EFDA–JET–CP(07)01–15

R. Cesario, C. Castaldo, A. Fonseca, V. Parail, P. Smeulders, M. Beurskens, M. Brix, G. Calabrò, P. De Vries, J. Mailloux, V. Pericoli, G. Ravera, R. Zagorski, and JET EFDA contributors

Lower hybrid current drive in experiments for transport barriers at high β_N of JET (Joint European Torus)

Lower hybrid current drive in experiments for transport barriers at high β_N of JET (Joint European Torus)

R. Cesario[1], C. Castaldo[1], A. Fonseca[2], V. Parail[3], P. Smeulders[1], M. Beurskens[3], M. Brix[3], G. Calabrò[1], P. De Vries[3], J. Mailloux[3], V. Pericoli[1], G. Ravera[1], R. Zagorski[4], and JET EFDA contributors*

[1] Associazione EURATOM/ENEA sulla Fusione Frascati Frascati, Italy
[2] Associação EURATOM/IST Centro de Fusão Nuclear, 1049-001 Lisbon, Portugal
[3] EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK
[4] Institute of Plasma Physics and Laser Microfusion, EURATOM Association Warsaw, Poland
** See annex of M. Watkins et al, "Overview of JET Results ",*
(Proc. 21st IAEA Fusion Energy Conference, Chengdu, China (2006).

Preprint of Paper to be submitted for publication in Proceedings of the
17th Topical Conference on Radio Frequency Power in Plasmas,
(Clearwater, Florida, USA, 7-9th May 2007)

ABSTRACT

LHCD has been used in JET experiments aimed at producing Internal Transport Barriers (ITBs) in highly triangular plasmas ($\delta \approx 0.4$) at high β_N (up to 3) for steady-state application. The LHCD is a potentially valuable tool for (i) modifying the target *q*-profile, which can help avoid deleterious MHD modes and favour the formation of ITBs, and (ii) contributing to the non-inductive current drive required to prolong such plasma regimes. The *q*-profile evolution has been simulated during the current ramp-up phase for such a discharge (B_0=2.3T, I_P=1.5 MA) where 2 MW of LHCD has been coupled. The JETTO code was used taking measured plasma profiles and the LHCD was modeled such that the deposition retains the spectral broadening due to parametric instability at the edge, and performs ray tracing and Fokker-Planck analyses in parallel and consistently at each step of the calculation, for each ray. The results are in agreement with MSE measurements and indicate the importance of the elevated electron temperature due to LHCD, as well as the driven current. During main heating with 18 MW of NBI and 3 MW of ICRH the bootstrap current also becomes large. JETTO modelling suggests that this can reduce the magnetic shear at large radius, potentially affecting the MHD stability and turbulence behaviour in this region. Modelling of the effect of LHCD in this phase of the plasma has allowed the power and antenna spectrum needed to provide noninductive current drive at large radii to be identified.

INTRODUCTION

A crucial issue for the development of steady-state tokamak regimes is the optimization of the *q*-profile evolution to avoid deleterious MHD modes while promoting the formation and sustainment of Internal Transport Barriers (ITBs) that enclose a large fraction of the plasma volume. The latter are favoured by the reduction of magnetic shear, which helps to suppress the effects of turbulent structures that contribute strongly to thermal transport in tokamak plasmas [1-3]. To build current density profiles with a large non-inductive contribution located at large radius, by means of the bootstrap mechanism and lower hybrid current drive (LHCD), is therefore very important: not only for the steady-state operation of a future nuclear fusion reactor based on the tokamak concept, but also for achieving the primary goal of producing high energy content in a large volume of fusion plasmas.

Considering the ITER-relevant conditions for fully non-inductive operation of $q_{edge} \approx 5$ and high triangularity (δ=0.4), experiments have been recently performed on JET aimed at improving the performance in β_N compared with previous ITB experiments performed with higher q_{edge} ($\approx$8) and lower triangularity. These previous discharges exhibited long duration ITBs that were interpreted as the effect of a low magnetic shear produced by LHCD, which was applied during both the current ramp-up and H-mode phases [4-6]. In the recent experiments a toroidal magnetic field B_0=2.3T and plasma current I_P=1.5MA have been utilized, with main heating powers of 17MW of neutral beam injection (NBI) and 4MW of ion cyclotron resonant heating (ICRH). During the plasma current rampup (prelude phase), up to 2MW of LHCD has been injected with the aim of affecting the current relaxation so as to provide an evolution of the q and magnetic shear profiles during the main heating phase which is suitable for ITBs.

• M.L.Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006), IAEA (2006)

Due to the high plasma density at the plasma periphery obtained in the main heating phase at high triangularity, the LHCD wave propagation encounters mode conversion into fast waves (referred as the LH wave inaccessibility condition). The density in this region is roughly a factor two higher than for JET ITB scenarios at low triangularity, and the plasmas have typical parameters: $n_{e0}\approx 4.2\times 10^{19}m^{-3}$; $n_e\approx 3.4\times 10^{19}m^{-3}$ at $R\approx 3.7$m (corresponding to $\rho\approx 0.8$); $R_{separatrix}\approx 3.9$m ($\rho\approx 1.0$). Consequently, the LH deposition profile cannot be assessed in the main heating phase, but only during the prelude. A realistic modelling of the q-profile evolution has been performed for experiments in which different LHCD power waveforms have been used with the aim of identifying the most suitable q-profile evolution for ITB performance. A predictive modelling has been also performed with the same input parameters, but with the LHCD continued during the main heating phase. This modelling indicates that a higher toroidal magnetic field (≈2.6T) would be necessary to achieve LH wave accessibility. In this condition the LH and bootstrap driven currents might cooperate to further improve the q and shear profile evolution (i.e. to produce a low shear at large radius sustained in time). This result is, however, preliminary as the analysis to evaluate the LHCD deposition profile in these regimes with high plasma density in the plasma periphery is still in progress. In particular, care must be taken to retain the effect of the LH spectral broadening in the Scrape-Off Layer (SOL) plasma in conditions that realistically represent the experiment [6-8].

LHCD DEPOSITION AND Q-PROFILE EVOLUTION

The LHCD deposition profile is obtained by a two-dimensional relativistic Fokker-Planck analysis in the LH^{star} code, which retains both the spectral broadening effects due to the non-linear physics of parametric instability at the plasma edge, and the toroidicity in the main plasma [6-8]. Figure 1 shows the LH-driven current density profile at a time point (t=2.5s) in the prelude phase with two different values of $n_{//}$: 1.84, which is routinely used in the JET experiments; and $n_{//}$=2.30, which is also achievable with the JET system but was not used in this particular pulse ($n_{//}$ is the wavenumber corresponding to the direction aligned with the confinement magnetic field). The LHCD deposition peaks respectively at $\rho\approx 0.39$ and $\rho\approx 0.51$ (ρ is the a-dimensional toroidal flux coordinate). With $n_{//}$ = 2.30 the power deposition in the plasma results also less localized than with $n_{//}$ =1.84. In the main heating phase the LH wave propagation encounters the condition of inaccessibility, which correctly leads to the failure of the WKB based ray-tracing model due to the occurrence of the fast wave mode conversion in the plasma. The LH waves are reflected back to the edge, but they might, however, penetrate into the plasma core due to the effect of the ray multi-reflections and toroidicity if the power spectrum at high $n_{//}$ were suitably increased. The available analysis tools cannot, however, determine the LH deposition profile in such conditions. It is considered that a slightly higher toroidal magnetic field (≥2.6T) and $n_{//}$=2.30 would be necessary to allow the LH deposition profile to be determined.

To obtain a realistic *q* and magnetic shear profile evolution in the conditions of the experiment the following approach has been used. The model of neoclassical resistivity (NCLASS) and the Faraday equation contained in the JETTO [9] code are used to determine the current diffusion in the plasma column by taking into account the data provided by experimental measurements, i.e. the kinetic profiles (including the plasma edge), the effective ion charge, the EFIT [10] equilibrium reconstructed using magnetic data, and the LHCD deposition profile calculated with LHstar. The EFIT code also provides the current density profile in the very early phase of discharge (*t*=1s), which is used as the initial condition for the JETTO simulation.

As a test, the modelled *q*-profile evolution is compared in Figure 2 with that provided by EFIT using only magnetic input data and by EFIT constrained by motional Stark effect (MSE) measurements. Agreement with the general trend of the measured *q*-profile evolution is observed. In addition, some local flattening during main heating phase (*t*=6s) at large radii (ρ≈0.8) is observed in the modelled *q*-profile, which indicates the occurrence of a localised region of low magnetic shear. Unfortunately, the EFIT reconstruction method and MSE measurements used to determine the *q*-profile do not allow a precise determination of such a feature localised in this region of the plasma. Figure 3 shows the radial profile during the main heating phase (*t*=6s) of the total plasma current density (frame a), which consists in the contributions: Ohmic, NBI, and bootstrap as displayed in frame b. The magnetic shear profile (Fig. 3 c) indicates the occurrence of a low shear region around ρ≈0.8. The observed shear reduction appears resilient to the uncertainty in the location of the pedestal of the plasma density profile, obtained from the two LIDAR diagnostic systems on JET (Fig. 3 d). In the present analysis we have overestimated this uncertainty, which is of order 5cm in major radius and is due mainly to uncertainties in the EFIT reconstruction. The reduction of the magnetic shear at large radius is due to a local peak of the bootstrap current density profile caused by the relatively high plasma densities and temperatures, with broad profiles, obtained in the experiment. Consistent with the expected effect of the low shear, a reduction of the electrostatic turbulence level has been observed by microwave reflectometry of the periphery (at ρ≈0.8) during the main heating phase, which is also accompanied by a quasiquiescent magnetohydrodinamic (MHD) activity during the whole main heating phase.

A preliminary analysis has been performed in a similar way for more recent experiments performed in the same conditions but without LHCD and with higher NBI power (≈21 MW). It indicates that low magnetic shear is again produced at large radius (ρ≈0.8) for three seconds (roughly half of the duration of the main heating phase) due to the effect of the local dominant contribution of the bootstrap current. During this phase turbulence stabilization and quasi-quiescent MHD have been also observed coinciding with a reduction of about a factor five in the electron thermal conductivity over most of the radial region, as found by transport analysis.

Simulations have also been performed in the conditions of these latter experiments, but assuming artificially the addition of LHCD (with $n_{// peak}$=2.3 and B_T=2.6 T for accessibility) in both the prelude and the main heating phases. The time evolution of the different components of plasma current is shown in Figure 4. The modelling indicates that a broader q-profile is prepared as a target for the main heating phase if the LHCD is switched-off in prelude phase (about 0.2s before the main heating) rather than continued up to the beginning of the main heating phase. This operation could be useful for two reasons: to slow the current diffusion from the plasma periphery due to the core LHCD; and prevent the formation of a core ITB due to the extreme magnetic shear reversal possible using during the LHCD prelude. Such ITBs at small plasma radius are not useful for producing either high fusion plasma performance or bootstrap current drive in the plasma periphery, as discussed in the introduction. In the main heating phase, the LHCD could be added to the bootstrap current to produce low magnetic shear at large radius, provided that the edge conditions would not inhibit the LH propagation into the bulk in these regimes with high density at the periphery [6-8]. Further data analysis of the SOL is in progress to determine the LH spectral broadening in this important region.

The present work highlights the important role of the lower hybrid current drive for the design of ITER relevant ITBs at high β_N by non-inductive currents driven at large radius.

LH-driven current density proifle obtained by the Lhstar code [R. Cesario, et al., Phys. Rev. Letters, **92** 17 (2004) 175002, R. Cesario, et al., Nucl. Fusion 46 (2006) 462-476] considering the recent parameters of the recent ITB experiments of JET. Two n// antenna spectra with peaks at 1.84 and 2.30 has been utilised. Operatine frequency: 3.7 GHz, power: 2 MW.

REFERENCES

[1]. F Romanelli, Zonca, Phy Fluids B 5 4041 1993
[2]. Beklemishev, Horton . Phy Fl B 4 2176 1992
[3]. Zonca, White, L. Chen, BAPS 48, No 7, 330 (2003)
[4]. Mailloux, et al., Phys. of Plasmas, **9**,5, (2002) 2156
[5]. Crisanti, et al., Phys. Rev. Lett., **88** (2002) 145004
[6]. R. Cesario, et al., Phys. Rev. Letters, **92** 17 (2004) 175002
[7]. R. Cesario, et al., invited presentation at the Topical Conference RF power in plasmas, Park City, Utah, USA 2005
[8]. R. Cesario, et al., Nucl. Fusion 46 (2006) 462-476
[9]. G. Cenacchi, A. Taroni, in Proc. 8th Computational Physics, Computing in Plasma Physics, Eibsee 1986, (EPS 1986), Vol. 10D, 57
[10]. K. Ida, Plasma Phys. Control. Fusion 40 (1998) 1492

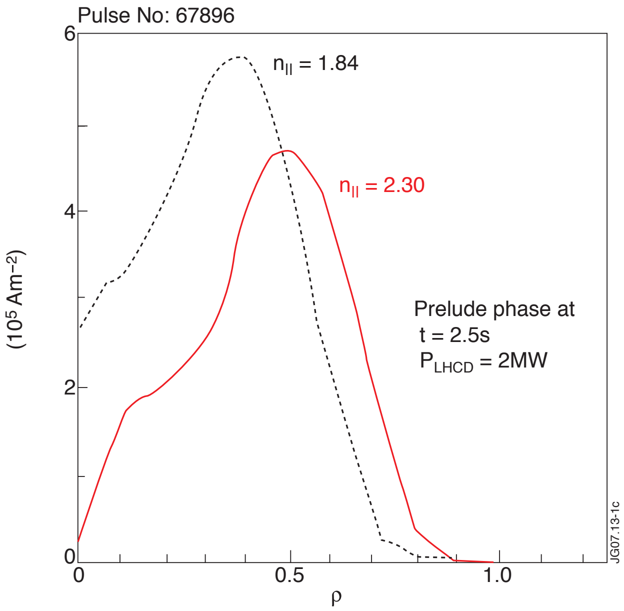

FIGURE 1. LH-driven current density profile obtained by the LH[star] code [R. Cesario, et al., Phys. Rev. Letters, **92** *17 (2004) 175002, R. Cesario, et al., Nucl. Fusion 46 (2006) 462-476] considering the recent parameters of the recent ITB experiments of JET. Two $n_{//}$ antenna spectra with peaks at 1.84 (utilized in the experiment) and 2.30 have been considered in the prelude phase (at t = 2.5s). Operating frequency: 3.7 GHz, power: 2 MW.*

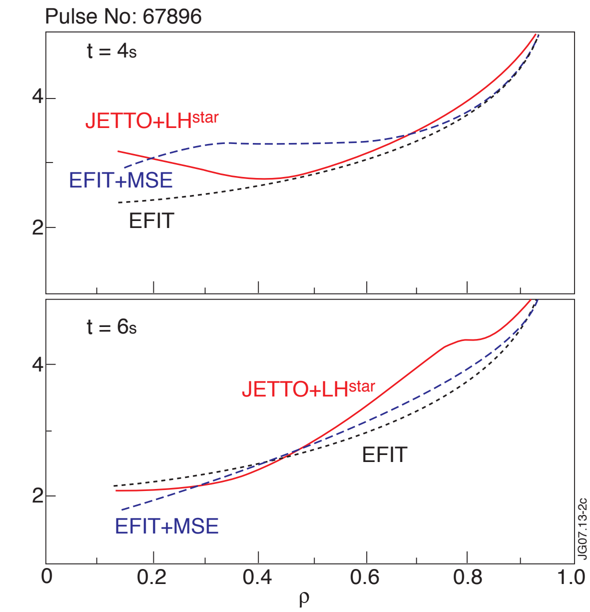

FIGURE 2. Evolution of the q-profile obtained by the JETTO code utilizing by inputs the kinetic, equilibrium and input power parameters utilized in the experiment. Two time points at the beginning (t = 4 s) and in the middle (t = 6 s) of the main heating phase have been considered for making comparison with the available data of EFIT and EFIT+MSE.

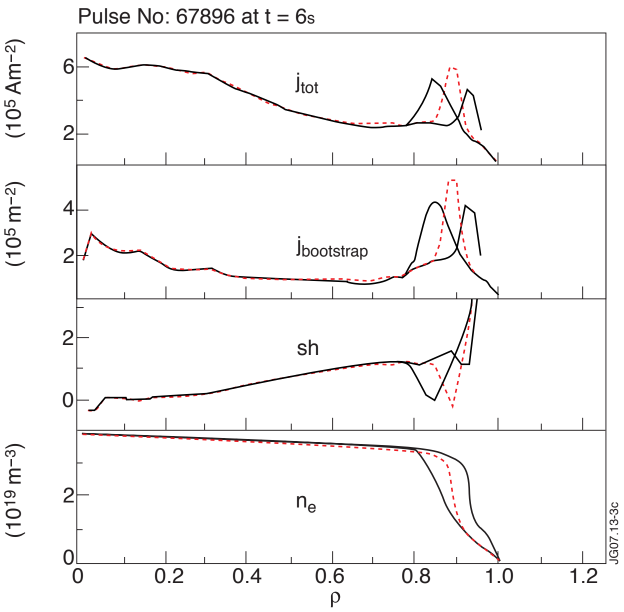

FIGURE 3. Modeling at time point (t = 6 s) of the main heating phase of the profiles of: plasma current density (a), bootstrap current density (b) and magnetic shear (c), considering the measurements uncertainties in the inputted plasma density profile (d).

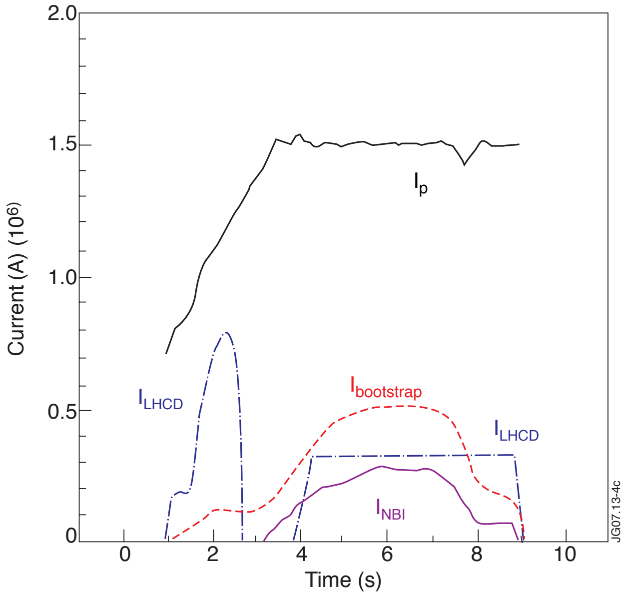

FIGURE 4. Predictive modeling of the time evolution of the different components of the plasma current considering the same parameters of the performed experiments, but with a higher toroidal magnetic field (2.6T) and 2 MW of LHCD with $n_{//}$=2.30 performed in combination with the main heating powers.