Formation of Laminar Electron Flow for a High-Power Sub-THz Gyrotron

Yuusuke YAMAGUCHI, Yoshinori TATEMATSU, Teruo SAITO, Ryosuke IKEDA, Jagadish C. MUDIGANTI, Isamu OGAWA and Toshitaka IDEHARA

Research Center for Development of Far-Infrared Region, University of Fukui, Fukui 910-8507, Japan

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This paper describes the design of a magnetron-injection gun for a 100 kW, 300 GHz gyrotron. With an increase in power and frequency, performance of the gyrotron becomes quite sensitive to the quality of the electron beam. Formation of a laminar electron flow is essential for the realization of a high quality beam with small velocity spread. In this study, a new method is proposed for the evaluation of the laminarity, and applied to the design optimization of the electrodes. It is found that the laminarity depends not only on the conventional design parameter of the cathode slant angle, but also on the spatial distribution of the electric field inside the beam.

Keywords: gyrotron, magnetron-injection gun, space charge effect, velocity spread, laminar flow

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Gyrotrons are capable of providing high-powers at millimeter and sub-millimeter wave lengths, and widely used in various fields of physics study and technological use. In the field of nuclear fusion research, MW class tubes with the frequencies from 28 to 170 GHz have been already utilized [1, 2]. Recently, development of a high power source in the sub-THz region is expected for the measurement of collective Thomson scattering (CTS) in the fusion plasmas. For use in the CTS diagnostics, an oscillation power of more than 100 kW is required at the frequency range of 300 ~ 400 GHz [3, 4]. In FIR, Univ. of Fukui, development of a high power tube is currently in progress. The frequency is set at 295 GHz with a magnetic field strength of 11.4 T in the cavity. In this study, the design consideration of a magnetron-injection gun (MIG) is performed by use of an electron trajectory code EGUN [5].

In order to achieve the output power of over 100 kW, an electron beam voltage of 65 kV, and current more than 10 A are required with the velocity pitch-factor α (the ratio of perpendicular to parallel velocities to the magnetic field line) of 1.2. The spread of α,

$$\alpha_{\text{spread}} \equiv (\alpha_{\text{maximum}} - \alpha_{\text{minimum}})/\alpha_{\text{average}}, \quad (1)$$

should be minimized because it decreases the oscillation efficiency and may cause the magnetic mirror reflection of a part of the electrons. With an increase in power and frequency, a large-current beam is compressed by an extremely strong magnetic field near the cavity. Then the beam will have a larger-current density, which enhances the influence of the space charge force on α_{spread}. Formation of a laminar electron flow is essential for reduction of the space charge effect and for realization of a high quality beam with small α_{spread} [6].

A triode structure is adopted to control the beam properties without changing the total beam energy. Figure 1 represents the schematic drawings of the electrodes which are used for the numerical computation of the beam trajectory. The radius of the cavity is 3.4 mm. In order to couple to the selected mode of $TE_{14,2}$, the electron beam should be injected into the cavity with the radius R_b of 2.42 mm. The radius of the emitting ring is set to 17.6 mm, from which the guiding-center of the electron arrives at R_b = 2.42 mm in the cavity. In this geometrical design, the magnetic compression ratio between the cavity and the emitting ring becomes 53.2. The distance between the cathode and first anode of 6.5 mm is derived under the condition, where the expected α at the cavity of 1.2 is obtained with the voltage V_{KA} between the cathode and the first anode smaller than 25 kV.

In the design optimization of the MIG, the beam trajectories, α_{average} and α_{spread} at the cavity are calculated for various shapes of the electrodes. An example of the calculated beam trajectories is shown in Fig. 1. The conventional design parameter has been the slant angle θ of the

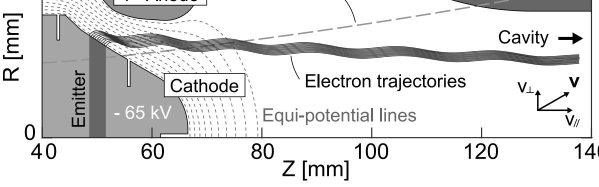

Fig. 1 An example of the electron beam trajectories.

author's e-mail: y-yama@fir.u-fukui.ac.jp

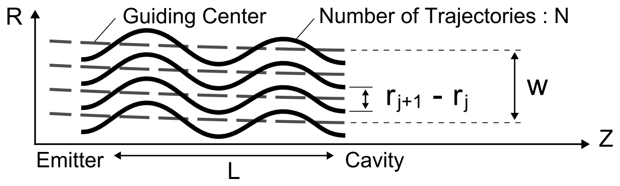

Fig. 2 Estimation of the laminarity.

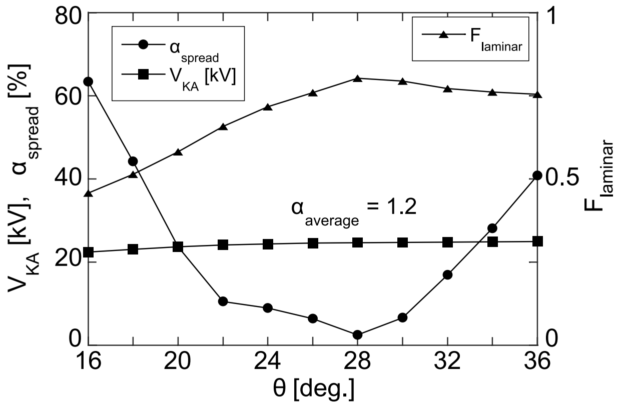

Fig. 3 Variation of the V_{KA}, the α_{spread} at the cavity and the laminarity as functions of the slant angle θ. By changing the V_{KA}, the averaged value of α at the cavity is fixed at 1.2.

emission surface to the magnetic field line, which should be larger than 25 degree for making a well laminated flow [7]. However, no method has been reported so far for the quantitative evaluation of the laminarity in the gyrotrons. In this study, the laminarity is newly defined as follows (Fig. 2, Eq. (2)),

$$F_{\mathrm{laminar}} \equiv \frac{1}{L}\int_L \frac{1}{1+d(z)}dz,$$
$$d(z) = \frac{1}{N-1}\sum_{j=1}^{N-1}\left|\frac{r(z)_{j+1}-r(z)_j}{w(z)/(N-1)}-1\right|, \qquad (2)$$

where, N is the number of the trajectories used for the calculation, r_j represents the radial position of the j-th trajectory numbered from the innermost trajectory. Each variable in Eq. (2) corresponds to the one in Fig. 2. The thickness w of the beam at the axial position z is estimated from the difference between the outermost and innermost guiding-center radii which are traced from both ends of the emitter. If all trajectories are placed at equally-spaced intervals over the axial length L from the emitting ring to the cavity, the value of F_{laminar} becomes unity. By use of this equation, it is confirmed that the calculated laminarity is closely connected with the slant angle θ and α_{spread} at the cavity (Fig. 3). In the calculations of the values shown in Fig. 3, $\alpha_{\mathrm{average}}$ at the cavity is kept to 1.2 by adjusting the V_{KA}, which is indicated at the left side longitudinal axis. As is clearly shown in the figure, the laminarity and α_{spread}

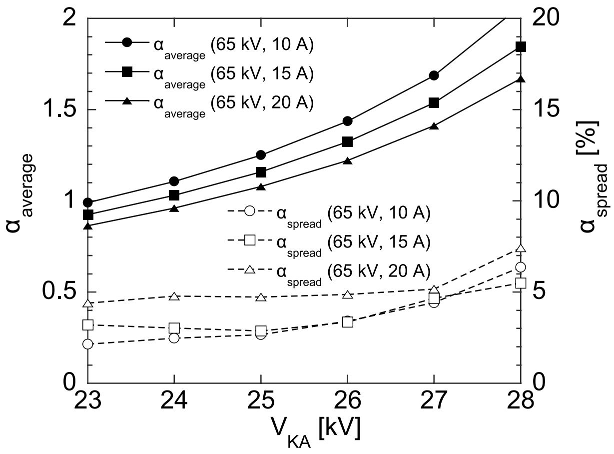

Fig. 4 Calculated pitch-factor α and α spread for the beam voltage of 65 kV, and the current of 10, 15, 20 A.

are not monotonically varied with θ. θ has an optimum value, with which the higher laminarity and smaller value of α_{spread} are realized. However, the reason why α_{spread} becomes worse rapidly at θ larger than 28 degree whereas F_{laminar} does not change so much is not clear at the moment. As the value of w increases with θ, the sensitivity of α_{spread} on F_{laminar} may become weak. Moreover, additional factors may play some roles on α_{spread} at θ larger than 28 degree. Exploration of these factors is one of the important future works.

The optimum value of θ depends on the detailed shapes of the first anode and the cathode, which determine the spatial distribution of the electric field. Therefore, the formation of a well laminated flow depends not only on the slant angle θ, but also on the spatial distribution of the electric field along the beam. In a well laminated beam, it is revealed that the axial pitch of each helical motion is modified so that every electron in the plane perpendicular to the field line has almost the same gyro-radius and almost the same phase of the gyration after passing between the cathode and the first anode. The resultant space charge distribution is almost uniform, and hence local concentration of the charge disappears.

We have carefully varied the spatial distribution of the electric field by changing the shapes of the electrodes, so as to minimize the α_{spread}. In this process, F_{laminar} is used as a useful figure of merit. The value of θ is finally determined at 28 deg. This results in a good configuration of the electrodes as well as a wide operation window of the MIG. In Fig. 4, $\alpha_{\mathrm{average}}$ and α_{spread} at the cavity are plotted as functions of V_{KA}. In the parameter range shown in Fig. 4, no mirror reflection of the electrons occurs. The $\alpha_{\mathrm{average}}$ decreases with increasing the beam current. The reason for this is thought to be the depression of the beam extraction voltage in the vicinity of the cathode, because of the space charge. However, the desired value of the $\alpha_{\mathrm{average}}$ of 1.2 are realized even at the beam current larger than 10 A. In all cases, the relatively low α_{spread} less than 5% has been achieved in the expected operating region of $\alpha_{\text{average}} = 1.0 \sim 1.3$.

An electron gun which is suitable for the new high-power sub-THz gyrotron has been successfully designed. In the future, we plan to clarify the relation between the laminarity and the profile of the electric field inside the electron beam.

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