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Influence of Possible Reflections on the Operation of European ITER Gyrotrons

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Abstract The theory describing the influence of reflections on operation of gyrotrons with radial output is used for evaluating the effect of reflections on the operation of the ITER 170 GHz 2 MW coaxial cavity gyrotron, which is under development, and the 170 GHz 1 MW cylindrical cavity gyrotron as a fall back solution.

Keywords Gyrotron · Window reflections

1 Introduction

Reflections of microwave power can take place at the gyrotron RF output window. The effect of window reflections on gyrotron operation has been studied extensively in the past, both theoretically [1–3] and experimentally [4, 5]. Low-power gyrotrons have an axial output. 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.

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 loses 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. The reflected Gaussian beam follows the reverse path and is transformed inside the launcher into the oppositely rotating mode which returns to the cavity. This means that in gyrotrons with a radial output and allowance for reflections one should from the very beginning consider competition between opposite rotations of one and the same mode in the cavity even in the case when the electron beam radius is chosen such that it favors clearly only one rotation.

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Europe is developing the 170 GHz 2 MW coaxial cavity gyrotron for ITER. However, due to numerous delays and existing uncertainties related to coaxial gyrotrons, it has been decided to work in parallel on the 170 GHz 1 MW gyrotron with a cylindrical cavity as a fallback solution. In these gyrotrons the launcher supports the negative rotation. This means that the positively rotating modes in the cavity diverge from the quasi-optical mode converter and do not reach the window at all. The negatively rotating modes in the cavity reach the window and are partially reflected. After reflections and a backward passage through the system of mirrors, these modes enter the launcher where they are transformed into the positively rotating modes, which are "injected" into the cavity with the amplitude proportional to the reflection coefficient.

2 Theory

The theory describing these phenomena has been developed in [6]. Here we mention only briefly that the boundary condition for the outgoing negatively and positively rotating modes can be written in the ordinary form:

$$f_{\pm}(\varsigma_{out},\tau)=\frac{i}{k_{\pm}}\frac{\partial f(\varsigma,\tau)}{\partial\varsigma}\Big|_{\varsigma=\varsigma_{out}} \tag{1}$$

However the boundary condition for the reflected modes which return to the cavity with positive rotation is modified:

$$f_{+}(\varsigma_{out},\tau)=\frac{i}{k_{+}}\frac{\partial f_{+}(\varsigma,\tau)}{\partial\varsigma}\Big|_{\varsigma=\varsigma_{out}}+Rf_{-}(\varsigma_{out},\tau-\tau_{del}) \tag{2}$$

Here reflections are taken into account by the second term, where R is the reflection coefficient. The dimensionless delay time is $\tau_{del}=\beta_{\perp}^{4}\beta_{||}^{-2}\omega_{c}t_{del}/8$, where $t_{del}=\frac{2l}{c}$ and l is the distance along the path between the resonator exit and the window, takes into account the fact that the reflected signal interacts with the exiting signal only after the time moment t_{del}. We assume that the path between the cavity exit and the window is approximately 140 cm, so the delay time that corresponds to the round trip is about 9 ns. At the same time, the cavity decay time,Q/ω, for a given frequency and the Q-factor of about 10^3, is close to 1 ns.

Table 1 Frequencies quality factors and reflection coefficients.

Mode	Frequency (GHz)	Quality factor	Reflection coefficient
34,19	170.02	1643	0
36,19	174.24	1729	0.36
35,19	172.13	1689	0.20
33,19	167.90	1584	0.18
32,19	165.79	1505	does not reach the window
34,20	175.38	1680	does not reach the window
33,20	173.26	1583	does not reach the window
32,20	171.15	1455	does not reach the window

3 Coaxial cavity gyrotron

The operating mode of the 170 GHz 2 MW coaxial cavity gyrotron is $TE^{-}_{34,19}$. We consider the negatively rotating modes $TE^{-}_{36,19}$, $TE^{-}_{35,19}$, $TE^{-}_{33,19}$ and the positively rotating modes $TE^{+}_{32,19}$, $TE^{+}_{34,20}$, $TE^{+}_{33,20}$, $TE^{+}_{32,20}$ as competitors in the cavity. The former are reflected from the window and return to the cavity as positively rotating modes. Information about the modes is summarized in Table 1.

The *operating parameters* of the gyrotron are: R_{el}=10.0 *mm*, *B*=6.86 *T*, I_{op}=80 *A*, U_{op}= 90 *kV*, and α_{op}=1.3.

In the calculations the following values of *numerical parameters* were used: U_{step}= 0.5 *kV*, t_{step}=0.02 *ns*, number of electrons = 25, and number of phases =13.

The window is designed such that the reflection coefficient for the operating mode is zero. The mode competition calculations were performed also with several nonzero values

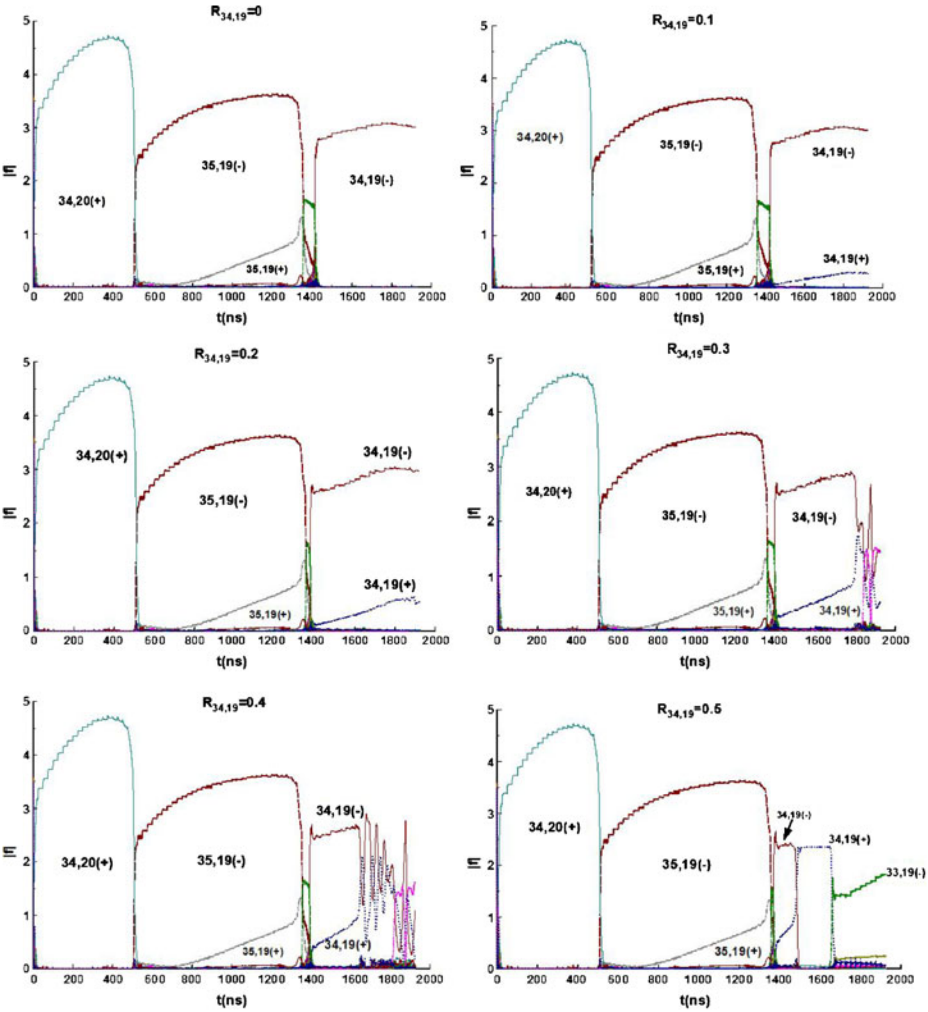

Fig. 1 Mode competition scenarios for different values of the reflection coefficient for the operating mode.

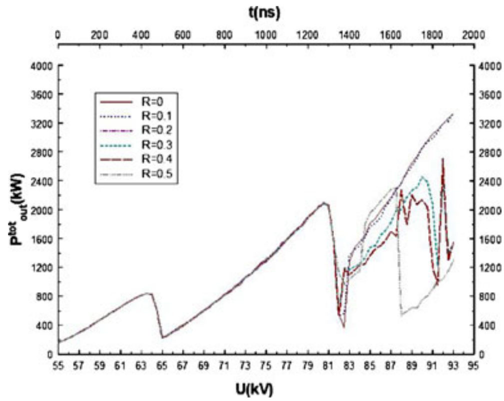

Fig. 2 The total output power as a function of time and voltage. It is seen that even in the case of relatively small reflection *R= 0.2* the maximal output at the operating voltage U_{op}=90 *kV* is noticeably smaller than in the case of no reflections.

of the reflection coefficient for the operating mode in order to understand feasible constraints. The results of the calculations are shown in Fig. 1.

It is obvious that mode competition scenario depends very strongly on the value of the reflection coefficient for the operating mode. Already for $R_{34,19}$=0.1 the positively rotating mode $TE^{+}_{34,19}$ is excited with noticeable amplitude. For $R_{34,19}$=0.3 and $R_{34,19}$=0.4 the two opposite rotations coexist with equal amplitudes, whereas for $R_{34,19}$=0.5 the positive rotation wins the competition and completely suppresses the negative rotation.

In Fig. 2 the total output power is shown as a function of time and voltage.

The total output power, i.e. the power at the exit from the cavity, can be represented as a sum of powers corresponding to the two rotations:

$$P^{tot}_{out} = P^{+}_{out} + P^{-}_{out} = |f^{+}|^2 + |f^{-}|^2 \tag{3}$$

Thus the output power corresponding to the operating mode can be calculated as follows:

$$P^{-}_{out} = \frac{P^{tot}_{out}}{|f^{+}|^2/|f^{-}|^2 + 1} \tag{4}$$

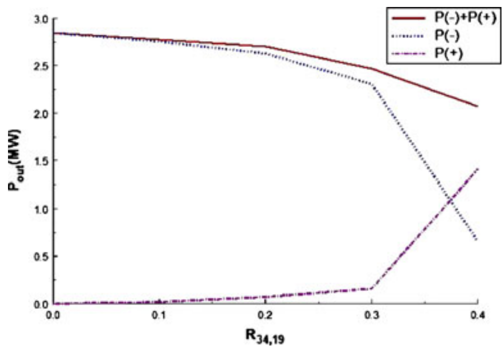

Fig. 3 Split power balance at U_{op}=90 *kV* (*t*=1750 *ns*). For $|R|_{34,19}$on the order 0.2 about 70 *kW* power is trapped in the tube as a stray radiation and about 2630 *kW* power leaves the tube.

Table 2 Frequencies quality factors and reflection coefficients.

Mode	Frequency (GHz)	Quality factor	Reflection coefficient
32,09	170.03	1026	0
34,09	176.09	1087	0.45
33,09	173.07	1058	0.27
31,09	166.99	994	0.26
30,09	163.94	967	0.46
32,10	178.77	1117	does not reach the window
31,10	175.70	1083	does not reach the window
30,10	172.61	1053	does not reach the window

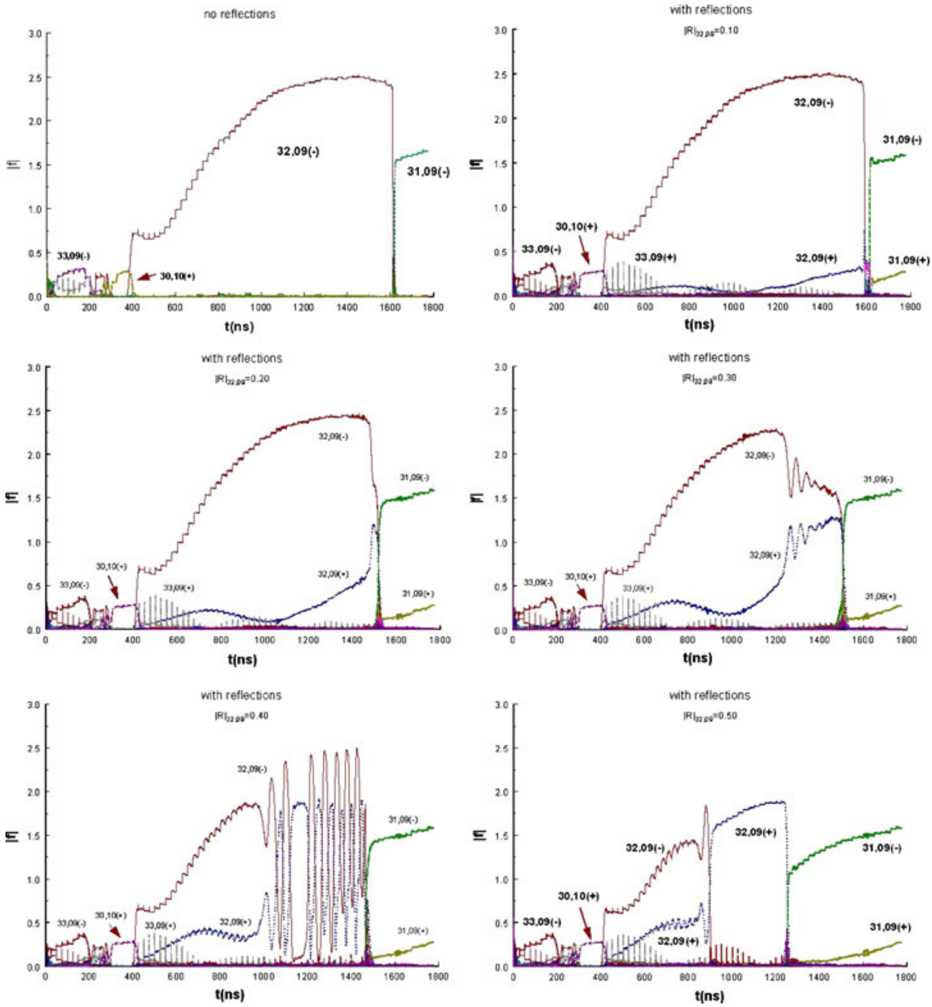

Fig. 4 Mode competition scenarios for different values of the reflection coefficient for the operating mode.

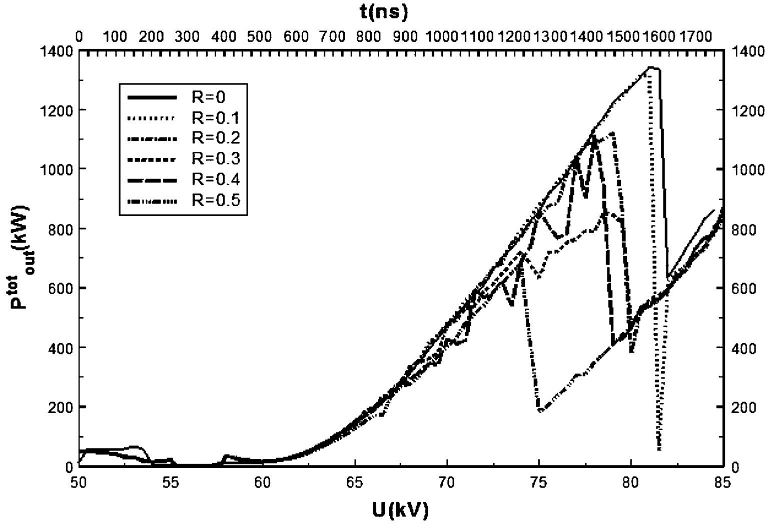

Fig. 5 The total output power as a function of time and voltage. It is seen that even in the case of relatively small reflection *R= 0.2* the maximal output at the operating voltage U_{op}=79 *kV* is noticeably smaller than in the case of no reflections.

This power leaves the gyrotron, but the power corresponding to the positively rotating mode

$$P^{+}_{out} = P^{tot}_{out} - P^{-}_{out} \tag{5}$$

remains inside the tube as a stray radiation. Taking the values of the ratio $|f^{+}|^{2}/|f^{-}|^{2}$ from Fig. 1 and the values of P^{tot}_{out} from Fig. 2, we obtain the split power balance shown in Fig. 3.

4 Cylindrical cavity gyrotron

The operating mode of the 170 GHz 1 MW cylindrical cavity gyrotron is $TE^{-}_{32,09}$. We consider the negatively rotating modes $TE^{-}_{34,09}$, $TE^{-}_{33,09}$, $TE^{-}_{31,09}$, $TE^{-}_{30,09}$ and the positively

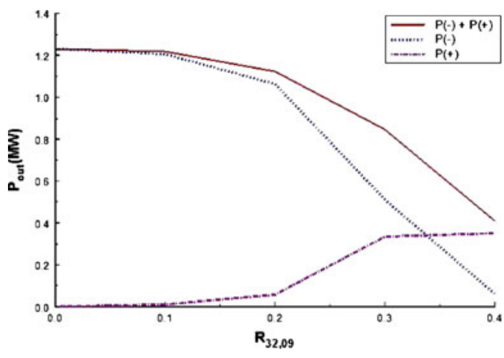

Fig. 6 Split power balance at U_{op}=79 *kV* (*t*=1450 *ns*). For $|R|_{32,09}$ on the order 0.2 about 60 *kW* power is trapped in the tube as a stray radiation and about 1060 *kW* power leaves the tube.

rotating modes $TE^{+}_{32,10}$, $TE^{+}_{31,10}$, $TE^{+}_{30,10}$ as competitors in the cavity. The former are reflected from the window and return to the cavity as positively rotating modes. Information about these modes is summarized in Table 2.

The *operating parameters* of the gyrotron are: R_{el}=9.50 *mm*, B=6.76 *T*, I_{op}=45 *A*, U_{op}= 79 *kV*, and α_{op}=1.3.

In the calculations the following values of *numerical parameters* were used: U_{step}=0.5 *kV*, t_{step}=0.02 *ns*, number of electrons = 25, and number of phases = 13.

The window is designed such that the reflection coefficient for the operating mode is zero. The mode competition calculations were performed also with several nonzero values of the reflection coefficient for the operating mode in order to understand feasible constraints. The results of the calculations are shown in Fig. 4.

It is evident that also in this gyrotron mode competition scenario depends very strongly on the value of the reflection coefficient for the operating mode. Already for $R_{32,09}$=0.1 the positively rotating mode $TE^{+}_{32,09}$ is excited with noticeable amplitude. For $R_{32,09}$=0.3 and $R_{32,09}$=0.4 the two opposite rotations coexist with equal amplitudes, whereas for $R_{32,09}$=0.5 the positive rotation wins the competition and completely suppresses the negative rotation.

In Fig. 5 the total output power is shown as a function of time and voltage.

In Fig. 6 we show the split power balance.

5 Conclusions

Mode competition scenario depends very strongly on the reflection coefficient. The value 0.2 can be considered as admissible upper limit in the two gyrotrons.

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