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Frequency Broadening of High Harmonic Fast Wave in Plasmas

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Abstract

The high harmonic fast wave (HHFW) is a promising candidate for driving noninductive current in plasmas with high dielectric constant, such as in a spherical tokamak. A broadening of the HHFW frequency spectrum has been observed in the TST-2 spherical tokamak [1]. If the broadening were caused by scattering of the HHFW by density fluctuations, the wave number could be altered and wave absorption could be affected. The time evolution of the HHFW spectrum was calculated and the experimentally measured spectrum was reproduced well under some conditions. The power deposition profile was calculated to become broader and shifted outward as a result of scattering, which may explain the deterioration of current drive efficiency observed in some experiments.

Keywords:

high harmonic fast wave, heating, spherical tokamak, scattering, density fluctuation

1. Introduction

Attractive features of the spherical tokamak (ST) include improved stability at high beta and high natural elongation [2]. Recent experiments performed on START [3], NSTX [4] and MAST [5] have demonstrated simultaneous achievement of good confinement and high beta [6]. For an ST reactor elimination of the Ohmic solenoid is necessary, and therefore non-inductive current drive by waves [7] or neutral beams injection is required. The HHFW, which is an electromagnetic wave in the frequency range of several times the ion cyclotron frequency, has good accessibility to the high density core plasma, and is therefore a promising candidate for driving current in plasmas with high dielectric constant.

The lower hybrid (LH) waves requires high wave numbers to satisfy accessibility, but in such a case the wave damps at in the plasma edge region before it can propagate into the core. The electron cyclotron waves cannot propagate in overdense plasmas (*i.e.*, high dielectric constant plasmas), in which $\frac{\Pi_e^2}{\Omega_e^2} \gg 1$, where Π_e is the electron plasma frequency and Ω_e is the electron cyclotron frequency. The HHFW can penetrate into the core, and because it is strongly damped in high beta plasmas, it may be possible to control the current density profile [8] in order to improve stability and confinement.

In an earlier HHFW experiment using a combline antenna, a broadening of the frequency spectrum was observed [1]. A similar broadening has also been observed in LH heating experiments [9,10]. A frequency broadening can arise from scattering by density fluctuations [11-13] or by parametric instability [9]. The density fluctuation has large amplitudes near the plasma edge. Waves propagating into the plasma could be scattered in the edge region by these low frequency fluctuations (*e.g.*, drift waves). Experimental results are described in Sec. **2**. The calculation model is described in Sec. **3**. The calculated results are compared with the experimentally measured spectrum in Sec. **4**. Conclusions are given in Sec. **5**.

2. Experiment

TST-2 is a spherical tokamak at the University of Tokyo, with major radius R = 0.38 m, minor radius a = 0.25 m, and aspect ratio A = 1.5. Typical values of the toroidal magnetic field and the plasma current are B_t = 0.2 T and I_p = 0.1 MA [1].

A 21 MHz sinusoidal wave is amplified to 32 W and is injected into the plasma. The incident wave is detected by a single-turn magnetic probe at the antenna. The scattered wave measured by a probe separated from the antenna by 60 degrees in the toroidal direction on the outward equatorial plane is discussed in this paper. The detected signal is amplified, mixed with a local oscillator at 21.1 MHz amplified again and digitized at 1 MHz. The frequency spectrum is

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obtained by Fourier transform.

In this paper, the frequency broadening of the HHFW is assumed to be caused by scattering by plasma density fluctuations, primarily at the edge. The fluctuation level was measured using the double probe technique. The frequency spectrum of the ion saturation current decays exponentially, with a characteristic frequency width of around 20 kHz (Fig. 1). The fluctuation level was around 30 % at the edge. We assume that the ion saturation current fluctuation is caused primarily by the density fluctuation.

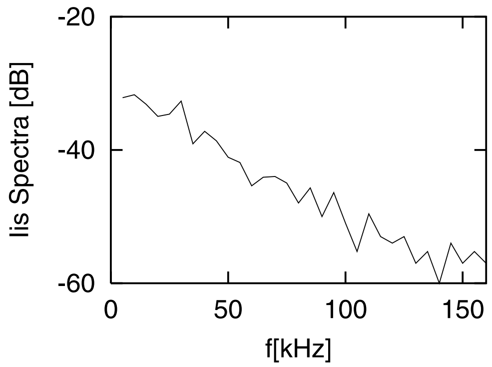

Fig. 1 Spectra of ion saturation current measured at the edge of plasmas.

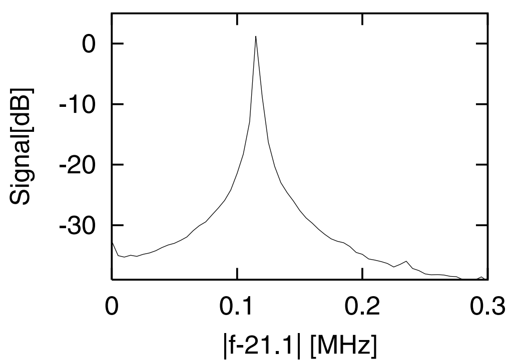

Fig. 2 Unscattered frequency spectrum (measured).

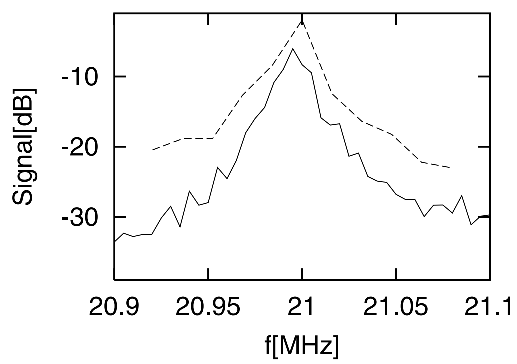

Fig. 3 Measured (solid line) and calculated (dotted line) frequency spectra.

The frequency spectrum measured at the antenna without plasma (unscattered spectrum) is shown in Fig. 2. The frequency spectrum measured by the probe 60 degrees away from the antenna toroidally with plasma (scattered spectrum) is shown in Fig. 3. The smooth spectrum (exponentially decay width, $f_{\exp\, decay} \approx 4\ kHZ$) becomes noisier ($f_{\exp\, decay} \approx 9\ kHZ$) and broader after being scattered in the plasma. A typical frequency width (FWHM) of the scattered spectrum is around 30 kHz. The fact that the scattered spectrum decays exponentially suggests that this broadening is caused by scattering by density fluctuations, whose spectrum decays exponentially. In an experiment with additional gas puff, a correlation between the frequency width and the plasma density measured by an interferometer was found. This effect is discussed in Sec. **4**.

3. Calculation model

Scattering of the LH wave was formulated before, but the electrostatic approximation was used. This approximation cannot be used for HHFW. We start with a cold plasma model with density fluctuations. The validity of using the cold plasma model was verified. In this HHFW experiment, the difference is of order $O(b_e)$, where $b_e = \left(\frac{k_\perp v_{T,e}}{\Omega_e}\right)^2 \approx 10^{-6}$. $\overleftrightarrow{D}(\vec{k},\omega)\vec{E}_{\vec{k},\omega} = \sum \frac{\omega\omega'}{c^2}\left(\overleftrightarrow{a}' - \overleftrightarrow{\mathbf{1}}\right)\vec{E}_{\vec{k}',\omega'}\left(\frac{\delta n}{N}\right)_{\delta\vec{k},\delta\omega}$, where $\vec{k},\omega$ are wave number and angular frequency of an incident wave, $\vec{k}',\omega'$ are those of a scattered wave, $\delta k = \left|\vec{k}' - \vec{k}\right|$, $\delta\omega = \left|\omega' - \omega\right|$, $\overleftrightarrow{a}_{\vec{k},\omega}$ is the dielectric tensor, $\overleftrightarrow{D}(\vec{k},\omega) = \vec{k}\times\vec{k}\times\overleftrightarrow{\mathbf{1}} + \frac{\omega^2}{c^2}\overleftrightarrow{a}_{\vec{k},\omega}$, $\left(\frac{\delta n}{N}\right)_{\delta\vec{k},\delta\omega} = \left|\frac{\delta n}{N}\right| \exp\left(-\frac{\delta k}{k_{fluct}} - \frac{\delta\omega}{\omega_{fluct}}\right)$ is the normalized density fluctuation, v_t is the thermal velocity, c is the speed of light, and summention is taken over all wave numbers $\vec{k}$ and angular frequencies ω. Based on the fact that the frequency broadening is small compared to the wave frequency itself, we expand $\omega \to \omega_{\vec{k}} + \mathrm{i}\frac{\partial}{\partial t}$ to obtain

$$\mathrm{i}\hat{e}_{\vec{k}}\cdot\frac{\partial\overleftrightarrow{\boldsymbol{D}}}{\partial\omega}\cdot\hat{e}_{\vec{k}}\frac{\partial\vec{E}_{\vec{k},\omega}}{\partial t} = -\sum\frac{\omega\omega'}{c^2}\hat{e}_{\vec{k}}\cdot\left(\overleftrightarrow{a}' - \overleftrightarrow{\mathbf{1}}\right)\cdot\hat{e}_{\vec{k}'}\vec{E}_{\vec{k}',\omega'}\left(\frac{\delta n}{N}\right)_{\delta\vec{k},\delta\omega},$$

where $\hat{e}_{\vec{k}}$ is the unit vector in the direction of electric field. Note $\hat{e}_{\vec{k}}\cdot\overleftrightarrow{\boldsymbol{D}}\cdot\hat{e}_{\vec{k}} = 0$. We consider three wave coupling, consisting of the incident HHFW, the low frequency density fluctuation, and the scattered HHFW. For the wave energy density u, we define $C_{\vec{k},\omega} = \sqrt{u_{\vec{k},\omega}} \propto \exp(-\mathrm{i}\omega t)$ and since

$u_{\vec{k},\omega} = \frac{\left\langle E^2\right\rangle}{8\pi}\frac{c^2}{\omega^2}\overleftrightarrow{\boldsymbol{D}}\left(\vec{k},\omega\right)$, we have the following relation,

$$\mathrm{i}\frac{\partial C_{\vec{k},\omega}}{\partial t} = \sum_\sigma \int \mathrm{d}\vec{k}'\int \mathrm{d}\omega' V\left(\vec{k},\vec{k}',\omega,\omega'\right)\left(\frac{\delta n}{N}\right)_{\delta\vec{k},\delta\omega},$$ where

$$V\left(\vec{k},\vec{k}',\omega,\omega'\right) = -\frac{\omega'\hat{e}\cdot\left(\overleftrightarrow{a}' - \overleftrightarrow{\mathbf{1}}\right)\cdot\hat{e}'}{2\sqrt{\hat{e}\cdot\overleftrightarrow{\boldsymbol{M}}\cdot\hat{e}}\sqrt{\hat{e}'\cdot\overleftrightarrow{\boldsymbol{M}}'\cdot\hat{e}'}},$$

$\overleftrightarrow{\boldsymbol{M}} \equiv \frac{\partial}{\partial\omega}\left\{\frac{c^2}{2\omega}\overleftrightarrow{\boldsymbol{D}}(\vec{\boldsymbol{k}},\omega)\right\}$, σ represents the mode of the wave.

Then following time evolution of the wave energy density

$u_{\vec{k},\omega}$ can be derived in the form of Pauli equation, $\frac{\partial u_{\vec{k},\omega}}{\partial t} = \sum_\sigma \int \mathrm{d}\vec{k}' \int \mathrm{d}\omega' \left| V\left(\vec{k}, \vec{k}', \omega, \omega'\right) \left(\frac{\delta n}{N}\right)_{\delta\vec{k},\delta\omega} \right|^2 \left(u^\sigma_{\vec{k}'\omega'} - u_{\vec{k},\omega}\right)$.
The wave can be converted to another mode with a certain probability. In this paper, we do not consider mode conversion, since there exist no other mode waves in the range $f_{incident} \pm 3 f_{fluct}$.

4. Results of calculation

The frequency spectrum calculated by the model described in Sec. **3** is compared with the measured spectrum in Fig. 3. Scattering was treated by the Monte-Carlo method. The wave is excited at the plasma edge and propagates in. Scattering and damping within each time interval Δt are calculated, till the wave is detected by a probe located 60 degrees away toroidally. The density fluctuation level was taken to be the value measured by a double probe. The frequency spectrum matches the experimentally measured spectrum the best when the typical wave number of the density fluctuation is 2000 m^{-1}. The simulation results indicate a correlation between the spectrum width and the core plasma density, as observed in a gas-puff experiment. Exponential decay width of 6.5 kHz (5 kHz in the experiment) at $n_{20} = 0.1$ [m^{-3}] increases 10.5 kHz (40 kHz in experiments) at $n_{20} = 0.3$ [m^{-3}]. At higher densities, the HHFW rays are shifted outward, where the density fluctuation is more intense. They then suffer heavier scattering, resulting in a broader spectrum. Also density fluctuation level will play an important role, which is not measured simultaniously.

The calculated damping profile (absorption profile) is shown in Fig. 4. The profile is broader and is shifted outward. The wave number vector is scattered mainly in the direction perpendicular to the magnetic filed with a small change of frequency, and the magnetic shear (the safety factor q varies from 8 at the edge to 4 at $r/a = 0.5$), causes a change in $k_{\|}$. Since the HHFW damps mainly by electron Landau Damping under the condition discussed in this paper, a broader profile is natural consequence of scattering. The outward shift is caused by scattering in the outer region, where the density fluctuation has a large amplitude. In the simulation, a large variation was observed in $k_\perp$ and therefore in $k_{\|}$. As the fluctuation level becomes higher, the waves suffer more scattering in the outer region and an additional peak in the absorption profile appears at an outer radius.

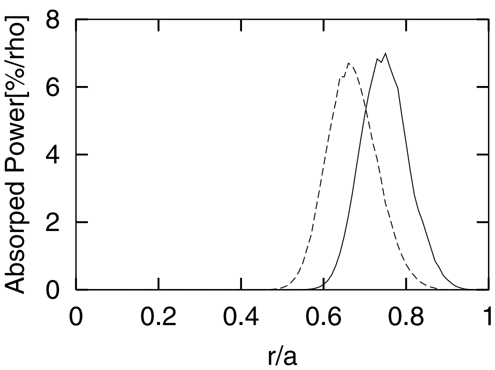

Fig. 4 Calculated absorption profiles with (solid line) and without (dotted line) scattering.

5. Conclusions

A broadening of the HHFW frequency spectrum was measured. The spectrum width was typically about 30 kHz (FWHM). A model without the electrostatic approximation was formulated. The time evolution of the frequency spectrum was studied by a Monte-Carlo simulation and was compared with experimental data. The experimentally measured spectrum was reproduced well when the typical wave number of the density fluctuation of 2000 m^{-1} was used. In a gas-puff experiment, a correlation between the plasma density and the scattered spectrum width was observed. The simulation results indicate that at higher densities, the HHFW with lower Alfvén velocity suffers heavier scattering at the edge, resulting in a broader spectrum. The damping profile was calculated to broaden a little with weak scattering, and an additional peak in the absorption profile appears at an outer radius with strong scattering. A density profile with a lower edge density is favorable to minimize the effects of scattering. This mechanism may also be used as a diagnostic to obtain information about the density fluctuation.

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