Electron Optic System of Powerful Large Orbit Gyrotron with Pulse Magnetic Field

ELECTRON OPTIC SYSTEM OF POWERFUL LARGE ORBIT GYROTRON WITH PULSE MAGNETIC FIELD

V. N. Manuilov,[1,2] T. Idehara,[1] M. Yu. Glyavin,[1] LaAgusu,[1] M. Kamada,[1] T. Kanemaki,[1] Wiehua Jiang,[3] and K. Yatsui[3]

[1]*Research Center for Development of Far-Infrared Region*
University of Fukui
Bunkyo 3-9-1, Fukui 910-8507, Japan
[2]*Radiophysical Department of Nizhny Novgorod State University*
603950, Gagarin av., 23, Nizhny Novgorod, Russia
[3]*Extremely High-Energy Density Research Institute*
Nagaoka University of Technology
Nagaoka, Niigata, 940-2188, Japan

Abstract. Short-pulse powerful Large Orbit Gyrotron with total electron energy about 400 kV and beam power in the cavity up to 100 MW is now under developing at FIR FU. Suitable for 200 ns pulse duration electron-optic system is analyzed. Results of numerical simulation for explosion emission cusp-type electron guns and magnetic field intensity about 8 T are presented. Sensitivity of the guns to small deviations from the nominal operating regime is investigated. Some versions of the gun with different accelerating potential as well as different beam current passing through the cavity (60-300A) are suggested. Current reduction simplifies the problems of mode competition and potential depression in the cavity, but at the same time decrease output power. To diminish current special diaphragms are suggested. Results of numerical simulation of collector corresponding to each version of the gun design including power density distributions along its surface are presented. It is shown that beam quality and collector regimes are suitable for LOG operation.

Key words: gyrotron, cusp-type electron gun, collector, multi beam systems, numerical simulation

1. Introduction

One of the most promising tubes to obtain high power generation in millimeter and submillimeter wavelength region is Large Orbit Gyrotrons (LOG) [1]. The most important advantage of this device is rather small magnetic field in the operating region due to the possibility to operate on high cyclotron harmonic number. But efficiency of such devices is rather small – usually some percents only [2]. So, to obtain high enough value of the output power it is necessary to use powerful electron beam.

Short-pulse powerful LOG is now under developing at FIR FU. In the previous publication [3] the general scheme of formation of an electron beam with total power close to 120 MW was given. It is based on using explosion emission to get high current (about 300 A) and cusp magnetic field for further formation of the helical electron beam (HEB) with suitable for gyrotron operation parameters. A High Voltage Power Supply with accelerating voltage about 400 kV developed recently in the Nagaoka University of Technology [4] will be used to accelerate electrons to high energy. Operating magnetic field is formed by pulse magnet with rather small dimensions that simplify the problem of HEB formation.

Preliminary analysis predicts the operating field B_0 in the range about 8 T and the accelerating voltage U_0 – within the interval 380-400 kV to solve the problem of mode competition, which is one of the most complicated tasks in the development of powerful short millimeter wavelength electron tubes [5]. The diminution of beam current I_0 simplifies this problem. So, optimization of electron guns corresponding to several specified values of B_0, U_0 and I_0 are considered.

High power electron beam complicate the collector design also even for short pulse duration. Results of calculations of corresponding collector versions for specified above gun versions are presented below.

2. Electron guns with current 200-300 A

Previous tube version [3] with B_0=12 T had maximum anode radius R_{amax}=70 mm. But considerations of technical factors show that it is necessary to decrease the mentioned values down to magnetic field intensity B_0 =7.6 T and R_{amax} = 48.8 mm. This changing of the operating magnetic field and the gun geometry may lead to two factors.

First, the total cathode current will change. But planned power supply can provide the cathode current not more than 14 kA [4]. In the previous gun version cathode current estimation gave the value 8 kA [3]. Evidently, decreasing of the maximum anode diameter cause increasing of the cathode current and it is necessary to check whether it is within admissible range or not.

Second, changing geometry and the value of B_0 in 1.5 times cause big deviation of the beam parameters. In this case the new circle of electron optic system optimization is needed. Both questions are investigated below.

Our gun uses explosion emission. So, the operating area of cathode is defined by the electric field distribution along its surface. The boundary value of electric field E to start explosion emission approximately exceeds value $E_{min}\approx30$ kV/mm. According to the calculated electric field distribution, $E>E_{min}$ to the right from the plane $z\approx-17$ mm. So, we assumed that the left emission boundary is $z=-17$ mm (Fig.1). In this case, total current is close to 9.65 kA. So, decreasing of the anode outer diameter leads to essential growing (about 20%) of the cathode current. But it is still below the admissible level.

During the electron optic system optimization the shape of electrodes and dimensions of all coils was kept the same as in the previous version [3] to shorten the time of gun design. The new position of main and counterrunning coils and their currents were found. In particular, it was obtained that minimal admissible distance between emitter and cavity $\Delta Z_{main}=120$ mm is more preferable. The main beam parameters and its variation with voltage are given in Table 1.

In the gun with lower voltage U_0 velocity spread increases approximately in two times (see Table 1), because the shape of electrodes was optimized for initial value of $U_0=400$ kV, but it is still in the admissible range.

Real accelerating voltage as well as position of the coils and their currents may differ from nominal. So, next set of calculations was devoted to the calculation of the beam parameters when the gun regime is a little bit different from optimized. Below the following deviations were investigated:

- ✓ changing of full accelerating potential U_0 within the range ±20 kV;
- ✓ changing of the current in the counterrunnning coils and main coil within the range ±2%;

✓ changing of the main coil position on ±0.5 mm.

Table.1. Main parameters of the electron beam.

	U_0=400 kV	U_0=381 kV
Operating beam current I_0, A	279.7	191.4
Mean pitch-factor g	1.46	1.66
Velocity spread $\delta v_\perp$	0.063	0.156
Average guiding center position R_{guid}, mm	0.039	0.047
Gyration radius in the cavity $r_{\perp 0}$, mm	0.273	0.275

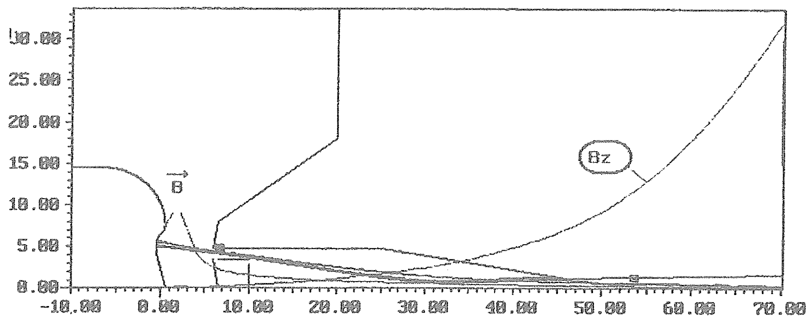

Fig.1. The shape of electrodes and magnetic field distribution in the channel region. Passing beam is shown.

According to the numerical data for all listed above deviations of operating parameters, velocity spread remains in the range 5-15% that is quite suitable for LOG operation. Deviation of the middle guiding center position from the axis does not exceed 0.07λ that is also essentially below the admissible level. When coils currents vary from the nominal values on ±2%, pitch-factor varies in the range 1.2-2.0. The same deviation of g is observed when the accelerating potential is varied in the range 380-420 kV. In this case the passing to the cavity current is between 200 and 300 A. In other cases the deviation of current not exceed 6% from nominal.

Comparison with the previous gun version [3] shows that the sensitivity of the new gun design is close to the gun with operating magnetic field 12 T and remains quite suitable for LOG operation.

3. Electron gun with decreased to 60 A current

Both considered in the previous item gun versions have big value of the operating current – between 200 and 300 A. It leads to two problems – big potential depression in the cavity and competition of operating mode with neighboring parasitic modes even when the second cyclotron harmonic is employed. According to calculations of starting currents and start-up scenario, both listed above problems are weakened, if the beam current I_0 decreases down to 60 A. For such big reducing of I_0 the correction of some parts of existing shape of electrodes must be performed.

The idea of decreasing operating current is to reduce the part of the current passing through the beam channel without changing conditions in the diode part of the gun (0 mm<z<6 mm – see Fig.1). Consequently, the geometry of the diode part is not changed. First possible approach is to reduce the gap between inner and outer anodes. If we want to obtain current 60A in electron gun with operating voltage 380 kV, we need to decrease the gap between inner and outer anodes approximately in three times (from initial value 1.3 mm to 0.4 mm, see Fig. 1). But in this case too high accuracy of alignment must be fulfilled. Second solution is to decrease the minimal radius of the beam channel R_{min} in the region 40mm <z< 50 mm. Preliminary estimations show that we have to change it on 0.2-0.3 mm. But again we need high accuracy of alignment and manufacturing of this part of the tube.

The most suitable method is to increase angular dimensions of the supporting lamellas of inner anode (Fig.2). The advantages of this way are the following:

- ✓ we keep rather big radial gap between inner and outer anodes;
- ✓ we have essentially more mechanical strength of supporting lamellas;
- ✓ we decrease the danger of overheating of supporting lamellas in many times.

There are some possible solutions for the suggested design: with one, two, four or even more sub-beams coming from anode hollows. To choose the most suitable solution we must keep in mind that we have some disadvantages as well.

First is the intersection of some part of subflow by the hollow walls due to the azimuthal drift. To reduce the current in the three times, the total azimuthal angle θ_{tot} of all sub-beams must be $2\pi/3$. The effect of azimuthal drift is small when the drift angle inside the hollow

$$\theta_{dr} << \theta_{tot}/N \quad (1)$$

where N – number of sub-beams. According to the results of numerical simulation $\theta_{dr} \approx 0.05$. So, our condition is valid even up to N=8 with big margin of safety. Of course, the less N, the better.

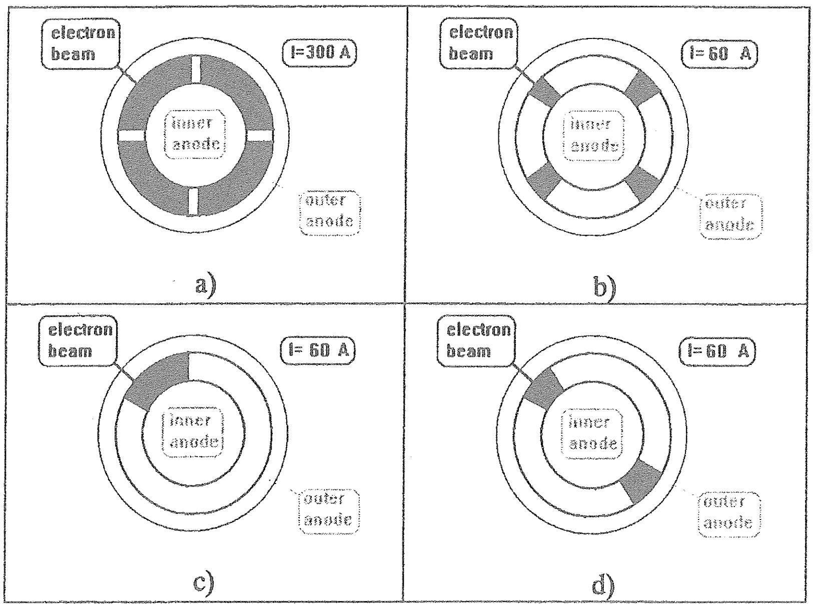

Fig.2. Initial form of the anode hollow with thin supporting lamellas (a) and some possible versions of thick supporting lamellas (b, c, d).

Then, to the right from the exit of the anode hollow the end distortion of the electric field produced by three-dimensional electrodes appears. But it seems to be rather small, because electrons have big longitudinal velocity and pass this region very rapidly. So, the most important and complicated problem is to diminish the influence of three-dimensional space charge distribution after the exit from the inner anode.

It is easy to understand that to the right from the inner anode the total space charge decreases in three times and besides that becomes three-dimensional. So, the conditions of electron beam formation change essentially, in principle. The disturbance of the beam parameters depends on the role of the space charge in the formation process after the inner anode exit. It is obvious, that if the deposit of the space charge forces F_ρ into this process in the region z>10 mm is negligible (see Fig.1), we obtain the same beam, as without supporting lamellas.

To investigate, what region of space charge is important for the beam formation, the code EPOSR [6] was modified in such a manner as to have the new option to "switch off" the space charge after some plane $z > Z_{switch}$. Three positions of plane $z=Z_{switch}$ was considered: $Z_{switch}=10$, 20, 30 mm. If $Z_{switch}=10$ (i.e. we switch off the space charge just after the exit from the anode hollows) all the beam is intersected by channel wall and there is no electrons coming to the cavity at all. Electrons are intersected mainly in the region $z\subset[40$ mm, 45 mm$]$ with minimal channel radius. If the plane Z_{switch} is shifted to $Z_{switch}=20$ mm, only about 10% of electrons passing through the anode hollow are able to overcome the region with minimal channel radius. But even for these electrons the oscillatory velocity become too high and finally they are reflected from the magnetic mirror before the cavity. And only if $Z_{switch}=30$ mm the beam parameters become close to the case, when all beam space charge is taken into account.

So, the region $z\subset[10$ mm, 30 mm$]$ (see Fig.1) is still very important for the beam to reach the cavity. It means that we must divide the beam on sub-beams in such a manner that the formation conditions are still close to axial-symmetric case in the specified above region. From this point of view, one sub-flow (see Fig.2) is the worst case. If N>8, the condition (1) violated essentially. It is better to keep the property of central symmetry. As a result, we have the choice among N=2, N=4 and N=8.

For N=8, the azimuthal angular dimension $\Delta\theta$ of each sub-flow is very small – only $\pi/12$. So the ratio of radial width of the beam Δr to linear azimuthal dimension $r_{beam}\Delta\theta$ is only about 1:1 and really the cross-section of sub-beam is close to a square (see Fig.3). In this case we shall have very big disturbance of the space charge electric field on the sub-beam edges in comparison with axial-symmetric beam and big difference in formation conditions even in the center of sub-beam. For N=4, the ratio $\Delta r/r_{beam}\Delta\theta\approx1:2$ and sub-beam is a rectangular with the specified ratio of sides (see Fig.3). So even from this consideration, it is seen that N=2 is the best, because we have biggest ratio $\Delta r/r_{beam}\Delta\theta \approx 1:4$ and keep central symmetry at the same time.

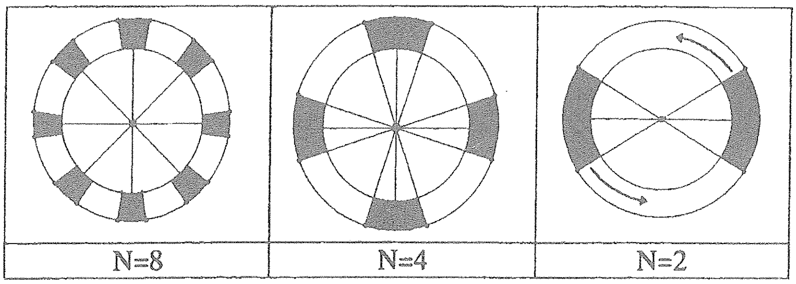

Fig.3. Position of sub-beams in azimuthal plane z=const. Arrows show the direction of rotation.

When any sub-beam passes through the region 10 mm< z <30 mm, it rotates around the axis. This fact may violate the central symmetry of the space charge distribution and leads to the formation of the whole beam as the double spiral. To keep the central symmetry conditions for space charge distribution, the azimuthal displacement $\theta_{dr\rho}$ of the sub-beam must be much smaller than the azimuthal angular dimension of sub-beam $\Delta\theta$ in the region, where the F_ρ action is important,

$$\theta_{dr\rho} << \Delta\theta \; . \qquad (2)$$

It is obvious, that it is quite easy for N=2 ($\Delta\theta=\pi/3$) to satisfy the above specified condition.

In the cylindrical channel, its walls screen the space charge forces with the scale close to channel diameter d_{chn}. Average channel diameter in the region $z\subset$[10 mm, 30 mm] $d_{chn}\approx$8-10 mm. So, the condition (2) must be valid within each interval with length about 8-10 mm inside the region $z\subset$[10 mm, 30 mm]. On Fig.4, the calculated dependence of angular position θ of the center of the sub-beam in the region $z\subset$[0 mm, 30 mm] is shown. It is seen that for N=2, condition (2) is valid with suitable accuracy. All of these facts lead to the conclusion that the most preferable case is N=2.

After plane z=30 mm, angle θ increases very rapidly: $\theta=10\pi$ even for z=70 mm. While, the spread of longitudinal velocities $\delta v_{\parallel} = g^2 \delta v_{\perp}$ is rather big. From data given in Table 1, we obtain in the cavity $\delta v_{\parallel} \approx 43\%$. The real velocity spread may be even bigger. So, in the intermediate region between z=30 mm and cavity, the beam is deformed from two spirals to the cylinder. It leads to two important conclusions. The first is that the potential depression in the cavity can be found from relation $\Delta U = I_0 \ln(R_{cav}/R_{beam})/2\pi\varepsilon_0\beta_{||}c$. Finally, we obtain ΔU=19.3kV for I_0=60A which is about 5% from full cavity potential. Next important conclusion is that for present tube design we can use axial-symmetric model for numerical analysis of interaction between the RF field and the electron beam, just as for calculations of the power density distribution in the collector region.

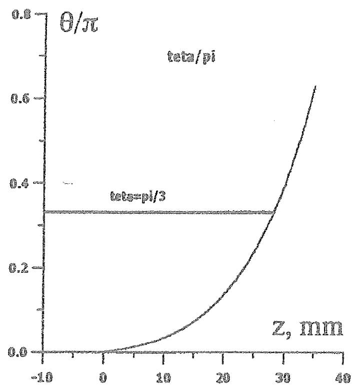

Fig.4. Angular position of electron in different planes.

4. Collector simulation

The power of the beam passing through the cavity may reach 120 MW. So, even for the pulse operation regime, the problem of the thermal effect on the collector is very severe.

The design of the present LOG has unusually difficult situations comparing with conventional electronic tubes and even most of LOGs with "hot" electromagnets axial magnetic field distribution. For case of LOG with cusp-type electron gun, existence of one reverse point of axial magnetic filed is typical (except LOG with post magnet – see [7]). But in our case, we have two such points: one is near emitter (see region $z \approx 3$ mm on Fig.1) and the other is in the collector region (see Fig. 5, 6). It leads to essentially smaller value of focusing magnetic field in the collector region. According to numerical calculation of the magnetic field, the absolute value of magnetic field intensity is less than 17 Gs in any point in the right hand side from the point of reverse. So, practically there is no any force to guide the beam after the point of reverse. But beam current I is very big – close to 300 A in the initial gun version. As a result, we may expect big influence of the beam own electric field on the beam track position and power density distribution as well.

It was assumed that in the cavity electrons are uniformly distributed over their phases of rotation and the form of the beam is like it is shown on Fig.7. The case for most "hard" collector regime when oscillations in gyrotron are absent is considered. Electron beam is considered as the set of some fractions with different position of guiding centers and different values of oscillatory velocity. The calculations were performed for the case of uniform distribution of guiding centers in the cavity within the radial interval [0.02 mm, 0.09 mm]. Oscillatory velocity distribution was chosen close to cosine one. Oscillatory velocity spread of 20 % was considered.

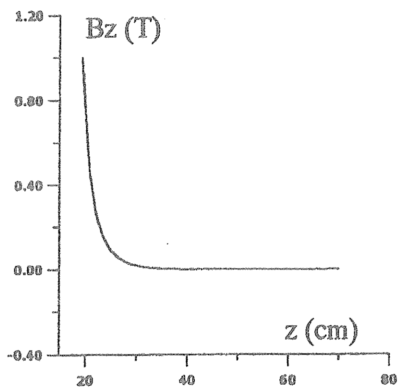

Fig.5. Common view of the axial magnetic field distribution in the collector region.

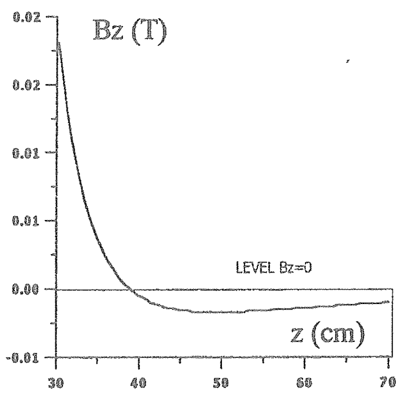

Fig.6. Axial magnetic field distribution in the zone of beam track on the collector.

Collector had cylindrical form with radius R_{coll}, except the "top" of collector, which had the form of cone with the radius of upper point r=0 and length of this part 20 mm. A few collector versions with R_{coll}=6, 8, 11 and 12.5 mm (maximum admissible value) are considered. Calculations were performed on the basis of EPOSR code [6] for two cases – with and without space charge force F_{ρ}. First case corresponds to the initial stage of the high voltage pulse when the "head" of the beam does not "feel" the own beam space charge forces. The second approach corresponds to the time interval when all relaxation processes are already finished and quasi-stationary state of the beam is established. Fig.8 illustrates the beam positioning in the collector area for collector radius of 12.5 mm.

Fig.9 presents power density distributions for both cases. Results of simulation show very big influence of the space charge on the beam track position and peak power density P_{max}. Space charge force $F\rho$ makes the track wider and pushes the track boundaries in both directions – to the cavity and to the top of the collector.

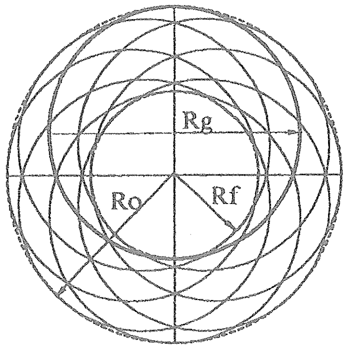

Fig.7. Qualitative picture of electron trajectories in the cavity. Projection of electron trajectories on plane z=const is shown.

Location z_{max} of the peak power point shifts toward the cavity due to the action of the space charge force, and peak power density becomes higher essentially. When space charge force $F\rho$ is neglected, value of P_{max} decreases from 10400 kW/cm^2 for R_{coll} =6mm to 2270kW/cm^2 for R_{coll} =12.5 mm. If $F\rho \neq 0$, P_{max}=15700 and 3670 for R_{coll}=6mm and 12.5mm, respectively. Displacement of z_{max} increases when R_{coll} is

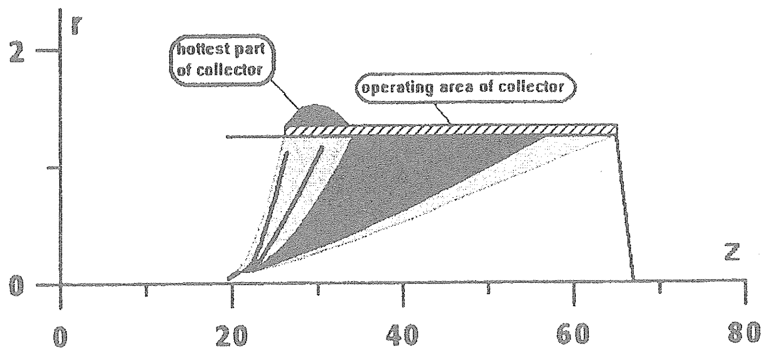

Fig.8. Zone of electron beam in the collector with biggest radius 12.5 mm. Trajectories corresponding to "central" part of the beam are shown. Black region corresponds to beam position when space charge forces are neglected.

increased and reaches approximately 7 cm for R_{coll} =12.5 mm. Difference between values of P_{max} corresponding to cases $F\rho=0$ and $F\rho \neq 0$ keeps approximately the same – about 50% (see Fig.9).

Value of P_{max} become quite acceptable when R_{coll} =11mm. Besides, for specified R_{coll} position of left boundary of the beam track

Z_{begin} is just on the border of admissible edge – z=268 mm. So, in practical design, collector radius R_{coll} =11mm can be used.

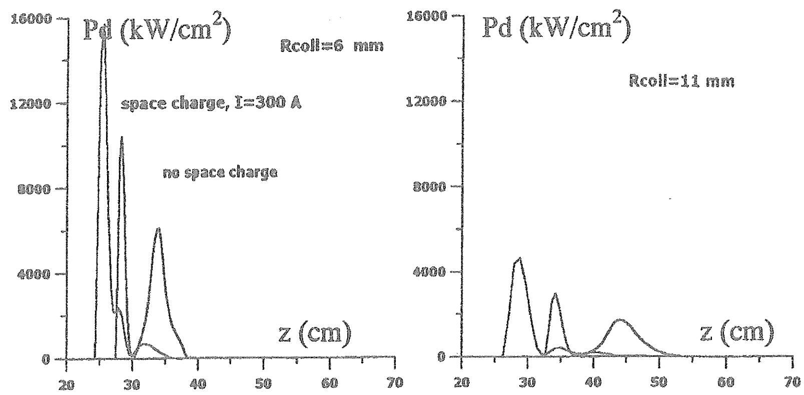

Fig.9. Power density distribution Pd(z) along the collector with R_{coll}=6 mm (left) and R_{coll}=11 mm (right).

The second version of collector corresponds to the gun with thick lamellas to reduce the passing current to 60 A. In this case, calculations were performed for collector radii R_{coll} = 6, 8, and 11 mm. Value of P_{max} decreases when R_{coll} is increased, and even for smallest R_{coll} =6 ·mm, P_{max}~2000 kW/cm^2. This is quite acceptable value of power density. For specified R_{coll}, position of left boundary of the beam track Z_{begin} is just on the border of admissible edge – 268 mm. However, in order to have some margin of safety, it is better to use in practical design collector with R_{coll} =8 or 11 mm.

5. Conclusion

Some versions of electron-optic system for powerful LOG with operating magnetic field close to 8 T are considered. It is shown that all versions form electron beam with pitch-factor value about 1.5-1.7 and velocity spread within the range 10-15% and have admissible sensitivity to small deviations from nominal operating regime. Operating current of considered electron guns vary between 200 and 300 A while accelerating potential changes in the range 380-400 kV. Total cathode current is essentially below maximum level admissible in the power supply.

To remove the problems of mode competition and potential depression in the cavity, the new gun version with beam current decreased to 60 A is suggested. For this purpose some thick lamellas between outer and inner anodes is installed to intersect the "superfluous" part of the passing beam. It is shown that optimum number of lamellas is two.

Two versions of collector - first for current I ≈300 A and second for I ≈ 60 A are considered. It is shown that position of the beam track and power density distributions are suitable for operation for both versions if collector radius is chosen close to 11 mm.

Acknowledgements

This work was supported partially by the Grant in Aid from Japan Society for Promotion of Science (JSPS) and RFBR Grant 02-02-17105. The design of the tube was carried out under nice collaboration among research centers in Japan (Fukui, Nagaoka) and Russia (Nizhny Novgorod).

References

[1] D.B. Mc Drmott, N.C. Luthmann, A. Kupiszewski, H.J.Jory, Small-signal theory of a large-orbit electron-cyclotron harmonic maser, Phys.Fluids., **26**, 7, 1936, (1983).

[2] V.L.Bratman, G.G.Denisov, Yu.K.Kalynov, S.V.Samsonov, A.V.Savilov, A.W. Cross, W.He, A.D.R.Phelps, K.Ronald, C.G.Whyte, A.R.Young, Novel types of cyclotron resonance devices, Proceeding of 4 th International Workshop on Strong Microwaves in Plasmas (held in Nizhny Novgorod, Russia), Vol. 2, pp. 683-702, (2000).

[3] T. Idehara, V.N.Manuilov, O. Watanabe, M.Kamada, La Agusu, K. Yatsui and Wiehua Jiang. Electron Gun for Powerful Large Orbit Gyrotron. Int. J. of Infrared and MM Waves, **25**, 1, 3, (2004)

[4] A.Tokuchi, N. Ninomiya, W. Jiang, K.Yatsui, Repetitive pulsed-power generator 'ETIGO IV', IEEE Transactionson Plasma Science, **30**, 1637, (2002).

[5] V.L.Bratman, B.S.Dumesh, A.E.Fedotov, V.N.Manuilov, Yu.K.Kalynov, M.M.Ofitserov, F.S.Rusin, S.V.Samsonov, Powerful sources of coherent submillimeter-wave radiation, Proceeding of 5 th International Workshop on Strong Microwaves

in Plasmas (held in Nizhny Novgorod, Russia), Vol. 1, pp.135-143, (2003).
[6] P.V. Krivosheev, V.K.Lygin, V.N. Manuilov, Sh.E.Tsimring, Numerical simulation models of forming systems of intense gyrotron helical beams, Int. J. of Infrared and MM Waves, 22, 1119, (2001).
[7] M. Glyavin, S. Sabchevski, T. Idehara, I.Ogawa, S.Mitsudo, K.Ohashi and H.Kobayashi, Numerical analysis of weakly relativistic large orbit gyrotron with permanent magnet ststem, Int. J. of Infrared and MM Waves, 21, 1211, (2000).