Lower hybrid current drive at densities required for thermonuclear reactors

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Abstract. For the progress of the thermonuclear fusion energy research based on the tokamak concept, it is essential to drive current non-inductively in high-density plasmas for producing steady state, thermally well insulated, stable and large volume plasmas. ITER (International Tokamak Experiment Reactor), as an example, will have relatively high densities at the periphery of the plasma column ($n_{e\_0.8} \approx 0.8 \cdot 10^{20}\,m^{-3} - 1 \cdot 10^{20}\,m^{-3}$ at normalised minor radius $r/a \approx 0.8$, where $r = a$ is the plasma minor radius at the last closed magnetic surface). The externally launched lower hybrid wave, producing the lower hybrid current drive (LHCD) effect is potentially the most suitable tool for driving current at large radii of fusion relevant plasmas, consistent with the needs of ITER. However, signs of penetration in the bulk of the coupled LH power didn't occur for plasma densities at the edge approaching ITER requirements. Wave-wave interactions at the plasma edge would explain the observed experimental behaviour. In LHCD experiments at relatively high plasma edge densities, the parametric instability (PI) produced spectral broadening becomes so strong that penetration into the plasma core is prevented. By numerical investigation, it was also predicted that the PI effect are mitigated when operating with relatively high electron temperatures at the plasma periphery, resulting in better wave penetration into the core of high-density plasmas. In order to test the effect of higher edge temperature (T_{e_outer}) in producing conditions favouring LH power penetration at high density, the flexibility of FTU operations have been exploited, consisting in the lithium-coated vessel, plasma column was leaned on the poloidal outer limiter, which reduces the plasma-wall interactions, consequent to the smaller plasma-wall wetting area. Gas fuelling assisted by pellet has been also used, with LH power coupled just after the pellet injection. We refer to these conditions as high T_{e_outer} regime, for distinguishing it from the standard regime described before. With this operation, plasma targets with much higher density (up to $\overline{n_e} \approx 2 \cdot 10^{20}\,m^{-3}$) have been obtained, with higher electron temperature at the periphery, ($T_e \approx 300$ eV at $r/a \approx 0.8$ and $T_e \approx 150$ eV at r/a ≈ 0.9, to be compared with $T_e \approx 100$ eV at $r/a \approx 0.8$ and $T_e \approx 50$ eV at $r/a \approx 0.9$ of standard conditions). Effects of LHCD have been observed for the first time in FTU at plasma density even higher than that required for ITER.

1. Introduction

Non-inductive current tools based on power externally launched in the plasma, would operate in ITER (International Thermonuclear Experiment Reactor) at relatively high plasma densities also in the layers of the plasma periphery were the first interaction with the launched power occurs. ITER requires at the periphery of the plasma column: $n_{e\_0.8} \approx 0.7 \div 1 \cdot 10^{20}$ m^{-3} at normalised minor radius $r/a \approx 0.8$, where $r=a$ is the plasma minor radius at the LCMS; similar values are also required at the magnetic axis (i.e.: $n_{e0} \approx n_{e\_0.8}$) [1]. Lower hybrid (LH) waves, coupled to plasmas by means of a phased waveguide array antennas [2], produce the LHCD effect [3,4] that was

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confirmed in tokamak plasma experiments that operated only at tokamak at plasma densities markedly lower than those required for ITER [5-12]. Penetration of the coupled LH power in the core, strongly degraded in JET for plasma density at the periphery exceeding a value ($n_{e\_0.8} \approx 0.3 \cdot 10^{20}\,\mathrm{m}^{-3}$) more than a factor two lower than the value required for ITER [13]. A similar behaviour was observed also in standard operating regimes of FTU [14].
Available data of modelling and experiments indicated that the undesired deposition of the coupled radiofrequency (RF) power at the very plasma edge could be due to the effect of non-linear plasma-wave interaction, namely the parametric instability (PI) [15-19], although other concomitant mechanism cannot be ruled out. PI produce a strong broadening of the antenna spectrum when operating at high plasma densities that are normally characterised by low electron temperatures [9,10]. Such behaviour occurs in FTU high plasma density discharges ($n_{e\_av} \approx 1 \cdot 10^{20}\,\mathrm{m}^{-3}$) characterised by low electron temperatures $T_{e\_0.8}$ ($\lesssim$0.1 keV) in the radial layer located from the antenna ($r/a \approx$1.01) up to 4/5 of the minor radius. The PI modelling shows also that higher operating temperatures in the regions of the plasma periphery obtained in a new regime referred to as high T_{e_outer} regime ($T_{e\_0.8} \gtrsim$ 0.3 keV plasma parameters, with $n_{e\_av} \approx 2 \cdot 10^{20}\,\mathrm{m}^{-3}$) would strongly reduce the spectral broadening thus enabling the penetration of the coupled LH power in the core [14]. This regime of FTU identified proper operations useful for diminishing the PI effect, thus enabling the LH power penetration and the occurrence of the LHCD effect at reactor-grade high plasma densities.
In the present paper we show: i) the basic PI modelling information useful for addressing the experimental operation, ii) the detail of the FTU operations necessary for producing LHCD effects at high plasma densities, and iii) formulate the procedure for producing the LHCD effects in devices supplied with limiter or divertor. The way for controlling the PI-produced spectral broadening can be summarised as follows: i) PI produces LH sideband waves that broaden in frequency and $n_{//}$ the antenna spectrum and strongly affects the radial profile of the LH power deposition in the plasma ($n_{//}$ is the wavenumber component parallel to the confinement magnetic field); ii) PI effects can become so strong at high plasma densities that they prevent the coupled LH power from penetrating to the plasma core; iii) high electron temperatures in the plasma periphery (at $r/a \approx$0.8, hereafter referred to as T_{e_outer}) should play a key role in mitigating the PI-induced spectral broadening and, consequently, allowing LH wave penetration in the core of reactor-grade plasmas; iv) relatively high T_{e_outer} may be produced in high-density plasmas by means of low particle recycling from the vessel wall [20] (as diagnosed by the D-alpha spectroscopic signal detected in the vacuum vessel chamber during experiments), and by absorption at the plasma edge via electron cyclotron resonant heating (ECRH) produced by externally launched radiofrequency power.

2. Spectral broadening modelling

The PI-induced spectral broadening is calculated by the LH[star] code [9,10,14] and used for determining the LH deposition in the plasma. Ion-sound-quasi-mode-driven LH sideband waves result to be the main cause of the spectral broadening. Frequencies and growth rates of the coupled modes are identified by solving the parametric dispersion relation [15-17]:

$$\varepsilon(\omega,\mathbf{k}) - \frac{\mu_1(\omega_1,\mathbf{k}_1,\mathbf{k}_0,E_0)}{\varepsilon(\omega_1,\mathbf{k}_1)} - \frac{\mu_2(\omega_2,\mathbf{k}_2,\mathbf{k}_0,E_0)}{\varepsilon(\omega_2,\mathbf{k}_2)} = 0 \qquad 1$$

ε is the dielectric function, ω, **k** are, respectively, the complex frequency and wavevector of the low frequency perturbation driving the PI. The suffix i=0,1,2, refers to the pump, the lower and the upper sidebands, respectively, while $\mu_{1,2}$ are the coupling coefficients referring to the lower and upper sidebands, respectively (see Ref. 10 for details). For tokamak plasma parameters, Eq. 1 generally individuates instabilities driven by low frequency modes in the range of ion-sound frequencies ($\omega << \omega_{ci}$). A solution of Eq. 1 for plasma parameters of the LH experiment on FTU is shown in the Figure 1.

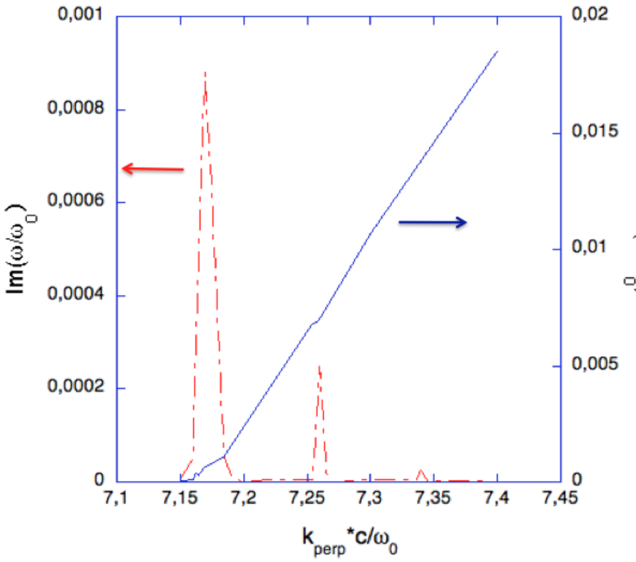

Fig. 1. Growth rate (in red and dotted/dashed line) and frequency (in blue and continuous line in the left box, dashed in the right box) of the quasi-mode driving PI for FTU plasma parameters of the plasma edge: $n_e \approx 0.02 \cdot 10^{20}$ m^{-3}, T_e=25 eV $n_{//0}$=2.0 (pump wave), $n_{//}$=9 (ion-sound quasi-mode), B_T =4.8 T, operating frequency: 8GHz.

Peaks of growth rate with decreasing amplitude with the abscissa parameter, $k_{perp}c/\omega_0$ occur. The first peak corresponds to PI driven by ion-sound quasi-mode (with $\omega<\omega_{ci}$). The other peaks refer to harmonic of ion-cyclotron harmonic frequencies with $\omega \approx p\omega_{ci}$, with p=1,2,…).. The solutions of Eq. 1 (at around $k_{perp}c/\omega_0$ ≈7.17) provide a potential source of broadening of the launched LH wave spectrum of the order 10 MHz. The plasma electron temperature mainly affects the growth rate. The highest value occurs for plasma regions radially located at the very edge (where T_e=10 eV). The growth rate diminishes for higher electron temperatures, and PI doesn't occur anymore for $T_e \gtrsim 500$ eV. Once identified wavenumber and frequency of the strongest coupled modes in the plasma, the LH^{star} code calculates the spectral broadening by taking into account the convective loss due to the geometry of the LH antenna and the plasma inhomogeneity [17,10]. The PI driven by ion-sound quasi-modes provide a source of broadening of the launched LH spectrum in frequency and $n_{//}$ as well. This circumstance is very important as, due to quasi-linear effects, the LH deposition profile results to be strongly dependent the $n_{//}$ spectrum resulting from the combination of the spectrum launched by the antenna and the LH sidebands produced by PI.. This spectrum should be considered as the effective *initial spectrum* available for propagation in the core, and corresponds to a continuously broadened spectrum from $n_{//peak}$ to $n_{//cut\text{-}off}$, where $n_{//peak}$ is the peak value of the spectrum launched by the antenna and $n_{//cut\text{-}off}$ is the maximum $n_{//}$ value of the PI sideband at the cut-off, which is determined by convective loss due to plasma inhomogeneity. As critical aspect for the LH spectral broadening modelling, it is important that the mechanism of wave convective loss due to plasma inhomogeneity [10] should be considered, as it is decisive for calculating the contribution of the PI-produced LH sideband waves with high wavenumber, necessary for determining the LH power deposition and the driven current in the plasma.

As result, for high-density plasmas of FTU performed in the reference standard regime that exhibits a cold plasma edge, a small pump power depletion fraction [16] (of about 0.1%) occurs for the sidebands with highest wavenumber (with $n_{1//} \cong n_{1//\_\text{cut-off}} \approx 30$). The frequencies of these sidebands are shifted from the pump up to about 20 MHz. Conversely, for the produced high T_{e_outer} regime, a much smaller spectral broadening is obtained as a consequence of lower PI growth rates. The LH sideband waves result to be much less shifted from the pump in wavenumber ($n_{1//} \lesssim 7$) and frequency ($\Delta f \lesssim 10$ MHz).

3. FTU experimental set-up

The description of the experimental device and the plasma operations useful for producing LHCD effect at high plasma density are given by following. The reference experiment [14] considered here has been carried out on the Frascati Tokamak Upgrade (FTU), which is a medium sized high magnetic field (up to 8 T) tokamak with a toroidal major radius on axis of 0.93 m and minor radius of 0.3 m. The machine produces plasmas with densities at or above the level of a reactor (line averaged density up to $4{\cdot}10^{20}$ m^{-3}) with a plasma current flat-top of 1.5 s duration. The options have been utilised (as motivated by following) of displacing the plasma, with circular cross section, respectively, both towards the toroidal limiter, which is located on the high field side and has a relatively large plasma-wall contact area (of about 1.7 m^2), or towards the poloidal limiter, located on the low field side, which has a much smaller plasma-wall contact surface (about 0.026 m^2).

Two different configurations have been utilised exhibiting different plasma edge temperatures in high-density plasma of FTU. The following options available on the FTU device have been exploited. *i*) Toroidal or poloidal limiter operations. With toroidal limiter operations, a stronger plasma-wall interaction occurs due to the larger plasma-wall contact area. In these conditions lower recycling and relatively low temperature at the plasma periphery generally occur. Conversely, in operation with the plasma displaced towards the poloidal limiter, the D-alpha emission level is about ten times smaller, and slightly higher electron temperatures are observed at the plasma edge than in similar experiments using the toroidal limiter. *ii*) Vacuum vessel covered by boron or lithium. Such coatings are both useful for improving plasma operations and reducing the plasma impurity content. With lithium, sprayed on the walls from the limiter, where it is present in liquid form [20], the plasma is particularly protected from fluxes of impurities with high values of effective electric charge, and is characterised by a level of recycling significantly lower than with a boron-coated vessel [21]. *iii*) Plasma fuelling assisted by pellet injection. FTU has a pneumatic single stage multibarrel pellet injector [22], capable of firing up to eight pellets per plasma discharge with a typical velocity of 1.3 km/s and a mass of the order of 10^{20} deuterium atoms. As critical aspect of the pellet technique, in order to achieve a deep plasma core fuelling for producing high electron temperature at the plasma periphery, proper velocity and mass of pellets should be set. In addition, the LH power switch-on time point should occur with some delay (of the order of 10 ms) with respect to the pellet injection, in order to prevent the ablation of pellet by the coupled RF power. *iv*) In order to further reduce the recycling, the technique of extra-gas fuelling in the early phase of discharge has been used. In the standard gas fuelling technique, the requested density value at the start of the LHCD pulse is set by the plasma density feedback control, which generally produces a continuous gas injection during the whole plasma discharge. Relatively high levels of recycling and low temperatures at the plasma periphery were obtained on FTU with this operation [14]. In the technique of extra-gas fuelling in the early phase of discharge, a large amount of gas should be injected in the early phase of discharge (but still during the plasma current flat-top), which transiently produces a plasma density slightly higher than the value required for the LHCD pulse. The density then falls to the required value after a delay during which a pause in the gas injection is programmed, so that low recycling occurs. By injecting pellets during the pause in the gas injection, plasmas with very high-density and low recycling should be produced.

Using all the methods (*i* – *iv*), the highest temperatures at the plasma periphery should be produced in high-density plasmas, as the experiment requires.

A further method for producing profiles with higher electron temperatures at the plasma edge can be provided by externally launched ECRH radiofrequency power coupled directly to the plasma electrons of the plasma periphery. In order to obtain the resonant condition, this operation needs to properly adjust the confinement magnetic field considering the ECRH operating frequency. In this way, LHCD effect in steady-state should be obtained. Such kind of experiment will be carried out on FTU, which has an ECRH system with operating frequency of 140 GHz and can couple radiofrequency power up to 1.6 MW.

3. Production of the plasma discharges

The standard regime plasma has been produced in FTU using a boron-coated vessel, the plasma column displaced towards the toroidal (internal) limiter and the standard gas fuelling technique. In these conditions high-density plasmas have been obtained with relatively low electron temperature at the plasma periphery. The plasma current was 0.35 MA or 0.52 MA and the toroidal magnetic field was 5.2 T or 5.9 T, respectively.

The high T_{e_outer} regime has been obtained using a lithium-coated vessel, plasma displaced towards the poloidal (external) limiter, extra-gas fuelling in the early phase of the discharge and pellet injection. The pellet has been fired (at t=0.7s) just before the LH power switch-on (with a 0.012 s delay) to prevent enhanced pellet ablation. The velocity and size of the pellets have been sufficient to produce the desired fuelling in the plasma core. A plasma current I_P= 0.6 MA and a toroidal magnetic field B_T=5.9 T have been used. The slightly lower magnetic field also used in the standard regime has been useful to obtain similar safety factors and plasma stability conditions in the two regimes.

3.1 Spectral broadening measurements

The LH spectral broadening monitor is useful for detecting wave-plasma edge interactions. It can be provided by a radio frequency probe located outside the machine at a port located several metres from the LH launcher. The sidebands frequency shifted of a large amount from the pump frequency line are generally characterised also by higher $n_{//}$ (which should be determined by modelling): their presence is important for assessing the RF power deposition profile in the plasma. In addition, the sideband level at 15-20 MHz from the pump frequency with respect to the noise level should be measured. It should be easily done by properly triggering the spectrum analyser with the LH power switch-on time point.

The electron temperature in the plasma region of the edge was predicted to be the most important parameter determining the PI-produced spectral broadening and, together, the penetration in the core of the coupled LH power [10,11].

These predictions have been recently confirmed by experiments on FTU [14]. The electron temperature at normalised minor radius r/a=0.7, for FTU discharges with same plasma density profiles and coupled LH power (0.35 MW). The RF probe data result consistent with the PI modelling results.

3.2 Hard X-ray measurements

The generation of LH-accelerated supra-thermal electrons has been detected in FTU by a high performance fast electron Bremsstrahlung (FEB) camera that measures hard X-ray emitted in the perpendicular direction. The FEB camera has a time resolution of 4 μs and uses two independent pinhole cameras with 15 lines of sight each [22]. Considering the poloidal cross-section of the torus, the horizontal camera is centred on an angle of 0 degree, and the vertical one is centred on an angle of -90 degree. Both cameras are identical including the viewing angles. For each line of sight there is a CdTe detector with a thickness of 2 mm and a square surface of 25 mm^2. The absorbers and screens used allow transmission for an energy range from 20 keV to 200 keV. The detector is closely connected to an appropriate pre-amplifier.

The coupled LH power appears to be fully deposited at the very edge of the plasma, consistently with the profile modelled with the LH^{star} code for the standard regime of FTU [14]. For the high T_{e_outer} regime, a change in the behaviour of the accelerated electrons occurs with respect to standard regime. In this new regime the LH effect persists to densities a factor two higher than in standard regime. The coupled LH power is deposited in the core, mainly at r/a = 0.3 – 0.4, consistently with the profile modelled with the LH^{star} code for the high T_{e_outer} regime of FTU. The radial profiles of the LH-driven current density are expected to have the same shape as the hard X-ray profile, as routinely assumed in tokamak experiment modelling.

4. LHCD operations at high plasma densities in different machines

We give by following information useful for producing operating conditions useful for LHCD at reactor-relevant plasma densities in different machines. The standard regime would be characterized by high density plasmas with low electron temperature at the edge. For plasma operations utilising limiters, the maximum level of particle recycling from the wall of the machine, useful for obtaining relatively low T_{e_outer}, should be produced by operating with the maximum plasma-wall contact area. In order to obtain a high recycling, the fuelling of the plasma discharge should be obtained only by gas puffing with the highest level during a time window close to that of the LH power pulse. With an LH frequency at around 8 GHz and $n_{//}$=2.1, plasma densities up to n_{e_av}≈2 10^{20} m^{-3}, $n_{e\_0.8}$≈0.8 10^{20} m^{-3} should be produced operating with toroidal magnetic field in a range useful for satisfying the LH accessibility condition.

The level of hard X-rays should be measured, checking the density value for signal reaching the noise level. The spectral broadening by the RF probe spectra should be measured. In plasma targets with n_{e_av}≳1e20, sidebands above the noise level should be detected up to frequencies shifted more than 10 MHz from the LH operating frequency. For lower operating frequencies the spectral broadening would result bigger.

The plasma density and electron temperature radial profiles should be measured. The electron temperature in the radial layer close to the LH antenna-plasma interface would likely result in the range T_e =5 eV – 20 eV, and in the range T_e =50 eV – 200 eV at a distance of about 0.12a – 0.15a inside the plasma (where $r=a$ is the plasma minor radius at the LCMS).

High-density plasmas with high electron temperature at the edge should be produced. For plasma operations utilising limiters, the minimum level of particle recycling from the wall, useful for obtaining relatively high T_{e_outer}, should be produced by operating with the minimum plasma-wall contact area.

The pellet fuelling should be utilised as it is the most powerful technique for producing plasma targets with higher T_{e_outer}. As critical phase of the experiment, in case no marked increase in

T_{e_outer} will be obtained, this behaviour should be attributed to a too low velocity of the pellet. For a minor radius of the plasma column of 0.3m, with density n_{e_av} =0.7 (T_{e0} =2keV for typical FTU plasmas), a velocity of 1.3 km/s for pellets with mass of 10^{20} deuterium atoms would be sufficient to produce deep fuelling useful for preparing targets with high plasma density and very low recycling.

As critical phase of experiment, the LH power pulse should be coupled at a time point just after the pellet, so that its ablation at the plasma edge by the RF power should be prevented. A delay of 10 ms – 20 ms should be generally sufficient. A longer delay should be avoided in order to prevent plasma edge cooling.

Utilising ECRH additional power, the T_{e_outer} should be further increased (possibly in steady-state) by operating with a proper value of the confinement magnetic field, in order to set the resonant layer at a normalised minor radius in the range: r/a=0.8–0.9.The plasma density and electron temperature radial profiles should be measured. The electron temperature would likely result in the range T_e =5 eV – 30 eV in the radial layer close to the LH antenna-plasma interface, and in the range T_e =200 eV – 500 eV at a distance of about 0.12a – 0.15a inside the plasma, (where $r=a$ is the plasma minor radius at the LCMS). Lower values of T_{e_outer} would prevent the occurrence of LH power penetration in the core. The line-averaged densities for the hard X-ray level reaching the noise level should be measured for the produced different regimes, and a plot like that of Fig.1a should be produced.

The nose level should be reached at operating line-averaged plasma densities that are markedly higher (of 50% or more) than in the low T_{e_outer} regime. The radial profiles from hard X-rays data should be produced as in Fig.1b. The spectral broadening by the RF probe spectra should be measured.

For operations producing sufficiently high values of T_{e_outer} and, possibly, clear LHCD effects, the sidebands should be below the noise level for frequency shifted more than 10 MHz from the operating LH line frequency.

5. Comments and conclusion

The occurrence of high growth rates is the condition necessary for broadening the launched LH spectrum. The results shown in the present paper confirm that operation with higher electron temperatures in the scrape-off and at the plasma periphery of the main plasma are recommended for diminishing the spectral broadening effect and for enabling the penetration of the coupled LH power in the core of high density reactor grade tokamak plasmas.

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