ENERGY TRANSPORT ANALYSIS OF HIGH TEMPERATURE AND HIGH DENSITY FTU PLASMA DISCHARGES

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Abstract

Some FTU plasma scenarios are characterised either by high electron temperature, produced by ECRH, or high densities, by pellet injection. This paper discusses the energy transport characteristics of these configurations and compares them with the predictions of mixed Bohm/Gyro-Bohm model that has been recently proposed. The Gyro-Bohm term of the model overestimate the measured energy transport in the conditions when it becomes relevant. The Bohm term alone seems to simulate correctly the experimental results, with exception of the post-pellet enhanced confinement.

1. INTRODUCTION

The recent experimental activity on FTU has produced plasma scenarios characterised by high electron temperature, with ECRH (Electron Cyclotron Resonance Heating) during fast current ramps, and high densities, by means of multiple injection of deuterium pellets penetrating beyond the sawtooth inversion radius. Low or negative magnetic shear configurations are often produced in the fast current ramps. The energy transport analysis of these plasma conditions provides information in a range of parameters that can not be easily reached in other tokamaks as they are typical of a compact high magnetic field machine (R=0.93 m, a=0.3 m, B_T=4÷8 T).

ECRH experiments [1] at 140 GHz have resulted in a maximum temperature up to 14 keV, with an electron temperature gradient in excess of 150 keV/m. Multiple pellet injection [2] produced high density plasmas with enhanced global energy confinement and peak electron density $n_e(0)\approx 4x10^{20}$ m^{-3}. The absence of the sawtooth activity for a significant time interval allows to perform the interpretative analysis of the energy transport in the core of the plasma discharge and provides some experimental data that can be used to test transport models.

In this work the recently proposed mixed Bohm-gyro-Bohm (BgB) model [3] is compared to the experimental data of the described plasma scenarios. The model was calibrated on JET experimental data and verified on the results of other large tokamaks (TFTR, DIII-D) and the comparison with FTU results extends the analysis in a different range of plasma parameters. Mixed BgB models [3,4,5] are characterised by a thermal diffusivity composed by two terms that can be interpreted as due to a turbulence with a scale length of the order of $(a\rho_i)^{1/2}$, the Bohm term, or with a scale length of the order of ρ_i, the Gyro-Bohm term, where a is the machine size and ρ_i the plasma gyro-radius. This approach is based on the experimental observation that the

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scaling of the energy transport seems to have Bohm or Gyro-Bohm features in different machines and plasma heating scenarios. Standard L mode discharges appear to be described by Bohm models while in the case of strong electron heating a Gyro-Bohm behaviour of the electron thermal diffusivity has been observed [4]. In the model [3] the Gyro-Bohm term becomes relevant at the high temperatures obtained in the ECRH during current ramp, while the Bohm term, that includes an explicit dependence on magnetic shear, is dominant in the other configurations.

The plasma energy transport has been evaluated using the EVITA code that allows both the interpretative and the predictive time-dependent analysis of a plasma configuration. The code solves the diffusion equations for the poloidal magnetic field, the electron and the ion temperatures using the plasma geometry obtained from the equilibrium reconstruction code, based on the magnetic measurements. Electron temperature is measured by ECE analysis and the results are in good agreement with Thomson scattering measurements. Plasma density profile is evaluated by the inversion of the line averaged densities measured by a 5 chords DCN interferometer. In the case of the pellet injection the Thomson scattering density profile are also used in the elaboration. The value of Z effective is obtained by the visible bremsstrahlung signals. Radiation losses are measured by a 12 chords bolometer array. The code evaluates the neutron yield which is compared to the experimental value to obtain information on the ion temperature. Deuterium is the working gas for all the described scenarios. The current density profile is obtained by the solution of the diffusion equation for the magnetic poloidal field and it has been checked that the obtained profiles are consistent with the MHD behaviour of the plasma discharges. The interpretative analysis of the discharge shows that, whenever the analysis can be performed (no saw-tooth activity), the core electron thermal diffusivity is typically in the range 0.2÷0.4 m^2/s, both for low and high values (5÷150 keV/m) of the electron temperature gradients.

2. ECRH ON FAST CURRENT RAMPS

In ECRH experiments, up to 700 kW of radio frequency power at 140 GHz have been injected during the current ramp-up phase of 700 kA plasma discharges. Heating at the fundamental frequency, with perpendicular, low field side launch with ordinary polarisation has been used, so that the resonant magnetic field is 5 T. Both on axis and off axis heating has been applied. No significant changes have been observed on density profiles during ECRH. Power deposition evaluations show that due to the modest initial optical thickness the first-pass absorption is incomplete (60%) at the start of the heating pulse but it approached 100% as soon as the temperature built up. The fast ramp scenario (5 MA/s) is illustrated in Fig. 1.

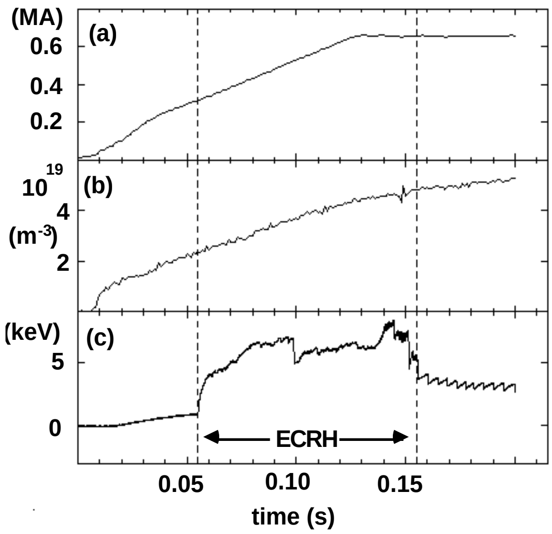

*FIG. 1 Fast current ramp time traces, pulse **12799,** 360 kW ECRH: (**a**) plasma current (**b**) central line averaged density (**c**) electron temperature at R=0.97 m, from ECE polycromator.*

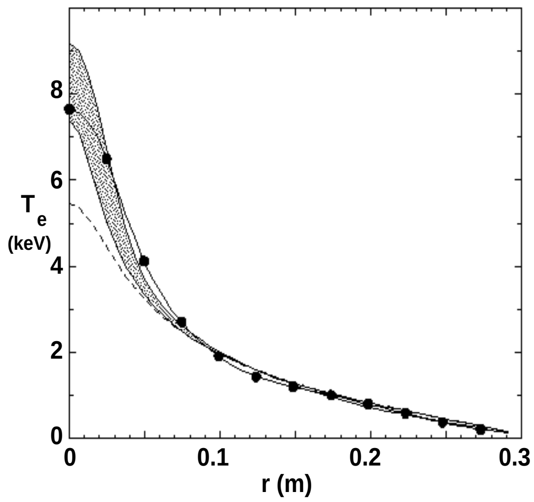

FIG. 2 Electron temperature profiles at t = 0.095 s , pulse 12799; filled points experimental data;simulation results: dotted line: BgB model, shaded area Bohm term only with hollow to peaked current density profile.

The start-up phase produces two qualitatively different plasma configurations characterised either by peaked or hollow temperature and current density profiles. The profiles can be somehow controlled by tuning the gas feed and the plasma position, but they depend also on the plasma impurity content. The two configurations have different MHD features.

2.1 On axis heating

When ECRH is localised at the plasma centre the hollow temperature profiles evolve into peaked ones, while current density profiles remain hollow until a MHD activity with the characteristics of a double-tearing mode at the resonant q=2 surface develops producing a temperature crash (e.g.. t≈ 0.1 s in Fig.1(c)). The crash results into a peaked current density profile and, after some delay, the saw-tooth activity appears and causes a decrease of the peak temperature. The temperature profiles before the crash, Fig. 2, are not consistent with the BgB model, where the Gyro-Bohm term overestimates the energy transport. The Bohm term only can simulate the experimental data, but the results depend on the detail of the magnetic shear profile, Fig. 2. In the case of pre-ECRH peaked current density profiles, which results in m=1 activity, the temperature shows an initial increase, in excess of 12 keV at high ECRH power, Fig. 3, followed by a decrease and the sawtooth activity onset. Also in this case the BgB model underestimates the experimental results, which can be reasonably reproduced by the Bohm term only, Fig. 3, at least for t< 0.120 s.

2.2 Off axis heating

When ECRH is localised off axis (5÷7 cm from the centre) the increase of the electron temperature is lower, due to the volume effect. In this case the hollow profile discharges show a behaviour that can be interpreted qualitatively as "diffusive", in the sense that electron temperature profiles remain hollow, Fig. 4, and evolve later to a more peaked profile. At these lower temperature values the Gyro-Bohm term of the BgB model is negligible and the data are roughly in agreement with the model. In the case of peaked pre-ECRH profiles, the profiles remain peaked, despite of the off-axis heating, Fig. 5, suggesting a "non diffusive behaviour" or the sign of an inward energy pinch. Nevertheless, the simulation with BgB is in agreement with the data, and the central temperature increase is explained by the residual central ohmic heating.

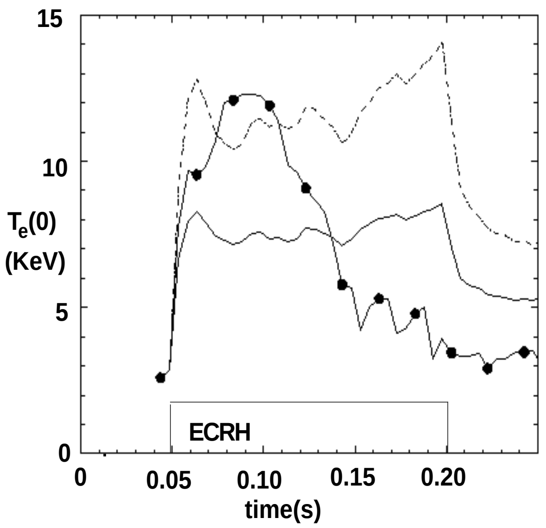

FIG. 3 Peak electron temperature versus time in the high power, 690 kW, ECRH pulse 14669; full points: experimental data; full line: BgB model simulation; dashed line: simulation with Bohm term only

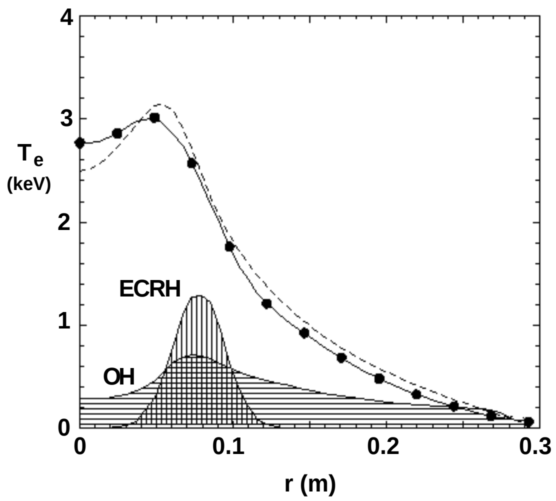

FIG. 4 Electron temperature profile at t=0.070 s, pulse 12953 with 325 kw ECRH power; full points: experimental data; dotted line: BgB simulation; the relative amplitude of ECRH and OH power density profiles are shown at the bottom.

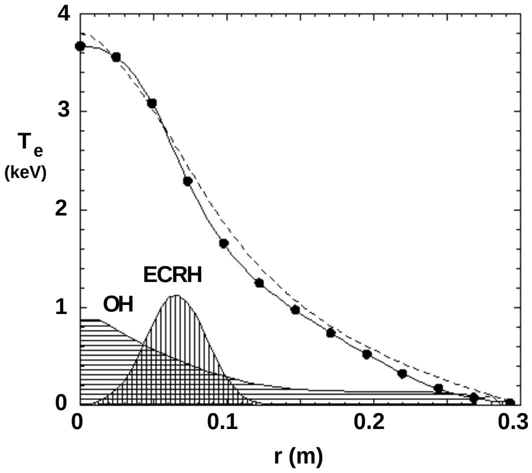

FIG. 5 Electron temperature profile at t=0.070 s, pulse 12616 with 290 kw ECRH power; full points: experimental data; dotted line: BgB simulation; the relative amplitude of ECRH and OH power density profiles are shown at the bottom.

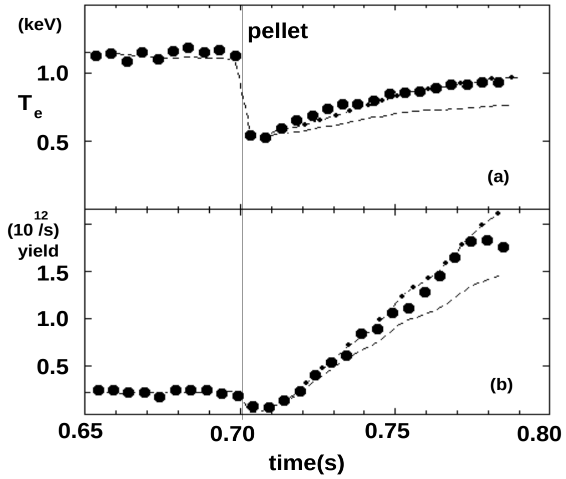

*FIG. 6 Pellet time traces; full points experimental data; (**a**) electron temperature at r=0.1 m; (**b**) DD neutron yield; dotted line: simulation with full BgB model; dotted line with points: simulation with BgB model for electrons and neoclassical ion transport.*

3. MULTIPLE PELLET INJECTION

In pellet injection experiments, I_p=700 kA, pre-pellet density $n_e \approx 1.2 \times 10^{20}$ m^{-3}, the sawtooth activity is temporarily suppressed and the energy confinement time increases up to 2 times the L mode value. The result was interpreted in the past as a reduction of both the electron and ion energy transport [2].The neutron yield is in agreement with 5 times the neo-classical ion transport in the pre-pellet phase reduced to a neo-classical value in the post pellet. The BgB model agrees both with electron and ion data in the pre-pellet phase but the post-pellet analysis requires BgB electron transport combined with ion transport reduced to the neoclassical value, Fig. 6, possibly due to the more peaked density profile. Standard ohmic discharges at the same line averaged density as the post-pellet phase are fully described by BgB model, in agreement with the L mode scaling typical of the saturated ohmic confinement regime (SOC).

4. CONCLUSIONS

In the cases where Gyro-Bohm term is negligible, as in the standard ohmic plasma in the SOC regime, the BgB model is in agreement with the data, with exception of the post-pellet phase that is consistent with a pure neo-classical ion transport. With ECRH, the model is able to explain some features of the off-axis heating experiments, while in the very high temperature cases, where the Gyro-Bohm term is relevant, it over-estimates the electron energy transport which seems to be consistent with the value of the Bohm term only.

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