Reflections in Gyrotrons With Axial Output

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***Abstract*—Influence of reflections on operation of gyrotrons with axial output is studied both theoretically and experimentally. By way of example the Fukui large orbit gyrotron with a permanent magnet operating in third harmonic at frequency 89 GHz is considered. In the case of strong reflection ($|R| = 0.6$), extreme sensitivity of output power on the reflection phase is found. A qualitative agreement between theory and experiment is observed.**

***Index Terms*—Frequency tuneability Rieke diagram, gyrotron, reflections.**

I. Introduction

REFLECTIONS of microwave power can take place at the gyrotron RF output window.

Advanced high-power gyrotrons used for fusion applications have radial output. Here, the RF signal after leaving the cavity hits the launcher in which an individual rotating high-order cavity mode looses its identity and is converted into a linearly polarized Gaussian output beam. This beam is guided by means of phase-corrected mirrors to the output window. In general, the RF signal reflected from the window is dissipated in the entire volume of the tube and only a small part returns to the cavity. Theoretical interpretation of experimental results as obtained, for example, in [1] on reflections in the $TE_{22,6}$ mode gyrotron operated at Forschungszentrum Karlsruhe, is complicated [2]. In calculations, it is assumed that reflections occur at the cavity exit and that the reflected RF signal returns to the cavity as the specific original cavity mode. Although predictions of such a simple model [3] cannot be tested experimentally, they give some feeling of possible impact of reflections on operation of gyrotrons with a radial output. In reality, the reflected Gaussian beam is transformed inside the launcher into the oppositely rotating mode which returns to the cavity. Competition between opposite rotations of one and the same mode in the cavity has to be considered. This interesting problem is under investigation and the results will be published somewhere else.

In this paper, we study reflections in low-power gyrotrons. Such gyrotrons have an axial output. In this case, the situation is much simpler. There are neither mirrors, nor launcher in the tube. No mode transformation takes place. The RF signal reflected from the window returns to the cavity as the original mode. A meaningful comparison between theory and experiment is possible using relatively simple tools described below.

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II. General Formalism

It is convenient to describe reflections by means of a complex reflection coefficient R written as [2]

$$R = |R| \cdot \exp\left[i\frac{4\pi}{\lambda}(L_R + \Delta L_R)\right] \tag{1}$$

where ℓ is the wavelength of gyrotron oscillations, L_R is the distance between the cavity exit and the reflecting plane, and ΔL_R is the shift of the plane. The period of the phase of R is $\Delta L_R = \lambda/2$. The reflection coefficient can be introduced into the usual boundary condition at the cavity exit

$$f(\varsigma_{out}, \tau) = \frac{i}{k} \cdot \frac{\partial f(\varsigma, \tau)}{\partial \varsigma}\bigg|_{\varsigma=\varsigma_{out}} \cdot \left(\frac{1-R}{1+R}\right) \tag{2}$$

where k is the wave number and f is the RF amplitude to be found by solving the system of partial parabolic differential equations [4]

$$\begin{cases} \frac{\partial p}{\partial \varsigma} + i\left(\Delta + |p|^2 - 1\right)p = if \\ \frac{\partial^2 f}{\partial \varsigma^2} - i\frac{\partial f}{\partial \tau} + \delta f = \frac{I}{2\pi}\int_0^{2\pi} p\, d\upsilon_0 \end{cases}. \tag{3}$$

Here, p is the transverse momentum of the electron, ς is the longitudinal coordinate, Δ is frequency mismatch, τ is time, δ is the cutoff frequency along ς, I is current, and ϑ_0 is the initial phase of the electron.

III. Fukui Gyrotrons

Gyrotrons developed at the Fukui University, Research Center for Development of Far Infrared Region (FIR), have medium power (several 10 W to several 10 kW) [5]. These gyrotrons are used as microwave sources for application to new far-infrared technologies. They have demonstrated frequency tuneability in a broad range (from 30 GHz to 889 GHz). All Fukui gyrotrons have axial output.

Reflections in these gyrotrons may result in a significant change of the output power. This is a serious problem for frequency-tuneable gyrotrons, especially for ultra broad-band Fukui gyrotrons. For example, in the 12-T gyrotron [6] which is step tuneable over the range 145–639 GHz, the output power in many modes was so low that it could not even be specified (see [6, Table I]). Understanding the influence of reflections on

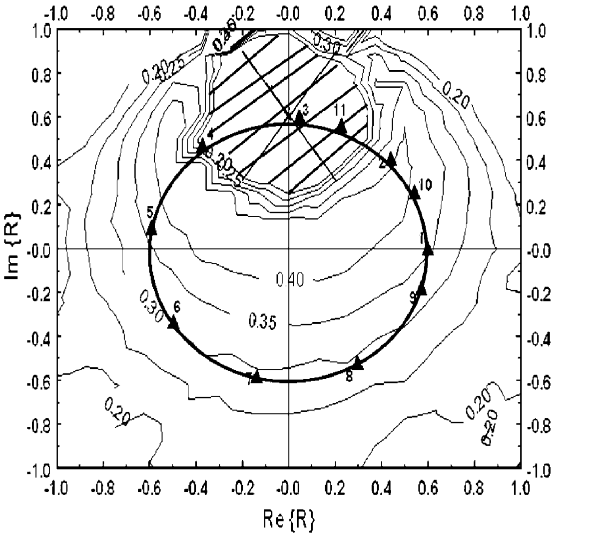

Fig. 1. Rieke diagram for the $TE_{3,1}$ mode. The equipower lines in arbitrary units cover power range $0.2, \ldots, 0.4$ in steps of 0.05. There are no oscillations in the crossed ⊗ region. The circle corresponds to $|R| = 0.6$ and the triangles with labels to indicated phases in Fig. 2.

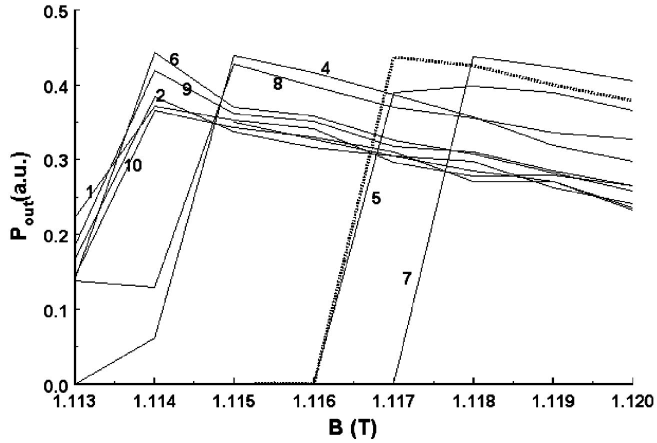

Fig. 2. Theoretical oscillation regions of the $TE_{3,1}$ mode for fixed $|R| = 0.6$ but different ΔL_R. The dotted curve marks the oscillation region in the case of no reflections. The curve 6 corresponding to $\Delta L_R = 1.0$ mm begins at 1.122 B and is outside the scale of the figure. The results at $B = 1.118$ T can be directly compared with the circle in the Rieke diagram shown in Fig. 1.

gyrotron operation is important for enhancing the most attractive feature of Fukui gyrotrons – their broad-band tuneability.

For our study, we have chosen the recently constructed large-orbit gyrotron [7]. This gyrotron has a permanent magnet. It operates at third harmonic in the $TE_{3,1}$ mode at frequency $F = 89$ GHz and at fourth harmonic in the $TE_{4,1}$ mode at frequency $F = 113$ GHz.

IV. Numerical Simulation

To model reflections in this gyrotron, we have chosen the third harmonic operation. For a specific operation point ($U = 37$ kV, $\alpha = 1.0$, $R_{\rm el} = 0.082$ mm, $I = 1.0$ A, and $B = 1.118$ T), we assumed arbitrary values of R and calculated the so-called Rieke diagram. In this diagram, contours of constant output power are plotted in the plane of the real and imaginary part of R (Fig. 1).

It is seen that the output power depends very strongly on both the magnitude and the phase of the reflection coefficient.

Next, for a specific absolute value of the reflection coefficient ($|R| = 0.6$) we calculated the oscillation region as a function of the magnetic field for many values of ΔL_R, varied from 0.0 mm (label 1) to 2.00 mm (label 11) in steps of 0.2 mm (see Fig. 2). Here, the convention is such that for ΔL_R the reflection phase is taken to be zero.

It can be seen that at low values of the magnetic field (hard excitation region) the output power very strongly depends on ΔL_R, i.e., on the phase of the reflection coefficient. The hard excitation region itself is displaced due to reflections. For some reflection phases the total operation region is significantly broadened (for example, 1), for other phases (for example, 7) it is strongly reduced in comparison with the reflectionless case (dotted curve).

It should be mentioned that reflections change not only the output power of a gyrotron, but also slightly change the oscillation frequency (the so called frequency pulling, see, e.g., [2]). In principle, this effect can be calculated also by means of the equation system (2) by dropping in it the time derivative, in other words, by using a self-consistent stationary theory. In this paper, this has not been done, because our primary interest, both from the theoretical and experimental point of view, lies in investigating efficiency (power) changes due to reflections. Frequency changes due to reflections are negligible corrections to individual oscillation frequencies in specific modes at specific magnetic fields in Fukui gyrotrons and are neglected.

V. Experiment

A boron nitride (BN) 1.0-mm-thick plate was manufactured. For frequency $F = 89$ GHz the reflection coefficient of this plate is $|R| = 0.6$. In the experiment, the plate was placed between two spacers. The lower spacer rests on the gyrotron window which is transparent for this frequency. The BN plate was moved between the two spacers within the 2 mm interval—which exceeds the required distance $\Delta L_R = \lambda/2 = 1.68$ mm—to move along the closed circle with the constant radius $|R| = 0.6$ in the Rieke diagram.

The results of the measurements are shown in Fig. 3.

It is also evident that the experiment demonstrates very strong dependence of the output power on the phase of the reflection coefficient. Shift of the hard excitation region to lower magnetic fields is also observed. It should be emphasized that curve numberings in Figs. 2 and 3 do not correspond to each other, because the absolute phase of the reflection coefficient which depends on the distance between the cavity exit and the gyrotron window is not known.

A quantitative comparison between theory and experiment is difficult, because in the experiment the precise value of the pitch factor was not known. On the other hand, calculations demonstrate that the dependence of the output power on the magnetic field, as shown in Fig. 2, is rather sensitive with respect to the pitch factor. For example, with $\alpha = 1.4$ and all other parameters as before, the theory predicts that for many reflection phases the generated power is higher than in the reflectionless case.

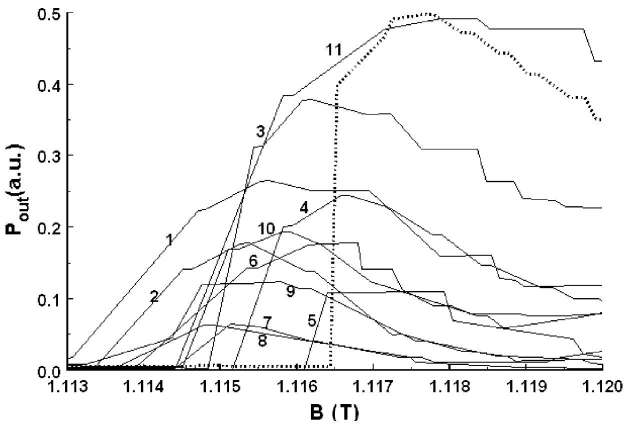

Fig. 3. Experimental oscillation regions of the $\mathrm{TE}_{3,1}$ mode for fixed $|R| = 0.6$ but different ΔL_R (0.0 – 2.0 mm) in steps of 0.2 mm. The dotted curve marks the oscillation region in the case of no reflections. There is no correspondence between numbering of the curves in this figure and in Fig. 2 (see text).

VI. Conclusion

In the case of large reflections considered in this paper, $(|R| = 0.6)$, high sensitivity of the efficiency of the gyrotron operation on the reflection phase is found both in the theoretical calculations and experimental measurements. This finding is important for the FIR FU gyrotron development program whose goal is to develop ultra broad-band tuneable gyrotrons. Optimal output power at all operating frequencies could be achieved by installing a carefully designed movable disk outside the gyrotron just above the gyrotron window. By individual adjusting of the distance between this disk and the window for each generated frequency at a particular magnetic field one could either increase or decrease the reflection and, thus, regulate the output power. This can be regarded as a superior alternative to elimination of reflections at all frequencies by using a Brewster window [8].

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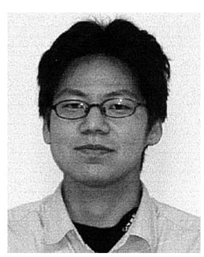

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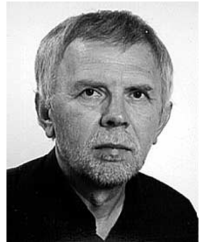

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