Dynamic regimes of cyclotron instability in the afterglow mode of minimum-$B$ electron cyclotron resonance ion source plasma

D Mansfeld$^1$, I Izotov$^{1,2}$, V Skalyga$^{1,2}$, O Tarvainen$^3$, T Kalvas$^3$, H Koivisto$^3$, J Komppula$^3$, R Kronholm$^3$ and J Laulainen$^3$

$^1$ Institute of Applied Physics of Russian Academy of Sciences, 46 Ulyanova st., Nizhny Novgorod, Russia
$^2$ Lobachevsky State University of Nizhny Novgorod (UNN), 23 Gagarina st., Nizhny Novgorod, Russia
$^3$ Department of Physics, University of Jyväskylä, Jyväskylä, Finland

E-mail: mda1981@appl.sci-nnov.ru

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Abstract
The paper is concerned with the dynamic regimes of cyclotron instabilities in non-equilibrium plasma of a minimum-$B$ electron cyclotron resonance ion source operated in pulsed mode. The instability appears in decaying ion source plasma shortly (1–10 ms) after switching off the microwave radiation of the klystron, and manifests itself in the form of powerful pulses of electromagnetic emission associated with precipitation of high-energy electrons along the magnetic field lines. Recently it was shown that this plasma instability causes perturbations of the extracted ion current, which limits the performance of the ion source and generates strong bursts of bremsstrahlung emission. In this article we present time-resolved diagnostics of electromagnetic emission bursts related to cyclotron instability in the decaying plasma. The temporal resolution is sufficient to study the fine structure of the dynamic spectra of the electromagnetic emission at different operating regimes of the ion source. It was found that at different values of magnetic field and heating power the dynamic spectra demonstrate common features: Decreasing frequency from burst to burst and an always falling tone during a single burst of instability. The analysis has shown that the instability is driven by the resonant interaction of hot electrons, distributed between the electron cyclotron resonance (ECR) zone and the trap center, with slow extraordinary wave propagation quasi-parallel with respect to the external magnetic field.

Keywords: cyclotron instability, afterglow discharge, microwave emission, plasma diagnostics, electron cyclotron resonance ion source, Z-mode emission

(Some figures may appear in colour only in the online journal)

1. Introduction
Microwave plasma discharges are extensively used in various branches of plasma technology, such as thin-film deposition, plasma etching, surface ion treatment and sputtering, sources of positive and negative ion beams, etc. A significant part of these discharges operates at low gas pressure with the plasma being heated through electron cyclotron resonance (ECR) and confined magnetically, e.g. in toroidal devices [1] and gas-dynamic traps [2]. The electromagnetic emission from ECR-heated (International Thermonuclear Experimental Reactor) ITER-like high temperature plasmas is used for imaging systems with spatial resolution [3], for example.

A specific feature of ECR heating is that the energy of the external source is mostly embedded in the transverse momentum of the electrons, thereby forming a positive gradient in the electron velocity distribution. Resonant interaction between the energetic strongly anisotropic electrons and
the electromagnetic waves makes the plasma prone to kinetic cyclotron instabilities, which manifest themselves as a generation of powerful electromagnetic radiation and bursts of energetic electrons from the magnetic trap. Studies of cyclotron instabilities in magnetically trapped laboratory plasmas have a long history, but they still remain topical, mostly with the advent of powerful sources of microwave radiation (especially, gyrotrons), which allow a sufficient increase in the energy input into the plasma, thereby increasing the energies and anisotropy of the non-equilibrium resonant particles. Cyclotron instability is an important channel for the loss of the excess energy stored by the electrons [4], hence limiting the range of achievable plasma parameters. For example, in modern ECR sources, which are widely used as injectors of heavy multi-charged ions into accelerators, the precipitation of particles due to instabilities significantly modifies the energy distribution function of the hot electrons and charge state distribution of the ions, thus limiting the average charge state of the extracted ion beams [5].

This paper is devoted to studying the dynamic regimes of cyclotron instabilities in a non-equilibrium plasma of a minimum-$B$ magnetic field configuration electron cyclotron resonance ion source operated in pulsed mode. The production of intense ion beams in so-called ‘afterglow’ mode is of significant interest since it allows the achievement of pulsed ion currents substantially higher than those during continuous (cw) operation [6, 7]. It is worth noting that all heavy ion experiments in the large hadron collider (LHC) at CERN are based on ion beams ($\text{Pb}^{27+}$) extracted from an ECR ion source operating in the afterglow mode [8]. The afterglow occurs when the microwave generator is switched off and the plasma begins to decay. The confinement time of cold, collisional electrons is shorter than the confinement time of relativistic hot electrons. Thus, the anisotropy of the electron velocity distribution function (EVDF) increases during the afterglow transient. The energy, which is stored mostly by hot electrons [9], is rapidly released in the form of particle losses and electromagnetic radiation in optical, microwave, and x-ray bands. Various types of instabilities can arise during the plasma decay, causing undesirable perturbations of the plasma parameters. The observed oscillations of the extracted ion current during the plasma decay were recently associated with a cyclotron instability driven by the resonant interaction of plasma waves with the hot electron component of the anisotropic velocity distribution [10]. In this article we study the fine structure of the dynamic spectra of electromagnetic emission bursts related to the cyclotron instability in the decaying plasma of a minimum-$B$ magnetic configuration electron cyclotron resonance ion source (ECRIS). The research results can also be applied to understanding the primary mechanisms of cyclotron instabilities of the same origin, e.g. the most powerful electromagnetic emission in the Earth’s magnetosphere (auroral kilometric radiations [11], very low frequency–extremely low frequency (VLF–ELF) emission) and other planets (e.g. Jovian decametric radiation [12]).

Bursts of energetic electrons and electromagnetic emission related to cyclotron instabilities of extraordinary waves propagating in a direction perpendicular to the magnetic field were studied earlier in the decaying plasma of an ECR discharge confined in a mirror axisymmetric magnetic trap [13, 14]. The nonlinear instability growth phase was explained in terms of a cyclotron maser model [15]. A new source of powerful THz radiation (based on the model) in which the plasma serves as a non-linear trigger element was then proposed [16]. A new regime of electron cyclotron instability aimed at explaining
the complex temporal patterns of the detected electromagnetic radiation observed in decaying plasma was discussed in [17].

Detailed investigations of the temporal frequency characteristics of the electromagnetic radiation generated during the plasma relaxation in an adiabatic magnetic trap have shown that the cyclotron instability occurs near the electron cyclotron frequency or its second harmonic [18]. The experimental challenge is that the dynamic spectra of short (tens of nanoseconds) electromagnetic pulses is rather wide, because the resonant electrons do not have a monoenergetic distribution and the region of wave–particle interaction is usually spread in a non-uniform magnetic field, which affects the local relativistic electron cyclotron frequency. Studying the fine structure of the dynamic spectra of the electromagnetic emission has become possible only recently with the advent of methods for measuring the electromagnetic field with high temporal resolution. The first experimental data on the dynamic spectra of five different types of kinetic instabilities in various conditions of ECR discharge plasma were obtained using this method [19]. The analysis of the recorded electromagnetic spectra presented in this paper allowed us to determine the most probable electromagnetic mode that is excited due to instability in the minimum-$B$ field configuration.

2. Experimental setup

The experimental data were taken with a room-temperature A-ECR-U-type JYFL 14 GHz ECRIS [20]. A schematic figure of the ECRIS and the experimental setup is shown in figure 1. The plasma was heated by 100–600W of microwave power of a klystron amplifier at a frequency of 14 GHz.
klystron was operated in a pulsed mode by controlling the low-power input signal from an oscillator with a fast radio frequency (RF)-switch. The magnetic field of the ion source is generated by two solenoid coils and a permanent magnet sextupole resulting in a so-called minimum-$B$ field configuration. The minimum value of the magnetic field ($B_{\text{min}}$) is achieved on the axis of the ion source in between the solenoid coils in the axial direction. On the other hand, the resonance condition for (non-relativistic) electron heating, i.e. $2\pi f_{\text{res}} = \frac{eB_{\text{ECR}}}{mc}$ ($f_{\text{res}}$ is the heating frequency, $c$ is the speed of light in vacuum, and $e$ and $m$ are the electron charge and mass, respectively), is satisfied on a closed (nearly) ellipsoidal surface with a constant magnetic field of $B_{\text{ECR}} = 0.5$ 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 $B_{\text{min}}/B_{\text{ECR}}$. The ion source was operated in the range of 0.68 < $B_{\text{min}}/B_{\text{ECR}}$ < 0.81. 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 [21]. A three-dimensional (3D) plot of the magnetic field lines depicting the position of the resonance surface is shown in figure 2(a), while figure 2(b) shows the magnetic field strength on the axis. A complete description of the magnetic field profile can be found in [10].

Argon plasmas in the pressure range of 1.2 · 10^{-7} to 1.6 · 10^{-6} 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 electron cyclotron instabilities were indirectly detected with a bismuth germanate (BGO) scintillator coupled with a Na-doped CsI photomultiplier tube (PMT) with < 4 μs resolution, as described in the previous work [5]. The detector is sensitive to variations of the bremsstrahlung power flux, i.e. bursts of wall bremsstrahlung generated by energetic electrons, which are expelled from the magnetic trap in ~10 μs bursts as a result of the instability. The leading edge of these bremsstrahlung bursts is coincident with the microwave emission, and can thus be considered as a fingerprint of the cyclotron instability. The plasma microwave emission was measured through a WR-75 waveguide port incorporated into the injection iron plug, and normally used for the injection of microwave power at a secondary frequency in two-frequency heating mode. The emitted microwave signal was guided into a Tektronix MSO 72504 DX oscilloscope through a WR-75 waveguide, high voltage break, waveguide-to-coaxial transition, power limiter, and tunable attenuator. The features of the oscilloscope, a 100 Gs s^{-1} sampling rate and a 25 GHz bandwidth, allowed the direct recording of the waveforms of the electromagnetic field emitted by the plasma with a temporal resolution of 20ps. The frequency response of the WR-75 waveguide and waveguide-to-coaxial transition was measured to be flat in the range of 8–15 GHz. The WR62 port was used for launching the 14 GHz microwave radiation.

The investigations were performed in decaying plasma after switching off the microwave signal klystron. The trailing edge of the transistor-transistor logic (TTL) signal controlling the RF-switch was used to trigger the oscilloscope for the high sampling rate acquisition of the microwave signal waveform.

3. Experimental results

Figure 3 presents the typical waveforms of the microwave electric field (upper curve) and bremsstrahlung (lower curve) signals recorded during the plasma decay. The data were taken in the afterglow of a plasma discharge, initially sustained by 600 W of injected microwave power at 2.1 · 10^{-7} mbar of argon and $B_{\text{min}}/B_{\text{ECR}} = 0.75$. The microwave bursts usually appear at 1–4 ms after the 14 GHz microwave signal is switched off, and consist of a sequence of pulses lasting typically 0.1–1.5 μs, with intervals of 1–10 ms. The bremsstrahlung power flux signal, which is attributed to the precipitation of hot electrons from the trap, consists of a sequence of peaks lasting for some tens of μs. Although the temporal resolution of the current-mode x-ray detector is not sufficient to detect variations in the bremsstrahlung signal at the level of 100 ns, it is evident that the leading edge of each x-ray pulse is perfectly coincident with the microwave emission packets.

Figure 4 shows dynamic spectrograms of the microwave bursts, subsequently emitted during the plasma decay at 1.2 ms (figure 4(a)), 2.96 ms (figure 4(b)), and 9.62 ms (figure 4(c)) following the trailing edge of the 14 GHz microwave pulse. The signal was treated with a Goertzel algorithm to build the spectral power density in each time domain in the range of 8–15 GHz with 10 MHz steps (the spectral power density of the signal is indicated with a false color). The horizontal line at 12.50 GHz is an artefact related to the sampling rate of the oscilloscope and subsequent analysis of the data. The emission of the first pulse starts at a frequency of 12.2 GHz and ends after 1 μs at 10.95 GHz, the second pulse lasts for 0.35 μs with the frequency decreasing from 11.25 GHz to 10.3 GHz. The third 0.1 μs pulse starts at 10.3 GHz and ends at 9.7 GHz. In other words, the frequency range of each wave packet is consistently lower in comparison with the preceding one. The dynamic spectrum of each pulse typically descends in frequency, whereas the rate of frequency drift is increased with each consecutive pulse. However, in some cases the last pulse in the described sequence exhibits quasi-monochromatic narrow-banded harmonics, as shown in figure 5.

The range of emission frequencies (12.2–9.7 GHz) during the plasma decay is comparable to the range of electron cyclotron frequencies between $B_{\text{ECR}}$ (0.5 T) and $B_{\text{min}}$ (0.41 T) at the trap center, i.e. 14–11.5 GHz. It is worth noting that a significant part of the microwave signal is emitted at frequencies below the cyclotron frequency at the trap center (11.5 GHz), which indicates that the wave–particle interaction can occur at Doppler shifted relativistic cyclotron resonance ($\omega = \omega_{\text{cycl}}\sqrt{1 - \frac{k_{\|}^2}{c^2}} - k_{\perp}$) where $\nu_{\text{cycl}} = \sqrt{\nu^2 + \nu^2}$ is the velocity of the hot electrons, $\nu_{\perp}$ and $\nu_{\parallel}$ are the longitudinal and transversal (with respect to the magnetic field) velocity components, and $k_{\parallel}$ is the longitudinal wavenumber.

The maximum amplitude of the microwave signal varies from 60 to 100 mV with −30 dB attenuation. Taking into account the input impedance of 50 ohm yields 70–200 mW peak power for the measured instability signals coupled to the waveguide. Unfortunately, the frequency-dependent coupling efficiency into the WR75-port, as well as the total power
reflected from the plasma are unknown, so only very rough estimates of emitted power can be made. Assuming that the radiation is emitted into a $4\pi$ solid angle and is measured at a distance of ~10 cm, i.e. the distance between the trap center and the entrance to the WR-75 waveguide, the upper limit of the microwave power can be estimated to be 70–200 W.

It was found that at different ion source settings ($B$-field strength, neutral gas pressure, and 14 GHz microwave power) the dynamic spectra demonstrate certain common features: (i) Decreasing frequency from burst to burst and (ii) a falling tone during a single instability burst.

The dependencies of the initial and final frequency of the first instability pulse on magnetic field and power, and the same dependence on the power for the second pulse are presented in figures 6(a) and (b). It can be seen from both figures that the initial frequency of the first instability pulse grows with the increase in magnetic field and power, while the final frequency saturates at high values of magnetic field and power. The initial frequency of the second pulse mostly depends on the value of the frequency of the first pulse, slightly overlapping it. The ending frequency of the second instability pulse has a maximum power of 400 W.

The magnetic field strength and heating power significantly affect the delay between switching off the klystron power and the appearance of the first instability pulse, as well as the number of instability events during the afterglow. The dependence of the delay between switching off the klystron and the appearance of the instability on the magnetic field strength and plasma heating power are shown in figures 7(a) and (b). The delay between the microwave switching off and the first instability event decreases monotonically on increasing the magnetic field strength, while the dependence on the heating power shows threshold-like dynamics being rather insensitive to power above 300 W. These observations can be explained by the fact that the instability growth rate depends on the density and anisotropy of the hot electrons, which are greatly increased at low gradients of magnetic field (corresponding to high $B_{\text{min}}/B_{\text{ECR}}$) and high power, as discussed in [10].

4. Discussion

The observed precipitation of energetic electrons from the trap and the generation of microwave bursts are inherently related to the excitation of electromagnetic waves due to cyclotron instabilities. The electron energy distribution function in the steady state of ECRIS plasmas is considered to consist of three main fractions: Cold (non-relativistic) electrons with an average energy $<E_{\text{cold}}>$ of 10–100 eV, warm electrons with $<E_{\text{warm}}>$ of 1–10 keV, and hot electrons with $<E_{\text{hot}}>$ > 10 keV up to 1 MeV [22, 23]. The dense (cold and warm) plasma component determines the dispersion relation and damping of the propagating waves, which can resonantly interact with the energetic electrons. Kinetic cyclotron instabilities are driven by the warm and hot electrons with an anisotropic velocity distribution, in which the transverse velocity (with respect to the external magnetic field) is considerably higher than the longitudinal velocity. The interaction between the high-frequency waves and resonant electrons leads to the rapid diffusion of the energetic electrons in the velocity space. These electrons are eventually expelled into the loss cone and precipitated from the trap.

The most important plasma parameter that greatly affects the dispersion and polarization properties of the excited waves is the plasma density of cold and warm electrons. The density was not measured in the present afterglow experiment, but can be estimated from well-known parameters of steady-state ECRIS plasma discharge. Experiments [22, 24] and simulations [25, 26] on ECRIS plasmas sustained by 14–18 GHz microwave radiation imply that their electron density, $n_e$, is below $10^{12}$ cm$^{-3}$ as a maximum, i.e. well below the critical density of $2.4 \times 10^{12}$ cm$^{-3}$. Since the electron plasma frequency, $f_{\text{pe}}$, is proportional to the electron density as $f_{\text{pe}} \propto n_e^{1/2}$, the maximum plasma frequency can be expected to be on the order of 9 GHz in the steady state. A certain freedom in the estimates of the plasma density is completely leveled by the fact that the experiments described in the present
paper were made in the decaying plasma of ECR discharge, and if plasma density was at a critical value for 14 GHz ($2.4 \cdot 10^{12}$ cm$^{-3}$) then at the moment of instability (1–4 ms after switching off the heating generator) the plasma density would be significantly lower. As soon as the microwave power is switched off the plasma begins to decay with different lifetimes for cold, warm, and hot electron components. Cold electrons have the shortest confinement time of some tens of microseconds and rapidly leave the magnetic trap long before the appearance of the instabilities. The warm electron component has a characteristic lifetime of 1 to 20 ms, as indicated by the bremsstrahlung measurements [27], and thus does not decay completely due to the onset of the instability, thereby determining the propagation of excited waves in the plasma.

Figure 4. (a)–(c) Dynamic spectrograms of three instability microwave pulses. The data are acquired with 400 W of injected microwave power at $2.1 \cdot 10^{-7}$ mbar of argon and $B_{\text{mid}}/B_{\text{ECR}} = 0.8$. 
The hot electrons are well confined in the magnetic trap for more than a second [28], and are believed to be responsible for the instabilities. The hot electrons bounce between the mirror points inside the magnetic trap implying that the maximum anisotropy \( v^2 / \nu^2 \gg v^2 \) of the EVDF is achieved at their reflection points resulting in enhanced amplification of the excited wave at these locations.

Let us define the mode of the excited wave in the afterglow using the experimental data together with the parameters of the ECRIS plasma and taking into account the dispersion relation for the warm electron component. We can neglect the contribution of thermal effects if we do not consider the exact cyclotron resonance condition, i.e. \( k|\mu| \ll \omega - \omega_{ce} \). The most evident influence of thermal corrections can be observed in the shift of the cut-off point of the dispersion relation, which allows the fast extraordinary waves to escape from the rarefied plasma [29]. Being quite typical for space plasma, this specific case could hardly be realized in the present experimental conditions.

The range of (cold) electron gyrofrequencies, \( f_{ce} = \omega_{ce}/2\pi \), is defined by the magnetic field configuration. Instabilities are observed when \( B_{\text{min}}/B_{\text{ECR}} > 0.75 \), i.e. \( B_{\text{min}} > 0.375 \) T, which implies that \( f_{ce} > 10.5 \) GHz in the whole plasma volume. Thus, it can be expected that in the experiments described here the condition \( f_{ce} > f_{pe} \) is always satisfied with \( n_e < 10^{12} \) cm\(^{-3}\).
The range of measured emission frequencies (9–12.5 GHz) during the instability corresponds to several scenarios of wave modes with right-hand polarization and effective interaction with the electrons.

Quasi-transversal (with respect to the external B-field) fast (X-) or slow (Z-) extraordinary modes can be excited in rarefied plasmas \([16, 30]\) when \(f_{pe}/f_{ce} < \beta = \langle v_{hot} \rangle / c\), where \(\langle v_{hot} \rangle\) is the average velocity of the hot electrons interacting with the excited wave and \(c\) is the (vacuum) speed of light. Such transverse modes are excluded at the initial stage of the afterglow (<10 ms) because in our experiment \(f_{pe}/f_{ce}\) is not significantly less than 0.2–0.5, which is the approximate range of \(\beta\) (10–60 keV electrons). Furthermore, the X-mode waves are excited at frequencies \(f > f_{ce} + f_{pe}^2/f_{ce}\), which is in contradiction to the observed emission below the minimum electron cyclotron frequency of cold electrons. Another argument against the afore-mentioned transverse modes comes from the falling tones of the dynamic spectrum of the microwave bursts. The discussed condition for right-hand polarized extraordinary mode should be first fulfilled for more energetic electrons corresponding to a lower (relativistic) electron cyclotron frequency, and thus should result in rising frequency tones as \(f = f_{ce} \sqrt{1 - \beta^2}\). Hence, only quasi-longitudinal modes will be considered hereafter.

Figure 8 shows the refraction index for waves with quasi-longitudinal (angle between wave vector and magnetic field, \(k^\parallel B = 5^\circ\)) propagation for \(f_{pe} = 6\) GHz \((n_e = 4.4 \times 10^{11}\) cm\(^{-3}\), which corresponds roughly to the assumed plasma density at the moment of the first instability event) and \(f_{ce} = 14\) GHz (which corresponds to the assumed spatial location of the maximum anisotropy of the hot electrons, i.e. \(B = B_{ECR}\)). The following conclusions are not sensitive to the choice of specific value of the plasma density, which has been used for illustration purposes. The whistler branch of the ordinary mode can be excited at frequencies \(f < f_{pe} < f_{ce}\), while the most effective excitation occurs near plasma resonance \(f = f_{pe}\). Thus, the frequency of the whistlers should strongly depend on the plasma density \([31]\), which is affected by the microwave power and neutral gas density (confirmed by the total extracted current). However, the plasma emission characteristics (frequencies) were experimentally demonstrated to be independent of the plasma parameters, and thus the excitation of the whistlers is considered improbable. Additional evidence against the whistlers comes from the fast sweeping tones of the dynamic spectrum of the electromagnetic signal: The frequency drops by 1–2 GHz for a few microseconds, which is too rapid to be explained by plasma density variations during the decay.

The most probable excited wave is the slow extraordinary Z-mode propagating quasi-longitudinally with respect to the external magnetic field. Such waves are excited with frequencies of \(f_{pe} < f < f_{ce}\), which matches the experimental conditions. In comparison to the whistlers, the refractive index of this mode does not approach infinity at \(f_{pe}\), which allows the wave to propagate through \(f = f_{pe}\) from the dense plasma into the vacuum. The dependence of the group velocity of the quasi-longitudinal mode on the plasma density is presented in figure 9. The group velocity \(V_g\) decreases with the growth of the plasma density, and becomes significantly less than the speed of light in a vacuum. This remarkable property favors the effective amplification of parallel Z-mode, in comparison with, for example, the transverse Z-mode, whose group velocity is close to \(c\) in rarefied plasma, since the interaction time with resonant electrons is greatly increased. Thus, the averaged exponential growth rate: \(G = \int_{-L/2}^{L/2} \gamma d\xi \approx \gamma L/V_g\) \((\gamma\) is the linear instability growth rate and \(L\) is the length of the interaction path\), which determines the total amplification of the wave on the interaction path, can become rather high even at small values of \(\gamma\). Moreover, at high plasma density even
during one pass through the interaction region can the wave gain enough energy to expel energetic electrons from the trap. In other words, for quasi-longitudinal Z-mode in dense plasma there is no need for multi-pass propagation in a resonator-like structure, which is quite typical for transverse modes [13] and whistlers [31].

All the previous conclusions were made under the assumption of uniform plasma distribution in the trap. However, the spatial distribution of plasma density in a magnetic trap of every ECRIS is non-uniform and should be taken into account when considering plasma instabilities. In our experiments we cannot measure the electron density profile inside the magnetic trap without disturbing the plasma (e.g. with Langmuir probes). Also, there is a lack of experimental information about density gradients in the papers of other ECR teams. However, the most encouraging conclusions about electron and ion density distributions both in the radial and axial directions in a hexapole trap can be made from the results of particle-in-cell (PIC) simulations [26]. In the transverse direction to the magnetic field the plasma is strongly non-uniform: The density gradients are more than $10^{12}$ cm$^{-3}$ per cm. On the other hand, the electron density profile in the axial direction is much smoother: It is completely uniform at a distance of more than half of the trap, gradually decreasing when approaching the extraction and injection sides of the source. The electromagnetic waves are excited in the frequency range of about 8–12 GHz, which corresponds to the range of the wavelength in a vacuum 2.5–3.7 cm. Taking into account the refraction index for Z-mode of about 2, the wavelength of the excited waves in plasma is about 1.2–1.8 cm. So, the non-uniformity of ECRIS
plasma (also as the strong non-uniformity of the magnetic field) in the transverse direction should be considered for the waves propagating in the transverse direction. But the propagation of the quasi-longitudinal Z-mode waves, which are being discussed in the present paper, would not be affected by small variations in the plasma density in the axial direction.

A detailed study of the growth rates and frequency spectrum of the cyclotron instability of Z-mode at small propagation angles was performed in [30]. The maximum growth rate of the longitudinal Z-mode is:

\[ \gamma_{\text{max}} = \frac{f_{\text{pe,hot}}^2}{f_{\text{ce}}} 2\sqrt{\pi} y (2by - 3) \exp(-y) \]  

where \( f_{\text{pe,hot}} \) is the plasma frequency of hot electrons, \( b = 1 - \frac{\beta^2}{f_{\text{ce}}} \beta = \frac{E_{\text{hot}}}{mc^2} \), \( E_{\text{hot}} \) is the energy of hot electrons, and \( y \) is derived from the following expression determining the optimal emission frequency \( f_{\text{opt}} \), which corresponds to the maximum growth rate:

\[ y = \frac{2}{\beta^2} \left( \frac{f_{\text{ce}}}{f_{\text{opt}}} - 1 \right) = \frac{5b + 3}{4b} + \sqrt{(\frac{5b + 3}{4b})^2 - \frac{9}{4b}} \]  

These formulae were obtained for the loss-cone distribution of hot electrons at the limit of maximum anisotropy, and can thus be applied for qualitative estimates of optimal frequency and the maximum growth rate of cyclotron instability in ECRIS plasma.

The dependencies of \( f_{\text{opt}} \) on the plasma density at different electron cyclotron frequencies (\( f_{\text{ce}} = 10, 12, 14 \) GHz) for a fixed energy of hot electrons (\( E_{\text{hot}} = 30 \) keV) and on the electron cyclotron frequency for a fixed plasma frequency (\( f_{\text{pe}} = 9 \) GHz) for three different values of hot electron energy (\( E_{\text{hot}} = 30, 60, 90 \) keV) are presented in figures 10 and 11 respectively. Optimal emission frequency \( f_{\text{opt}} \) depends only weakly on the plasma density (\( f_{\text{pe}} \)), but is mostly affected by the local electron cyclotron frequency and the average energy of the hot electron population interacting with the wave. It can be clearly seen from the figures that \( f_{\text{opt}} \) decreases both by increasing the hot electron energy, and by decreasing the magnetic field (\( f_{\text{ce}} \)).

The range of the plasma density for the most effective amplification of the quasi-longitudinal slow extraordinary wave is limited by the polarization properties. At high plasma density, i.e. \( f_{\text{opt}} < f_{\text{pe}} \), the interaction with the electrons is weakened due to the left-handed polarization of the wave [32]. At low plasma density or higher electron energies, i.e. \( f_{\text{pe}}/f_{\text{ce}} < \beta \), the amplification of the longitudinal waves is not effective due to relativistic effects, and the excitation of the transverse extraordinary modes is favored [30].

Based on the listed (basic) properties of the quasi-longitudinal Z-mode a scenario of cyclotron instability in decaying plasma, which explains the main features of the electromagnetic emission spectrum, can be deduced. Let us assume that during the stochastic heating stage of the ECR discharge the hot electron population is distributed axially between the center of the trap and the ECR surface. Since the maximum anisotropy is achieved near the local reflection point of the bouncing electrons (\( \psi_1 = 0 \) at the mirror point), it can be argued that the most effective interaction is initiated near the cold electron cyclotron frequency \( f_{\text{ce}} = f_{\text{mw}} = 14 \) GHz. The increase in the frequency of the first pulse with increasing the magnetic field and power (figures 6(a) and (b)) may be explained by the shift in the maximum density of the hot particles towards the ECR surface. However, the conditions for Z-mode wave excitation are not fulfilled immediately after switching off the microwave power as the plasma density should decay enough to reach \( f > f_{\text{pe}} \) for right-handed polarization. We suppose that the reason for the delay is related to the rather high hot electron energy, which causes the optimum emission frequency to shift lower. Thus, the moment of the appearance of the first electromagnetic pulse is determined by the characteristic lifetime of the cold (warm) electron component.

The wave begins to propagate towards the descending magnetic field and is amplified by the hot electrons distributed between the ECR zone and the center of the magnetic trap. The decrease in the local electron gyrofrequency results
in the falling spectral tone of the electromagnetic emission. The non-linear dynamics of the wave–particle interaction can be qualitatively described by the following equations for the hot electron density $N_h$ and the electromagnetic energy density $E_w$ [13, 33, 34]:

$$\frac{dN_h}{dt} = -\alpha E_w N_h$$
$$\frac{dE_w}{dt} = \hbar E_w N_h - \nu E_w$$

(3)

The first equation describes the losses of hot electrons induced by the high-frequency field (the $\alpha$ parameter characterizes the particle losses) and the second equation describes the field growth or decay, depending on the growth ($h = \gamma/N_h$) and damping ($\nu = \tau_\text{el} - \text{electron collision}$) rates. Using equation (1) for the range of plasma frequencies $f_{pe} = 6–9$ GHz, $f_{ce} = 14$ GHz, $E_h = 30$ keV gives an estimated maximum growth rate of $(0.07–0.09)N_h$. Taking the density of the hot electron population of about $\sim 10^9$–$10^9$ cm$^{-3}$ will result in $\gamma_{\text{max}} \approx 10^7 \div 10^8$ s$^{-1}$, which is the same order with the estimation of the growth rate roughly deduced from the experimentally observed pulse duration ($\gamma_0 \sim \tau^{-1}$, $\tau \approx 10 - 1000$ ns) at the initial (linear: $E \sim e^\gamma$) stage of the cyclotron instability. Thus, the growth rate significantly exceeds the damping rate ($\nu \sim 10^2$ s$^{-1}$). As soon as the instability growth rate is proportional to the density of the hot electrons (see formula (1)) the dynamics of the instability will be determined solely by the losses of hot electrons into the loss-cone. In other words, if the conditions for the excitation of quasi-longitudinal Z-mode are fulfilled ($f_{\text{opt}} > f_{pe}$), the instability will last until the damping rate exceeds the growth rate. This conclusion is supported by the saturation of the final frequency of the first instability pulse (figures 6(a) and (b)).

Besides the hot electron losses the electromagnetic pulse can stop due to modifications in the polarization properties of the wave. This interpretation is supported by the fact that
the decrease in the emission frequency is much faster than the decay of the warm plasma component, i.e. the system can go below the threshold due to the left-handed polarization of the extraordinary mode at $f_{\text{opt}} < f_{pe}$. The (down)shift of the emission frequency is caused by decreasing the local relativistic electron cyclotron frequency, which can occur due to the previously discussed shifting of the interaction region to a lower magnetic field. Another possible option is related to the reduction of $f_{\text{ce}}$ due to the relativistic effects for hot electrons with higher energies. The maximum growth rate is realized for the hot electrons with moderately low energies [30], which are first precipitated from the trap during the instability, thereby increasing the mean energy of the remaining hot electrons.

As soon as the first electromagnetic pulse is emitted and a certain fraction of the hot electrons has left the trap, the system becomes stable until the plasma decays enough to again fulfill the condition $f_{\text{opt}} > f_{pe}$. The delay between the first and the second electromagnetic pulses depends on the characteristic time of the plasma decay. The generation of the next pulse of Z-mode starts at the spatial location where the hot electrons have remained (see the experimental data in figure 6(b), where the initial frequency of the second pulse is of the same order as the final frequency of the first one), thus shifting the interaction region towards the trap center. The generation of the pulse sequences will repeat until all the hot electrons have left the trap and the emitted frequency spectrum covers the whole bandwidth, which corresponds to the interaction region between the ECR heating zone and the trap center. This can explain the maximum in the dependence of the final frequency of the second instability pulse on the microwave power (see figure 6(a)): At low power the instability occurs in a very rarefied plasma so the whole hot electron population can escape during the interaction, while at higher power (plasma density) the mechanism of changes in the polarization properties plays a more important role ($f_{\text{opt}} < f_{pe}$).

It is worth mentioning that each subsequent burst of electromagnetic emission occurs at a lower plasma density, meaning a higher group velocity of the slow extraordinary wave (see figure 9). The interaction with the electrons becomes faster and results in a steeper slope of the emission spectrum from pulse to pulse (see figures 4(a)–(c)): i.e. The frequency of the last pulse in a sequence drops as fast as 1–2 GHz in 30–70 ns. These dispersion properties also explain the shape of the spectrum depicted in figure 12, which was recorded 20 μs before switching off the klystron. The gentle slope of the spectrum exhibits a dominant frequency of 12.6 GHz and corresponds to the generation of the quasi-longitudinal extraordinary mode with a very low group velocity. This regime of cyclotron instability was already investigated in sustained plasma [35] and is possibly a particular case of the previously discussed mechanism in dense plasma.

At a later stage of plasma decay (>10 ms) the plasma density can become so low that the condition for the excitation of the transverse Z-mode ($f_{\text{opt}}/f_{\text{ce}} < \beta$) can be fulfilled for hot electrons. These changes in the scenario of cyclotron instability can be clearly seen from the dynamic spectrum of the last electromagnetic burst (see figure 5): The rapid falling tone is replaced by the generation of a narrow-banded emission. This regime is concerned with interaction of the transverse Z-mode with hot electrons located at the trap center and is quite typical for rarefied plasma [13, 14].

5. Conclusion

The proposed mechanism of cyclotron instability allows the explanation of the basic properties of the dynamic spectra of the observed microwave emission in the decaying plasma of a minimum-B ECRIS. The analysis has shown that the instability is driven by the resonant interaction of hot electrons, distributed between the ECR zone and the trap center, with a slow extraordinary wave that propagates quasi-parallel to the magnetic field. The characteristic timescales of the instability, such as the delay after switching off the microwave power and the repetition period between pulses, are dictated by the rate of the plasma decay. The slope of the frequency spectrum during the pulse depends on the absolute value of the plasma density, which determines the group velocity of the Z-mode. The falling frequency tones of each pulse as well as the total downward trend of the whole spectrum during the decay are associated with the decrease in the local relativistic cyclotron frequency. The research results can be claimed not only to improve the understanding of modern ion sources, but also to advance studies of wave–particle interactions in non-equilibrium plasma.

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