Modelling of LHCD at various densities in Tore Supra tokamak

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Introduction

In the Tore Supra (TS) tokamak, lower hybrid (LH) waves are used extensively to heat electrons and drive toroidal current. A characteristic effect of LH waves is to significantly modify the electron distribution function through Landau damping by pulling a tail of fast electrons [1]. Besides driving a toroidal current, this suprathermal electron population affects many properties of the plasma, including : 1) bremsstrahlung and electron cyclotron emissions, which can be used as LHCD diagnostics; 2) runaway electrons; 3) ripple losses; 4) MHD instabilities such as electron fishbones and sawteeth; 5) plasma rotation; etc. Consequently, there is a strong interest in reliable modelling of LHCD discharges, which require Fokker-Planck calculations. Besides the mechanisms listed above, LHCD modelling is applied to the comparison between fully active multijunction (FAM) and ITER-relevant passive active multijunction (PAM) launchers in TS [2]. More generally, modelling is essential to extract the relevant physics of LHCD as a controller of the current profile. In this paper, a new modelling suite for LHCD in TS in presented. It is applied under diverse plasma density conditions in order to characterize different wave propagation regimes and determine the validity limits of the model.

Modelling suite for LHCD in Tore Supra

The modelling scheme is graphically presented in Fig. 1-a. The evolution of the tokamak discharge is simulated by the code METIS, which uses a waveform relaxation scheme to converge towards the solution from an initial guess. METIS computes current and heat sources and solves the current diffusion equation, along with moment equations for the MHD equilibrium. For the interpretative simulations of TS discharges presented in this paper, the temperature and density profiles were obtained from the TS database by fitting experimental measurements. The LH current profile is decomposed as $J_{\rm LH} = \eta_{\rm LH} f_{\rm LH}(\rho) P_{\rm LH}$, where $P_{\rm LH}$ is the coupled power and $f_{\rm LH}(\rho)$ is a form factor defining the radial profile. A estimation for $f_{\rm LH}(\rho)$ is obtained from the Abel-inverted fast-electron bremsstrahlung (FEB) emission profile. The CD efficiency $\eta_{\rm LH}$ is adjusted by matching the evolution of the edge poloidal flux with experimental measurements.

The LH power spectrum is calculated by the code ALOHA [3] from the phase and power

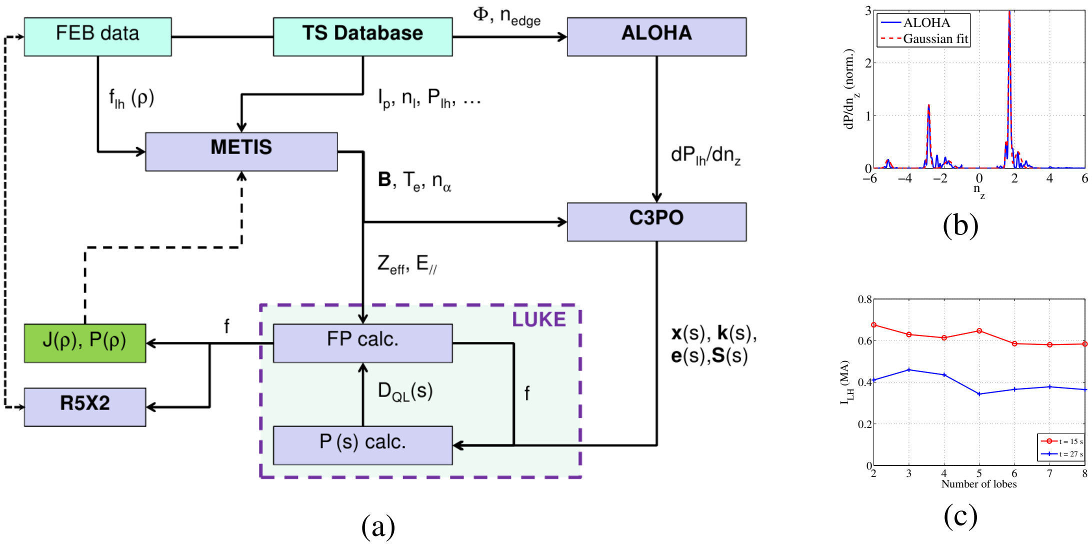


Figure 1: Modeling suite for LHCD in Tore Supra (a); ALOHA power spectrum and C3PO selection of six main lobes (b); Driven current calculated as a function of the number of lobes selected (c).

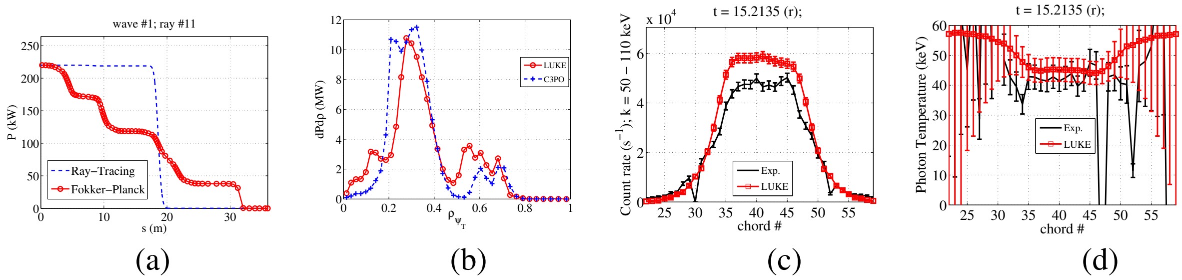


Figure 2: Comparison between linear (ray-tracing C3PO) and quasilinear (Fokker-planck LUKE) power deposition: power flow along a ray (a) and total deposition profile (b). Comparison between experimental and reconstructed FEB signals as a function of the chord number: count rate (a) and photon temperature (b) in the photon energy range 50-110 keV.

distribution within the waveguides. The LH wave propagation is represented by a ensemble of rays calculated by the ray-tracing code C3PO [4] in the geometric optics formalism. In the toroidal direction, rays are distributed in Fourier space from the power spectrum as shown in Fig. 1-b for TS #45525 at $t = 27$ s. In order to reduce the numerical effort, only a selection of lobes is kept from the original ALOHA spectrum. Extensive LHCD simulations using a varying number of lobes show very little variation above six lobes, as illustrated in Fig. 1-c for TS #45525 at $t = 15$ s and $t = 27$ s. In the poloidal direction, rays are distributed in the real space using one launching position per waveguide row [1].

Ray characteristics such as position, wave vector, power flow, and polarization, are used to

[1]It is also possible to use a Fourier space distribution in the poloidal direction using the 2-D ALOHA power spectrum), thus accounting for the phase difference between rows.

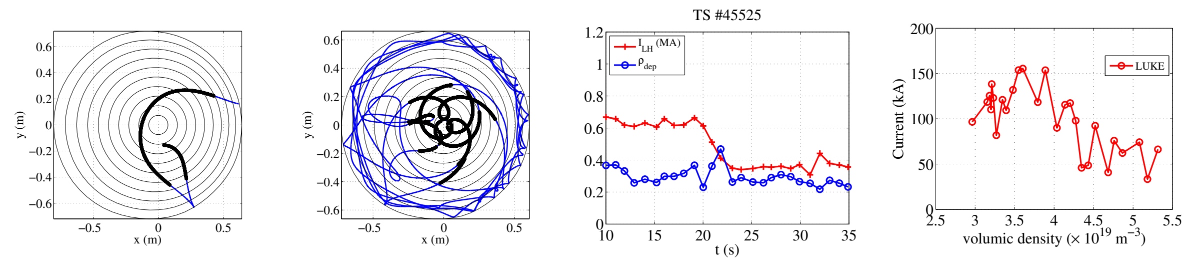
built the quasilinear diffusion coefficient for the relativistic fully-implicit 3-D Fokker-Planck solver LUKE [5]. An essential aspect of Fokker-Planck calculations for LHCD is to ensure that the power flow along each ray, hence the diffusion coefficient, be consistent with the distribution function. This process requires iteration between the wave energy equation and the Fokker-Planck equation until convergence is obtained on the power flow along each ray. It is important to note that convergence on a single moment of the distribution function, such as the total LH power deposition profile, is not sufficient to ensure consistency, as very different power flows along each ray can yield nearly identical radial damping profiles, as illustrated in Fig. 2-a,b. This apparent paradox is explained by the quasilinear process of pulling an electron tail - or filling the spectral gap - by which each step in the ray damping occurs at the same radial location.

Once the electron distribution is computed, any moment of interest can be calculated. Essential moments include the driven current profile and the power deposition profile. These moments can be reinserted into METIS to correct the LH heating and CD source, in an iterative process towards a fully self-consistent state of the LHCD modelling suite. This is particularly important when using the PAM launcher, for which a specific study shows that the Abel-inverted FEB profile is a poor estimate of the current profile [2].

In the absence of reliable current profile measurement in Tore Supra, the FEB signal measured by hard X-ray (HXR) cameras provides the best diagnostic for the fast electron physics, with good simultaneous resolution in time, space and energy [6]. Thus, a synthetic diagnostic was implemented in the code R5X2 [7] to calculate the FEB emission and integrate along the lines of sight, for a direct comparison with HXR measurements. HXR signals typically present an exponential energy dependence and can be characterized by a count rate and a photon temperature within a relevant energy range (50-110 keV). A comparison between experimental and reconstructed signals is presented in Fig. 2-c,d. It shows a remarkable agreement, particularly concerning the width of the count rate profile (Fig. 2-c) and the photon temperature (Fig. 2-d), which are relevant characteristics for the current profile and CD efficiency, respectively. Such comparisons are systematically performed to assess the quality of the simulations.

LHCD modelling at low and high density

Relevant experimental LHCD parametric dependencies - with respect to the initial parallel index of refraction $n_{\parallel 0}$, the launched power P_{LH}, the plasma density, the plasma current, the toroidal magnetic field, etc - are typically smooth and reproducible. In order to fully validate LHCD modelling, the same dependencies must be found in the simulations. Whenever the comparison fails contributes to define the validity limits. This paper focuses on the plasma density. A low-density, full CD case (#45525, $\bar{n} = 1.4 \times 10^{19}$ m^{-3}) and a high density case [8] (#45155,



(a) (b) (c) (d)

Figure 3: Comparison between low-density discharge 45525 (a,c) and high-density discharge 45155 (b,d). Ray propagation (a,b) and evolution of the driven current (c,d).

$\bar{n} = 5.8 \times 10^{19}$ m^{-3}) are compared. In the low density case (Fig. 3-a), a ray corresponding to the main spectral lobe is quickly absorbed after one edge reflection only. In the high-density case (Fig. 3-b), the accessibility condition first restricts the ray propagation to the edge on the low field side. Once the ray finally penetrates into the plasma, it undergoes many reflections before the power is fully absorbed. In the first case, the ray propagation is deterministic and the time-evolution of the driven current is robust (Fig. 3-c). In the second case, the ray propagation is chaotic and so are CD calculations (Fig. 3-d). The high-density case is clearly beyond the validity limits of the ray-tracing / Fokker-Planck model.

Conclusion

This paper presents a complete modelling suite for LHCD in Tore Supra, which is validated by comparing the experimental and reconstructed FEB emission. This capability opens a large range of applications involving fast electron physics. However, the validity of the underlying ray-tracing / Fokker-Planck model is restricted to low-density plasmas ($\bar{n} \lesssim 2 \times 10^{19}$ m^{-3}) for which the ray propagation is not dominated by stochasticity.[2]

References

[1] N. Fisch, Phys. Rev. Lett. **41** 873 (1978)
[2] E. Nilsson, et al., same conference.
[3] J. Hillairet, et al., Nucl. Fus. **12** 125010 (2010)
[4] Y. Peysson, J. Decker, and L. Morini, Plasma Phys. Control. Fusion **54** 045003 (2012)
[5] J. Decker and Y. Peysson, Euratom-CEA report EUR-CEA-FC-1736 (2004)
[6] Y. Peysson and F. Imbeaux, Rev. Sci. Instrum. **70** 3987 (1999)
[7] Y. Peysson and J. Decker, Phys. Plasmas **15** 092509 (2008)
[8] M Goniche, et al., Plasma Phys. and Control. Fusion **52** 124031 (2010)

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