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Simulations of Tore Supra Lower Hybrid Current Drive Experiments

Y.Peysson, J. Decker and V. Basiuk

Association Euratom-CEA, CEA/DSM/DRFC, CEA-Cadarache, 13108, Saint Paul lez Durance, France

1. Introduction

Numerical simulations of lower-hybrid current drive are generally based on ray-tracing calculations to determine the LH wave characteristics and on Fokker-Planck (FP) calculations with quasilinear (QL) diffusion to calculate the phase-space distribution function and thus evaluate the driven plasma current [2]. In this model, a spectral width $\Delta N_{\parallel}$ must be associated with each ray in order to obtain a finite diffusion coefficient D_{ql}.

So far, the use of a very large number of rays is considered as the standard prescription for all LHCD simulations in order to fill the well known spectral gap and make the current density profile independent of the ray stochasticity. This description has two major drawbacks. It leads to very long calculation times especially for modeling advanced tokamak scenarios, where most of the driven current has a non-inductive nature. Besides, in simulations using many rays, the values of $\Delta N_{\parallel}$ that must be taken to ensure the stability of kinetic calculations is always much larger than the incremental spectral separation between rays, thus preventing any physical interpretation or justification for the choice of $\Delta N_{\parallel}$.

Meanwhile, recent calculations have shown that power deposition profile is completely determined by QL coupling and is almost independent of the number of rays used in the simulations, provided the spectral gap is bridged by a small fraction of the LH power at high $N_{\parallel}$. The tail of fast electrons which is therefore pulled out from the thermal bulk acts like a seed in the QL absorption process, and contributes to the full damping of the remaining part of the power spectrum at low $N_{\parallel}$. From these results, a new simulation scheme based on the use of one or very few rays (one per poloidal row of the LH grill for the main lobe, which is the only relevant part for the driven current) has been proposed [1], where the spectral width $\Delta N_{\parallel}$ associated with each ray can recover its natural physical interpretation, while the computational effort can be considerably reduced.

In this work, the range of applicability of this original method is first demonstrated by considering three LHCD regimes which are representative of almost all cases that may be found in tokamak current drive simulations. All calculations are performed with the new fast ray-tracing code C3PO coupled to the 3-D Fokker-Planck solver LUKE [3]. A special attention is then paid to LHCD on the Tore-Supra tokamak, for which accurate steady-state parametric dependencies of the hard X-ray (HXR) fast electron bremsstrahlung profile with $N_{\parallel}$ have been experimentaly investigated [1]. This database offers a unique opportunity to test code predicting capabilities for LH power absorption profile as well as global current drive, in particular when the toroidal upshift is very small and the spectral width broadening plays the dominant role in the wave absorption process.

1. LINEAR DAMPING LIMIT

Recently, benchmarking of LHCD codes with application to ITER-relevant regimes have been performed, which represents a unique opportunity for highlighting the pertinence of the few ray approach [4]. Indeed, for the target plasma corresponding to the reference scenario IV which has been considered in this study, the linear single pass absorption holds, as a result of a strong toroidal upshift in a hot and dense shaped plasma. With an initial $\Delta N_{\parallel 0}$=0.052 taken constant along ray propagation, power absorption profile is almost independent of the launching position and the total numbers of rays coupled to the plasma, since contributions of all passes of the same ray for calculating D_{ql} on each flux surface are negligible. With only three rays (one per poloidal position for the main lobe only, the secondary lobe contribution being negligible for current drive), it is then possible to recover with C3PO/LUKE code not only the current density profile found by GENRAY/CQL3D using 80 rays, but also the same parametric $1/N_{\parallel}$ dependency of the LHCD efficiency expected from Fish's theory [5]. By slightly varying $\Delta N_{\parallel}$ around its initial value, it is possible to find the optimal value current drive efficiency with a very small computational effort. The excellent agreement shown in Fig.1 between the few and multiple ray approaches is just the consequence of the validity of the linear damping limit.

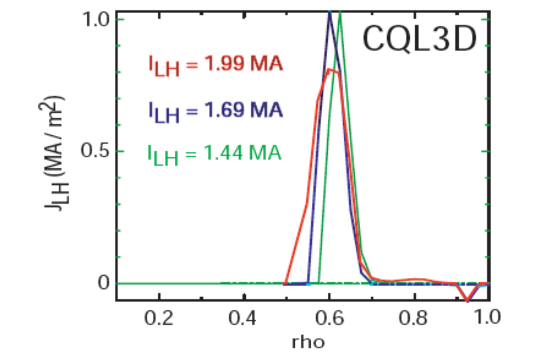

Fig.1a: LHCD in ITER as calculated by GENRAY/CQL3D code for three initial $N_{\parallel 0}$ values using 80 rays [4]. (red: 1.9, blue: 2.0, green: 2.1).

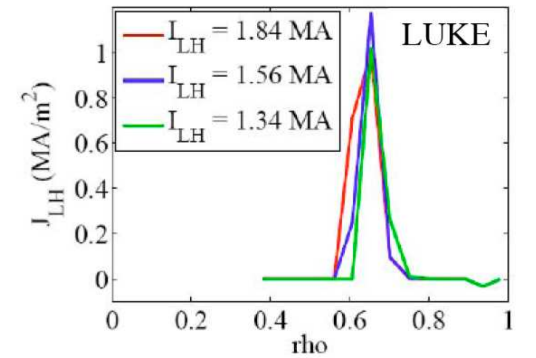

Fig.1b: LHCD in ITER as calculated by C3PO/LUKE code for three initial $N_{\parallel 0}$ values using three rays [4]. (red: 1.9, blue: 2.0, green: 2.1).

3. QUASILINEAR REGIME WITH STRONG TOROIDAL UPSHIFT

When ray absorption is weaker, the calculation of D_{ql} on each flux surface requires to fully consider the contribution of all rays, but also all passes of the same ray in the same flux surface. In that case, the QL self-consistency between D_{ql} and the distribution function is crucial for the calculation of the current density profile. The primary requirement is that power carried by each ray is effectively fully absorbed by the plasma. Such a constraint may be easily achieved for few rays, while it becomes more and more difficult for an increasing number of rays. Indeed, the rate of convergence to ensure the full QL self-consistency for each ray is considerably lowered, because of the huge number of inter- and intra-ray couplings [1,6]. In this case, the usual criterion of convergence based on the apparent stability of the predicted current density profile cannot be consistent with the full QL solution and a strong difference is therefore expected between few and multiple rays approaches.

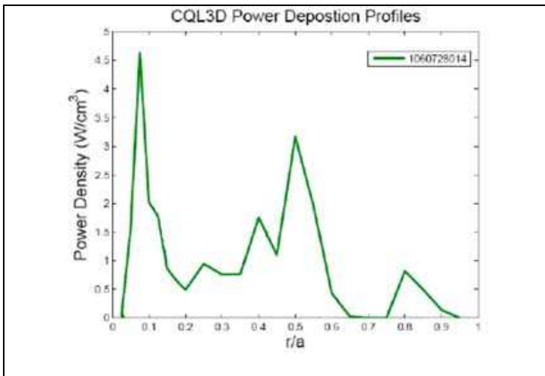

Fig.2a: LH power absorption profile in C-MOD tokamak as calculated by GENRAY/CQL3D code for $N_{\parallel 0}$=1.55 using 80 rays [6]. The calculated profile is close to the shape given by the linear model (Fig. 4b).

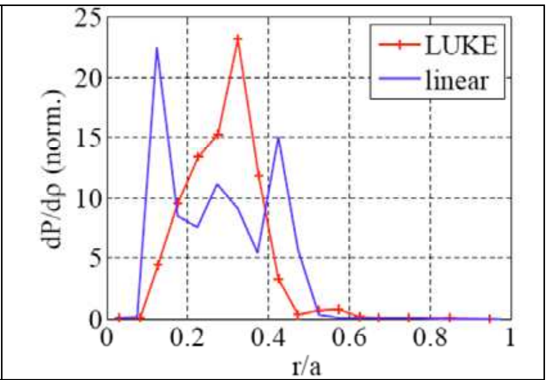

Fig.2b: LH power absorption profile in C-MOD tokamak as calculated by C3PO/LUKE code for $N_{\parallel 0}$=1.55 using 4 rays [6]. The selfconsistent solution (red) is completely different from the profile calculated by the linear model.

Comparisons between simulations performed with the standard multiple ray modeling technique using GENRAY/CQL3D code, and the few rays approach as done with C3PO/LUKE code for full LHCD simulations in the C-MOD tokamak gives an enlightening illustration of the strong difference between the two methods. As shown in Fig.2, the power absorption profile obtained with 80 rays is very closed to the linear profile calculated with four rays. When full QL convergence is achieved, the absorption profile exhibits a completely different shape with a single broad peak, while the total current level predicted by the code is very close to the experimental observation. Conversely, in the multiple ray description, while V_{loop}=0V is fully achieved experimentaly, an ad-hoc Ohmic electric field contribution must be introduced in the simulations for increasing the predicted current value close to the experimental 1.0MA value [7]. All these differences suggest that the use of a large number of rays in the simulations have prevented the RT/FP code to converge towards the correct QL solution.

4. VERY WEAK ABSORPTION AND SPECTRAL BROADENING

In modeling LHCD for C-MOD tokamak, $\Delta N_{\parallel 0}$=0.22 is taken constant along ray propagation like for ITER. Indeed, even if the absorption rate is significantly lower in this case, the spectral gap in C-MOD can be nevertheless well bridged after few passes in the plasma, as a result of its D-shape. For Tore Supra tokamak, whose poloidal cross-section is almost circular, the toroidal upshift is always very small at low plasma current (~0.5 MA), the typical operating regime for which full current drive discharge longer than six minutes have been successfully performed [7]. If the spectral broadening is taken constant along ray propagation, the spectral gap can be brigded after a very large number of passes, but in this case, the predicted LH current is twice the experimental observation, while the predicted current density profile is too off-axis as compared to fast electron bremsstrahlung in the hard x-ray (HXR) range of photon energy [8]. In order to recover the correct non-inductive current level, it is necessary to introduce a spectral broadening along the ray path. In the simple model here considered, a linear dependence is taken with the ray length s. As shown in Fig. 3, the LH current drops rapidly when the broadening rate α increases. Interestingly, the predicted LH current becomes rapidly independent of α, and close to the experimental level, without any need of an ad-hoc anomalous fast electron radial transport. Furthermore, in this parameter regime, the current density profile peaks at r/a = 0.2, in excellent agreement with HXR profile. This result suggests that the current drive efficiency and the current density profile are both strongly governed by a fast broadening of the LH power spectrum in Tore Supra because the absorption of the LH wave is very weak. When spectral broadening predominates over toroidal upshift for bridging the spectral gap, the predicted LHCD efficiency becomes poor, since the fast electron tail cannot be pulled up to high energies.

From this study, an universal picture of LHCD in tokamaks emerges, in which the CD efficiency results from a competition between two different mechanismes: toroidal upshift or broadening of the LH power spectrum. According to this simple model, an improvement of the CD efficiency in Tore Supra may only result from an increase of the total plasma current at which operation is performed (higher ratio B_p/B) since its plasma shape is fixed. This is consistent with the tendency observed experimentaly [8].

When $N_{\parallel 0}$ evolves from 1.88 to 2.32 at fixed input power level, the wave absorption profile deduced from HXR is shifted from ρ = 0.18 to 0.25. Even if HXR profiles are strongly fluctuating as function of time, as shown in Fig. 4, the mean shift of the radial position at which HXR emission peaks is very reproducible. This is confirmed by the capability to feedback control the power absorption location of the RF wave using $N_{\parallel 0}$ as an actuator. However, even if the averaged peak position is grossly recovered within the error bars whatever $\alpha \geq 0.03$, it turns out that the small experimental radial shift with $N_{\parallel 0}$ is always beyond model capabilities. Indeed, no clear outward radial shift with $N_{\parallel 0}$ can be predicted. Nevertheless, the relative decrease of the HXR intensity with $N_{\parallel 0}$ shown in Fig. 4 is consistent with the reduction of the calculated LH current, as expected from Fisch's current drive theory. These results illustrate that salient features in momentum dynamics are well described by kinetic calcualtions, while fundamental limitations remain for describing radial localization of Lh current density with a ray-tracing coupled to a Fokker-Planck solver. The introduction of a small radial transport of 0.2 m^2/s, whose effect is self-consistently coupled with quasilinear absorption does not change the results here presented.

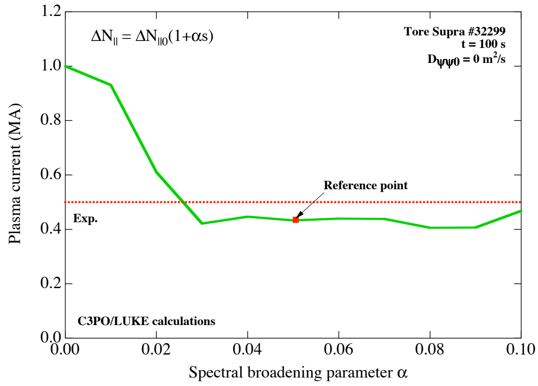

Fig.3a: LH current level for Tore Supra GigaJoule discharge predicted by C3PO/LUKE code using four rays.

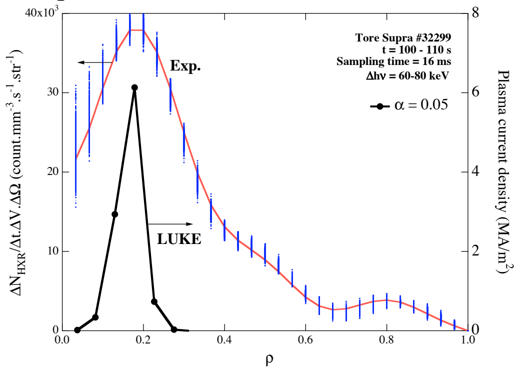

Fig.3b: Comparison between predicted current density profile ($\alpha = 0.05$) by C3PO/LUKE code using four rays, and the measured non-thermal bremsstrahlung emission profile.

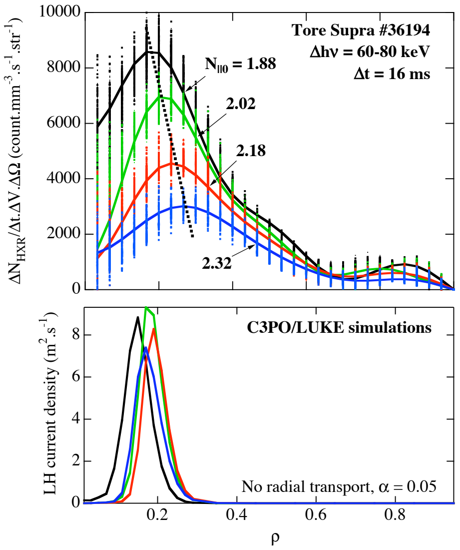

Fig.4a: Fast electron bremsstrahlung profile in the HXR photon energy range for different $N_{\|0}$. Error bars are evaluated at different times. Below, C3PO/LUKE predictions.

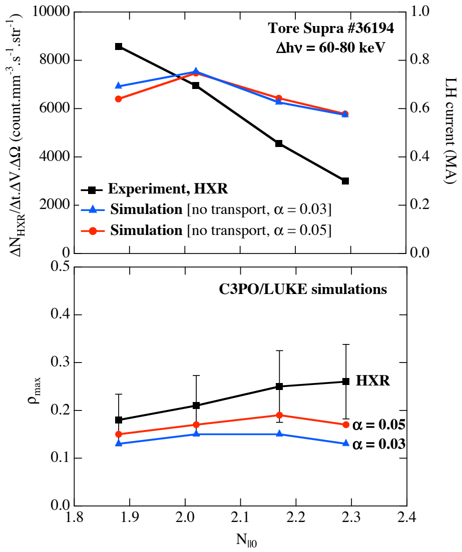

Fig.4b: Evolution of the radial position of the maximum of the HXR profile and the LH driven current as a function of $N_{\|0}$. The predicted radial location of the maximum of the HXR profile is close to the experimental observation.

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