LHCD studies towards long-pulse plasma with high performance in EAST

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Abstract

Lower hybrid current drive (LHCD) is an important heating system for long pulse plasma with high performance in EAST. The effect of LH (lower hybrid) wave frequency on LHCD characteristics has been studied on EAST for the first time with two different frequencies (2.45 and 4.6 GHz), showing that higher frequency improves penetration of the RF power into the plasma core, leading to a better effect on plasma characteristics. The improvement in LHCD is mainly ascribed to a reduction in parametric instability (PI) and a lesser extent collisional absorption (CA) in the edge region with the 4.6 GHz wave, demonstrating the role and mitigation of parasitic effects of edge plasma. These results are encouraging that LHCD is essential for current profile control in reactor grade plasmas.

1. Introduction

In order for the tokamak to be a commercially viable energy source, it will be necessary to operate these devices in 'advanced' modes characterized by high energy confinement and high fractions of the non-inductive bootstrap current [1]. LHCD [2-4] in principle satisfy this current profile control need, but the coupled radiofrequency (RF) power faces the challenge of effectively penetrating into the main plasma at the relatively high edge density, possibly due to PI [5, 6], CA [7] and scattering by density fluctuation (SDF) [8,9] in the edge region. Here, we describe experiments and analysis that demonstrate the beneficial effects of increasing LH frequency on LHCD at high density.

2. Experiment and results

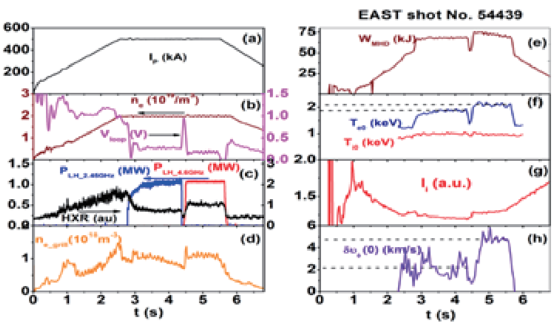

Fig. 1 Typical waveforms with 2 LH frequencies

The typical discharge (#54439) waveforms with a coupled power (P_{LH}~1MW) and an almost constant density (n_e=2.0 × $10^{19}m^{-3}$) in a LSN configuration are shown in Fig. 1. The peak value of the antenna power spectrum has a refractive index along the direction of the toroidal magnetic field of $N_{//0} \approx 2$, which satisfies the wave accessibility condition for the operating condition [10]. It is seen that the residual voltage

(V_{loop}) (Fig.1 (b)) at 2.45 GHz (0.27V) is larger than with 4.60 GHz (0.15V), implying a higher CD efficiency with a higher LH source frequency. Consistently, higher hard X-ray emission (HXR) from fast electrons is observed. Better plasma heating effect also occurs for 4.6 GHz as indicated by plasma stored energy (W_{MHD}), central electron temperature (T_{e0}) and central ion temperature (T_{i0}) measured by a X-ray Crystal Spectrometer (XCS) [11]. Also, the internal inductance (l_i) is higher with 4.6 GHz operation, indicating a more peaked current profile. A larger change of plasma rotation (co-current) occurs in the core with 4.6 GHz measured by XCS during LHCD phase, possibly due to the different LH power deposition and the absorbed LH wave momentum [12]. Frequency spectra detected by an RF probe located outside the machine, which documents the occurrence of wave-plasma interactions shows (see Fig. 2) that a clear spectral broadening of the LH pump wave (Δf_p) occurs and is larger for 2.45GHz (1.6MHz) than for 4.6GHz case (0.74MHz) [13], which is measured at 20 dB below the peak (for the line frequency, $\Delta f_p \lesssim 0.1$ MHz).

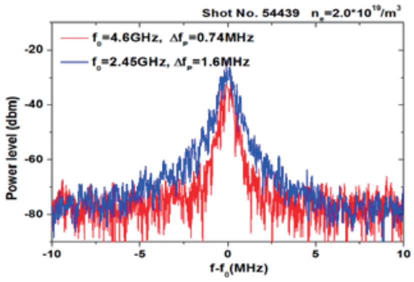

Fig. 2 PI measurements

Further experiments with 3 densities are performed, demonstrating that the above PI effect on LHCD capability. The typical waveforms are shown in Fig. 3, showing that with the density increase, the difference in Vloop increases, in agreement with the change in ECE, suggesting a higher CD capability at 4.6GHz wave.

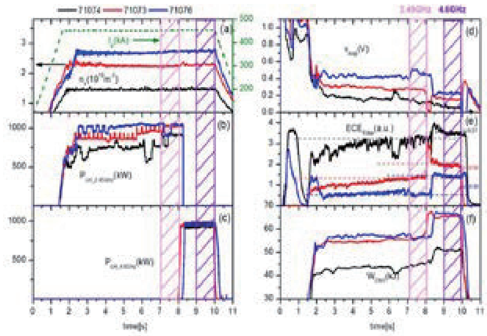
Fig. 3 Typical waveforms with 3 densities

Results show that a stronger LHCD effect occurs by operating at 4.6 GHz than at 2.45 GHz in terms of driven current, plasma heating, modification of current profile, plasma rotation, and RF probe spectrum signals. Furthermore, such discrepancy increases with density.

3. Analysis

Effects of PI and SDF in modifying the initial wave spectrum, as well CA, may play an important role in determining properties of wave propagation and damping in the plasma, hence possibly affecting power deposition and current drive. With the experimental parameters in Fig. 1, using a ray-tracing/Fokker-Planck code (C3PO/LUKE) [14], power deposition and driven current profiles were calculated using the initial nominal antenna spectrum [13]. Though the calculated driven current with 2.45GHz wave is somewhat smaller (about 10kA) than with 4.6 GHz wave, it cannot completely account for the experimental discrepancy (~100kA) estimated by the loop voltage, which is little affected by the change of electron temperature. Therefore the contributions of PI and SDF effects should be considered.

Using the same edge plasma parameters for 2.45 GHz and 4.6 GHz LHCD plasmas, the effect of SDF on the power spectrum *vs*. the parallel refractive index has been evaluated following Ref. 15. Results show that the drift-wave scattering has a negligible effect, producing a spectral broadening $\Delta N_{//}$ less than about 0.25 for 2.45 GHz source and less than about 0.15 for 4.6 GHz source in the region of the LH power absorption (r/a ~ 0.9). Compared to the PI induced spectral broadening $\Delta N_{//}$>>1 in the edge region with relatively low (15 eV) edge electron temperature, such broadening is not dominant. Therefore, the different LHCD effect observed with different source frequencies should be not ascribed to the SDF.

Conversely, signatures of PI could be recognized in the aforementioned RF probe spectra that clearly indicate non-linear wave plasma interaction attributable to PI mechanism. With standard EAST parameters in Fig. 1, using the LHPI (Lower Hybrid Parametric Instability) code [16], which has the special feature of modeling the PI mechanism retaining convective losses due to plasma inhomogeneity and finite extent of the pump wave region, the calculated frequencies and growth rates of PI driven mode are shown in Fig. 4, in which the EAST antenna dimensions, edge plasma parameters of n_{ea} = 4×10^{17} m^{-3} and T_{ea} = 30 eV, and $n_{//}$=5 of the low frequency driving quasimode have been considered. For the pump frequency of 4.60 GHz, the analysis shows that the PI mechanism is mostly driven by a low frequency quasi-mode having a maximum homogeneous growth rate ($\gamma/\omega_0 \approx 8\text{x}10^{-4}$) that is slightly smaller (by about 20%) than for operating frequency of 2.45 GHz, implying a stronger PI effect in the case of 2.45 GHz source operation, consistent with the RF probe data. Further modeling (Fig. 5) done by MIT group [17] shows that, with the edge density increase, a stronger PI growth rate increases for the 2.45GHz wave, indicating the PI could be more dominant at higher density.

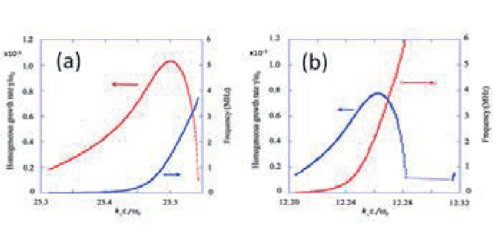

Fig. 4 PI modelling (n_{ea} = 4×10^{17} m^{-3} T_{ea} = 30 eV). (a) 2.45GHz, (b) 4.6GHz

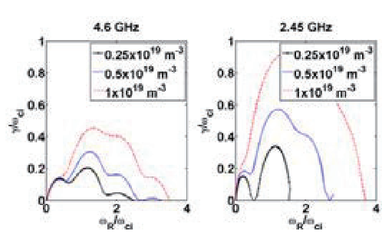

Fig. 5 PI modeling for different edge densities

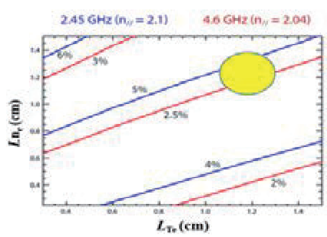

Fig. 6 Round trip loss contours *vs* scale lengths in SOL

In addition, CA loss in the edge region could be another candidate for the discrepancy since CA damping should decrease as a function of frequency [7]. For the typical scale length of $Ln_e \sim L_{Te} \sim$ 1.2 cm in EAST, WKB analysis of the absorption based on a plane-stratified SOL model (see Fig. 6) shows that the CA loss in the SOL for a LH wave passing into and out of the SOL (i.e. the 'round trip') is about 5% at 2.45 GHz and half that at 4.6 GHz, being in agreement with the results with GENRAY code [18]. Although this 'round-trip' damping through the SOL is low, the cumulative damping after several passes is by no means negligible since the core electron temperature is not high enough for the waves to be absorbed in a single pass into the plasma and the LH rays actually undergo many radial reflections in the SOL as indicated by the ray tracing /Fokker Planck simulations.

4. Conclusion

Available data of experiments performed on EAST show that, compared to 2.45GHz, operation at higher frequency (4.6 GHz) improves penetration of the coupled RF power into the plasma core. Studies show that such beneficial behavior could be a consequence of the diminished parasitic effects of the plasma edge expected to occur through PI and CA mechanisms. In addition, the parasitic effects would be further diminished under reactor conditions where a markedly warmer edge and core plasma would exist as compared to present experiments. These results bode well for the use of the LHCD actuator as an essential tool for current profile control in a thermonuclear fusion reactor.

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