Observation and analysis of lower-hybrid-current-drive density limit in EAST

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Abstract

Lower hybrid current drive (LHCD) experiments with line-averaged density up to \( \sim 5.1 \times 10^{19} \text{ m}^{-3} \) were performed in EAST L-mode plasmas. When the line-averaged density rises above a critical value, the hard x-ray (HXR) emission falls to the noise level, indicating that the LHCD density limit is encountered. The experimental results show that the LHCD density limit can be increased with higher wave source frequency \( (f_0) \) and higher magnetic field \( (B_t) \). Although a higher LHCD density limit is obtained by a higher magnetic field for both 2.45 GHz and 4.6 GHz waves, the results show a stronger dependence on the magnetic field for the 4.6 GHz case. Analysis suggests that, for normal operation with a relatively low magnetic field \( (1.6 \leq B_t \leq 2.5 \text{ T}) \) on EAST, the dominant mechanisms responsible for the LHCD density limit are different between the 2.45 GHz and 4.6 GHz waves. The wave accessibility plays a more significant role during 4.6 GHz LHCD experiments, while parasitic losses due to parametric decay instability (PDIs) dominate the accessibility issue in the 2.45 GHz case. Collisional loss in the scrape-off layer (SOL) may explain the 4.6 GHz result when combined with the accessibility limit at high density and low temperature.

Keywords: lower hybrid current drive, current drive efficiency, density limit, parametric decay instability, wave accessibility

(Some figures may appear in colour only in the online journal)

1. Introduction

Lower hybrid current drive (LHCD), characterized by the highest current drive efficiency with respect to other auxiliary heating and current drive (CD) methods, has been successfully used in present tokamaks. In this paper the CD efficiency is defined as \( \eta = \frac{\pi R I_{LH}}{P_{LH}} \text{ (A W}^{-1} \text{ m}^{-2}) \), where \( \pi_0 \) is the line-averaged density, \( R \) the major radius of the device, \( I_{LH} \) the driven current by LH wave and \( P_{LH} \) the LH power. Since its start in the early 1980s [1, 2], significant progress has been achieved in long-pulse steady-state operation. Fully non-inductive plasma discharges of up to 3.6 MA on JT-60U [3] and 3 MA on JET [4] have been obtained with LHCD. A plasma current of 0.5 MA has been sustained with LHCD in a steady-state regime for up to 6 min on Tore-Supra [5]. Recently on
EAST, a long-pulse H-mode scenario over 100 s with a current fraction of LHCD $\sim 75\%$ [6], and a stationary I-mode plasma with a world-record pulse length of 1056 s sustained by LHCD and electron cyclotron resonance heating (ECRH) [7] have been realized. LHCD is expected to be the most efficient tool for driving off-axis current in ITER advanced scenarios and is under consideration for heating and CD upgrades [8, 9]. However, nearly every experiment to date [10–12] shows that the value of the crucial quantity $I_{\text{LH}}/P_{\text{LH}} (\text{A W}^{-1})$ decreases with electron density more strongly than the theoretical expectation which scales with the inverse of density [13]. Furthermore, some experiments encountered a ‘density limit’ problem, namely, the current-drive effects disappear above a critical density [14, 15]. In order to obtain more complete physical and numerical models which can be used with increased confidence to assess LHCD at high density for extrapolation to ITER advanced scenarios, a joint ITPA (International Tokamak Physics Activity) of systematic multi-machine investigations was carried out including Alcator C-Mod, Tore Supra, FTU and EAST devices [16]. Many extremely valuable results have been obtained. For example, Alcator C-Mod [17] and Tore Supra [18] experiments indicate that collisional absorption in the scrape-off layer (SOL) and wave scattering from fluctuations are important loss mechanisms, respectively. Extension of density limit was demonstrated on FTU [19] and Alcator C-Mod [20] by using lithiation and at a lower Greenwald fraction at the same line-averaged density, both favorable for reducing the wave–plasma interactions at the plasma edge. Previous investigations on EAST [21–23] show that lithiation and higher wave frequency can help to improve the ratio of $I_{\text{LH}}/P_{\text{LH}}$, but the line-averaged density coverage in the past LHCD experiment is limited to the range of $n_e < 3.5 \times 10^{19} \text{ m}^{-3}$; namely, the experiments did not reach the LHCD density limit for 4.6 GHz wave. New experiments are performed to investigate the LHCD density limit at high density, extending the line-averaged density to $5.1 \times 10^{19} \text{ m}^{-3}$. Here the density limit is the critical density at which the hard x-ray (HXR) count rate falls to the noise floor. Recent scenario developments on EAST are focused at high density to demonstrate reactor-relevant plasma $\beta$ [24, 25]. In this density regime, both wave accessibility and edge non-linear effects need to be considered.

This paper compares the quantity of $I_{\text{LH}}/P_{\text{LH}}$ at higher density with different wave source frequencies ($f_0$) and magnetic field ($B_t$). The dominant mechanisms responsible for the 2.45 GHz and 4.6 GHz LHCD density limits are investigated. The organization of this paper is as follows. The experimental set-up is shown in section 2. Section 3 describes the experimental observation of density limit on EAST with 2.45 GHz and 4.6 GHz waves, respectively. An analysis of the potential mechanisms responsible for the anomalous loss of quantity $I_{\text{LH}}/P_{\text{LH}}$ is given in section 4. Finally, we summarize the paper in section 5.

2. Experimental set-up

Experimental Advanced Superconducting Tokamak (EAST) is a fully superconducting tokamak with an ITER-like divertor configuration. The main characteristic is steady-state long-pulse operation and the main mission is to conduct ITER-like steady-state advanced plasma science and technology research. It is a medium-sized tokamak with a major radius of 1.89 m, and a minor radius of 0.45 m. There are two high-power LHCD systems on EAST with different operating frequencies (2.45 GHz/4 MW [26] and 4.6 GHz/6 MW [27]). LH power is coupled to the plasma using a fully-active-multijunction (FAM) launcher for both systems (see figure 1). The whole launcher for 2.45 GHz is made of 20 modules (5 rows $\times$ 4 columns), corresponding to 20 klystrons. Each klystron has been tested in laboratory to have a capability of delivering 200 kW for 1000 s. For the 4.6 GHz launcher, it consists of 24 klystron modules (12 rows $\times$ 6 columns, one klystron corresponds to 3 rows $\times$ 1 column). Each has the capability of delivering 250 kW for 1000 s. The total size of the launchers is 0.736 m in height $\times$ 0.472 m in width and 0.776 m $\times$ 0.442 m, respectively for 2.45 GHz and 4.6 GHz waves. For both launchers, the power directivity, defined as power ratio in negative parallel refractive index ($N_i$) to the total radiated power can be as high as...
The launched power spectrum for 2.45 GHz (red) and 4.6 GHz (blue) LH waves. The peak parallel refractive index of the first main lobe is 2.1 (2.45 GHz) and 2.04 (4.6 GHz). The spectral width of the first main lobe ($\Delta N_||$) is 0.5 (2.45 GHz) and 0.3 (4.6 GHz).

Figure 4. Typical waveform of density limit experiment with 2.45 GHz LH wave. $I_p$ plasma current; $n_e$ line-averaged density; SMBI supersonic molecular beam injection; $P_{LH,2.45}$ 2.45 GHz LH power; $V_{loop}$ loop voltage; $T_{e0}$ electron temperature at plasma center; HXR hard x radiation; $T_{e,\text{ECE}}$ electron temperature measured by ECE; $Z_{\text{eff}}$ effective charge number.

76%, and the reflection coefficient less than 1% around the optimum density [28].

A 20-chord poloidally viewing HXR diagnostic (see figure 2) measures the fast electron bremsstrahlung emission. A detector with a 2 mm aluminum vacuum window measures the HXR energy of 20–300 keV every 1 ms. The HXR count rate is taken as a proxy for the density of the fast electrons generated by LHCD.

There are two radio frequency (RF) probes (loop antennas) located outside the EAST vacuum vessel for measuring the LH wave signals. The LH wave in plasmas (which is an electrostatic wave) can pass through the evanescence region between the cut-off layer and vacuum but with strongly attenuation ($\sim$e-folding), just like the process that the LH power radiated from an external antenna can tunnel through the vacuum region and the cut-off layer [29]. This (quasi) electrostatic mode then can be converted into an electromagnetic wave by the frequent and probable perturbation effects of any type allowing to generate the magnetic field component. The converted electromagnetic wave will exit the vacuum vessel through a dielectric window, in front of which the RF antennas are placed. The detected RF signals are then sent to two frequency spectrum analyzers with a frequency resolution of 30 kHz every 20 ms during LH power injection. The RF probe spectrum consists of RF power reflected back outside from the device. In order to measure the RF waves after the interaction with plasmas,
rather than from the LH launchers directly, the RF probes are located far from the LH launchers. The detected signal qualitatively documents the nature of interactions between the LH waves and the plasmas. This diagnostic technique was usually adopted for monitoring wave–plasma edge interactions, such as the parametric decay instability (PDIs) of LH waves in many LHCD experiments [30–32].

All the eight discharges analyzed in this paper are performed in L-mode deuterium plasmas with upper single null (USN) divertor configuration. In order to reach the LHCD density limit, the plasma density was ramped throughout each discharge. The launched power spectra are shown in figure 3. The peak $N_{||}$ of the first main lobe is 2.1 and 2.04 for 2.45 GHz and 4.6 GHz LH waves, respectively. The spectral width ($\Delta N_{||}$) of the first main lobe is $\sim$0.5 (2.45 GHz) and $\sim$0.3 (4.6 GHz), namely, the variation in $N_{||}$ is from 1.85 (1.89) to 2.35 (2.19) for 2.45 GHz (4.6 GHz) waves. The narrower spectral width for the 4.6 GHz wave is due to the larger number of sub-waveguides in one row and a higher source frequency (i.e., $\Delta N_{||} \propto 1/(n \cdot f)$ with $n$ the number of sub-waveguides). The coupled LH power is about 1.0 MW for both 2.45 GHz and 4.6 GHz LHCD experiments with the same plasma current of 400 kA and four toroidal magnetic field values on the magnetic axis ($B_t = 1.6$ T, 1.8 T, 2.25 T, and 2.5 T).

3. Experimental results

Figure 4 shows the time evolution of several key plasma parameters during a typical ramped density discharge (#85094) with 2.45 GHz LHCD. The line-averaged plasma density $\bar{n}_e$ was increased from 1.3 to $4.2 \times 10^{19}$ m$^{-3}$ gradually during the plasma current plateau by feed-back control with supersonic molecular beam injection (SMBI). The LH power was injected when the plasma current reached the flat top. Although the coupling was not good at the beginning due to the relatively low density, the injected power kept nearly constant when density increased to $2.5 \times 10^{19}$ m$^{-3}$. The line integrated x-ray emission on the central chords (from 8 to 20) was decreased during density ramping up and dropped to the noise level when density increased to $3.5 \times 10^{19}$ m$^{-3}$, indicating reaching the LHCD density limit. At the same time, the non-thermal ECE temperature at the plasma edge ($\rho \sim 1$) decreases to a level that is in agreement with the Thomson scattering measurement (several 10s of eV), suggesting the fast electron population generated by LH waves disappeared. A similar discharge (#93280) with density ramping up and 4.6 GHz LHCD is shown in figure 5. It is seen that the LHCD density limit occurs at $t = 5.6$ s with $\bar{n}_e \sim 5.1 \times 10^{19}$ m$^{-3}$. As the density increases, the electron temperature at plasma center ($T_{e0}$) drops with time for both discharges since the LH heating power is constant ($\sim$1.0 MW).

Figure 6 shows the line-integrated HXR emission as a function of the line-averaged density with different LH wave frequencies ($f_0 = 2.45$ GHz and 4.6 GHz) and magnetic fields ($B_t = 1.6$ T, 1.8 T, 2.25 T, and 2.5 T). The HXR count rates fall as density rises, and then above a critical density, the count rates fall to the noise level, indicating that the LHCD density limit occurs. By comparing the variation of HXR emission with the plasma density, we can find that for a given source frequency at a higher magnetic field, the quantity $I_{LH}/P_{LH}$ and LHCD density limit are increased gradually. Meanwhile, there is a clear frequency dependence during our experiments; namely, for a given magnetic field, the HXR data in the 2.45 GHz case shows that its level is always lower than that for the 4.6 GHz. Consequently, higher source frequency and higher magnetic field are beneficial to increasing both LHCD density limit and quantity $I_{LH}/P_{LH}$. Note that the density range for the case of 2.45 GHz with $B_t = 1.8$ T (#93292) is very small. Here we use a power-law fitting to evaluate the density...
Figure 6. Hard x-ray count rates as a function of the line-averaged density with magnetic fields ($B_t$). (a) For 2.45 GHz and (b) for 4.6 GHz LHCD.

This conclusion can also be drawn from comparing the residual loop voltage ($V_{\text{loop}}$) with different magnetic field and LH wave frequencies, as shown in figure 7. A lower residual loop voltage is observed in higher source frequency or higher magnetic field cases.

The dependence of density limit ($n_{e,\text{limit}}$) on wave frequencies and magnetic fields is plotted in figure 8. We can see that the LHCD density limit for 4.6 GHz wave is higher by a factor of 1.2–1.5 than the 2.45 GHz wave. A dependency of density limit on wave frequency, $n_{e,\text{limit}} \propto f_0^{0.45}$, is found in one machine with the same plasma conditions. Similar results were also observed on Versator II tokamak, but with lower plasma parameters ($\bar{n}_e < 2.5 \times 10^{19} \text{ m}^{-3}$) and lower LH power ($P_{\text{LH}} < 100 \text{ kW}$) [33]. The benefit of higher magnetic field and higher frequency on CD efficiency was also found in the earlier LHCD experiments with two frequencies (2.45 and 8.2 GHz) on TRIAM-1M tokamak [34–36], although these experiments were performed at low plasma densities ($\bar{n}_e < 1.0 \times 10^{19} \text{ m}^{-3}$).

Besides, the LHCD density limit during 4.6 GHz experiments show stronger dependence on the magnetic field than that of 2.45 GHz.

4. Analysis of the observed different LHCD density limit

The purpose of this section is to analyze the observed LHCD density limit given in section 3 and hence to look for potential mechanisms for the anomalous loss of quantity $I_{\text{LH}}/P_{\text{LH}}$ at high density.

4.1. Wave accessibility

When the LH waves propagate from the plasma edge into the core region, with density increasing, they may meet the mode conversion layer where the $N_{||}$ of the LH waves approaches to the local $N_{||,\text{acc}}$ expressed by [37, 38]

$$N_{||,\text{acc}} = \frac{\omega_{pe}}{\omega_{ce}} + \sqrt{1 + \left(\frac{\omega_{pe}}{\omega_{ce}}\right)^2 - \left(\frac{\omega_{pi}}{\omega_{ce}}\right)^2},$$

with $\omega_{pe,(i)}$ the local electron (ion) plasma frequency, $\omega$ the wave frequency, and $\omega_{ce}$ the local electron cyclotron frequency respectively. This accessibility condition determines the maximum value of the parallel wave phase velocity during the wave propagations. The LH waves radiated by multijunction as slow waves cannot penetrate into the mode conversion layer and they will be mode converted to the fast waves at the layer, which then will propagate back to the edge region. In FTU, a marked drop of CD efficiency was observed when the wave accessibility became poor [12]. In JET, the LH power absorption coefficient decreased significantly with reduced wave accessibility [39]. In JT-60U, the accessibility condition was found to play an important role in determining the CD efficiency and the driven current profiles [40]. The effects of accessibility condition in LHCD experiments at high density has not been investigated on EAST thus far.

According to the equation (1), LH wave accessibility is improved by increasing the magnetic field, which can explain the higher $I_{\text{LH}}/P_{\text{LH}}$ at higher magnetic field observed on EAST at a fixed source frequency. A dependence of LHCD efficiency on the magnetic field was also found in Alcator C Tokamak [30]. However, the accessibility effects cannot explain the difference between 2.45 GHz and 4.6 GHz LHCD experiments, because for a given $N_{||}$ value, the wave accessibility is worse for a higher frequency wave.

It is important to point out that, due to the toroidal effects, the $N_{||}$ may shift down or shift up during the LH waves propagation [41]. In this paper, the role of wave accessibility in 2.45 GHz and 4.6 GHz LHCD experiments at high density is studied by using a ray-tracing code GENRAY [42], which considers the toroidal effects. The wave propagation is calculated from the cold plasma dispersion relation [41]. The collision damping with a simple scrape-off layer (SOL) model $\sim \exp(-r/\lambda)$ is considered, where $r$ is the distance from the last closed flux surface (LCFS), and $\lambda$ is the decay length.
Figure 7. The residual loop voltage ($V_{\text{loop}}$) as a function of line-averaged plasma density.

Figure 8. Observed LHCD density limit ($n_{\text{e,limit}}$) plotted versus the magnetic field for 2.45 GHz (red) and 4.6 GHz (blue) waves respectively.

length. The density/temperature profiles measured by Thomson scattering, and the effective charge number ($Z_{\text{eff}}$) used for all the simulation studies are shown in figures 9 and 10. Only the first main lobe of the power spectrum is considered (see figure 3) and for this lobe we calculate 13 rays with $N_\parallel$ varies from $N_\parallel\text{peak} – \Delta N_\parallel/2$ to $N_\parallel\text{peak} + \Delta N_\parallel/2$. Modeling and simulations show that the evolution of $N_\parallel$ along the ray trajectories depends on the poloidal launching position [41, 43]. In our simulations, 5 poloidal locations and 4 poloidal locations are considered for 2.45 GHz and 4.6 GHz waves respectively, corresponding to waveguide arrays of the LH antennas.

Figures 11(a) and (b) show the simulated ray trajectories in poloidal cross-section at 2.45 GHz and 4.6 GHz with low density and high temperature. The density and temperature profiles assumed for the simulations correspond to figures 9(a) and 10(a), namely, $n_e = 2.2 \times 10^{19} \text{ m}^{-3}$ for both LH waves, $T_{\text{e0}} \sim 2.5 \text{ keV}$ and $\sim 2.9 \text{ keV}$ for 2.45 GHz and 4.6 GHz waves respectively. It is seen that all the rays of 2.45 GHz and 4.6 GHz can penetrate into the plasma core during the first pass, indicating the accessibility condition is well satisfied for both waves. Due to the high temperature, most of the wave power are rapidly absorbed in four and two radial passes for 2.45 GHz and 4.6 GHz waves respectively. Figures 12(a) and (b) show the simulated results with the LHCD density limit observed during the experiments ($n_{\text{e,limit}} = 3.5 \times 10^{19} \text{ m}^{-3}$ for 2.45 GHz and $n_{\text{e,limit}} = 5.1 \times 10^{19} \text{ m}^{-3}$ for 4.6 GHz). The corresponding density and temperature profiles are plotted in figures 9(d) and 10(d). All the rays at 2.45 GHz can penetrate into the plasma interior even during the first pass. Due to the relatively low electron temperature ($T_{\text{e0}} \sim 1.3 \text{ keV}$), only a small amount of the launched power is absorbed during the first few passes. On the other hand, with high density and low temperature ($T_{\text{e0}} \sim 0.75 \text{ keV}$), the rays at 4.6 GHz cannot penetrate into the inner region and travel around the plasma periphery during the first few passes. Figures 13(a) and (b) illustrate the variation of $N_\parallel$, the local accessibility criterion ($N_\parallel^{\text{acc}}$), and the normalized radius ($\rho$) as a function of the poloidal length of ray trajectory with different poloidal locations at high density case. The initial $N_\parallel$ are 2.1 and 2.04, respectively for 2.45 GHz and 4.6 GHz waves, corresponding to the peak $N_\parallel$ value of the first main spectral lobe. It is seen that the accessibility is well guaranteed for the 2.45 GHz wave before the power fully is absorbed when the rays undergo a large $N_\parallel$ upshift. For 4.6 GHz, the rays initially propagate inward until they reach the accessibility layer ($N_\parallel = N_\parallel^{\text{acc}}$) where a mode conversion from the slow wave to the fast wave, and back to the slow wave at the slow-wave cut-off layer in the plasma periphery. These rays experience many reflections between the mode conversion layer ($\rho > 0.8$) and the edge density cutoff layer. As a consequence, the power loss in the SOL due to the electron–ion collision ($P_L$) is
Figure 9. Density and temperature profiles used for the ray-tracing/Fokker–Planck simulations which are measured by Thomson scattering at four time points during discharge #85094 with 2.45 GHz LHCD.

Figure 10. Density and temperature profiles used for the ray-tracing/Fokker–Planck simulations which are measured by Thomson scattering at four time points during discharge #85094 with 4.6 GHz LHCD.
Figure 11. Ray trajectories in the poloidal plane calculated with the GENRAY code including propagation in the SOL region for 2.45 GHz (a) and 4.6 GHz (b) with low density \(n_e = 2.2 \times 10^{19} \text{ m}^{-3}\) and high temperature. The color-bar denotes the normalized ray power to the initial power. The thick red curve indicates the last closed flux surface and the black circles at the low field side represent the poloidal launching locations.

Figure 12. Ray trajectories in the poloidal plane calculated with the GENRAY code including propagation in the SOL region for 2.45 GHz (a) and 4.6 GHz (b) with the LHCD density limit observed during the experiments \(n_{e,\text{limit}} = 3.5 \times 10^{19} \text{ m}^{-3}\) for 2.45 GHz and \(n_{e,\text{limit}} = 5.1 \times 10^{19} \text{ m}^{-3}\) for 4.6 GHz.
high as \( \sim 65\% \) (see figure 14). However, for the 2.45 GHz case with the LHCD density limit of \( 3.5 \times 10^{19} \text{ m}^{-3} \), the collisional loss fraction is only 32\%. These results indicate that accessibility plays a significant role in 4.6 GHz LHCD experiments at high density, while it is not an issue for 2.45 GHz case.

Based on the output of GENRAY, the bremsstrahlung emission can be predicted by the Fokker–Planck solver CQL3D [44], so that we can compare the experiments with simulations. Figure 14 shows the experimental and predicted HXR emission versus different line-averaged densities. The temperature/density profiles and the effective charge number assumed

Figure 13. The variation of parallel refractive index \( (N_{||}) \), the local accessibility criterion \( (N_{||}^{\text{acc}}) \), and the normalized radius \( (\rho) \) as a function of the poloidal length of ray trajectory. Five poloidal rows of the waveguides are considered for the 2.45 GHz LH wave shown in (a), and four poloidal rows of the waveguides are considered for the 4.6 GHz LH wave shown in (b).
Figure 14. Comparison of the fast electron bremsstrahlung emission between the experiments and the predictions by GENRAY/CQL3D code package (top panel), and the collisional absorption ratio versus line-averaged density (bottom panel). The density and temperature profiles used for all the simulations are shown in figures 9 and 10 for 2.45 GHz and 4.6 GHz waves respectively.

Figure 15. Comparison of the fast electron bremsstrahlung emission and collisional absorption ratio calculated with the different density and temperature profiles (hollow triangles and circles), and with different density but same temperature profiles, namely, keeping the temperature profile unchanged as shown in figures 9(a) and 10(a) for all the simulations (solid triangles and circles).

for all the simulations are shown in figures 9 and 10. For each density case, the temperature profile is updated. It is seen that the modeling reproduces the decline of the HXR counts at a high density for the 4.6 GHz case. For 2.45 GHz case, the simulated bremsstrahlung emission at high density is higher than the experimental data by a factor of $\sim 3$. An overestimate of the HXR counts predicted for 2.45 GHz case suggests that some mechanism(s) responsible the loss of CD efficiency during experiments is not considered in our modeling, which will be discussed in next section. The modeling results also show a higher collisional power loss for the 2.45 GHz than the 4.6 GHz wave with comparable density. This is because that
the rays with lower frequency have a lower cut-off density, so that they can propagate further away from the LCFS in the SOL. Secondly, the collision damping rate is inversely proportional to the square of source frequency [18, 45].

In our experiments, the electron temperature decreases with density increasing (as evident from figures 9 and 10), which play an important role in determining CD efficiency. According the CD theory [13], higher temperature corresponds to higher velocity of resonant electrons, which means lower collisionality, and thus higher CD efficiency. The improvement of CD efficiency with temperature was demonstrated in JT-60U [46], JET [47] and FTU [48] experiments. In order to study the effects of temperature on the HXR observations in our experimental, we keep the temperature profiles constant, but use different density profiles (shown in figures 9(a)–(d) for 2.45 GHz and shown in figures 10(a)–(d) for 4.6 GHz) in the simulations, namely, use the temperature profiles shown in figures 9(a) and 10(a) for all the simulations with 2.45 GHz and 4.6 GHz waves. Figure 15 compares the modeling results with temperature profiles updated (hollow triangles and circles) and with constant temperature profiles (solid triangles and circles). It is seen that the power loss due to electron–ion collision decreases for both LH waves when keeping the temperature profile as constant. For example, at the LHCD density limit ($n_e\text{ limit} = 3.5 \times 10^{19} \text{ m}^{-3}$ for 2.45 GHz and $n_e\text{ limit} = 5.1 \times 10^{19} \text{ m}^{-3}$ for 4.6 GHz) the $P_{\text{cl}}/P_{\text{tot}}$ decrease by $\sim 35\%$ and by $\sim 42\%$ for 2.45 GHz and 4.6 GHz respectively. With constant (high) temperature profiles, the $N_\parallel$ upshift required for quasi-linear electron Landau damping condition ($N_\parallel \sim 6.5/\sqrt{\langle T_e \rangle \text{ (keV)}}$) decreases. As a result, the ray propagation may evolve from multi-pass regime to single or few radial passes regime, leading to lower power absorption in SOL region. The calculated HXR count rate with constant temperature profiles increases by $\sim 40\%$ and by a factor of $\sim 2.9$ for 2.45 GHz and 4.6 GHz waves, with respect to the cases with the updated temperatures profiles. In addition to the decrease in collisional power loss, higher electron temperature is another factor contributed to the higher HXR emission. The CQL3D modeling results show that the ratio of the driven current

Figure 16. Comparison of the frequency spectrum between 2.45 GHz (a) and 4.6 GHz (b) LH waves.
Figure 17. Frequency-integrated spectral power of the pump and the first down-shifted sideband. (a) For 2.45 GHz and (b) for 4.6 GHz LH waves.

\( (I_{\text{LH}}) \) to the electron Landau damping power \( (P_{\text{el}}) \) increases by \( \sim 20\% \) and by \( \sim 60\% \) for 2.45 GHz at \( \bar{n}_e = 3.5 \times 10^{19} \text{ m}^{-3} \) and 4.6 GHz at \( \bar{n}_e = 5.1 \times 10^{19} \text{ m}^{-3} \).

4.2. Parametric decay instabilities

Parametric decay instabilities (PDIs) are a non-linear wave interaction with the density fluctuations at plasma edge [49, 50], which have been measured in many LHCD experiments such as FTU [19], Alcator C-Mod [51] and Tore Supra [52]. As the parametrically excited sideband waves, which lead to a power depletion of pump waves, are expected to have a substantially higher value of \( N_{\text{LH}} \) than the pump wave, the current drive efficiency will be reduced significantly. According to the theory [53], the PDI ion cyclotron (IC) growth rate is inversely proportional to the squared ratio \( \omega_0/\omega_{\text{LH}} \), where \( \omega_{\text{LH}} \approx \omega_0/(1 + \omega_0^2/\omega_{\text{ce}}^2)^{1/2} \), is the lower hybrid frequency. A correlation between the LHCD density limit and the parameter \( \omega_0/\omega_{\text{LH}} \) was found in Alcator C tokamak [10]. For the case of

\( B_i = 2.5 \text{T}, \) the value of \( \omega_0/\omega_{\text{LH}} \) is estimated to be \( \sim 3.2 \) (5.5) for 2.45 GHz (4.6 GHz) waves when reaching the LHCD density limits of \( 3.5 \times 10^{19} \text{ m}^{-3} \) (5.1 \( \times 10^{19} \text{ m}^{-3} \)), where the frequency \( \omega_{\text{LH}} \) is evaluated at the center of the plasma. Accordingly, a stronger PDI process is foreseen with 2.45 GHz waves than 4.6 GHz.

4.2.1. Measurements of the frequency spectrum. The frequency spectra measured at two different densities are shown in figures 16(a) and (b), respectively, for 2.45 GHz and 4.6 GHz waves. It is seen that the spectral broadening of the pump waves represented by the pump width is similar in the low-density case for both LH waves. Here, the pump width \( \Delta f_P \) is defined as the full width 20 dB below the maximum. When the density increased to \( 3.5 \times 10^{19} \text{ m}^{-3} \), the observed pump broadening of 2.45 GHz waves is more severe than 4.6 GHz, i.e. the pump width of 2.45 GHz is almost double that of 4.6 GHz. In theory, a modification of the launched \( N_{\text{LH}} \) spectrum will occur simultaneously in the same process of producing a frequency broadening [54], leading to a degradation of CD efficiency. Correlation between the degradation of CD efficiency and the frequency broadening was observed during the ASDEX experiments [11].

In addition to more significant pump broadening, we observed an ion cyclotron sideband down-shifted by approximately 15 MHz from the operating frequency at 2.45 GHz. The strength of the ion cyclotron sideband (\( P_{\text{IC}} \sim \sim 35.5 \text{ dBm} \)) is about 16\% of the pump waves (\( P_0 \sim 27.8 \text{ dBm} \)). Given that the width of the sideband is much broader than that of the pump waves, the frequency-integrated spectral power of the sideband waves is comparable to that of the pump. Besides, the peak value of the pump wave decreased by a factor of 8 when the density increases from 2.2 to \( 3.5 \times 10^{19} \text{ m}^{-3} \). For 4.6 GHz case, it is only reduced by a factor of 4 and there is no sideband detected.

Figures 17(a) and (b) plot the frequency-integrated spectral power of the pump waves (with \( \pm 0.2 \text{ MHz} \) around the operating line frequency) and the first down-shifted sideband
Figure 19. Growth rate spectra for 2.45 GHz (red) and 4.6 GHz (blue) LH waves at different radial locations ($R = 2.30$ m, close to the LCFS, $R = 2.325$ m, the middle of the SOL, $R = 2.355$ m, the antenna mouth). The electron density and temperature assumed for the PDI modeling are shown in figure 18. The magnetic field on the axis $B_t = 2.5$ T. The magnetic field at $R = 2.30$ m, 2.325 m and 2.355 m are $1.94$ T, $1.97$ T and $1.99$ T.

Figure 20. Wave accessibility ($N_{\parallel}^{\text{acc}}$) and parametric decay instabilities (PDIs, indicated by the value of $\omega_0/\omega_{LH}$) assessment for ITER steady-state, inductive and hybrid scenarios and CFETR hybrid scenario. The parameters for ITER scenarios are: $\omega_0 = 2\pi \times 5.0$ GHz, $B_t = 5.3$ T, $n_{e0} = 7.3$ (steady-state), $10.2$ (inductive), $8.6$ (hybrid) $\times 10^{19}$ m$^{-3}$. The parameters for CFETR hybrid scenario are: $\omega_0 = 2\pi \times 4.6$ GHz, $n_{e0} = 12 \times 10^{19}$ m$^{-3}$, and $B_t = 6.5$ T.

(with $\pm 2$ MHz around the peak) with respect to the line-averaged density, respectively for 2.45 GHz and 4.6 GHz waves. The integrated spectral power of the pump waves, which drive current effectively, is lowered by $\sim 67\%$ when density increases to $3.5 \times 10^{19}$ m$^{-3}$, and the ratio of the side-band waves to the pump reach up to $\sim 35\%$ for 2.45 GHz. As mentioned above, since these side-band LH waves have much high $N_{\parallel}$, this power transferred from the pump is expected to be absorbed in the edge region with a negligible CD efficiency. These results suggest that the PDI effects could be the main mechanism responsible for the observed loss of quantity $I_{LH}/P_{LH}$ for 2.45 GHz. On the other hand, it is difficult to link the degradation of the quantity $I_{LH}/P_{LH}$ to the power depletion of pump waves at around 4.6 GHz, because the pump power at the LHCD density limit still remains about 73\% (compared to the low-density case). The spectral power of 2.45 GHz and 4.6 GHz waves is not compared directly, because neither the sensitivity of the RF probes to LH waves at around 2.45 GHz and 4.6 GHz nor the transmission loss is exactly the same.

4.2.2. PDI modeling and analysis. A PDI modeling with the MP-PDI code [10, 49, 55] by solving the parametric dispersion is performed. The PDI driven mode growth rate normalized by its own cyclotron frequency ($\gamma/\omega_{ci}$) is evaluated. The electron density and temperature profiles in the SOL utilized for the PDI modeling are shown in figure 18, which are measured by reciprocating probes during discharge #85093 at $t = 7.8$ s, corresponding to $n_e = 3.6 \times 10^{19}$ m$^{-3}$. The macroscopic parameters of discharge #85093 are $I_p = 400$ kA, $B_t = 2.5$ T and
LH power at 4.6 GHz–1.0 MW, which are similar to #85094. We consider three radial locations, $R = 2.30$ m (close to the LCFS), $R = 2.325$ m (the middle of the SOL), and $R = 2.355$ m (the antenna mouth). The electron density/temperature and magnetic field assumed for performing the simulations at these three locations are, $3.4 \times 10^{18}$ m$^{-3}$, 21 eV, 1.94 T; $9.0 \times 10^{18}$ m$^{-3}$, 36 eV, 1.97 T; $20.7 \times 10^{18}$ m$^{-3}$, 70 eV, 1.99 T. The ion temperature is assumed to be the same as $T_e$. The LH power density is calculated by $P_{\text{LH}} = P_{\text{LH}}/S$, where $P_{\text{LH}} = 1.0$ MW for both 2.45 GHz and 4.6 GHz waves and the surface area of power radiation $S = n \times L_x \times L_z$ with $n$ the number of active waveguides, $L_x$, and $L_z$ the width and height of the active waveguides. The detailed dimensions of both antennas are described in [28]. The parallel refractive index of the pump wave and ion mode is set to 2.0 and 8.0 respectively. In this model, the convective growth or the saturation mechanism are not considered. Besides, it is assumed that the angle between the perpendicular wavenumbers of the lower sideband and the pump wave equals to 90 degrees. The modeling results are illustrated in figure 19, where $\omega_B$ is real part of the PDI driven mode frequency. It is clear that the growth rates for 2.45 GHz case are higher by a factor of two than those for 4.6 GHz in the range of normalized frequency ($\omega/\omega_{ci}$) considered for each radial location. This result is qualitatively in agreement with the spectral measurement, namely, the spectral width of 2.45 GHz waves is larger than that of 4.6 GHz waves. The growth rate is peaked at the first ion cyclotron harmonic at the far SOL (near the antenna mouth), which is consistent with the spectral measurements of 2.45 GHz. The maximum growth rate away from the antenna mouth occurs at above the second IC harmonics for both LH waves, due to the non-resonant quasimodes ($\omega \approx k_i \times \nu_{ik}$) on top of the ion cyclotron quasimodes ($\omega \approx n \omega_{ci}$) [53]. The experimental measurements of the 4.6 GHz wave spectrum are characterized by the absence of ion cyclotron sidebands, implying that the consideration of the convective growth is critical. Nevertheless, the results of lower growth rates at a higher frequency, which are evaluated in the homogeneous plasma limit, are in line with the experimental observation, namely, weaker ion-cyclotron PDI behavior with higher frequency LH wave.

5. Summary and conclusions

LHCD experiments with different magnetic fields were performed at high density for 2.45 GHz and 4.6 GHz waves, respectively. We observed that when the density increased above a critical density, the current-drive effects indicated by the HXR emission disappeared. By raising the source frequency from 2.45 GHz to 4.6 GHz, the LHCD density limit has been increased by a factor of 1.2–1.5. The HXR production rates improve with a higher magnetic field for both LH waves, but the experiments show a stronger magnetic field dependence of the LHCD density limit for a 4.6 GHz wave than 2.45 GHz. These observations are in line with our past results reported in [21–23], but we extended the density regime and conducted a magnetic field scan in this paper.

Wave accessibility effects have been studied for the first time in high-density plasmas on EAST, using a ray-tracing code GENRAY which includes toroidal wave propagation effects. Simulations show that when reaching the LHCD density limit, the 4.6 GHz waves mainly propagate around the plasma periphery during the first few passes and cannot penetrate the plasma interior, while for the 2.45 GHz case, the accessibility condition is well satisfied even on the first pass. Ray tracing/Fokker–Planck models of GENRAY/CQL3D, which includes collisional damping effects, can reproduce the decline of the HXR counts at a high density for the 4.6 GHz case. On the contrary, the modeling results show a large discrepancy with the experimental data for 2.45 GHz LHCD at high density.

The spectral measurements indicate that the PDI behavior in the 2.45 GHz case is much stronger than that in the 4.6 GHz case at high density. Larger spectral broadening of the pump wave at 2.45 GHz is observed, accompanied by an ion cyclotron sideband with power comparable to the pump wave, documenting the stronger occurrence of non-linear decay of the pump wave. The integrated spectral power of the pump wave is decreased to $\sim 33\%$ above a critical density, while for 4.6 GHz, the pump power still remains at about 73%. PDI calculations show that the growth rates in the 2.45 GHz case are almost double that in the 4.6 GHz case, which is in line with the observation that stronger PDI behavior occurred in the 2.45 GHz LHCD experiments.

In conclusion, the results presented in this paper indicate that, on EAST, when operating with the magnetic field in the range of $1.6 \leq B \leq 2.5$ T, wave accessibility is the dominant mechanism for the 4.6 GHz LHCD density limit, and for the 2.45 GHz case, parasitic losses due to PDIs dominate the wave accessibility. In order to enhance the CD capability, the 2.45 GHz system will be replaced by a new 4.6 GHz/4 MW system with a passive–active–multijunction (PAM) launcher, which can solve the PDIs issue. The accessibility issue at 4.6 GHz could be mitigated by raising the magnetic field. For example, the LHCD density limit can be increased to $\sim 7.6 \times 10^{19}$ m$^{-3}$ when the magnetic field is upgraded to 3.5 T, according to the scaling ($n_{\text{e,limit}} \propto B_1^{1.8}$) found in this work. In this case, the ratio $\omega/\omega_{ci}$ is still as high as 4.1. A rough assessment of wave accessibility and PDIs (indicated by the value of $\omega/\omega_{ci}$) for ITER (steady-state, inductive and hybrid) scenarios and CFETR hybrid scenario is illustrated in figure 20 (red stars). The parameters for ITER scenarios are: $\omega_0 = 2 \times 5.0$ GHz, $B_1 = 5.3$ T, $n_{\text{e,0}} = 7.3$ (steady-state), 10.2 (inductive), 8.6 (hybrid) $\times 10^{19}$ m$^{-3}$ [56]. The parameters for CFETR hybrid scenario are: $\omega_0 = 2 \times 4.6$ GHz, $n_{\text{e,0}} = 12 \times 10^{19}$ m$^{-3}$, and $B_1 = 6.5$ T [57]. The accessibility condition can be satisfied with $N_{||} = 1.8$ for both ITER and CFETR scenarios. If we adopt the results of Alcator C tokamak, $\omega/\omega_{ci} \approx 2$ as a threshold value for the plasma condition of PDIs excitation, the source frequency of 4.6 GHz on CFETR, corresponding to $\omega/\omega_{ci} \sim 3.2$, is acceptable. On ITER with 5.0 GHz LH waves, it has a great margin of operation for all scenarios since $\omega/\omega_{ci} > 4.0$.

It is worth pointing out that the regime under investigation in this paper is an L-mode plasma, which is different from the high performance H-mode plasmas for a reactor scenario. The temperature will be much higher in the high $\beta$ plasmas. The
modeling analysis indicates that with density increasing, the drop in temperature is another important factor accounting for the LHCD density limit for both 2.45 GHz and 4.6 GHz waves. Future work will study the LHCD characters in high density and high β plasmas.

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References

[1] Yamamoto T. et al 1980 Phys. Rev. Lett. 45 716
[2] Bernabei S. et al 1982 Phys. Rev. Lett. 49 1255
[3] Naito O. (the JT-60 Team) 1993 Plasma Phys. Control. Fusion 35 B215
[4] JET Team 1995 Plasma Physics and Controlled Nuclear Fusion Research Proc. 15th Int. Conf. Sevilla, 1994 vol 1 (Vienna: IAEA) p 423
[5] V. Houtte D., Martin G., Bécoulet A., Bucalossi J., Giruzzi G., Hoang G.T., Loarer T. and Saoutic B. (on behalf of the Tore Supra Team) 2004 Nucl. Fusion 44 L11
[6] Gong X.Z. et al 2019 Nucl. Fusion 59 086030
[7] Song Y.T. et al 2022 Realization of thousand-second improved confinement plasma with super I-mode in tokamak EAST Sci. Adv. (accepted)
[8] Bibet Ph. et al 2005 Fusion Eng. Des. 74 419
[9] Hoang G.T. et al 2009 Nucl. Fusion 49 075001
[10] Takase Y., Porkolab M., Schuss J.J., Watterson R.L., Fiore C.L., Slusher R.E. and Surko C.M. 1985 Nucl. Mat. Energy 28 983
[11] Pericoli-Ridolfini V., Giannone L. and Bartiromo R. 1994 Nucl. Fusion 34 469
[12] Pericoli-Ridolfini V. et al 1999 Phys. Rev. Lett. 82 93
[13] Fisch N.J. 1987 Rev. Mod. Phys. 59 175
[14] Luckhardt S.C., Porkolab M., Knowlton S.F., Chen K.-L., Fisher A.S., McDermott F.S. and Mayberry J. 1982 Phys. Rev. Lett. 48 152
[15] Cesario R., Amicucci L., Castaldo C., Kempenaars M., Jachmich S., Mailloux J., Tudisco O., Galli A. and Krivsa A. 2011 Plasma Phys. Control. Fusion 53 085011
[16] Ding B.J. et al 2018 Nucl. Fusion 58 095003
[17] Wallace G.M. et al 2010 Phys. Plasmas 17 082508
[18] Goniche M. et al 2010 Plasma Phys. Control. Fusion 52 124031
[19] Cesario R. et al 2010 Nat. Commun. 1 55
[20] Baek S.G. et al 2018 Phys. Rev. Lett. 121 055001
[21] Ding B.J. et al 2018 Nucl. Fusion 58 126015
[22] Li M.H. et al 2019 Plasma Phys. Control. Fusion 61 065005
[23] Baek S.G. et al 2021 Nucl. Mater. Energy 26 100955
[24] Huang J. et al 2020 Plasma Phys. Control. Fusion 62 014019
[25] Zhai X.M. et al 2022 Nucl. Fusion 62 076015
[26] Shan J.F. et al 2010 A new 4 MW LHCD system for EAST 23rd IAEA Fusion Energy Conf. (Daejeon, Korea, 11–16 October 2010) (https://www-pub.iaea.org/MTCD/Meetings/PDFplus/2010/cn180/cn180_papers/exw_p7-29.pdf)
[27] Liu F.K. et al 2016 Fusion Eng. Des. 113 131
[28] Li M.H. et al 2020 AIP Conf. Proc. 2254 080005
[29] Brambilla M. 1976 Nucl. Fusion 16 47
[30] Porkolab M. et al 1984 Phys. Rev. Lett. 53 450
[31] Cesario R., Bartiromo R., Cardinali A., Paoletti F., Pericoli-Ridolfini V. and Schubert R. 1992 Nucl. Fusion 32 2127
[32] Pericoli-Ridolfini V., Bartiromo R., Tuccillo A.A., Leuterer F., Soldner F.-X., Steuer K.-H. and Bernabei S. 1992 Nucl. Fusion 32 286
[33] Mayberry M.J., Porkolab M., Chen K.-I., Fisher A.S., Griffin D., Kaplan R.D., Luckhardt S.C., Ramos J. and Rohatgi R. 1985 Phys. Rev. Lett. 55 829
[34] Moriyama S., Nakamura Y., Nagao A., Jotaki E., Nakamura K., Hiraki N. and Itoh S. 1990 Nucl. Fusion 30 47
[35] Sakamoto M. et al 2000 Nucl. Fusion 40 453
[36] Peysson Y. et al 2020 J. Fusion Energy 39 270
[37] Stix T.H. 1962 The Theory of Plasma Waves (New York: McGraw-Hill)
[38] Golant V.E. 1972 Sov. Phys. - Tech. Phys. 16 1980
[39] Pericoli-Ridolfini V. et al 1997 Plasma Phys. Control. Fusion 39 1115
[40] Ikeda Y. et al 1994 Nucl. Fusion 34 871
[41] Bonoli F.T. and Enghandle R.C. 1986 Phys. Fluids 29 2937
[42] Smirnov A.P. and Harvey R. 1995 Bull. Am. Phys. Soc. 40 1837
[43] Peysson Y. et al 2016 Plasma Phys. Control. Fusion 58 044008
[44] Harvey R.W. and McCoy M. 1992 The CQL3D Fokker–Planck code Proc. IAEA Technical Committee Meeting on Simulation and Modeling of Thermonuclear Plasmas (Montreal, Canada) (Vienna: International Atomic Energy Agency) pp 489–526 (https://www.compoxco.com/ cql3d_manual_150122.pdf)
[45] Barbato E. 2011 Nucl. Fusion 51 103032
[46] Ushigusa K., Imaiz T., Ikeda Y., Naito O., Uehara K., Yoshida H. and Kubo H. 1989 Nucl. Fusion 29 1052
[47] Ekedahl A. et al 1998 Nucl. Fusion. 38 1397
[48] Ridolfini V., Calabrò G. and Panaccione L. (FTU team and ECH group) 2005 Nucl. Fusion 45 1386
[49] Porkolab M., Bernabei S., Hooke W.M., Motley R.W. and Nagashima T. 1977 Phys. Rev. Lett. 38 230
[50] Liu C.S. and Tripathi V.K. 1986 Phys. Rep. 130 143
[51] Baek S.G. et al 2013 Plasma Phys. Control. Fusion 55 052001
[52] Goniche M. et al 2013 Nucl. Fusion 53 033010
[53] Porkolab M. 1977 Phys. Fluids 20 2058
[54] Takase Y. et al 1984 Phys. Rev. Lett. 52 274
[55] Baek S.G. et al 2014 Phys. Plasmas 21 061511
[56] Decker J. et al 2011 Nucl. Fusion 51 073025
[57] Wallace G.M., Ding B.J., Li M.H., Chen J., Baek S.G., Bonoli P.T., Shirawi S., Liu L. and Wu C.B. 2021 Nucl. Fusion 61 106009