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**Abstract**. The dynamic behavior of the edge pedestal in the edge transport barrier (ETB) formation discharge (H-mode) [Okamura S. et al., J. Plasma Fusion Res. **79** (2003) 977] in the compact helical system (CHS) is investigated. Edge Harmonic Oscillations (EHOs) having a fundamental frequency of 2-4.5 kHz, depending on the magnetic configuration, and their second harmonic are observed when the density gradient of the pedestal reaches a certain threshold. There are two groups of so-called EHOs in the CHS. One is located in the edge region where the $\iota = 1$ surface exists, and the other is in the core region (although we also call it EHO in this paper) around the half radius where the $\iota = 0.5$ surface exists. The magnetic probe signal is revealed to reflect the latter mode, showing the poloidal mode number of 2, while that for the edge BES channel is 1. The density build-up saturates simultaneously with the increase of EHOs in the edge BES channel, which suggests that to a considerable extent the mode increases the particle transport.

## 1. Introduction

Properties of the edge pedestal determine not only the core plasma confinement but also the particle and heat fluxes onto the plasma facing components. In order to improve the plasma parameters, the formation of a transport barrier is indispensable, but the impurity species needs to be exhausted to achieve steady-state operations. The ELM-free H-mode, such as the quiescent H mode (QH-mode), might be a preferable scenario, because of its ability to cope with the edge pedestal and particle exhaust through the EHO without an accompanying heat load onto the divertor plate, which is a problem in the ELMy-H mode[1-4]. Recently, the EHO has been observed in the compact helical system (CHS) in discharges with an edge transport barrier (ETB) [5,6].

The CHS is a middle-size low aspect-ratio helical device ($R$ = 1 m, $a$ = 0.2 m). ETB can be achieved with two high-power neutral beam injection (NBI) systems, both of which are installed tangentially to the toroidal field in the co-direction. We have determined that in addition to a lower density limit of around 1.5 x $10^{13}$ $cm^{-3}$, a minimum threshold in the absorbed NBI power density ($P_{in}/n_e$) of about 2 x $10^{11}$ $kW/cm^3$ is required to achieve the H-mode transition[5]. For a local measurement of both the density gradient and fluctuations, we have developed a beam emission spectroscopy (BES) system in the CHS [7]. In the case where the heating power exceeds a certain threshold, a transition phenomenon characterized by sudden drop in the temporal evolution of the $H_\alpha$ intensity can be observed (Fig. 1(a, b))[8]. Figure 1(c) shows the BES signals for $r/a$ = 0.95 and $r/a$ = 1.03, which are denoted as BES(0.95) and BES(1.03), respectively. These values show that the density inside the last closed flux surface (LCFS) increases at the transition while that outside the LCFS decreases, indicating the formation of the edge pedestal. The increase in the stored energy $W_p$ , in the typical condition, reflects the increase in the density(Fig. 1(d)). We categorize the waveform

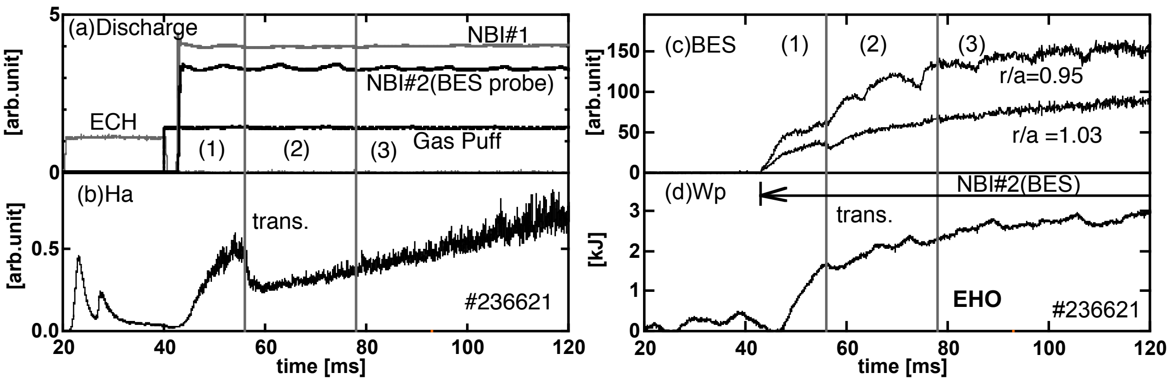


*Fig. 1. Typical waveforms of the discharge with the ETB transition. (a)discharge conditions, (b) $H_\alpha$ intensity, (c) BES signals for r/a = 0.95 and r/a = 1.03, respectively, and (d) stored energy. Dips in BES(0.95) are caused by the fluctuations in the beam energy, which could occasionally shift out the emission line spectrum from the pass-band of the interference filter. $R_{ax}$ = 92.1 cm and $B_q$ = -50%.*

into three phases as indicated in Fig. 1: (1) the L-phase before the transition, (2) the density build-up phase, and (3) the ETB-saturation phase. It should be noted here that the H-mode is supposed to be an indirect driving force through which the density/pressure gradient increases around the location where the EHOs is enhanced.

In this paper, we review the early observation of the EHOs in the CHS, pointing out its peculiarities. Then we discuss a current interpretation of the characteristics of the EHO signal with respect to the spatial distribution of the mode and the behavior of the density pedestal in response to the EHO activities.

## 2. First observation of the EHOs in CHS

EHOs in the CHS were first observed using BES in the edge region and soon were recognized to appear clearly in magnetic probe (MP) data. For a *standard* configuration where the magnetic axis position $R_{ax}$ = 92.1 cm, the toroidal magnetic field strength at the magnetic axis $B_{ax}$ = 0.95 T, and the quadrupole field component $B_q$ = -50 % (of the intrinsic component formed by the helical coils), the initial features of the EHO are listed below[9]:

(i) The EHOs are located around the rotational transform $\iota$ = 1 surface ($r/a$ ~ 0.95) where the density gradient becomes steeper, — namely, the pedestal region.

(ii) There is a threshold NBI power for the onset of the EHO (1.2 MW), which is higher than that of the ETB (1.0 MW).

(iii) A fundamental frequency of 4.5 kHz accompanies the second harmonic.

(iv) When the EHO amplitude increases, the build-up of the density gradient at the pedestal seems to be saturated.

As has been shown in ref. [9], these characteristics of the EHO in the CHS are similar to that observed in tokamaks even though the current profiles of the two devices are quite different.

In addition, from the radial coherence and phase between BES channels [10]:

(v) The first harmonic exists over a wider radial position, while the second harmonic can be observed only in the edge channel.

(vi) There is a radially decreasing phase shift, consistent with a radial outward propagation with an apparent velocity of several hundred m/s.

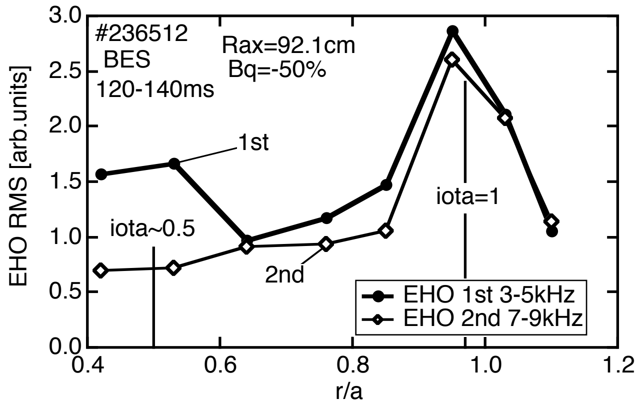


*Fig. 2. Spatial profile of the EHO measured by BES.*

From the mode analysis using the poloidal and toroidal magnetic probe arrays, the following peculiar features of the EHOs (up to the third harmonics for the $R_{ax}$ = 91.1 cm configuration) have been recognized[11]:

(vii) Although located around the ι = 1 surface, the poloidal and toroidal mode numbers (*m*, *n*) are (-2,1), where the negative sign denotes the propagation in the electron diamagnetic direction. On the other hand, the ι = 0.5 surface is around *r*/*a* ~ 0.5.

(viii) The higher harmonics have the same mode number as the first harmonic, indicating the phase velocity of the *p*-th harmonic is *p*-fold faster than that of the first harmonic.

(ix) The phase difference between the harmonics lies on the (*m*, *n*) = (-2,1) mode structure, due to which the shape of the row signal depends on the phase parameter $\phi$ - 2$\theta$.

Therefore, the relationship between the EHO in the edge region and something on the ι = 0.5 surface may be required to clarify the physical mechanism of these peculiarities.

## 3. EHOs observed in BES and MP signals

In contrast to the fact that the MP cannot determine the location of the mode of the magnetic fluctuation (except by inference from the mode number), BES yields spatial information about the density fluctuation, although the spectra are less clear due to the superposition of the broadband turbulent spectra and a relatively poor signal-to-noise ratio. The intensity distribution of the first and second harmonics of the EHO is shown in Fig. 2. A recent measurement has revealed that the frequencies of the fundamental spectra for the inner and edge BES channels sometimes differ by a very small amount. Therefore, by choosing such conditions, we get the frequency spectra for BES(0.53), BES(0.95) and the MP(33$^o$) (see ref. [11] for the MP arrangement) shown in Fig. 3(a)-(c), together with their cross-coherence in Fig. 3(d)-(f). One can see from these figures that the MP signal contains both components, the first harmonic for BES(0.53) and the second one for BES(0.95), even though the correlation is strong with BES(0.53). However, the higher harmonics is very weak in BES(0.53). Since the cross-coherence between BES(0.53) and BES(0.95) shows moderate coherence for the frequencies of 3.5 and 4.5 kHz and their harmonics, they seem to have an influence on each other. In fact, the frequency peaks in BES(0.95) can be slightly observed even in the cross-coherence between BES(0.53) and the MP.

The temporal evolution of the peak frequency, determined using Gaussian fitting around the frequency peak, is shown in Fig. 4(a). The first harmonic frequency in BES(0.53) and MP perfectly coincide with each other, while there is an evident discrepancy in that in BES(0.95). The frequency separation is more evident when the quadrupole field (see section 4) is increased, as shown in Fig. 4(b). It should be mentioned that the observation normalized radii

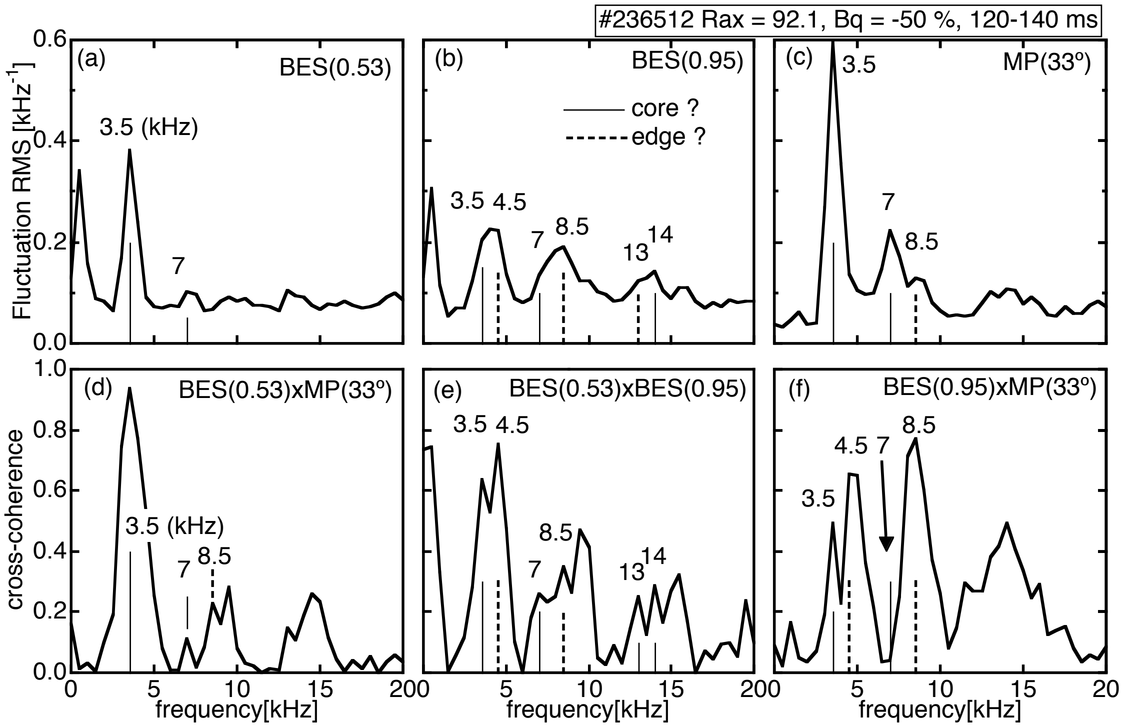


*Fig. 3. Frequency spectra (a-c) and cross-coherence (d-f) of the EHO. (a) BES(r/a = 0.53), (b) BES(r/a = 0.95), (c) MP(33°), (e) BES(0.53)&MP(33°), (d)BES(0.53)&BES(0.95) and (f) BES(0.95)&MP(33°).*

depend on the magnetic configurations, so that we denote BES(edge or core) in the discussion of the $B_q$ dependence. By taking the first harmonic in BES(core), as shown in Fig. 4(c), the deviation in that in BES(edge) is obvious, especially in the second harmonics. Because the frequency in our previous observation was the same for both BES channels, as well as we have focused mainly on the edge chords, we could not distinguish the position where there is the main correlation with the MP. In other words, the mode number deduced from the MP signal is not the EHO to the letter, the "edge". Therefore arises the question: What is the mode number of the EHO observed in BES(0.95).

It was difficult to obtain the poloidal wavenumber $k_\theta$ in BES because the wavenumber resolution was insufficient in the previous poloidal optical system[11]. Therefore, we have

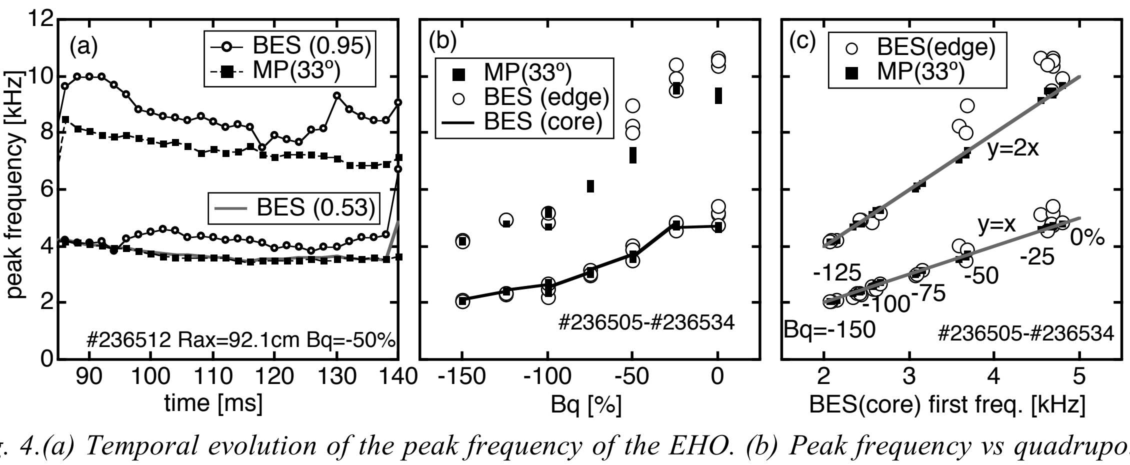


*Fig. 4.(a) Temporal evolution of the peak frequency of the EHO. (b) Peak frequency vs quadrupole field components. (c) Comparison of the frequency with that of the first harmonic for BES(core).*

rotated the direction of the fiber array by π/8 rad to align it with the magnetic flux surface. Then, the EHO can be observed in all channels covering the poloidal angle $\Delta\theta = \pi/2$. Since the shape of the flux surface is elongated, the corresponding mode number should be defined as the number of waves per length of the arc observed, $\Delta l$ (= 17 cm) as $m = k_\theta(\Delta l/\Delta\theta)$. The measured mean poloidal wavenumber is $k_\theta = 0.1$ rad cm$^{-1}$, which corresponds to $m = -1$.

For confirmation of this result, we have performed a mode analysis of the MP signals separating the frequency components for BES(0.53) and BES(0.95). $B_q$ = - 50 % in this case [#236514]. The second harmonic is used to yield better separation, *i.e.*, 7 kHz for the inner and 8.5 kHz for the edge BES channel. The temporal evolution of the mode numbers is shown in Fig. 5. The poloidal mode number of the edge mode over most of the time axis is m = -1, while that of the inner mode is -2.

Now we can conclude that the EHO in the MP observes the $m/n$ = -2/1 MHD mode at the ι = 0.5 surface around $r/a \sim 0.5$, while EHO in the edge BES observes the -1/1 MHD mode at ι = 1 surface around $r/a \sim 0.95$. This fact tells us that one should be careful in interpreting the MP data alone. The reason why the fundamental frequency for different poloidal modes is so close, meaning that the rotation velocity is exactly doubled, cannot be explained at present. Nonetheless, an understanding of why the MP is less sensitive to the EHO(0.95) might give us information about the electrostatic and/or electromagnetic features of the EHO that should be investigated in the future.

## 4. The shape of the waveform of EHOs

The name of the EHO originates in the fact that the higher harmonics accompany the low frequency sinusoidal oscillation through an application of the Fourier analysis. It can safely be said from items [vii-ix] in Section 2, that this Fourier mode can be understood as a distortion of the first harmonic, because the wavenumber of each harmonic is the same, which leads to a variation in the shape of the temporal signal along the (-2, 1) mode structure. However, the reason for this possible distortion as well as the mechanism of the spatial variation has not yet been understood.

Since this previous analysis of the MP and BES(0.95) signals was revealed to be for the inner mode at the ι = 0.5 surface and the edge mode at the ι = 1 surface, respectively, we compared the amplitude ratio of the second to the first harmonic at the radial position of the maximum 2nd harmonic amplitude, as an indication of the degree of distortion. Moreover, in

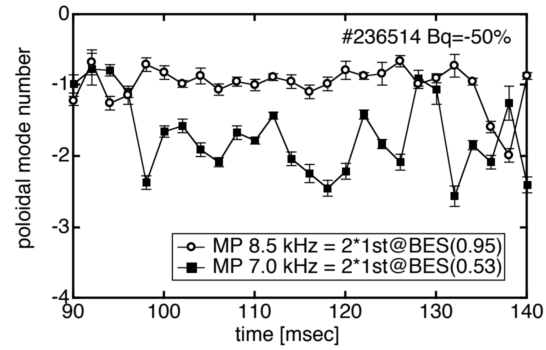


*Fig.5. Temporal evolution of the poloidal mode number m.*

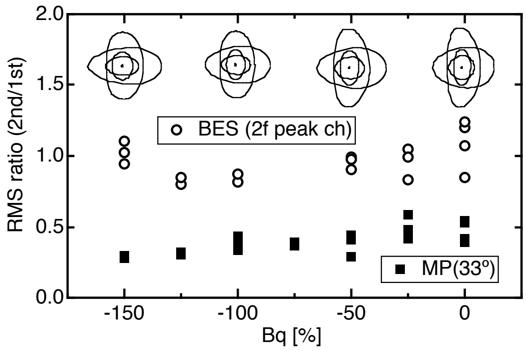


*Fig. 6. Ratio of first to second harmonics vs $B_q$. The shapes of the magnetic surfaces are shown above.*

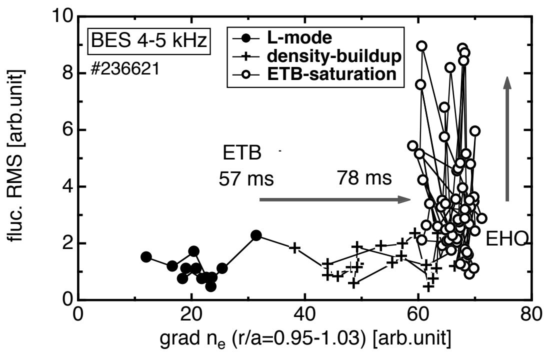


*Fig. 7. The amplitude of the first harmonic of the EHO as a function of the density gradient measured using BES.*

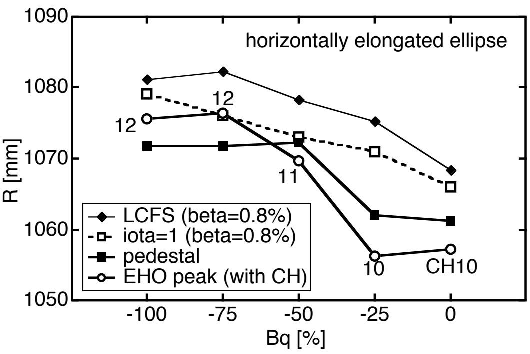


*Fig. 8. Dependence of the position of LCFS,the* $\iota$ *=1 surface, the pedestal and the peak EHO on* $B_q$.

order to investigate the response to the magnetic configuration, we conducted the quadrupole field ($B_q$) scan experiment, in which the ellipticity of the plasma changes. The zero average ellipticity ($B_q$ = -100 %) means the intrinsic quadrupole component formed by the helical coils is cancelled out. As can be seen in Fig. 6, the ratio has a minimum value around the position where the average ellipticity is small for BES(0.95) while the MP(33º) shows monotonic dependence on $B_q$. For $B_q$ = -75 %, the second harmonic was not observed in BES(0.95) and for -125 and -150%, the positions of the maximum amplitude of the first and second harmonics are different. These observations suggest the superposition/co-existence of the multiple modes. Further investigation considering the phase between harmonics is needed to clarify the reason why the shape changes along with the mode structure.

## 5. Correlation of the EHO with the behavior of the edge pedestal

In order to examine the excitation and saturation mechanism of the EHO, the amplitude of the fundamental frequency is plotted as a function of the density gradient in Fig. 7. The EHO is enhanced when the gradient achieves a certain threshold. The gradient stays almost constant after the enhancement of the EHO. For the discharges with an EHO, the gradient in the ETB-saturation phase did not vary significantly, even as the heating power increased. This response can be observed for $B_q$ = -100 ~ 0 %. The position of the peak EHO amplitude is close to the position of the pedestal, determined by the position of the maximum density gradient as shown in Fig. 8. Although it is difficult to precisely resolve this small difference in the position in the present BES system, the pedestal seems to be formed slightly inside the $\iota$ = 1 surface. The EHOs look as if they dissipate themselves with the density outside the $\iota$ = 1 surface.

In these conditions, the additional gas is puffed throughout the discharge/heating, which means that the particle source continually exists in the edge region. Therefore, it was difficult to determine the mechanism of the formation of the pedestal, and the effect of the EHOs. The recent experiments have revealed that if the gas puffing is interrupted after the ETB formation, the electron temperature, inferred from $n_e$ and $W_p$, first decreases and then changes to an increase, as shown in Fig.9. In this condition, the edge density profile is governed more by the particle transport in the core region than the particle source in the edge. There is a clear difference between the cases without (#236606) and with (#236609) the EHO in BES(0.95), even though the EHO in the BES(0.53) exists in both cases. As shown in Fig.10, after the EHO excited, the density gradient at the core decreased while that at the edge increased —small pedestal was formed—, implying that the radial particle flux is increased. The

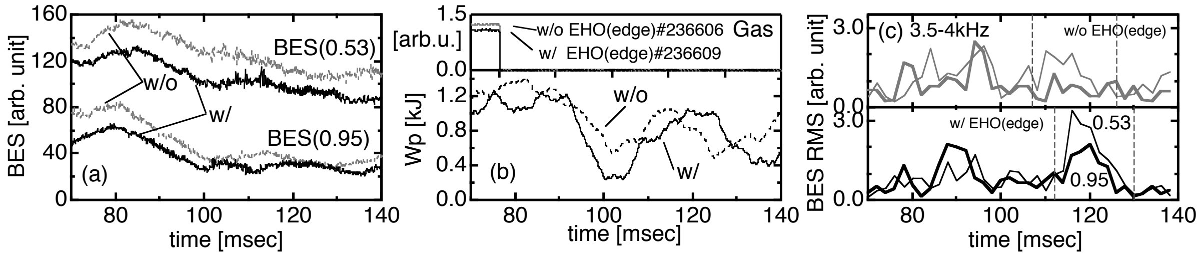


*Fig. 9. Discharge interrupting the gas puff in the middle of the H-mode. The cases with and without the EHO in BES(0.95)around 115 ms are compared. EHOs around 90 ms are the same one as that for the case with the continuous gas puff. (a) BES intensitis.(b) $W_p$ with the gas puff conditions. (c) EHO amplitude for 3.5-4 kHz for BES(0.53) and BES(0.95). The EHO in the shot 236606 is observed only in BES(0.95).*

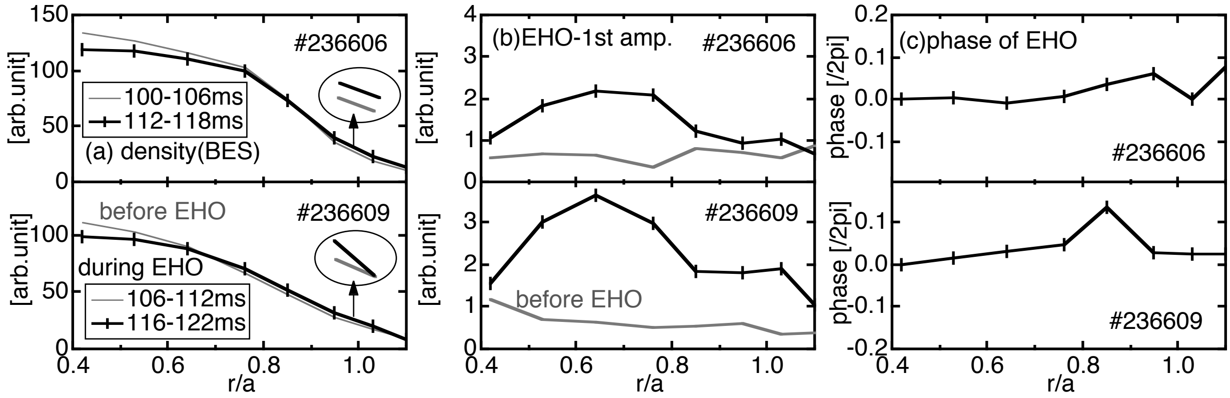


*Fig. 10. Comparison of the changes in the profiles as the EHOs (global) increase around 115 ms between with and without the EHOs (edge) . (a)Density profile by BES. (b) EHO amplitude for the first harmonic. EHO in the edge channel cannot be observed for the shot 236606. (c) Phases of the first harmonic of the EHO.*

fluctuation amplitude around the EHO frequencies (3.5-4 kHz) was larger for the discharge with the EHO in BES(0.95). The phase of the EHO was almost uniform in the radial position, indicating that the oscillation was a global-type MHD mode on the rigidly rotating reference flame, having a broad eigenfunction.

Since presumably the temperature is also increased while this weak density pedestal is forming, this response can also interpreted as being against the pressure gradient (a feature of the EHO in tokamak [3]). Note that in the previous case with gas puffing, the temperature stays rather constant during the density pedestal formation, possibly due to the ionization processes which consume the electron energy in the edge region.

From these observations, we can address a hypothesis that may explain the physical mechanism qualitatively. So-called EHOs, even if they are in the core region in our case, may *moderately* increase the particle flux. As a result, the edge pedestal is formed slightly inside the $\iota = 1$ surface when the EHO increases. During the gas puffing, the density build-up in the core cannot be suppressed by the core EHO alone, because the enhancement of the flux is moderate. The EHOs in the edge, on the other hand, may increase the flux (presumably driven at the $\iota = 1$ surface and enhanced around the pedestal ?), but the effect may be smaller than that in the core. Nevertheless, they could scrape off the density outside the pedestal to sustain it. In the case without gas puffing, the EHOs in the edge need not to be so large, because the particle flux (including the ionization source) is also small. The structure of the EHO is the mixture of the modes around the $\iota = 0.5$ and the $\iota = 1$ surfaces, which is difficult to be distinguished unless the frequency is different. These modes excite simultaneously at a certain threshold of the density/pressure profile, suggesting the possibility of a coupling between modes.

## 6. Conclusions

The EHO in the CHS has many similarities to that observed in tokamaks. However, a recent experiment has revealed that the MP detects the "EHO-like" inner mode at the $\iota = 0.5$ surface, while it is the EHO at the $\iota = 1$ surface that saturates the edge pedestal. The obvious detection of this mode at the edge occurs only with BES. This fact reminds us that the use of the MP alone could lead to a wrong conclusion. The following items are those which should receive further investigation:
- The driving mechanism of EHOs both in the core and the edge
- The origin of the dependence of the shape on the mode structure
- The reason why the MP is less sensitive to the EHO in the edge
- A rigorous explanation of the phase velocity of the EHOs at $\iota = 0.5$ and 1
- The mechanism of the saturation of the pedestal after the EHO is excited, and related issues.

A comprehensive understanding of the mechanism of the EHOs might be a key issue in developing efficient control of steady-state operations in forthcoming fusion reactors.

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