

## High Plasma Density Lower-Hybrid Current Drive in the FTU Tokamak

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Studies on the current-drive (CD) efficiency have been carried out in the FTU tokamak with 8 GHz lower-hybrid waves up to line-averaged plasma density  $\bar{n}_e > 1 \times 10^{20} \text{ m}^{-3}$ . High efficiencies, larger than  $0.2 \times 10^{20} \text{ m}^{-2} \text{ A/W}$ , are obtained for clean plasma conditions, with no significant degradation as the density is increased up to the accessibility limit. The electron temperature affects favorably the CD efficiency. Impurity influx never limits the machine operations up to the maximum coupled power of 1.7 MW. [S0031-9007(98)07877-6]

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The generation of toroidal current in tokamak plasmas with lower hybrid (LH) radio frequency waves is one of the best tools for controlling the current profile shape to attain advanced plasma scenarios in a fusion reactor. The achievement of a large efficiency is of primary importance since it determines the amount of the required power, and hence it has a great impact on the project of a reactor.

The Frascati Tokamak Upgrade (FTU) has been devoted to providing detailed experimental information on this issue, and in particular on the behavior of the LH current drive (LHCD) efficiency in the plasma density regimes foreseen for ITER [1] (line averaged density  $\bar{n}_e \approx 1 \times 10^{20} \text{ m}^{-3}$ ). The CD efficiency is defined as  $\eta_{\text{CD}} = I_{\text{LH}} \bar{n}_e R / P_{\text{LH}}$  [ $10^{20} \text{ m}^{-2} \text{ A/W}$ ], where  $I_{\text{LH}}$  is the LH driven current and  $R$  is the tokamak major radius. In the following the units of  $\eta_{\text{CD}}$  will be understood. At such high plasma densities only Alcator C [2] studied LHCD until now. A rather low efficiency was quoted,  $\eta_{\text{CD}} \approx 0.12$  for toroidal magnetic field  $B_T = 10 \text{ T}$ , as compared with that achieved at much lower densities on the largest tokamaks, as JET [3] or JT-60 [4], where  $\eta_{\text{CD}} \approx 0.3$  at  $\bar{n}_e \leq 0.2 \times 10^{20} \text{ m}^{-3}$ . The results obtained on FTU,  $\eta_{\text{CD}} \approx 0.2$  at density and magnetic fields close to those of Alcator C, show that the origin of such a difference can be traced back to the favorable scaling of  $\eta_{\text{CD}}$  with  $\langle T_e \rangle$ , the volume averaged electron plasma temperature. Indeed, the main difference between FTU and Alcator C experiment is that considerably higher  $T_e$  values are obtained in FTU, peak values  $T_{e0} > 2.0 \text{ keV}$  against  $T_{e0} \approx 0.6 \text{ keV}$ , according to what is deduced from Refs. [2,5].

The FTU experiment is particularly suited for the high plasma density, since the high  $B_T$ , up to 7.1 T, and the

high LH frequency,  $f_0 = 8 \text{ GHz}$ , allow us to minimize the negative effects on the CD efficiency found previously in these regimes [6,7].

In this Letter we present the LHCD efficiency studies performed on FTU in the following ranges:  $0.3 \leq \bar{n}_e \leq 1.15 \times 10^{20} \text{ m}^{-3}$ ,  $0.2 \leq P_{\text{LH}} \leq 1.1 \text{ MW}$ ,  $0.22 \leq I_p \leq 0.7 \text{ MA}$ ,  $4 \leq B_T \leq 7.1 \text{ T}$ . Four different phasings of the LH launching grill have been tested, namely  $65^\circ$ ,  $75^\circ$ ,  $90^\circ$ , and  $120^\circ$ . The peak values of the launched  $N_{\parallel}$  spectrum ( $N_{\parallel}$  is the index of refraction parallel to  $B_T$ ) are  $N_{\parallel 0} = 1.32, 1.52, 1.82, 2.43$ , respectively. No operational limit was met so far due to impurity influx: LH pulses with a transmitted power density at the grill mouth larger than  $10 \text{ kW/cm}^2$  and longer than 0.7 s are routinely and safely run, even at the highest  $P_{\text{LH}}$  up to now achieved, i.e.,  $P_{\text{LH}} = 1.7 \text{ MW}$ . The value of the effective ion charge  $Z_{\text{eff}}$  during the LH phase is similar to the Ohmic (OH) value at  $\bar{n}_e > 1 \times 10^{20} \text{ m}^{-3}$  ( $Z_{\text{eff}} \leq 1.3$ ), whereas for  $\bar{n}_e \leq 0.5 \times 10^{20} \text{ m}^{-3}$  it increases typically from nearly 2 to about 3. This large increase at low density is normal on a machine with entirely metallic walls [8] upon an increase of the total input power from approximately 0.45 MW to more than 0.9 MW.

The limited LH power routinely available so far has allowed us to achieve a full CD phase only for  $\bar{n}_e \leq 0.5 \times 10^{20} \text{ m}^{-3}$ : a relevant example of the time evolution of the main plasma quantities is given in Fig. 1. The LH power sustains steadily the plasma current longer than 0.5 s (the estimated inductive time scale  $\tau_{\text{L/R}}$  is  $\leq 0.4 \text{ s}$ ) at  $\bar{n}_e = 0.45 \times 10^{20} \text{ m}^{-3}$ , central density  $n_{e0} = 0.7 \times 10^{20} \text{ m}^{-3}$ , and produces  $T_{e0} \geq 4 \text{ keV}$ , upon stabilization of the sawtooth activity. For higher density only partial CD is

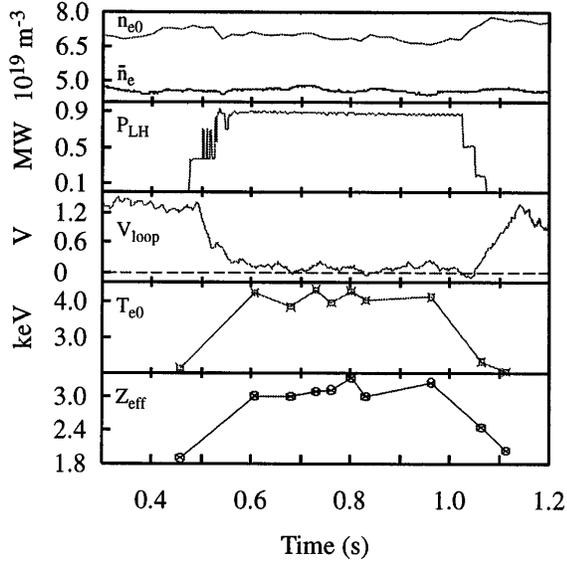


FIG. 1. Temporal evolution of the main plasma quantities during a full CD phase at low density.

obtained:  $\bar{n}_e = 0.9 \times 10^{20} \text{ m}^{-3}$  ( $n_{e0} = 1.2 \times 10^{20} \text{ m}^{-3}$ ) a drop up to 50% of the loop voltage  $V_1$  with  $T_{e0} > 2 \text{ keV}$  has been achieved. Nevertheless, even in partial CD regimes we can evaluate  $\eta_{CD}$  quite reliably, more than in other tokamaks, because in FTU the effect of the residual electric field on the suprathermal electron tail is small, within the experimental errors. Indeed, the efficiency for a clean plasma  $\eta_{CD}$  can be inferred from the linear law, derived from the definition of the CD efficiency:

$$\frac{I_{LH}}{I_p} = h \eta_{CD} (Z_{\text{eff}} = 1). \quad (1)$$

The quantity  $h = \frac{P_{LH}}{\bar{n}_e I_p R} \frac{6}{Z_{\text{eff}}^{+5}} \left[ \frac{W}{A \times 10^{20} \text{ m}^{-2}} \right]$  includes the effect of the impurities on the CD [9] and can be easily measured. The right evaluation of the ratio  $I_{LH}/I_p$  may not be easy, but in FTU it is within the experimental uncertainties, as shown by the good linearity of the data presented in Fig. 2, where  $I_{LH}/I_p$  is plotted versus the parameter  $h$  (see, in particular, those referring to a fixed density). The error estimated for  $\eta_{CD}$  is close to 20%. Only quasisteady states are considered, where the internal inductive effects are negligible and the electric field is almost radially uniform. We calculated  $I_{LH}/I_p$  from the change in the LH phase of the loop voltage and of the bulk conductivity  $\sigma$ , which is simply proportional to the volume average  $\langle T_e^{3/2} \rangle$  and inversely to  $Z_{\text{eff}}$ , but we neglected the effect of the residual electric field on the fast electron tail, i.e.,

$$\frac{I_{LH}}{I_p} = 1 - \frac{V_{1,LH} \langle T_{e,LH}^{3/2} \rangle Z_{\text{eff,OH}}}{V_{1,OH} \langle T_{e,OH}^{3/2} \rangle Z_{\text{eff,LH}}}. \quad (2)$$

Not considering the effect of the electric field on the hot electron tail can indeed lead to overestimate  $I_{LH}$  [10], but the FTU data themselves show that this error

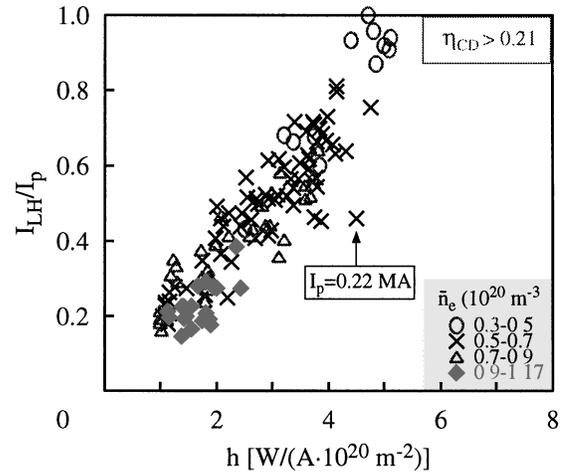


FIG. 2. Plot of the ratio of the LH driven current to the total current versus the quantity  $h$  defined in the text. Different symbols refer to different densities (see legend). Note how a fraction of about 50% has been driven at  $\bar{n}_e \approx 0.9 \times 10^{20} \text{ m}^{-3}$  and how the points at high density are indistinguishable from the low density ones.

is smaller than the experimental one, except for cases not considered here of low density and low LH power. This view is further supported by theoretical estimates of the hot electron contribution to  $\eta_{CD}$  in FTU, made from just the experimental data, following Ref. [10], and from the evaluation of the collision operator according to simple 1D models. The only preliminary data on hard x-ray fluxes, available on FTU, support the choice of these models, giving a fast electron slowing down time in agreement with the Asdex density scaling [11].

Therefore we are confident that the linear extrapolation to  $I_{LH}/I_p = 1$  yields the correct value for  $\eta_{CD}$ ,  $\eta_{CD} \approx 0.22$  in full CD operation. Within the accuracy of the measurements no deviation from linearity turns out on the basis of the density. In addition, it must be pointed out that the correction for  $Z_{\text{eff}}$  is quite negligible at high densities, where  $Z_{\text{eff}} \approx 1$ .

In Fig. 2 only  $N_{||0} = 1.52$  and  $1.82$  have been considered and all the data with low accessibility have been discarded in order to have a homogeneous database. As a measure of the degree of accessibility we consider in this paper the quantity  $D_{N||} = N_{||\text{cr}} - N_{||0}$ .  $N_{||\text{cr}}$  is approximately  $\propto n_e^{0.5}/B_T$ , and it is evaluated here using the line averaged density. For the data of Fig. 2 we imposed  $D_{N||} \leq 0.05$ , because for larger values the LH ray penetration at first pass inside about  $\frac{2}{3}$  of the FTU minor radius becomes very marginal. So we excluded all the points with  $B_T = 4 \text{ T}$ , which have  $D_{N||} > 0.2$ .

In Fig. 3 instead, the effect of the accessibility is pointed out by plotting all the  $\eta_{CD}$  data versus  $D_{N||}$ .

Regarding shots at  $\bar{n}_e \approx 1 \times 10^{20} \text{ m}^{-3}$ , the group of points with  $N_{||0} = 1.82$ , together with those with  $N_{||0} = 1.52$  and  $B_T = 7.1 \text{ T}$ , have a good degree of accessibility

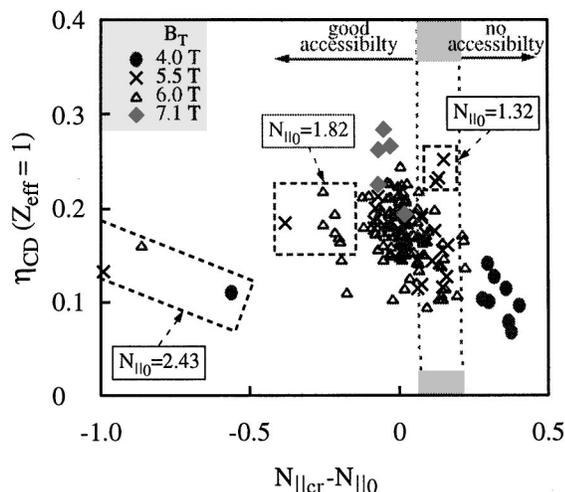


FIG. 3. Plot of the estimated CD efficiency versus the accessibility parameter  $D_{N||}$  (see text). For  $D_{N||} > 0.05$  the ray penetration becomes marginal. Different symbols refer to different magnetic fields  $B_T$ .  $N_{||0} = 1.52$ , unless otherwise specified.

( $D_{N||} \approx -0.2$  and  $\approx 0$ , respectively) and exhibit  $\eta_{CD} \approx 0.2$ . Instead, the group with  $N_{||0} = 1.52$  and  $B_T = 6$  T, has a marginal accessibility ( $D_{N||} \approx 0.14$ ). Consequently, the CD efficiency shows values spread down to less than 0.1. Here the details of the radial profiles strongly affect the penetration of the LH waves inside the plasma and the CD effects show a great variability from shot to shot and an irregular behavior even during a single LH pulse.

In the highly inaccessible region  $D_{N||} > 0.2$ , the points with  $B_T = 4$  T and  $N_{||0} = 1.52$ , show a marked drop of  $\eta_{CD}$ , despite the rather low density,  $\bar{n}_e \approx (0.6-0.7) \times 10^{20} \text{ m}^{-3}$ . This behavior agrees with the observations made on JET [6], where the absorbed LH power fraction strongly decreases as the LH accessibility conditions are no more satisfied.

The highest points at  $B_T = 7.1$  T ( $\bar{n}_e \approx 0.7 \times 10^{20} \text{ m}^{-3}$ ,  $I_p = 0.7$  MA) may be overestimated by 15% respect to the other points, because for them the weight of the hot conductivity is heavier.

Finally, the comparison between different launched spectra shows how the CD efficiency gets smaller as the  $N_{||0}$  is increased, i.e., the LH waves become slower. This could be seen selecting the data with  $B_T = 5.5$  T in Fig. 3, and joining with a line the uppermost points of each  $N_{||0}$  group (for them  $\bar{n}_e \approx 0.55 \times 10^{20} \text{ m}^{-3}$ ). The effect is smaller than that observed on Asdex [12] or PLT [13], where a dependence approximately like  $1/N_{||0}^2$  is found, but larger than found in JET, where negligible changes are observed upon varying the launched  $N_{||}$  spectrum [14].

We stress that the data of Fig. 3 show no clear trend with  $\bar{n}_e$ , inside each fixed  $B_T$  group, whereas they show an increase of  $\eta_{CD}$  with  $\langle T_e \rangle$ , above the experimental un-

certainties. This is evidenced in Fig. 4 where the FTU  $\eta_{CD}$  data, selected as the average at four values of  $\langle T_e \rangle$  inside the spanned range 0.36–0.92 keV, are compared with those from other tokamaks [10,12,13,15,16] extrapolated to clean plasma conditions ( $Z_{\text{eff}} = 1$ ). The largest  $\langle T_e \rangle$  interval available in the literature is examined, from the coldest (HT-6B [16]) to the hottest (JET [3]) device. Except for Alcator C for which  $\eta_{CD}$  is taken at  $\bar{n}_e \approx 1 \times 10^{20} \text{ m}^{-3}$ , the highest reported efficiencies in the range  $1.7 \leq N_{||0} \leq 1.9$  are considered, if available. Otherwise, they are corrected for the different LH phase velocity according to Fisch's formula [9]. It is evident that the favorable scaling with  $\langle T_e \rangle$  applies to all tokamaks, and not only to single devices [3,4].

Several mechanisms for the enhancement of  $\eta_{CD}$  with  $T_e$  have been proposed by the theory [17,18], but it must be pointed out that  $T_e$  affects also the PLH deposition profile, and hence can change the fraction of the LH absorbed power as observed in JET [6]. The beneficial effect of a  $T_e$  increase on  $\eta_{CD}$  has been observed also directly in FTU during the recent combined LHCD + electron cyclotron heating experiments [19].

In summary, in FTU with the high frequency (8 GHz) LH system we have reached a good efficiency of current drive,  $\eta_{CD} \approx 0.2 \text{ A} \times 10^{20} \text{ m}^{-2}/\text{W}$  at line average plasma density  $\bar{n}_e$  in excess to  $1 \times 10^{20} \text{ m}^{-3}$ , in quasi-steady-state conditions for times longer than the skin time. We attribute the fact that the efficiency is larger than in Alcator C to the higher FTU electron temperatures. This is an encouraging result in view of the application of the LH

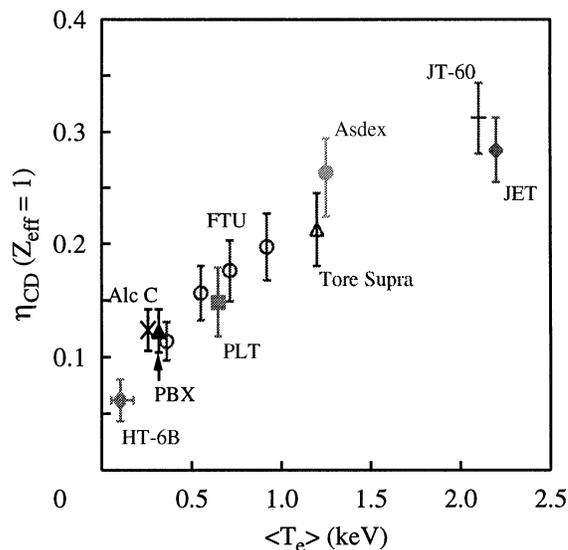


FIG. 4. Comparison of the highest values of the CD efficiency on various tokamaks as a function of the volume averaged electron temperature  $\langle T_e \rangle$ . For Alcator C the result for  $\bar{n}_e = 1 \times 10^{20} \text{ m}^{-3}$  is considered. The vertical bars indicate the range of results obtained for the given  $\langle T_e \rangle$ . ( $\diamond$ , JET; +, JT-60;  $\bullet$ , Asdex;  $\triangle$ , Tore Supra;  $\circ$ , FTU;  $\blacksquare$ , PLT;  $\blacktriangle$ , PBX;  $\times$ , Alc. C;  $\diamond$ , HT-6B.)

waves on ITER like devices, since it confirms the possibility to attain efficiencies as high as those found at much lower density in JET and JT-60. In FTU the electron temperature apparently determines the CD efficiency, in agreement with what is deduced from the comparison of other tokamaks data. Density affects  $\eta_{CD}$  only through the LH wave accessibility: a marked drop of  $\eta_{CD}$  is observed when the accessibility conditions are no more satisfied. This supports the prediction of the quasilinear theory that the quantity  $P_{LH}/n_e$  characterizes properly the LHCD also at high density, i.e., that the LH suprathreshold electron tail has a slowing down time increasing almost linearly with  $n_e$ , according to the classical theory [9]. No undesired LH behavior, as the onset of parametric decay instabilities or significant spectral pump broadening or generation of fast ion tails, has occurred until now. On the contrary, fast electron tails are well developed even beyond the first pass accessibility limits at  $\bar{n}_e \approx 1.35 \times 10^{20} \text{ m}^{-3}$ . No dangerous influx of impurities occurs during correct operations of both plasma and LH grill up to the so far maximum coupled power of 1.7 MW.

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