*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, O-1.04 (2002)*

Electron Internal Transport Barriers with ECRH and LHCD in the FTU tokamak

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Internal transport barrier (ITB) regimes were observed in circular shaped discharges of the Frascati Tokamak Upgrade (FTU) tokamak, operating at low plasma density ($n_{eav} \leq 0.5\ 10^{20}$ m^{-3}). ITBs were previously obtained with Electron Cyclotron Resonance Heating (ECRH, 1.1 MW, 140 GHz) both on the current ramp [1] and during the current plateau in combination Lower Hybrid current drive (LHCD, 2.2MW 8GHz) [2]. Furthermore, ITBs with Ion Bernstein Wave heating have also been observed [3]. In the present paper, recent ITB scenarios at higher densities are presented. In these experiments, LHCD allows preventing the onset of MHD activity, typically sawteeth instabilities , by modifying the current density profile. A proper electron temperature target for LH absorption and current drive can be obtained utilising the localised ECRH power deposition. Moreover, a benefit from improved confinement regimes can be taken by ECRH central power absorption, thus enhancing the ITB performances. Two different schemes are exploited by coupling the additional RF power during the plasma current ramp up and during the current flat top. In Fig. 1 the central electron temperature of the ITB performances are plotted versus the line averaged plasma density. The data are selected by using the ITB criterion: $\rho^*_{Te} > 0.015$

during a time window $\Delta t > 2\ \tau_E$ [4], where $\rho^*_{Te} = \rho_S/L_{Te}$, τ_E is the L-mode confinement time (typically 20÷30 ms). Most of ITB discharges shown in Fig. 1 exhibit a stationary behaviour: the ITB phase lasts several confinement times and terminates due to lack of RF powers.

In shot 20859 (with RF power during the plasma current ramp-up) the central density is about 0.9 10^{20} m^{-3}, the on axis electron temperature is 11 keV, the ITB phase time duration is 0.25s corresponding to 10 τ_E (Fig.2). Transport analysis and evaluation of the current density profile have been carried out by the JETTO code [5]. The LH power deposition and current drive profiles are calculated by 1-D Fokker-Planck Bonoli code. The ECRH power deposition is calculated by a ray-tracing code. As a result a reduction of the electron thermal diffusivity occurs, more pronounced in the time interval 0.24-0.34sec. A negative magnetic shear configuration is obtained by the modelling. An ITB expansion is observed, which might be correlated to a broadening of the LH power deposition profile. An improvement of the ion confinement is observed in the time range 0.24-0.34 sec (see Fig. 3). The ion thermal diffusivity in FTU can be often modelled by an anomaly factor of the neoclassical diffusivity [6]. The time evolution of the experimental neutron rate and the experimental ion temperature on axis can be modelled, provided a reduction of the anomaly factor of 60% is assumed. A noticeable plasma density peaking is also observed during this ITB phase. The ITB degradation is followed by the onset of MHD m=1, m=2 coupled modes (at t = 0.34 s). As a modelling result, the magnetic surface with q=1 is present in the plasma core consistently to the onset of MHD activity.

Stationary ITBs are obtained by coupling the LH and ECRH power during the current flat top. An example is shown in Fig. 4. The ITB phase ends due the lack of ECRH and LH powers during the discharge. The electron temperature evolution, calculated considering the electron thermal diffusivity given by the Bohm-gyroBohm (BgB) shear dependent model

[7], shows a good agreement with the experimental results. The BgB model, without shear dependent corrections, does not reproduce the Te profile during the ITB phase. Therefore, an important role is played by the low/negative magnetic shear in reducing transport.

The stationary ITBs obtained in FTU at high density and high temperature plasmas are relevant for the advanced scenarios of ITER.

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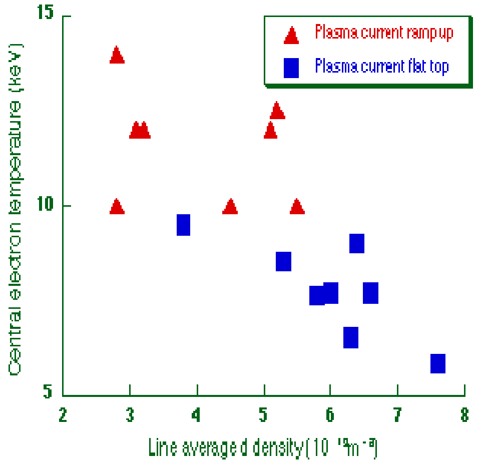

Fig.1

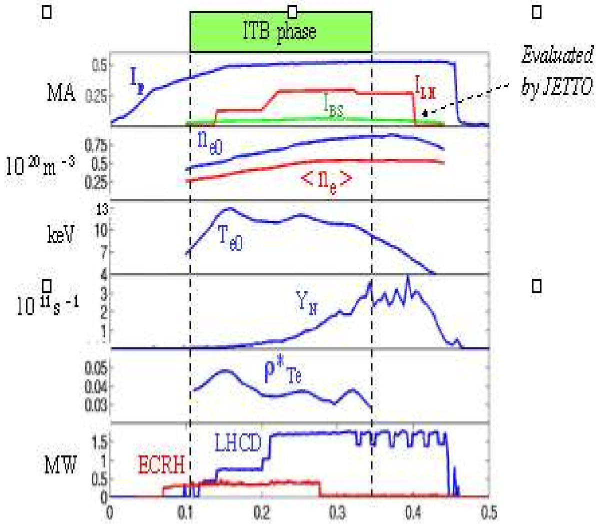

Fig.2

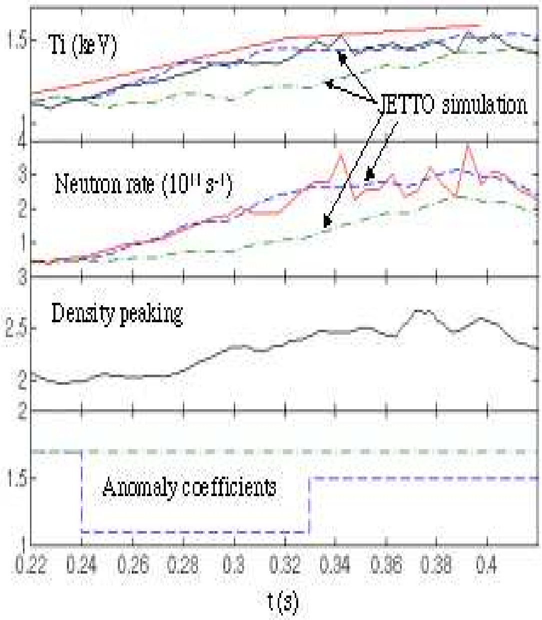

Fig. 3

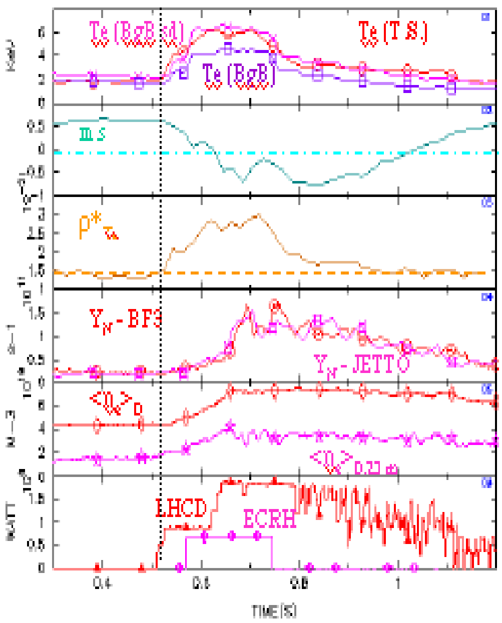

Fig. 4