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

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The dipole fusion concept is an innovative confinement configuration capable of achieving ultra-high β states suitable for burning advanced fusion fuels [1-3]. In the RT-1 (Ring Trap 1) experiment [2], a magnetically levitated high-temperature superconducting coil generates a magnetic field globally analogous to the magnetospheres of planets like Jupiter. RT-1 has successfully demonstrated the stable generation of plasmas with local β reaching 100% [4]. In the process of generating high-β plasmas in the dipole field configuration, interactions between charged particles and waves play a crucial role. At RT-1, various fluctuation phenomena are observed [5-7], depending on parameters such as plasma pressure, temperature anisotropy of high-energy electrons, and background neutral pressure. Previous studies have investigated the mode structures and conditions of fluctuation appearance, for low-frequency fluctuations [5,6] observed in the formation process of peaked structures in a strong magnetic field region, and whistler-mode chorus emissions [7] associated with the population of high-energy electrons. While significant progress has been made in understanding the characteristics of these fluctuations, direct studies on their effects on transport phenomena and structure formation remain unexplored. As shown in Fig.1, a strong correlation between the fluctuation levels and the degradation of confinement time, suggesting that fluctuations play a significant role in plasma transport. Understanding the role of fluctuations on the transport and self-organization processes in the magnetospheric configuration is critical for further improving confinement performance toward the realization of advanced fusion. This study reports on advances in understanding particle transport phenomena driven by whistler waves and low-frequency fluctuations in the RT-1 device.

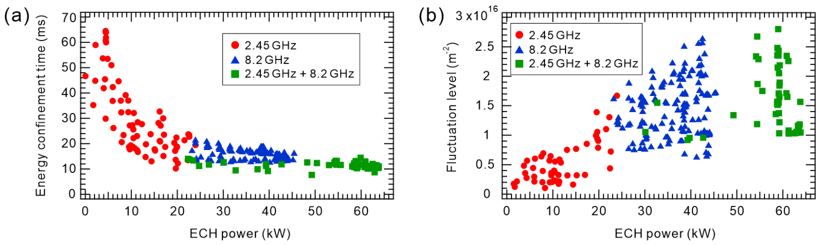

Fig.1: (a) Energy confinement time $\tau = W/P$, evaluated from the plasma stored energy W and ECH power P, and (b) plasma density fluctuation level measured with a microwave interferometer, both as functions of the heating power of ECH provided by 2.45 GHz and 8.2 GHz microwave.

In high-β plasmas with high-energy electrons in RT-1, whistler waves have been observed below the electron cyclotron frequency as intermittent chorus emissions, equivalent to those observed in the geospace environment [7]. The occurrence rate and intensity of these fluctuations exhibit a positive correlation with plasma pressure, and they arise only when the plasma contains a significant high-energy electron component. Hot electrons with temperature anisotropy, generated by electron cyclotron heating (ECH), destabilize the whistler waves. These waves undergo nonlinear growth in the non-uniform magnetic field, leading to chirping. In RT-1, we installed a electrostatic probe capable of selectively collecting high-energy electrons exceeding approximately 5 keV near the vacuum wall to directly detect escaping electrons. As shown in Fig.2, the current signal of high-energy electrons exhibits intermittent fluctuations that are similar to the magnetic fluctuations. Simultaneous measurements with a Bdot probe revealed that roughly half of high-energy electron events coincide with detected chorus emission events. However, fluctuations

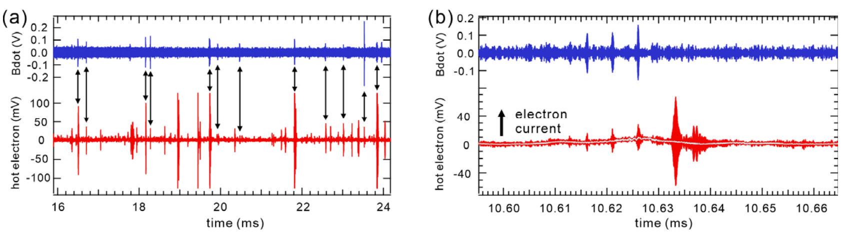

Fig. 2: (a) Magnetic field fluctuations measured by the B-dot probe (top, blue) and electron current (bottom, red) at the plasma periphery measured by a high-energy electron probe. (b) Enlarged view of the fluctuation signal detected by the high-energy electron probe (bottom, red), along with its numerically low-pass filtered waveform (light blue), in comparison with the B-dot probe signal (top, blue).

in the high-energy electron current signal are sometimes observed even when magnetic fluctuations are not detected. According to multipoint measurements with Bdot probes, these chorus-emission magnetic fluctuations propagate along magnetic field lines in the poloidal direction but are quite localized in the toroidal direction. It is possible that chorus emission events occur at toroidally distinct locations even when the current Bdot probe did not detect local fluctuations. Based on this assumption, high-energy electron signals that are not synchronized with magnetic fluctuations may be attributed to chorus emissions generated in regions undetectable by the current Bdot probe configuration. This suggests that high-energy electron losses driven by fluctuations exhibit a broad toroidal sensitivity and likely occur over an extensive spatial range. Notably, within the measurement scope of this study, line-integrated electron density signals from a microwave interferometer did not show clear evidence of fluctuations, suggesting that the proportion of high-energy electrons lost is relatively small along the line-of-sight integration of the interferometer. Further studies are needed for the significance of the observed phenomena on the spatial structures of plasmas and global confinement properties.

In a dipole magnetic field, right-hand circularly polarized waves can efficiently heat electrons. Test particle orbit calculations were performed in the peripheral confinement region of RT-1 to simulate the effects of electric fields generated by the chorus emissions. As shown in Fig. 3, under the electric fields corresponding to the maximum observed fluctuation intensity, electrons gain energy from the waves and are accelerated to relativistic energies within 10 μs, comparable to or below the duration of typical fluctuation events. In the peripheral region of RT-1, when the kinetic energy exceeds approximately 10 keV, electron trajectories can be chaotic and are not well trapped in the peripheral magnetic field, leading to the increase in the fraction of electrons lost to the chamber wall. These calculation results agree with the detection of high-energy electrons on the chamber wall, suggesting that whistler waves driven by the temperature anisotropy of hot electrons can further accelerate some of electrons, leading to the increased loss of particles. Experimentally, under conditions where the fill gas pressure is quite reduced and the fraction of high-energy electrons is very high, significant electron density fluctuations were observed in synchronization with electromagnetic fluctuations. Elucidating the relationship between these large density fluctuations and chorus emissions remains as a future work.

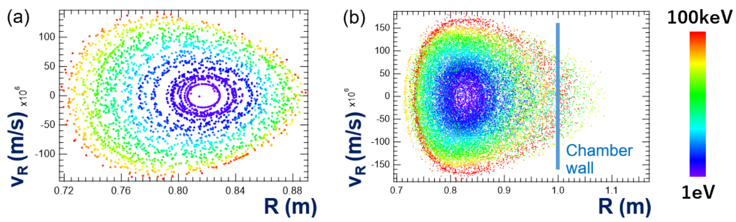

Fig. 3: Poincaré plot of an electron (initial kinetic energy is 1 eV) accelerated by the electric field of whistler waves in the dipole magnetic field of RT-1 at the edge region, for (a) 10 μs and (b) 500 μs after the start of wave application. The colour shows the kinetic energy of the electron.

In addition to chorus emissions, we also investigate the relationship between low-frequency fluctuations [5,6] and particle transport in RT-1. The low-frequency fluctuations observed in RT-1 consist of a turbulent component with no distinct frequency peaks and coherent components with multiple peaks around 1 kHz [5]. These frequencies are comparable to or exceed the toroidal circulation frequency of charged particles trapped in RT-1, making them capable of inducing 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 stable structures peaked in the high-field side. High time-resolution measurements using triple probes have revealed that the temporal variations of coherent low-frequency fluctuations are predominantly driven by electron density fluctuations $\widetilde{n_e}$, while the fluctuations in electron temperature $\widetilde{T_e}$ are negligible. Under conditions where the magnetic component of the fluctuations is relatively small and electrostatic fluctuations dominate [6], the radial particle flux across magnetic field lines in a dipole field with a purely poloidal magnetic field B is driven by toroidal electric field fluctuations $\widetilde{E_\theta}$ and is given by $\Gamma = < \widetilde{n_e}\widetilde{E_\theta} > /B$. A multi-tipped electrostatic probe array has been introduced into RT-1, and the negligible electron temperature fluctuations allow precise determination of toroidal electric field fluctuations using floating potential measurements. While the time-averaged net particle flux has not yet been evaluated, toroidal electric field fluctuations have been detected, and their intensity is observed to increase during the occurrence of coherent low-frequency fluctuations.

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