Reflections in Gyrotrons with Radial and Axial Outputs. A Comparison.

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Abstract- **Influence of reflections on operation of gyrotrons with radial and axial outputs is compared. In the former case no rigorous theoretical estimates are possible, while in the latter case accurate theory can be developed and compared with experiments.**

Introduction.

Reflections of microwave power can occur at the gyrotron RF output window.

In advanced high-power gyrotrons with a radial output 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 which is guided by means of phase corrected mirrors to the output window. The RF signal reflected from the window is dissipated in the entire volume of the tube. Part of it finds the way back to the cavity in all possible modes. No specific models exist for description of this complicated process. For example, this makes strict quantitative theoretical interpretation [1] of the interesting experimental results on reflections in the $TE_{22,6}$ mode gyrotron operated at Forschungszentrum Karlsruhe [2] difficult. In the simplest model it can be 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 an oversimplified model cannot be tested experimentally, it gives some feeling of possible influence of reflections in gyrotrons with a radial output.

In conventional gyrotrons with an axial output no mode transformation takes place and the RF signal reflected from the window returns to the cavity as the original mode. In this case rigorous comparison between theory and experiment is possible.

Formalism.

It is convenient to describe reflections by means of the complex reflection coefficient R written as [1]

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

where λ is the wavelength of gyrotron oscillations, L_R is the distance between the cavity exit and the reflecting load, and ΔL_R is the shift of the load. The period of the phase of R is $\lambda/2$ with respect to ΔL_R . The reflection coefficient can be introduced into the usual boundary condition at the cavity exit:

$$f\left(z_{out}, t\right) = \frac{i}{k} \cdot \left. \frac{\partial f(z,t)}{\partial z} \right|_{z=z_{out}} \cdot \left(\frac{1-R}{1+R} \right), \qquad (2)$$

where k is the wave number and f is the RF amplitude.

Radial output.

As an example, we consider the coaxial cavity gyrotron operated at Forschungszentrum Karlsruhe [3]. This gyrotron will be modified to meet ITER specifications. In particular an output window consisting of a single CVD diamond disk is suggested. In order to keep reflections at the nominal frequency 170 *GHz* small, the thickness of the disk is chosen to be 1.852 *mm*. This should guarantee a power reflection less than 1% for the nominal $TE_{34,19}$ mode. Reflections of neighboring competing modes increase with their distance from the nominal frequency, as shown in Fig. 1.

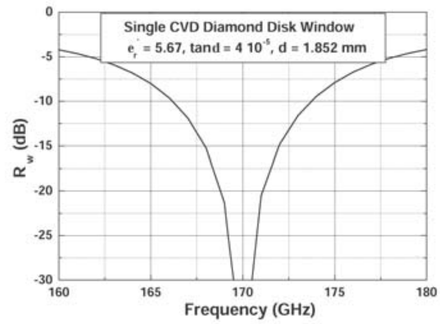

Fig. 1. Reflection coefficient for the reflected power of a single 1.852 *mm* CVD diamond disk window as a function of frequency.

To model reflections in this gyrotron, arbitrary values of R have been assumed and the so-called Rieke diagram has been calculated where contours of constant output power are plotted in the plane of the real and imaginary part of R (see Fig. 2).

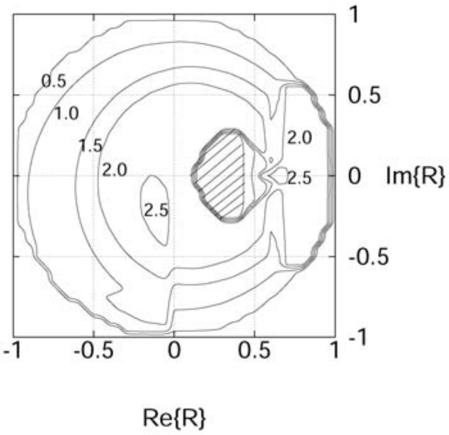

Fig. 2. Rieke diagram for the $TE_{34,19}$ mode. The equipower lines cover power range 0,…,2.5 *MW* in steps of 0.5 *MW*. There are no oscillations in the diagonally hatched region.

Calculations have been carried out in the single-mode approximation by means of the time-dependent self consistent code [4] for solving partial parabolic differential equations describing gyrotron oscillations. It can be seen that in the worst case (R is real and positive) it is possible to obtain high-power ($P_{out} > 2$ MW) oscillations if $|R| < 0.15$. This means that the amount of the reflected power is not allowed to exceed 2% ($R_w = |R|^2$). This condition is fulfilled by the designed output window. In principle even higher output power (~2.5 MW) at this specific operation point could be achieved by introducing artificial reflections. This possibility is only of an academic interest, because reflections in gyrotrons with radial output cannot be controlled in any predictable way.

Axial output.

In the case of an axial output a rigorous reflection theory can be developed and corresponding experiments can be performed. To illustrate this, we use the Fukui large orbit gyrotron (LOG) [5] operating at third harmonic in $TE_{3,1}$ mode at frequency $F = 89.13$ GHz and at fourth harmonic in $TE_{4,1}$ mode at frequency $F = 112.79$ GHz. In Figs. 3 and 4 theoretical predictions are shown for the output power as a function of the magnetic field B for fixed values of the beam voltage 37 kV and the beam current 1.3 A.

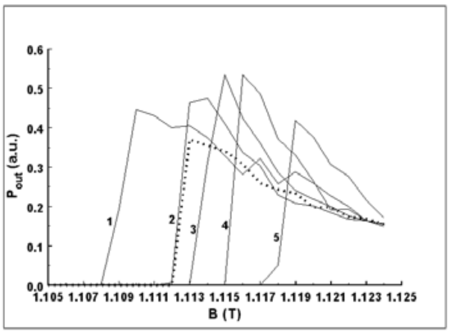

Fig. 3. Oscillation regions of the $TE_{3,1}$ mode for fixed $|R| = 0.6$ but different ΔL_R. 1: 0.36λ, 2: 0.06λ, 3: 0.08λ, 4: 0.10λ, 5: 0.14λ; λ = 3.36 mm. The dotted curve marks the oscillation region in the case of no reflections.

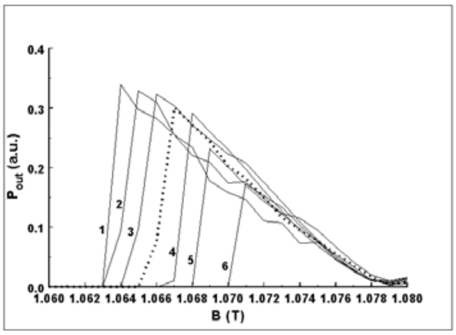

Fig. 4. Oscillation regions of the $TE_{4,1\ mode}$ for fixed $|R| = 0.6$ but different ΔL_R. 1: 0.02λ, 2: 0.30λ, 3: 0.48λ, 4: 0.46λ, 5: 0.44λ, and 6: 0.42λ; λ = 2.66 mm. The dotted curve marks the oscillation region in the case of no reflections.

It can be seen that reflections strongly influence the gyrotron operation, especially in the case of the $TE_{3,1}$ mode (Fig. 3). For different shifts ΔL_R. of the reflection plane the hard excitation region is displaced to different values of the magnetic field. This makes it possible to operate the gyrotron at high output power in a much broader range of the magnetic field. For example, the power $P_{out} = 0.35$ can be obtained throughout the interval 1.109 $T < B <$ 1.120 T in comparison with the narrow interval around 1.113 T corresponding to operation without reflections. Even in the case when the border of the hard excitation region is not displaced (B = 1.112 T), reflections increase efficiency by deforming RF field profile, moving its maximum towards the cavity exit and eliminating overbunching (Fig. 5). It is interesting that overall efficiencies for this mode are higher with artificially introduced reflections. This indicates that the chosen operating parameters of LOG for the given cavity are not optimal for a matched load.

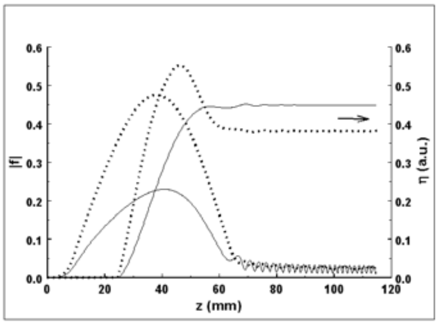

Fig. 5. RF field profile $|f|$ and efficiency η as a function of the longitudinal coordinate z in the cavity. Here the magnetic field B = 1.113 T. Solid lines: $|R| = 0.6$ and $\Delta L_R = 0.06\lambda$, dotted: $|R| = 0$. To be compared with Fig. 3.

Experiment.

In experiment a plate with a high reflection coefficient can be placed on the top of the gyrotron window, as was done in [6] where influence of reflections on power spectrum of gyrotron oscillations was studied. To test the theoretical predictions shown in Figs. 3 and 4 for the Fukui LOG, a Boron Nitride (BN) 1.04 mm thick plate will be used whose reflection coefficient $|R|$ = 0.6 is one and the same for the two modes. By shifting this plate within the interval $0 < \Delta L_R < \lambda/2$ relative to the gyrotron window, whose reflection coefficient is assumed to be zero, the phase of the reflection coefficient can be changed. In Rieke diagram this means a controlled motion around the circle with a constant radius $|R|$.

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