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Microwave Emission from ECR Plasmas under Conditions of Two-Frequency Heating Induced by Kinetic Instabilities

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Abstract. Multiple frequency heating is one of the most effective techniques to improve the performances of ECR ion sources. It has been demonstrated that the appearance of the periodic ion beam current oscillations in ECRIS at high heating power and low magnetic field gradient is associated with kinetic plasma instabilities. Recently it was proven that one of the main features of multiple frequency heating is connected with stabilizing effect, namely the suppression of electron cyclotron instability in ECRIS plasmas. Due to this kind of stabilization it is possible to run the ion source in stable mode using higher total microwave power and thus to obtain better ion beam parameters. Unfortunately, even with using of such technique at some threshold level the plasma becomes unstable. This work is devoted to experimental investigations of the peculiarities of cyclotron instability in the case of two-frequency heating. It was found out that the plasma microwave emission spectrum related to instabilities is affected by the division of injected power shared between the heating frequencies, though the main emission lines in the spectrum are proven to be independent on heating frequencies.

INTRODUCTION

Conventional Electron Cyclotron Resonance Ion Sources (ECRISs) with a minimum-B magnetic field configuration have been widely used as injectors of multicharged ion beams into accelerators and as charge breeders for the same purpose for a long period. The physical principles of these devices are rather well-studied although there are still numerous unexplained experimental observations related to their plasmas. A long-standing inexplicable observation has been the ms-scale oscillation of the extracted ion beam current. [1, 2, 3]. These perturbations are especially harmful for applications of high performance ion sources requiring supreme temporal stability. The magnetic field of modern ECRISs [4] is a superposition of solenoid and sextupole fields. The resulting minimum-B topology provides a closed ECR surface for efficient resonant energy transfer from microwaves to the plasma electrons, enables sufficient plasma confinement for the step-wise ionization of high charge states, and suppresses magneto-hydrodynamic instabilities. The electron energy distribution resulting from the resonant heating and long confinement time of energetic electrons is strongly anisotropic and is considered to consist of (at least) two main populations: cold (and warm) electrons with an average energy of $E_{e,cold}$ = 10 eV–10 keV and hot electrons with $E_{e,hot}$ > 10 keV up to 1 MeV. Such non-equilibrium plasmas are prone to kinetic instabilities driven by warm and hot electrons whose transverse (with respect to the external magnetic field) velocity dominates over the longitudinal velocity [5]. It has been proven that the kinetic instabilities of cyclotron type are the reason for the periodic oscillation of the extracted beam current with a maximum amplitude of several tens of percent [6, 7] and simultaneous powerful bursts of microwave and x-ray radiation. It has been shown that the cyclotron instabilities lead to significant electron losses and subsequent increase of the plasma potential perturbing the ion confinement [8] at temporal interval which is less than the production time of high charge state ions. Since the microwave power and the magnetic field strength are the main parameters determining the threshold for the instabilities, it implies that further increase of those, being probably the most common brute force method of improving ECRIS performance, will not be successful without suppressing the instabilities. An inevitable feature of the cyclotron instability is the

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emission of electromagnetic (EM) radiation due to resonant amplification of plasma waves as a result of nonlinear interaction with “hot” electrons. The microwave emission during the onset of the cyclotron instability has been thoroughly studied in various experiments of ECR-heated plasmas in a simple mirror and minimum-B traps [5].

The present paper is devoted to investigations of microwave emission pattern induced by kinetic instabilities under two-frequency heating of ECRIS plasmas. Two-frequency heating was first introduced in 1990s [9] and is widely used in modern ECRISs. The essence of the method lies in the injection of lower frequency (and usually lower power) microwaves in addition to the primary microwave radiation into the ECRIS plasma. Such technique allows increasing the average charge and current of the extracted ion beam in comparison to single frequency heating (even) at the same level of total injected microwave power. A common interpretation of the effect is based on a volumetric effect, i.e., enlargement of the volume of efficient power absorption, which is believed to enhance the ionization efficiency due to increased density of hot electrons, and improved electron confinement. However, recent investigations on two-frequency heating mode have suggested another hypothesis explaining its impact on ECRIS performance, which might be connected with suppression of cyclotron instabilities [10].

EXPERIMENTAL SETUP

The experimental data were taken with the room-temperature AECR-U type JYFL 14 GHz ECRIS 14 operating with oxygen. The magnetic field of the ion source is generated by two solenoid coils and a permanent magnet sextupole. The injection and extraction mirror ratios as well as the B_{min} (magnetic field in the trap center) can be adjusted (not independently however) by varying the coil currents. The primary microwave power at 14.085 GHz frequency is provided by a klystron amplifier and launched into the plasma chamber (R = 39 mm, L = 270 mm) through WR62 waveguide port. The secondary power at tunable 10.75 GHz–12.4 GHz frequency is provided by a traveling wave tube amplifier (TWTA) and launched into the plasma chamber through the same WR62 waveguide port using a magic tee (see Fig. 1) for this experiment. The maximum powers of the klystron and the TWTA were limited to 600 W and 200 W, respectively. Such values correspond to a normal operating range of the JYFL 14 GHz ECRIS in which the two-frequency heating typically enhances the extracted beam currents of highly charged ions, e.g., Kr^{25+} and Xe^{30+}, by a factor of 2–5. Frequencies emitted by the plasma were measured through a WR-75 waveguide port incorporated into the injection iron plug and normally connected to the TWTA. The emitted microwave signal was guided into an oscilloscope through WR-75 waveguide, vacuum window, 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 microwave pulses emitted by the plasma with a temporal resolution of 12.5 ps. The microwave signal fed directly to the input channel of the oscilloscope through the attenuator and limiter was used to trigger the high sampling rate data acquisition of the microwave signal waveform. The experimental setup is described thoroughly in Ref. [10].

RESULTS

Figure 1(a) presents typical spectrograms of microwave signals recorded during a single instability event. The duration of the microwave emission in the given example is approximately 5 μs. The data were taken with oxygen plasma, at $4*10^{-7}$ mbar and 600 W of injected microwave power at 14 GHz frequency, and 100 W at 12.45 GHz. Similar to previous experiments, the emitted microwave signal was observed to consist of discrete packets having a temporally falling tone in 8-26 GHz range lasting typically 100–1500 ns and separated by some hundreds of ns. Their relative magnitudes and temporal separations were observed to depend on the ion source settings, i.e., magnetic field strength and microwave power.

The Figure 1(b) shows a number of Fourier spectrums of microwave emission for different combinations of power combinations. The frequencies of the main emission lines do not change with the heating power distribution. However, the emission power distribution over the spectrum is affected by the heating power distribution. Moreover, it can be noted that the main emission lines are the same as in the case of single frequency heating reported before [5]. In the case of 14 GHz wave power within 300-550 W and 12.45 GHz wave at 200 W no emission was found, which is consistent with the observed parametric space of two-frequency stabilization [10].

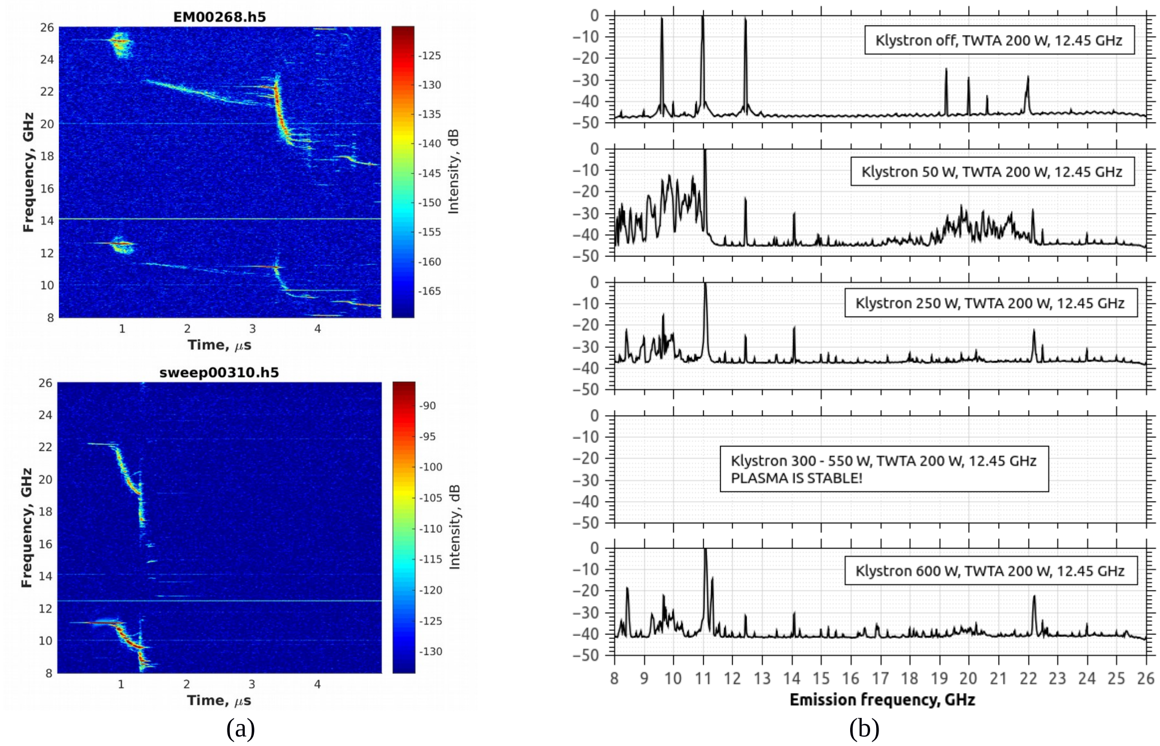

FIGURE 2. Typical spectrograms of microwave bursts (a) and the microwave emission spectra for different heating power distributions (b).

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REFERENCES

1. V. Toivanen, O. Tarvainen, J. Komppula, and H. Koivisto, J. Instrum. **8**, T02005 (2013).
2. G. S. Taki, P. R. Sarma, R. K. Bhandari, A. G. Drentje, T. Nakagawa, and P. K. Ray, in Proceedings of the APAC07, TUPMA116, Indore, India (2007).
3. B. P. Cluggish, L. Zhao, and J.-S. Kim, Nucl. Instrum. Methods Phys. Res., A **631**, 111 – 120 (2011).
4. D. Leitner, C. M. Lyneis, S. R. Abbott, D. Collins, R. D. Dwinell, M. L. Galloway, M. Leitner, and D. S. Todd, Nucl. Instrum. Methods B **235**, 486 (2005).
5. I. Izotov, T. Kalvas, H. Koivisto, R. Kronholm, D. Mansfeld, V. Skalyga, and O. Tarvainen. Physics of Plasmas **24**, 043515 (2017).
6. O. Tarvainen, I. Izotov, D. Mansfeld, V. Skalyga, S. Golubev, T. Kalvas, H. Koivisto, J. Komppula, R. Kronholm, J. Laulainen, and V. Toivanen, Plasma Sources Sci. Technol. **23**, 025020 (2014).
7. O. Tarvainen, J. Laulainen, J. Komppula, R. Kronholm, T. Kalvas, H. Koivisto, I. Izotov, D. Mansfeld, and V. Skalyga, Rev. Sci. Instrum. **86**, 023301 (2015).
8. O. Tarvainen, T. Kalvas, H. Koivisto, J. Komppula, R. Kronholm, J. Laulainen, I. Izotov, D. Mansfeld, V. Skalyga, V. Toivanen, and G. Machicoane, Rev. Sci. Instrum. **87**, 02A703 (2016).
9. Z. Q. Xie and C. M. Lyneis, in Proceeding of 12th International Workshop on ECR Ion Sources, Riken (RIKEN, Institute for Nuclear Study, Japan, 1995), p. 24.
10. V. Skalyga, I. Izotov, T. Kalvas, H. Koivisto, J. Komppula, R. Kronholm, J. Laulainen, D. Mansfeld, and O. Tarvainen. Physics of Plasmas **22**, 083509 (2015).