly factor in thermal ion transport coefficient. The code assumes that the electric field is completely diffused at the starting time, that is a good approximation, as at this time the temperature is low.

Up to 800 kW of ECRH have been applied during current ramp-up. Density increased along with the current, from 3 to $5 \times 10^{19}$ m$^{-3}$ during the entire current ramp. The central temperature

roll over after t=0.09 s occurred at constant central pressure. The ECRH beam waist was about 2 cm. The e-i coupling was weak and ion temperature remained at about 1 keV. Neutron yields were in agreement with $\chi_i = 1 \div 3 \times \chi_{i,Chang-Hinton}$ in all cases. The evolution of some relevant quantities of a typical discharge with 800 kW of ECRH on-axis during the fast current ramp, is shown in fig 2. The global confinement time ($\tau_E$) is shown together with the ITER89P and the Lackner-Gottardi (LG) scalings; the better agreement is found with the latter. This is the same situation as in low density Ohmic discharges (Linear Ohmic Confinement)[5]. While the global confinement follows L-mode scalings, the thermal diffusivity in the plasma core remains low even at high temperature gradient, as it is shown in fig 3, where the heat flux is plotted versus the temperature gradient for two discharges with 0.8 MW of ECRH, and compared with 0.35 MW case and with OH discharges. It can be seen that the temperature gradient has been increased by a factor 10 without producing any appreciable increase in $\chi_e$.
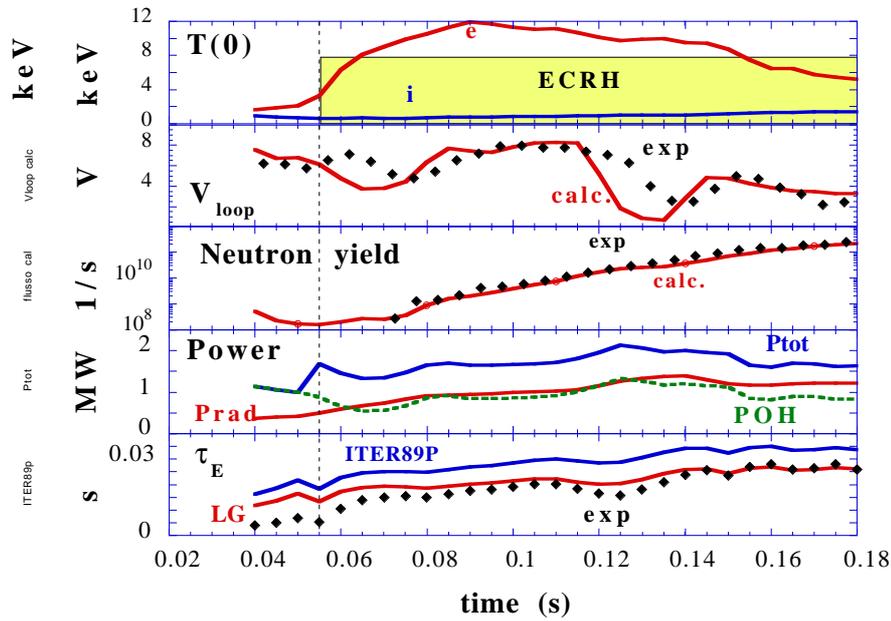


**Fig.2.** *Time behaviour of some relevant quantities.*

**Comparison with BgB model.** The central value of $\chi_e$ (~$0.2 \div 0.4$ m²/s) has been compared with the values predicted by the mixed Bohm-gyroBohm model [2],

$$\chi_e = \alpha_B D_B \frac{a}{L_{Te}} q^2 f(s) + \alpha_{gB} D_B \frac{\rho}{L_{Te}}$$

where, $D_B = T_e/16B_T$, $L_{Te} = T_e/T_e'$, $\rho$ is the electron Larmor radius and $\alpha_B$ and $\alpha_{gB}$ are two constants. $f(s) = s^2/(1+s^3)$ for s>0, and 0 elsewhere; s is the magnetic shear.
It has been found that the gyroBohm term, due to the high temperature gradient value, predicts $\chi_e$~ 5 m²/s, while the Bohm term, owing to the strong reduction at low magnetic shear, gives values that are close to the experimental ones. The shear factor has been tested on two discharges with different q profile evolution, as inferred by the diffusion calculation and the MHD activity, but with identical macroscopic parameters. One of this discharges (#15500), had a broad pre-ECRH temperature profile and developed a Double Tearing reconnection (DTM) that is a clear symptom of a reversed shear profile, in qualitative agreement with the calculated q(0). The other discharge (#15020), had a more peaked pre-ECRH temperature profile, and a very low MHD activity. The calculated q profiles were narrower than that of the previous discharge. The two temperature profiles at the maximum of $T_e(0)$ (before the DTM) reconnection) are very similar. The simulation with the Bohm term predicted a peak temperature
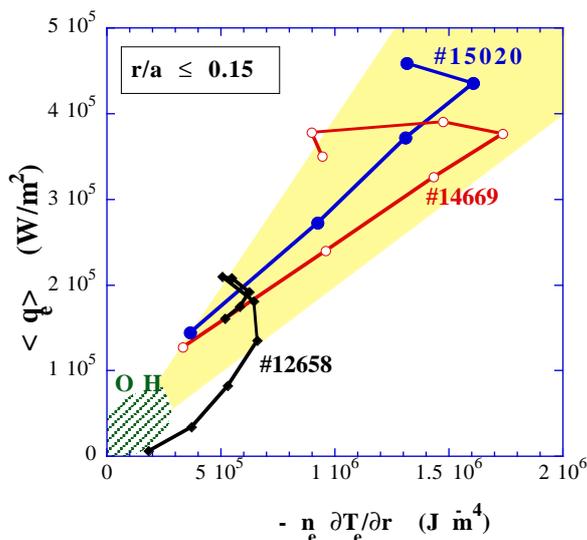
**Fig 3**. *The electron thermal flux is plotted versus the temperature gradient, for high temperature plasmas. Ohmic discharges are also indicated for comparison*

of 9 keV and 8 keV for the cases with reversed and monotonic q, respectively, while the measured peak temperature of both discharges was 11 keV. However, due to the uncertainty affecting the central q profile we cannot give a definitive answer about the shear effect on the transport, but we have an indication that it does not always account for the low core transport at least in the framework of the BgB model.

Applying 0.8 MW of ECRH off-axis on an initially peaked temperature profile, the temperature profiles remained peaked during all the ECRH period. A central temperature of 8 keV was obtained, until the sawteeth start up. The central $\chi_e$ remained below 0.5 m$^2$/s up to half radius, notwithstanding the global energy confinement was still close to the LG scaling. This probably is due to the fact that the input power is negligible in that region where the diffusion is low. Within the resonance radius the conductivity became slightly negative, but the uncertainty on the Ohmic input in that region does not allow to draw final conclusions on the existence of a non diffusive term. The simulation with Bohm term of BgB model does not reproduce the peaked profile, and gives a central temperature of 4.5 keV.

The central diffusion during the current ramp with a strong ECRH heating can be compared with that of the flat–top phase when the sawteeth are stabilized by the off-axis ECRH. In the last case, the experimental $\chi_e$ has the same value as that on the current ramp, within half minor radius. The full BgB model gives a good description of the temperature evolution of the sawteeth stabilized discharges, but in this case the temperature gradient is low, so the gB term gives a negligible contribution. The global confinement time of this discharge is again described by the LG scaling both in the OH and the heated phase, but the ITER89P scaling in the heated phase is very close to the LG one.

**Conclusion**. High temperature ECRH discharges keep having low central heat diffusion, as Ohmic discharges, and their global confinement time follows the L-mode LG scaling.
The BgB model can describe temperature profiles in almost all condition provided the gB term is neglected. It can not reproduce the evolution of the off-axis heating when the profiles remain peaked. The shear factor of BgB is important in depressing the central diffusion but it can't account for the transport in discharges with different shear profile.

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