33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-1.122 (2006)

Modelling of experiments with ITER-relevant q-profile control at high β_N by means of the lower hybrid current drive

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Abstract. Recent works [1,2], including the effect of spectral broadening due to wave physics of the plasma edge, show that non inductive current is efficiently driven in internal transport barrier (ITB) plasmas in JET [1-3], at about two thirds of the minor radius, by lower hybrid current drive (LHCD). Modelling of q and magnetic shear profiles has been used to design ITER-relevant ITB discharges for JET at high β_N ($\approx$2.5). This shows that low/negative shear ($s\approx$-0.1) at normalized radii $\rho \approx 0.71$ and $\rho \approx 0.75$ would be sustained for two seconds by operating with launched $n_{//\mathrm{Peak}}$ =2.3. Results of LHCD modelling relevant to the ITB scenario of ITER [4] are discussed. The current (efficiency, $\eta \approx 0.2\times10^{20}$ MA m^{-2} MW^{-1}) is mostly driven at: *i*) at $r/a \approx 0.80$ by considering moderate LH spectral broadening effects at the edge, *ii*) at $r/a \approx 0.75$ with weaker effects, as would be expected in the case of lower operating electron temperatures in the scrape-off layer (SOL). ITB experiments of FTU at high magnetic field (8T) by means of LHCD performed during the current ramp-up are also considered. Predictive modelling of combined LHCD and electron cyclotron heating (ECH) in extraordinary (X)-mode has been performed to try to find ways to extend the ITB parameter-space.

Internal transport barriers are routinely produced in JET utilising NBI (neutral beam injection, 17 MW) and ICRH (ion-cyclotron resonant heating, 5MW) as the main heating power sources early in the discharge, before the plasma current has fully penetrated. The application of LHCD (2.4 MW) during the plasma current ramp up (prelude phase) and during the edge H-mode allowed producing ITBs with improved performance (at B_T=3.4T and I_P=2.3 MA) [3]. These ITBs were interpreted in terms of low magnetic shear produced by LHCD in the radial region close to the ITB radial foot [1,2]. The LHCD deposition profile was modelled by ray-tracing in toroidal geometry, utilising a two-dimention Fokker-Planck solver and, for achieving the necessary precision, the spectral changes of the refractive index in toroidal direction have been considered, as produced by *both* ray propagation and effect of physics of the edge [1,2]. In the present work, the evolution of the q-profile and the transport analysis have been produced by the JETTO [5] code implemented with the LHCD model. An experiment of JET performed with lower magnetic field (B_T=2.6T and P_{NBI} ≈14 MW) is considered as reference for producing a modelling relevant to ITBs at high β. The LH-driven current density profile is obtained in the prelude phase (t= 3 s), and in the main heating phase (t= 5 s, the non-inductive current fractions result I_{LHCD}/I_P≈0.3, $I_{non\text{-}inductive.}/I_P$≈ 0.5). The LHCD antenna spectrum with peak at $n_{//}$=1.8, utilised in the experiment, and at $n_{//}$=2.3 are considered. As result, see Fig.1, the LH deposition profile is peaked around the middle of the plasma radius in the prelude, and at two thirds of the minor radius in the main heating phase. The more off-axis deposition is obtained by means of the higher $n_{//}$ spectrum. The q-profile evolution has been modeled, see Fig. 2, by inputting the LH deposition profiles in the JETTO code, as well as, according to experimental data, the kinetic profiles, the effective ion charge and the magnetic measurement reconstruction. The code solves the electron and ion energy conservation equation and Faraday equation by assuming neoclassical resistivity. With 2.8 MW of LHCD power continued during the main heating phase, and the $n_{//}$=2.3 spectrum, a low-negative magnetic shear layer results sustained for several seconds at large radii (ρ ≈0.75). This condition might be useful for building radially broad ITBs at high β, for ITER-relevant experiments of JET.

The LHCD (at f_0 =5 GHz) modelling for the ITB (n.4) scenario of ITER [5] has been performed by considering the effect of the physics of the edge, which broadens the $n_{/}$ spectrum launched by the antenna and, consequently, determines the LHCD deposition profile. Such phenomenon is expected to play an important role, especially at the high operating densities of ITER [1,2]. A slab plasma with radial T_e profiles with different parameters are assumed, so that T_e =7 eV, or T_e =15 eV occurs at the antenna mouth, and, 3 cm away: T_e =50 eV, or T_e =100 eV. In these layers, the density profile makes $\omega_{pe}/\omega_0 = 1 - 5$, respectively. With P_{LHCD} =10 MW, about 10% of the power spectrum results broadened at higher $n_{//}$, and ≤ 5% for the high temperature case, as shown in the Fig. 3 (small box). Consequently, the LHCD deposition profile results peaked at r/a ≈0.75 (I_{LHCD}=0.55MA), and at $r/a \approx 0.80$ (I_{LHCD}=0.34MA) for the low temperature case, as shown in Fig.3. For further lower electron temperatures in the SOL, which possibly occur for operations with a higher recycling, the LHCD becomes more and more weaker, and the deposition more and more at the periphery of plasma.

ITB regimes have been considered for FTU plasmas at high magnetic field (8T) and medium plasma current (0.7 MA), performed by the cooperation of LHCD and ECH in X-mode. The LHCD deposition profile is consistent with the FEB measurements in FTU. The q-profile evolution and the transport analysis have been performed for the realistic parameters of the experiment. In the interpretative mode of JETTO, the thermal conductivity profiles are calculated, whereas the plasma density and temperature profiles, the plasma current, the toroidal magnetic field, the effective ion charge, the plasma radiation profiles and the magnetic reconstruction are inputted according to the data of an experiment of FTU, performed without additional RF heating and current drive powers. The T_i profile evolution is modelled assuming neoclassical transport, in which the ion diffusion coefficient is varied according to an anomaly factor in order to reproduce neutron flux. In the predictive mode, the electron and ion temperature profiles are calculated by utilising the transport model Bohm-Gyrobohm shear dependent [6]. The initial profile of plasma current is set with the constraint that the q-profile evolution crosses the q=1 surface at the time of the sawtooth onset observed in the experiments. As result, the predicted evolution of the electron temperature profile is in agreement with the experiment (ohmic power only). The time traces of the main plasma parameters are shown in the Figure 4. The measured evolution of the central electron temperature (Fig. 4c) is compared with JETTO predictive modelling by assuming: *i*) ohmic heating only, *ii*) add LHCD power, *iii*) add LHCD and ECH power. An ITB with central electron temperature of about 8 keV ($\langle n_e \rangle \approx 7\ 10^{19}\ m^{-3}$) is expected to be sustained in FTU by utilising current ramp-up, LHCD and ECH.

The utilised model provides an important tool for interpreting and designing ITER-relevant experiments that require the current profile control by means of LHCD.

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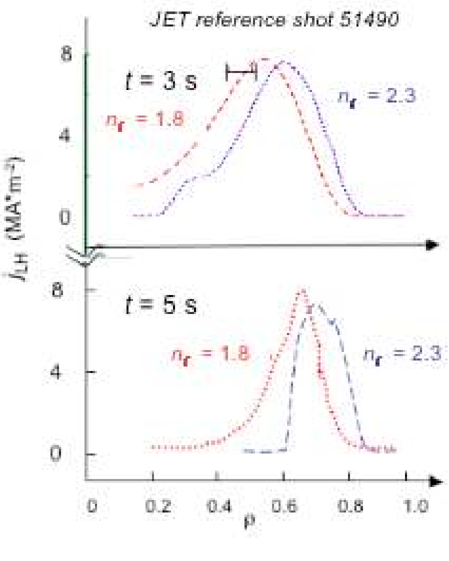

Figure 1 LH-driven current density profile modelled in the prelude and in the main heating phases of an ITB of JET (B_T=2.6T, I_P=2.4MA, P_{LHCD}=2.4 MW). Different antenna phasing are considered, producing spectra with peak at $n_{//}$=1.8 (as utilised in the experiment) and $n_{//}$=2.3.

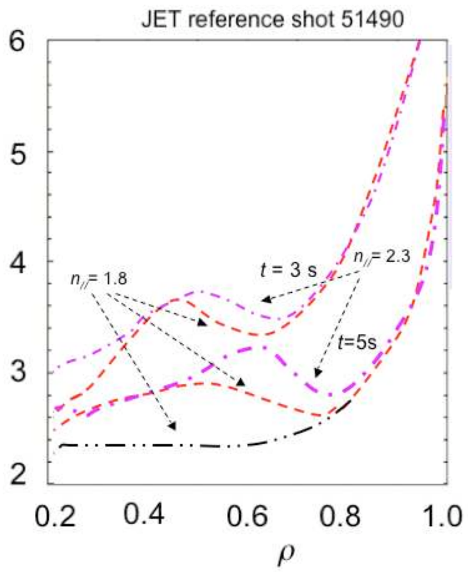

Figure 2. q-profile evolution modelled for the ITB of JET considered in Fig. 1 (P_{LHCD}=2.4 MW). LHCD prelude only ($n_{//}$=1.8): dotted-dotted-dashed/black line, LHCD continued during the main heating phase with $n_{//}$=1.8: dashed/red lines, with $n_{//}$=2.3: dotted-dashed/pink lines.

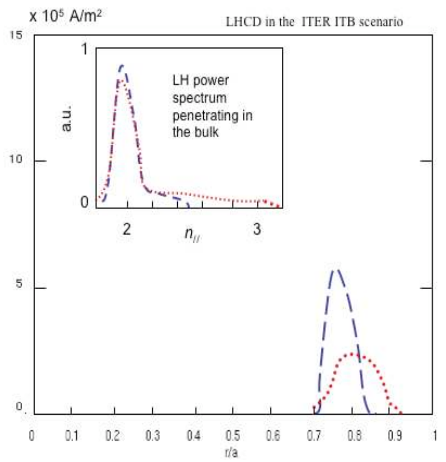

Figure 3. LH driven current density profile for the ITB scenario of ITER. P_{LHCD}=10 MW is assumed. Two different $n_{//}$ spectra are considered as effect of the physics of the edge: operating electron temperature in the middle of the SOL of 100 eV (dashed/blue curves) and 50 eV (dotted/red curves)

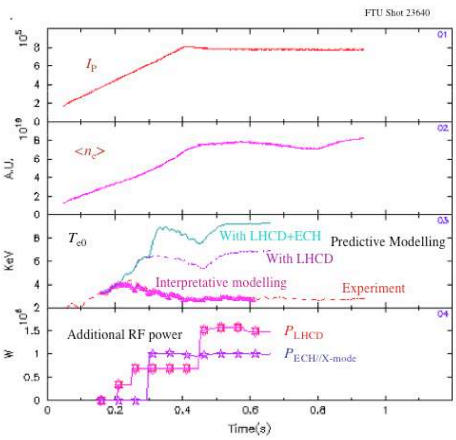

Figure 4. Time evolution of the main parameters of the reference experiment for modelling: plasma current (a), line averaged density (b), central electron temperature by: Thomson scattering (c, dotted-dashed-red line), predictive modelling: with ohmic heating only (dashed-red-line), by adding the LH power of box d (dotted-dashed -pink line), by adding LHCD and ECH power of box d (continuous-light blue line).