Electron Gun For Powerful Large Orbit Gyrotron

ELECTRON GUN FOR POWERFUL LARGE ORBIT GYROTRON

T. Idehara,[1] V. N. Manuilov,[1,2] O. Watanabe,[1] M. Kamada,[1] La Agusu,[1] K. Yatsui,[3] and W. Jiang[3]

[1]*Research Center for Development of Far-Infrared Region*
Fukui University
Bunkyo 3-9-1, Fukui 910-8507, Japan
[2]*Radiophysical Department of Nizhny Novgorod State University*
690005, Gagarin av., 23, Nizhny Novgorod, Russia
[3]*Extremely High-Energy Density Research Institute*
Nagaoka University of Technology
Nagaoka, Niigata, 940-2188, Japan

Abstract In the article, results of numerical simulation of the gun with the cusp of magnetic field are presented. Short pulse version of the gun with explosion emission is investigated. Some preliminary analytical estimation of the beam and gun parameters are performed. Then, numerical optimization of the electrodes shape as well as magnetic field distribution is carried out. For preliminary separation of electrons and formation of the rectilinear beam, anode diaphragm is installed. After then, additional selection of electrons for decreasing the ripple is performed. For this purpose, channel walls are used for interception of some part of the electron beam. Reverse of the magnetic field in the diode part of the gun is formed. So, the formation of the rectilinear beam is combined with the region, where electrons obtain initial gyration energy. To prevent the disperse action of the own beam space charge forces, the system with big gradient of magnetic field (about 0.5-1 kGs/mm) is needed. According to results of the simulation, helical electron beam can be performed even at total compression ratio about 1000 and current density more than 50 kA/cm^2. The designed electron gun provides acceptable performance for the large orbit gyrotron, such as operating current close to 300 A, the pitch-factor value about 1.5-1.7, deviation of the guiding centers from the axis (the ripple) $\lambda/10$ and $\lambda/6$ for operation on 3-rd and 5-th cyclotron harmonic correspondingly (wavelength λ=0.5 and 0.3 mm) and velocity spread within the range 10-15%.

Keywords: Large Orbit Gyrotron, Electron gun, Powerful gyrotron, Cyclotron harmonics

1. Introduction

One of the most important tasks in high power electronics is the development of RF sources in submillimeter wavelength region. Among a lot of different devices such as conventional gyrotrons, CARM and some others, which could reach, in principle, specified frequency range, one of the most promising is Large Orbit Gyrotrons(LOG) [1]. The most important advantages of this tube are rather small magnetic field in the operating region and decreasing of the problem of mode competition due to use of the operating mode with azimuthal index equal to the harmonic number. However, efficiency of such a device is rather small – usually several percents only [2]. In order to obtain high output power, it is necessary to use a powerful electron beam with large gyration radius.

Recently, in Extremely High-Energy Density Research Institute, the Nagaoka University of Technology, a High Voltage Power Supply with the accelerating voltage of 400 kV and the maximum beam current of 14 kA was developed [3]. This power supply was successfully used to get 170 MW microwave output power in virtual cathode oscillator [4]. In Research Center for Development of Far-Infrared Region, Fukui University (FIR FU), the SC magnet providing the operating magnetic field 12 T was already installed [5] and pulsed coil with the same intensity of the magnetic field is being developed. Combination of such a high voltage power supply with the magnet system providing the magnetic field of 12 T opens the possibility to construct a LOG, which achieves the border of terahertz frequency range with output power above of 1-2 MW under a short pulse operation.

In this paper, high power electron beam formation system for a LOG operating at third to fifth cyclotron harmonics is discussed. There are some ways to form axis-encircling electron beam, which is the most suitable for LOGs [6, 7]. Usually, the rectilinear electron beam is formed first. After then, it passes through the non-adiabatic magnetic field region provided by a undulater (kicker) or a cusped magnetic field. In such a region, electrons begin the gyration motion around the axis and finally the Helical Electron Beam (HEB) is formed. In centimeter or even millimeter wavelength region, the system with kicker is quite enough to form the HEBs with suitable quality [6]. But in submillimeter wavelength region, the magnetic compression ratio becomes larger (up to several thousands) and this effect enhances a velocity spread of beam electrons. At the same time, it is shown, that high quality of electron beam can be kept even in the systems with a cusped magnetic field. So, it seems that the system with a cusped magnetic field is reliable. In the following sections, the beam formation system with a cusp field is discussed.

2. A preliminary analytical estimation and a design of magnet system

Let us consider the following scheme of the system for formation of an axis-encircling electron beam (see Fig.1). An electron is accelerated in the electron gun in the axial direction up to the velocity v and then reaches the magnetic cusp region. We will consider the simplest case when the magnetic field is uniform in the gun region at the intensity of $-B_1$ and changes quickly in the cusp region to the intensity of $+B_2$. After that, electrons experience an adiabatic compression region where the field intensity is increasing up to value B_0. Of course, such a jumping magnetic field does not exist in real situation. However, it is a good approximation when the characteristic scale L_B of the magnetic field is much larger than the step h of electron trajectory. Usually, this condition is valid, because the value of the magnetic field B_C in the gun region is so small.

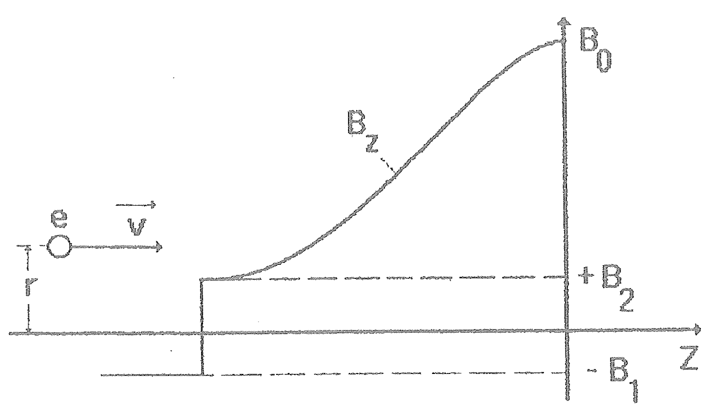

Fig. 1 Magnetic field distribution in the beam formation region.

On the basis of the Bush theorem, it is easy to find that the oscillatory velocity after the cusp is

$$v_{\perp 2} = r\frac{d\theta}{dt} = \frac{\eta r}{2}(B_1 + B_2)\,, \tag{1}$$

Here, $\eta = e/m$, e is an electron charge, m its relativistic mass. From this relation, we can derive that the relative velocity spread is

$$\delta v_{\perp} = \frac{\Delta r}{r}\,, \tag{2}$$

where Δr is the radial width of the beam at the cusp entrance. To suppress the velocity spread, it is necessary to use rather thin electron beams. It is easy to prove that the displacement of the guiding center from the axis is equal to zero only in the case of symmetric cusp ($B_1 = B_2$). Therefore, only this case will be considered below. Let us use the following notation: magnetic field intensity in cathode region $B_C = B_1$, cathode radius $r_C = r$, pitch-factor in the cavity $g = v_{\perp 0}/v_{\| 0}$, where $v_{\perp 0}$ and $v_{\| 0}$ are oscillatory and longitudinal velocities, c light velocity. In the case of jumping magnetic field, the radial position of electron is not changed. It is easy to obtain

$$B_c = \frac{g^2}{1+g^2}\frac{c^2(\gamma^2-1)}{(\eta r_c)^2 B_0}\,, \tag{3}$$

for given U_0 and B_0, where $\gamma = 1 + eU_0/m_0c^2$ and m_0 is the electron rest mass. Thus, we have only one free parameter, that is, cathode radius r_C.

Another important parameter is the beam current I. In real guns, only a part of the beam electrons have suitable trajectories with longitudinal velocity (see below chapter 4). In order to provide small velocity spread, we need to keep the ratio $\Delta r/r = \delta v_{\perp} = \text{const}$. If we introduce the current density j_C at the cathode surface, the current I may be represented in the following form

$$I = 2\pi\, \delta v_{\perp}\, r_C^2 j_C. \tag{4}$$

Usually, an electron gun producing a rectilinear beam operates in space charge limiting regime. In our case, the accelerating potential belongs to the intermediate region between non-relativistic and ultra high relativistic regions. Simple estimations show that for U_0=400 kV, the well-known Chaild-Lengmur low for j_C

$$J_c = \frac{4}{9}\varepsilon_0\sqrt{2\eta}\,\frac{U_0^{3/2}}{d^2} \tag{5}$$

gives more accurate prediction of current density. Finally, substituting the j_C into (4), we have the following relation between d and r_C:

$$d^2 = r_c^2 \cdot 2\pi \cdot \delta v_\perp \frac{4}{9}\varepsilon_0\sqrt{2\eta}\,\frac{U_0^{3/2}}{I} \tag{6}$$

As we have already mentioned, r_C is a free parameter. If we use a large value of r_C, magnetic field will be too small. It leads to increasing of the sensitivity of the formation system to the influence of the external magnetic field. It is well known that such fields can be about several Gauss at least. Actually, it would be better to use B_C higher than 100 Gauss. Finally, we choose r_C=5 mm. In this case, B_C=120 Gauss according to eq. (3). If I=300 A, $\delta v_\perp$=0.2, we can obtain d=8mm from eq. (6). We should note that chosen value of d allows to satisfy also the conditions when explosion emission from "cold" cathode takes place: $E_C = U_0/d > E_{min} =$ (0.3-1.0)10^8 V/m [9].

The system with a cusp magnetic field is characterized by the existence of rather long region with weak magnetic field intensity after the diode part of electron-optic system. In the specified region, a space charge force F_ρ is much stronger than the focusing magnetic force F_B. It may cause the large ripple and even intersection of electrons by the walls of transportation channel. To diminish the influence of the space charge forces, it is necessary to use as large gradient dB_z/dz of axial magnetic field as possible. The most natural way to produce large value of dB_z/dz is to use coils with small dimensions. We will consider a hot pulse coil with a small dimension which provides the field intensity B_0=12 T in operating space (see Fig. 2).

The cusp of the magnetic field is produced by the set of five cathode coils with the inner diameter of 200 mm. It allows to have small distance L_{CC}=130 mm cathode-cavity and $dB_z/dz \approx 0.5$-1 kGs/mm.

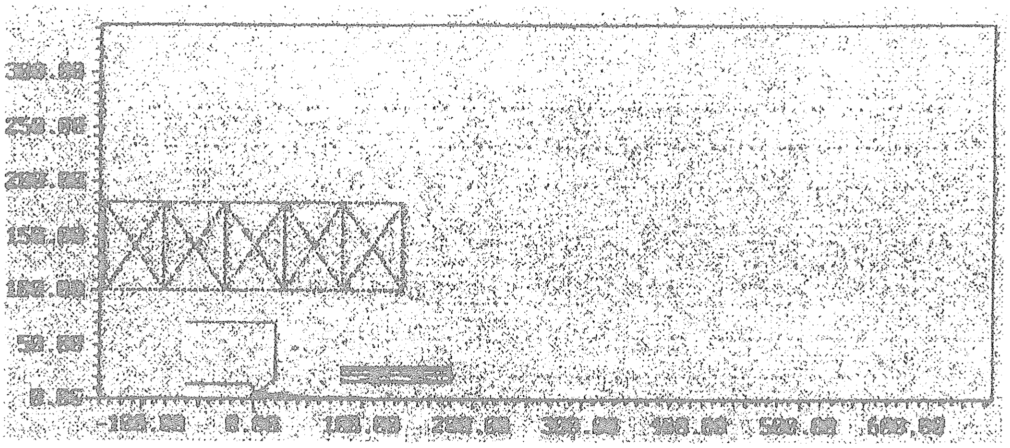

Fig.2 Main (right) and counterrunning coils (left) in pulsed magnetic system. Gun position is shown.

3. Electron gun design

First, we have to note that gun optimization for LOGs is essentially more difficult than the analogous task for conventional gyrotron MIGs, because of well known restrictions on values of pitch-factor and velocity spread. [9] It is necessary to keep very small deviation from the axis for guiding center position [1, 2, 7]. The task become even more complicated, if the explosion emission takes place due to two additional factors: extremely high space charge forces, which usually tend to break beam quality, and very wide and unpredictable emission area (see below).

The simulation was carried out on the basis of EPOSR code [10], which allows to take into account real space distribution of the magnetic and electric fields within two-dimensional model. The space charge forces as well as own beam magnetic field was also included into numerical model.

A thin hollow rectilinear beam is produced at first by an electron gun and passes through the cusp region. In principle, for this purpose two kinds of formation systems may be used. The first candidate is the "blade" cathode [11] with very small radius of cathode curvature and we obtain the "dotty" source of electrons. Such cathodes were successfully used in relativistic BWOs [12]. However, a simple analytical estimation as well as a numerical simulation shows that in our case we will have a very large angular dispersion which results in a large beam ripple and only a small part of current is able to follow in axial direction.

Next, the gun with "face plate" cathode is considered below. Recently, such guns were used successfully in gyro-TWTs to form an axis-encircling electron beam [13]. In the case, the emission takes place practically from all cathode area where the electric field $E > E_{min} \approx (0.3\text{-}1)10^8$ V/m. To provide the thin hollow electron beam propagating in axial direction, we have to cut out some part of the beam only by establishing special diaphragm. In this case, only some percents of total cathode current can enter to the cavity. When the explosion emission takes place, the cathode works in space charge limiting regime. So, the current density distribution depends on the strength of the electric field E on the emitter surface. The higher value of E is applied, the more current density is extracted. At the same time, in the "face plate" cathode, rather small part of the current passes through the beam channel in the longitudinal direction. It is necessary to diminish the useless part of the current. For this purpose, the gun geometry was optimized in such a manner as to diminish the corresponding electric field along the upper part of the cathode. As a result, emission takes place mainly from plate and arc parts of the cathode (see Fig. 3), where the electric field exceeds the lower boundary of explosion emission (30 kV/mm) and useless part of current became approximately 1.5 times lower. According to the results of numerical simulation, total cathode current is about 8 kA.

After the optimization of both the diaphragm shape and beam channel, calculated beam parameters are shown in Table 1 (see also Fig. 3):

Table 1 Optimized parameters of the electron beam.

Operating beam current	I=279 A
Mean pitch-factor	g=1.74
Velocity spread	$\delta v_{\perp}$=0.073
Average guiding center position	$R_{guid} \approx \lambda/6$

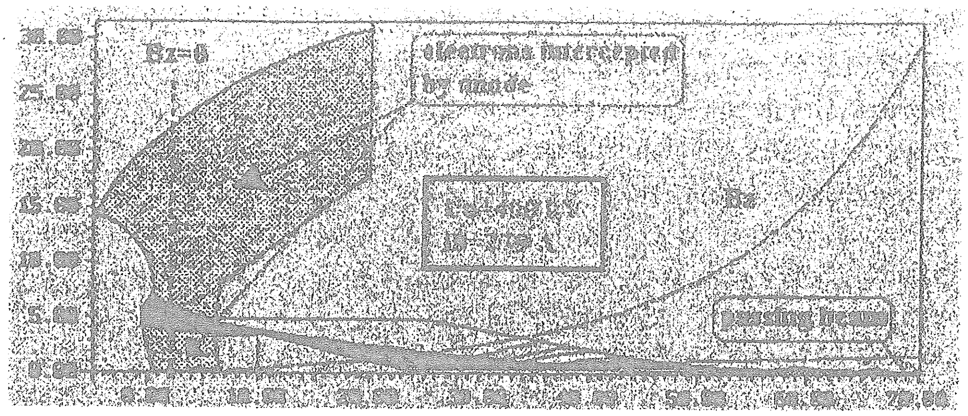

Fig. 3 Electron trajectories in the beam formation system

Position of the electron orbits is close to the position of "ideal" (i.e. rotating around the axis) electron beam (see Fig.4). Position of electron beam in the cavity will be the same (in the scale of gyration radius), because in the plane z=71 mm , $B_Z \approx B_0/3$ and force $F_\rho << F_B$.

Real operating regime differs from nominal due to some reasons. So, it is necessary to investigate the sensitivity of the gun to small deviations in operating regime. The special set of calculations was devoted to investigation of the following two factors:

1) changing of the full accelerating potential U_0 within the range ±20 kV from nominal;
2) changing of the current in the counter-running coil within the range ±2 % from nominal.

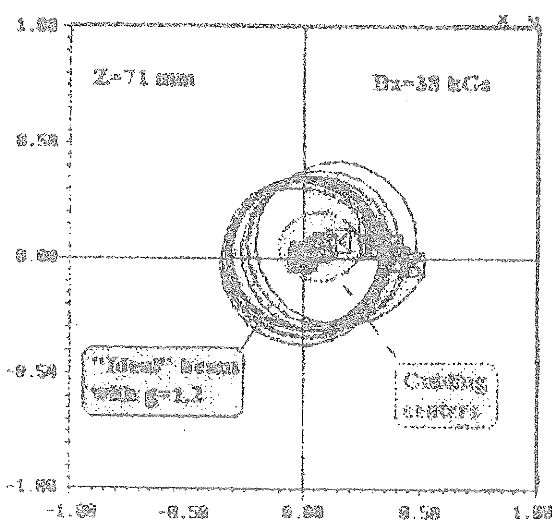

Fig. 4 Projection of one circle of electron trajectories passing through the channel on intermediate plane z=71 mm. All electrons start from the same azimuthal position θ=0.

The results of calculations are presented in Tables 2 and 3.

Table 2 Beam parameters corresponding to different values of U_0. In brackets, values corresponding to the third harmonic operation (n_H=3, λ=0.5 mm) are specified. R_{0mid}, R_{0min}, R_{0max} - correspondingly middle, minimum and maximum radial position of the guiding center in the cavity.

U_0, kV	I_{pass}, A	R_{0mid}/λ	g	$\delta\beta_\perp$	R_{0min}/λ	R_{0max}/λ
380	191	0.177 (0.106)	1.81	0.065 (0.213)	0.03 (0.02)	0.32 (0.19)
390	291	0.186 (0.111)	1.80	0.087	0.04 (0.02)	0.33 (0.20)
400	279	0.160 (0.096)	1.74	0.073	0.03 (0.02)	0.31 (0.19)
410	290	0.204 (0.122)	1.75	0.100	0.06 (0.04)	0.35 (0.21)
420	228	0.222 (0.133)	1.91	0.043	0.20 (0.12)	0.24 (0.14)

It is necessary to note that while the accelerating potential changes there are no essential changes in $\beta_\perp$ value. It is quite obvious, because the rotation energy depends mainly on the difference between values of magnetic field before and after the cusp. According to numerical data for lowest considered value of U_0=380 kV, there is some amount of electrons (about 10%) which are reflected from the magnetic mirror in the intermediate region between the cathode and cavity and then intersected with channel walls. In Table 2, two values of velocity spread with taking into account this fraction (see data in the brackets) and without this fraction are presented. The passing current decreases essentially, when the deviation from nominal regime exceeds ±15 kV. When the accelerating potential decreases, it is quite obvious, because the total current of the gun decreases (in a non relativistic approximation $I \sim U_0^{3/2}$, in ultra high relativistic $I \sim U_0$). In opposite case, the total gun current increases, but conditions at the entrance to the beam channel change and the part of electrons moving through the channel decreases. Some differences in values of current for the range of

$U_0 \subset [390\ \mathrm{kV},\ 410\ \mathrm{kV}]$ are caused by errors of discontinuity during numerical simulation.

So, it is possible to make the conclusion that admissible conditions are as follows; value of accelerating potential is 400±15 kV, slight deviation of the guiding centers close to $\lambda/6$, and velocity spread within the range 10-15%. If we consider 3-rd cyclotron harmonic, the deviation of guiding centers in the scale of wavelength is essentially smaller - $\lambda/10$ (see corresponding data in brackets).

Table 3 Beam parameters corresponding to different current in cathode coils. In the brackets, values corresponding to the third harmonic operation (n_H=3, λ=0.5 mm) are specified. ($I_{coilmax}$=300 A).

$I_{coil}/I_{coilmax}$	I_{pass}, A	R_{0mid}/λ	g	$\delta\beta_\perp$	R_{0min}/λ	R_{0max}/λ
0.81	280	0.182 (0.109)	1.19	0.152	0.02 (0.01)	0.34 (0.20)
0.82	280	0.181 (0.109)	1.43	0.114	0.02 (0.01)	0.33 (0.20)
0.83	279	0.160 (0.096)	1.74	0.073	0.03 (0.02)	0.31 (0.19)
0.84	279	0.173 (0.104)	2.15	0.055	0.05 (0.03)	0.29 (0.17)

According to Table 3, beam parameters depend on the coil current I_{coil} very weakly. The behavior of pitch-factor value is in good agreement with analytical estimations: while I_{coil} grows, the difference between both magnetic fields before and after the cusp grows and it leads to growing of oscillatory velocity. At the same time, the total velocity is kept constant, so pitch-factor also grows. According to the Table 3, the range of $I_{coil}/I_{coil\_max} \subset [0.81,\ 0.84]$ is admissible.

4. Conclusions

Possible ways to form powerful axis-encircling electron beam with energy 400 keV for a further use as an active media in submillimeter wavelength region LOG with output power up to several megawatt are considered. The guns with cusp magnetic field and explosion emission are studied. It is shown that for LOG with operating magnetic field 12 T, it should be possible to form HEB with current close to 300 A and current density more than 50 kA/cm^2, while the pitch-factor value is about 1.5-1.7 and velocity spread is within the range 10-15%. Middle deviation of guiding centers is $\lambda/10$ and $\lambda/6$ for 3-rd and 5-th cyclotron harmonic, correspondingly. Obtained beam parameters allow to reach beam power close to 120 MW and to expect LOG output power 2-5 MW in short-pulse operation in submillimeter wave region including the magic 1 THz benchmark.

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