Ultra-High Velocity Ratio in Magnetron Injection Guns for Low-Voltage Compact Gyrotrons

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Abstract: Low-voltage compact gyrotron is under development at the University of Electronic Science and Technology of China (UESTC) for industrial applications. Due to the low operating voltage, the relativistic factor is weak, and interaction efficiency could not be high. Therefore, a magnetron-injection gun (MIG) with an extremely high velocity ratio $\alpha$ (around 2.5) is selected to improve the interaction efficiency. As beam voltage drops, space charge effects become more and more obvious, thus a more detailed analysis of velocity-ratio $\alpha$ is significant to perform low-voltage gyrotrons, including beam voltage, beam current, modulating voltage, depression voltage, cathode magnetic field, and magnetic depression ratio. Theoretical analysis and simulation optimization are adopted to demonstrate the feasibility of an ultra-high velocity ratio, which considers the space charge effects. Based on theoretical analysis, an electron gun with a transverse to longitudinal velocity ratio 2.55 and velocity spread 9.3% is designed through simulation optimization. The working voltage and current are 10 kV and 0.46 A with cathode emission density 1 A/cm$^2$ for a 75 GHz hundreds of watts’ output power gyrotron.

Keywords: velocity ratio; velocity spread; low-voltage; gyrotrons; MIG; particle simulation; space charge effects

1. Introduction

Gyrotron is a kind of vacuum electronic device, of which the operation is based on the stimulated cyclotron radiation of electrons oscillating in a strong magnetic field. In a gyrotron, electrons that are emitted by the cathode, are accelerated in a strong electric field. While the electron beam travels through the intense magnetic field, the electrons start to gyrate at a specific frequency given by the strength of the magnetic field. In the beam–wave interaction circuit, located at the position with the highest magnetic field strength, the electromagnetic radiation is strongly excited. The output radiation leaves the gyrotron through a window and the spent electron beam is then dissipated in the collector. In general, the cyclotron interaction condition is $\omega - k_z v_z \approx s\Omega_e / \gamma$, where $\omega$ is the frequency of the electromagnetic wave, $k_z$ is the axial wave number of the operating mode, $v_z$ is the axial velocity of the electron passing through the cavity, $s$ is the harmonic number, $\Omega_e (= eB_0 / m_e c)$ is the rest-mass (m_e) electron cyclotron frequency, and $\gamma$ is the relativistic factor of the electron. As the above principle of stimulated cyclotron radiation, the electrons energy can be transferred to the fast-wave in the interaction circuit. Thus, it can be operated at high-order mode in the cavity, the dimensions of the
interaction structure can be much larger compared to the wavelength of the radiation, which provides capability to generate extremely high-power radiation.

Due to its excellent power output in the millimeter-wave and sub-millimeter wavebands, gyrotron has caused extensive and in-depth research by experts and scholars all over the world [1]. Lots of researches are focused on high-power, high-voltage gyrotrons used in ITER (International Thermonuclear Experimental Reactor), EAST(Experimental Advanced Superconducting Tokamak), etc. [2]. Currently, low-voltage gyrotron with hundreds of watts to several kilowatts output power has been arousing the interest of many scientists, because they are preferable from the engineering and reliability point of view [3,4]. For low-voltage gyrotrons, the problem of efficiency must be solved due to the weak relativistic factor. A prodigious amount of work has been done to improve the efficiency of gyrotron, like installing depressed collectors [5], changing the interaction structure [6], and using double electron-beam [7,8]. In this paper, we proposed a way to improve the beam–wave interaction by increasing the pitch factor. The interaction process of the gyrotron is mainly between the transverse electron cyclotron velocity and the perpendicular electric field, so increasing the velocity ratio can directly improve the interaction efficiency and thus becomes a key method to improve the efficiency of the low-voltage gyrotron. The efficiency of interaction is limited by the \( \eta = \frac{E_\perp}{E_{\text{Total}}} \leq \frac{a^2}{1 + a^2} \), where \( E_\perp \) is the transverse energy, \( E_{\text{Total}} \) is the total beam energy, \( \alpha = \frac{V_\perp}{V_z} \). Electron efficiency \( \eta_e \) was shown in Figure 1, when the velocity ratio reaches 3 the electron efficiency comes to 90% which is remarkable during the beam–wave interaction [9]. This scheme adopts a triode type magnetron injection gun with thermionic cathodes within the velocity spread under 10% [8]. The final ratio of transverse to longitudinal velocity in the interaction region is typically between \( \alpha = 1 \) and \( \alpha = 2 \) for gyrotrons [10]. The most frequent velocity ratio used in the MIG is 1.5 and it rarely exceeds 2, so the feasibility of ultra-high velocity ratio (MIG) is particularly valuable in compact gyrotron. In 2007, MIT has achieved a 3.5 kV gyrotron with a MIG, velocity ratio ranges from 2 and 5 with an operating current 10 mA [11]. The present development status of low-voltage (less than 10 kV) gyrotron improves the efficiency by increasing the pitch factor within low velocity spread, which are shown in Table 1. However, the operating current is often extremely low around 100 mA, with an output power of 10 W.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Effect of the velocity ratio variation on limiting current with different beam voltage.
Table 1. Performance parameters of latest low-voltage gyrotron.

| Institution        | Voltage (kV) | Current (mA) | Pitch Factor ($\alpha$) | Velocity Spread | Power (W) | Efficiency |
|--------------------|--------------|--------------|-------------------------|-----------------|-----------|------------|
| MIT [11–15]        | 3.5          | 50           | 2                       | 8%              | 12        | 6.8%       |
|                    | 12.3         | 25           | No Mention              | No Mention      | 14        | 4%         |
|                    | 13           | 100          | 2                       | 4%              | 16        | 1.2%       |
|                    | 10.1         | 190          | 2                       | 4%              | 18        | 0.9%       |
|                    | 16.65        | 110          | 1.8                     | 3%              | 9.3       | 0.5%       |
| FIR FU [16]        | 10           | 50           | No Mention              | No Mention      | 10        | 2%         |

MIT (Massachusetts Institute of Technology)
FIR FU (Research Center for Development of Far-Infrared Region, University of Fukui)

The required properties of the electron beam are basically determined by the chosen operating mode, frequency, and output power [3,17]. Parameters of this specific low-voltage gyrotron are shown in Table 2. According to the theory of space charge effects, the operating current is restricted. At the same time, considering the power requirements, beam voltage and current should reach a certain level. Restrictions of velocity ratio are investigated including the electrostatic field, limiting current, and velocity spread. Both theoretical analysis and particle-in-cell (PIC) simulation are adopted to investigate the feasibility of ultra-high velocity ratio MIG and give a specific design of MIG. The purpose of the present paper is to analyze the possibilities of ultra-high pitch-factor ($\alpha$) for MIG operating at low-voltage with operating current about 500 mA. This paper is organized as follows. In Section 2, fundamental effects electrostatic and magnetostatic field on the $\alpha$ are analyzed theoretically, space charge effects in low-voltage operation are demonstrated, and velocity spread relevant to pitch factor is studied. In Section 3, a numerical simulation is implemented to obtain a specific MIG with ultra-high $\alpha$ and appropriate velocity spread. Variation of $\alpha$ and perpendicular velocity spread ratio with operating current and modulating voltage are studied. Conclusions and plans are discussed in Section 4.

Table 2. Basic specifications of low-voltage gyrotron.

| Parameters            | Value       |
|-----------------------|-------------|
| Operating Mode        | TE01        |
| Beam Voltage ($U_b$)  | 10 kV       |
| Beam Current ($I_b$)  | 0.5 A       |
| Output Power ($P$)    | 0.5 kW      |
| Output Frequency ($f$) | 75 GHz     |
| Main Magnet ($B_0$)   | 2.7 T       |

2. Theoretical Calculation

2.1. Sensitivity Analysis of $\alpha$ for Axisymmetric Electric and Magnetic Field

The MIG is immersed in the crossed uniform electrostatic field and magnetic field. The electric field distribution is mainly determined by the geometry, voltage of the cathode, and modulating anode. The magnetic field is a uniform axial magnetic field that can ignore the radial component. Electrons moving in the increasing magnetic field leads to the momentum conversion to the transverse direction which is called adiabatic compression. According to adiabatic approximation theory, the transverse velocity at the ending position of the MIG area $\beta_{\perp 0}$ is defined by [18]:

$$
\beta_{\perp 0} \approx \frac{1}{\gamma_0 c} b^{1/2} E_c \cos \theta_c = \frac{1}{\gamma_0 c} \frac{B_0^{1/2}}{B_c^{3/2}} E_c \cos \theta_c
$$

(1)
$b$ is the magnetic compression ratio $b = B_0 / B_c$; $B_0$ and $B_c$ are main magnetic field and cathode magnetic field, respectively. Magnetic compression could not be too high in case electrons reverse. $\gamma_0$ is the relativistic factor within the beam voltage in the absence of voltage depression, $E_c$ is defined by

$$E_c \approx U_{\text{mod}} \frac{\cos \theta_c}{R_c \ln[1 + (d \cos \theta_c)R_c]}$$

(2)

$d$, $R_c$, $\theta_c$ are geometric factors which are shown in Figure 2, the MIG’s Schematic. $U_{\text{mod}}$ is the modulating anode voltage. So the velocity ratio could be defined by:

$$\alpha = \frac{\beta_{\perp 0}}{(\beta_{\perp 0}^2 - \beta_{\perp 0}^2)^{1/2}} = \frac{\beta_{\perp 0}}{(1 - \gamma_0^2 - \beta_{\perp 0}^2)}$$

(3)

where $\beta_0$ and $\gamma_0$ are the normal velocity and constant relativistic factors that are determined by the accelerating voltage $U_b$. Actually, the beam voltage has little influence on the $\alpha$, and $\alpha$ can increase dramatically with the modulating anode voltage. Based on these equations, the pitch factor could be higher enough; however, Equations (1)–(3) have not taken the space charge effect into account. So the trade-off about these parameters is significant to investigate.

![Figure 2](image_url)  

**Figure 2.** Schematic outline of the MIG.

### 2.2. Space Charge Limits

The space charge effect of the gyrating beam is defined in terms of the voltage depression $V_{\text{dep}}$ and the limiting current $I_L$ [19,20]. The potential within the electron beam is reduced with respect to the wall potential due to the space charge in the electron beam. In a cylindrical waveguide, the depression voltage is the potential between the waveguide wall and the electron beam axis.

$$V_{\text{dep}} = \frac{1}{4\pi \epsilon_0 c} \frac{I_b}{B_\parallel} G(R_i, R_o, R_a)$$

(4)

where the $G(R_i, R_o, R_a)$ is called the geometrical factor defined by:

$$G(R_i, R_o, R_a) = 2 \ln\left(\frac{R_o}{R_i}\right) + \left[1 - \frac{2R_i^2}{(R_o - R_i)(R_o + R_i)} \ln\left(\frac{R_o}{R_i}\right)\right]$$

(5)

where $R_o$, $R_i$, and $R_a$ are the radius of the interaction waveguide, the out-radius of the electron beam, and the inner-radius of the electron beam which are determined by the specific requirements of the interaction, $\beta_{\parallel}$ is the longitudinal velocity normalized to light velocity. The cross-section of the orbital cyclotron electron beam is shown in Figure 3. The average radius of guiding electron beam is defined by:

$$R_S = \frac{R_c}{b^{1/2}}$$

(6)
The $R_c$ is the radius of the cathode. When a thin annular beam with the $R_o - R_i << R_i$, the geometrical factor can reduce to $G(R_i, R_o, R_d) \approx 2 \ln(R_d/R_g)$, which results in:

$$V_{dep} \approx 60 \frac{I_a}{P_{eq}} \ln \left( \frac{R_d}{R_g} \right)$$

(7)

Based on the designed parameters, the geometrical factors are obtained. Coupling efficiency between the electron beam radius $R_g$ and desired modes, which is satisfied as followed:

$$C_{mn} = \left( \frac{s^2}{2^{s+1}} \right)^2 \frac{j_{m+2}^2(k_{mn} R_g)}{(x_{mn}^2 - m^2)j_{in}^2(x_{mn})}$$

(8)

where $s$ is the harmonic order, $k_{mn}$ is the eigenvalue of TE$_{mn}$ mode, $x_{mn} = k_{mn}/R_d$.

![Figure 3. Schematic view of the electron beam cross-section at an arbitrary axial position.](image)

The coupling efficiency of adjacent modes were shown in Figure 4, the guiding radius of 1.2 mm was chosen as the operating electron beam radius. In addition, the main electron beam factors are exhibited in Table 3 [19].

![Figure 4. The coupling factor of different modes variation on beam radius.](image)
Table 3. Cross-section geometrical parameters of electron beams.

| Parameters       | Value    |
|------------------|----------|
| The guiding radius ($R_g$) | 1.2 mm   |
| The inner radius ($R_i$) | 1.1 mm   |
| The outer radius ($R_o$) | 1.3 mm   |
| The interaction radius ($R_a$) | 2.45 mm  |

The limiting current is defined by [21]:

$$IL = 1.707e4y_0\left[1 - (1 - \beta_{||0}^2)^{1/3}\right]^{1/2} \frac{1}{G(R_i, R_o, R_a)}$$  (9)

where $\beta_{||0}$ is the axial propagation constant defined by $\beta_{||0} = V_{30}/c$, and $G$ is the geometric factor defined previously. Results obtained from the equation $IL$ are shown in Figure 1, there is a clear trend of decreasing limiting current when increasing $\alpha$ and dropping beam voltage. The electron efficiency is proportional to the velocity ratio. The potential dropping caused by the space charge effect limits the current flow in space.

However, a higher $\alpha$ will cause the limit current to decrease, and when the operating current is close to the limit current, it will cause the reversal of the electron beam, which drastically affects the emission and interaction efficiency. It seems very critical to obtain an optimal $\alpha$ value through theoretical analysis. To obtain a satisfactory electron beam quality, the operating current cannot exceed 0.5 of the limit current [9,17,21].

2.3. Velocity Spread

The total energy of the electron beam is always the same as a consequence of energy conservation [22]. However, during the adiabatic process, the perpendicular and parallel energy are distributed in a different way, which results in the velocity spread. The velocity spread is defined by

$$\frac{\Delta \beta_{||}}{\beta_{||}} = \alpha^2 \frac{\Delta \beta_{\perp}}{\beta_{\perp}}$$  (10)

where $\Delta \beta$ means the difference of maximum and minimum velocity. The velocity spread consists of axial and perpendicular velocity spread, which could reduce the efficiency of the beam–wave interaction and limit the achievable velocity ratio [23]. The velocity spread is implied as $\delta_{\beta_{\perp}} = \Delta \beta_{\perp} / \beta_{\perp}$. Generally speaking, there are a lot of effects causing velocity spread, including initial thermal velocity spread, the roughness of the electron-emitting surface, the non-uniform distribution of the electric and magnetic field, and the effect of space charge [20]. This work only focused on the last two items in principle. Due to the non-uniform electric and magnetic field, the velocity spread is given below [24]:

$$\delta_{\beta_{\perp}} \approx \frac{2R_c \cos \theta_c}{d}$$  (11)

where $d$ is the distance between the cathode bottom and modulating anode, and it is often a large parameter. So, $\delta_{\beta_{\perp}}$ from (11) is usually small. Space charge effects have a great influence on the velocity spread, especially for large currents. However, the effect of space charge on the electron beam depends on the beam trajectory. According to research in [24,25], an electron-gun with quasi-laminar beams could diminish $\delta_{\beta_{\perp}}$. Thus, this design would use a MIG with a large inclination of emission to obtain quasi-laminar beams. Furthermore, the max velocity ratio is constrained by velocity spread, which is defined by:

$$\alpha_{\text{max}} = \frac{\bar{\beta}_{\perp}}{\bar{\beta}_{||}} = \frac{1}{\left(2\Delta \beta_{\perp \text{max}} / \beta_{\perp}\right)^{1/2}}$$  (12)
where $\bar{\beta}$ is the average velocity of electron beam. According to this equation, when the velocity spread is under 10%, the velocity ratio can reach 2.5. When the operating current is approaching the current limits electron beam begins to reverse, which causes the velocity spread sharply increased [26].

2.4. Summary

Taken together, these results suggest there is an indication that the high velocity ratio $\alpha \geq 2$ is fully achievable when the operating voltage and current are 10 kV and 0.5 A, respectively. Optimal electron beam parameters by calculation are shown in Table 4. But there are still a lot of conflicting requirements, so numerical simulation is implemented to find the optimal trade-offs.

| Parameters                  | Value  |
|-----------------------------|--------|
| Max Velocity ($\alpha_{\text{max}}$) | 2.5    |
| Velocity Spread ($\delta_{\beta_{\perp \text{rms}}}$) | 10%    |
| Voltage Depression (Vdep)   | 286 V  |

3. Numerical Simulation by Magic 2D PIC Code

Based on the theory of the MIG [18,27], fundamental design factors were calculated and given in Table 5. Particle simulations are important to verify the beam performance of any specific gun design. 2D Magic code was adopted to optimize the parameters of the MIG and Magic was considered as a convinced software to calculate the particle motion and beam–wave interaction, which includes the space charge effect. The calculation in the Magic 2D code was performed with a mesh size of 0.3 and 0.1 mm in the z and r direction. The geometry model and electron trajectory cooperated with the axial magnetic field and were shown in Figure 5. Beam voltage and current were 10 kV and 460 mA, respectively. Electron momentum is defined by $P = m \times v$, perpendicular and longitudinal momentum were shown in Figure 6a,b. Energy transferred to the transverse direction from the axial direction due to the adiabatic compression. When the transverse-to-axial velocity ratio reached the maximum, as shown in Figure 6c, electrons leave the electron area and then turn into the interaction area. Specific parameters of the electron beam are shown in Table 6, with 2.55 velocity ratio and 9.33% perpendicular spread ratio.

![Figure 5](image-url)

**Figure 5.** Optimized geometry, magnetic field profile and beam trajectory of MIG by Magic code.
Figure 5. Optimized geometry, magnetic field profile and beam trajectory of MIG by Magic code. (a)  (b)  (c)

Figure 6. The value for (a) longitudinal momentum, (b) perpendicular momentum, and (c) transverse-to-axial velocity ratio as a function of axial distance.

Table 5. Optimal geometric factors of MIG.

| Parameters                                | Value   |
|-------------------------------------------|---------|
| Modulating Voltage (U_{mod})              | 7.5 kV  |
| Average Radius of Cathode (R_{c})         | 4.65 mm |
| Thickness of Emitter Ring (L_{s})         | 1.5 mm  |
| Tilt Angle of Cathode (\theta_c)          | 18.4°   |
| Distance between Cathode and Modulating Anode (d) | 3.91 mm |

Table 6. Optimized beam parameters obtained by Magic 2D simulation.

| Parameters                              | Value   |
|-----------------------------------------|---------|
| Average Beam Radius (R_g)               | 1.2 mm  |
| Velocity Ratio (\alpha)                | 2.55    |
| Perpendicular Velocity Spread Ratio (\delta_{\perp,mid}) | 9.33%     |
| Full Radial Width                       | 0.22 mm |
Based on the theoretic calculation in Figure 1, when the limiting current is 0.824 A, the operating voltage is 10 kV and the velocity ratio is 2.55. Due to the working current being generally selected as half of the limit current, numerical simulation is adopted to investigate the sensitivity of the beam current around the 0.416 A for $\alpha$ and spread. From Figure 7 it can be seen that when the current is 0.416 A, the velocity ratio is the lowest, with velocity spread of 9.4% and $\alpha$ 2.55. This is also self-consistent with the previous maximum velocity ratio and velocity spread relationship in Section 2.3 Equation (12). As shown in Figure 7, with the increasing of the beam current, the velocity ratio would decrease, but when it exceeds a value, the velocity spread would boost rapidly.

![Figure 7](image-url)  
**Figure 7.** Sensitivity analysis of beam velocity ratio and perpendicular velocity spread ratio for modulating anode voltage.

Taking into consideration both the experiment and the theory, the electrical field of the cathode can be convenient to modulate to obtain a satisfactory electron beam. So, particle simulation is adopted to analyze the sensitivity of the modulating voltage for the velocity ratio and velocity spread when beam voltage and current are 10 kV and 0.46 A, respectively. What can be clearly seen in Figure 8 is the continual growth of the velocity ratio and slight fall of the perpendicular velocity spread with the increasing modulating voltage. Therefore, the simulation is consistent with the theory study.

![Figure 8](image-url)  
**Figure 8.** Variation of velocity ratio ($\alpha$) and perpendicular velocity spread ratio with operating current.

### 4. Conclusions

The purpose of the current study was to determine the feasibility of the ultra-high velocity ratio of MIG for low-voltage gyrotron. The theory of space charge effects and particle simulation were adopted to investigate the velocity ratio and velocity spread of MIG.
This work proposes a direct and convenient way (ultra-high velocity ratio) to enhance the efficiency of low-voltage gyrotron, which operates at 10 kV or even low-voltage, while maintaining a large operating current (about 0.5 A), improving the velocity ratio, and restricting the velocity spread. Furthermore, the theoretical analysis and numerical simulation were adopted to verify the feasibility of the ultra-high velocity ratio. The results show that the velocity ratio of 2.55 and the velocity spread of 9.33% are achievable by optimizing the electron gun geometric factors, magnetic field, operating current, and modulating anode voltage.

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