Measurement of 3-D Mode Structure of the Edge Harmonic Oscillations in CHS using Beam Emission Spectroscopy

T. OISHI, S. KADO[1)], M. YOSHINUMA, K. IDA, T. AKIYAMA, T. MINAMI, K. NAGAOKA, A. SHIMIZU, S. OKAMURA and CHS group

National Institute for Fusion Science, Toki, Gifu 509-5292, Japan
[1)]*High Temperature Plasma Center, The University of Tokyo, Kashiwa, Chiba 277-8568, Japan*

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The 3-D spatial structure - radial locality and poloidal/toroidal mode numbers - of the magnetohydrodynamic fluctuation called "edge harmonic oscillation (EHO)" in the compact helical system (CHS) was investigated using beam emission spectroscopy (BES) as the diagnostic method of the local density fluctuations and the magnetic probe array. We found two groups of harmonic oscillations in CHS, one with a frequency of 4.0 kHz and a harmonic located in the edge region of the normalized minor radius $\rho = 0.95$ near the rotational transform $\iota = 1$ surface, and the other with a frequency of 3.5 kHz and a harmonic located in the core region $\rho = 0.53$ near the $\iota = 0.5$ surface. The magnetic probe signals showed that the poloidal/toroidal mode numbers of the edge mode and the core mode were $-1/1$ and $-2/1$, respectively. They were consistent with the rotational transform of the magnetic field at the locations of those modes.

Keywords: density fluctuation, magnetohydrodynamics, edge harmonic oscillation, compact helical system, beam emission spectroscopy, H-mode, edge transport barrier

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1. Introduction

Fluctuations of plasma parameters have been considered to correlate with the properties of plasma confinement. One of important piece of information about the characteristics of the fluctuation is its spatial structure, represented by its radial locality and/or poloidal/toroidal mode number. For magnetohydrodynamic (MHD) oscillation in magnetically-confined torus plasmas, we might estimate its locality from the mode number measured using magnetic probes and the position of the rational surface in relation to the corresponding rotational transform. However, accurate locations of the fluctuations can be obtained only by using method of local diagnostics.

Recently, a coherent MHD mode that has characteristics similar to those of edge harmonic oscillation (EHO) [1–4] in the quiescent H-mode of tokamaks has been observed in the edge transport barrier (ETB) discharges of the compact helical system (CHS), which is a low-aspect-ratio, middle-sized heliotron (major radius = 1 m, minor radius = 0.2 m, toroidal period number = 8, polarity = 2) [5, 6]. EHO is an edge-localized MHD mode consisting of a fundamental frequency of several kilohertz and its harmonic components. It has been recognized that EHO in tokamaks enhances particle transport through the boundary instead of intermittent exhaust by the edge localized modes (ELM) [3, 7, 8]. Therefore, it is important to investigate the characteristics of EHO in CHS from the viewpoint of particle transport control.

author's e-mail: oishi@nifs.ac.jp

In the present study, the 3-D spatial structure represented by radial locality and poloidal/toroidal mode numbers of EHO in CHS was investigated using beam emission spectroscopy (BES) as the diagnostic method for the local density fluctuations and magnetic probe array.

2. Experimental Setup

BES has been developed in CHS to simultaneously measure both local density fluctuations and gradients [9, 10]. The BES method detects emissions from the collisionally excited neutral beam atoms (denoted as "beam emission") [11]. In the present experiment, H_α emission from the neutral hydrogen atomic beam for heating was measured as the beam emission. The spatial channels used in BES consist of 16 optical fibers with an object lense. Since the observable region is the intersection of the beam line and the sightline for each fiber channel, local values and their correlations are available. One can select the arrangement of the fibers in the radial or poloidal direction to measure each structure of the fluctuations. Figure 1 shows the poloidal cross section including the point where the optical axis crosses the beam axis. The BES signal is dominated by the emission released from this cross section for the poloidal measurement. The arrangement of fiber images for the poloidal measurement of BES is also shown in this figure. The direction of the fiber array is rotated by $\pi/16$ rad to align it with the magnetic flux surface. The hatched chords (even-numbered) seen in this figure were used in this study. The spatial pitch Δx was 2.6 cm, which yields

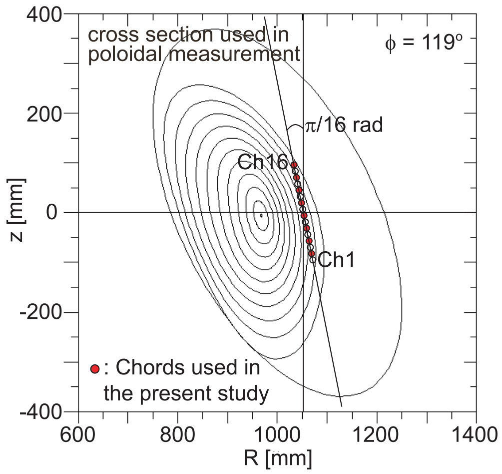

Fig. 1 Poloidal cross section including the point where the optical axis crosses the beam axis.

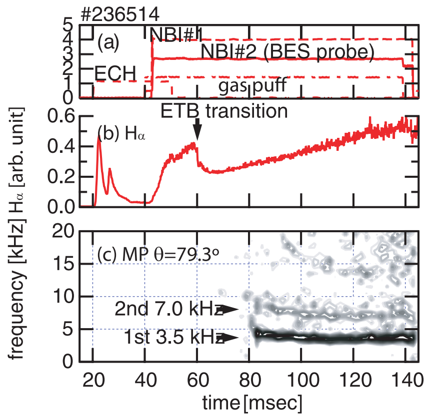

Fig. 2 Typical experimental conditions and temporal evolution of plasma parameters for a discharge showing the ETB transition: (a) heating condition, (b) H_α intensity, and (c) magnetic fluctuation. The ETB transition occurred at 60 msec. A coherent oscillation which consists of a 1st harmonic with the frequency of 3.5 kHz and a 2nd harmonic appeared from 82 msec to 142 msec.

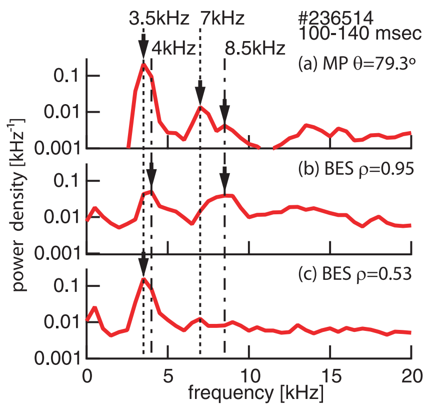

Fig. 3 Power density spectra of (a) the magnetic fluctuation, (b) the density fluctuation at $\rho = 0.95$, and (c) the density fluctuation at $\rho = 0.53$.

the Nyquist wavenumber, $k_N = \pi/\Delta x$, of 1.21 rad cm^{-1}.

Magnetic probe array was also used to measure both the poloidal and toroidal structures of the fluctuations. The poloidal magnetic probe array consists of sixteen probes covering the poloidal angle $\Delta\theta = 235.5$ deg [12]. Five toroidal magnetic probes covering the toroidal angle $\Delta\phi = \pi$ were located at every $\pi/4$ section at the major radius $R = 1.2$ m.

3. Experimental Results

Figure 2 shows typical experimental conditions and the temporal evolution of the following plasma parameters for a discharge showing the ETB transition: (a) heating condition, (b) H_α intensity, and (c) magnetic fluctuation. Plasma was initiated by electron cyclotron heating and was further heated by two neutral beam injection (NBI) systems. Additional gas was puffed as a means to increase density. The standard magnetic field configuration of CHS was applied, in which the vacuum magnetic axis position R_{ax} was 92.1 cm from the torus center, the toroidal magnetic field strength at the magnetic axis B_{ax} was 0.95 T, and the magnitude of the quadrupole field B_q denoting the degree of cancellation of the intrinsic quadrupole component formed by the helical coils was −50 %. In the cases in which the heating power exceeded a certain threshold, a sudden drop in the H_α intensity signal was observed, as shown in Fig. 2 (b). It has been found that the line-averaged density, the edge density gradient, and the stored energy begin to increase at the transition [13–17]. In the latter half of the phase having ETB, magnetic fluctuations consisting of the 1st harmonic with the frequency of 3.5 kHz and the 2nd harmonic increase as shown in Fig. 2 (c).

Radial distribution of the density fluctuations can be measured using BES with the radially-aligned sightlines. The normalized radius ρ was determined based on the magnetic flux surfaces calculated using the three-dimensional equilibrium code VMEC [18] for $\beta = 0.8$ %, which yielded the observable region of BES. In our previous study, we focused on the measurement of the radial profile of the mode at the edge region of $\rho > 0.7$. In addition to that, we tried to observe not only the edge region but also the core region. In the present study, eight sightlines from $\rho = 0.42$ to $\rho = 1.10$ with a separation between the sightlines of about 0.1 in the normalized minor radius were used for the radial measurements. Figure 3 shows the power density spectra of (a) the magnetic fluctuation, (b) the density fluctuation at $\rho = 0.95$, and (c) the density fluctuation at $\rho = 0.53$. These spectra were averaged over 100-140 msec, which is the period in which the coherent oscillation appears in the magnetic fluctuation. As shown in Fig. 3 (b), the edge density fluctuation has a frequency spectrum with 1st and 2nd harmonic components. We have called this mode "EHO" because of the shape of its spectrum and its

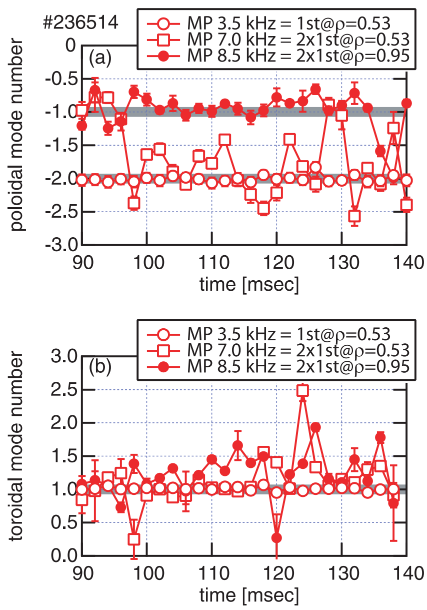

Fig. 4 Temporal evolutions of the (a) poloidal and (b) toroidal mode numbers of the 3.5 kHz, 7.0 kHz and 8.5 kHz modes.

locality, even though it has not yet been clarified whether or not the mechanism of this mode and that of the EHO in tokamaks are exactly the same. There is a rational surface with the rotational transform $\iota = 1$ at the position $\rho = 0.97$, which is near the peak position of EHO. Moreover, we found that there is a coherent fluctuation at the core region at $\rho = 0.53$ after the extension of the observable region. There is an $\iota = 0.5$ rational surface at the position $\rho = 0.5$, which is near the position of this core mode. The shape of the frequency spectrum of the magnetic fluctuation is similar to that of the edge density fluctuation as shown in Fig. 3 (a) and (b). Therefore, this magnetic fluctuation has been regarded as the edge oscillation in our previous study [5, 19]. However, recent observation has revealed that the frequencies of this mode differ slightly between the magnetic fluctuation (1st 3.5 kHz, 2nd 7.0 kHz) and the edge density fluctuation (1st 4.0 kHz, 2 nd 8.5 kHz) as shown in these figures. On the other hand, as shown in Fig. 3 (a) and (c), the frequency of the core density fluctuation, 3.5 kHz, is exactly the same as that of the 1st harmonic of the magnetic fluctuation. These results indicate that the clear peaks of 3.5 kHz and 7.0 kHz in the magnetic fluctuation reflect the harmonic oscillation in the core (denoted as "HO (core)" hereafter) actually. Furthermore, a small peak of 8.5 kHz can be found in the magnetic fluctuation as shown in Fig. 3 (a), as the 2nd component of the harmonic oscillation in the edge (denoted as "HO (edge)" hereafter).

To confirm the existence of these two pairs of harmonic modes, the mode number of each mode was analyzed. Figure 4 shows the temporal evolutions of the (a) poloidal and (b) toroidal mode numbers of the 3.5 kHz,

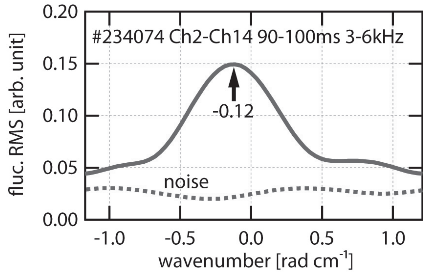

Fig. 5 Wave number spectrum of the 1st harmonic of the HO (edge) measured using BES.

7.0 kHz, and 8.5 kHz modes measured using magnetic probes. The signs are defined such that the ion diamagnetic direction and counterclockwise direction are positive for poloidal and toroidal mode numbers, respectively. The poloidal/toroidal mode number m/n of the HO (core) at the frequencies 3.5 kHz and 7.0 kHz was $-2/1$ while that of the HO (edge) 8.5 kHz mode was $-1/1$.

The 1st frequency of the HO (edge), 4.0 kHz, is difficult to find in the magnetic fluctuation spectrum because it is very close to the large 3.5 kHz peak. Therefore, we tried to measure the poloidal wavenumber of the 1st component of the HO (edge) directly using BES with the poloidally-aligned sightlines. Figure 5 shows the poloidal wavenumber spectrum of the 1st harmonic of the HO (edge) measured using BES. It is obtained using the BES chords from #2 to #14 shown in Fig. 1 where the 1st mode of the HO (edge) was observed. In this measurement, $B_q = 0\,\%$ was applied to scan the position of the plasma so that the position of the HO (edge) matches the observation area. The corresponding normalized radius at the positions of the sightlines was about $\rho = 0.8$-0.9. As shown in this figure, the poloidal wavenumber k_θ was found to be 0.12 rad cm^{-1}. We can obtain the poloidal mode number $m = -1$ from this wavenumber using the relationship $m = k_\theta(\Delta l/\Delta\theta)$, where $\Delta l(= 15.6\,\text{cm})$ and $\Delta\theta(= 1.5\,\text{rad})$ refer to the length and the poloidal angle covered by the BES chords from #2 to #14, respectively.

These results lead us to the following conclusion. There are two pairs of harmonic oscillations in the ETB discharges in the CHS, one called HO (core) having the mode number $m/n = -2/1$ and located at $\rho = 0.53$ near the $\iota = 0.5$ rational surface, and the other called HO (edge) having the mode number $m/n = -1/1$ and located at $\rho = 0.95$ near the ι 1 rational surface. Note that the magnetic probes were sensitive to the HO (core). This fact means that we cannot distinguish the HO (core) and the HO (edge) without local measurement such as BES. It should be investigated why the magnetic probes are less sensitive to the HO (edge).

Another question remains to be solved in the future. It was revealed that the 1st and 2nd harmonic components have the same mode number, which is $-2/1$ for the HO (core) and $-1/1$ for the HO (edge). Mode number analysis using the magnetic probes has shown the same result for the HO (core) including the 3 rd harmonic [20]. This means that the phase velocity of the pth harmonic is p times larger than that of the 1st harmonic. Note that we use the expression "pth harmonic" focusing on the shape of the frequency spectra of the HO (core) and HO (edge) having frequencies which are p times larger than those of the fundamental oscillation, even though the dispersion relationships of both the HO (core) and HO (edge) are different from that of the conventional MHD oscillation having harmonics. If the frequency of the 1st harmonic is determined by the $E \times B$ poloidal rotation, the rotation velocities at $\rho = 0.95$ (HO (edge), $m = 1$, 4 kHz) and $\rho = 0.53$ (HO (core), $m = 2$, 3.5 kHz) are estimated to be about 4800 m/s and 1200 m/s in the electron diamagnetic direction, respectively, where the averaged minor radius of the last closed flux surface is 0.2 m. Each value is almost consistent with the rotation velocity measured using charge exchange recombination spectroscopy [21]. On the other hand, the phase velocity of the harmonic components other than the 1st harmonic cannot be explained by the $E \times B$ rotation. Therefore, the phase difference between the harmonic components having different frequencies varies spatially. The simultaneous measurement of magnetic fluctuations at multiple poloidal and toroidal points using magnetic probe array has revealed that this phase difference is a unique function of the poloidal and toroidal angle [20]. This regularity of the phase difference suggests that the harmonic components correlate with each other in some way. Further research is needed to explain the peculiar dispersion relationship of this mode.

Future study includes investigation of the driving mechanism of both the HO (edge) and the HO (core). We have found that the edge density gradient increases after the ETB transition and the HO (edge) is excited when the density gradient achieves a certain threshold. Recently, we observed a case in which only the HO (core) was excited, while the HO (edge) was not [22]. This indicates that the HO (core) can be considered independent of the threshold of the edge density gradient for the excitation of the HO (edge). The edge density gradient in the case of excitation of both the HO (core) and HO (edge) is larger than that in the case of excitation of only the HO (core). Therefore, the conclusion remains unchanged that an increase in the edge density gradient is necessary to excite the HO (edge). We should investigate the correlation between the HO (core) and the core density gradient in the future. This can be achieved by accurate evaluation of the beam attenuation in the core to obtain the core density gradient from the BES signals.

4. Summary

Coherent fluctuation which is considerably similar to EHO in tokamaks was observed in CHS. There are two pairs of harmonic components at different radial locations. One locates in the edge region near the $\iota = 1$ rational surface, and has been called EHO in CHS. The other locates in the core region near the $\iota = 0.5$ rational surface. The mode numbers are consistent with the respective rational surfaces. At present, we can distinguish these two modes only by using BES. Therefore, we conclude that the local fluctuation measurement can play a significant role in the investigation of the characteristics of the fluctuations.

Acknowledgments

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