

Interpretation of the q-profile dependence of the LH power deposition profile during LHCD experiments on Tore Supra

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1. Introduction

Identification of parameters and scenarios allowing to control accurately the Lower Hybrid (LH) power deposition profile remains nowadays one of the most challenging task in view to achieve steady-state advanced tokamak operation. The hard X-ray tomographic system of Tore Supra is a powerful tool to carry out this type of studies, by allowing measurements of the LH power deposition profile at a level of accuracy which has never been reached so far on any tokamak [1,2]. Recent observations by means of this diagnostic are reported, which bring evidence of the highly sensitive dependence of LH power deposition on the safety factor profile. The radial position of the wave absorption, which has been investigated both in transient (during plasma current ramp-up) and stationary (during I_p flat-top) regimes, during shots where the ohmic contribution to the total plasma current is dominant, shows a strong correlation with the value of I_p and the position of the $q = 1$ surface. Elements of interpretation of this behaviour are found using ray-tracing and Fokker-Planck (RT/FP) simulations, carried out with a new ray-tracing program coupled to equilibrium reconstruction code IDENT-D [3].

2. Experimental study of the dependence of LH power deposition profile on safety factor profile

Numerous experiments have been carried out at various plasma current values ($0.6 \leq I_p \leq 1.6$ MA) and moderate input LH power levels ($P_{LH} \leq 2.5$ MW) to study the dependence of LH power deposition profile on the safety factor profile, in regimes where the ohmic contribution to the total plasma current is dominant ($25\% \leq I_{LH}/I_p \leq 50\%$). The value at which the launched LH power spectrum is peaked ranges between $n_{//peak} = 1.8$ and 2.3, with a full width of 0.4. However, since the LH power deposition profiles are very weakly dependent of the waveguide phasing but of the strong toroidal upshifts and downshifts, as observed experimentally, variations of this parameter are not critical for the following analysis. Core electron density ranges between 2.0 and $3.0 \times 10^{19} \text{ m}^{-3}$. It is observed that at low plasma current values ($I_p \leq 1$ MA) the LH power deposition profile is peaked or weakly hollow, and always localised in the inner region of plasma $r/a \leq 0.3$. Moreover, it becomes broader as I_p is increased, and may fill the whole region $r/a \leq 0.6$ at very high I_p values ($I_p = 1.6$ MA for this serie of discharges). The broadening of LH power deposition profile as I_p increases, which has been already observed in other machines and also with the former HXR diagnostic of Tore Supra [4-7], is verified either during I_p flat-top (fig. 1) or during LHCD assisted current ramp-up experiments, in which the position of the maximum of the HXR emissivity between 60 and 80 keV shifts towards the plasma edge as I_p increases and remains constant once the flat-top is reached (fig. 2 and 3).

A more detailed study concerning the safety factor profile in these discharges shows evidence of a strong correlation between the outermost peak of HXR emissivity and the $q = 1$ surface : during I_p ramp-up discharges, the HXR profile becomes slightly hollow roughly at the same time the $q = 1$ surface appears in the plasma, the occurrence of $q_0 = 1$ being deduced from polarimetry measurements (fig. 4). Furthermore, both in stationary and transient conditions, the localisation of the observed HXR outermost peak is close to the radial position of the $q = 1$ surface, determined by the IDENT-D code (fig. 5).

Interpretation of these data is not straightforward since the electron temperature profile broadens as I_p increases, which is in itself a source of broadening of the LH power deposition profile. Nevertheless, the both spatial and time correlation with the $q = 1$ surface, as well as the reproducibility of the LH power deposition behaviour in a wide range of density and

temperature profiles gives strong confidence that details of the safety factor profile have a large direct effect on the LH wave propagation and/or absorption.

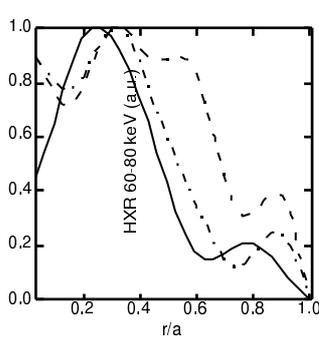


Figure 1 : Abel-inverted HXR emissivity profiles between 60 and 80 keV for 3 shots at different I_p values, during I_p flat-top. $B_t = 3.8$ T, $n_{//peak} = 1.8$, $T_{e0} \sim 3.7$ keV, n_{e0} varying between 2 and $3 \times 10^{19} \text{ m}^{-3}$. $I_p = 1.0$ MA (solid), 1.4 MA (dash-dot), 1.6 MA (dash).

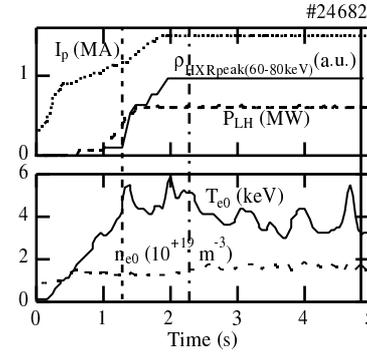


Figure 2 : Time evolution of the plasma current, LH power, central electron temperature and density, and position of the maximum of the HXR emission between 60 and 80 keV ($\rho_{HXRpeak(60-80keV)}$), for LHCD assisted ramp-up discharge #24682 ($n_{//peak} = 2.3$).

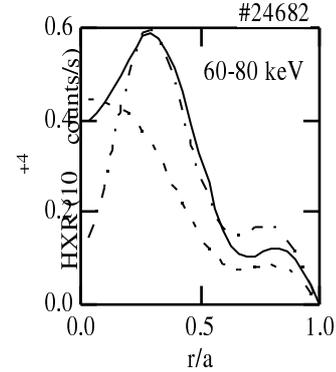


Figure 3 : Abel-inverted HXR emissivity profiles between 60 and 80 keV for shot #24682 (cf. fig. 2) at three different times : 1.3 s (dash), 2.3 s (dash-dot), and 4.9 s (solid).

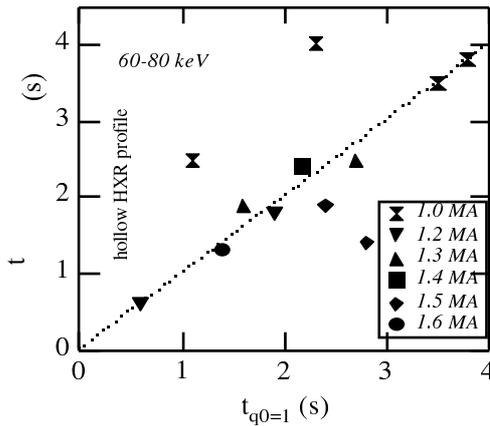


Figure 4 : Time of transition to hollow HXR profile in I_p ramp-up experiments vs. time of occurrence of $q = 1$ surface in the plasma from polarimetry measurements.

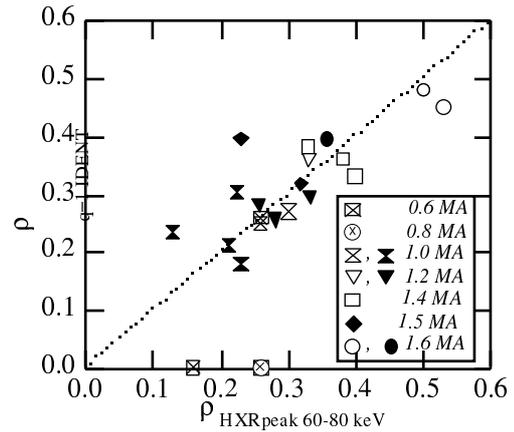


Figure 5 : Position of the $q = 1$ surface as determined by IDENT-D code vs. position of the maximum of the HXR profile at 60-80 keV, for ramp-up experiments (filled markers) and flat-top measurements (hollow markers) at different plasma currents.

3. Interpretation

Ray-tracing calculations carried out with equilibria reconstructed from experiments predict an outwards shift of the LH power deposition profile as I_p increases, in agreement with the radial broadening of the HXR emission (fig. 6). However, simulated profiles are much narrower than experimental observations. A similar agreement is also found during LH assisted current ramp-up phase, though in this case results of the simulation are sensitive to input density and temperature profiles, which contrasts with the robustness of the experimental behaviour. Since simulations taking into account no specific modeling of the $q = 1$ surface predict a dependence of LH power deposition profile on the value of I_p similar to experimental observations, it seems that no new physical effect is introduced by the presence of the $q = 1$ surface in the plasma. The experimental evidence of strong correlation between LH power deposition profile and the position of the $q = 1$ surface hence leads to the conclusion that the latter plays in this type of discharges the role of a characteristic parameter of the safety profile which is representative of the influence of equilibrium on LH wave propagation.

In Tore Supra, like in most present day tokamaks, the LH wave propagates in the "few pass" regime [6] : since electron temperature is not high enough to cause wave absorption on its first pass from the launcher towards plasma center, ray trajectories have to be followed during a longer time to determine the position where strong wave damping will occur. The stochastic nature of LH wave propagation makes the rays highly sensitive to details of plasma equilibrium, and no simple rule may be found to predict the resulting power deposition profile. However, observations of the ray trajectories shows that off-axis absorption is in "few pass" configurations always triggered by strong $n_{//}$ -upshift related to reflection of the rays in the bottom (or top, depending on the orientation of plasma current and toroidal magnetic field [8]) part of the plasma (fig. 7 and 8). Hence, for a given electron temperature profile, the broadness of LH power deposition profile entirely depends on the fact that some rays may or may not undergo reflection at strongly negative Z (Tore Supra case), where Z is the vertical coordinate, with origin at the equatorial mid-plane of the torus.

For the serie of discharges studied in this paper, where current density profile is peaked and total current dominated by the ohmic contribution, it appears that high I_p equilibria with a broad $q = 1$ surface lead to fast and important $n_{//}$ -upshift because most rays undergo their first reflection in the bottom part of the plasma, which results in off-axis power deposition. In lower current configurations, two combined effects contribute to make the rays damp near plasma center : the first reflections do not occur at strongly negative Z , resulting in a weak $n_{//}$ -upshift (or even downshift) during the first pass. This $n_{//}$ -upshift is not large enough to fill the spectral gap in the major part of the plasma except in the center, where electron temperature is maximum. Hence weak $n_{//}$ -upshifted rays are easily absorbed in the central part of the plasma. The second point is that even when some rays undergo reflection in the strongly negative Z region after a few pass, their $n_{//}$ -upshift appears to be less important than in high current cases. This effect could be justified by means of the shape of the rays by considering the usual expression of $dn_{//}/d\theta$ (θ is the poloidal angle) which may be deduced from equation (6) of ref. [8] with the assumption of circular concentric magnetic surfaces and taking electrostatic approximation for the dispersion relation. Though this expression has no explicit q -dependence, the fact that LH rays turn faster in a poloidal cross-section at low q (high current) provides higher variation of θ during one reflection, and therefore greater $n_{//}$ -upshift. This explanation is nevertheless only a clue, since the electrostatic expression of $dn_{//}/d\theta$ is in most cases found to strongly underestimate the $n_{//}$ -upshift in the negative Z region, as compared to RT calculations taking into account electromagnetic terms of the dispersion relation and the exact structure of the equilibrium. More accurate calculations have to be carried out to justify rigourously the observed greater $n_{//}$ -upshift at negative Z in high I_p equilibria.

4. Conclusion

Experimental observations using the HXR tomographic system of Tore Supra have brought evidence that the LH power deposition profile becomes broader and shifted towards plasma edge as plasma current is increased in discharges where the current density profile is peaked and total current dominated by the ohmic contribution. A correlation between the position of the LH outermost absorption peak and the location of the $q = 1$ surface is also observed. Ray-tracing/Fokker-Planck simulations taking into account the experimental equilibrium show a similar tendency as HXR measurements without any specific modeling associated to the $q = 1$ surface, which seems to be merely a characteristic parameter of the influence of plasma equilibrium on LH wave propagation. In these simulations, the shift of the profile towards plasma edge at high I_p is due to two combined trajectory effects related with

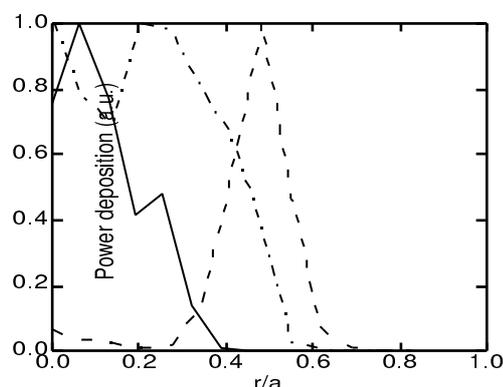


Figure 6 : Simulated power deposition profiles for the three shots presented in fig.1 : $I_p = 1.0$ MA (#25375, solid), 1.4 MA (#25351, dash-dotted), 1.6 MA (#25367, dashed)

wave propagation in the bottom zone of the plasma, where important $n_{//}$ -upshift occurs : in high current equilibria where exists a broad $q = 1$ surface, rays undergo reflection in the bottom zone of the plasma during their first pass, and hence rapid $n_{//}$ -upshift. Furthermore, this upshift is more important than for similarly bottom-reflected rays in lower current configurations. No rigorous explanation has yet been found to this last effect, though the q -dependence of the shape of the rays is likely involved.

These encouraging interpretative results show that though still failing to reproduce the detailed shape or certain small variations of LH power deposition profile, RT/FP modeling is a useful tool for interpreting general tendencies of the experimental phenomenology in the complex "few pass" case.

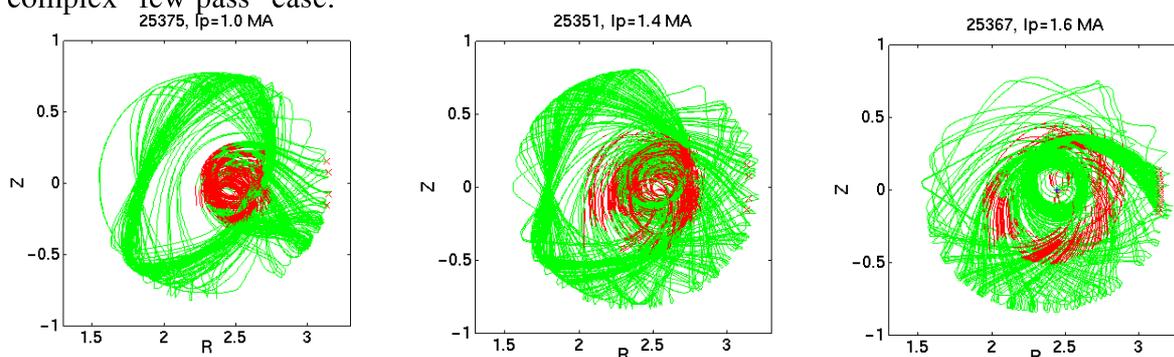


Figure 7 : projection of the ray trajectories in a poloidal section for three different plasma current values (same discharges as in fig. 1 and 6). R is the major radius and Z the vertical coordinate, in meters. The red (dark) part of the rays are locations of strong absorption. Red (dark) crosses indicate the different launching points. 80 rays were used in these simulations.

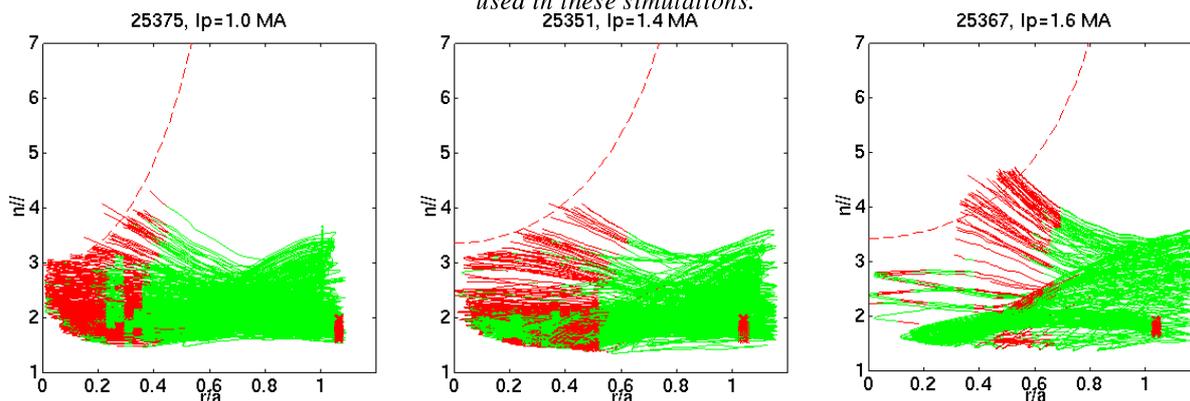


Figure 8 : $n_{//}$ of the rays as a function of normalised small radius for the same discharges as in fig. 7. The red (dark) part of the rays are locations of strong absorption. The dashed curve plots the criteria of strong electron

Landau damping, i.e. $n_{//} = 7/\sqrt{T_e}$, where T_e is the electron temperature.

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