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O. Dumbrajs, T. Saito, Y. Tatematsu, and Y. Yamaguchi

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Influence of the electron velocity spread and the beam width on the efficiency and mode competition in the high-power pulsed gyrotron for 300 GHz band collective Thomson scattering diagnostics in the large helical device

O. Dumbrajs, 1, 2 T. Saito, 1 Y. Tatarnatsu, 1 and Y. Yamaguchi 1
1Research Center for Development of Far-Infrared Region, University of Fukui (FIR UF), Bunkyo 3-9-1, Fukui-shi, Fukui-ken 910-8507, Japan
2Institute of Solid State Physics, University of Latvia, Kengaraga Street 8, LV-1063 Riga, Latvia

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We present results of a theoretical study of influence of the electron velocity spread and the radial width on the efficiency and mode competition in a 300-kW, 300-GHz gyrotron operating in the TE 222 mode. This gyrotron was developed for application to collective Thomson scattering diagnostics in the large helical device and 300-kW level high power single TE 222 mode oscillation has been demonstrated [Yamaguchi et al., J. Instrum. 10, c10002 (2015)]. Effects of a finite voltage rise time corresponding to the real power supply of this gyrotron are also considered. Simulations tracking eight competing modes show that the electron velocity spread and the finite beam width influence not only the efficiency of the gyrotron operation but also the mode competition scenario during the startup phase. A combination of the finite rise time with the electron velocity spread or the finite beam width affects the mode competition scenario. The simulation calculation reproduces the experimental observation of high power single mode oscillation of the TE 222 mode as the design mode. This gives a theoretical basis of the experimentally obtained high power oscillation with the design mode in a real gyrotron and moreover shows a high power oscillation regime of the design mode. Published by AIP Publishing. [http://dx.doi.org/10.1063/1.4962575]

I. INTRODUCTION

The gyrotron is a source capable of producing high power levels at millimeter-wave frequencies for many applications, including collective Thomson scattering (CTS) diagnostics in magnetic fusion devices. Sub-THz high power gyrotrons have been developed for application to the power source of the CTS diagnostics. 1, 2 A 300GHz band high power gyrotron has been manufactured for real application to the power source of the CTS diagnostics on the large helical device. 3 First experimental results of this gyrotron are presented in Ref. 4.

In order to realize high power and high efficiency, a single mode oscillation is inevitable. The study of mode competition is therefore very important. This importance increases with power and frequency. Experimental studies and theoretical works on mode competition have been accumulated [for example, Refs. 5–7 are good references for the theoretical studies], and recently, an experimental study with a high power subTHz gyrotron has been carried out. 8 In addition, a proper start-up scenario considering a finite voltage rise time is also very important, because in real gyrotrons, the operating voltage rises in a finite time. Conditions for high power and high efficiency oscillation of the desired mode have been investigated theoretically and experimentally. 9–11 Recently, we analyzed the influence of the finite voltage rise time on mode competition for the practical 300-GHz gyrotron. 12 In this study, the voltage rise times corresponding to a real power supply were used. It was found that over 300kW power stable oscillations in the TE 222 mode can be achieved with a high efficiency even for the case of the operation with the use of a simple resistive divider for setting the modulation anode voltage. This feature is independent of the voltage rise time, which is partly due the characteristics of whispering gallery modes and competition with Δm = −1 mode can be avoided. In the case of a finite voltage rise time longer than the cavity decay time, the transition from the backward wave oscillation regime to the gyrotron regime is observed during the start-up phase. This is consistent with the temporal dependence of the frequency mismatch. The magnetic field regime of single-mode, high-stationary power oscillation of the TE 222 mode has a sharp boundary at the lower field side. The frequency mismatch is about 0.6 at this boundary. This feature well corresponds to the experimental observation. This study has shown the time evolution with which a real gyrotron reaches high power stationary oscillation. In addition, below this boundary, low power oscillations are observed in the TE 212 and TE 222 simultaneously. With further decrease in the magnetic field, mode hopping from the TE 222 mode to the TE 212 mode is observed in the start-up phase.

However, the study in Ref. 12 did not take into account the effects of the electron velocity spread and the finite width of the electron beam. It is known that the electron velocity spread and the finite width of the electron beam deteriorate the gyrotron efficiency. 13, 14 The electron velocity spread and the finite width of the electron beam increase the starting current, 15 and the finite width influences the mode interaction. 16 Therefore, the second step simulation study including

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these two effects is necessary to investigate the ranges of high power stable oscillation, decrease in efficiency and mode competition.

The present paper considers these two effects simultaneously and demonstrates their influence not only on the efficiency of the gyrotron operation but also on the mode competition for finite and instant voltage rise times. Our study has two aspects. First, complex effects of the finite voltage rise time and the electron velocity spread or the finite width of the electron beam are investigated for a high power subTHz gyrotron. Second, the present simulation uses a realistic voltage rise time, and moreover, the electron beam parameters are obtained from the design calculation. The velocity spread and the beam width are in a relation of trade-off. Therefore, use of the realistic beam parameters is very important to make the study realistic. The present study forms a theoretical base of the $TE_{22,2}$ mode high power single mode oscillation of the existing 300-kW gyrotron.

The paper is organized as follows. In Section II, we generalize the self-consistent, time dependent, and multimode formalism to include the electron velocity spread and finite beam width. Section III contains the results of efficiency and mode competition calculations in the presence of the electron velocity spread. The results of the influence of the finite electron beam width are presented in Section IV. Finally, Section V presents the conclusions from the study.

II. SELF-CONSISTENT, TIME DEPENDENT, AND MULTIMODE FORMALISM WITH INCLUSION OF ELECTRON VELOCITY SPREAD AND FINITE BEAM WIDTH

The self-consistent, time dependent, and multimode formalism was derived in Ref. 17 and reviewed in Ref. 18. Simulation codes based on this theory have been developed. The simulation code used in the present study is also based on this theory and has been used many times in practical calculations, for example, in Refs. 19–21. The same code was used in the study of Ref. 12. In the presence of the electron velocity spread and the finite beam width, the system of two equations of the self-consistent, time dependent, and multimode formalism can be modified as follows to properly include normalization of the electron velocity and the electron beam width:

$$\frac{\partial^2 f_s}{\partial \xi^2} - in_s \frac{\partial f_s}{\partial \tau} + n_s \delta f_s = \int \Phi(\beta_\parallel) \cdot G(\tau) \begin{pmatrix} \phi \beta_\parallel \\ \psi \beta_\parallel \end{pmatrix} \begin{pmatrix} \beta_\parallel \\ \beta_\perp \end{pmatrix}^{n_s} \beta_\parallel J_{m_\perp} \left( \frac{\nu R_c}{R(\xi)} \right) f_s \exp \left[ i \left( \Delta_{\parallel} \beta_\parallel + \psi_s \right) \right],$$

(1)

$$I_s = 3.76 \times 10^{-1} |A| \beta_\parallel^{2(n_s - 4)} \cdot n_s \cdot \left( \frac{n_s}{2 \pi n_s} \right)^2 \times \frac{1}{\gamma_{rel}^2 \int f_s(\nu_s)(\nu^2 - m^2)\,d\nu}.$$

(3)

where $\gamma_{rel}$ is the relativistic factor and $I_s$ stands for the real beam current in Ampere.

We define $\Phi(\beta_\parallel)$ as the electron transverse velocity distribution function normalized to unity $\int \hat{D}(\beta) \Phi(\beta) d\beta = 1$ and $G(\tau)$ is the electron beam width function normalized to unity $\int G(\tau) d\tau = 1$.

Equation (1) has to be supplemented by the initial condition $p(0) = \exp(i \nu_0)$, $0 \leq \nu_0 < 2\pi$, while Eq. (2) should be supplemented by both the initial and boundary conditions. The initial condition can be given as $f(z, 0) = f_0(\xi)$, where $f_0(\xi)$ is the rf field profile obtained in the cold-cavity approximation. The boundary condition can be written as follows:

$$f_0(\xi_{out, \tau}) = \frac{1}{k_s} \frac{\partial f_0(\xi, \tau)}{\partial \xi} \bigg|_{\xi = \xi_{out}}.$$

(4)

where $k_s = 2c \beta_\perp^2 \omega_{cy}(\nu^2 - m^2) / R(\xi)$ is the dimensionless axial wave number. In Ref. 22, a Gaussian electron velocity distribution was proposed which was subsequently used by many researchers (see, e.g., Refs. 7, page 83...
and 23–26). In the present study, we prefer to use a more realistic triangular distribution

\[
\beta_{\perp \text{min}} = \bar{\beta}_\perp - \frac{1}{2} \Delta \beta_{\perp} \cdot \bar{\beta}_\perp
\]

\[
d\beta_{\perp} = \frac{\Delta \beta_{\perp} \cdot \bar{\beta}_\perp}{N}
\]

\[
\beta_{\perp j} = \beta_{\perp \text{min}} + \left( j - \frac{1}{2} \right) d\beta_{\perp}
\]

\[
\beta_{\parallel j} = \sqrt{\frac{\gamma_{\text{rel}}^2 - 1}{\gamma_{\text{rel}}^2} - \beta_{\perp j}^2}
\]

\[
\Phi_j = C \left( j - \frac{1}{2} \right) \quad \text{for} \quad j \leq \frac{N}{2}
\]

\[
\Phi_j = C \left( N - j + \frac{1}{2} \right) \quad \text{for} \quad j > \frac{N}{2}
\]

Here, \( \Delta \beta_{\perp} = (\beta_{\perp \text{max}} - \beta_{\perp \text{min}}) / \beta_{\perp \text{average}}, j = 1, 2, \ldots, N \), and \( C \) is determined by the normalization

\[
\sum_{j=1}^{N} (\beta_{\parallel j} \Phi_j) \cdot d\beta_{\perp} = 1.
\]

The efficiency is given by the expression

\[
\eta = \frac{\gamma_{\text{rel}}}{2(\gamma_{\text{rel}} - 1)} \cdot d\beta_{\perp} \sum_{j=1}^{N} \left( \eta_{\perp j} \beta_{\parallel j}^2 \Phi_j \right).
\]

In the case of no velocity spread, one should remove all \( \beta \) from the above system of equations and put \( \beta_{\perp j} \Phi_j \beta_{\perp} = 1 \).

For the efficiency, the standard definition should be used

\[
\eta = \eta_{\perp} \cdot \frac{\alpha^2}{1 + \alpha^2} \cdot \frac{\gamma_{\text{rel}} + 1}{2\gamma_{\text{rel}}},
\]

where \( \alpha = \beta_{\perp} / \beta_{\parallel j} \).

The total power is defined as

\[
P_{\text{out}} = U \cdot I \cdot \eta.
\]

Here, the steady state operating voltage and current are \( U = 65 \text{ kV} \) and \( I = 15 \text{ A} \). In what follows we use six velocity components (\( N = 6 \)).

We describe the electron beam width by a rectangular distribution with nine components

\[
R_{el, l} = \bar{R}_{el} + 0.25(l - 5) \delta R_{el}, \quad 1 \leq l \leq 9,
\]

where \( \bar{R}_{el} \) is the radius of an infinitely thin electron beam and \( \delta R_{el} = (R_{el, \text{max}} - R_{el, \text{min}}) / 2 \) is the half-width of the beam. The value of \( \bar{R}_{el} \) is 3.662 mm in the following calculations. It corresponds to the optimum beam coupling to the operating \( TE_{22,2} \) mode. It should be emphasized that in the rectangular distribution all components are treated with one and the same probability.

III. CALCULATIONS WITH VELOCITY SPREAD

Detailed computations at six different magnetic fields\(^{12} \) have shown that in this gyrotron the operating \( TE_{22,2} \) mode basically competes only with the parasitic \( TE_{21,2} \) mode. At \( B = 11.45 \text{ T} \), the operating \( TE_{22,2} \) mode does not oscillate, because the frequency mismatch \( \Delta_{22,2} \) for it is too large. The mode \( TE_{21,2} \) oscillates instead, albeit with low efficiency, because the frequency mismatch for it is not optimum at this magnetic field. At magnetic fields \( B = 11.65 \text{ T} \) and \( B = 11.70 \text{ T} \), two mode oscillations are observed also with low efficiencies. At \( B = 11.72 \text{ T} \), the parasitic mode is completely suppressed and the \( TE_{22,2} \) mode oscillates with a high efficiency producing about 400 kW power (see Fig. 2 in Ref. 12).

In the present study, we choose these four magnetic fields because this range of the magnetic field covers the regime of the frequency mismatch where characteristic differences are observed as shown below. The quantity \( \Delta \beta_{\perp} \) depends on both the magnetic field and the operating voltage. In the present study, this quantity is predicted by the EGUN code\(^{26} \) and is used in the distribution (5). In the present careful design of the electron gun,\(^{4} \) \( \Delta \beta_{\perp} \) is rather small: \( \sim 0.08 \text{ at 40 kV and } \sim 0.01 \text{ at 65 kV} \). In the calculations, we consider several values of the velocity spread \( M \cdot \Delta \beta_{\perp} \). As mentioned in Sec. II, the steady state operating voltage is 65 kV. It starts from 40 kV and the increment of the operating voltage is 1 kV for each step in the case of the finite voltage rise time. The rate of voltage increase is 1 kV/0.4 ns, which corresponds to the fast voltage rise time case in Ref. 12. The operation voltage reaches the steady state value of 65 kV in 10 ns. We have observed no difference between the fast voltage rise time case and the slow voltage rise time case; 1 kV/4 ns. Then, in the present study, we show the fast voltage rise time case as the finite voltage rise time case. Numerical results of \( \Delta \beta_{\perp} \) calculated by the EGUN code are used at each voltage rise step. It should be noted that in Ref. 12 \( \beta_{\perp} \) was evaluated by means of an analytic expression. This explains some non-essential differences between the results presented in Ref. 12 and in what follows.

A. Magnetic field \( B=11.45 \text{T} \)

In Fig. 1, we show the dependence of power on the velocity spread. It is seen that the power decreases smoothly with the velocity spread. At this magnetic field, as mentioned above, the single mode oscillation of the \( TE_{21,2} \) mode takes

![FIG. 1. Stationary state power of the \( TE_{21,2} \) mode as a function of velocity spread.](https://example.com/f1.png)
place without the velocity spread. The velocity spread does not change this situation as shown in Fig. 2. Figure 2 also indicates that the velocity spread does not influence the mode competition scenario. Since the frequency mismatch for the operating $TE_{22,2}$ mode is too large, the single $TE_{21,2}$ mode oscillation is realized for a wide range of operation conditions. No difference is found between the finite and instant voltage rise times.

B. Magnetic field $B=11.65 \, T$

At this magnetic field, a strong multimoding is observed as shown in Figs. 3 and 4. In the case of velocity spread, some electrons have lower or higher velocities which are favorable for interacting with the $TE_{22,2}$ mode. With the increasing spread, the amplitude of the $TE_{22,2}$ mode becomes larger than that of the $TE_{21,2}$ mode. In the instant voltage rise time case, the time needed to reach the equilibrium is longer.

It should be noted that at low voltages (finite voltage rise time) and large velocity spreads, the perpendicular velocity $\beta_\perp$ may become so large that the parallel velocity $\beta_{\|} = \sqrt{1 - 1/t_{\text{ref}}^2 - \beta_\perp^2}$ becomes imaginary. In this case, this happens for $M > 15$ (Fig. 5). Therefore, no result is shown for $M > 15$ in the case of finite voltage rise time.

C. Magnetic field $B=11.70 \, T$

At this magnetic field in contrast to Ref. 12, we do not find two mode oscillations for the finite voltage rise time with and without velocity spread as shown in Figs. 6 and 7. For the instant voltage rise time, on the other hand, two mode oscillations are observed. This is an important difference between the finite voltage rise time and the instant

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**FIG. 2.** Amplitude of the $TE_{21,2}$ mode $|f(\tau_{\text{out}})|$ as a function of time (solid $M = 0$, bold for $M = 25$).

**FIG. 3.** Amplitudes as functions of time (solid for instant voltage rise time, bold for finite voltage rise time). No velocity spread.

**FIG. 4.** Amplitudes as functions of time (solid for instant voltage rise time, bold for finite voltage rise time). With velocity spread $M = 15$.

**FIG. 5.** Total stationary state power as a function of velocity spread. Circles correspond to instant voltage rise time, triangles to finite rise time.

**FIG. 6.** Amplitudes as functions of time (solid for instant voltage rise time, bold for finite voltage rise time). No velocity spread.
voltage rise time. (Results obtained with the slow and fast voltage rise times coincide.) As plotted in Fig. 8, the power predicted with the instant voltage rise time is much smaller. This is because in the case of the instant voltage rise (starting at 65 kV) the frequency mismatch is favorable for both the $TE_{21,2}$ mode ($\Delta_{21,2} = 0.2$) and the $TE_{22,2}$ mode ($\Delta_{22,2} = 0.7$) which leads to multimoding with low power. In the case of the finite voltage rise (starting at 40 kV), the frequency mismatch for the $TE_{22,2}$ mode starts from around zero and increases with time up to a favorable value ($\Delta_{22,2} = 0.7$) (see Fig. 3 in Ref. 12). As for the $TE_{21,2}$ mode, the frequency mismatch remains negative or around zero during most of the startup phase. Thus, the operating mode suppresses the parasitic $TE_{21,2}$ mode at the very beginning and does not allow the parasite to grow at higher voltages. Single mode oscillation of the $TE_{22,2}$ mode results in the high power. The dependence of power on the velocity spread is very weak for both voltage rise times at this magnetic field. Recalling that at 65 kV $\Delta f_{\text{th}}$ is in the order of 0.01, we can see that the maximum considered spread is small which explains the weak dependence of power on velocity spread as shown in Fig. 8.

Doppler shift is negligible in the cavity for the stationary gyrotron oscillation with an almost zero axial wave number. Then, the weak dependence of power on the velocity spread is observed.

D. Magnetic field $B = 11.72 T$

At this magnetic field, stable high-power oscillations of only the operating $TE_{22,2}$ mode are observed at the stationary state (Fig. 9), because for this mode the frequency mismatch is optimal ($\Delta_{22,2} = 0.6$), while for the parasitic $TE_{21,2}$ mode $\Delta_{21,2} = 0$ at the stationary state. Then, for the stationary state, there is no difference between the instant and finite voltage rise times. As in the previous case (Fig. 8), also at this magnetic field, the electron velocity spread just slightly decreases the power (Fig. 10).

IV. CALCULATIONS WITH THE FINITE BEAM WIDTH

A. Magnetic field $B = 11.45 T$

The half-width 0.13 mm is used as the typical design value of the present gyrotron for all values of the magnetic field. At this magnetic field, single mode oscillation of the $TE_{21,2}$ mode is realized. The finite width slightly increases the power (Fig. 11) at the stationary state (Fig. 12). This can be understood by examining the dependence of the coupling coefficient of the mode $TE_{21,2}$ on the electron beam radius shown in Fig. 13. The value $R_{cT} = 3.662 \text{ mm}$ (vertical dotted line) is optimal for the $TE_{22,2}$ mode. With an increase in width, the coupling for the $TE_{21,2}$ mode improves, which explains why the power increases.
B. Magnetic field $B=11.65 \, \text{T}$

At this magnetic field for small half-width, the multi-mode oscillations are observed (Fig. 14). For larger half-width, the operating $TE_{22,2}$ mode begins to lose the competition and the parasitic $TE_{21,2}$ mode oscillations take over which explains the low-power oscillations are observed (Fig. 15).

C. Magnetic field $B=11.70 \, \text{T}$

At this magnetic field for small half-width, the multi-mode oscillations with dominance of the operating $TE_{22,2}$ mode are observed (Fig. 16). For larger half-widths, the operating mode is suppressed and single $TE_{21,2}$ mode oscillations set in, because the coupling of this mode becomes stronger (Fig. 13). However, the power is low (Fig. 17).
because the frequency mismatch at this magnetic field for the $TE_{21,2}$ mode is very small ($\Delta_{21,2} = 0$).

**D. Magnetic field $B=11.72\ T$**

It is seen that single $TE_{22,2}$ mode oscillation is sustained for the design value of the beam half-width of 0.13 mm (Fig. 18) with high power (Fig. 19). Oscillation powers for beam half-width of 0 mm and 0.13 mm indicate the single $TE_{22,2}$ mode power. Since $B = 11.72\ T$ is near the lower boundary of the region of single $TE_{22,2}$ mode oscillation with zero beam width, beam half-widths larger than 0.13 mm have a significant effect. The coupling coefficient with a weight of the beam width becomes small for both the $TE_{21,2}$ mode and $TE_{22,2}$ mode. The present calculations imply that the $TE_{21,2}$ mode becomes relatively strong with the beam width and starts to compete with the $TE_{22,2}$ mode, which results in the decrease of power.

**V. DISCUSSION AND SUMMARY**

Several conclusions can be drawn from the calculations shown in Secs. III and IV.

(1) As a result of very careful design of the gun, this gyrotron is very robust with respect to the electron velocity spread. At the optimal magnetic field 11.72 T for the operating $TE_{22,2}$ mode, the theoretical value of the velocity spread predicted by the electron gun code ($M = 1$) does not affect the efficiency. Even with the spread 25 times as large as the design value ($M = 25$), the efficiency decrease is marginal (Fig. 10). On the other hand, the finite electron beam width affects the gyrotron operation much more critically. The beam half-width predicted by the gun code 0.13 mm leads already to 1.5% power decrease for the steady state single $TE_{22,2}$ mode oscillation (Fig. 19).

(2) At the magnetic field 11.45 T where single mode $TE_{21,2}$ parasitic oscillations are predicted also in the design calculation without velocity spread, there is also a large margin for the $TE_{21,2}$ mode oscillation with respect to velocity spread (Fig. 1). For the competing $TE_{21,2}$ mode, an interesting phenomenon has been found with respect to the beam width: with the increasing beam width the efficiency somewhat increases (Fig. 11). This is the opposite effect to the operating $TE_{22,2}$ mode that the beam width tends to reduce the efficiency. Thus, the beam width occasionally causes positive or negative effects depending on the relative position of the electron beam to the distribution of the coupling coefficient.

(3) At the magnetic field 11.65 T where multimoding is predicted, the efficiency slightly increases with spread. Some difference in the results obtained with the instant and finite voltage rise times has been found (Figs. 3 and 4). At this field, the behavior of the gyrotron is very sensitive with respect to the beam width. The beam half-width predicted by the gun code 0.13 mm leads already to 30% power decrease (Fig. 15).

(4) At the magnetic field 11.70 T where also multimoding is predicted, slow power decrease with increasing velocity spread is observed (Fig. 8). However, the results obtained with the instant and finite voltage rise times differ drastically (Figs. 6 and 7). Also at this magnetic field, the behavior of the gyrotron is rather sensitive with respect to the beam width. The beam half-width predicted by the gun code 0.13 mm leads to 8% power decrease (Fig. 17). These observations show that the velocity spread and the beam width can change the
oscillation characteristics at the operation condition where mode competition is expected.

(5) The finite beam width has substantial effects on the power and the mode competition scenario except at 11.72 T where the high power single $TE_{22,2}$ mode oscillation is observed for the design value of 0.13 mm. On the contrary, the velocity spread seems to have weaker effects than the beam width. This reflects the design of the electron gun considering the tradeoff between the velocity spread and the beam width. A thinner beam has higher space-charge density which prevents reduction of the velocity spread. Moreover, the emitting belt on the cathode should have a certain width for a necessary current. An extremely small velocity spread has been realized for the electron gun of the present gyrotron with very careful consideration. This is the reason of the rather weak effect of the velocity spread even for the multiplication factor of $M$ as large as 25. In addition, the wavelength as short as 1 mm enhances the effects of the beam width. The simulation calculations in the present study indicate importance to use the real design parameters.

We can very briefly summarize the present study as follows. At magnetic fields, where multimoding occurs, both the velocity spread and the beam width may strongly influence the mode competition scenario. In addition, since the mode competition scenario sensitively depends on the voltage rise time, calculations with a realistic voltage rise time are important.

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