EXPERIMENTAL STUDY OF AN INTENSE RELATIVISTIC HELICAL ELECTRON BEAM FORMED USING INTERCEPTION OF THE ELECTRONS REFLECTED FROM THE MAGNETIC MIRROR*

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Abstract

A new method of formation of pulsed intense relativistic helical electron beams (HEBs) for gyroresonance devices has been presented. The method aimed at increasing the pitch-factor and reducing the velocity spread of HEBs is based on the application of a special diaphragm installed at the beginning of the transportation channel in a minimum of HEB paths. The electrons from the cathode primarily bend round the diaphragm, while the electrons reflected from the magnetic mirror (located between the cathode and the transportation channel) precipitate on the diaphragm. It is shown that the interception of the reflected electrons enables one to increase the HEB pitch-factor. Otherwise, the accumulation of space charge impairs HEB characteristics and induces HEB-current modulation.

INTRODUCTION

The prospects of raising the power of pulsed gyrotrons are associated with the use of HEBs having significantly relativistic particle energies and currents I close to the maximum (Langmuir) current J_L of the electron gun. At the same time, the specific character of gyrotrons, namely, the use of the oscillatory energy of electrons, requires HEBs with sufficiently high pitch-factors g (the ratio of transverse $v_\perp$ and longitudinal $v_\|$ components of the velocities in the operating space), while the spread of electrons over transverse velocities $\delta v_\perp$ is low [1]. These requirements are contradictory; hence the solution of the problem of the gyrotron power increase becomes more complicated.

Adiabatic magnetron-injection guns (MIGs) traditionally used for HEB formation are affected by the electron space charge impairing HEB characteristics. Therefore, most of gyrotrons employ HEBs with their currents amounting only to $(0.1 \div 0.2)\cdot J_L$ [1]. In guns with beam compression by an adiabatic magnetic field, a considerable excess of this current level limits the achievable pitch-factor, since the occurring fractions of electrons with high oscillatory velocities accumulate in the trap between the cathode and the area of a growing magnetic field. This reduces the pitch-factor, increases the transverse-velocity spread, and even results in a HEB stability loss [2]. Electron-optical calculations show that multiple transit of the electrons locked in the trap can lead not only to a spread of the electron velocity components at a constant value of the velocity, but also to an energy spread, that is a more dangerous factor of efficiency reduction of devices [3].

The solution of these problems was begun with the use of an electron-optical system (EOS) capable of fast and non-adiabatic ejection of electrons from the cathode to the high-potential area, and of simultaneous minimization of the number of the electron path periods from the cathode to the operating space of a microwave device [4]. As the study shows, this reduced the negative influence of the space charge and conserved a suitable quality and stability of the electron beam up to the currents of $(0.1 \div 0.2)\cdot J_L$. It should be noted that the trapped electrons also appeared under the conditions of non-adiabatic HEB formation at a higher level of current.

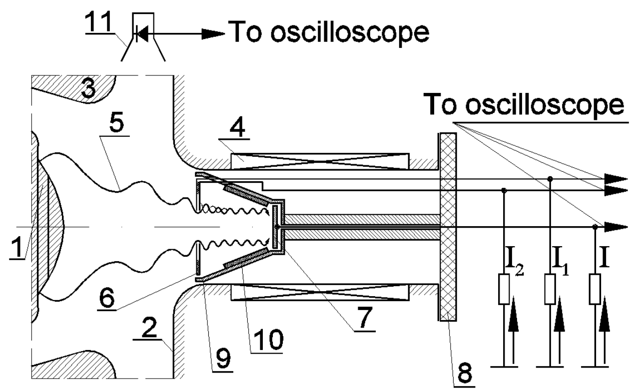

Figure 1: Schematic of the experiment: (1) cathode, (2) anode, (3) intermediate anode, (4) solenoid of guiding magnetic field, (5) electron beam, (6) diaphragm for separate current measurements of the electrons incident on it from the left I_1 and from the right I_2, (7) collector of the electron beam for measurement of current I, (8) dielectric flange, (9) cone, (10) microwave absorber, (11) receiving microwave horn.

Then, to eliminate the trapped electrons, we used characteristic features of the non-adiabatic MIG described above. It is typical of this EOS that the beam remains laminar at the first turns of the electron path, i.e., all particles in the primary beam oscillate approximately in phase close to the guiding field line. At the same time, after reflection in the non-uniform magnetic field their paths do not coincide with the primary ones. This allows intercepting a considerable part of the reflected flow by means of a diaphragm located in a minimum of primary electron paths (see 6 in Fig. 1). To conserve the configuration of fields in the gun, it is expedient to install the diaphragm inside the transportation channel, i.e., outside of the MIG electric field. High efficiency of

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eliminating the trapped electrons by this diaphragm was confirmed by the studies carried out under the modeling conditions (at reduced accelerating voltage of 11 kV in a wide range of currents up to the conditions of current limitation by the space charge) [5].

This work continues [5] and describes experimental tests of the proposed method of fast reflected-electron interception for the operating parameters of the beam (voltage 280 kV, current 60 A).

RESULTS OF THE EXPERIMENTAL STUDY

Similarly to [5], the study used the "Saturn" accelerator [6] and EOS of a high-power relativistic gyrotron with an operating frequency of 30 GHz and an output power of several megawatts. The gun possessed an impregnated aluminate-barium cathode [7] with an operating temperature of 1050 ÷ 1100°C. The gun operated under the conditions of temperature limitation of the cathode current.

The diaphragm location was determined by the technique thoroughly described in [5]. The technique involves a movable double diaphragm and a beam collector (see Fig. 1) both made of graphite to reduce the reflection of incident electrons. The diaphragm side nearest to the collector recorded precipitation of the electrons reflected from the magnetic mirror and prevented their incidence on the cathode side of the diaphragm; on the other hand, the collector side was protected from incidence of the primary beam electrons. By moving the electrode system along the longitudinal axis and by measuring currents on each side of the diaphragm and on the collector, one can determine the required location of the diaphragm and the interception degree of primary and reflected electrons.

To prevent self-excitation of the space between the diaphragm and the collector, the electrodes were fixed inside a cone made of stainless steel, whose inner surface was covered with plates of special microwave absorbent. It was ascertained in tests that under some conditions, spurious generation arising in spite of measures undertaken for its suppression could distort measurement results and naturally affect operation of a device. Onset of microwave radiation traveling towards the gun electrodes was monitored by a receiving waveguide horn placed near a high-voltage insulator of the gun and by typical recording equipment. The study has revealed that at the instant of the generation occurrence the collector current was growing, which testified to a loss of the oscillatory energy of electrons and a decrease of the pitch-factor. Furthermore, in some cases the generation onset caused strong distortions in the signal shapes of currents from the sides of the diaphragm, the collector, and even from the voltage sensor of the gun. This implies a considerable influence of microwave radiation on the gun operation, i.e., pre-breakdown conditions. These phenomena can be explained by a well-known scenario [8], namely, by electron microwave discharges, leading to desorption of residual molecules off the walls and their ionization, with creation of plasma rapidly propagating along the beam transportation channel, violating the conditions of beam formation, and initiating gun breakdowns.

The experiment has demonstrated that if spurious microwave radiation is absent or low, i.e., there are no intense discharges, one can considerably increase beam compression without signal shape distortions and gun breakdowns. The studies carried out without a diaphragm showed that at rather strong compression the collector current began to fall and could decrease more than twice. Therefore, the results of the modeling experiments under the space-charge-limitation conditions [5] indicating a decrease of the collector current due to the reflected electrons repeated qualitatively. According to the broad-band oscilloscope measurements, as the beam current reaching the collector decreases, its amplitude is strongly modulated at the frequency of longitudinal oscillations of the electrons in the trap (see Fig. 2). This result for gyrotron EOS first mentioned in [9] is also in a qualitative agreement with the numerical simulation results [10] which evidence that beam instability is caused by a large number of the reflected electrons involved by a large pitch-factor. The measurements also showed that the above-mentioned modulation can be eliminated by interception of the reflected electrons by the diaphragm.

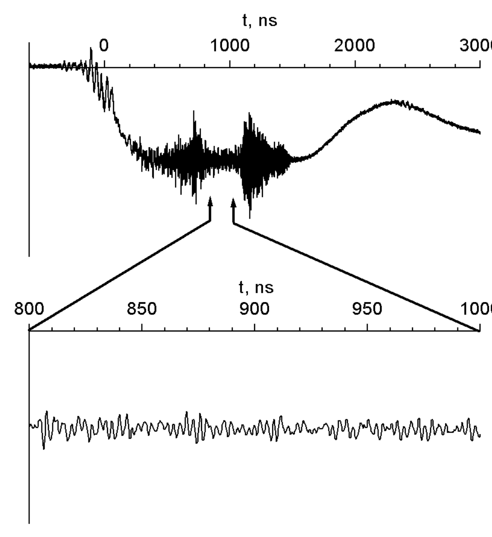

Figure 2: Oscilloscope record of the collector current modulated at the frequency of longitudinal oscillations of electrons in the trap.

Measurements with a diaphragm 34 mm in diameter showed that under the modelling conditions, the laminarity degree of the electron beam was sufficiently high. The diaphragm displacement by ±2 mm from the required position along the longitudinal coordinate has almost no influences on the current values on the diaphragm sides and the collector. Typical oscilloscope records of voltages and currents are presented in Fig. 3. It is seen that at the leading edge of the pulse when the oscillatory velocity of electrons is small, almost total current is intercepted by the cathode side of the diaphragm. As the voltage approaches the nominal value, the beam pitch-factor grows, electrons begin to bend round the diaphragm, and a current on the collector appears. It is also seen that a small increase in voltage at the pulse peak results in a drop of the collector current and in a growth of the diaphragm one, which corresponds to an increase in the number of the electrons reflected from the magnetic mirror with the pitch-factor growth.

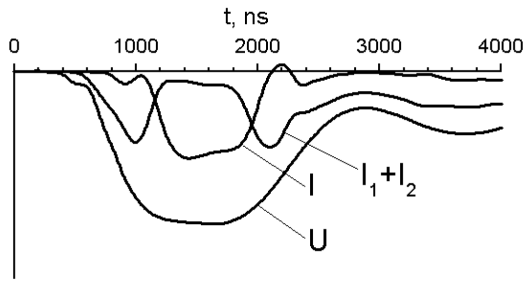

Figure 3: Typical oscilloscope records of voltage *U*, collector current *I*, and total current on both sides of the diaphragm.

The velocity spread measurement showed that the diaphragm installation led to a growth of the pitch-factor from 1.25 to 1.4, and to a decrease of the velocity spread from 25% to 20%. In this configuration, the transverse energy being an important beam parameter from the viewpoint of gyrotron efficiency remained practically constant in spite of a loss of some current on the diaphragm (12%). According to the preliminary current measurements, for the assigned values of compression and diaphragm diameter, the primary beam electrons bend round the diaphragm, while the current loss is caused by the interception of the reflected electrons. An attempt to increase the pitch-factor by enhancing compression in the presence of the diaphragm was successful, but the velocity spread increased due to a growing portion of electrons with low oscillatory velocities. These changes can be explained by an increase of the gap between the beam and the diaphragm at compression enhancement, and hence by penetration of part of the reflected electrons into the gun area. The smaller diaphragm 32 mm in diameter proved to be non-optimum from the viewpoint of current losses, but permitted to obtain record values of the pitch-factor. Application of this diaphragm enabled us to provide so strong compression of the beam that the primary beam electrons passed by the diaphragm and without reaching the collector (the appropriate current is zero) they turned round and were almost entirely intercepted by the collector side of the diaphragm. Thus one can, in principle, realize a beam with any value of the pitch-factor; however, this is compensated by the current loss and the larger the pitch-factor, the higher the loss. To confirm the above-stated, the velocity spread of the beam was measured by means of a magnet analyzer [5] at two compressions, when 60% and 30% of the beam current reached the collector, while the rest of the electrons were reflected and intercepted by the diaphragm. It follows from the results in Table 1 that record values of pitch-factors were obtained. In both cases, the velocity spread was about 10%, which also corresponded to the level of record values.

Table 1: Parameters of formed HEB

	Spread, %	**Pitch-factor**	**Formed HEB current, A**
1	10	2.1	35
2	13	2.7	20

Therefore, the experimental studies have shown that in the absence of a diaphragm the beam pitch-factor automatically reduces at enhanced magnetic compression due to the occurrence of reflected electrons. Besides, instability arises in the beam, which manifests itself as beam current modulation (depth of ~20%) at the frequency of longitudinal electron oscillations in the trap with a period of ~3 ns. The application of a diaphragm intercepting the reflected electrons, first, eliminates the beam current modulation and, second, allows forming beams with record values of the pitch-factor, though with a considerable current loss. At moderate beam compression, when part of the reflected electrons is small, their interception by the diaphragm makes it possible to raise the beam pitch-factor for the conserved total transverse energy of the beam in spite of a loss of part of the current on the diaphragm, and to decrease the velocity spread. In devices sensitive to velocity spread, the use of a diaphragm can result in an increase of their efficiency.

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