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 experimental studies at the RT-1 levitated dipole on the fluctuations of plasma that are related to the transport and structure formation in a dipole magnetic field configuration [1-3]. On low-frequency fluctuations, which appear in the structure formation phase, we observed that (1-1) the electromagnetic fluctuation mode at high-β states [4] 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 [5]. 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. According to orbit analysis, electrons are efficiently accelerated by the excited whistler waves in the geometry of RT-1, some of which are not trapped in the confinement region. It is possible that the effects of such wave particle interaction are related to the previously reported sudden decrease of electron density in the very high-β and low-density operation of RT-1.

1. Introduction: The magnetospheric configuration, created by a levitated superconducting dipole field coil, is one of innovative fusion plasma experiments that is globally equivalent to the configuration of a planetary magnetosphere [1]. Because of its strongly inhomogeneous field strength and compressive effects of magnetic field lines, plasma is stabilized even in the bad curvature region in the dipole magnetic field. Stable confinement of high-β plasma has been realized in the RT-1 [2] of The University of Tokyo and LDX [3] of MIT. These studies are important for the realization of stable formation of high-β plasma toward the burning of advanced fuels [1] in a future fusion reactor. Various types of waves are excited in plasmas in the dipole field and play an important role on the transport and structure formation through wave particle interactions. Among these fluctuation phenomena, self-organization of high-β states of dipole plasma is understood as a relaxation process in the phase space [6] that is observed as inward (or up-hill) diffusion [4] caused by low-frequency fluctuations. Also, nonlinear growth of waves and formation of energetic particles are important mechanisms for the understanding of transport properties in fusion plasmas. In this study, we report the recent progress on the understanding of fluctuation activities of plasmas in RT-1 in both the low-frequency and cyclotron frequency ranges that are related to transport phenomena.

2. Spatial structure of low-frequency fluctuations: On low-frequency fluctuations, their spatial profiles and parameter dependence were investigated using a movable Langmuir probes and multi-point magnetic probes (Bdot probes). At RT-1, we have observed coherent electromagnetic modes at 0.7 kHz and 1.0 kHz as well as a turbulent-like component (Fig.1) [4]. Because the measurement points were limited to the vicinity of the chamber wall and the centre stack with the Bdot probe diagnostics, detailed internal structure of the fluctuations were not clear in previous studies. In this work, we installed a Langmuir probe array with improved durability to measure electrostatic fluctuations inside the hot-electron plasma during a several seconds of high-β discharges. These measurements revealed several important properties of the low-frequency fluctuations. (1-1) While coherent magnetic fluctuations appeared only in high-β conditions, coherent electrostatic fluctuations with the same frequencies are observed even in lower β states. (1-2) Multi-point measurements of electrostatic fluctuations inside the plasma showed that the wave has a toroidal mode number of 3 or 4, which does not depend on the magnetic surface function. This is consistent with the observation of clear coherent fluctuation mode in line-density fluctuations measured with interferometers. (1-3) The propagation direction of the low-frequency fluctuations was usually in the electron diamagnetic direction. The direction reversal was observed according to the plasma parameters by inserting the probe structure inside the plasma. These new findings do not contradict the understanding that the drift motion of density ununiformity (similar to the so-called entropy mode [5]) creates magnetic fluctuations in high-β plasmas.

3. Fluctuations in electron cyclotron range: For higher-frequency waves, we extended the measurement frequency range of magnetic fluctuations and observed spontaneously excited modes near the local electron cyclotron frequency. To conduct fluctuation measurements at higher frequency range with 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 (Fig.2). It was observed that the amplitude and frequency often showed large temporal variation, indicating the nonlinear growth of the oscillation mode. The main characteristics of this mode are as follows. (2-1) 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. (2-2) 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 considerable ratio of hot electrons exist at high-β operation. (2-3) 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 are 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 wave. 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.

4. Effects of flow and pressure profiles on the fluctuation activities: For the understanding of fluctuations and related phenomena in the high-β plasma of RT-1, the spatial profiles of toroidal velocity and plasma pressure are very important information. Formation of sufficient plasma pressure is a necessary condition for the emergence of both low-frequency and cyclotron frequency range fluctuations. Analysis of the internal flow velocity using the coherence imaging spectroscopy (CIS) technique was implemented in RT-1 to reconstruct the two-dimensional profiles of toroidal flow velocity and ion temperature. It was confirmed with the CIS measurements that the relatively strong toroidal flow is formed around the strong magnetic field region near the pressure peak inside the confinement region. These results suggest that E×B drift as well as the diamagnetic effects should be considered for the analysis of the drift motion of plasma. Clear dependence of the propagation velocity on the radial electric field strength is still not very clear in the present initial experiments.

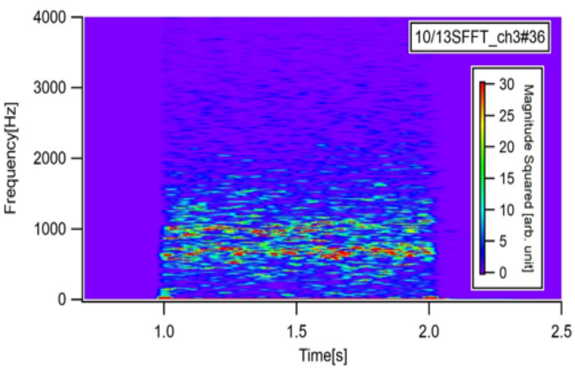

Fig.1: Frequency power spectrum of low-frequency electrostatic fluctuations of high-β plasma.

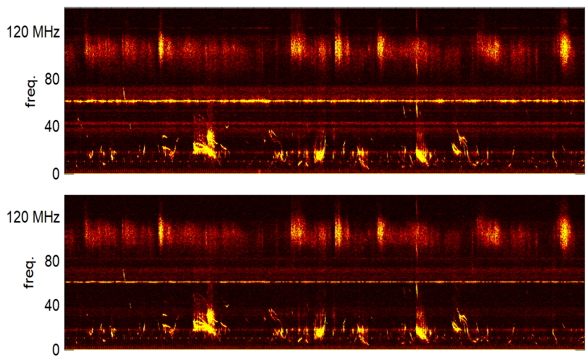

Fig.2: Fluctuations in the electron cyclotron frequency range measured at a same poloidal cross section.

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