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Modeling of fast electrons losses in magnetic toroidal ripple during the application of Lower Hybrid wave in Tore Supra

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1. Introduction

Fast electrons interacting resonantly with the Lower Hybrid (LH) wave along the toroidal field can be toroidally trapped in local magnetic mirrors between two consecutive coils through pitch angle scattering. Without collisional detrapping, the trapped fast electrons are lost to the vacuum vessel during their vertical drift motion along iso-magnetic field lines. In consequence, some serious damage to inner vessel components may occur for low density plasma and high injected power levels.[1-3] Experimental results on the losses of these collisionless fast electrons driven by the LH wave in Tore Supra have been already studied extensively.[3] Therefore, in this paper, the relativistic bounce-averaged Fokker-Planck (F-P) simulation with a simple modeling of two dimensional fast electron dynamics in momentum space is carried out for the consistency of experimental observations at a variety of plasma conditions and injected LH wave power levels. A reasonable agreement is found between simulation and experimental result obtained by the diagnostic DRIPPLE dedicated to magnetic ripple loss measurements.

2. Modeling of losses of fast electrons trapped in magnetic ripples

In order to estimate consistently the losses of collisionless fast electrons induced by the magnetic ripple during the application of the LH wave in Tore Supra, a 2-D relativistic bounce-averaged F-P solver has been modified by including the effect of toroidal magnetic ripple on fast electron dynamics

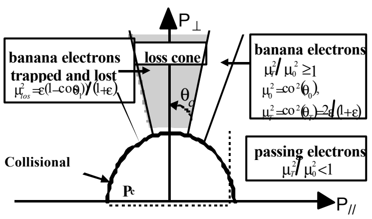

Fig. 1 : Loss cone in momentum space

generated by the LH wave: (1) the bounce-averaged Fokker-Planck collision coefficients are corrected due to the effect of the magnetic ripple on both the orbits of circulating and banana electrons[4] and (2) the loss cone in momentum space, characterized by its angular half width θ_c (Fig.1) and bounded at the low energy by collisional detrapping threshold, is introduced, which represents a coarse but realistic description of physics that comes into play for these electrons.[1,2,4] The calculation of the flux of fast electrons entering the loss cone allows to evaluate the associated current of electrons leaving the plasma, the drifting time scale being much lower than the collisional one.[4] The boundaries of loss cone, depending on the plasma equilibrium and collisionality, are determined from the good confinement domain defined by the usual criterion $\alpha^* \geq 1$.[1,3-5] All electrons whose banana tips are outside this domain are entering into the loss cone, and except if their kinetic energy is low enough with respect to the collisional detrapping threshold, they are expected to drift in the ripple well region and therefore do not participate to the momentum collisional exchange. The LH physics is described by a simple quasi-linear domain, whose box shape roughly describes most of the ingredients of resonance interaction between two-velocity boundaries.[6]

3. Comparison of ripple loss currents between the simulations and measurements

The magnetic ripple induced loss currents during a typical LH discharge of Tore Supra are displayed in Fig.2. Here, the numerical simulations are performed assuming constant quasi-linear diffusion coefficients in the resonance momentum domain such that $D_0 = 2$, $v_1 = 3.5$ and $v_2 = 5.0$. Despite of the time evolution of electron density, a good agreement is found between measurements and simulations. The radial profile of the density is taken into account, while Z_{eff} is assumed to be constant ($Z_{eff} = 2$) across the plasma. In Fig.3, total ripple induced loss currents of fast electrons determined by DRIPPLE and averaged over the time intervals of LH wave pulses are compared to the simulations for four selected TS discharges. The simulations reproduce quite well the experimental results within 30%, in different plasma parameters and injected LH wave power levels. The discrepancy is reasonable according to the uncertainty of input parameters due to experimental errors.

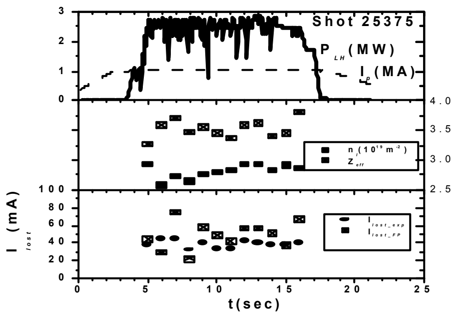

Fig. 2 Ripple loss currents during a discharge #25375

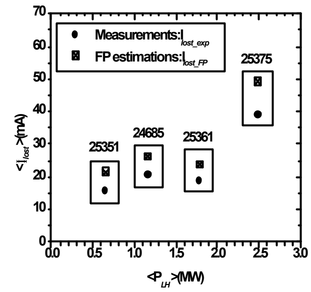

Fig. 3 Total ripple loss currents

In Figs.4 and 5, the radial profiles of I_{lost}^{FP} (the simulations) and I_{lost}^{Exp} (the observations), are displayed for three representative LH discharges. The radial profiles of two shots (very similar in Z_{eff} and density) at fixed I_p are similar despite of the difference in P_{LH} (the position of the maximum remains at the same place), while at larger I_p, it tends to be shifted off-axis. This radial dependence seems to come from the modifications of super-trapped domain through the detrapping probability and its width, rather than the consequence of the shift of the fast electron source, since the normalized parameters characterizing the quasi-linear LH domain in momentum space are assumed constant whatever the plasma location. The experimental profile turns out to be always broaden than the predicted one, since the experimental one represent the flux of fast electrons whose banana tips are located inside a vertical cylinder of a diameter around 5 cm and a given radial position associated to one collector by means of iso-B reconstruction, while the predicted one does the flux of lost electrons at the same flux surface. Nevertheless, the predicted profile behaves like its experimental counterpart. In the core of the plasma, no collisionless electrons are observed, since they are all well confined. This observation also permit to understand that the radial transport of fast electrons is quite negligible inside the plasma, since, otherwise, trapped fast electrons coming from the center would fill up external collectors. As long as larger r / a values are concerned, a significant fraction of the fast electrons generated by the LH wave are trapped and lost in magnetic ripple well, since the detrapping probability remains low in this region of the plasma. Indeed, the fairly high density in this region is still counterbalanced by a high electron temperature, leading to a weak friction coefficient. However, at larger plasma radius, r/a >0.5, the decrease of the temperature makes p_c / p_{th} nearly constant across the plasma (Fig.6), while the angular width of the super-trapped cone matches the bouncing domain. Therefore, the intersection between the quasi-linear domain and the trapped region takes place at momentum values below p_c, and therefore no electrons are lost in the magnetic ripple, as observed experimentally.

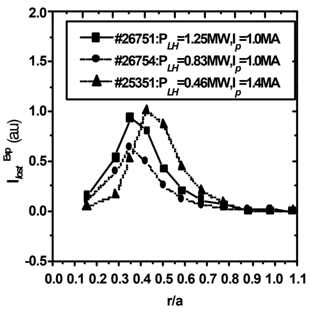

Fig. 4 Radial profiles of I_{lost}^{Exp}.

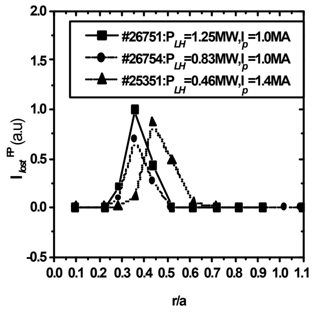

Fig.5 Radial profiles of I_{lost}^{FP}.

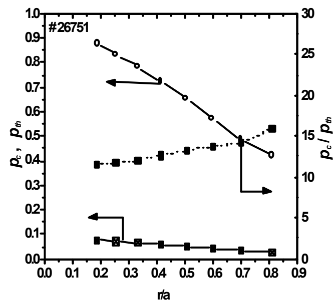

Fig.6 Profiles of p_{th}, p_c, p_c / p_{th}

4. summary

With the coarse LH modeling, the present analysis provides an interesting insight of the fast electron dynamics in momentum space. First the ripple current profile is likely very weakly dependent of the LH power deposition in most plasma regimes found in Tore Supra. Secondly, the ripple losses are determined by a narrow ripple loss window, which depends on plasma equilibrium and temperature and density profiles.

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