LH Current Drive at ITER Relevant Condition in FTU Tokamak

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Abstract. Full non-inductive current drive has been obtained on FTU at plasma densities and toroidal fields close to those expected for ITER. This paper extends the previous LHCD database for FTU to cleaner plasma conditions obtained after boronization of the first wall. With an LH power of 1.8 MW, a current of 0.5MA has been fully driven at line averaged densities up to $0.8\cdot10^{20}$ m^{-3}. These discharges show an increase of the electron temperature up to 5 keV and a complete stabilization of the sawteeth activity. The current drive (CD) efficiency (η_{CD}) is close to $0.30\cdot10^{20}$ $W\cdot A^{-1}\cdot m^{-2}$. An $N_{||}$ scan is reported with a complete transport analysis. The favourable behavior of faster power spectra is evidenced on both the electron thermal diffusivity and η_{CD}. A comparison of the electron energy confinement time with the ITER97L-Thermal scaling exhibits a substantial agreement or even an improvement during the LHCD phase. The update of the FTU LHCD database confirms the favourable dependence of η_{CD} with the volume averaged electron temperature.

1.Introduction

In burning experiments such as ITER, non-inductive CD will be necessary in order to achieve several tasks, in particular proper shaping of the current profile for the advanced or steady state scenarios and stabilization of MHD activity [1,2,3,4]. At present, most LHCD tokamak experiments are limited to line averaged density (n_e) and toroidal field (B_t) far from those foreseen for ITER ($1\cdot10^{20}$ m^{-3}, 5.3 T). In this sense the FTU tokamak remains a favourite experiment for its high density (up to $3.0\cdot10^{20}$ m^{-3}), toroidal field (up to 8 T) and the LH frequency (8 GHz) chosen to cope with high-density regimes. In particular the latest FTU experiments exploit the CD scenario in the range of B_t from 5 to 7 T and n_e from 0.8 to $1.2\cdot10^{20}$ m^{-3}, contributing to the completion of the LHCD international database.

This work reports the results concerning the improved LHCD efficiency (η_{CD}) at high density achieved in the latest experiments and the analysis of LH power deposition and energy transport for an $N_{||}$ (parallel index of refraction) scan experiment. The improved η_{CD}, respect to the past, has been obtained in optimised cleaning conditions of the vacuum vessel after the application of boron implantation procedure. This relieves any inherent uncertainty to the correction of η_{CD} by the impurity concentration. The $N_{||}$ scan (even if to be completed) certainly shows higher CD efficiency and heating for the faster spectra. The analysis points out the role played by the localisation of the power deposition profile and suggests the parameters for the design of an LH system for ITER.

2. Experimental Setup

FTU is a circular tokamak (R_0 = 0.935 m, a = 0.30 m) operating at plasma current (I_p) in the range 0.35 - 1.6 MA. The additional heating consists of three different RF systems: Lower Hybrid Wave, Electron Cyclotron Wave and Ion Bernstein Wave. The LH system is based on 6 gyrotrons (8 GHz, 1 MW, 1 s) connected with the tokamak hall with 40 m of circular waveguide, transmitting TE01 mode. The power is then distributed through two distinct phase controlled launchers capable each to couple up to 1.2 MW to the plasma. The system routinely delivers 2.0 MW, corresponding to a net power density of 6.2 kW/cm^2

at the wave-guides mouth. In optimised coupling conditions, the global reflection coefficient is in the range of 8÷15%.

3. Full Current Drive Experiments

FTU has extended the database for full CD to the domain $0.5 < n_e < 0.8 \cdot 10^{20}\ m^{-3}$ and $0.35 < I_p < 0.5$ MA. *FIG.1* reports the temporal evolution of major plasma parameters for a full CD shot at high n_e ($0.75 \cdot 10^{20}\ m^{-3}$). The power available in this experiment was 1.8 MW, launched at $N_{||} = 1.52$, with $B_t = 7.2$ T and $I_p = 0.5$ MA. An increase from 2 to 6 keV of central electron temperature (T_e) was observed, together with a full suppression of sawtooth activity. The neutron yield increases by a factor 6 corresponding to an ion temperature increase of 0.25 keV through electron-ion collisions. The averaged Z_{eff} is 1.6 during the ohmic phase against a figure of 2.7 during LHCD. The resulting η_{CD} is equal to $0.23 \cdot 10^{20}$ $W \cdot A^{-1} \cdot m^{-2}$ and taking in account the Z_{eff} correction [5] reaches the value of $0.28 \cdot 10^{20}$ $W \cdot A^{-1} \cdot m^{-2}$, a value higher than previous experiments at lower density and in poorer plasma cleaning conditions [6,7]. In this computation, for the following and for the FTU database, the contribution of the bootstrap current has not been taken into account; in the extreme case the over-estimation of η_{CD} is below 15%.

4. Partial Current Drive Experiments

For experiments with higher density, up to $1.2 \cdot 10^{20}\ m^{-3}$, the obtained LHCD fraction of I_p is up to 75%, depending on the launched power. For the reference shot presented in *FIG.2*, the I_{CD} was 60% of the plasma current, with $n_e = 1.1 \cdot 10^{20}$ and I_p, B_t, $N_{||}$ being the same of the full CD experiment. The coupled LH power was 1.5 MW and η_{CD} is $0.18 \cdot 10^{20}$ $W \cdot A^{-1} \cdot m^{-2}$, Z_{eff} is 1.3 leading to a negligible correction. The sawtooth period increases from 5 to 24 ms. The lower T_e explains the degradation in the efficiency, compared to the full CD discharge. The lack of power and the resulting lack of a well-developed high-energy electron tails must be taken in account. A large neutron increase is observed (factor of 5) which corresponds to an ion temperature variation of 0.2 keV. Taking into account the low T_e increase (0.9 keV) compared to the full CD experiments, this implies that also in this case the collisionality leads to a significant transfer of energy from electron to ion.

5. $N_{||}$ Scan

As a completion of the LHCD study in high-density regimes, an $N_{||}$ scan has been performed. At the same density ($0.9 \cdot 10^{20}\ m^{-3}$), plasma current (0.5 MA) and magnetic field (7.2 T), 1.2 MW of LH power was injected with 3 different $N_{||}$ (1.52, 1.82, 2.46). The relative increases of T_e between the ohmic and the LH phase are 1.3, 1.4, 0.85 keV respectively. Correspondingly Z_{eff} always increases from 1.1 to 1.6. The two lower $N_{||}$ exhibit the same η_{CD} ($0.23 \cdot 10^{20}\ W \cdot A^{-1} \cdot m^{-2}$) even if the 1.52 case shows an accessibility only of 80%. The higher $N_{||}$ has a lower η_{CD} ($0.14 \cdot 10^{20}\ W \cdot A^{-1} \cdot m^{-2}$). These figures are computed once the current density profile is well diffused. The analysis of the deposition profile, calculated independently using a Bonoli-like code (actually an old version of the code still running in the laboratory) and the FRTC (Fast Ray Tracing Code), shows that in the $N_{||}=2.46$ case most of the power is deposited in a region within $r/a \leq 0.3$ while in the lower $N_{||}$ cases this region is within $r/a \leq 0.2$ (*FIG. 3*).

6. Transport Analysis and Data Base

A complete transport analysis has been carried out on the present experiments. Two codes have been used: the ASTRA code connected to the FRTC module and the JETTO code which makes use of the LH deposition profile computed by the Bonoli-like code. Although the physics underlying both codes is the same, the analysis has been done in order to increase the confidence in the final results.

The full current drive discharge shows a narrow deposition profile well inside r/a = 0.2 (*FIG. 4*). The transport analysis shows an improvement of the energy confinement time with respect to ITER97L-Thermal of 1.5 for ASTRA and 1.4 for JETTO. The ASTRA-FRTC code computes an LH absorbed power of 80%, whereas JETTO assumes 100%.

As far as the $N_{||}$ scan experiments are concerned the ASTRA code shows a lower thermal diffusivity for the 1.52 and 1.83 $N_{||}$ cases compared to the $N_{||}$=2.46 case (*FIG. 5*). No sign of ITB formation has been detected in all experiments. The energy confinement times compared to the ITER97L-Thermal scaling do not deteriorate and even improve during the LHCD phase (*FIG. 6*).

Finally, all the data presented in this work have been added to the FTU database concerning the efficiency of current drive. The improvement of η_{CD} obtained in the latest results is clearly observed in the plot of *FIG. 7* and is certainly due to the better cleanliness conditions of the vacuum vessel after the application of the boron implantation procedure. This has permitted to obtain full CD at higher I_p and higher densities. Indeed, the recent data are more reliable than the past as part of the old dataset was computed extrapolating from partial CD conditions and was obtained at higher Z_{eff} values. The latest results confirm the linear growing trend of η_{CD} versus the volume averaged temperature ($\langle T_e \rangle$) and extend the efficiency up to $0.30 \cdot 10^{20}$ $W \cdot A^{-1} \cdot m^{-2}$. The $\langle T_e \rangle$ appears to be the main ordering parameters together with an increasing trend with faster $N_{||}$ spectrum. It has to point out that the present results have been obtained at B_t of 7.2 T whereas most of the previous database was collected at 6 T for which the accessibility is lower.

7. Conclusions

The FTU experiments have shown the capability of driving current by LH waves with high efficiency in plasma conditions relevant for ITER. Full current drive has been obtained at $n_e = 0.8 \cdot 10^{20}$ m^{-3}, I_p = 0.5 MA and B_t = 7.2 T reaching an efficiency of $0.3 \cdot 10^{20}$ $W \cdot A^{-1} \cdot m^{-2}$ at T_e = 5 keV. A clean vacuum vessel, obtained by Boron implantation procedure, has been crucial to obtain this result. The $N_{||}$ scan points out a favourable dependence of the η_{CD} for the faster spectra. The energy confinement times scales as the ITER97L-Thermal during the ohmic phase and is above it (up to a factor 1.5) during the LHCD phase. The extension of the FTU η_{CD} database confirms a linear dependence on the $\langle T_e \rangle$ in the limit of the densities investigated. These results provide important information for the design of LHCD systems for ITER and any future experiments.

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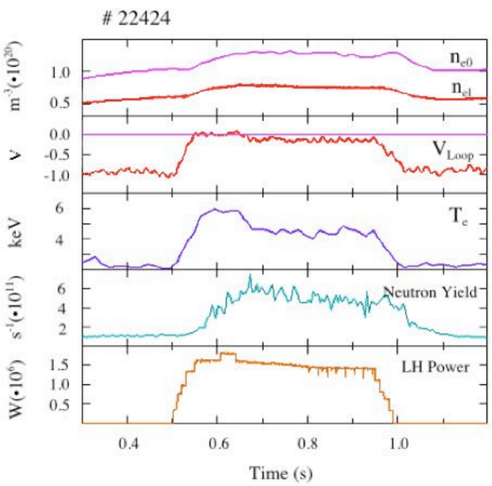

FIG. 1. Discharge #22424, full CD at I_p= 0.5MA, B_t= 7.2T. Temporal evolution of peak and line averaged density, loop voltage, electron temperature, fusion neutron yield and LH power.

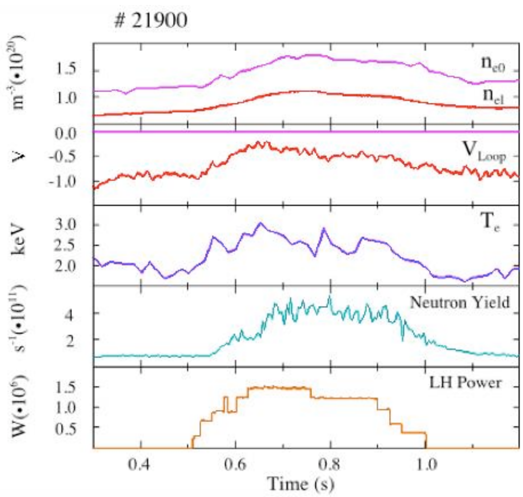

FIG. 2. Discharge #21900, partial CD at I_p= 0.5MA, B_t= 7.2T. Temporal evolution of peak and line averaged density, loop voltage, electron temperature, fusion neutron yield and LH power.

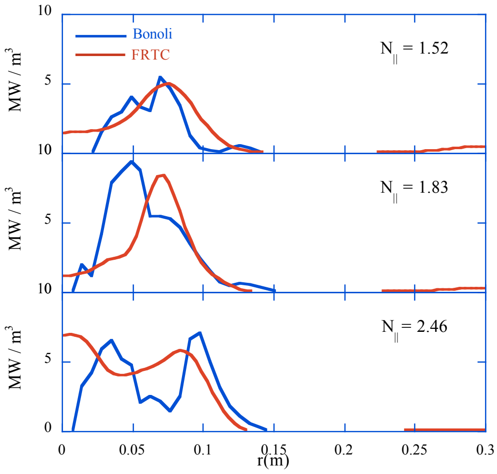

FIG. 3. Discharges #22071, 22066, 22077, $N_{||}$ scan at I_p= 0.5MA, B_t= 7.2T. Comparison of the LH power deposition profile at different $N_{||}$. The two curves refer to the FRTC (red) and the Bonoli-like code computation (blue).

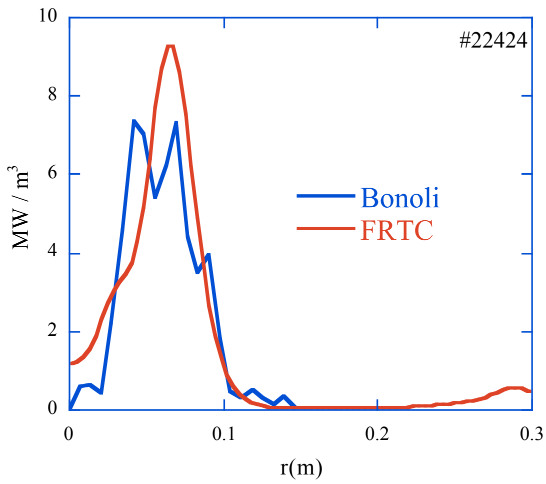

FIG. 4. Discharge #22424, I_p= 0.5MA, B_t= 7.2T, $N_{||}$= 1.52. Deposition profiles. The two curves refer to the FRTC (red) and the Bonoli-like code computation (blue).

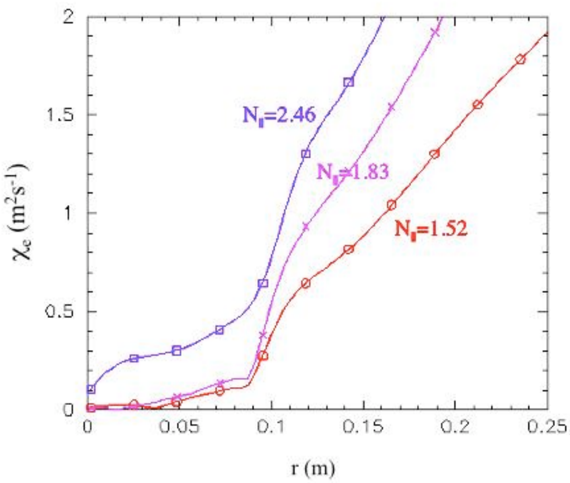

FIG. 5. Comparison of the electron thermal conductivity for the three different $N_{||}$ cases during the LH phase (ASTRA evaluation).

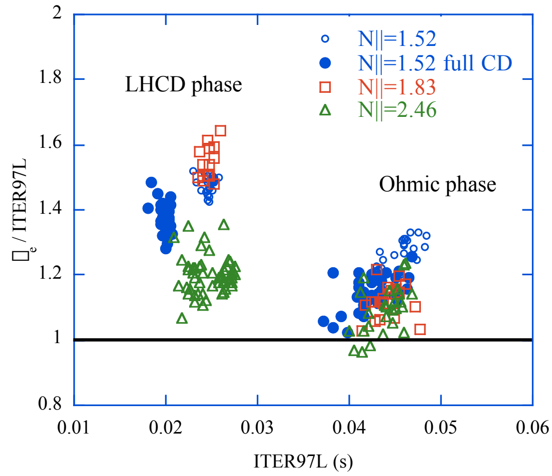

FIG. 6. Energy confinement time compared to the ITER97L-Thermal scaling. The points, for each $N_{||}$, show the confinement times from a single discharge in stationary conditions (JETTO evaluation).

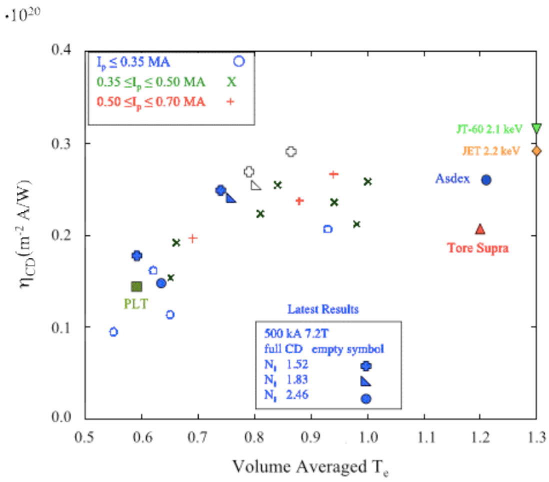

FIG.7. FTU database of current drive efficiency versus the volume averaged electron temperature.