27th EPS Conference on Contr. Fusion and Plasma Phys. Budapest, 12-16 June 2000 ECA Vol. **24B** (2000) 788 -791

1D simulations of current profile control in purely non-inductive discharges for the Tore Supra CIEL project

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1. Introduction

The upgrade of the Tore Supra inner vessel components (CIEL project [1]) and of its various heating systems will provide a unique opportunity to study enhanced confinement regimes in high-power discharges, which will be sustained on a reactor-relevant time-scale by purely non-inductive current drive (lower hybrid waves and bootstrap). The ability to control the localisation of the non-inductive current sources in steady-state conditions, which is a primary requirement for such advanced tokamak operation, is addressed by carrying out fully consistent 1D simulations of electron heat transport, plasma equilibrium and current drive (CD). Since lower hybrid (LH) waves in CIEL high-density scenarios are absorbed in the "few pass" regime, it is critical to carry out the simulations using a Ray-Tracing/Fokker-Planck (RT/FP) code, which provides a realistic description of LH waves propagation and absorption in this regime [2-4]. Fully consistent steady-state plasma equilibria are hence obtained by running successive iterations between the DELPHINE RT/FP code [3,4] and the ASTRA transport code [5]. The results of the simulations are presented, and the strong coupling between plasma current density profile and LH power deposition is analysed. Consequences for current profile control by monitoring the launched LH power spectrum in such plasma configurations are also discussed.

2. Description of scenario and modelling

Simulations are carried out for CIEL high-density deuterium plasmas : volume-averaged electron density $\langle n_e \rangle = 5.0\times10^{+19}$ m^{-3}, effective charge $Z_{eff} = 1.72$, toroidal field $B_t = 4$ T, major radius R = 2.4 m, minor radius a = 0.72 m, circular cross-section. Heating and CD powers are : $P_{ICRH} = 10$ MW (hydrogen minority heating scheme, 50 % of power deposited on electrons, broad central deposition), $P_{ECRH} = 2$ MW (central deposition), $P_{LH} = 12$ MW (3 grills), with 60 % of the LH power contained in the main peak of the launched $n_{//}$-spectrum, whose central value $n_{//0}$ ranges from 2.0 to 2.6. Since it is presently not possible to update LH power deposition with the RT/FP code while ASTRA is running, the following coupling method is used : ASTRA calculates a standard plasma evolution towards a steady state with fixed LH power deposition and driven current density profiles, as given by the RT/FP code. The obtained steady-state plasma equilibrium and electron temperature profile are then used as input in DELPHINE to calculate a new LH current and power deposition. Though radial diffusion of fast electrons is likely negligible is such plasmas [6], these LH profiles are smoothed using a radial diffusion coefficient of the order of 0.5 m^2/s, mainly for numerical reasons, but also to account for the fact that measured LH power deposition profiles are systematically broader than the prediction of standard RT/FP codes [4,7]. The smoothed LH profiles are then given as input for a new ASTRA calculation. This process is iterated until a constant LH power deposition profile is reached. In ASTRA calculations, density profile is kept constant, and electron heat transport is computed using the mixed Bohm-gyroBohm model with shear function described in [8]. This model takes into account a reduction of the electron heat diffusion coefficient for low or negative magnetic shear, and has been extensively validated on Tore Supra [8,9]. Bootstrap current is self-consistently calculated in ASTRA using Hirschmann model.

3. Results

Simulations show that the strong dependence of LH power deposition on the plasma current density profile j(r) is the dominant physical effect which regulates the characteristics of the discharges. This is easily observed by considering successive intermediate steps of the convergence between the codes (fig. 1) : the LH power deposition is rather central when calculated from a plasma equilibrium with hollow current density profile, while it is strongly off-axis when the maximum of the starting current density profile is close to the centre. Hence LHCD systematically tends to broaden and smooth the initial current density profile, whatever its shape. This behaviour is directly linked to the evolution of $n_{//}$ along the ray path during its very first reflections, which completely governs the localisation of the LH power deposition in the few-pass regime [3]. As shown on fig. 1, the $n_{//}$-upshift is rather fast (resp. slow) when plasma equilibrium has a peaked (resp. hollow) current density profile, which provides off-axis (resp. central) absorption. Such a mechanism is also at the origin of the plasma current dependence previously observed in discharges with dominant inductive current drive [3].

Since LH waves drive in these discharges about 60 % of the total current, and since bootstrap current is mainly localised just inside the magnetic shear reversal provided by LH hollow power deposition, the total current density profile j(r) and the one driven by LH waves have a similar shape. Therefore, LH power deposition is self-regulated through its dependence on the total current density profile. A major consequence of this process is the reduction of the current profile control capability expected by monitoring the launched $n_{//}$-spectrum.

Control of LH power deposition may however be recovered when $n_{//0}$ may be tuned from the Mid-Radius Accessibility Limit (MRAL) to the Central Electron Landau Damping Condition (CELDC) [10]. This requires to adjust plasma parameters to the $n_{//0}$ tuning range of the LH grill, which is done here with high density $\langle n_e \rangle = 5.0\times10^{+19}\ m^{-3}$ and strong and radially broad electron heating, providing a central electron temperature T_{e0} ~ 6-8 keV. Since $n_{//0}$ tuning range is usually small with multijunctions grills ($\Delta n_{//0}$ ~ 0.6), MRAL and CELDC must be close to each other (separated by $\Delta n_{//}$ ~ 1), but must not overlap since it would prevent to drive current in the plasma core with LH waves. In this configuration, two extreme positions of LH power deposition may be obtained by monitoring $n_{//0}$, since reflection at the MRAL leads to ray trajectories with large $n_{//}$-upshift and off-axis absorption [3,11], while LH power is absorbed in the plasma core when rays are close to the CELDC (fig. 2). This configuration also allows to reduce considerably the influence of the LH self-regulation process, because MRAL and CELDC are reached in single pass. Self-regulation proceeds by modifying the $n_{//}$-downshift which occurs just after launch, and which is large (resp. small) in equilibria with peaked (resp.

hollow) current density profile (fig. 1). This alters the expected power deposition in the following manner : with $n_{//0}$ = 2.0 (hollow LH power deposition), the initial $n_{//}$-downshift is small, so that part of LH power gains access to the plasma core, providing some central absorption. Conversely, with $n_{//0}$ = 2.6 (peaked LH power deposition), the initial $n_{//}$-downshift is large, so that part of LH power is not absorbed in the plasma core, and undergoes during second pass $n_{//}$-upshift and off-axis absorption, thus broadening LH power deposition towards plasma edge (fig. 2). However, since the major part of LH power reaches with the chosen parameters MRAL or CELDC during the first pass whatever the evolution of $n_{//}$, the self-regulation process does not modify the main localisation of current drive. Therefore, an efficient control of LH power deposition and current density profile may be obtained by tuning $n_{//0}$ from 2.0 to 2.6 in CIEL discharges at high density and strong and radially broad electron heating.

4. Conclusion

These simulations have allowed to investigate for the first time the self-regulating mechanism which rules the LH power deposition profile in purely non-inductive discharges dominated by LHCD in the few pass regime. The phenomena and current profile control methods described above are particularly relevant for present day tokamaks with non-negligible inverse aspect ratio, where electron temperature is close but not yet equal to first-pass ELD condition, but also for the plasma current ramp-up phase in the future ITER device. This work also shows that it is critical to use a RT/FP code coupled to self-consistent transport and equilibrium calculations to provide a correct modelling of the j(r)-dependence of LH power deposition profile in the few pass regime. A real coupling between the two codes has to be carried out to study the dynamical aspect of scenarios, in particular the temperature and current density periodic oscillations which may occur in configurations with hollow and significantly off-axis LH power absorption [12,13]. Finding methods to stabilise these oscillations is a critical issue for the sustainment of enhanced confinement over a large fraction of the plasma volume.

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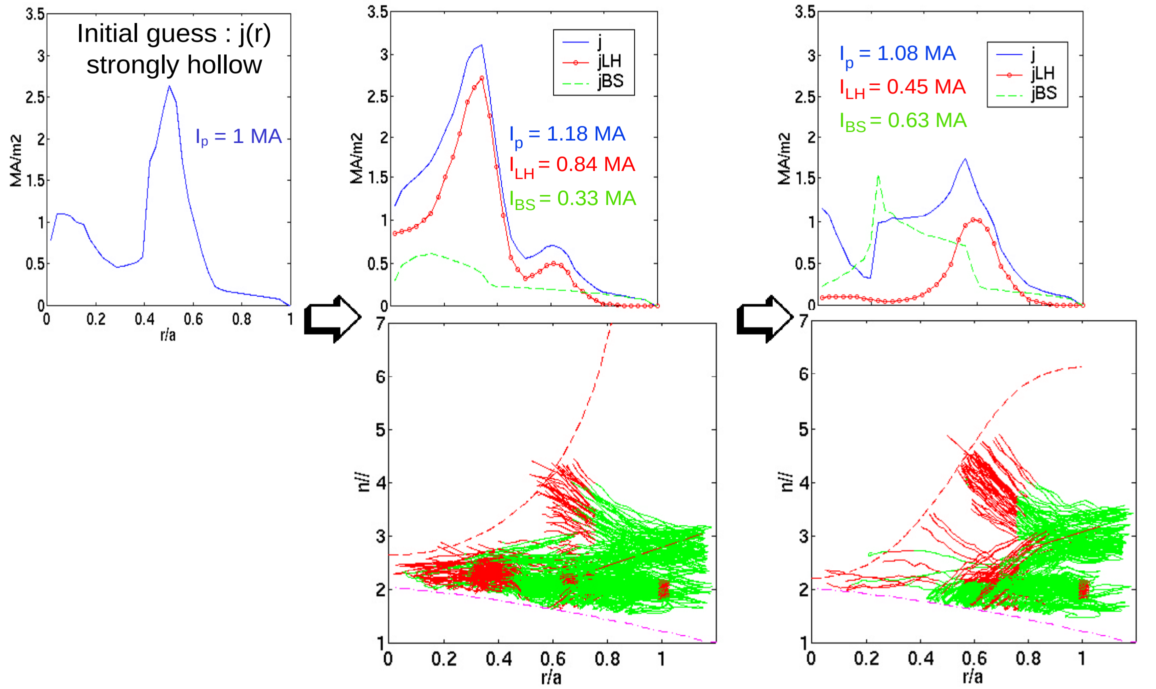

Figure 1 : Successive iterations for the case $n_{//0}$ = 2.0 (from left to right). Top row : current density profiles (dashed : bootstrap; circle : lower hybrid; solid : total). Bottom row : corresponding LH rays propagation ($n_{//}$ versus normalised radius); dashed : ELD condition $n_{//} = \frac{7}{\sqrt{T_e}}$; dash-dotted : accessibility condition $n_{//} = \frac{\omega_{pe}}{\Omega_{ce}} + \sqrt{\varepsilon_{\perp}}$ (notations of ref. [10]). Red (darker) zones of rays indicate strong power absorption.

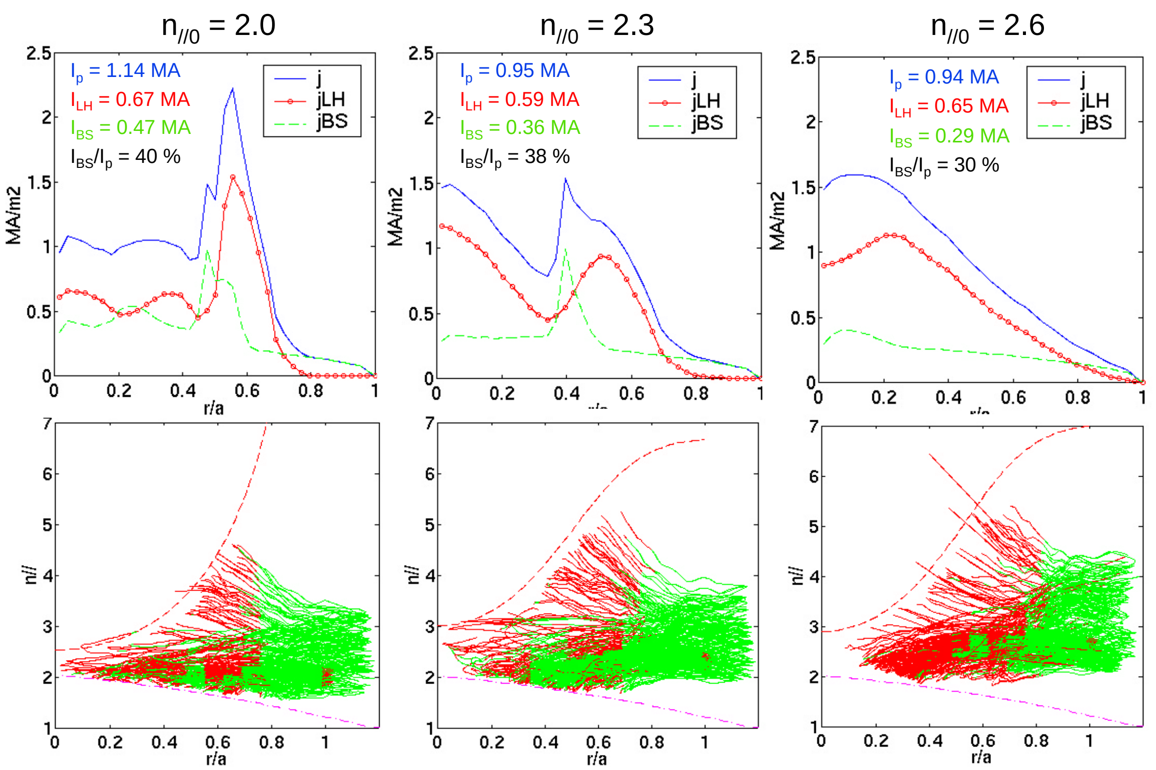

Figure 2 : Final results after convergence for cases $n_{//0}$ = 2.0 (left column), $n_{//0}$ = 2.3 (middle), $n_{//0}$ = 2.6 (right). Top row : current density profiles. Bottom row : corresponding LH rays propagation.