RECENT ADVANCES IN THE UNDERSTANDING OF FLUCTUATION ACTIVITIES OF HIGH-BETA PLASMA IN RT-1

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Abstract

We report the progress of fluctuation studies in the RT-1 (Ring Trap 1) levitated dipole experiment particularly focusing on the conditions of appearance and spatial structures of low-frequency modes. We introduced movable Langmuir probes capable of operating under the high-heat flux conditions, and investigated the spatial structures of electrostatic fluctuations in the plasma and compared them with magnetic fluctuation properties. We observed that low-frequency electrostatic fluctuations in low-beta plasma transition into electromagnetic modes in a density reconstruction phase of high-beta operation, the latter of which have been identified with edge magnetic probes. Multi-point measurements with the Langmuir probes revealed that, in low-beta plasma, the fluctuations propagate in the electron diamagnetic direction and have a toroidal mode number of 3 or 4 on different magnetic surfaces. In the reconstruction phase of spatial profile of high-beta plasma, the phase velocity of the fluctuations has a clear dependence on the magnetic surfaces and reverses its toroidal propagation direction according to plasma conditions. These observations are consistent with the interpretation that density fluctuations transported by the drift motion of plasma generate magnetic fluctuations in high-beta conditions, suggesting a similarity with the so-called entropy mode. Furthermore, we expanded the measurement frequency range of the magnetic probes to explore higher-frequency fluctuations. Initial measurements revealed coherent fluctuation modes below the local electron cyclotron frequency.

1. INTRODUCTION

The goals of RT-1 [1] are to understand self-organization mechanism of very high-beta plasma [2] in a dipole magnetic field configuration and its application to the advanced fusion concept [3]. Plasmas confined in the steep magnetic gradients of the dipole field exhibit unique stable properties. Spontaneous formation of high-beta plasma has been observed in both planetary magnetospheres and laboratory plasmas [3,4]. Fluctuation-induced transport effects play crucial roles in the formation process of plasma structures. Such fluctuation effects often drive the diffusion of plasmas, leading to the decrease of density gradients (flattening) in the confinement region. However, in the dipole magnetic field, the density flattening is realized in the phase space, which results in the formation of a structure with a peak in a strong magnetic field region. Successful formation of stable high-beta structures in the dipole field configuration have been realized in RT-1 and LDX [4]. Efficient radial transport and structure formation in the dipole magnetic field are driven by low-frequency fluctuations on the order of kHz. In previous studies in RT-1, density reconstruction and low-frequency fluctuation were simultaneously observed [5]. In this process, a density flattering caused by a rapid neutral gas injection is subsequently followed by the reformation of a high-beta state peaking toward the strong magnetic field region. During the reconstruction phase of the high-beta peaked structure, low-frequency fluctuations with distinguishable frequency peaks near the diamagnetic drift frequency were continuously observed [6]. Although these fluctuations were mainly measured using magnetic probes (Bdot probes) positioned in the peripheral region of the experiment, similar fluctuations were also observed with interferometry and spectroscopy measurements. Additionally, it has been suggested that mechanical structures placed inside or near the plasma influenced the behaviour of low-frequency fluctuations. For further understanding of the nature of these fluctuations and related transport phenomena in the entire plasma region, it is crucial to elucidate the spatial structure of fluctuations within the plasma.

In this study, we focus on the spatial structure and conditions of occurrence of electrostatic and magnetic fluctuations in RT-1. In addition to the Bdot magnetic probes, we introduced movable Langmuir probes capable of operating in high-heat flux region of the plasma, aiming to understand the internal structure of fluctuations in comparison with the nature of magnetic fluctuations. These measurements are expected to provide new insights into self-organization processes of the plasma in the dipole field configuration. Previous study suggested that large mechanical structure affects the behaviour of fluctuations when they are placed close to or inside the plasma. To minimize perturbations, we removed the mechanical structures of an ICH (Ion cyclotron resonance heating) antenna [5] located in the high field region of the experiment for this study. In the following sections, we will describe the experimental setup in the RT-1 device, measurement methods including the newly introduced movable Langmuir probe, and experimental results including the spatial structures and occurrence conditions of the low-frequency fluctuations. We will also report the initial results of higher-frequency fluctuation activities in the dipole field measured with fast Bdot probes.

2. EXPERIMENTAL SETUP AND DIAGNOSTICS

Figure 1 schematically illustrates the structure and measurement system of the RT-1 device [7]. Inside the vacuum chamber, a high-temperature superconducting coil with Bi-2223 tapes carries a permanent current of 250 kA and is magnetically levitated, in order to minimize perturbations to the plasma. The coil levitation is achieved using the attractive force generated between the feedback-controlled lifting coil magnet (28.8 kA), located on the upper part of the vacuum vessel. During magnetic levitation experiments, a magnetic field configuration with a separatrix is generated, as shown in Fig. 1 (a). Plasma heating is performed with electron cyclotron resonance heating (ECH) using 2.45 GHz microwave with a maximum power of 20 kW. As indicated in the X-ray image in Figure 1 (a), the plasma pressure of RT-1 is primarily generated by the high-temperature electron component generated by ECH. This leads to the creation of plasmas with local beta values reaching up to 100% near the pressure peak [5]. The measurement system of RT-1 [7] includes microwave interferometers, X-ray detection with pulse height analysis, an X-ray CCD camera, several spectroscopic diagnostics, and a Thomson scattering system. The discharge duration of RT-1 is on the order of one second, which is similar to the timescale of the evolution of low-frequency fluctuations. To investigate the relatively long-term behaviour of electrostatic fluctuations, Langmuir probes with large stainless-steel electrodes were introduced, which enabled measurements inside the high-beta plasmas. These Langmuir probes can measure electrostatic fluctuations at the probe electrodes with a flat frequency response of up to 30 kHz.

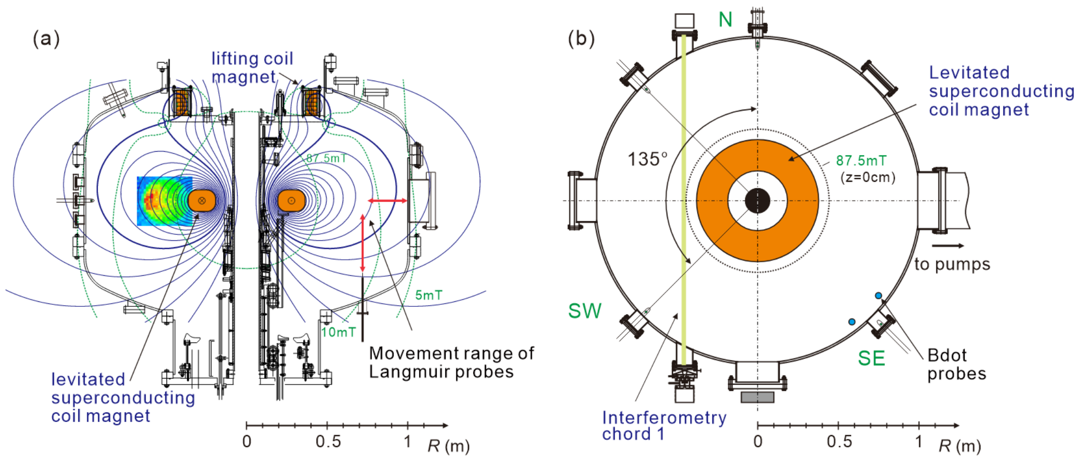

FIG. 1. (a) Cross-sectional and (b) top-view diagrams of the magnetically levitated dipole, "artificial magnetosphere" plasma experiment device RT-1. Colour contour in (a) shows an X-ray image.

3. SPATIAL PROFILES OF ELECTRON DENSITY AND TEMPERATURE

Figure 2 shows the density distribution measured with Langmuir probes introduced on the equatorial plane at Z = 0 cm and from the lower port of the chamber. Without the coil levitation, i.e. when the coil was placed on a mechanical support structure at Z = 0cm, relatively flat density distributions were generated. Finite plasma density was measured in a region close to the vacuum vessel wall, indicating that the wall worked as a kind of a limiter. In contrast, during coil levitation, significant density gradients were generated near the separatrix. These trends are consistent with the density distribution reconstruction results obtained through interferometry [7]. In the coil levitation operation, low-density plasma was observed to be distributed even outside the separatrix. Simultaneous measurements with Langmuir probes placed at different toroidal positions showed relatively good agreement, indicating that the plasma exhibits good toroidal symmetry. The introduction of the Langmuir probes up to a few centimetres from the separatrix had a minimal impact on the line integrated density and diamagnetic signal of plasmas. When these Langmuir probes were further inserted inside the separatrix, as shown in Fig.2 (b), the insertion effects were no longer negligible. When the probe was placed at Z = -15 cm, the diamagnetic signal decreased by approximately 30%.

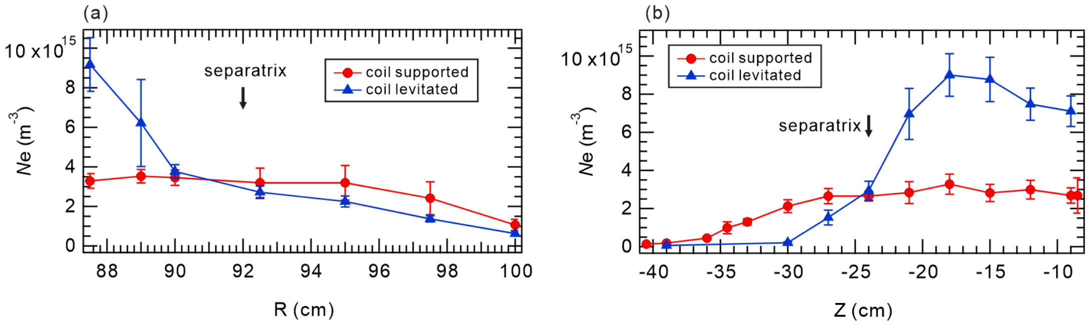

FIG. 2. Electron density distribution measured with coil levitation (triangles) and without levitation (mechanically supported, circles), using Langmuir probes introduced from (a) the equatorial plane and (b) the lower part of the device.

Figure 3 shows the floating potential and electron temperature measured at the equator (Z = 0cm plane) of the device. The Langmuir probes apparently measured the low-temperature bulk component of electrons. Within the measurable region of the plasma, the electron temperature is approximately 10 eV or lower, and gradually increasing inward. By using the relationship between the floating potential V_f and the space potential V_p,

$$V_p = V_f + \frac{k_B T_e}{e}(3.3 + 0.5 \ln \mu)$$

where μ is the normalized ion mass with respect to hydrogen, the radial electric field strength is estimated to be less than 100 V/m. The $E \times B$ drift velocity in the measured range is on the order of km/s, which is on the order of magnitude smaller than the grad B and curvature drift velocity. In the evaluation of drift velocities, at least in the peripheral region, the electric field does not play a significant role. Electric fields in the higher-density regions further inside the plasma are beyond the scope of the present study with the Langmuir probe measurements.

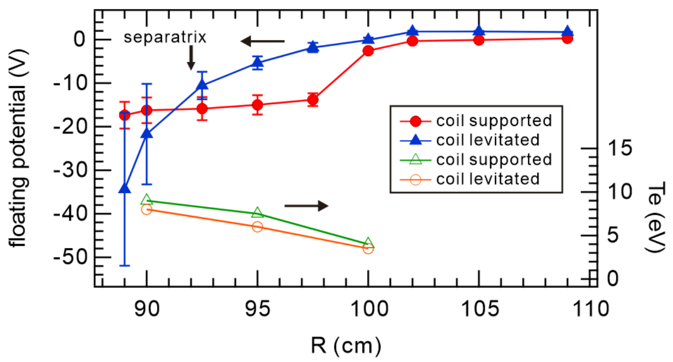

FIG.3. The spatial distribution of floating potential and electron temperature measured on the equator (Z = 0cm).

4. CONDITIONS FOR THE ELECTROSTATIC AND ELECTROMAGNETIC FLUCTUATIONS

In RT-1, low-frequency fluctuations with two distinguishable frequency peaks have been observed in high-beta plasma during the reconstruction phase of the spatial structures [6]. Typical procedures to induce these low-frequency fluctuations are as follows. During the high-beta and peaked profile plasma discharge, density flattening is realized by using additional neutral gas puffing. Subsequently, a peaked structure is gradually formed again in the strong magnetic field region through inward transport. During this profile reconstruction process, low-frequency fluctuations with multiple frequency peaks are observed. According to magnetic fluctuation measurements, fluctuations with distinct frequency peaks appear only when two conditions are met: perturbation to the plasma caused by the mechanical support structures for the superconducting coil is minimized by the coil levitation. Also, density reconstruction must be induced by the additional gas puffing during the discharge [6]. In this study, these fluctuations were simultaneously measured using Langmuir probes and Bdot probes. The frequency spectra of electrostatic fluctuations measured by a Langmuir probe placed at $R = 97.5$ cm and magnetic field signals measured by a Bdot probe at $R = 99$ cm were compared for cases with and without gas puffing, focusing on relatively high-beta plasma generated by 15 kW 2.45 GHz ECH.

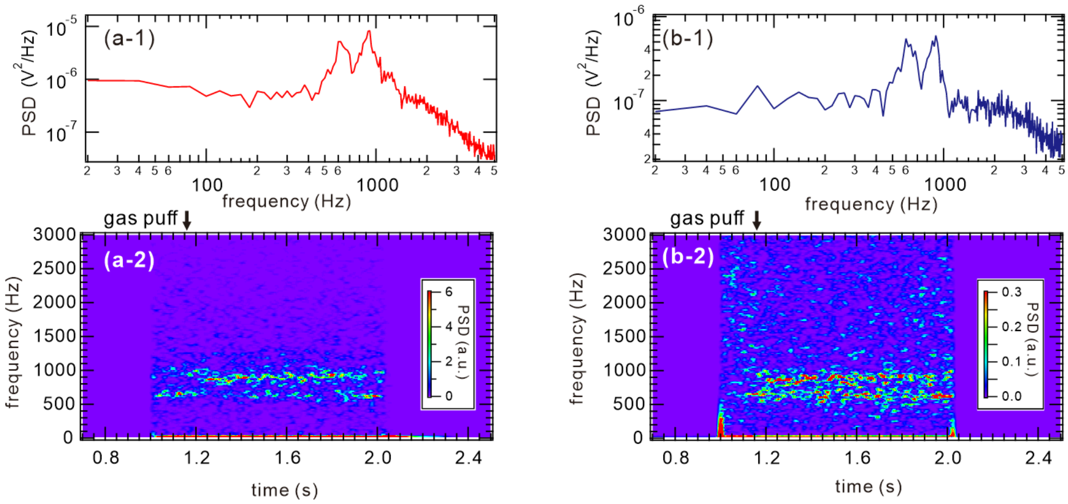

FIG.4. The power spectral density (PSD) and its time evolution of fluctuations observed by (a) a Langmuir probe and (b) a magnetic probe with gas puffing at $t = 1.16$ s during the discharge. Fluctuations with clear two peaks appeared in both electrostatic and magnetic fluctuations of the plasma.

Figures 4 and 5 compare the (a) electrostatic and (b) magnetic fluctuations with and without additional gas puffing. The gas puffing was conducted at $t = 1.16$ s in order to induce density reconstruction only in Fig. 4. The panels show (1) the power spectral density (PSD) during plasma discharge and (2) the time evolution of PSD. During the reconstruction phase of the electron density, magnetic fluctuations with frequency peaks around 1 kHz and 0.7 kHz were dominant, as shown in Fig. 4 (b). While the major fluctuation component was a mode peaked at 1 kHz, but as the density became steeper, difference between the intensity of modes at 1 kHz and 0.7 kHz were considerably smaller. The fluctuation tendency was similar for the electrostatic fluctuation as shown in Fig. 4 (a). In Fig. 5, (a) electrostatic and (b) magnetic fluctuations were measured without additional gas puffing. Although no clear frequency peaks originated from plasma activities were observed in the magnetic signals in this condition, electrostatic fluctuations with frequency peaks at dominant 0.7kHz and weaker 1kHz were still found in the PSD and its time evolution, as shown in Fig. 5 (a).

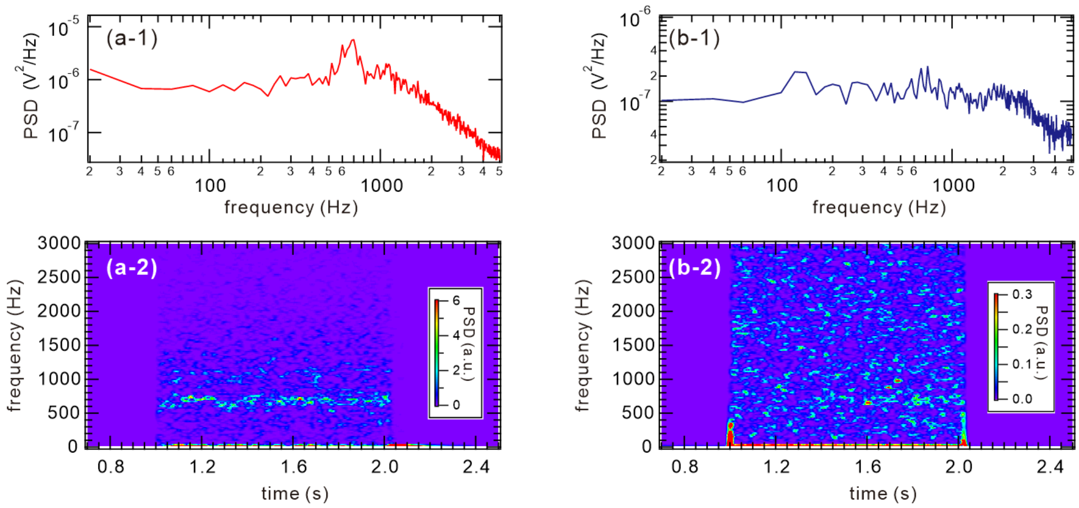

FIG.5. PSD and its time evolution of fluctuations without additional gas puffing, measured with (a) Langmuir probe and (b) magnetic probe. In the absence of gas puffing, only electrostatic fluctuations were dominant and have a peak at 0.7 kHz. No clear peaks were found in magnetic fluctuations.

Figure 6 plots the intensity and frequency of electrostatic and magnetic fluctuations as a function of plasma pressure (diamagnetic signal) with additional gas puffing during discharge. As shown in Fig. 6 (a), electrostatic component is dominant in both 0.7kHz and 1 kHz for low-beta conditions. In contrast, the intensity of magnetic fluctuations strongly depends on the beta value of plasma. The signal level of magnetic fluctuations at both 0.7 and 1 kHz was below the detection limit when the diamagnetic signal is below 0.6 mWb, relatively low-beta conditions. For higher beta operations, the magnetic fluctuation component rises steeply, exhibiting the electromagnetic nature of the fluctuation. These observations indicate that the rather steady fluctuations peaked at approximately 0.7 kHz, which exists as an electrostatic mode, is transformed into stronger fluctuations with a clear magnetic component, and also a new electromagnetic mode at 1 kHz emerges in the density reconstruction phase. As shown in Fig. 6 (b), the observed frequency peaks do not show a strong dependence on plasma pressure but has a tendency of lower frequency for high-beta conditions.

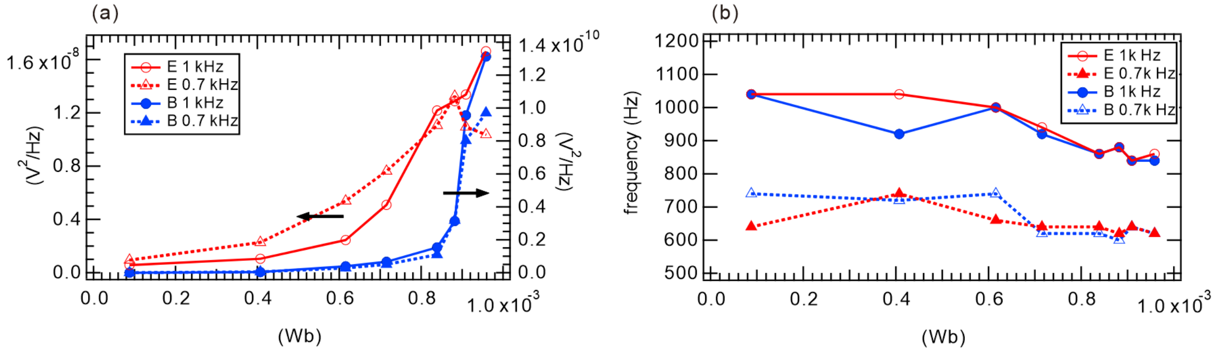

FIG. 6. (a) Fluctuation intensity of electrostatic an magnetic components at 0.7 kHz and 1 kHz, and (b) the peak frequency values, both of which are shown for different diamagnetic signal values (plasma beta).

5. SPATIAL STRUCTURES OF FLUCTUATIONS IN LOW-BETA AND HIGH-BETA CONDITIONS

Toroidal mode number of the low frequency fluctuations were calculated with multi-point measurements of electrostatic fluctuations inside the plasma with Langmuir probes. Figure 7 plots the mode number of 0.7 kHz and 1 kHz fluctuations for low-beta cases, which has a value of 3 or 4, and does not strongly depend on the radial position of the measurement position. This is consistent with the observation of clear coherent fluctuation mode in line-integrated electron density measured with microwave interferometers. The propagation direction of the low-frequency fluctuations was in the direction of electron diamagnetism for the lo-beta conditions. As explained in the next section, the propagation direction and phase velocity of the wave depend on the plasma conditions. It is noted that the removal of ICH antenna affected the fluctuation behaviour from the previous experiments.

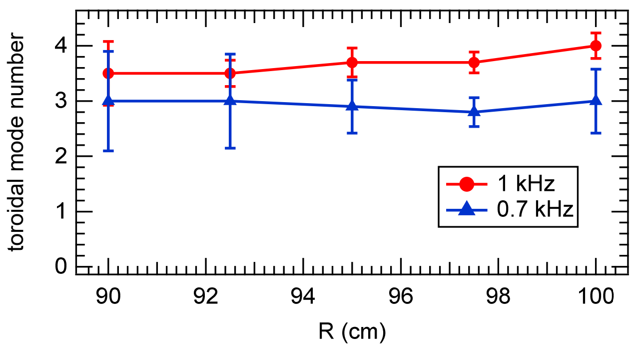

FIG. 7. Toroidal mode numbers of 0.7 kHz and 1 kHz fluctuation modes estimated from measurements with Langmuir probes positioned at same radial positions (R) and toroidally 90 degree separated.

For higher-beta operation, as shown in Fig. 8, the toroidal direction of the phase velocity reversed according to the plasma parameters by inserting the probe structure inside the plasma. As shown in the figure, when the vertically inserted Langmuir probe was outside or at the peripheral region of the plasma, the fluctuation wave propagates in the electron diamagnetic direction. However, this direction reversed when the probe was positioned at a distance greater than $Z = 21$ cm (more than 3 cm inside from the position of the separatrix), as shown in the figure. These characteristics of the fluctuations may suggest a connection to the so-called entropy mode [9].

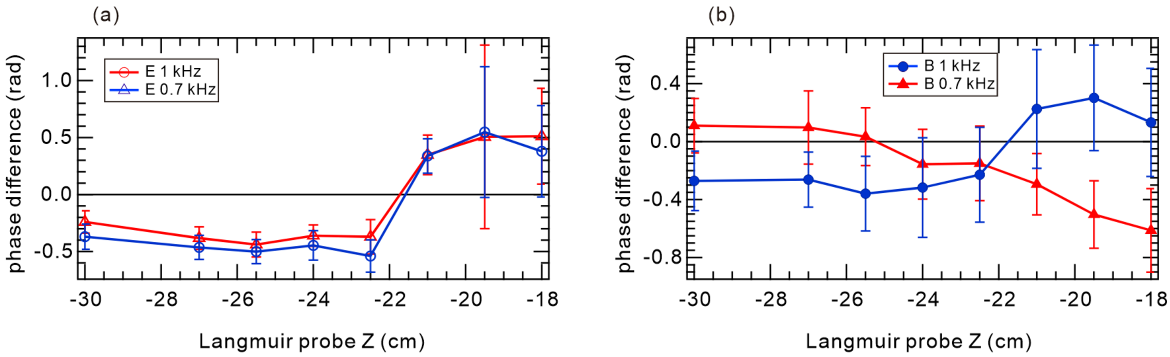

FIG.8. Phase difference of (a) electrostatic and (b) magnetic fluctuations measured with toroidally separated probes. Negative phase difference corresponds to the toroidal phase velocity in the electron diamagnetic direction.

6. ON HIGHER FREQUENCY FLUCTUATION ACTIVITIES

For higher-frequency fluctuations, we extended the measurement frequency range of Bdot probes and observed spontaneously excited modes of fluctuations near the local electron cyclotron frequency (Fig. 9). To conduct fluctuation measurements at higher frequency range with a higher noise immunity, we used a fast Bdot probe with a Pockels electrooptic sensor as well as conventional fast Bdot loop probes. In the ECH plasma that presumably has strong electron temperature anisotropy, we observed intermittent electromagnetic and electrostatic fluctuations in hot-electron high-β plasmas. It was observed that the amplitude and frequency often showed large temporal variation, indicating the nonlinear growth of the fluctuation mode. The main characteristics of this mode are as follows. (1) The observed electromagnetic waves basically propagate along the magnetic field lines and are very localized in the toroidal direction, which is in marked contrast to the previously reported flute-like modes of hot-electron plasma in the dipole field configuration. (2) The condition for the fluctuation emergence shows a strong dependence on the β value of plasma due to the hot electron component. The fluctuation is active only when a considerable ratio of hot electrons exists at high-β operation. (3) The dispersion relation obtained from multi-point fluctuation measurements is rather consistent with the whistler wave, which can be destabilized according to the velocity distribution of hot electrons. These measurements suggest that the whistler waves were spontaneous excited in hot-electron high-β plasma with temperature anisotropy. In the dipole magnetic field, electrons are efficiently heated by the burst of these whistler waves. Particle orbit analysis confirmed that the trajectories of such energetic electrons often take chaotic motions, which can lead to rapid loss of particles. At very high-β and very low-density states of RT-1, sudden decrease of electron density was sometimes observed, which may be related to the loss of very hot electrons generated by the interaction with the burst of whistler waves.

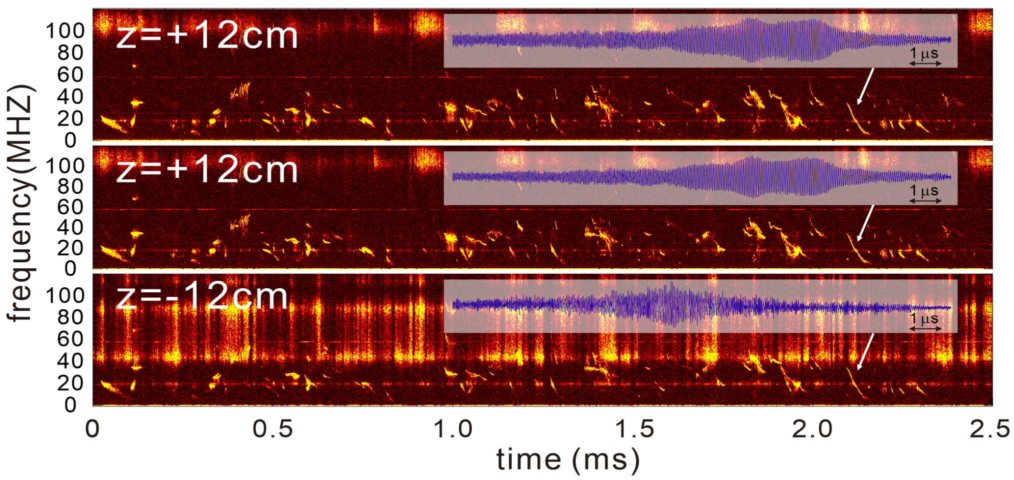

FIG.9. Example of sub-cyclotron frequency range magnetic fluctuations measured at different positions on a same magnetic field line of the dipole field.

7. SUMMARY

In this study, we report the progress of experimental studies conducted at the RT-1 levitated dipole on plasma fluctuations related to transport and structure formation in a dipole magnetic field configuration. Regarding low-frequency fluctuations that appear during the structure formation phase, our observations revealed that (1-1) the electromagnetic fluctuation mode at high-β states was excited as an electrostatic mode for low-β plasmas, (1-2) this wave propagated in the toroidal direction with a mode number of 3 or 4 according to multi-point electrostatic measurements, and (1-3) the wave propagation changed its toroidal direction depending on plasma parameters. These results agree with an understanding that the drift motion of density ununiformity creates magnetic fluctuations in high-β states and are consistent with several characteristics of the so-called entropy mode. We also extended the measurement frequency range of magnetic fluctuations and observed intermittent excitation of coherent waves around the local electron cyclotron frequency. We measured that (2-1) these waves propagated along magnetic field lines, (2-2) appeared only in hot-electron high-β plasma created by ECH, and (2-3) its dispersion relation was consistent with the R-wave. These observations indicate the spontaneous excitation of whistler waves in hot electron plasma.

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