Fast frequency sweeping events in the electron cyclotron emission of nonequilibrium plasma confined in a tabletop mirror trap

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Abstract. Complex dynamics has been observed in the spectra of electron cyclotron emission of nonequilibrium plasma confined in a tabletop mirror trap. Microwave emission is a set of highly chirped radiation bursts with both increasing and decreasing frequencies which are repeated periodically. Such chirped bursts are not described well in the framework of a standard quasilinear approach. On the other hand, the simultaneous observation of several chirped bursts in the same frequency range is typical of the formation of nonlinear phase-space structures in the vicinity of the wave-particle resonances in the kinetically unstable plasma, also known as the “holes and clumps” mechanism.

1. Introduction
Chirped electromagnetic emission in a frequency range of 30–300 kHz is generally observed in toroidal magnetic traps during the development of the Alfvén wave turbulence driven by high-energy beams of ions or alpha particles [1, 2]. The frequency sweeping events associated with the development of the high-energy particle-driven Alfvén instabilities were detected at the DIII-D, JT-60U, ASDEX-Upgrade, MAST, NSTX, START, and LHD machines in regimes with neutral beam injection heating. To study and interpret such chirped emission bursts, the “holes and clumps” mechanism (or Berk-Breizman model [3]) has been suggested, where the simultaneous observation of several chirped bursts in the same frequency range is described as the formation of nonlinear phase-space structures in the vicinities of the wave-particle resonances in the kinetically unstable plasma.

In the laboratory experiments we have observed potentially the same mechanism acting in a much higher frequency range. The obtained data provided the first experimental evidence in favor of the spontaneous formation of the self-consistent structures similar to the Bernstein-Green-Kruskal waves near the wave-particle resonances in the frequency range corresponding to millimeter wavelengths in the laboratory plasma confined in a mirror trap. The goal of this work is to study the fine time-frequency characteristics of the electromagnetic radiation. It became possible to perform such studies only recently due to the development of methods for measuring the electromagnetic field with high temporal resolution. First experimental results were discussed in [4]. Here we will analyze the general features of the frequency sweeping events in decaying ECR discharge plasma.
2. Experimental setup

The experiments were performed in plasma of electron cyclotron resonance (ECR) discharge sustained by gyrotron radiation (frequency is 37.5 GHz, power is up to 80 kW, and pulse duration is 1 ms) in an open axially symmetric mirror magnetic trap [5]. The schematic view of the setup is shown in Figure 1. Microwave radiation is launched through the input window and is focused in the heating region of the discharge chamber. The radiation intensity in the focal plane is about 10 kW/cm² and the average power density is 100 W/cm³.

The discharge chamber is placed inside the mirror magnetic trap, consisting of pulsed coils with the maximum magnetic field strength of 4.3 T; the pulse duration is about 7 ms. The length of the magnetic trap is 22.5 cm, mirror ratio is about 5. Plasma is initiated and sustained by gyrotron radiation under ECR conditions at the fundamental cyclotron harmonic at a frequency of 37.5 GHz which corresponded to a magnetic field strength of 1.34 T. The resonance surface is between the magnetic mirror and the center of the discharge chamber. Pressure of neutral gas is about \(10^{-6}\) Torr; and it increases up to \(10^{-4} - 10^{-3}\) Torr during the ECR discharge. The facility is working in a pulse-periodic regime with at least 10 seconds delay between shots.

3. Experimental results

In the experiments, we obtained data on the intensity and dynamic spectrum of the stimulated electromagnetic plasma radiation. In the microwave measurements, we used the broadband horn antenna which has the uniform bandwidth in the range of 2–20 GHz and the high-performance oscilloscope (Keysight DSA-Z 594A, the analog bandwidth is 59 GHz, and the sampling rate is 160 GSample/s). The antenna bandwidth covered the frequency range up to the second harmonic of the electron gyrofrequency \(f_{ce}\) in the trap center. The dynamic spectra were calculated from the recorded data by the short-time Fourier transform with the Hamming window and the original noise reduction algorithm. Simultaneously with the electromagnetic radiation, we measured precipitation of high-energy electrons (>10 keV) from the trap ends using a p-i-n diode detector with a time resolution of approximately 1 ns.

The ECR discharge plasma consists of at least two components: the cold dense component \((N_c \sim 10^{12} - 10^{13} \text{ cm}^{-3}, T_c \sim 100-300 \text{ eV})\) with an isotropic velocity distribution and the less dense component with anisotropic distribution function which consists of hot electrons \((N_h \sim 10^{10} - 10^{11} \text{ cm}^{-3}\) and energies are in the range from 10 to hundreds of keV) [5].

Experiments were performed in two gases: nitrogen and argon. In these gases, the processes of plasma decay, which start after the ECR heating is switched off, are characterized by the different time scales. The decay of nitrogen plasma proceeds faster due to the dissociative recombination of molecular ions, which is the main recombination mechanisms in the late decay stage [6]. In argon plasma, the plasma density decay is mainly caused by the three-body electron recombination. In total, 54 experimental shots were performed in nitrogen plasma, while only 23 of them contained the frequency sweeping events which will be discussed below. At the same parameters of the experiment, the fraction of unstable events in argon plasma was much less: 146 experimental shots were performed, while only 11 observations of the instability have been found.
Microwave emission with the frequency sweeping events was observed in the stage of plasma decay with a time delay of 0.1–2 ms after the ECR heating was switched off. The time delay between the end of ECR heating pulse and the start of the instability development could be explained by the polarization depression effect in the background plasma [4], when instability is suppressed in dense plasma. Another important feature which accompanies the instability development is a decreasing ambient magnetic field.

**Figure 2.** The dynamic spectrum of microwave emission with chirped patterns. The top panel shows the whole scenario of the instability development together with the time evolutions of the electron cyclotron frequency and its second harmonic in the trap center (black and green lines, respectively). The bottom panel shows the zoomed dependence with a continuous train of chirping events.

**Figure 3.** The histogram of the emission frequencies of the separate chirps for the discharges in nitrogen (blue) and argon (red).

As a rule, in the beginning of the instability development, a broadband (with a bandwidth about 1 GHz) continuous emission occurs with frequencies below the electron gyrofrequency $f_{ce}$. After the
initial phase, which is out of the scope of the present study, the emission is observed only in a few frequency bands which are independent of the experimental conditions. The emission frequency is always less than the electron gyrofrequency in the trap center. Within each frequency band, the emission spectrum is a set of fast narrowband chirped bursts, which consist from periodical batches with several bursts in each or quasi-continuous series of bursts with duration of up to 1 ms. The instability development is illustrated in Figure 2, where the dynamic spectrum is shown. We note that the second harmonic of the microwave emission was observed and its spectrum repeated the fine spectral structure of the emission of the fundamental harmonic.

The statistical analysis of the experimental data shows that the separate frequency bands in the emission spectra are similar for all experimental shots performed in a certain gas. Figure 3 shows histograms of the emission frequencies of the separate chirps for the discharges in nitrogen and argon. It can be seen that there are several narrow frequency peaks from which the chirps with raising and falling frequencies start. The widths of the peaks are determined by the maximum frequency deviations from the initial frequency in the chirped structures. For the discharges in nitrogen, the peaks are observed at frequencies of 4.35, 4.9, 6.2, 7.3, 7.6 and 9 GHz. For the discharges in argon, the peaks are observed at frequencies of 7.6, 8.8, 9 and 9.85 GHz. The central frequencies of the peaks do not depend on the ambient magnetic field. Therefore, they can be associated with the excitation of certain electromagnetic modes in a metal discharge chamber filled with rarefied magnetized plasma.

4. Discussion and conclusions
The frequency sweeping events in the microwave emission spectrum may be well explained in the framework of the Berk-Breizman model [3]. As an electromagnetic mode develops, most of the particles respond adiabatically to the wave and only a small group of resonant particles becomes mixed and causes the local flattening of the distribution function in phase space within or near the separatrixes formed by the waves. However, when there is the linear dissipation in the background plasma, the plateau distribution becomes unstable and the mode tends to grow explosively. That results in the formation and subsequent development of the long-living structures (as compared to the linear growth) in the particle distribution, the so-called holes (a depletion of particles) and clumps (an excess of particles). Their subsequent convective motion in phase space is synchronized to the change in the wave frequency, thus leading to the formation of complex chirped patterns in the dynamic spectra of unstable waves. The distinctive feature of the instability under investigation is the considerable effect of electron collisions on its development which provides a dissipation channel for electromagnetic energy, which results in the formation of characteristic chirped elements in the emission spectra.

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