LHCD study toward to high performance plasma in EAST

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Abstract

A 4.6 GHz lower hybrid current drive (LHCD) system has been firstly commissioned in EAST in 2014 campaign. Effect of turbulence on plasma-coupling and the comparison between 2.45 GHz and 4.6 GHz are compared, suggesting a better coupling for 4.6 GHz LHW. Studies show that compared to H-mode, the plasma-wave coupling indicated by the mean reflection coefficient is better in the case of L-mode plasma, suggesting the lower density in the case of H-mode. Compared to 2.45 GHz LHW, 4.6 GHz LHW has a better capability on current drive, plasma heating, confinement improvement, modifying current profile, possibly due to less parametric instability in this case.

1. Introduction

Lower hybrid current drive (LHCD) [1–3] plays a key role in controlling current profile in tokamak experiments aimed at achieving important goals relevant to fusion plasma. Lower hybrid wave (LHW)-plasma coupling and current drive (CD) at high density, related to turbulence, are two important issues in achieving lower hybrid current drive (LHCD) high confinement plasma. In fusion plasmas, intermittent density fluctuations were observed in nearly all the devices where Langmuir probe measurements were performed. The statistical properties of the turbulent signals in four different type devices (Tore Supra with circular cross-section limiter-bounded plasma [4], Alcator C-Mod with a divertor configuration [5], MAST with vacuum chamber walls far from the plasma last closed flux surface [6] and the PISCES linear plasma device [7]) are found to be identical allowing to conclude that intermittent convective transport by avaloids is universal in the sense that it occurs and has the same properties in many confinement devices with different configurations[8]. Since density fluctuation is edge region will affect the grill density, the LHW-plasma coupling is easily to be influenced by such burst behaviour. Also, it is reported [9-12] that the density fluctuations has some effect on wave propagation and current drive capability. In turn, it could be possible that the LHW may affect the turbulence. In Tore-supra, study [13] shows that the effect of ICRH on turbulence takes place in the vicinity of the active antenna but not necessarily magnetically connected to it. In addition, how to improve the CD capability at high density is a challenge, including looking for a suitable condition for good CD effect.

In EAST, both 4.6 GHz/6 MW and 2.45 GHz/4 MW LHCD system have been installed. Related experimental results at high density have been reported in Refs [11, 12, 14-19]. Since LHW-plasma coupling and LHW propagation are both related with LHW frequency, it is necessary to investigate the related physics with these two systems.

2. Relationship between fluctuation and coupling

As we know, density profiles in front of the LHW launcher are the important factors affecting the

LHW-plasma coupling characteristics [20-23]. Such density is affected by the turbulence and edge localized mode (ELM) behaviour, since they will give rise to the increase of edge density. To investigate the LHW-plasma coupling, the probability distribution function (PDF) of reflection coefficient (RC) and raw ion saturation signals, showing a statistics property of the coupling and density fluctuation, are utilized. Investigating the PDF's of turbulent fluctuations in general was emphasized by the Kolmogorov article, often called K41 [24], in which he assumed that fluctuations are random. Because the PDF of a random variable is Gaussian, it was rather straightforward to check this hypothesis by mainly using the normalized third order moments of the fluctuating signal. For a signal denoted by x, the skewness factor is defined as $\langle x^3\rangle/\langle x^2\rangle^{3/2}$ and is equal to 0 for a Gaussian distribution reflecting its symmetry around the average value. Figure 1 is the typical plasma wave form of 4.6 GHz LHCD, including L-mode, ELMy H-mode and ELM-free mode. The PDF of RC in the above three modes are plotted in Fig. 2. It is shown that the averaged RC (<RC>: around the peak value of RC) in L-mode is lower than that in H-mode, implying better coupling in L-mode discharge. Though the averaged RC are very similar for the ELMy and ELM-free plasma, the little difference in skewness is still observed. The positive value means the counts of distribution in the range of RC> <RC> is higher than that in the range of RC <<RC>, whereas the negative valve means the opposite behaviour. This suggests that ELMy behaviour leads to the increase of grill density compared to the ELM-free case.

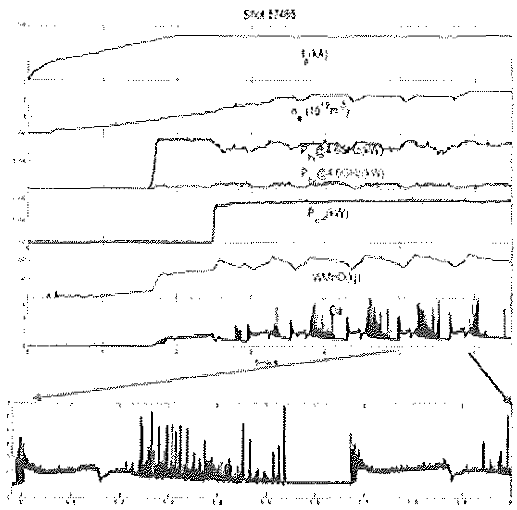

Fig. 1 Typical LHCD H-mode waveform

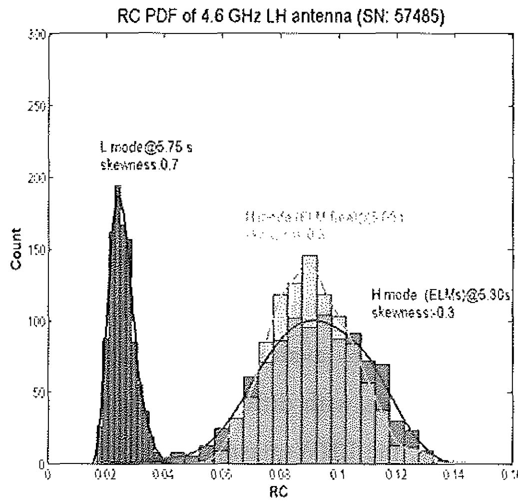

Fig. 2 PDF of RC

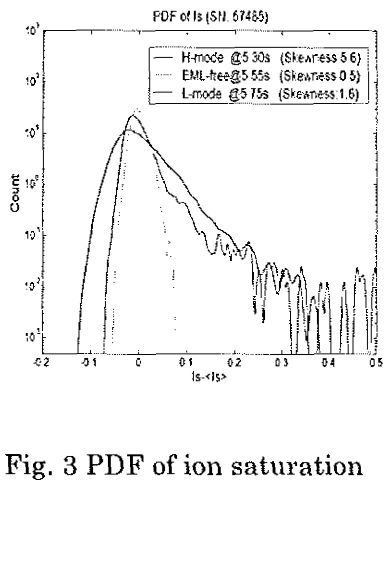

Fig. 3 PDF of ion saturation

Figure 3 shows the PDF of raw ion saturation current reflecting density fluctuation measured by Langmiur probes installed at the mouth of LHCD antenna. It is seen that in L-mode and ELMy plasma, an obvious positive skewness is observed, meaning a strong deviation from Gaussian distribution at the positive fluctuation. Also, a longer tail in the positive part in ELMy plasma, suggesting ELM leads to the density increase with the burst. In addition, in the ELM-free plasma, the PDF is very close to Gaussian distribution, implying less 'blob' compared to the other two cases.

3. LHCD characteristic comparison between 4.6 GHz and 2.45 GHz LH waves

Many parameters may affect LHCD effect, such as wall condition, magnetic configuration, target plasma, and so on. In order to rule out such effects, two different frequency waves with the same power (P_{LH} = 1.05 MW) were injected successively in one discharge with almost constant density (n_{e_av} = 2.0 × $10^{19}m^{-3}$) and the typical waveform are shown in Fig. 4. It is seen the difference in residual voltage (V_{loop}) and ECE super-thermal T_e is obvious between two waves, which definitely justifies better CD efficiency for 4.6 GHz waves. The residual voltages are 0.49 V and 0.36 V respectively for current drive with 2.45 GHz and 4.6 GHz. Better plasma heating effect for 4.6 GHz can be obtained from the time evolution of plasma stored energy (W_{MHD} ~ 68.3 kJ and 74.8 kJ, respectively for 2.45 GHz and 4.6 GHz). Also, the internal inductance is higher with the 4.6 GHz LH wave injection, meaning the peaker power deposition. This is in agreement with the line integrated measured HXR profile (Fig. 5). The plasma rotation is observed during LHCD application. For similar power input, measurements show larger rotation change with 4.6 GHz. Seen from the IR picture shown in Fig. 6, the bright belt is observed in the bottom of the divertor for both 2.45 GHz and 4.6 GHz LHW plasma and the brightness with 4.6 GHz is stronger. Such belt should not be the hot spot since the belt is symmetric in toroidal direction. The temperature induced from IR is also shown in Fig.4, showing higher temperature with 4.6 GHz LHW, possibly due to larger stored energy and stronger heat transport. A comparison of frequency spectra between two waves is illustrated in Fig. 7, from which it is seen that more significant broadening occurs for 2.45 GHz case, indicating stronger PI behaviour. This possibly explain the better CD effect with 4.6 GHz LH wave.

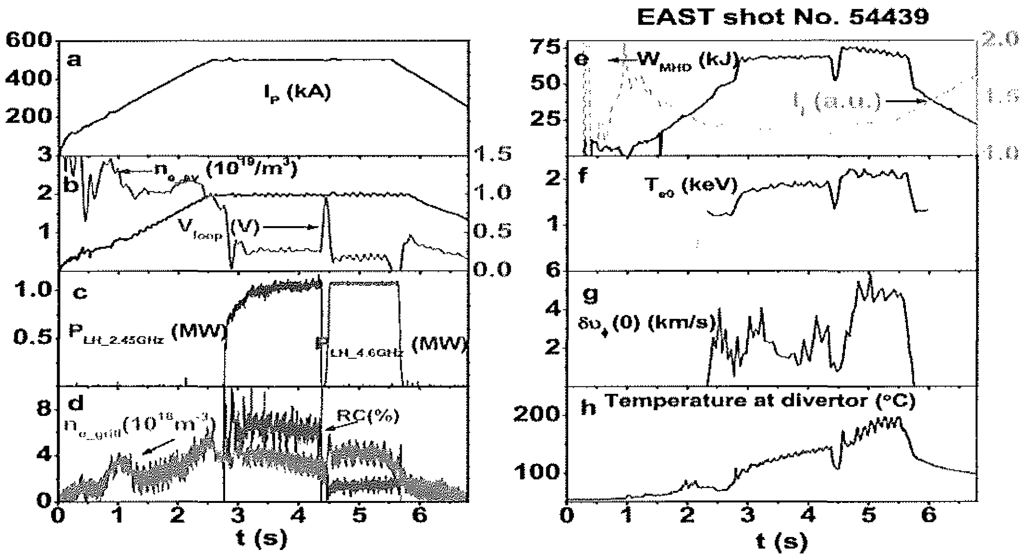

Fig .4 Typical waveform for comparison 2.45 and 4.6 GHz LHCD characteristic

The PDF of the RC is plotted in Fig. 8, showing that the averaged RC with 4.6 GHz is lower and the coupling is better, which is in agreement with the RC shown in Fig. 4. Though this is conflict with the lower density requirement for coupling with higher frequency, which is indicated by a cut-off density determined by $n_{e,co} = (\omega^2 m_e)/(4\pi e^2)$, where /ω/ is the wave frequency, /m/$_e$ is the electron mass and /e/ is the electron charge, it is in agreement with the higher grill density with 4.6 GHz LHW measured by

Langmuir probe, possibly implying the stronger ionization capability of 4.6 GHz LHW. The distribution is almost Gaussian, which is different from shown in Fig.2. The possible reason could be different experiment conditions.

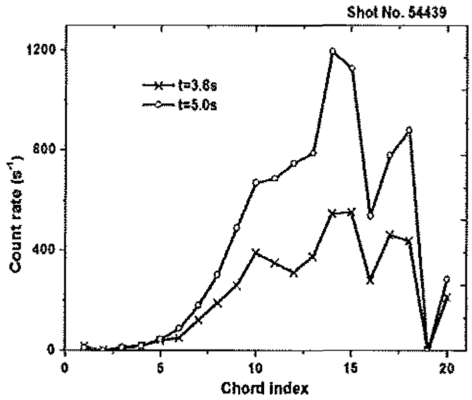

Fig. 5Line integration of HXR

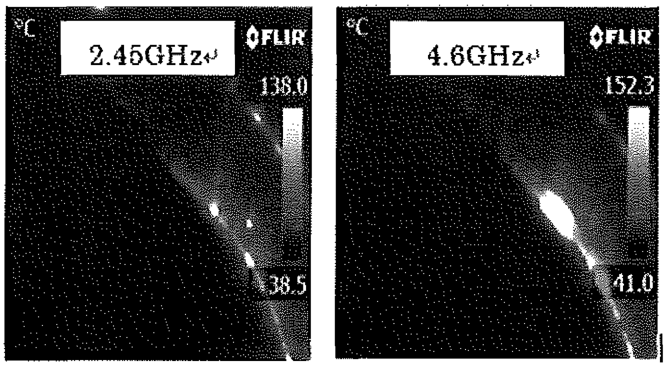

Fig. 6 IR picture of the divertor

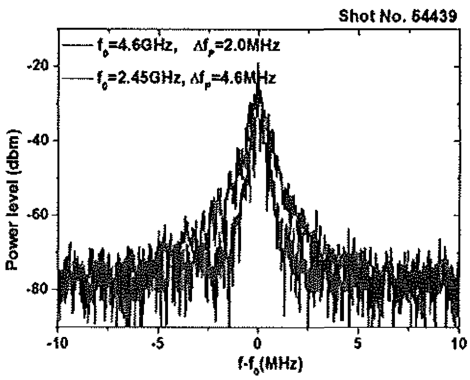

Fig. 7 PI signal by RF antenna

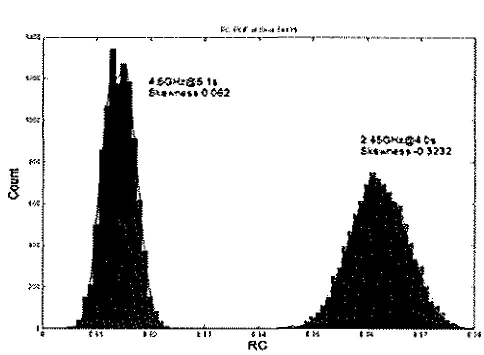

Fig. 8 PDF comparison of RC

Next, we would like to investigate the dependence of CD capability on the line averaged density with the two frequency wave. Usually, hard X-ray (HXR) from fast electrons generated by LH waves is taken as a significant feature of the LH driven current and the HXR count rate can also be taken as a proxy for the density of the fast electron. Although the CD efficiency cannot be obtained quantitatively from the HXR count rate, we can use it to assess the relative change of CD efficiency. Unfortunately, the hard X-ray results for the 4.6 GHz case are not available. Therefore, we use the non-thermal ECE instead, which is also sensitive to fast electrons, since they are both available for the cases and the trends of dependence of HXR and ECE temperature on the density are almost same with 2.45 GHz LH plasma, which can be seen in Fig. 9. It is seen that the variations of both HXR count rates and ECE temperature conform to the $1 / n_{e\_av}$ scaling with the density smaller than $2.0 \times 10^{19}m^{-3}$, but for higher density they fall much more steeply than $1 / n_{e\_av}$ indicating anomalous loss of CD efficiency. First of all, it must be pointed out that during the density ramped up, the accessibility condition is satisfied, because of the sufficiently high values of launched refractive index ($N_{//0} = 2.1$) and toroidal magnetic field ($B_t = 2.3$ T). For the case of 4.6 GHz, the ECE temperature does not drop quickly until up to density of $2.0 \times 10^{19}m^{-3}$. Results clearly show that, with 4.6 GHz LH wave, the density at which the fast electron emission deviates from the curve of 1/n is larger than that with 2.45 GHz, implying better CD effect of 4.6 GHz. It can be also seen that the difference in current drive between two waves becomes more significant with density increasing.

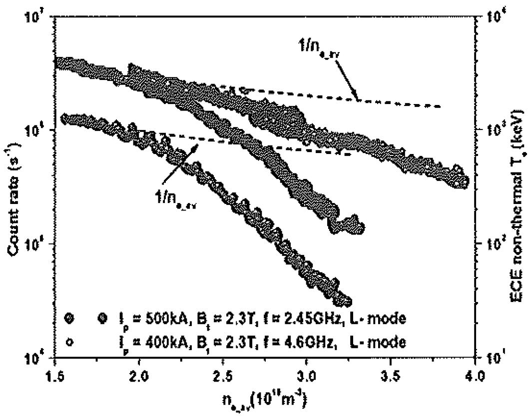

Fig.9 Normalized HXR counts and ECE temperature as a function of density

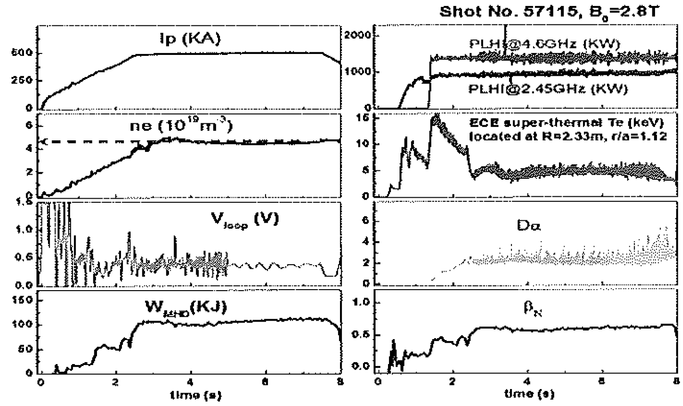

Fig.10 Typical LHCD H-mode plasma at high density

By means of 4.6 GHz and 2.45 GHz LHCD system, H-mode plasma is obtained at relatively high density. The typical wave form is shown in Fig.10 Seen from ECE, even if at n~4.5 × 10^{19}m^{-3}, part of current is driven by LHW since ECE could come from the fast electron emission generated by LHW.

Next we would like to roughly compare the effect of LHW on confinement with the two systems. It is analyzed by investigating the effect of LH power on stored energy and the results are shown in Fig.11, in which $P_{tot} = P_{OH} + P_{LH\text{-}2.45} + P_{LH\text{-}4.6} + P_{ICRH}$. It is seen that, for a same injected power, the stored energy decrease with increasing $P_{LH\text{-}2.45}$, whereas for the case of 4.6 GHz, it seems opposite, or at least the stored energy doesn't decrease with increasing $P_{LH\text{-}4.6}$. This implies 4.6 GHz LHW has a better effect on confinement than 2.45 GHz one.

Since PI behaviour is less with 4.6 GHz LH wave, such PI behaviour could be responsible for the lower CD effect with 2.45 GHz LH wave. Therefore, high LH frequency wave is preferred in the LHCD experiment at high density.

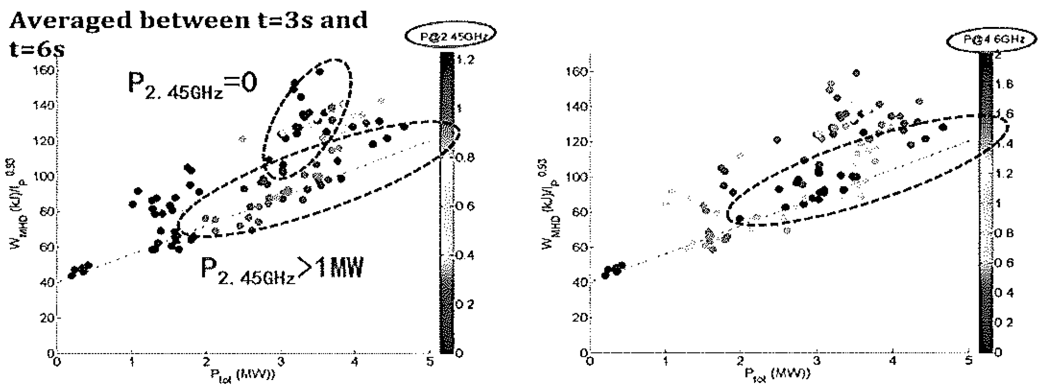

Fig. 11 Dependence of stored energy on LH power variation ((a) 2.45 GHz, (b) 4.6 GHz)

Conclusions

Effect of turbulence on plasma-coupling and the comparison between 2.45 GHz and 4.6 GHz are compared by investigating the statistics property of RC and ion saturation, suggesting a better coupling for 4.6 GHz LHW. Studies show that compared to H-mode, the plasma-wave coupling indicated by the mean reflection coefficient is better in the case of L-mode plasma, suggesting the lower density in the case of H-mode. Results show that, compared to 2.45 GHz LHW, 4.6 GHz LHW has a better capability on current drive, plasma heating, confinement improvement, modifying current profile, being nearly in agreement the less parametric instability in this case.

Acknowledgements:

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References:

[1] N. J. Fisch, Phys. Rev. Lett. 41 (1978) 873.
[2] S. Bernabei, et al Phys. Rev. Lett. 49 (1982) 1255.
[3] N. J. Fisch, Rev. Mod.Phys. 59 (1987)175.
[4] Tore Supra Team, Nuclear Fusion, 40 (2000) 1047
[5] B. LaBombard, et al., Phys. Plasmas 8 (2001) 2107
[6] A. Sykes, et al., Phys. Plasmas 8 (2001) 2101
[7] D. Geobel, et al., Rev. Sci. Istrum. 56 (1985) 1717
[8] Y. Ghassan, et al., Phys. Plasmas 10 (2003) 419.
[9] Y. Peysson, J. Decker, L. Morini, et al Plasma Phys. Contr. Fusion 53 (2011) 124028.
[10] P. T. Bonoli and E. OTT, Phys. Fluids25 (1982) 359.
[11]B J Ding, et al., Nucl. Fusion 53 (2013) 113027.
[12] B J Ding, et al., Nucl. Fusion 55 (2015) 093030.
[13] G.Y. Antar, M. Goniche, A. Ekedahl and L. Colas, Nucl. Fusion 52 (2012) 103005.
[14] F K Liu, B J Ding, et al., Nucl. Fusion 55 (2015) 123022
[15] B.J. Ding, et al Phys. Plasma 19 (2012) 122507
[16] B. J. Ding. et al Phys. Plasma 18 (2011) 082510
[17] L.Zhang, et al Phys. Plasma 20 (2013) 062507
[18] E.H. Kong, et al Plasma Phys. Control. Fusion 55 (2013) 065008
[19] M. H. Li, et al Phys. Plasmas 21 (2014) 062510.
[20] J. Stevens, et al Nucl. Fusion 21(1981) 1259.
[21] M. Preynas, et al Nucl. Fusion 51 (2011) 023001.
[22] M. Brambilla, Nucl. Fusion 16 (1976) 47.
[23] M. Preynas, et al Nucl. Fusion 53 (2013) 013012
[24]A. N. Kolmogorov, C. R. Acad. Sci. URSS 30 (1941) 301.