Evolution of energy spectra of the electronic component for plasmoids generated under autoresonance conditions in a long magnetic mirror

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Abstract. We performed a 3D numerical simulation of plasmoid generation with a relativistic electron component under gyromagnetic autoresonance conditions in a long mirror trap. We studied the process of plasmoid formation, the spatiotemporal dynamics and the evolution of the energy spectra of the electron component of the plasma and the efficiency of electron trapping as a function of the experimental parameters.

1. Introduction
Our prior study \cite{1} provided experimental and numerical simulation results that demonstrated the possibility of autoresonant acceleration of plasma electrons in a reversible magnetic field of a long magnetic mirror. The experimental set-up (Figure 1) is a cylindrical microwave cavity (mode TE118, frequency of $f = 2.45$ GHz) placed in an axisymmetric magnetic field of an extended mirror configuration ($L = 80$ cm) with magnetic field induction at the trap center, $B = 1200$ G. A stationary magnetic field is created by three pairs of coaxial coils fed by three DC sources. The reverse pulsed magnetic field is created by coils located at the maxima of the electric component of the microwave field of a standing wave (the 2 and 7 half-waves). Changing the current in the pulse coils to a certain maximum value results in the reducing the magnetic field induction in the regions of the 2nd and 7th half-waves to a value that corresponds to the classical electron cyclotron resonance (ECR) (Figure 2). Then, the current in the pulse coils decreases, resulting in restoration of the initial profile of the magnetic field produced by the stationary coils, and the electrons of the produced ECR plasma become trapped in the autoresonant acceleration mode.

As a result of the autoresonant interaction of the plasma electrons with a microwave field in a magnetic field that is increasing in time, the gyromagnetic autoresonance (GA) \cite{2} and two electron bunches with an average energy of several hundred keVs are formed, which are dumped upon the magnetic field profile recovery into the central region of the trap and are held in the magnetic mirror for a long time.

The purpose of this study was to perform a computer simulation of the energy spectra evolution for the electron component of the plasma using the experimental parameters and to study the efficiency of electron trapping into autoresonant acceleration.
2. Numerical model

A 3D numerical model was built based on the PIC method of particles in a cell that allows for electrostatic interactions, as described in detail in ref. [2]. It was adapted to the study the creation processes of plasma bunches in a long magnetic mirror. The equation of motion of electrons that accounts for relativistic effects has the following form:

\[
\frac{u^{n+1/2} - u^{n-1/2}}{\Delta \tau} = g^n + \frac{u^{n+1/2} + u^{n-1/2}}{2\gamma^n} \times b^n
\]

where \(u\) is the electron momentum in \(m_0c\), and

\[
g = \frac{E}{B_0}, \quad E = E_{hf} + E_s + E_i
\]

is the superposition of the electric component of the microwave field, \(E_{hf}\) (mode TE\(_{111}\)). The self-consistent electric field produced in plasma \(E_s\), and the induced electric field \(E_i\) arising due to the change of the magnetic field over time, and

\[
b = \frac{B}{B_0}
\]

is the dimensionless induction of the magnetic field, where

\[
B = B_\mu + B_{imp}
\]

is the superposition of stationary and pulsed magnetic fields, and

\[
\Delta \tau = \omega \cdot \Delta t
\]

is the time step of the motion equation integration, and

\[
\gamma^n = (1 + (u^n)^3)^{1/2}
\]

is the relativistic factor \(n\) is the sequence number of the motion equation integration step.

We used the Boris scheme to solve the electron motion equation [3]. Ions under the experimental conditions remain unmagnetized and do not interact with the microwave field. Under this condition, only the self-consistent electric field arising in the plasma was taken into account in the ion motion equation.

The particles hitting the chamber walls were considered lost, and their ionization processes were not taken into account. When the pulsed magnetic field reaches its maximum value in the zones of the second (–23.25 to –15.5 cm) and seventh (15.5 to –23.25 cm) half-waves of the microwave field in the cavity, the induction of the resulting magnetic field is in the value interval that corresponds to the

Figure 1. The experimental set-up.

Figure 2. 3D view of the magnetic field induction in relative values at the moment when pulsed coils reach the maximum value of the current.
classical ECR conditions. Under these conditions, a neutral single-ionized low-temperature plasma (Te ≤ 20 eV) is simulated in the ECR regions of the interactions, and the temperature of the ions (argon) did not exceed a fraction of an electron-volt.

3. Simulation results and discussion

The evolution of the plasma parameters was studied using 3D modeling. The simulation was conducted for the following main parameters: a microwave field intensity of E = 0.25...3.00 kV/cm, an initial plasma density of n = 10^{10} cm⁻³, a rise (decrease) in time of the pulsed magnetic field of 5 µs, a minimum value of the magnetic field in local magnetic traps of B = 870 G, and when the microwave field was turned off after the magnetic field’s profile recovery.

The interaction of electrons with the microwave field under GA conditions leads to the creation of two local bunches of accelerated electrons in the regions indicated above. The spatial distributions of the plasma components are shown in Figures 3a–3c. Figure 3a shows the dominant distribution of the electrons trapped in the GA mode and the non-trapped electrons and ions at the initial GA stage. The trapped electrons are compact bunches concentrated in the regions of interaction with the microwave field. Non-trapped electrons drift in the longitudinal direction, and some of them fall on the end walls of the cavity.

![Spatial distributions of trapped electrons (red), non-trapped electrons (green) and ions (blue) in the ZY section at various time points.](image)

The local magnetic traps are asymmetric and shift toward the center of the system as the pulsed magnetic field decreases. This leads to two effects. First, some of the trapped electrons make an oscillation bounce in addition to the GA regions, passing to the regions of neighboring half-waves. This results in a broadening energy spectrum for the trapped electrons. Second, some electrons fall out of local traps and drift to the center of the system (Figure 3b). With the complete restoration of the magnetic field profile and the disappearance of local magnetic traps, the resulting bunches drift to the center of the system (Figure 3c).
Figure 4. Spectra of the electron component of the plasma at various time points with an electric field strength of the microwave field of $E = 1 \text{ kV/cm}$.

Figure 5. Energy spectrum of electrons at various values of microwave field strength after the end of the GA cycle: 1 – $E = 250 \text{ V/cm}$; 2 – $E = 1 \text{ kV/cm}$; 3 – $E = 3 \text{ kV/cm}$.

Figure 4 shows the change in the electron energy spectrum for equal intervals of time during the process of increasing the magnetic field up to its original profile recovery. As shown in Figure 4, a pattern for the energy spectrum of accelerated electrons (curve 1) is formed during the initial GA stage. The spectrum is close to the Gaussian curve, and the average energy of trapped electrons is 50 keV. The spectrum represented by curve 1 corresponds to the spatial distribution of electrons shown in Figure 3a. With a further increase in the magnetic field over time, the shape of the spectrum remains virtually unchanged. The spectrum only broadens, and the number of trapped electrons slightly decreases (curves 2–4). Figure 5 shows a comparison of the electron energy spectra obtained at various electric microwave field strengths in a plasma with the same initial mean density of $n = 10^{10} \text{ cm}^{-3}$. A comparison of the spectra shows a pronounced dependence of the electron capture efficiency, which is defined as the ratio of the number of trapped electrons ($N_{\text{tr}}$) to the initial number of plasma electrons ($N_0$), on the width of the energy spectrum and on the microwave field strength. The electron trapping efficiency is at its peak at $E = 1.0 \text{ kV/cm}$ and reduces when both the microwave field strength decreases and increases. This effect is associated with the impact of the plasma's own electric field on the capture of electrons, which arises as a result of the electron acceleration and the emerging partial separation of the plasma components. It reaches 400 V/cm after the magnetic field’s profile recovery and results in a release of the generated bunches to the trap center. With the computer simulation, we studied the formation of plasmoids with a moderately relativistic electron component and found that the time dependences of the spatial distributions of the plasma components and the energy spectra evolution for the electron components of the plasma. There is an optimal value of the electric microwave field strength at which the electron trapping in the GA mode is the most intensive. The results of the previous numerical GA simulation [1, 2] are in good agreement with the experimental data. This provides a basis for using the data obtained in this study to optimize further experimental studies for the generation and accumulation of relativistic plasmoids in a long magnetic mirror.

Acknowledgments
The publication was supported by the Russian Science Foundation (Grant No. 17–12-01470).

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