Modelling of LHCD in high magnetic field, high density tokamak configuration.

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Abstract. New modelling results (performed by means of “Raystar” code, a 2D ray-tracing-Fokker-Planck numerical tool) are presented with the aim of assessing the radial LH-driven current profiles in tokamak devices characterized by high density and high magnetic field as recently proposed by MIT. The modelling calculation is performed as function of plasma and antenna parameters, in particular the peak n_e, the width of the launched RF power spectrum, the coupled power, the launched position of the antenna (high field side injection) and the kinetic profiles. Moreover by launching LH antenna spectra with a suitable n_e width the power spectrum propagating in the plasma is weakly modified by quasi-linear broadening effects. Non-linear interactions with plasma density fluctuations of the thermal background are also negligible, as well as the PI at the plasma edge. The LHCD efficiency has been calculated and correlated to these parameters.

1. Introduction
The project ARC [1] and, more recently, the project SPARC [2] by MIT as compact, high magnetic field and high-density tokomaks have re-launched the Lower Hybrid Current Drive (LHCD) concept as method for actively and efficiently generating current in the outer radial half of plasma. In particular, driving current near the pedestal layer of H-mode regimes could help preventing the onset of MHD instabilities detrimental for confinement. The idea relies essentially on the injection of RF power from the high-field side of the tokamak [3,4], which enables lower hybrid (LH) waves to better penetrate into the plasma bulk, owing to negligible effect of spectral broadening that wave-scattering by density fluctuations is expected to occur in this condition. Moreover by injecting LH from the high field side it is possible to choose a sufficiently low n_e (at the grill antenna) owing to a favourable accessibility condition, and this results in a higher LHCD efficiency.

In order to be economic, i.e., feasible, a tokamak reactor needs exploiting the current that the plasma steadily self-produces via particle transport (bootstrap) effect, in the presence of pressure gradient across the column that largely occurs near the radial periphery [5,6]. Therefore, this region should be taken under control against turbulent transport that can dramatically reduce the thermal insulation of the plasma column.

The key for accomplishing this task is the current drive (CD) by LW waves. The method can match the natural current profiles and offers much higher efficiency than other CD tools. Unfortunately for decades the LHCD concept could not be extrapolated to reactor relevant high values of plasma density and temperature. In particular too high temperature was preventing penetration of the launched RF
power into the plasma [7], and a greater flexibility of the method should be necessary.

We present here results obtained by a numerical model, useful for assessing the LHCD profiles \( j_{LH} \) in the plasma, which has a much simpler architecture [8] than other approach based on the so-called multi-pass. The latter is not relevant for a reactor. The method utilised here has allowed individuating in the spectral width of the launched antenna spectrum a new key for improving flexibility in shaping the \( j_{LH} \) profile and for removing the obstacle for RF power penetration represented by too high temperatures of reactor plasmas, by means of a narrower antenna spectrum [9]. Code robustness is supported by proven capability of performing successful interpretation [10,11] of LHCD experiments [12], and prediction of guidelines for breakthrough of LHCD method at reactor-relevant high plasma densities established on FTU (Frascati Tokamak Upgrade) [13].

Non-linear topic [14] has been extended to the LHCD regime to the point of capture in the spectral broadening the cause of more peripheral RF deposition observed in the experiments [10–12]. Indeed, in milestone experiments of JET of long-lasting transport barrier sustained by LHCD [12], the assessed non-linear spectral broadening enabled to model the \( j_{LH} \) profile in agreement with measurement of LHCD effect [10,11]. The same work enabled predicting that higher temperature of high-density plasma edge should be useful for reducing the undesired spectral broadening occurring in operations at high plasma densities and enabling the RF penetration into the plasma, as however QL theory expects [13].

The paper is organized as follows: In Section 2 an explanation of the numerical code and a description of the SPARC tokamak plasma is given. In Sec. 3 the results of the numerical code are presented and discussed. In Sec. 4 the conclusion are give.

2. Description of the ARC tokamak and plasma and antenna parameters

Although bootstrap current will provide a majority of the total current, significant auxiliary current drive will be necessary to sustain the plasma. The ARC reactor has been proposed as Fusion Nuclear Science Facility (FNSF) [1] in USA. In ARC auxiliary heating will be necessary to bring the plasma to a state in which fusion alpha heating becomes dominant. In particular the RF current drive in the range of the LH wave results to be the most flexible way to drive the current and to supplement the bootstrap current in the external half radius of the plasma. ARC is a \( \sim 200 – 250 \, MW \) tokamak reactor with a major radius of \( R_0 = 3.3 \, m \), a minor radius of \( a = 1.1 \, m \), plasma elongation 1.84, triangularity 0.67, Shafranov shift \( \Delta = 0.24 \, m \), plasma current \( I_p = 7.8 \, MA \), edge safety factor \( q_a = 4.7 \) and an on-axis magnetic field \( B_0 = 9.2 \, T \). The bootstrap fraction is only \( \sim 63\% \), which requires a relatively large external control of the current profile. External current drive is provided by RF launchers that are using \( 25 \, MW \) of lower hybrid wave power with an efficient current drive with a chosen frequency \( 8 \, GHz \). The other plasma characteristics of ARC are a peak density \( 1.8 \times 10^{20} \, m^{-3} \), and peak electron temperature \( 27 \, keV \). In Figs 1 and 2 the kinetic profiles obtained by running a transport code are presented as function of the normalized poloidal flux \( \rho = \left( \frac{\psi}{\psi_0} \right)^{1/2} \), where \( \psi_0 \) is the value of the flux at the last closed magnetic surface. On the same plot (dotted blue line) is reported the interpolating analytical function (polynomial) as well as the SOL profiles with a decay length \( \lambda = 0.1 \, m \) we have used in the simulation.
Figure 1. Plasma density as function of the normalized poloidal flux $\rho = \sqrt[\psi (\psi_0)}$ in units of $10^{20} \text{m}^{-3}$.

Concerning the LH antenna characteristics it is relevant the choice to inject the wave from the high field side. The relatively high frequency 8 GHz is chosen to avoid parasitic damping on $\alpha$ particles, which occurs when the perpendicular phase velocity of the wave $v_\perp$ matches the alpha birth velocity [15]. The injection from the high field side instead helps the injection of low $n_\parallel$ spectrum because increases the accessibility and improve the CD efficiency. Another feature of internal launch is that owing to a relatively high magnetic field the effect of spectrum broadening due to the density fluctuations is attenuated and the spectrum (relatively narrow) does not broaden favoring a more internal EL (Electron Landau) absorption owing to the high electron temperature. The antenna grill is located 1.75 m above the mid-plane on the high field side. The LH antenna is envisioned to be a single row of toroidally continuous waveguides operating in a passive-active mode. Each guide is 7mm wide times 60 mm high. In Fig. 3 is depicted the power spectrum in arbitrary units vs the parallel wavenumber and the integrated power. In practice the spectrum can be well approximated by two Gaussian:

$$P(n_\parallel) = P_0 e^{-\frac{(n_\parallel - n_{\parallel, \text{peak}})^2}{\sigma}}$$

, centered for $n_\parallel > 0$ at $n_{\parallel, \text{peak}} = 1.67$, and $\sigma = 0.05$, $P_0 = 1$; and for $n_\parallel < 0$, $n_{\parallel, \text{peak}} = -8.5$, $\sigma = 0.05$, and $P_0 = 0.25$.
3. Numerical results of the Raystar code

The Raystar code consists of several modules each of them is devoted to keep in the simulation all the feature of the physics of LH propagation and absorption. In this simulation we have used the quasilinear module that includes a 2D ray-tracing propagation (in the magnetic equilibrium coordinate), coupled to a quasilinear 2D (in velocity space) Fokker-Planck routine that accounts for the quasilinear absorption of the wave. The numerical results of Raystar are summarized in the following plots showing the power deposition and current drive profiles, the damping rate and the global absorbed power and generated current (efficiency) in several antenna and plasma conditions. In a first set of figures we present a standard low field side injection when coupling the spectrum of Fig. 3, and considering the plasma parameters of ARC described in Sec. 2, including the kinetic profiles of Figs. 1 and 2; and propagating the wave from the equatorial plane in the low field side. In Fig. 4 and Fig. 5 we have plotted respectively the power deposition and current driven profiles vs the normalized radial variable \( r \). It is possible to notice that the spectrum is entirely absorbed at the first pass and the deposition peaks at \( \rho = 0.6 \) (half radius). In Fig. 5 the absorbed power in Watt and global current in Ampere are calculated showing that the coupled power (directivity 60\%) of around 6MW is completely absorbed by the plasma at the first pass and produce a global current of 1.2 MA with an efficiency of \( \eta = 0.5 \).
Figure 4. Power deposition and current drive profiles (red line power, blue line current) vs the plasma normalized radius $\rho$ obtained for the kinetic profiles in Figs. 1 and 2 and coupled spectrum as in Fig. 3, and low field side injection.

The effect of broadening the power spectrum (to both density fluctuation or PI activity at the plasma edge) is illustrated by considering the following spectra coupled to the plasma in the low field side (Fig. 6)

Figure 5. Absorbed power and global generated current related to the deposition profiles of Fig. 4.

Figure 6. Power spectrum in arbitrary units generated by the LH antenna of ARC at various width.

The effects of the spectrum on the wave absorption and penetration in the plasma is reported in the following figures. In Fig. 7 the current drive $A/m^2$ is reported for the four spectra defined in Fig. 6. As it is possible to see clearly on the figure the peak of the current drive moves towards the external
zone of the plasma from around $\rho = 0.6$ up to 0.7 as established and studied (also by means of an analytical model) in details in Refs. [16,17]. In particular for the very large spectrum (pale blue in Fig. 6) it is possible to observe a relevant absorption around the pedestal layer. This is due to the fact the slower components of the spectrum are efficiently absorbed when the temperature increases strongly (pedestal). In Fig. 8 where we have plotted the quasi-linear damping rate (defined as $\hat{P} = \int_{\eta_{tr}}^\eta_{tr} dn_{tr} e^{-\int_{\eta_{tr}}^\eta_{tr} dx}$, $P$ is the normalized power) vs $\rho$, this fact results clearer. Near the pedestal a relatively large fraction of power (40%) is absorbed near the pedestal layer forming a thin layer of current, the remaining power (ascribed to the faster part of the spectrum) is able to reach a more internal region and peaks the current around $\rho = 0.7$.

Now we consider the LH propagation from the high field side injection. As stated previously the antenna can be accommodated in the high field side of the tokamak 1.75m above the mid-plane, and the LH can propagate toward the plasma centre from the high field side. This has a practical advantage i.e. the accessibility of the entire spectrum is improved although the high density and the peak of the $n_e$ can be reduced improving as well the efficiency of the CD. Another advantage is that the spectrum when propagating in high magnetic field feels less the effects of density fluctuation and remains sufficiently narrow conserving the same shape without broadening. In Figs. 9 the current density profile is shown at various width of the spectrum $\Delta n_{tr} = 0.05 - 0.1$, and several launched (absorbed) power $P_{abs} = 11 - 18 - 22 - 31 MW$, showing that more or less the penetration is included between $\rho = 0.5 - 0.6$ . It is easily to recover the feature that narrower is the spectrum deeper is the penetration layer. The role played by the power for the same spectrum width is less evident in this case.
4. Conclusions

A preliminary numerical analysis of the Lower Hybrid applied to ARC tokamak reactor characterized by high density and high magnetic field has been performed with the numerical tool Raystar considering various configurations of the spectrum width and injected power as well as conventional injection of the wave from the outer mid-plane and injection from high field side. Although injection from the outer mid-plane (low field side) does not present particular problem and the deposition of the power and the consequent current drive occurs in layer included from half radius to the pedestal zone, the high field side injection is preferred because of the more flexibility in the control of the spectrum. The accessibility is guaranteed also for very low parallel wavenumbers and the effects of density fluctuations is strongly reduced. Good efficiency can be also obtained.

Acknowledgments

Authors wish to acknowledge fruitful discussions with Dr. Paul Bonoli, and to thank him for having furnished the data, equilibrium and kinetic profile of ARC.

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