CDP/04

HIGH DENSITY LOWER HYBRID CURRENT DRIVE AND ION BERNSTEIN WAVES HEATING EXPERIMENTS ON FTU

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Abstract

An investigation of the efficiency of CD in the LH range of frequncy on FTU was performed up to densities above $1\times10^{20}m^{-3}$. The dependence on temperature, density, magnetic field was elucidated. Preliminary results on IBW are reported.

The 8 GHz FTU Lower Hybrid (LH) experiment aims to investigate the possibility of achieving high Current Drive (CD) efficiency at the high plasma density ($\bar{n}_e \approx 1\cdot10^{20}m^{-3}$) foreseen for a reactor. In JET [1] or JT-60U [2] a CD efficiency $\eta_{CD} \approx 0.3$ [$10^{20}m^{-2}$*A/W] has been obtained at lower density $\bar{n}_e \le 0.2\cdot10^{20}m^{-3}$ while, in the past, Alcator C [3] at high density quoted a rather low efficiency $\eta_{CD} \approx 0.12$ at B_T=10 T and with a frequency of 4.6 GHz. To Test the Ion Bernstein Wave (IBW) heating scenario a two waveguides phasable grill has started experiments to couple high frequency 433 MHz waves to FTU plasmas via slow wave.

The LHCD experiment was carried out in the following ranges: $0.2\le P_{LH}\le1.1$ MW, $0.3 \le \bar{n}_e \le 1.15\cdot10^{20}m^{-3}$, $0.22\le I_p\le0.5$ MA, $4\le B_T\le7.1$ T. Four different phasing of the LH launching grill have been tested corresponding to peak values of the $N_{\|}$ spectrum $N_{\|0}$=1.32, 1.52, 1.82, 2.43. 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 kW/cm^2 and longer than 0.7 s are routinely and safely run, even at the highest P_{LH} up to now achieved, i.e. P_{LH}=1.7 MW. The value of the effective ion charge Z_{eff} during the LH phase is similar to the ohmic (OH) value at $\bar{n}_e > 1\cdot10^{20}m^{-3}$ ($Z_{eff}\le1.4$), whereas for $\bar{n}_e \le 0.50\cdot10^{20}m^{-3}$ it rises typically from nearly 2 to about 3. This Z_{eff} increase at low density was discussed in Ref. [4] for various total input power.

The limited LH power routinely available so far has allowed to achieve full CD only for $\bar{n}_e \le 0.5\cdot10^{20}m^{-3}$. At higher density only partial CD is obtained with a drop of the loop voltage V_l up to 50% at $\bar{n}_e = 0.9\cdot10^{20}m^{-3}$ and I_p=0.5 MA. In the partial CD regimes we estimate the CD efficiency, for a clean plasma (Z_{eff}=1), from to the following evaluation of the ratio I_{LH}/I_p:

(1)
$$\frac{I_{LH}}{I_p} = 1 - \frac{V_{l,LH}}{V_{l,OH}} \cdot \frac{\left\langle T_{e,LH}^{3/2} \right\rangle}{\left\langle T_{e,OH}^{3/2} \right\rangle} \cdot \frac{Z_{eff,OH}}{Z_{eff,LH}}$$

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together with the linear law, derived from the definition η_{CD} itself: $I_{LH}/I_p = h*\eta_{CD}$ ($Z_{eff}=1$)

Here, the quantity $h \equiv \frac{P_{LH}}{\bar{n}_e \cdot I_p \cdot R} \cdot \frac{6}{Z_{eff}+5} \quad \left[\frac{W}{A \cdot 10^{20} m^{-2}}\right]$ includes the effect of the impurities on the CD [5] and can be easily measured. I_{LH}/I_p is calculated taking into account the change in the LH phase of V_l and of the bulk conductivity σ, but neglecting the effect of the residual electric field on the fast electron tail. This latter is small in FTU, within the experimental errors, as shown by the good linearity of the data themselves, presented in Fig. 1 as a plot of I_{LH}/I_p versus h. The evaluation either of the collision operator by using 1-D models, and of the hot electron contribution to η_{CD} directly from the data, following Ref. [6], confirms that neglecting the residual electric field causes in FTU an error less than 20% on η_{CD}. This uncertainty may become larger only at low density and quite low LH power. These cases, which exhibit large residual loop voltages, are not reported here.

In order to have a homogeneous database we included in Fig 1 only data with a good degree of accessibility, for which an equatorially launched LH ray can penetrate, at first pass, inside at least 2/3 of the minor radius. Indeed, as soon as this condition is violated, either by lowering B_T or $N_{||0}$, or by increasing $\bar{n}_e$, the experimental CD efficiency drops substantially. We stress that no deviation from linearity turns out on the basis of the density alone and that the correction for Z_{eff} is negligible at high densities, where $Z_{eff}\approx1$. Therefore we are confident that an efficiency $\eta_{CD}>0.2$ is actually attained at high density, $\bar{n}_e \geq 1 \cdot 10^{20} m^{-3}$.

In order to show that the only fundamental limit to the efficiency is the LH wave accessibility to the plasma core we plotted in Fig. 2 all the available data versus the quantity $D_{N||}=N_{||acc}-N_{||0}$, which is a good measure of the degree of accessibility under the different experimental conditions: for $D_{N||}>0.05$ the LH ray penetration at first pass inside about 2/3 of the FTU minor radius becomes very marginal. $N_{||acc}$ is the lowest (critical) value of $N_{||}$, with which in a slab geometry a plane wave can penetrate into a region with given $\bar{n}_e$ and B_T [5], and it is evaluated here using the line averaged density.

Regarding shots at $\bar{n}_e \approx 1 \cdot 10^{20} m^{-3}$, the group of points with $N_{||0}=1.82$, together with those with $N_{||0}=1.52$, and $B_T= 7.1$ T, have a good degree of accessibility ($D_{N||}\approx-0.2$ and ≈0 respectively) and exhibit $\eta_{CD}\approx0.2$. Instead, the group with $N_{||0}=1.52$, and $B_T= 6$ T, has a marginal accessibility ($D_{N||}\approx0.14$). 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 behaviour 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 η_{CD}, despite the rather low density, $\bar{n}_e \approx 0.6-0.7 \cdot 10^{20} m^{-3}$. We stress again that no clear trend with $\bar{n}_e$ is recognised inside each fixed B_T group, whereas the different electron temperatures are partially responsible for the scattering of the points. Indeed, an increase of η_{CD} with the volume averaged temperature $<T_e>$, is observed beyond the experimental uncertainties, as discussed also in Ref [7].

In Fig. 3 the η_{CD} values, extrapolated to clean plasma conditions ($Z_{eff}=1$), in the largest $<T_e>$ interval available in the literature , from the coldest (HT-6B [8]) to the hottest (JET [1]) device, are plotted versus $<T_e>$. The highest efficiencies reported in the literature are considered here, if available, otherwise they are corrected for the different LH phase velocity according to Fisch's formula [5]. The only exception being Alcator C for which η_{CD} is taken at $\bar{n}_e \approx 1 \cdot 10^{20} m^{-3}$, in the range $1.7 \leq N_{||0} \leq 1.9$.

The positive trend of η_{CD} with $<T_e>$ therefore applies to all tokamaks [9], not only to single devices as FTU, JET or JT-60 and it is consistent with the hypothesis [10] that the power absorption condition determines the upper limit of the LH $N_{||}$ spectrum inside the plasma: i.e.

the launched power is partially transferred to higher $N_{||}$ until most of the power is absorbed. The broadening of the launched $N_{||}$ spectrum up to such limit decreases with the temperature thus accounting for the observed η-scaling. Other possible mechanisms have been suggested [11], and it must be considered that T_e can affect also the P_{LH} deposition profile and hence can change the fraction of the LH absorbed power, as observed in JET [12].

In conclusion, in FTU we have reached a good LH efficiency of current drive, $\eta_{CD}\approx 0.2\cdot 10^{20}$ $m^{-2}*A/W$ at line averaged plasma density $\bar{n}_e$ in excess to $1\cdot 10^{20} m^{-3}$, in a quasi steady state conditions for times longer than the skin time. Higher efficiencies in these regimes are precluded only by the rather low temperatures, as evidenced by the direct comparison with the Alcator C results. As a matter of fact the main difference between FTU and Alcator C is that substantially higher T_e values are achieved in FTU, peak values $T_{e0}>$ 2.0 keV against $T_{e0}\approx 0.6$ keV, according to Refs. [3, 12]. The high frequency used on FTU (8 GHz) prevents undesired interactions with the edge plasma, as the onset of parametric decay instabilities or significant pump frequency spectral broadening, which are sign of degraded CD performance [12, 13]. No dangerous influx of impurities occurs during correct operations of both plasma and LH grill up to 1.7 MW, the maximum coupled power so far. Even at higher densities ($\bar{n}_e \approx 1.35\cdot 10^{20} m^{-3}$), where fast electron tails are still well developed, the reduced accessibility of the LH waves to the plasma core is the principal limiting factor to LHCD.

The IBW experiment on FTU (f=433 MHz, corresponding to the 4th Ω_{cH} at B_T=8 T) is the first experiment utilising a waveguide antenna [15] similar to the grill antennas of the Lower Hybrid current drive experiments. This antenna excites slow electron plasma waves which are expected to mode convert into IBW, near the cold Lower Hybrid resonance layer located in the scrape-off plasma. The converted hot plasma wave propagates to the plasma core for directly coupling to ions [16]. The antenna capability to couple the RF power to the plasma has been successfully tested. About 300 kW of RF power, only limited by the present capability of the RF power supply, were coupled to the plasma without arcing in the antenna waveguides.

The corresponding RF power density is about 1.3 kW/cm^2, a value in the range of the performance expected by extrapolating the best results obtained by the waveguide grill antennas employed in the Lower Hybrid experiments (fig. 4). Although operating at higher frequencies, these experiments need to launch the same slow electron plasma wave as in the IBW experiment. The maximum RF power density is likely limited by non linear phenomena induced by the wave electrostatic potential, which modify the plasma density profile at the antenna-plasma interface. This threshold depends on the ratio of the wave energy to the plasma kinetic energy.

The trend of the measured RF power antenna reflection coefficients with the plasma density was found in a good agreement with the one expected by the waveguide IBW antenna coupling model [15,17], giving confidence that the antenna can work properly in launching the slow wave necessary for the IBW experiment.

The attractive features of the IBW heating scheme expected by the linear theory have not been fully demonstrated in the previous IBW experiments, probably due to the role played by non-linear phenomena, similar to the above mentioned phenomena limiting the injected RF power density. These phenomena can also inhibit the wave propagation and can produce impurity injection [18,19,20]. The IBW experiment on FTU operates at a frequency 2÷10 times higher than the previous IBW experiments. Due to the f_0^{-2} dependence of the ponderomotive potential, the IBW experiment on FTU is expected to be less affected by parasitic ponderomotive phenomena. At present we are examining effects on neutral emission and electron plasma temperature occurring when the harmonic resonance is located inside the plasma.

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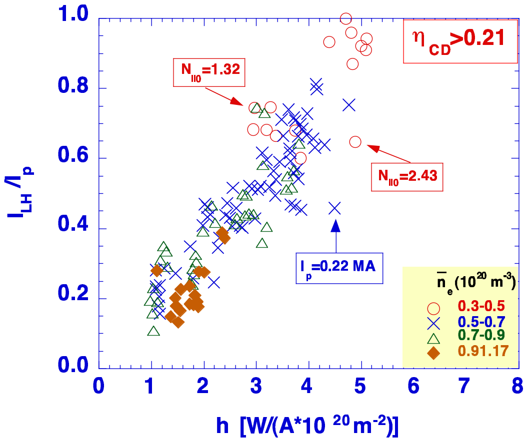

FIG. 1 - Plot of the ratio of the LH driven current to the total current versus the quantity h defined in the text

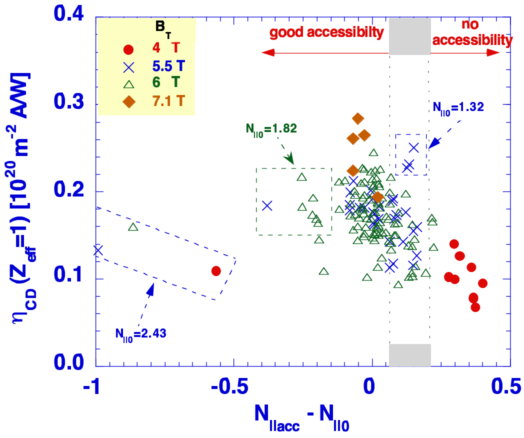

FIG. 2 - Plot of the estimated CD efficiency versus the accessibility parameter $D_{N||}$ (see text). For $D_{N||}$>0.05 the ray penetration becomes marginal.

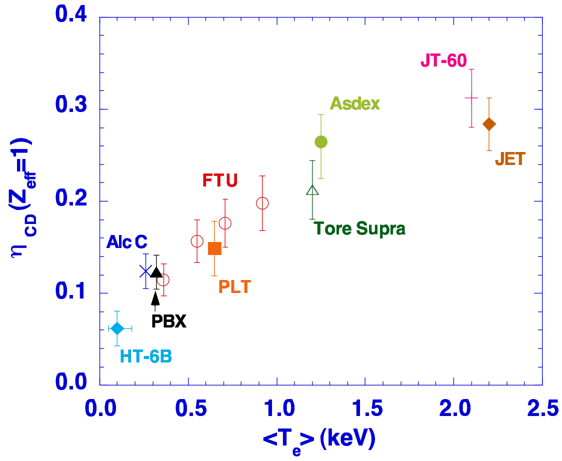

FIG. 3 - Comparison of the highest values of the CD efficiency on various tokamaks as a function of the volume averaged electron temperature <T_e>

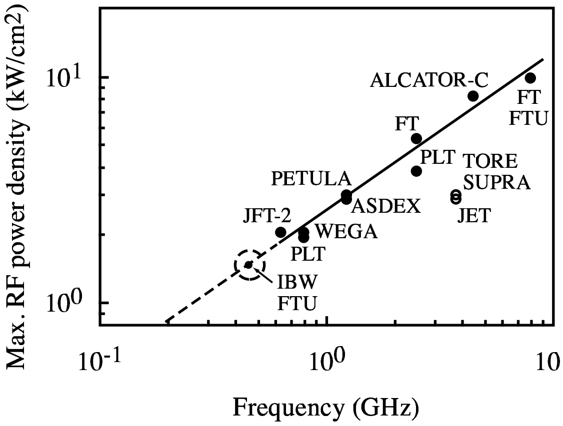

FIG. 4 - Power Density performances of LH array grill vs. Frequency