OBSERVATION OF FLUCTUATION-INDUCED PARTICLE TRANSPORT PHENOMENA IN THE RT-1 LEVITATED DIPOLE

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Abstract

We report progress in the experimental understanding of particle transport phenomena associated with low-frequency and sub-electron cyclotron frequency range fluctuations in the levitated dipole device RT-1. During the occurrence of low-frequency fluctuations that accompany the formation of peaked high β structures in the dipole magnetic field, multi-point measurements with electrostatic probes detected electric field fluctuations with a toroidal component. Simultaneous measurements of electron density fluctuations revealed that, during these events, a steady inward particle flux directed toward the strong magnetic field side is generated. In contrast, during burst-like fluctuations of whistler-mode chorus emissions at higher frequencies, outward losses of hot electrons were observed, suggesting the possibility of electron acceleration by right-hand polarized (R) waves and subsequent orbit stochasticity leading to particle loss.

1. INTRODUCTION

In recent years, research aimed at advanced fusion based on innovative confinement configurations, as alternatives to the mainstream tokamak approach, has been actively conducted. Among these configurations, the levitated dipole configuration is distinguished by its ability to stably sustain ultra high β states suitable for advanced fusion without relying on plasma current [1–3]. In the RT-1 (Ring Trap 1) [2] and LDX (Levitated Dipole Experiment) [3] facilities, a magnetically levitated superconducting coil produces a magnetic field analogous to the magnetospheres of planets such as Earth and Jupiter in the laboratory. In such highly nonuniform fields, the compressibility of magnetic field lines provides stabilizing effects, enabling the realization of relaxed states with steep pressure gradients with high β. As a result of these effects, self-organization into flattened structures in phase space [4], as well as the stable formation of plasmas with locally β values reaching 100%, has been experimentally demonstrated in dipole configurations [5].

In RT-1 and LDX, a variety of fluctuation phenomena have been observed depending on parameters such as plasma pressure, the temperature anisotropy of high-energy electrons, and the background neutral gas pressure [6–8]. During the formation of high β plasmas in a dipole magnetic configuration, interactions between charged particles and waves are considered to play a crucial role. Figure 1 shows the dependence of fluctuation levels and plasma diamagnetic signals on heating power. With increasing heating power, the stored energy exhibits a tendency toward saturation, while the fluctuation level increases, suggesting that fluctuations contribute to plasma transport. Previous studies have investigated low-frequency fluctuations observed during the formation of peaked structures in the strong-field region [6,7], as well as whistler-mode chorus emissions associated with high-energy electron populations [8], focusing on their mode structures and conditions of occurrence. While significant progress has been made in understanding the characteristics of these fluctuations, their direct impact on transport processes and structure formation remains poorly understood. Elucidating the role of fluctuations in transport and self-organization in magnetospheric configurations is critically important. Such understanding is essential for improving confinement performance toward the realization of advanced fusion.

In this study, we focus on particle transport associated with two typical fluctuation phenomena observed in RT-1: low-frequency fluctuations and whistler-mode chorus emissions. In RT-1, two characteristic equilibrium structures are typically observed, a peaked high β state and a flattened low β state. Depending on the operating conditions, transitions between these equilibria have been observed. In particular, gas puffing experiments reveal both the flattening of peaked structures and their subsequent reconstruction [5,6]. Radial transport driving such structural evolution is believed to be strongly influenced by low-frequency fluctuations. Theoretically, in the highly inhomogeneous dipole field, the formation of peaked structures has been shown to correspond to diffusion processes that increase entropy [9]. Low-frequency fluctuations with frequencies comparable to or exceeding the toroidal drift frequency of charged particles are considered to act as waves driving self-organization.

At higher frequencies, below the electron cyclotron frequency, whistler waves are excited due to the temperature anisotropy of hot electrons. In high-β plasmas in RT-1 containing energetic electrons, whistler waves are observed as intermittent chorus emissions below the electron cyclotron frequency [7], similar to those detected in space environments. The occurrence rate and intensity of these fluctuations are positively correlated with plasma pressure and appear only when a significant population of energetic electrons is present. Hot electrons with temperature anisotropy produced by electron cyclotron heating (ECH) destabilize whistler waves, which undergo nonlinear growth in the inhomogeneous magnetic field and evolve into chirping emissions. Right-hand polarized (R) waves readily resonate with electrons, leading to relativistic acceleration, and the resulting high-energy electrons with chaotic orbits are expected to be difficult to confine in the peripheral magnetic field of RT-1. In the following, we report recent progress in understanding these particle transport phenomena in RT-1 driven by low-frequency and whistler waves fluctuations.

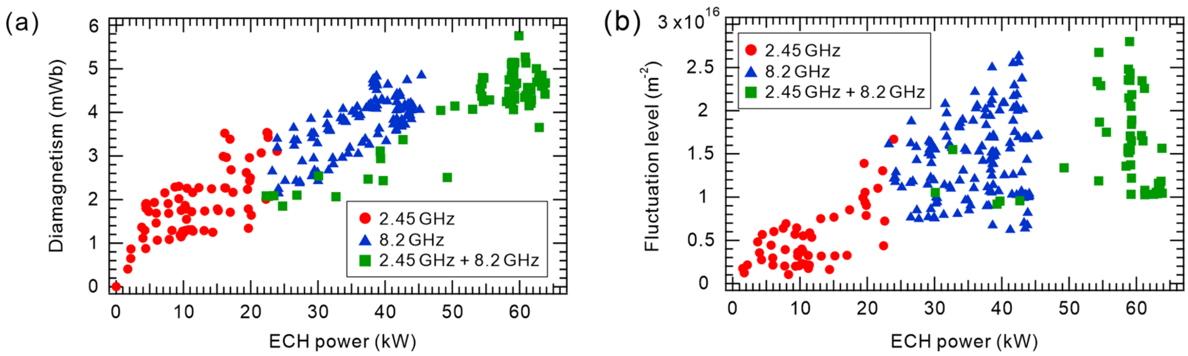

FIG. 1. Diamagnetic signal of plasmas, roughly proportional to the stored energy and (b) fluctuation level of electron density measured with a microwave interferometer. Both are shown as functions of the injected powers of 2.45 and 8.2 GHz ECH microwaves.

2. EXPERIMENTS ON LOW-FREQUENCY FLUCTUATIONS

2.1. Flux measurements with three-pin Langmuir probes

Low-frequency fluctuations in RT-1 have so far been studied mainly using diagnostics such as interferometers and magnetic probes [5,6]. In order to detect the radial particle flux associated with these fluctuations, we have carried out measurements of particle flux using Langmuir probes in RT-1. As is well known, when both electric and magnetic field fluctuations exist in a plasma, the time-averaged particle flux driven by these fluctuations is given by [10]

$$\Gamma_{r,e} = \langle \tilde{n}\tilde{v} \rangle = \frac{\langle \widetilde{n_e}\widetilde{E_{tr}} \rangle}{B} - \frac{\langle \widetilde{J_{\parallel,e}}\tilde{B}_r \rangle}{eB} \qquad (1)$$

where in the present study we focus on the first term, corresponding to transport due to electric field fluctuations. In a dipole configuration with a purely poloidal magnetic field, it is the toroidal component of the electric field that drives the radial E×B drift motion responsible for cross-field particle transport. Regarding the magnetic fluctuation term, a previous study clarified the relationship between electric and magnetic components of low-frequency fluctuations. As plasma pressure increases, the low-frequency fluctuations in RT-1 transition from electrostatic modes to electromagnetic modes. Up to plasmas with moderately high β, electric field fluctuations dominate over magnetic fluctuations, and even at higher β the electric field component is always present. Therefore, transport driven by electric field fluctuations is considered to consistently play a primary role in RT-1 plasmas. On the other hand, transport due to low-frequency magnetic fluctuations in higher-β plasmas remains an open issue and is beyond the scope of the present study.

To evaluate the radial particle flux driven by electrostatic fluctuations, fluctuations of the electric field and density were measured with good temporal resolution using a triple Langmuir probe [11]. Among the three electrodes of the probe, two electrodes separated by 4 mm in the toroidal direction were used to measure electric field fluctuations. Figure 2 shows an example of floating potential ϕ_f measurements obtained with each electrode operated as a single probe. Depending on the measurement conditions, a phase difference was observed, indicating the possible presence of electric field fluctuations in the toroidal direction. The relationship between the floating potential ϕ_f and the plasma potential ϕ_s can be expressed as [9]

$$\phi_s = \phi_f + \alpha k_B T_e \qquad (2)$$

where, for a plasma with a Maxwellian distribution, and for a hydrogen plasma α = 2.81. The objective is to evaluate the electric field with high temporal resolution using the multiple measurements of ϕ_f. In Eq. (2), ϕ_s contains information on both ϕ_f and T_e. Thus, in general, accurate evaluation of electric field fluctuations requires information on temporal evolution of both of these parameters.

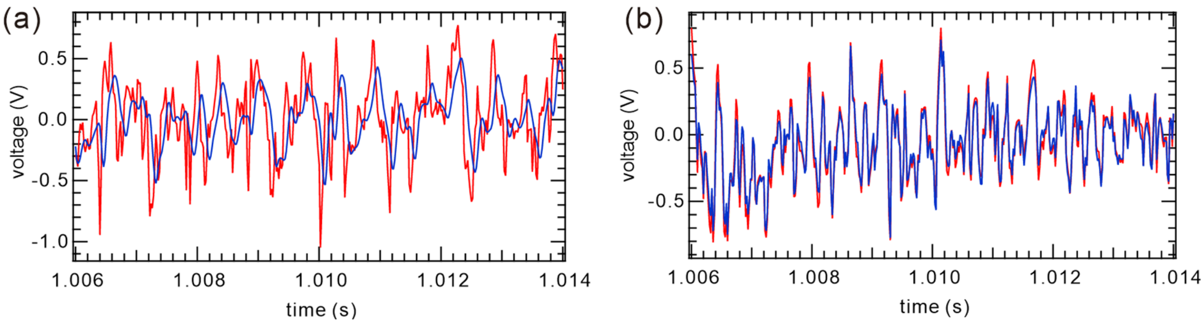

FIG. 2. Time evolution of the floating potential ϕ_f measured with two electrostatic probes separated by 4 mm in the toroidal direction under (a) low-β and (b) high-β plasma conditions.

For the steady component, previous studies have shown that RT-1 plasmas exhibit good axisymmetry, and differences in steady plasma parameters between positions separated by ~4 mm in the toroidal direction are negligibly small. Therefore, assumption of identical steady-state electron temperatures at the two electrode positions is considered a reasonable approximation. On the other hand, the spatial structure of low-frequency fluctuations is not self-evident, and it has not yet been clarified whether the time-varying component of the electron temperature in Eq. (2) can be neglected in evaluating the electric field fluctuations.

Fluctuations in electron density and electron temperature associated with low-frequency oscillations were evaluated using a triple Langmuir probe [11]. The low-frequency fluctuations observed in RT-1 consist of a turbulent component with no distinct frequency peaks and a coherent component with multiple peaks around 1 kHz [5], the latter being the focus of this study. Since these frequencies are comparable to or exceed the toroidal circulation frequency of charged particles trapped in RT-1, they can induce radial transport across magnetic field lines through the breakdown of the third adiabatic invariant. Indeed, the emergence of coherent fluctuations has been observed during the self-organization process of the stable structures peaked at the higher magnetic field side. While low-frequency fluctuations have previously been measured mainly with magnetic probes and microwave interferometers, the properties of their density and temperature components were not separately investigated in detail.

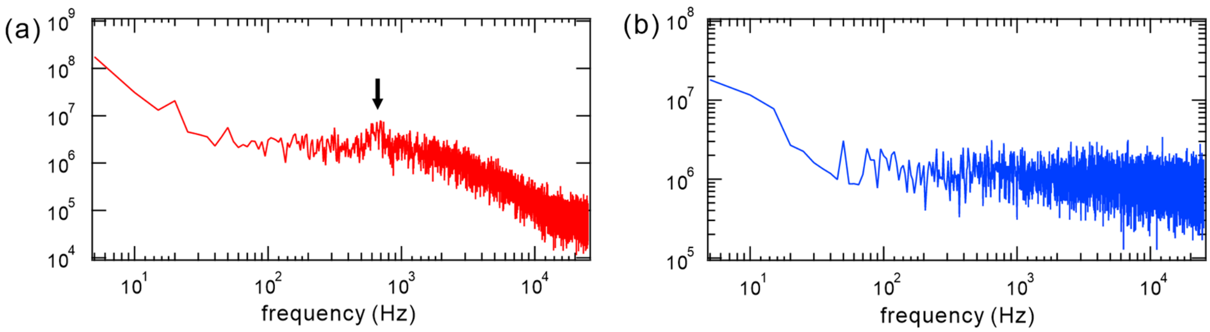

FIG. 3. Frequency power spectra of (a) electron density and (b) electron temperature obtained with the triple-probe voltage method during the occurrence of low-frequency fluctuations.

Figure 3 shows the frequency power spectra of electron temperature and electron density signals obtained using the triple-probe current method for low-frequency fluctuations in RT-1. Electron density fluctuations exhibit a clear peak around 1 kHz, corresponding to the frequency of coherent fluctuations (arrow in Fig. 3(a)), whereas no prominent peak is observed in the electron temperature spectrum in the same frequency range. This indicates that the coherent component of low-frequency fluctuations consists predominantly of electron density fluctuations $\widetilde{n_e}$, while electron temperature fluctuations $\widetilde{T_e}$ are relatively small. Under this condition, it is a good approximation to treat T_e measured at two nearby points as temporally constant in Eq. (2), and the toroidal electric field between two floating potential probes separated by a distance d can be evaluated as

$$E = \frac{\phi_{f1} - \phi_{f2}}{d} \qquad (3)$$

For electron density measurements, the third probe positioned midway between the two electrodes was used to measure the electron saturation current,

$$I_{e0} = \frac{1}{4} n_e e \left(\frac{8k_B T_e}{\pi m_e}\right)^{1/2} S \qquad (4)$$

where S is the probe area [11]. As in the case of electric field measurements, the smallness of electron temperature fluctuations in RT-1 low-frequency modes allows the use of this electron saturation current to evaluate density fluctuations. To avoid contamination by voltage fluctuations, the probe bias was set sufficiently above the plasma potential to ensure saturation. From the electric field and density evaluated in this manner, the fluctuating particle flux was determined by extracting only the fluctuating components (with the DC components removed) and using the steady magnetic field value at the probe location.

2.2. Particle flux measurement results

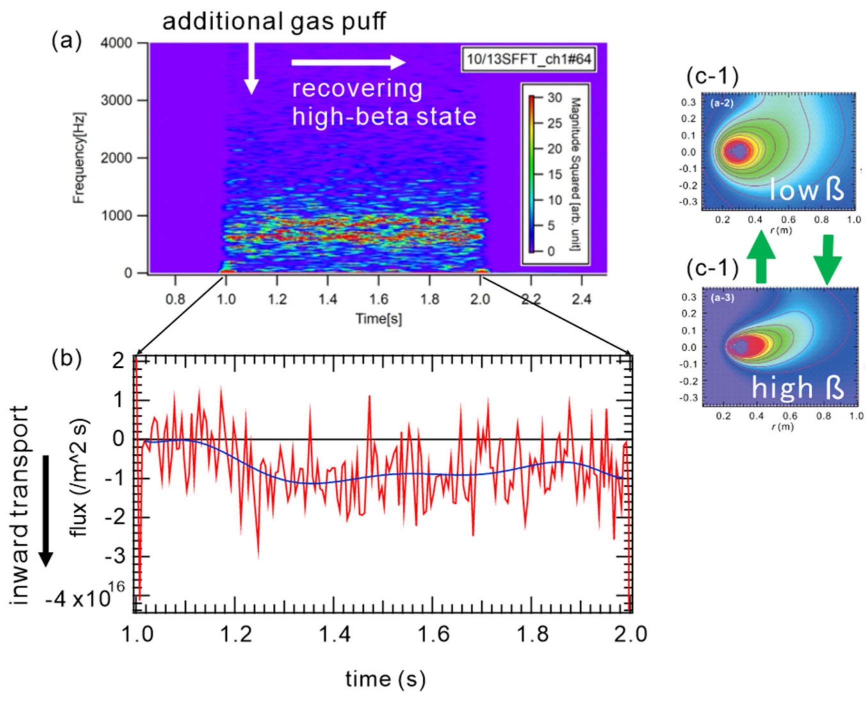

FIG. 4. (a) Typical frequency spectrum of low-frequency fluctuations in RT-1, (b) radial particle flux during plasma production, and (c) typical density profiles in high-β and low-β states.

As shown in Fig. 4, the particle flux measurement described above was applied to plasmas produced in RT-1 by 2.45GHz electron cyclotron heating (ECH). This shot represents a typical operation used in RT-1 experiments to study plasma self-organization: microwaves are injected from $t = 1$ to 2 s to produce the plasma, and a gas puff is applied at $t = 1.1$ s. As shown in Fig. 4(c), plasmas produced in the dipole magnetic field of RT-1 exhibit two equilibrium modes depending on experimental conditions: (c-1) a low-β state with a relatively flat pressure profile, and (c-2) a high-β state with a peaked structure in the strong-field region. The high β state realized immediately after the start of microwave injection at t = 1 s is rapidly destroyed by the injection of neutral gas from the puff, resulting in a low-β plasma with a flat profile. The plasma then gradually reconstructs its structure to recover the high-β state. As shown in Fig. 4(a), low-frequency fluctuations at 1 kHz appeared during this structural reconfiguration phase. In this experiment, a gas puff was applied at 1.1 s after plasma formation to collapse the high-β equilibrium, leading to a flat profile that subsequently reorganized into a peaked structure through inward transport. Figure 4(b) shows the radial particle flux driven by electric field fluctuations, evaluated with the method described in the previous subsection. During the interval from t=1 to 1.1 s, when the plasma maintained a stable high-β equilibrium, the time-averaged flux remained nearly zero. In contrast, after the gas puff at t=1.1 s, when the plasma transitioned to the low-β state, an inward particle flux was observed.

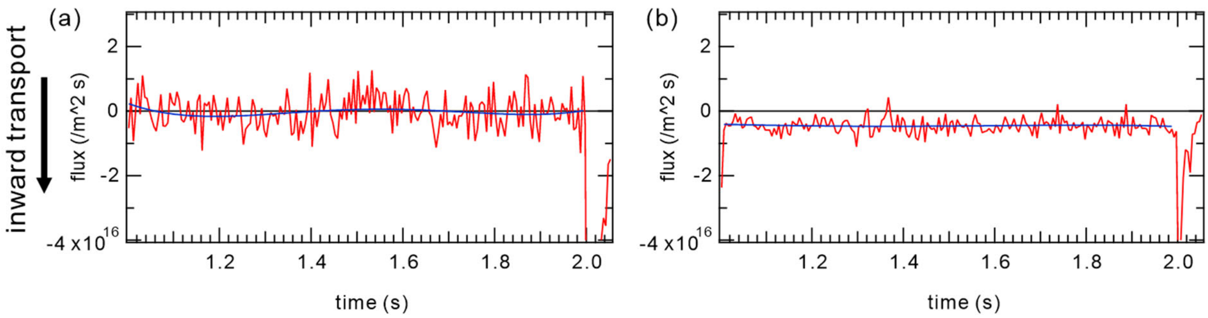

FIG. 5. Measured particle flux in (a) high-β and (b) low-β states without additional gas puffing.

Figure 5 shows the radial particle flux under conditions where plasmas were produced steadily without additional gas puffing. By varying the microwave heating power, measurements were carried out for (a) high-β plasmas with peaked structures on the strong-field side and (b) low-β plasmas with relatively flat profiles. In the case of high-β plasmas, where the peaked structure had already been established, no clear radial transport was observed. In contrast, in the low-β state, the appearance of a distinct inward particle flux was evident. This result suggests that particle flux arises in the direction of establishing the stable state of plasmas in a dipole magnetic field [1], corresponding to flattening in phase space and the formation of a peaked structure in real space.

3. EXPERIMENTS ON WHISTLER WAVE FLUCTUATIONS

3.1 Simultaneous observation of magnetic fluctuations and lost electron current

In RT-1, in addition to studies on low-frequency fluctuations, investigations have been conducted on the relationship between chorus emissions [5,6] and particle transport. To explore the connection between burst-like whistler waves and transport, an electrostatic probe capable of selectively collecting energetic electrons with energies above ~5 keV was installed near the vacuum chamber wall of RT-1 to directly detect lost electrons. As shown in Fig. 6, the current signal of energetic electrons exhibited intermittent variations similar to those of magnetic fluctuations. Simultaneous measurements with a B-dot probe revealed that approximately half of the energetic electron events coincided with detected chorus emission events. However, fluctuations in the energetic electron current signal were also observed in cases where no magnetic fluctuations were detected.

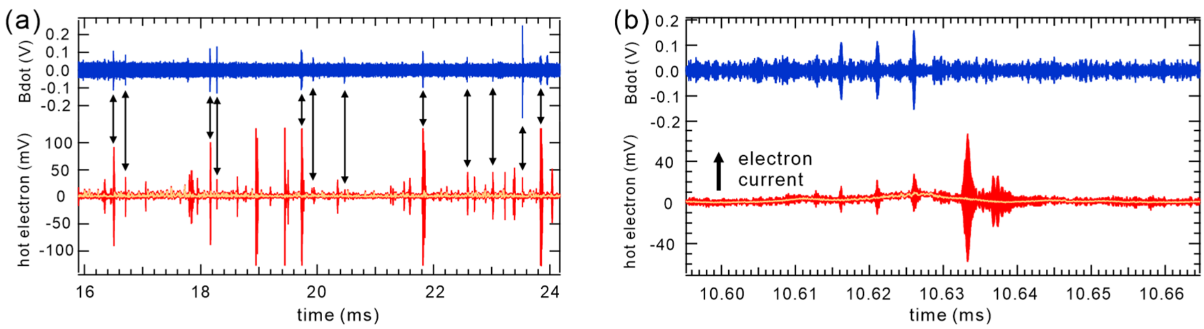

FIG. 6. (a) Magnetic field fluctuations measured by the B-dot probe (top, blue) and electron current (bottom, red) at the plasma periphery measured by a high-energy electron probe. (b) Enlarged view of the fluctuation signal detected by the high-energy electron probe (bottom, red), along with its numerically low-pass filtered waveform (light blue), in comparison with the B-dot probe signal (top, blue).

Multi-point measurements with B-dot probes showed that the magnetic fluctuations corresponding to chorus emissions propagate along magnetic field lines in the poloidal direction but are localized in the toroidal direction. Thus, it is possible that chorus emission events occurred at other toroidal locations where the present B-dot probes could not detect the local fluctuations. Based on this assumption, high-energy electron signals not synchronized with magnetic fluctuations are considered to be caused by chorus emissions generated in regions outside the sensitivity of the installed B-dot probes. This suggests that fluctuation-driven energetic electron losses have broad toroidal sensitivity and may occur over an extended spatial region.

It is noteworthy that, within the range of measurements in this study, no clear evidence of fluctuations was observed in the line-integrated electron density signals measured by the microwave interferometer. This indicates that the fraction of lost energetic electrons is relatively small when integrated along the interferometer line of sight. Further investigations are required to clarify the implications of the observed phenomena for plasma spatial structure and overall confinement properties.

3.2 Electron orbit in dipole magnetic field and strong whistler wave

In a dipole magnetic field, right-hand circularly polarized waves can efficiently heat electrons. To simulate the effect of electric fields generated by chorus emissions in the peripheral confinement region of RT-1, test-particle orbit calculations were performed. As shown in Fig. 7, under electric fields corresponding to the maximum fluctuation amplitudes observed experimentally, electrons gain energy from the wave and are accelerated to relativistic energies within ~10 μs, comparable to or shorter than the duration of a typical fluctuation event. In the peripheral region of RT-1, electron orbits become chaotic once their kinetic energy exceeds ~10 keV, and they are no longer well confined by the edge magnetic field, resulting in an increased fraction of electrons lost to the chamber wall. These calculations are consistent with the experimental observation of energetic electrons detected at the chamber wall, suggesting that whistler waves driven by hot-electron temperature anisotropy further accelerate a fraction of electrons and enhance particle losses.

Experimentally, under conditions of substantially reduced neutral gas pressure and a very high fraction of energetic electrons, pronounced electron density fluctuations synchronized with electromagnetic fluctuations were observed. Clarifying the relationship between such large density fluctuations and chorus emissions remains an important subject for future study.

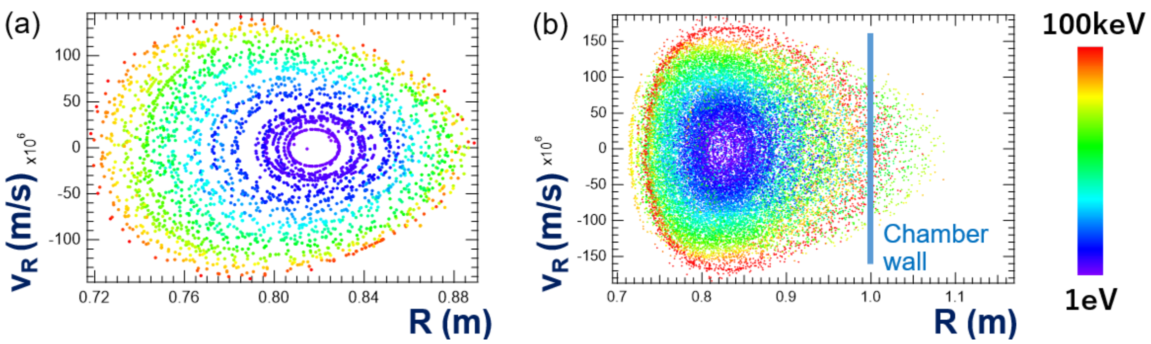

FIG. 7. Poincaré plot of an electron (initial kinetic energy is 1 eV) accelerated by the electric field of whistler waves in the dipole magnetic field of RT-1 at the edge region, for (a) 10 μs and (b) 500 μs after the start of wave application. The colour shows the kinetic energy of the electron.

4. SUMMARY

In this study, particle transport phenomena associated with low-frequency fluctuations and whistler-mode chorus emissions were investigated in the levitated dipole device RT-1. Using Langmuir probes, the radial particle flux driven by electric field fluctuations was measured for the first time in RT-1. The results demonstrated that coherent low-frequency fluctuations are primarily associated with electron density variations, and that these fluctuations generate an inward flux during transitions from low-β to high-β states, thereby contributing to the self-organization of peaked plasma structures. In addition, whistler-mode chorus emissions driven by hot-electron temperature anisotropy were found to coincide with intermittent energetic electron losses, consistent with test-particle simulations showing rapid relativistic acceleration and orbit stochasticity in the peripheral region. These results suggest that fluctuation-driven transport plays dual roles: low-frequency fluctuations drive inward particle transport that supports structure formation, while whistler-mode fluctuations can enhance energetic electron losses. Further investigations of the interplay between coherent fluctuations, particle transport, and plasma structure formation will be crucial for advancing our understanding of confinement physics in dipole plasmas and for exploring their potential as a candidate for advanced fusion concepts.

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