Direct Measurements of High Harmonic Fast Wave Profile in the UTST Spherical Tokamak Plasma

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The spatial distribution of the radiofrequency (RF) magnetic field associated with a high harmonic fast wave (HHFW) was measured using an array of magnetic probes in the plasma inside the University of Tokyo Spherical Tokamak (UTST). Data obtained from 25 probes (19 locations for toroidal polarization and 6 locations for vertical polarization) distributed along the poloidal cross section were analyzed. The RF magnetic field is polarized in the toroidal direction, indicating that the HHFW is excited in the plasma. The RF field is weak on the inboard side. Analysis of the group delay suggests that the waves travel long distances in the plasma, probably because of poor absorption. No indication of parametric decay was observed up to 80 kW of injected RF power.

Keywords: High Harmonic Fast Wave (HHFW), spherical tokamak

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A high harmonic fast wave (HHFW) is used to heat electrons and sustain the plasma after spherical tokamak (ST) formation by the double null merging technique in the University of Tokyo Spherical Tokamak (UTST) [1]. HHFW is suitable for electron heating of high-β ST plasmas [2]. Efficient electron heating was confirmed experimentally with the National Spherical Torus Experiment (NSTX) [3]. However, parametric decay instability (PDI) in the edge plasma region and degradation of electron heating were observed with NSTX and the Tokyo Spherical Tokamak-2 (TST-2) [4, 5]. It is important to confirm the excitation and propagation of HHFW in the plasma core region. In this paper, results of direct measurements of the radiofrequency (RF) magnetic field associated with a HHFW are presented.

UTST is an ST device with the following typical parameters: R_0 (major radius) = 0.43 m, a (minor radius) = 0.17 m, B_t (toroidal magnetic field) = 0.15 T, and I_p (plasma current) = 100 kA. The frequency of the externally applied RF power (21 MHz) is more than ten times the hydrogen ion cyclotron frequency. The HHFW antenna consists of two poloidal current straps separated in the toroidal direction by 22.5°. When they are excited out of phase, the toroidal mode number of the excited HHFW is ±8 (which corresponds to the toroidal wavenumber of $k_\phi = \pm 13\,\mathrm{m}^{-1}$). This is referred to as double-strap excitation. When only one strap is excited (single-strap excitation), a broader toroidal wavenumber spectrum centered around $k_\phi = 0$ is excited. A 2-dimensional (2-D) 9×9 magnetic probe array is inserted into the plasma at the poloidal section that is 45° away from the antenna toroidally. Magnetic field components in the toroidal direction (B_ϕ) and vertical direction (B_z) can be measured at each probe location. Data from only 25 probes (8 toroidal fields and 6 vertical fields on the midplane, and 11 toroidal fields off the midplane) were taken simultaneously in this experiment due to limitation of number of digitizers. Probes are separated from each other by 70 mm in the radial direction and 60 mm in the vertical direction.

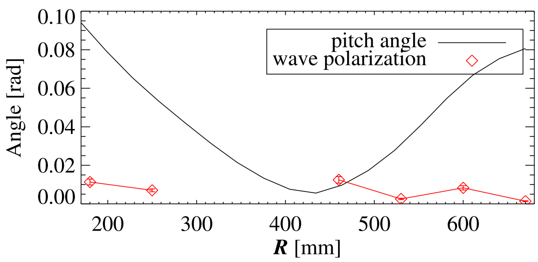

Fig. 1 2-D RF magnetic field polarization angle profile on the midplane (diamonds). The polarization angle should be smaller than the upper limit given by the magnetic field pitch angle (solid line).

Figure 1 depicts the 2-D (z-ϕ) wave polarization angle (defined as $\tan^{-1}[B_z/B_\phi]$) profile on the midplane. In these

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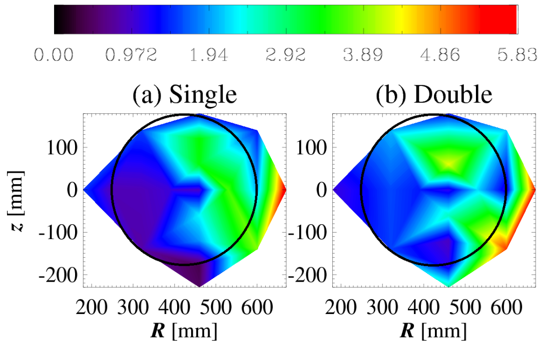

Fig. 2 2-D RF B_ϕ profiles for (a) single-strap and (b) double-strap excitations. Black ellipses indicate the LCFS.

plasmas, because the lower hybrid frequency is greater than the wave frequency, the slow wave (lower hybrid wave) is evanescent. The dominantly toroidal polarization of the magnetic field is consistent with excitation of the HHFW.

Two-dimensional RF toroidal magnetic field profiles for single-strap and double-strap excitations are shown in Fig. 2. In both cases, the RF field amplitude rapidly decreases outside the last closed flux surface (LCFS). The RF field amplitude gradually decreases inside the plasma. However, this plasma, with electron temperature T_e = 20 eV and electron density $5 \times 10^{18} < n_e < 2 \times 10^{19}\ \mathrm{m}^{-3}$, lacks a strong absorption and cutoff layer.

The delay time of the RF field modulation between different probes reflects the propagation of the wave. To avoid uncertainty in the timing of modulation, the initial ramp-up phase of the RF pulse is analyzed. The cross-correlation coefficient, R_{xy}, which gives the similarity of the two signals x and y, is defined as

$$R_{xy}(\tau) = \frac{\overline{x(t)y(t+\tau)}}{\sqrt{\overline{x^2}}\sqrt{\overline{y^2}}},$$

where the overbar denotes an average over time t. Because the probe signal at $r = +140$ mm is closest to the HHFW antenna, it is fixed as the reference. The cross-correlation coefficient should comprise a peak at a corresponding delay time. The delay becomes negative when signal is advanced with respect to the reference signal. When a ramp-up waveform is dissimilar to the reference waveform, it is difficult to determine the delay time, and the results are unstable. Therefore, only data with peak cross-correlation coefficients exceeding 0.99 were utilized.

The same analysis was carried out for vacuum injection data. In the absence of plasma, the wave fields do not modulate; hence, the delay times are stable and accurate (Fig. 3 (a)). Because this delay corresponds to differences in cable length, this component is subtracted from the delay for the plasma injection case (Fig. 3 (b)).

For the plasma injection case depicted in Fig. 3 (b), the range of data is indicated by the error bar, and 50%

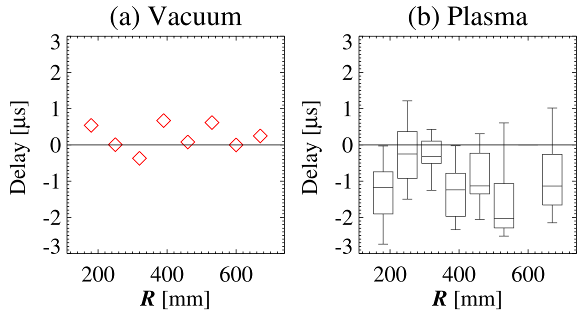

Fig. 3 Delay times for RF injection into (a) vacuum and (b) plasma. The vacuum case reflects differences in experimental setup. In (b), the boxes represent 50% confidence range and the median is shown by the horizontal line inside the box. The error bar spans the entire data range.

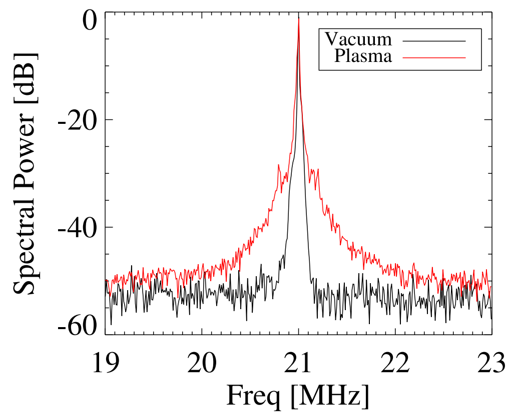

Fig. 4 Frequency spectra of magnetic probe signals for vacuum (black) and plasma (red) injection.

confidence level is indicated by the box. The Alfven velocity, which characterizes the speed of HHFW, is $v_A \sim 7 \times 10^5$ m/s. The delay time corresponding to the propagation distance, which is equal to the probe spacing, is of the order of 100 ns. However, the experimentally observed delay times are of the order of μs, and exhibit large scatter. These observations imply that the wave propagation distances are long (∼ 5 m) because of weak absorption. In addition, the phase and amplitude of the HHFW can be distorted significantly due to the effects of density fluctuations along the propagation path.

In addition, frequency spectra were calculated for all magnetic probe signals. Spectra characteristic of PDI were not observed.

In summary, excitation and propagation of the HHFW to the plasma core region were confirmed by direct measurements of the RF magnetic field inside the plasma. No indication of PDI was observed up to 80 kW of injected RF power. An analysis of the 2-D RF field profile revealed that the RF field is very small on the inboard side. Analysis of the group delay suggests that the wave absorption is weak, and the waves travel long distances.

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