Parameters of plasma bunches generated in a long mirror trap under conditions of gyromagnetic autoresonance

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Abstract. Temporal evolution of the spectrum and intensity of bremsstrahlung generated by the plasma bunches formed in a symmetric long mirror trap under conditions of gyromagnetic autoresonance was studied experimentally in detail. Bremsstrahlung was detected by two identical detectors installed in the axial and radial directions with respect to the stationary magnetic field. The results show that the radiation is spatially inhomogeneous. The parameters of the spectra measured in the radial direction strongly depend on the amplitude of the pulsed magnetic field, while the spectra measured in the longitudinal direction are determined mainly by the ECR conditions in the phase of filling the trap with the primary plasma. The integrated intensities, obtained with allowance for the refined form factors of the generated bunches recorded using the high-speed photochronography, made it possible to determine the number of primary plasma particles trapped in the autoresonance mode.

1. Introduction
The plasma bunches with high-energy electron component can be generated in different ways. The most used methods are the compression of the primary plasma by the time-varying magnetic field [1, 2] and the pulsed heating performed under the resonance conditions [3]. Previously [4, 5], it was shown that the plasma bunches with the high-energy electron component can be produced in the adiabatically increasing magnetic field under conditions of the electron cyclotron resonance (ECR): the effect of gyromagnetic autoresonance (GA). During this process, a relativistic change in the electron mass is automatically compensated by a change in the magnetic field and the resonance conditions are satisfied. This leads to the formation of the long-lived relativistic plasma bunches, which have the form of an ion-filled cloud of high-energy electrons with an average energy of the order of several hundred kiloelectronvolts, which is confined by the external magnetic field. In this paper, we have studied experimentally the scenario of the gyromagnetic autoresonance process in the reverse magnetic field of the mirror trap. Time evolutions of the bremsstrahlung intensity and spectra observed in experiments correspond to the dynamics of the generated plasma bunches with high-energy electron component, both in the gyromagnetic autoresonance phase and in the confinement stage. The goal of this work is to study the temporal evolution of the bremsstrahlung spectra both in the stages of autoresonance acceleration and confinement of the generated bunches in the stationary field of the mirror trap.

2. Experimental setup and diagnostic methods
The experimental facility is a cylindrical microwave resonator (the TE₁₁₈ mode is used, the resonance frequency is 2.45 GHz) installed inside the axisymmetric magnetic field of the mirror trap (R = 1.2,
L = 80 cm, where R is the mirror ratio, and L is the resonator length). The magnetic field induction in the minimum of the trap is 1250 G.

The pulsed magnetic field required for the creation of the GA regime is generated by the pulsed current flowing through the pair of coils coaxial with the stationary magnetic field coils. The pulsed magnetic field coils are installed in the electric field antinodes of the TE$_{118}$ mode standing wave symmetrically with respect to the trap magnetic field minimum. The 3D graphic image of the experimental facility and the axial distributions of the resulting magnetic field induction in the reverse coils of the pulsed field at different times during the current rise time are shown in Fig. 1a.

The direction of the current in the pulsed coils provides the creation of the pulsed magnetic field with an induction directed oppositely to that of the stationary field, thereby locally reducing the resulting magnetic field. At time of reaching the maximum pulsed field induction, at which the resulting field amounts to B = 875 G (figure. 1a), under conditions of the electron cyclotron resonance, the initial plasma is formed in two axially symmetrical electric field antinodes of the standing wave (in the second and the seventh antinodes, corresponding to the axial coordinate ranges of [–23.5 cm; –15.5 cm] and [15.5 cm; 23.5 cm], respectively). The reduction of current in the pulsed coils and the restoration of the stationary magnetic field initial profile in the presence of the microwave field ensure the trapping and acceleration of plasma electrons, setting the GA regime and generation of plasma bunches in two symmetrical zones of the facility. The facility operating cycle is shown in figure 1b. In the A phase, the resulting magnetic field is adjusted in accordance with the ECR conditions within two zones of the trap. In the B phase, as a result of interaction with the ECR field, the initial plasma is formed in two local zones of the trap. In the C phase, the GA mode is formed, and, in the D phase, the produced plasma bunch is confined in the stationary field of the mirror trap. Waveforms of the microwave heating pulse and the pulsed magnetic field characterizing the experimental scenario are presented in figure 1b. The restoration of the initial stationary magnetic field profile with a small gradient leads to the displacement of the formed bunches into the trap region of the minimum magnetic field and their accumulation there.

**Figure 1.** (a) The facility image and the axial distributions of the resulting magnetic field at different times. (1) The microwave resonator, (2) the stationary magnetic field coils, (3) the pulsed magnetic field coils, (4) the loop antenna inputting the microwave power, and (5) the pumping cubes. (b) Operating cycle of the facility.

The experiments were carried out under the following conditions: the plasma-forming gas pressure ranged from $P = 1 \times 10^{-5}$ Torr to $P = 5 \times 10^{-5}$ Torr, the microwave power was maintained at a constant level of 2500 W, the duration of the microwave pulse was $\tau = 1.1$ ms, the off-duty time was $T = 90$ ms, and the maximum induction of the reverse magnetic field was 500 G. The stationary magnetic field profile was maintained constant, and the induction in the minimum of the trap was 1250 G. The spectra were obtained after the produced plasma bunches interacted with the gas target, and xenon...
(Xe) was the working gas. The total time of the X-ray spectra acquisition in a number of pulses was 3 seconds.

Bremsstrahlung arising during the interaction of plasma bunches with the gas target was recorded both in the transverse and axial directions with respect to the stationary magnetic field using two identical spectrographs based on the NaI (Tl) 40 × 40 mm scintillators with the magnetic shielding, as well as the multichannel pulse analyzers. Calibration of the spectrometric tract was performed using the reference radiation sources (241Am, 133Ba, 57Ti). Radiation from the interaction region was recorded by the detectors installed behind the 1-mm-thick aluminum windows. Both detectors were shielded by the 1-cm-thick lead screens in order to reduce the effect of background radiation. The fields of view of the transverse and longitudinal detectors at the resonator midplane were 30 and 115 cm², respectively.

3. Results and discussion

In the course of experimental studies, the bremsstrahlung spectral characteristics were measured at different times of the working cycle. This made it possible to obtain time dependences of the maximum achievable energy of the hot electron component and the photon yield in different stages of the GA regime, as well as in the confinement stage, at different pressures. Figure 2 shows the bremsstrahlung spectrograms obtained at different times of the facility operating cycle. The spectral measurements were performed during 150 µs after the formation of the initial ECR plasma (phase B). Up to the 500th µs of the working cycle, the GA phase proceeds, and then the plasma bunch is confined in the magnetostatics field of the mirror trap. The characteristic feature of the spectra recorded in the transverse direction consists in the fact that the maximum electron energy is determined by the amplitude of the pulsed magnetic field (figure 3). The maximum energy (300 keV) was recorded at $B_{imp} = 500$ G in 450 µs after the start of the operating cycle (figures 2 and 3).

![Figure 2](image-url)

**Figure 2.** Time evolutions of bremsstrahlung spectra during the operating cycle recorded in the (a) transverse and (b) axial directions

At the same time, the maximum energy recorded in the longitudinal direction does not exceed 70 keV (figure 2b).
Figure 3. Changes in the maximum energy during the operating cycle (the red dotted line is the end time of the GA phase).

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Figure 4. Photon yield at different times of the working cycle in the (a) transverse and (b) longitudinal directions.

Processing the obtained spectrograms makes it possible to reveal the characteristic changes in the integrated radiation intensity and to determine the number of particles trapped in the GA mode in the case when the integrated intensity reaches its maximum value at the beginning of the confinement stage. Figure 4 shows the photon yields in both the transverse and longitudinal directions at different pressures; the red line corresponds to the end of the GA phase, that is, to the restoration time of the initial magnetic field profile in the trap. As can be seen, the maximum photon yield in the transverse direction is achieved at the end of the GA phase (τ = 500 μs, figure 4a), and further, in the confinement phase, it remains almost unchanged within ~700 μs. The photochronographic measurements of the dynamics and spatial structure of a plasma bunch were performed synchronously with the spectral measurements in the longitudinal direction. In previous experiments, the radiometric measurements were performed [5], in which, in the confinement phase, the solid targets were introduced into the region of the plasma bunch localization. All these measurements made it possible to more accurately determine the linear dimensions of the formed bunches: the average radius was found to be in the range from 2 to 2.5 cm that coincides with the calculated Larmor radius of the accelerated electrons. According to the method proposed in [6], and taking into account the acceptance solid angle, the recorded integrated intensities, as well as the measured form factors of the bunches, allowed determining the number of particles in a bunch at the beginning of the confinement phase, which turned to be ~2·10^{10} electrons at an amplitude of the pulsed magnetic field of 500 G and microwave power of 2500 W. We also notice the distinctive features of the bremsstrahlung spectra recorded in the axial direction: the maximum photon yield recorded by the longitudinal detector is achieved in the B phase at time of filling of the trap with the initial plasma. By the end of the GA phase, the photon yield in the longitudinal direction sharply decreases (figure 4b) and, subsequently, in the D phase of plasma confinement it becomes insignificant.
In the GA phase, within the time interval of 250–500 µs, the photon yield (figure 4a), as well as the maximum energy (figure 3), linearly increase, remaining the same in order of magnitude. This fact indicates that the number of trapped particles is almost constant and varies only slightly due to the electron scattering on the gas target.

Conclusions

The obtained results show that the plasma bremsstahlung radiation is not homogeneous, and the parameters of the spectra measured in the transverse direction strongly depend on the amplitude of the pulsed magnetic field, while the spectra measured in the axial direction are determined only by the ECR conditions in the phase of filling the trap with the primary plasma. Experimentally, the difference was found in the temporal evolutions of the photon yields in both the axial and transverse directions during the acceleration and confinement stages. The X-ray spectrometric measurements performed and the corrected results on determining the linear dimensions of the generated bunches made it possible to determine the number of primary plasma electrons trapped in the autoresonance mode. The obtained results contribute to understanding the processes of generation and confinement of such plasma bunches, and also make it possible to trace the temporal dynamics of their characteristic parameters.

Acknowledgments

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