On the role of rf-scattering in the electron losses from minimum-\(B\) ECR plasmas

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Abstract.

The measurement of the axially lost electron energy distribution escaping from a minimum-\(B\) electron cyclotron resonance ion source (ECRIS) in the range of 4 – 800 keV is reported. The experiments have revealed the existence of a clear hump at 150-300 keV energy, containing up to 15% of the lost electrons and carrying up to 30% of the measured energy losses. The mean energy of the hump is independent of the microwave power, frequency and neutral gas pressure but increases with the magnetic field strength, most importantly with the value of the minimum-\(B\) field. Experiments in pulsed operation mode have indicated the presence of the hump only when microwave power is applied, confirming that the origin of the hump is rf-induced velocity space diffusion. Particle-in-cell simulation results and a quasi-linear diffusion model are presented to limit the possible mechanisms populating the loss cone at electron energies corresponding to the experimental observations.

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1. Introduction

The present article elaborates on previous research on the electron energy distribution in high-frequency minimum-B electron cyclotron resonance ion source (ECRIS) reported in [1]. The measurements reported hereafter, being more precise and extensive, confirm the characteristics of the energy distribution of electrons escaping the magnetic trap obtained previously both qualitatively and quantitatively. Furthermore, the results reveal hitherto unexplored features of the energy distribution that allow extending the knowledge of basic plasma physics of ECR-heated plasmas.

The measurement technique first employed in [1], was noticeably enhanced, resulting in a wider energy range available for the analysis, being now from 4 keV up to 450-800 keV depending on the dataset. This was done to focus on the high energy tail of the lost electron energy distribution (LEED), as the earlier measurements, limited to energies below 250 keV, had suggested a hump \( df_e/dE > 0 \) at energies exceeding 200 keV [1]. Although it could be argued that the electrons with energies on the order of hundreds of keV play a minor role in ionization (which is the most relevant process for the application of an ECRIS) due to small electron impact ionization cross-section at relativistic energies, their energy distribution is still of great interest from the fundamental plasma physics point-of-view. In particular, high-energy electrons are considered to be responsible for the onset of cyclotron instabilities, which are widely recognized as a factor limiting the ECRIS performance [2, 3]. Accumulation and losses of such energetic electrons are relevant for the local structure of the plasma potential and are believed to influence the overall plasma confinement including electrostatic trapping of the high charge-state ions [4]. Therefore, investigation of a high-energy tail of the LEED is considered to be of fundamental interest.

2. Experimental apparatus

The experimental data were taken with the JYFL 14 GHz ECRIS [5], shown schematically in Figure 1. The source uses an Nd-Fe-B permanent magnet sextupole arrangement and two solenoid coils to form a minimum-B structure for plasma confinement. The axial field strength can be varied by adjusting the solenoid currents, which affects the injection and extraction field values \( (B_{inj} \text{ and } B_{ext}) \), as well as the \( B_{min}/B_{ECR} \) ratio \( (B_{ECR} = 0.5 \text{ T at } 14 \text{ GHz}) \). In other words, \( B_{min} \) cannot be adjusted independently unlike in most high-performance ECR ion sources equipped with more than two coils. The reader is referred to [1] for more details on the magnetic field configuration. The solenoids were adjusted both simultaneously and independently, which allowed a comparison of the magnetic field configurations with (almost) the same \( B_{min} \) but having different \( B_{inj} \) and \( B_{ext} \), thus testing certain hypotheses about physical processes affecting the lost electron energy distribution. The electrons in the ECRIS plasma were heated either by 10-600 W of microwave power at 14 GHz provided by a klystron amplifier, or 100-200 W of microwave power in the range of 11.4 - 12.7 GHz using a TWT amplifier connected to a secondary waveguide port.

Typical neutral gas pressures were in the \( 10^{-7} \) mbar range. Oxygen was used in the present study to make it coherent with the previous ones, though some data were acquired with argon to confirm the observations and test for their dependence on a gas composition. The electron flux escaping the confinement through the circular extraction aperture \( (\varnothing=8 \text{ mm}) \) was collimated with two \( \varnothing=5 \text{ mm} \) collimators placed between the ion source and the 90° bending magnet used as an electron spectrometer. The electrons were finally detected with a secondary electron amplifier equipped with yet another \( \varnothing=5 \text{ mm} \) entrance collimator, placed in the beamline downstream from the bending magnet. The extraction electrodes normally used for optimizing the ion beam optics and the above aluminium collimators were all grounded and all magnetic components (solenoids and XY-magnets) were turned off to avoid steering or focusing the electrons and thereby affecting their energy-dependent transmission probability from the ion source to the detector.

The polarity of the bending magnet power supply was changed from the normal operation where the magnet is used for \( m/q \)-separation of high charge state positive ions. The magnetic field deflecting the electrons was measured with a calibrated Hall probe. The energy distribution of the electrons precipitating from the trap was then determined by ramping the field of the bending magnet, detecting the electron current from the amplifier with a picoamperemeter and applying a set of corrections, taking into account
the transport efficiency, electron backscattering and secondary electron yield. Further details of the data processing can be found from [1].

3. Experimental results

3.1. Experiments with continuous microwave injection

The LEED was measured as a function of the microwave power, microwave frequency, magnetic field strength and gas pressure in the stable operating regime (unless otherwise stated) of oxygen and argon plasma.

Figure 2 shows the electron current (arbitrary units) as a function of the electron energy at different microwave powers in the range of 10 - 600 W with 14 GHz. Both coils were operated with an equal current of 510 A, yielding $B_{\text{inj}} = 1.979$ T, $B_{\text{min}} = 0.376$ T, $B_{\text{ext}} = 0.916$ T and $B_{\text{min}}/B_{\text{ECR}} = 0.753$. The injection field is stronger in spite of the equal coil current due to the presence of an iron plug shaping the field at the injection. The oxygen pressure (hereafter measured without plasma) was $3.4 \cdot 10^{-7}$ mbar. Total electron losses, $F = \int_{\varepsilon_{\text{min}}}^{\varepsilon_{\text{max}}} f(\varepsilon) d\varepsilon$, where $\varepsilon$ is the electron energy and $f(\varepsilon)$ is the measured LEED, and the corresponding average energy of the escaping electrons, $\varepsilon_{\text{avg}} = F^{-1} \int_{\varepsilon_{\text{min}}}^{\varepsilon_{\text{max}}} f(\varepsilon) \varepsilon d\varepsilon$, are plotted in Figure 3.

The most pronounced change in LEED is the magnitude of a high-energy hump observed at energy of $\sim 200$ keV. The magnitude of the hump increases noticeably with power, whereas the overall LEED shape is preserved. The hump contains 10-15% of the total electron flux and accounts for more than 30% of measured energy losses, which makes it of fundamental interest as discussed in the following sections. Another clearly distinguishable change occurs when the power...
changes from \( P = 50 \) to \( P = 250 \) W. While the magnitude of the LEED in the range \( \varepsilon > 30 \) keV grows monotonically with power, it exhibits a drop in the range \( \varepsilon < 30 \) keV, which leads to a growth in the average energy seen in Figure 3 whereas the total losses are almost constant in this power range. Both at low (\( P < 50 \) W) and high (\( P > 250 \) W) power, the average energy decreases while the total losses increase with power, the latter being expressed by the whole curve shifting up in Figure 2. It is unclear from the data in Figure 3 whether the growth of the total losses and the hump itself are associated with an increase in plasma density (thus, enhancing collisional losses), which apparently follows from the increase of the power, or due to an increase in rf-induced loss rate, which also grows with the magnitude of the microwave field \( \mathcal{B} \).

Both, the total losses and the average energy, exhibit a change of behaviour at power of \( \sim 250 \) W: the total losses reach a local plateau between 100 and 250 W and then continue to grow monotonically at higher power; meanwhile the average energy starts to decrease slowly when the power exceeds 250 W. The saturation with the microwave power has been associated elsewhere with the saturation of the plasma energy content \[1\] and confirmed with the JYFL 14 GHz ECRIS by measuring the volumetric rate of inner shell ionization (through the detection of characteristic x-ray emission) with the ionization rate per unit of absorbed power saturating at 250 W \[1\] independent of the neutral gas pressure. Altogether these experimental findings and the observed decrease or increase of the LEED average energy and electron flux imply that the microwave power becomes insufficient to maintain a certain EED at the saturation point.

The dependence of LEED on the oxygen pressure is shown in Figure 4 with the corresponding average energy and total losses plotted in Figure 3. Neither the LEED nor the average energy and total losses in the energy range of \( 4 < \varepsilon < 800 \) keV change noticeably with the gas pressure. The gas pressure apparently affects the plasma density and, therefore, the observation suggests that the plasma density hardly affects the electron losses in the energy range probed here.

The dependence of LEED on the magnetic field strength, expressed in terms of \( B_{\text{min}}/B_{\text{ECR}} \), in the energy range of 4-800 keV is shown in Figure 5. Both, the average energy and total losses, depicted in Figure 7, clearly depend on the magnetic field. The magnetic field here was changed by adjusting the current in both coils symmetrically, yielding \( B_{\text{inj}} = 1.88 \) T, \( B_{\text{min}} = 0.33 \) T, \( B_{\text{ext}} = 0.84 \) T for \( B_{\text{min}}/B_{\text{ECR}} = 0.663 \) and \( B_{\text{inj}} = 2.05 \) T, \( B_{\text{min}} = 0.41 \) T, \( B_{\text{ext}} = 0.97 \) T for \( B_{\text{min}}/B_{\text{ECR}} = 0.824 \) at the extremes of the range used here. The increase of the magnetic field by 15% decreases the axial electron losses (with energies above 4 keV) by more than an order of magnitude and causes the average energy of those electrons to increase by a factor of 1.5. The increase of the magnetic field strength at constant resonant field (microwave frequency) obviously lowers the magnetic field gradient at the resonance zone, which presumably leads to a more effective ECR interaction \[12\] and an increase in the average electron energy. On the other hand, the increase of the magnetic field leads to more electrons being trapped. Experimental observations are in good agreement with the above reasoning.

Contrary to microwave power and neutral gas pressure having a negligible effect on the energy of the LEED hump, its position shifts considerably with magnetic field; from \( \sim 170 \) keV at \( B_{\text{min}}/B_{\text{ECR}} = 0.663 \) to \( \sim 300 \) keV at \( B_{\text{min}}/B_{\text{ECR}} = 0.824 \).

The data shown in the present article as well as in the previous study \[1\] implies that the magnetic field is the most influential ECRIS parameter affecting the LEED. This is best visible at high energies including...
the hump of the distribution. It is worth noting that the high-energy hump has been also observed in wall-bremsstrahlung spectra of the same ion source at similar energies of \( \sim 200 \) keV, shifting towards higher energies with the increase of magnetic field but remained unaffected by the change of microwave power or neutral gas pressure. Although the bremsstrahlung spectrum does not yield unambiguous information on the electron energy distribution and is affected by the collimation, the presence of the hump in the wall bremsstrahlung spectrum allows one to expect the presence of a similar hump in the energy distribution of the lost electrons causing the bremsstrahlung, which is exactly the observation reported here.

In order to determine which magnetic field-related quantity is responsible for the hump energy, a series of experiments was conducted measuring the LEED with different combinations of magnetic field and microwave frequency/power. The magnetic field was varied by tuning the coils independently. In this case the change of the extraction coil current affects the \( B_{\text{min}} \) and \( B_{\text{ext}} \), keeping \( B_{\text{inj}} \) almost unaffected, whereas the change of the injection coil current keeps \( B_{\text{ext}} \) roughly constant, but affects \( B_{\text{min}} \) and \( B_{\text{inj}} \). Operating the coils at different combinations of currents therefore allows one to identify the most influential magnetic field parameter on the hump of the LEED. The heating frequency was varied by using either the 14 GHz klystron or the TWT amplifier tuned to 11.4 GHz, 11.56 GHz, 11.70 GHz or 12.7 GHz at different power levels. Only single frequency heating mode was investigated and the TWT frequencies were selected by minimizing the reflected power. Oxygen with \( 3.5 \cdot 10^{-7} \) mbar pressure was used in these experiments. Finally, argon with the same pressure of \( 3.5 \cdot 10^{-7} \) mbar was used at 14 GHz.

It was found that only \( B_{\text{min}} \) had a clearly distinguishable effect on the hump energy, which increased with \( B_{\text{min}} \), as demonstrated in Figure 8. As an example, the electron mean energy in the hump as a function of \( B_{\text{ext}} \) is shown in Figure 9, in order to demonstrate its scatter. Finally, Figure 10 shows the energy of the hump (in false color, interpolated) against currents of the injection and extraction coils together with isolines of the hump mean energy (solid magenta), \( B_{\text{min}} \) (solid black), \( B_{\text{inj}} \) (dashed red), and \( B_{\text{ext}} \) (dotted blue). The data in Figure 11 underlines the fact that the energy of the hump follows the change of \( B_{\text{min}} \), not other magnetic–field–related quantities.
The observation suggests that there is a certain process that affects the formation of the hump on the distribution function of the lost electrons, that does not depend neither on the frequency or power of the heating radiation, nor on the gas type or the local mirror ratios (injection and extraction), but only on the absolute minimum value of the magnetic field in the center of the trap. Similar statement was made in [15], where the bremsstrahlung spectral temperature (being correlated, but not equal to the electron temperature) was found to depend on $B_{\text{min}}$ and to be independent of the heating frequency (in a stable regime of operation, free of cyclotron instabilities). It should be explicitly pointed that the bremsstrahlung spectra in [15] were those emitted from the confined plasma, whereas all data presented here relates to the escaping particles. However, similar dependencies suggest a strong correlation between the energy distributions of lost and confined electrons.

3.2. Experiments with pulsed microwave injection

To determine the origin of the LEED hump visible at 170 - 300 keV the experiment with pulsed microwave injection was conducted with 14 GHz at 1 Hz pulse repetition rate and $\sim 0.62$ duty factor. The pulsed power was set to 260 W and the oxygen pressure to $3.5 \cdot 10^{-7}$ mbar. The coils were energized symmetrically with a current of 500 A, yielding $B_{\text{min}}/B_{\text{ECR}} = 0.735$. The average energy of the lost electrons, electron flux and heating pulse (schematically) are shown as a function of time ($t = 0$ corresponds to the leading edge of the microwave pulse) in Figure 11 for the beginning (a) and the end (b) of the heating pulse.

The electron flux rises abruptly (see Figure 11a) immediately with the heating power from a very low yet non-zero level, experiencing a moderate overshoot and then slowly reaches the steady-state. The overshoot could be correlated with the preglow peak being thoroughly studied in [16, 17, 18, 19]. The non-zero electron flux before the microwave pulse can be explained by the heating power duty cycle. The time between consecutive pulses is short enough for electrons to remain confined in the trap for the whole time between pulses. At the trailing edge the flux drops abruptly together with the power (Figure 11b). However several bursts are seen during the plasma decay, unambiguously matching with the afterglow kinetic instabilities [20, 21], which are always present since regardless of the initial plasma energy content defined by the ion source settings there will be a moment during the transient when the instability growth rate exceeds its damping rate [20, 22]. Following the instabilities the electron flux keeps decaying with a time constant of several tens of ms (not shown in the Figure 11), which corresponds to the Coulomb scattering time for an energy of several keVs, being commonly considered as an average energy of electrons confined in ECRIS plasmas. The authors would like to point the Reader’s attention to the fact that the electron flux drops by a factor of two within less than one millisecond after the microwave power is switched off. This time is very short to be related to Coulomb scattering given the average energy of electrons, which suggests that the rf-induced scattering process [6, 7, 8] is comparable to electron losses by collisional scattering in continuous operation mode of the ECRIS.

Contrary to the electron flux, the average energy of the lost electrons drops with the leading edge of the microwave pulse, as the ECR heating starts to
supply electrons with a wide energy spectrum. At the trailing edge of the microwave pulse the average energy exhibits some oscillations and then starts to rise slowly, finally reaching the value shown just before the consecutive pulse. The increase of the average energy is presumably related to the probability of Coulomb scattering decreasing with the electron energy, which implies that the confinement time of the high energy electrons is longer than the microwave off period in this case [23].

The lost electrons energy spectrum as a function of time on both sides of the trailing edge of the microwave pulse is shown in Figure 12. The electron flux is shown with false color. The afterglow instabilities are well visible, expelling significant number of electrons in a wide energy range at \( t = 627, 627.5, 629 \) and 636.5 ms. The moment of the microwave power being switched off is clearly seen in the spectrum and is also marked with a dotted vertical line. In addition to the drop of the total electron flux, discussed earlier, there is a noticeable change in the spectrum at energies above 100 keV related to the microwave power being switched off. The LEED hump is clearly visible at \( \sim 200 \) keV when the microwaves are on, disappearing abruptly with the microwaves being turned off. This observation indicates that the microwave–electron interaction is responsible also for the existence of the hump in the LEED. Vertical slices of the spectrum at various times are shown in Figure 13. The curves are plotted by integrating the signal in each energy bin within the time limits indicated in the plot legend (here \( t = 0 \) ms corresponds to the microwave switch on). Some data in the range \( 10 – 30 \) keV has been removed due to electrical noise. The curves in Figure 14 show the evolution of LEED, reaching the steady-state after \( \sim 100 \) ms of microwave heating. The same characteristic time to reach a steady-state level is found for parameters such as bremsstrahlung and ion currents [14, 18]. Although the hump at 200 keV appears almost immediately, it takes several tens of ms for it to reach the full magnitude. This indicates that the accumulation of electrons forming the discussed hump takes considerable time, which is consistent with the hypothesis of microwave heating being a prerequisite for the process populating the loss cone.

4. PIC simulation

In an attempt to reproduce the measured energy distributions of the lost electrons, in particular the microwave-induced high-energy hump, we used the NAM-ECRIS (Numerical Advanced Model of Electron Cyclotron Resonance Ion Source) code [24, 25].
main features of the code are described below. The model calculates both the ion and electron dynamics in the ion source by running two separate modules that exchange the relevant information between each other. The electron module traces the electron movement in the source magnetic field taking into account the electron Coulomb scattering in collisions with ions and other electrons. The microwave heating is treated as kicks in particle’s velocity whenever the electron crosses the point where the ECR condition is satisfied. The magnetic field at the relativistic resonance is

\[ B_{\text{res}} = \frac{1}{s} B_0 \gamma \left( 1 \pm \frac{V_\parallel}{V_\phi} \right) \]  

where \( B_0 = 0.5 \text{ T} \) for 14.0 GHz microwaves (the resonant magnetic field with no Doppler shift, i.e. the “cold” resonance), \( s = 1, 2 \) for the fundamental and the second harmonics of the resonance, \( \gamma \) is the relativistic factor, \( V_\parallel \) is the longitudinal electron velocity, \( V_\phi \) is the wave phase velocity along the magnetic field line, the positive sign stands for the blue-shifted resonance and the negative sign - for the red-shifted one.

The wave phase velocity is calculated from the dispersion relation for the right-hand polarized (whistler) wave in cold plasma as

\[ \frac{c^2}{V_\phi^2} = n_\parallel^2 = 1 - \frac{\omega_p^2 / \omega^2}{1 - \omega_B / \omega} \]  

where \( n_\parallel \) is the longitudinal refractive index, \( \omega_p, \omega, \) and \( \omega_B \) are the plasma, microwave and electron cyclotron angular frequencies, respectively. The velocity “kicks” are calculated both perpendicular and along the local magnetic field line. The kick phase is a random value, whereas the kick magnitude is proportional to the local electric field. The simulation does not take into account spatial variations of the electric field, but rather treats it as a free parameter. Inelastic collisions of electrons are modeled using excitation cross-sections from \cite{27} and ionization cross-sections from \cite{28}. The electron energy losses due to the emission of electron-cyclotron radiation are also taken into account. Electrons are reflected from the walls if their energy along the magnetic field lines is less than 50 eV, which is an order-of-magnitude estimate of the plasma potential.

Figure 15 presents the comparison of the experimental LEED and the corresponding distribution function simulated with NAM-ECRIS code. Distributions are normalized to the unity square. The model qualitatively reproduces the hump and its energy (close to 200 keV), whereas the overall shape of the LEED is not well described by the simulation. The origin of the hump modeled with NAM-ECRIS lies in the Doppler-shifted relativistic fundamental harmonic ECR, which apparently occurs close to extraction magnetic mirror for electrons with energies \( \sim 200-300 \text{ keV} \) heated by 14 GHz radiation, thus enhancing losses of such electrons. According to this approach, the hump energy should depend on the magnetic field near the extraction as well as the microwave frequency. However, the data in Figures 11 to 13 prove that the energy of the hump is independent of the extraction field and rather depends on the \( B_{\text{min}} \) value as described above. This fact implies that there is an additional process which is not taken into account by using the described approximation with the fundamental harmonic ECR heating.

It is worth noting that for relatively large plasma density the resonance condition for the second ECR harmonic is fulfilled close to \( B_{\text{min}} \) position: \( \gamma B_0 \gamma \approx 0.36 \text{ T} \), yielding the energy of 225 keV (\( \gamma = 1.44 \)), which is very close to the experimentally observed peak. However, if the peak would be caused by the second harmonic of the ECR heating, its energy would depend on both \( B_{\text{min}} \) and the frequency, i.e. on the value of \( B_{\text{min}} / B_{\text{ECR}} \), which contradicts the experimental observations indicating that the hump position is not shifted with the frequency change if \( B_{\text{min}} \) remains constant.

5. Quasilinear diffusion and rf-scattering

In order to seek for an alternative mechanism possibly explaining the observed LEED hump we discuss the concept of quasilinear diffusion. It can be shown that following quantity is conserved in the interaction of an electron with electromagnetic radiation under ECR \cite{20,27,28}:

\[ \varepsilon - \omega J_\perp = \mathcal{K} = \text{const} \]  

where \( \varepsilon = mc^2(\gamma - 1) \) is the electron kinetic energy, \( J_\perp = p_\perp^2 / 2m \omega_B(z) \) is the transverse adiabatic invariant (\( \omega_B(z) \) denotes the gyrofrequency varying along the magnetic field line). Lines of \( \mathcal{K} = \text{const} \) are those of quasilinear diffusion in the momentum space. The cyclotron interaction is reduced to the alignment of the
electron distribution function along these lines when the quasilinear approximation is fulfilled [9], which is generally the case for the ECRIS. Such a process is usually limited either by the particle entering the loss cone or by reaching the energy and transverse adiabatic invariant value at which the ECR condition is no longer satisfied anywhere in the inhomogeneous magnetic field. Another possible mechanism for limiting the quasilinear diffusion is the so-called super-adiabatic effects [8], which we will not consider here due to the steady-state plasma density in ECRIS believed to be too high for superadiabatic effect to exist.

The ECR condition [1] may be rewritten using [2] as:

$$\frac{\omega_B}{\omega} - \gamma = \pm \sqrt{(\gamma^2 - 1) \left( 1 - \frac{\omega_p^2/\omega^2}{1 - \omega_B/\omega} \right) \left( 1 - \frac{\omega_B}{\omega_m} \right)}$$

(4)

where \(\omega_m\) is the gyrofrequency at the electron mirroring point. It is fulfilled for all particles reaching the cold electron resonance zone, if the plasma is not too rarefied and the heating frequency is above the minimum “cold” frequency in the system \(\omega > \omega_{B_{min}}\). Due to the strong slowing–down of the right-hand polarized waves in the vicinity of the “cold” ECR, the condition of the electron to reach the cold resonance may be written as:

$$\frac{\omega}{\omega_m} = \frac{2J_1 \omega}{(\gamma^2 - 1)mc^2} < 1$$

(5)

A similar condition may be written for the electron to enter the loss cone:

$$\frac{\omega_{B_{max}}}{\omega_m} = \frac{2J_1 \omega_{B_{max}}}{(\gamma^2 - 1)mc^2} = 1$$

(6)

It is convenient to introduce the variable \(\kappa\):

$$\kappa = \frac{\omega_{B_{min}}}{\omega_B} \frac{\beta^2}{\beta^2} = \frac{2J_1 \omega_{B_{min}}}{mc^2(\gamma^2 - 1)}$$

(7)

Then, \(0 \leq \kappa \leq 1\), and the loss cone becomes a vertical line in \((\kappa, \gamma)\) space: \(\kappa_{loss} = \omega_{B_{min}}/\omega_{B_{max}}\).

The group of diffusion lines (it is only \(K\) that differs) in \((\kappa, \gamma)\) space for \(B_{min} = 0.372\) T, \(B_{max} = B_{ext} = 0.908\) T and heating frequency of 14 GHz are shown in Figure 16 in solid black lines. A quasi-one-dimensional distribution function localized along the line \(K = 0\) (depicted with a bold black line) is formed from initially low-energy electrons. This diffusion asymptote lies entirely in the region fulfilling the inequality \(\omega > 2\omega_{B_{max}}/\omega - 1 = 2.44\), \((\varepsilon = 736\) keV\), which is much higher then the hump energy found in the experiment. Thus, the hump observed in every LEED shown above may not be solely explained by quasilinear diffusion as a result of interaction with the heating wave only. (The arguments against the second ECR harmonics were discussed above).

However, let’s assume there exists a secondary electromagnetic wave with frequency \(\omega_2\) below the minimum cyclotron frequency: \(\omega_2 < \omega_{B_{min}}\). A group of diffusion lines for such a frequency \(\omega_2/2\pi = 4.72\) GHz are also plotted in Figure 16 with blue color. The magnetic field is the same as for the 14 GHz diffusion lines (black). The wave with \(\omega_2 < \omega_{B_{min}}\) cannot be slowed down by the plasma significantly (see eq. 2). Therefore, there is a minimum electron energy at which the interaction with the wave is possible at the Doppler-shifted relativistic resonance according to eq. 3 which is shown with dotted magenta line (the limit was calculated for \(\omega_p^2/\omega^2 = 0.2\)). It can be derived from equations 4 and 7 that the energy limit shifts upwards with lower plasma density, coinciding with the diffusion line tangent to \(\kappa = 1\) (bold blue in Fig. 10) when \(\omega_p \rightarrow 0\).

When the secondary electromagnetic wave is excited, the quasi-one-dimensional distribution function spreads along the blue diffusion lines corresponding to the additional frequency. In this case, two mechanisms of electron losses exist. The first one is the direct diffusion along blue lines when interacting with the second frequency. Secondly, diffusion along blue lines may “transfer” particles onto black diffusion lines corresponding to the main frequency (14 GHz), and these diffusion lines may then lead to the loss cone. Thus, adding the secondary frequency introduces additional losses of energetic electrons. Depending on the frequency of the secondary wave, the additional electron losses may be introduced either in the whole energy range (when \(\omega_2 > \omega_{B_{min}}\)), or, when \(\omega_2 < \omega_{B_{min}}\), be more pronounced only at energies higher than a \(\gamma\) value. \(\gamma\) is defined as a point, where diffusion line tangent to \(\kappa = 1\) enters the loss cone.

It appears that the experimentally observed dependence of the hump energy on \(B_{min}\) shown in Figure 3 is reasonably well reproduced in the frame
of the above hypothesis assuming that the secondary frequency is constant, i.e. independent on any of ECRIS parameters, and in the range of 4.10–5.40 GHz. Such comparison is shown in Figure 17 where all the data from Figure 8 is merged and plotted with black crosses representing the electron energy at the peak of the hump. For each experimental data point, theoretical limits are estimated with the procedure explained above. The given range of frequencies covers 95% of the electrons (±2σ) in a Gaussian fit representing the hump after subtracting the exponentially decreasing background distribution of electrons. The procedure for extracting the energy range of the hump is clarified in Fig. 18 showing an example of a measured LEED and the hump after background subtraction.

If there is an electromagnetic wave in the above frequency range, it might be responsible for the observed hump formation in the LEED. However, the existence of such a low frequency in the plasma chamber must be experimentally confirmed, and the mechanism of its excitation must be clarified. There are several observations of frequencies sufficiently lower than the heating frequency being excited in an ECRIS plasma [20, 29, 30, 31]. Although the excitation of these frequencies was clearly related to the onset of cyclotron instabilities, even a weak (therefore so far undetected) emission in the relevant range could be enough to drive electrons into the loss cone. It is important to highlight that the instability mechanism needs a seed frequency as it is understood. Emission in the relevant frequency range was detected in the regime when no obvious indications of plasma instability were present [31].

The described approach may explain the observed shape of LEED and its dependencies on parameters, though the origin of the secondary electromagnetic wave has to be yet defined. According to the experimental data, this supposed wave is turned on and off together with the heating radiation, though its frequency is independent of the primary heating frequency. A possible candidate for such a wave might be the electromagnetic cavity mode excited by a strongly heated plasma inside. It is then possible to explain the slow appearance and fast disappearance of the hump seen in Figures 13 and 14. When the heating wave is turned on, it acts as a (relatively weak) source of energetic electrons, so it takes some time to accumulate enough electrons and build up the intensity of a wide spectrum electromagnetic emission, exciting the (probably, spatially selected) cavity mode, which in turn forces these electrons to the loss cone. Once the heating wave is turned off, the source of high-energy electrons disappears, and relaxation of the hump is then defined by ω2–rf-induced scattering to the loss cone only, which is a fast (quasilinear) process.

6. Conclusion

The existence of a hump in the energy distribution of electrons escaping the magnetic confinement of the ECRIS axially carrying more than 30% of the energy (for electrons with energies above 4 keV) was demonstrated. It was found that the energy of the hump depends only on $B_{\text{min}}$ and hardly on other parameters of the magnetic field. Neither does it depend on the heating power and frequency or the gas pressure and type.

The reported experimental data and its comparison to the PIC modeling allows excluding some plausible mechanisms, such as direct interaction with the heating wave and its harmonics. Within the frame of quasi-linear diffusion concept the hypothesis explaining the hump formation is proposed. The hypothesis based on the assumption of the cavity mode excitation by the volumetric cyclotron emission of energetic electrons. The excited mode then scatters energetic electrons to the loss-cone, forming the hump.

The aforementioned hypothesis motivates further
experiments including careful investigation of a electromagnetic emission of the magnetically confined plasma of an ECRIS in the frequency range below $\omega_{B_{\text{min}}}$ and close to the fundamental cavity modes.

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