Observation of CW to pulsed mode transition of cyclotron maser emission from magnetic mirror

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Abstract

The first experimental evidence of the controlled transition from the generation of periodic bursts of electromagnetic emission into continuous wave (CW) regime of a cyclotron maser formed in magnetically confined non-equilibrium plasmas is reported. The approach to the transition to CW regime, which requires fine tuning of the magnetic field, was found experimentally. From a theoretic point of view, the observed transition is related to the Poincare–Andronov–Hopf bifurcation: a stationary point attributed to CW generation becomes unstable through the birth of a stable limit cycle. The kinetic cyclotron instability of the extraordinary wave of weakly inhomogeneous magnetized plasma is driven by the anisotropic electron population resulting from electron cyclotron plasma heating in MHD-stable minimum-B open magnetic trap. Except being of fundamental interest in the context of space cyclotron masers in planet magnetospheres and other astrophysical objects, our results are important for applications, in particular for the development of ECR ion sources.

Introduction

Resonant interaction between energetic electrons and the electromagnetic waves makes the plasma prone to electron cyclotron instabilities which are one of the main mechanisms for generating nonthermal radiation in the magnetoactive plasma. The instability is driven by the presence of positive gradients ($df/dv > 0$) in the resonant particles velocity space distributions whose formation is directly associated with particle acceleration mechanisms and is universal for both space and laboratory plasma. Studies of electron cyclotron instability of non-equilibrium plasma have led to creation of plasma cyclotron maser paradigm – the mechanism, which explains a rich class of phenomena of coherent radioemissions generation in the magnetospheres of the Earth and planets, in solar coronal loops and in the atmospheres of stars, and in laboratory magnetic traps [1]. The development of cyclotron instability under such conditions results in the generation of periodic, quasi-periodic (QP) or stochastic broadband pulses of emission. Each electromagnetic pulse is accompanied by pulsed precipitations of fast electrons from the trap as they lose transverse momentum and fall into the loss cone due to the interaction with waves. Owing to the sharp decrease in the free energy, the system falls under the instability threshold; after that, a comparatively slow preparation of the subsequent burst (accumulation of resonant particles) begins, and the process repeats. The observation of QP bursts of stimulated electromagnetic radiation accompanied by particle precipitations from the trap was studied in a number of laboratory experiments [2,3]. Recently the intense bursts of microwave emission were detected during Edge Localized Mode (ELM) event [4]. The brightness temperature of these emissions are much greater than any plausible electron temperature that proves the generation of coherent radiation due to maser mechanisms. Nevertheless, a continuous wave (CW) generation is also possible when the system stays near the instability threshold, and the accumulation and emission phases are not separable, i.e. the number of high-energy particles delivered by a source is constantly equal to the number of precipitating particles. The steady-state emission of plasma cyclotron maser was extensively studied theoretically (see [1] and references therein), but it has never been detected reliably in a laboratory because of the narrow region of plasma parameters where the regime exist. In this paper we present the first experimental evidence of transition from generation of quasi-periodic bursts of electromagnetic emission to continuous wave (CW) regime of electron cyclotron instability in an open magnetic trap.

2. Experimental setup

The experimental data were taken with the room-temperature A-ECR-U type Electron Cyclotron Resonance Ion Source (ECRIS) at JYFL accelerator laboratory [5]. The microwave power at tunable frequency (10.75 GHz–12.4 GHz) is provided by a traveling wave tube amplifier (TWTA) and launched into the plasma chamber through WR62 waveguide port. In the experiments reported here the plasma was heated at the frequency of 11.8 GHz and at power range of 100-250 W. The magnetic field of the ion source is generated by two solenoid coils and a permanent magnet sextupole resulting to a so-called minimum-B field configuration. The minimum value of the magnetic field (B_{min}) is achieved on the axis of the ion source in between the solenoid coils in axial direction. On the other hand, the resonance condition for (non-relativistic) electron heating, is satisfied on a closed (nearly) ellipsoidal surface with constant magnetic field of B_{ECR} = 0.42 T. The magnetic field strength can be adjusted by varying the solenoid coil currents, which affects the injection and extraction mirror ratios as well as the B_{min}/B_{ECR}. The ion source was operated in the range of

$0.75 < B_{min}/B_{ECR} < 0.99$. The strength of the sextupole field on the plasma chamber wall at the magnetic pole is 1.07 T when the solenoids are not energized [6]. Oxygen plasmas in the pressure range of $4\cdot10^{-7} \div 5\cdot10^{-7}$ mbar were studied. The pressure readings were measured outside the plasma chamber with an ionization gauge connected to a radial diagnostics port of the ion source.

The emitted microwave plasma emission was guided into a Keysight DSOV334A oscilloscope through WR-75 waveguide, high voltage break, waveguide-to-coaxial transition, power limiter and tunable attenuator. The features of the oscilloscope - 80 Gs/s sampling rate and 33 GHz bandwidth - allowed direct recording of the waveforms of electromagnetic field emitted by the plasma with temporal resolution of 12.5ps.

3. Experimental results and discussion

Typical emission patterns in the burst and cw regimes of the electron cyclotron instability are presented in Fig. 1. Panel (a) is related to the intensity of the microwave emission in cw (upper plot) and burst (lower plot) regime. The corresponding dynamic spectrogram is shown in the panel (b). In burst regime the microwave signal consists of a series of wave packets with duration of 1 μs and repetition period of 2 μs. Depending on the experimental conditions, the duration varies from 0.1 to 5 μs, simultaneously the period varies from 1 μs to 10 ms. The frequencies of the most pronounced discrete lines are 10.8, 9.0, and 8.86 GHz. The repetition period of the pulses decreases with increasing microwave power while their amplitude and spectrum are unaffected. In the steady-state (cw) regime the frequency of cw plasma emission is 8.45 GHz and is independent of the heating power.

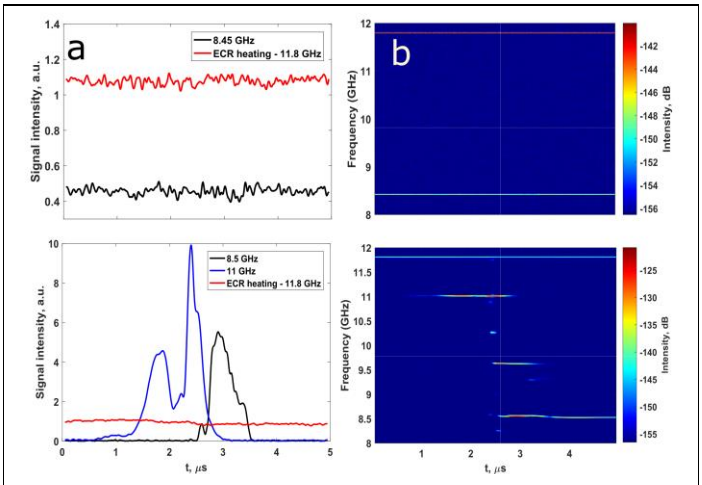

Figure 1. Intensity of microwave emission (panel «a») and dynamic spectra of plasma emission in 8-12 GHz range (panel «b») to the generation of cw emission (upper plot) at B_{min}/B_{ECR} = 0.947 and periodic bursts (lower plot) at B_{min}/B_{ECR} = 0.935. Stray radiation of the heating TWT amplifier at 11.8 GHz is shown with a red line.

The dependence of the specific generation regime look as follows. No enhanced cyclotron (maser) emission from the plasma is observed in low magnetic fields when B_{min}=B_{ECR} < 0.88. A reproducible generation of quasiperiodic bursts near the fundamental and second electron cyclotron harmonics is observed at B_{min}=B_{ECR} = 0.88–0.93. The cw generation near the fundamental harmonic is detected at stronger field when B_{min}=B_{ECR} = 0.94–0.98. With further increase of the magnetic field, plasma heating becomes inefficient since the ECR absorption volume is small, and the cyclotron instability shows stochastic features.

The observed microwave emission is inherently related to the excitation of electromagnetic waves due to a kinetic cyclotron instability. The most unstable mode is apparently the slow extraordinary wave propagating quasi-longitudinally to the external magnetic field and excited in the frequency range between the electron plasma and cyclotron frequencies. A significant part of the microwave power is measured at frequencies below the cyclotron frequency in the trap center, which indicates that the wave-particle interaction occurs at the relativistically down-shifted cyclotron resonance.

The observed transition from generation of quasi-periodic bursts to cw emission is related to the Poincar´e-Andronov-Hopf bifurcation; namely, a stationary point attributed to cw generation becomes unstable through the birth of a stable limit cycle [7]. A self-consistent evolution of particles and waves was described by the quasilinear theory with perturbative approach that involves many overlapped waveparticle resonances as a basis for diffusive particle transport in the phase space. It was shown that for the fixed ECR heating frequency, the stationary generation corresponds to a higher magnetic field in comparison to the burst regime. Also the transition to the cw regime requires fine tuning of the source of nonequilibrium electrons in the phase space.

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