Comparative modelling of LHCD with Passive-Active and Fully-Active Multijunction launchers in the Tore Supra tokamak

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Introduction

In the Tore Supra tokamak, lower hybrid (LH) waves for heating and current drive are coupled to the plasma using a Fully-Active-Multijunction (FAM) launcher and/or a Passive-Active-Multi-junction (PAM) launcher. The latter was installed recently to test an ITER-relevant antenna design. Both launchers yield comparable current drive efficiencies in Tore Supra experiments in full current drive in relatively low density condition ($\bar{n} < 2 \times 10^{19}$ m^{-3}) at 500 kA [1, 2]. To simulate the current drive process, a suite of codes specifically coupled and optimized for LHCD modelling is used [3], including a code for equilibrium and transport (METIS), LH wave propagation (C3PO) [4], electron distribution function (LUKE) [5], and fast electron bremsstrahlung (FEB) emission reconstruction (R5X2) [6]. This modelling suite provides a calculation of the current profile, LH power deposition, and a synthetic diagnostic for the FEB measured by the hard X-ray (HXR) cameras installed on Tore Supra.

To demonstrate the capabilities of the LHCD simulation suite and compare the FAM and PAM designs, a number of Tore Supra discharges have been simulated, in which either the C3 (FAM) or C4 (PAM) launcher is used. This study is restricted to relatively low density cases ($\bar{n} < 2 \times 10^{19}$ m^{-3}) for which LHCD simulations are valid [3]. It also focuses on fully non-inductive scenarios with feedback controlled zero loop voltage, so that the LH driven current can be derived from the measured plasma current and estimates of the bootstrap fraction.

Spectral properties and driven current

Two Tore Supra discharges with LH current driven by C3 (#31527) and C4 (#45525) are compared. The main parallel refractive index of both wave spectra is $n_{\parallel 0} = 1.7$. This value corresponds to optimum operation settings for C4 rather than for C3, which couples best at $n_{\parallel} = 2.0$. The LH wave coupling is modelled by the code ALOHA [7], which calculates detailed wave power spectra from waveguide power and relative phasing. The LH spectrum depends upon the plasma density at the launcher mouth n_e. The C4 launcher has its optimum operation, that is, its highest directivity and lowest reflection coefficient, near the cut-off density ($n_e = 1.7 \cdot 10^{17}$ m^{-3}), whereas C3 is optimal at higher edge density (about 2-3 times the cut-off density). In ALOHA, a two gradients model is used to extrapolate the density profile in the private plasma and the scrape off layer (SOL) from the density n_e at the launcher mouth.

Previous current drive simulations of Tore Supra discharges with Fokker-Planck codes systematically overestimated the current drive efficiency by up to a factor two for FAM driven scenarios. Given experimental evidence that the LH power is indeed properly coupled to the plasma, and since the directivity of FAM spectra is very sensitive to the edge density when close to the LH wave cut-off, a possible explanation is that n_e was overestimated because it was taken from Langmuir probe measurements somewhere in the private plasma. In the present work, n_e is obtained by matching the reflection coefficients (RC) from ALOHA simulations with experimental measurements. For the pulse #31527, measurements indicate $RC = 5\%$, which in ALOHA corresponds to an edge density of 1.3×10^{17} m^{-3} and a directivity, defined as in [8]

$$D = (1 - RC) \times n_{\parallel peak}^2 \left(\int_1^{\infty} \frac{1}{n_\parallel^2} \frac{\mathrm{d}P}{\mathrm{d}n_\parallel} \mathrm{d}n_\parallel - \int_{\infty}^{-1} \frac{1}{n_\parallel^2} \frac{\mathrm{d}P}{\mathrm{d}n_\parallel} \mathrm{d}n_\parallel \right), \tag{1}$$

of 0.32 when using two density gradients model. This is to be compared with the Langmuir probe measurements, which yield $n_e = 4.0 \cdot 10^{17} m^{-3}$ and a directivity of 0.48. Extensive simulations of C3 discharges using this procedure yield current drive efficiencies that are close to experimental observations.

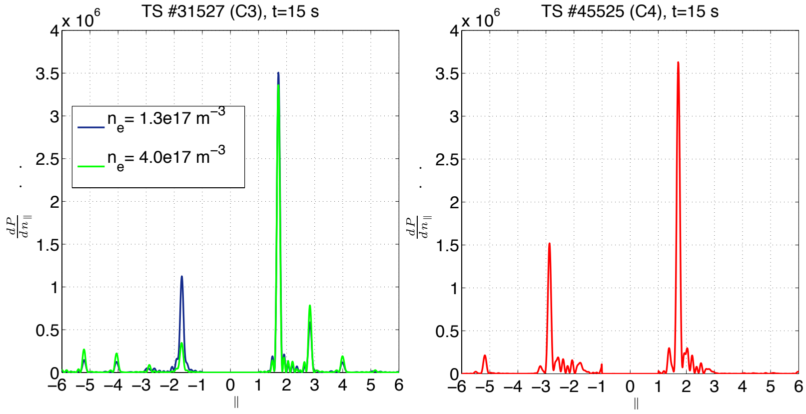


Figure 1: Coupled LH spectrum for C3 (left) with two values of edge density at the launcher and C4 (right) launchers.

The LH spectra for the C3 and C4 cases modelled in ALOHA are shown in Fig. 1. As a linear estimate, the driven LH current depends on $n_\parallel$ as $J_{LH} \propto sign(n_\parallel)/n_\parallel^2$ [9]. In the C3 spectrum, the negative $n_\parallel$ spectrum is approximately distributed between harmonics of the main $n_\parallel$. The main negative contribution to J_{LH} comes from $-n_{\parallel 0}$, which is deposited as the same radial location as $n_{\parallel 0}$ and thus simply reduces the driven current without changing the shape of the profile. In the C4 spectrum, a secondary lobe carries a significant fraction of the power at a relatively low value of $|n_{\parallel}| \neq n_{\parallel 0}$ ($n_{\parallel} = -2.9$ in our case). This lobe is a characteristic feature of waveguide structures where passive waveguides are positioned between the active waveguides. For ITER-like conditions, the passive waveguides are necessary to allow for a sophisticated cooling system [2]. The main and secondary lobes are generally absorbed at different radial regions and drive currents in opposite directions, thus modifies the current profile (Fig. 3(a)). In our case (#45525) C3PO/LUKE predicts that the secondary lobe is absorbed fairly centrally in a single pass ($r/a \sim 0.2$) where it reduces the current locally.

Fast electron bremsstrahlung reconstruction

The reconstructed HXR signal from fast electron bremsstrahlung shows good agreement - both in shape and absolute amplitude - with experimental measurements for both C3 and C4 launchers in the energy range 50-110 keV (Fig. 2). This comparison validates the modelling process. Because the main and secondary lobes in the C3 spectrum deposit the power at the same radial locations, the current profile is not affected when the directivity decreases, but the current drive efficiency is reduced.

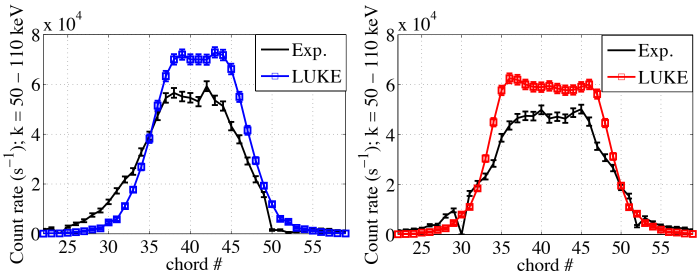
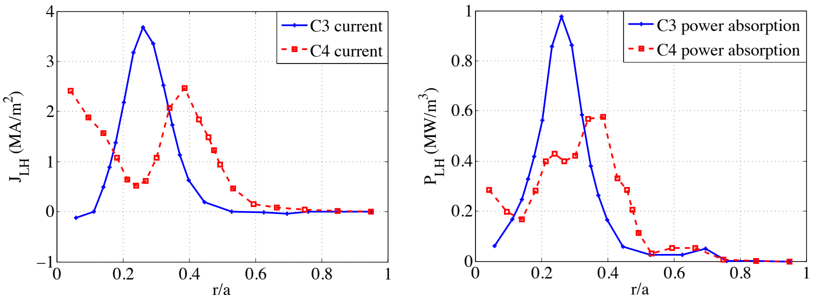


Figure 2: Reconstructed HXR signal compared with measurements in the energy range 50-110 keV for C3 (left) and C4 (right) driven discharge.

In the C4 case, the power from the secondary lobe is generally not deposited in the same radial location as the main lobe, such that the power and current profiles do not overlap (Fig. 3(b)).

Because the perpendicular FEB emission does not depend upon the toroidal direction of the emitting electron, the radial FEB profile is more representative of the power deposition profile than the current profile. Therefore, the PAM current profile can differ significantly from the one obtained with the FAM launcher in similar conditions, even though measurements of HXR signals due to FEB emission may be similar in the two cases. This study also shows that it is generally appropriate to use Abel-inverted FEB profiles as estimates of the LH current profile for



(a) Current profile. (b) LH power absorption profile.

Figure 3: Output from C3PO/LUKE code for C3 (blue) and C4 (red) driven current.

integrated modelling of FAM scenarios. However, the two profiles can be significantly different in PAM scenarios, for which this estimation procedure is not valid.

Conclusion

The reconstruction of the HXR emission from FEB bremsstrahlung shows good agreement between simulations and fully non-inductive Tore Supra LHCD experiments with both C3 (FAM) and C4 (PAM) launchers in low density and high temperature conditions for which the wave is absorbed in few passes. When the launcher mouth density is obtained by matching the reflection coefficient of ALOHA simulations with experimental measurements, ray-tracing and Fokker-Planck simulations provide a good estimate of the driven current, with efficiencies comparable for C3 and C4. The contribution of the secondary lobe specific to PAM spectra results in a modified current profile that can differ significantly from the Abel-inverted FEB profile.[1]

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