MEASUREMENTS OF NON-THERMAL ELECTRON POPULATION DURING LOWER-HYBRID HEATING IN ASDEX

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It has been recognized in recent years that e.m. waves in the lower hybrid (LH) frequency range can produce important effects when absorbed by plasma electrons like, for example, current generation, plasma heating and current profile modification. In these conditions the electron distribution function is not maxwellian but becomes enhanced at high energy depending on the power and phase velocity spectrum of the launched waves /1/.

The aim of the present paper is to study the plasma-wave interaction by experimentally determining the fractional population of non-thermal electrons under different plasma conditions. The experiments were carried out on the ASDEX divertor tokamak, where current drive and plasma heating can be studied up to an injected power of 1 MW at a frequency of 1.3 GHz. By changing the relative phase between successive elements in an eight-waveguide grill, the shape of the $N_{\parallel}$ index spectrum as well as its directionality can be controlled.

Data on the fractional population n_T of tail electrons were obtained from measurements of the intensity ratio of a dielectronically excited satellite line to the main resonance line of He-like titanium ions by means of high resolution X-ray spectroscopy /2/. A detailed description of the experimental apparatus and of the data analysis procedure can be found elsewhere /3/.

The results obtained in a current drive shot are compared in Fig. 1 with those obtained during electron heating. The two discharges have the same toroidal magnetic field and plasma current and nearly equal injected RF power ($P_{RF} \simeq 800$ kW) and electron density ($\bar{n}_e \simeq 1.2 \times 10^{13}$ cm^{-3}). The shape of the launched spectrum is nearly identical in the two cases and is characterized by $\langle N_{\parallel} \rangle = 2$.

In the first case the plasma current is almost completely driven by the RF waves and the feedback system regulates the ohmic power transformer to keep the plasma current to the pre-injection value; consequently the toroidal electric field is strongly reduced and comes near to zero. In these

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conditions a rough estimate of the fractional population of tail electrons can be obtained by assuming from quasi-linear theory that a unidirectional plateau is formed in the toroidal direction in the velocity space from a low value V_1, a few times the thermal speed, up to a value $V_2 \gg V_1$, determined by the accessibility condition ($V_2 \simeq c/1.55$ for the present case). In this hypothesis the central current density is given by:

$$j_{RF}(0) = e\,\frac{V_2 + V_1}{2}\;n_{RF}(0)$$

where $n_{RF}(0)$ is the total density of RF-generated suprathermal electrons in the plasma center. This expression can be compared with the value obtained by assuming the q value in the plasma center close to unit, as, deduced from Li-beam measurements /4/:

$$j_{RF}(0) = \frac{2}{\mu_o}\frac{B_T}{R}$$

when R, the plasma major radius, is equal to 166 cm in ASDEX. When the value of the central electron density ($n_e(0) = 1.5 \times 10^{13}\ cm^{-3}$) is taken into account we obtain for the current drive discharge $n_T(0) = 1\ \%$ in good agreement with data in Fig. 1.

When we compare complete current drive with electron heating discharges we find a considerable enhancement of the non-thermal population in the latter case (Fig. 1). This could be explained by a better power absorption in the plasma, possibly due to small differences in the spectrum at high $N_{\parallel}$. However this should lead to an increase in the thermal energy content in heating discharges which is not observed.

Thus the higher content of non-thermal electrons in heating discharges seems to indicate that the tail extends to energies higher than in current drive discharges. However the minimum $N_{\parallel}$ accessible to the plasma center is nearly the same in the two cases and so the only possible explanation for the results is that the toroidal electric field, which is nearly vanishing only in the current drive case, is effective in accelerating the electron tail to higher energies. It is worth to note that in the heating discharges discussed here the value of the electric field is about 1.4 % of the critical runaway field. This results in a critical velocity of 0.56 c, which is lower than the upper limit of the quasilinear plateau, $V_2 = 0.62$ c, as deduced from accessibility condition.

Magnetic measurements also show that in the discharges considered here the plasma pressure becomes strongly anisotropic in the heating case while LH current drive leads to nearly isotropic heating (Fig. 2). The parallel and perpendicular components of the plasma pressure were derived from three independent measurements of β_p (diamagnetic beta), $\beta_p^{equ} + l_i/2$ (β_p^{equ} = equilibrium beta) and l_i /4/.

The influence of the shape of the $N_{\parallel}$ spectrum on the non-thermal population was also studied. A power scan with $\langle N_{\parallel}\rangle = 2$ and $\langle N_{\parallel}\rangle = 4$, (Fig. 3) shows for both cases a nearly linear dependence upon the injected power but faster waves are more effective in generating fast electrons. This is in agreement with observed heating efficiency as well as with current drive experiment results /5/.

Also shown in Fig. 3 are two measurements taken during opposite current drive experiments. In this case the waves have to push the electrons against the applied toroidal field and consistently a lower number of tail electrons is observed.

A density scan was also performed at a medium power level ($P_{RF} \simeq 430$ kW). This is not enough to obtain complete current drive except at very low density. The results of the measurements are shown in Fig. 4. For $\bar{n}_e \geq 1 \times 10^{13}$ cm^{-3} the loop voltage is nearly equal for current drive and heating discharges with $\langle N_\parallel \rangle = 2$. The different behaviour in the partial current drive and heating cannot be due to electric field effects and is not fully understood. We note, however, that in this experiment heating discharges have a higher electron temperature.

At the highest density all the three spectra give nearly the same result. This corresponds to the point where the heating efficiency for the electrons is just starting to deteriorate because of the increasing ion absorption /5/. In these conditions we performed spatially resolved measurements for two values of the injected power at $\langle N_\parallel \rangle = 2$ (Fig. 5): we obtained hollow profile, showing a lack of wave penetration to the plasma center.

To check problem of wave accessibility to the plasma center, $\langle N_\parallel \rangle = 4$ spectrum was studied in the same plasma conditions, although at a reduced power level ($P_{RF} = 300$ kW), and the n_T profile was still found to be hollow. It can then be concluded that in the ion interaction regime the penetration of the waves to the plasma center is inhibited possibly due to the absorption by the plasma edge.

References

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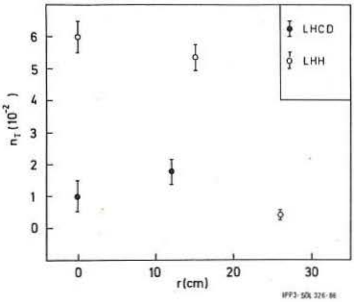

Fig. 1: The fractional population of non-thermal electrons is plotted versus the plasma radius for current drive and electron heating discharges. The plasma parameters are: $I_p = 300$ kA, $B_T = 2.4$ T. $\bar{n}_e = 1.2 \times 10^{13}$ cm^{-3} and $P_{RF} = 800$ kW. The launched spectrum has $\langle N_\parallel \rangle = 2$.

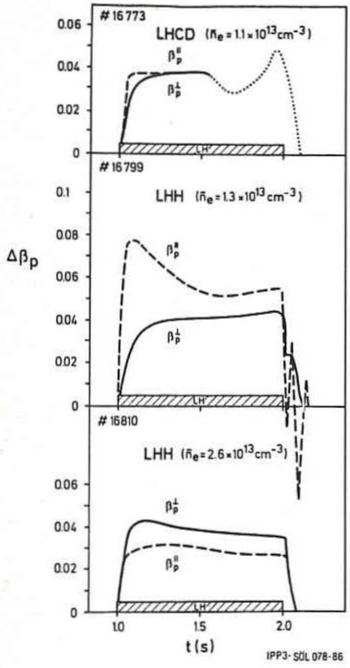

Fig. 2: Increment of $\beta_p^{\parallel}$ and β_p for LHCD and LHH at low and high electron density.

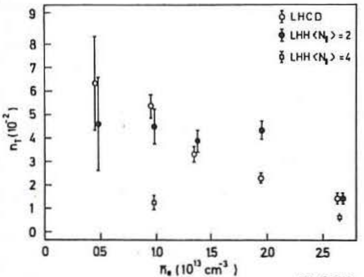

Fig. 4: Density scan for current drive with $\langle N_{\parallel}\rangle = 2$ and heating discharges with $\langle N_{\parallel}\rangle = 2$ and $\langle N_{\parallel}\rangle = 4$. Other plasma parameters are: $I_p = 300$ kA, $B_T = 2.2$ T, $P_{RF} = 430$ kW. Data refer to r = 11 cm.

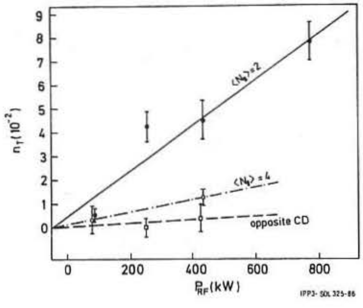

Fig. 3: Power scan for heating discharges with $\langle N_{\parallel}\rangle = 2$ and $\langle N_{\parallel}\rangle = 4$ and for opposite current drive. Plasma parameters are: $I_p = 300$ kA, $B_T = 2.2$ T, $\bar{n}_e = 1.0 \times 10^{13}$ cm^{-3}. Data refer to r = 11 cm.

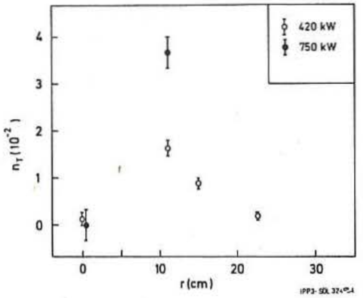

Fig. 5: Profiles of the fractional population of nonthermal electron for discharges near to the regime of prevailing ion absorption. Plasma parameters are: $I_p = 300$ kA, $B_T = 2.2$ T, $\bar{n}_e = 2.6 \times 10^{13}$ cm^{-3}. The launched spectrum has $\langle N_{\parallel}\rangle = 2$.