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ABSTRACT

The lower hybrid current drive efficiency of 66 Tore Supra pulses has been investigated. The ohmic part of the plasma current (0.6-0.9MA) is very small (V_{loop} <50mV) for most of the pulses. Different scaling laws were tested with three input parameters: the wave directivity, the plasma current (Ip) or the volume average temperature ($<T_e>$) and the effective charge (Z_{eff}). When applying these scaling laws to four JET pulses, no discrepancy is found except for the high plasma current ($I_p = 2.0$MA) pulse. Finally the best fit was found by replacing T_e (or I_p) by the thermal electron confinement time. This result is supported by the hard X-ray (HXR) diagnostic indicating a fairly good correlation between the plasma edge HXR emission, normalized to the central emission, and the thermal electron confinement time.

1. INTRODUCTION

Lower Hybrid Current Drive (LHCD) efficiency as high as $3\text{-}3.5\times10^{19}$ $A.W^{-1}.m^{-2}$ has been reported on JET [1] and JT-60U [2]. The scaling of the efficiency with plasma parameters has been long debated and a simple scaling, the so-called JT-60 scaling, $\eta = 12 <T_e>/(5+Z_{eff})$, has been proposed. However the database provided by the different tokamaks indicates a large scattering of the experimental points. Surprisingly this scaling does not take into account the $N_{||}^{-2}$-weighted directivity of the wave as predicted by theory. Moreover most of the pulses were not fully LH driven and the calculation of the efficiency with a residual DC electric field is a difficult task, sensitive to different plasma parameters: with the 1-D CRONOS code [3], we verified for example that, for a JET discharge with a loop voltage as low as 29mV, neglecting the electric field leads to an over-estimation of the efficiency by 40%. A previous study [4] indicates that the plasma current could play a major role for the current drive efficiency, following similar findings on JT-60 [1]. In order to investigate more in details the scaling parameters of the LHCD efficiency, a data base of 66 Tore Supra pulses was constituted. In addition four JET pulses were analyzed.

2. THE DATA BASE

66 Tore Supra pulses with LHCD only (no other additional heating) were selected. For these pulses the loop voltage, averaged on a time interval larger than 1s (2s for 90% of pulses), is ranging between –28mV and +95mV. The time slice was chosen in order to have stationary conditions. Only four shots have a loop voltage above 50mV. For these shots the current drive efficiency was carefully computed by means of CRONOS. For the others, a 0-D correction of the plasma conductivity was applied. The exactitude of this correction was verified by means of CRONOS. The normalized directivity D_n defined as

$$D_n = \int_{N_{acc}} 4 \frac{P(N_{||})dN_{||}}{N_{||}^2} - \int_{-}^{-N_{acc}} \frac{P(N_{||})dN_{||}}{N_{||}^2}$$

where N_{acc} is the minimum parallel index for which the wave is accessible to the plasma (N_{acc} =

1.25), was computed for each pulse. This directivity varies between 0.49 and 0.94 when $N_{||}$, for which $P(N_{||})$ is maximum, varies between $N_{||0} = 1.7$ and $N_{||0} = 2.3$. It should be noted that the unequivocal relationship between D_n and $N_{||0}$ holds only for regular power feeding in amplitude and phase.

Other parameters vary in the following range: 0.3-0.9MA for the plasma current I_p, 1.3-3.1×10^{19} m^{-3} for the line-averaged density with a peaking factor in the 0.2-0.6 range, 2.1-4.6MW for the LHCD power, 0.65-1.75keV for the volume-averaged temperature $<T_e>$, 1.6-5.3 for the line-averaged effective charge Z_{eff}. For these rather low density pulses with quasi central LH deposition, the DELPHINE ray-tracing code indicates the deposition to be centered on $r/a \approx 0.2$, in agreement with hard X-ray measurements. The electron temperature profile is peaked and Te(0)/$<T_e>$ varies between 3.0 and 5.5. Toroidal field is between 3.5 and 3.9T at the center. When the bootstrap current Ibs, whose contribution is small ($0.05<I_{bs}/I_p<0.20$) is taken into account, the measured LHCD efficiency varies between 0.4 and 0.9×10^{19} $A.W^{-1}.m^{-2}$.

The four JET pulses were achieved at higher plasma current (1.1-2.0MA) with a volume-averaged temperature in the range of 1.4-2.5keV. Two pulses were performed at rather low loop voltage (29 and 64mV), the two others at high loop voltage during the current ramp-up phase for the first one and in Counter Current Drive (CCD) configuration for the second one. Power deposition is centered on $r/a = 0.4$, except for the CCD case where the broad deposition is centered on $r/a = 0$ [5]. Efficiency varies between 0.9 and 1.55×10^{19} $A.W^{-1}.m^{-2}$.

3. SCALING LAWS

From the Tore Supra pulses, scaling laws are established with different input parameters by a least-square method. The scaling with three input parameters D_n, Z_{eff} and $<T_e>$ (or I_p) indicates a dependence on directivity which is only with a power law close to 0.5 whereas theory would predicts a linear dependence. The power law for the temperature dependence is also close to 0.5, i.e. weaker than the JT-60 scaling. The $Z_{eff}^{-0.27}$ dependence is indeed the closest power law to the $6/(5+Z_{eff})$ scaling and for the range of experimental Z_{eff}, they differ by less than 5%. The $<T_e>$ and I_p scalings (figure 1) have almost the same power law for this third parameter and the standard deviations ($\sigma = 0.07/0.08$) are very close. This result is due to the very high correlation between $<T_e>$ and I_p data for this database

When these two scalings are applied to the JET pulses, a rather good agreement is found with a significant discrepancy only for the 2MA pulse with the highest efficiency: the computed efficiency is lower (by 30%) from the experimental efficiency for the T_e scaling. For the I_p scaling, the discrepancy is only 15%. The current drive efficiency was computed, considering an upper bound $N_{||L}$ ($= c/2.5v_{th}$) of the up-shifted $N_{||}$ spectrum, with the experimental profiles of density and temperature. Profiles of Z_{eff} are calculated assuming a peaking factor of 0.4 and power deposition is assumed to be centered on $r/a = 0.2$ with a width of 0.3. The calculated directivity D_n was also taken into account. A good agreement is found with the same standard deviation than the scaling law with $<T_e>$ ($\sigma = 0.07$).

4. HARD X-RAY MEASUREMANTS

From the 59 chord hard X-ray (HXR) diagnostic installed on Tore Supra, the width of the LH deposition profile was characterized by computing the ratio of a central chord (HXR40, r/a~0) to an outer chord (HXR29, r/a~0.5). When the efficiency is plotted as a function of this ratio, a close correlation is found for most pulses (figure 3). For the low $N_{||}$ cases ($N_{||}$ <1.75) with rather peaked HXR profiles (ratio >4), the efficiency is clearly larger. This diagnostic is also sensitive to direct losses of fast electrons at the plasma edge: the signal of the two chords viewing the toroidal limiter is very large during LHCD, typically from 2 to 10 times that of the central chord. We found a good correlation between this normalized signal and the confinement time of the thermal electrons estimated from the n_e, T_e profiles. When the confinement time increases by a factor 2, this ratio decreases by a factor ~10. In order to further document the close relationship between the fast electron and thermal electron confinement, a new scaling of the efficiency is performed where $<T_e>$ /Ip is replaced by the electron confinement time tE,th. For the Tore Supra pulses, the best fit ($\sigma = 0.056$) is found with this input parameter (figure 4). This scaling fits the JET pulses although the 2MA pulse is above (+30%) the scaling.

CONCLUSION

For the range of plasmas parameters accessible on Tore Supra, the scaling of the current drive with $<T_e>$ is clearly weaker than the linear scaling. The Z_{eff} dependence ($1/(5+Z_{eff})$), suggested by strong physics arguments, is actually found. Because of the strong correlation between Ip and the <Te> of this data base, the most relevant parameter cannot be clearly identified, although the 2MA JET pulse suggests that the current is the scaling factor. Peaked LH deposition profiles lead, in most cases, to higher current drive efficiency. The confinement of fast electrons, closely related to that of thermal electrons, play a key role for the efficiency.

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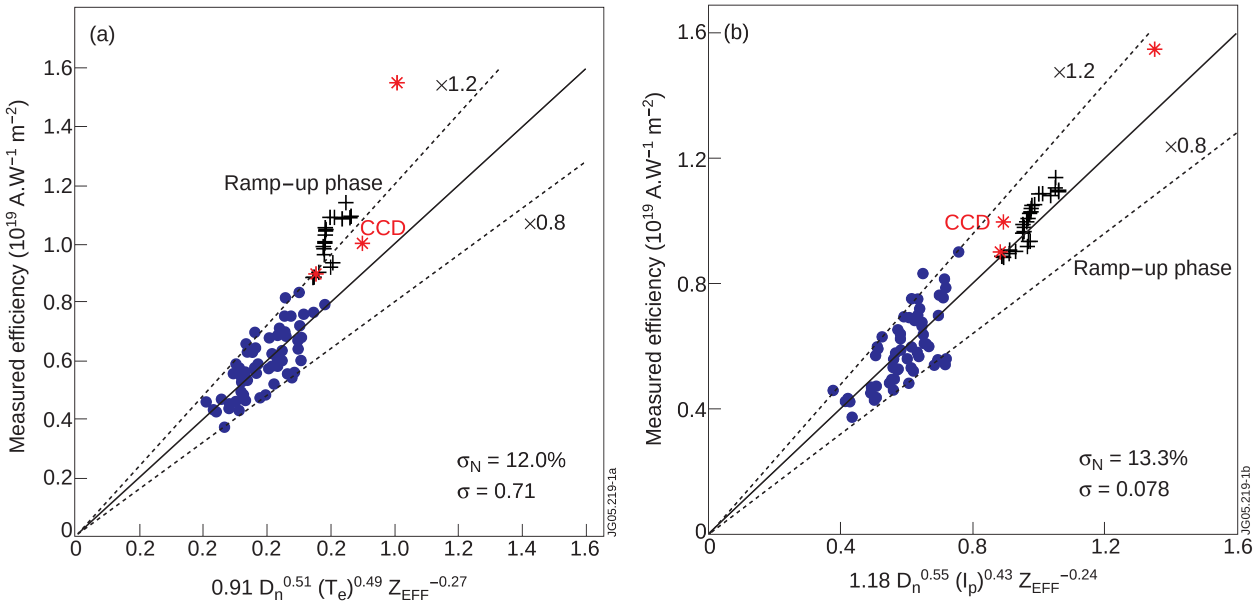
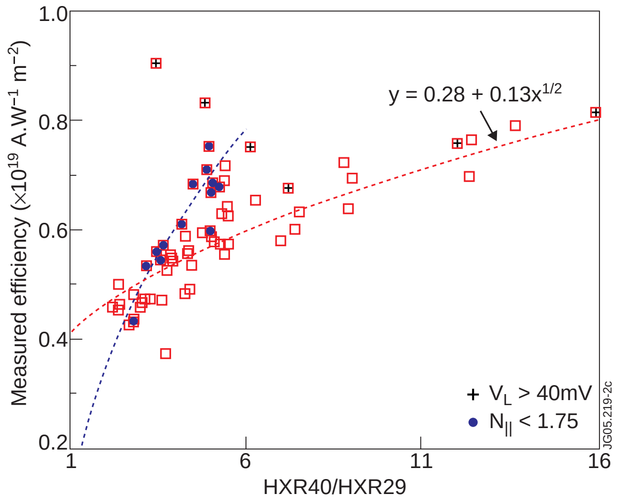


Figure 1: Measured current drive efficiency as a function of the scaling law established with D_n, Z_{eff} and a) $<T_e>$, b) I_p. from the Tore Supra database (circles). The JET pulses(*) are plotted with these scalings. For the JET pulse in the ramp-up phase (+), different times are shown.



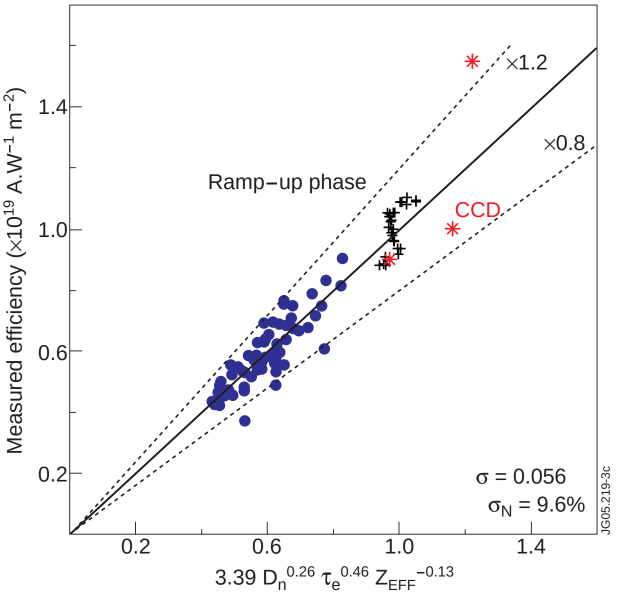


Figure 2: Measured efficiency as a function of the width of the HXR emission.

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Figure 3: Measured efficiency as a function of the scaling law established with D_n, Z_{eff} and $\tau_{E,th}$. Same symbols as figures 1 and 2.