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Influence of reflections on the operation of the 2 MW, CW 170 GHz coaxial cavity gyrotron for ITER

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Abstract
The influence of reflections on the operation of the 2 MW, CW 170 GHz coaxial cavity gyrotron oscillating in the $TE^-_{34,19}$ mode is studied. In particular, frequency-independent power reflections, e.g. from plasma or some elements of the transmission line, larger than 1% and occurring in a poor phase may lead to oscillation breakdown and should be avoided. Frequency-dependent reflections from a specially designed diamond window influence mode competition, but contract the oscillation region of the operating mode noticeably only under the unrealistic assumption that all reflected power returns to the cavity. The conclusion is that the gyrotron is sufficiently robust against possible negative effects related to reflections.

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1. Introduction

For fusion experiments of the next generation such as the international thermonuclear experimental reactor (ITER), a microwave power of about 20 MW at 170 GHz operating in a quasi-CW regime is foreseen. To reduce the costs of the electron cyclotron wave system, an increase of the output power per unit to about 2 MW is desirable. Coaxial cavity gyrotrons have the potential to fulfil this requirement as has been demonstrated within a development program performed as an ITER task at Forschungszentrum Karlsruhe [1–6]. In particular, the following experimental studies have been performed with the coaxial gyrotron operating in the $TE^-_{31,17}$ mode at 165 GHz:

- investigation of stable operating conditions and of efficient microwave power generation,
- investigation of the performance with increasing pulse lengths,
- measurement of the mechanical stability of the coaxial insert under operating conditions,
- measurement of losses at the coaxial insert and comparison with calculations,
- investigation of the microwave stray radiation captured inside the gyrotron tube,
- study of the mechanism of parasitic low frequency ($\leqslant$100 MHz) oscillations,
- measurements of the influence of the misalignment of the coaxial insert on the operating conditions of the gyrotron,
- fast frequency tuning (within 0.1 ms) by applying a bias voltage at the insert.

In figure 1 the schematic layout of this gyrotron is shown.

It can be said that the physical basis for fabrication of a 2 MW, CW 170 GHz coaxial cavity gyrotron, as specified by ITER, has been proven. As a first step towards such a gyrotron some theoretical work has already been done. For example, in [7] the $TE^-_{34,19}$ mode has been selected as the operating mode and mode competition calculations have been performed.

In this paper we analyse the influence of possible reflections on the operation of the ITER gyrotron. Reflection of microwave power from the output window or other components as well as incomplete mode conversion can result in significant stray radiation captured inside a gyrotron. In experiments with the $TE^-_{28,16}$ coaxial cavity gyrotron (see [2]) it has been shown that the stability of operation suffers from stray radiation, e.g. due to increased occurrence of electron beam instabilities. The stability can be enhanced by absorbing the stray radiation with suitable material placed inside the

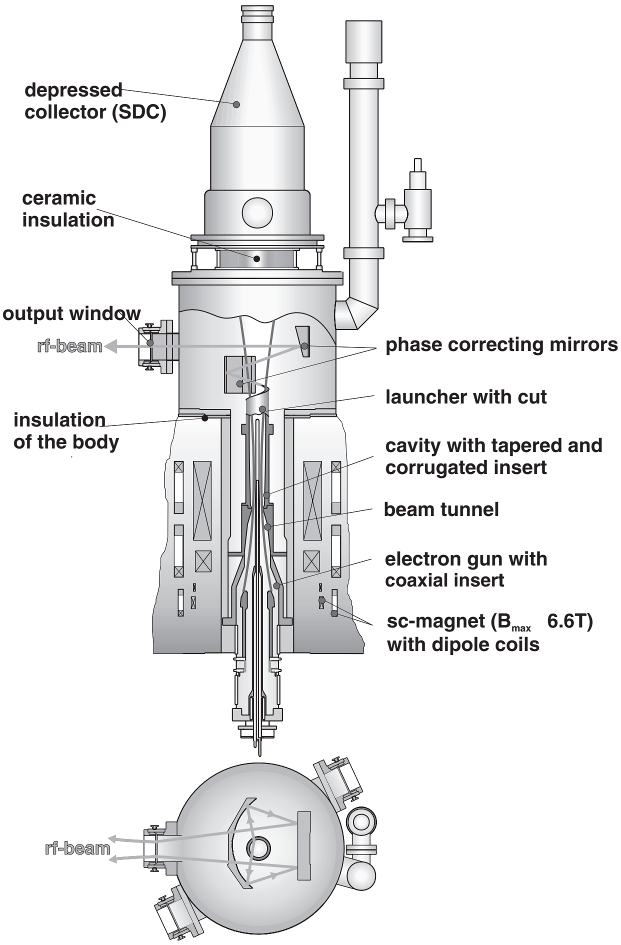

Figure 1. Schematic layout of the coaxial cavity gyrotron with radial output.

tube. Nevertheless, reflections should be avoided to make the accessible parameter range as wide as possible.

2. Reflections

Reflections of microwave power can occur at the gyrotron RF output window as well as along the transmission system with an additional window at the torus side. While reflections along the transmission system and the plasma depend weakly on frequency and are difficult to control, it is relatively easy to avoid frequency-dependent reflections from the gyrotron window by designing it carefully. For the coaxial cavity gyrotron for ITER an output window consisting of a single CVD diamond disc is suggested. In order to keep the reflections at the nominal frequency 170 GHz small, the thickness of the disc is chosen to be 1.852 mm. This should guarantee a power reflection less than 1% for the nominal mode. However, reflections of the neighbouring competing modes increase with their distance from the nominal frequency, as shown in figure 2. In table 1 we list all the relevant modes with their frequencies and reflection coefficients for the amplitude deduced from figure 2 by means of the relation $|R| = 10^{|R_w|/20}$.

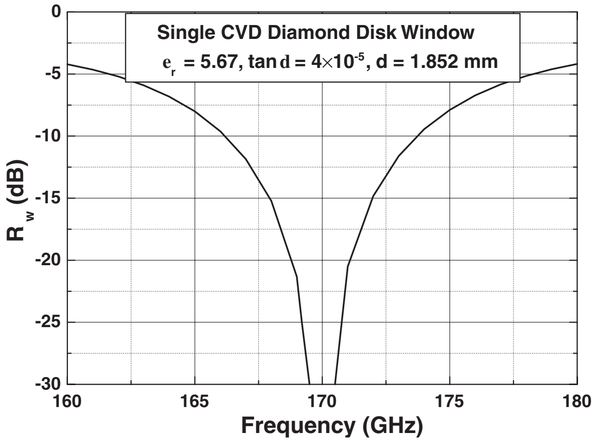

Figure 2. Reflection coefficient for the reflected power of a single 1.852 mm CVD diamond disc window as a function of frequency.

Table 1. The operating $TE^-_{34,19}$ and competing modes with their frequencies and amplitude reflection coefficients. Rotation '+' means counter-rotating with the electrons and '−' co-rotating. In the calculations it was assumed that counter-rotating modes were not reflected (see text).

Mode	Rotation	F (GHz)	$\|R_s\|$
34, 19	−	170.00	<0.10
36, 19	−	174.24	0.36
35, 19	−	172.13	0.20
33, 19	−	167.90	0.18
32, 19	+	165.79	0.34 (0)
34, 20	+	175.38	0.42 (0)
33, 20	+	173.26	0.28 (0)
32, 20	+	171.15	0.10 (0)

3. Description of reflections

The influence of reflections on gyrotron operation has been studied in several papers by means of different methods (see [8–11] and references therein). In [8] the dependence of mode competition scenario on reflections was studied and the need to use the self-consistent approach was emphasized. Here the reflection was simulated by an iris in a waveguide, the reflection coefficient was considered as a complex quantity, and the delay time describing the accumulation of the phase in the passage of the wave to the reflection point and back was introduced. In [9] the effect of wave reflection on the single-mode operation of a gyrotron was investigated with the help of Rieke diagrams and numerical results corresponding to experiments performed with the $TE^-_{22,6}$ 140 GHz gyrotron operating at Forschungszentrum Karlsruhe were presented. In [10, 11] a time-domain analysis of gyrotron operation in the presence of reflections was developed and applied to the same gyrotron. Here the influence of the distance to the reflecting load on the gyrotron behaviour was demonstrated. It was also shown that the traditionally accepted scenario of the transition from the single-frequency stationary operation regime to the chaotic nonstationary regime due to an increase of operating current [12] in the case of reflections should be rather replaced by a very complicated periodic and quasi-periodic behaviour.

In conventional gyrotrons with an axial output it can be assumed that a part of a specific RF cavity mode is reflected from the window and returns to the cavity. The reflection coefficient, the distance to the load, and the delay time have transparent meanings. In gyrotrons with a radial output (figure 1) this transparency is lost. After leaving the cavity the RF signal hits the launcher in which individual (one or several) rotating high-order cavity modes lose their identity and are converted into a linearly polarized Gaussian output beam which is guided by means of phase correcting mirrors to the output window. The reflected RF signal is partially dissipated in the entire volume of the tube and partially finds its way back to the cavity in all possible modes. No specific models exist for description of these complicated processes. In the light of this we simply assume that the reflections occur just at the exit from the cavity and the entire reflected RF signal in a specific cavity mode returns to the cavity. The reflection is described by a complex reflection coefficient; no distance to the reflection point and no delay time are involved in the theory.

4. Formalism

Our study is based on the following system of partial differential equations [13] which describe self-consistently mode competition in gyrotrons:

$$\frac{\partial p}{\partial \zeta} + \mathrm{i}(|p|^2 - 1)p = \mathrm{i}\sum_s f_s \exp[\mathrm{i}(\Delta_s\zeta + \psi_s)],$$

$$\frac{\partial^2 f_s}{\partial \zeta^2} - \mathrm{i}\frac{\partial f_s}{\partial \tau} + \delta_s f_s = I_s \frac{1}{4\pi^2}\int_0^{2\pi}\int_0^{2\pi} p\,\mathrm{d}\vartheta_0 \exp[-\mathrm{i}(\Delta_s\zeta + \psi_s)]\,\mathrm{d}\phi. \qquad (1)$$

Here p is the complex transverse momentum of the electron normalized to its initial absolute value, $\zeta = (\beta_\perp^2\omega_c/2\beta_\parallel c)z$ is the dimensionless longitudinal coordinate, $\beta_\parallel = v_\parallel/c$ and $\beta_\perp = v_\perp/c$ are normalized electron velocities, c is the velocity of light, z is the longitudinal coordinate, $(\omega_c/2\pi)$ [GHz] $= 28B$ [T]$/\gamma_{\mathrm{rel}}$ is the electron cyclotron frequency, B is the magnetic field in the resonator, $\gamma_{\mathrm{rel}} = 1 + U_b\,[\mathrm{kV}]/511$ is the relativistic factor, $U_b = U_c - U_d$ is the beam voltage, U_c is the cathode voltage, U_d is voltage depression, $\Delta_s = 2\beta_\perp^{-2}(\bar{\omega}_s - \omega_c)\omega_c^{-1}$ is the frequency mismatch, $f_s(\zeta, \tau)$ is the RF field in the resonator, $\psi_s = 8\beta_\parallel^2\beta_\perp^{-4}(\bar{\omega}_s - \omega_c)\omega_c^{-1}\tau + (1 \mp m_s)\phi$ is the phase of the mode, m_s and ϕ are the azimuthal index and coordinate, respectively, $\tau = \frac{1}{8}\beta_\perp^4\beta_\parallel^{-2}\omega_c t$ is the dimensionless time, t is time, $\delta_s = 8\beta_\parallel^2\beta_\perp^{-4}[\bar{\omega}_s - \omega_{\mathrm{cut},s}(\zeta)]\omega_c^{-1}$ describes variation of the cut-off frequency $\omega_{\mathrm{cut},s}(\zeta)$ along the resonator axis, $\bar{\omega}_s$ is the cut-off frequency at the exit from the resonator, and I_s is a dimensionless current which includes the RF field and electron beam coupling

$$I_s = 0.94 \times 10^{-4} I_0 \beta_{\parallel 0}\beta_{\perp 0}^{-6}\frac{J_{m_s\pm 1}^2((2\pi/\lambda_s)R_{\mathrm{el}})}{\gamma_{\mathrm{rel}}(\nu_s^2 - m_s^2)J_{m_s}^2(\nu_s)}. \qquad (2)$$

Here I_0 is the beam current in amperes, J_{m_s} is the Bessel function, λ_s is the wavelength, R_{el} is the electron beam radius, and ν_s is the zero of the derivative of the Bessel function. This expression for the current is valid for conventional cavity gyrotrons. For coaxial cavity gyrotrons it is more complicated (see, e.g., [8]). The subscript s refers to the sth mode.

The first equation in the system (1) has to be supplemented by the initial condition $p(0) = \exp(\mathrm{i}\vartheta_0)$ with $0 \leqslant \vartheta_0 < 2\pi$. Without reflections the wave freely propagates in the longitudinal direction once it leaves the interaction space. In real gyrotron resonators this is described by imposing the following boundary condition at the end of the exit cone:

$$\left[\frac{\partial f_s(\zeta, \tau)}{\partial \zeta} + \mathrm{i}k_s f_s(\zeta, \tau)\right]\Bigg|_{\zeta=\zeta_{\mathrm{out}}} = 0, \qquad (3)$$

where $k_s = 2c\beta_\parallel\beta_\perp^{-2}\omega_c^{-1}[\bar{\omega}_s{}^2/c^2 - \chi_s^2(\zeta)/R_{\mathrm{cav}}^2(\zeta)]^{1/2}$ is the dimensionless wave number, χ_s is the eigenvalue of the mode, and R_{cav} is the cavity radius.

Theoretically reflections in the widest sense can be described by introducing the normalized complex reflection coefficient R_s:

$$R_s = \frac{\partial f_s/\partial z + \mathrm{i}k_s f_s}{\partial f_s/\partial z - \mathrm{i}k_s f_s}, \qquad (4)$$

which for $R_s = 0$ reduces to the usual boundary condition (3). We now can formulate a generalized boundary condition for the second equation of the system (1)

$$f_s(\zeta_{\mathrm{out}}, \tau) = \frac{\mathrm{i}}{k_s}\frac{\partial f_s(\zeta, \tau)}{\partial \zeta}\Bigg|_{\zeta=\zeta_{\mathrm{out}}} \cdot \left(\frac{1 - R_s}{1 + R_s}\right). \qquad (5)$$

5. Single-mode calculations

We first assume that the operation parameters of the gyrotron are such ($R_{\mathrm{el}} = 10$ mm, $I_0 = 70$ A, $U_b = 90$ kV ($\alpha = 1.3$), $B = 6.86$ T) that a single-mode operation in the nominal $\mathrm{TE}_{34,19}^-$ mode is ensured and pose the question how reflections might influence the output power. This question can be conveniently answered by plotting contours of constant output power in the plane of the real and imaginary parts of the reflection coefficient. Such plots are called Rieke diagrams.

We solved the system of equations (1) in the single-mode approximation for the operating $\mathrm{TE}_{34,19}^-$ mode for many values of R. On the basis of these computations we constructed the Rieke diagram shown in figure 3. It can be seen that in the worst possible case when the reflection coefficient is real (poorest phase) for obtaining high-power ($P_{\mathrm{out}} > 2$ MW) single-mode oscillations the condition $|R| < 0.1$ must be satisfied, which means that the amount of reflected power should be less than 1%.

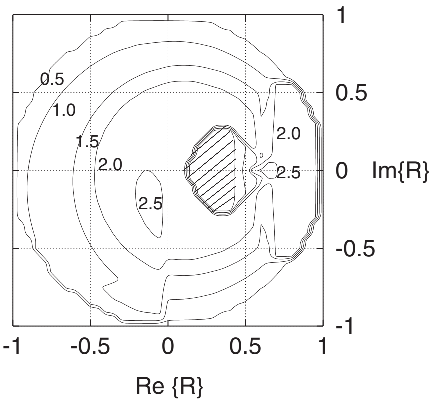

Figure 3. Rieke diagram for the $\mathrm{TE}_{34,19}^-$ mode. The equipower lines cover power range 0–2.5 MW in steps of 0.5 MW. There are no oscillations in the diagonally hatched region. The operating parameters are $R_{\mathrm{el}} = 10$ mm, $I_0 = 70$ A, $U_b = 90$ kV ($\alpha = 1.3$), and $B = 6.86$ T.

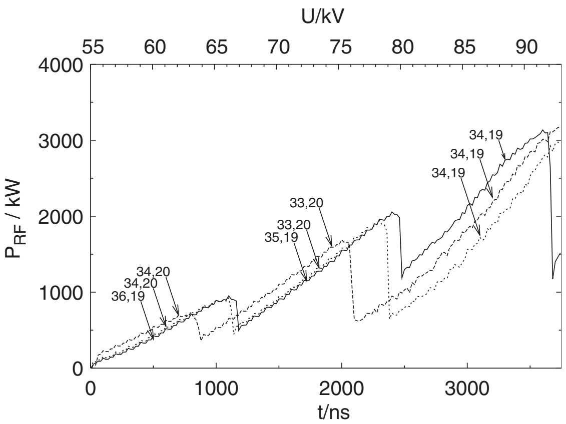

Figure 4. Mode competition scenario on the assumption that there are no reflections. The output power corresponding to $B = 6.84$ T is plotted with ——, to $B = 6.86$ T with - - - -, and to $B = 6.88$ T with $\cdots\cdots$.

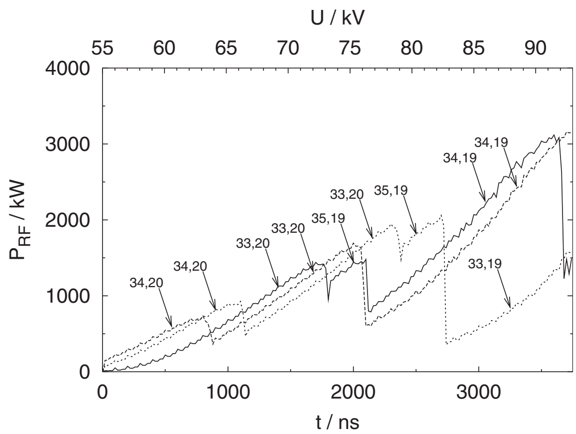

Figure 5. Mode competition scenario in the case of reflections given by figure 2 and table 1. It was assumed that $R_s = 0$ for counter-rotating modes. Other conventions are the same as in figure 4.

6. Mode competition calculations

The mode competition scenario for the nominal operating parameters of the gyrotron and three magnetic fields $B = 6.84$, 6.86, and 6.88 T without allowance for reflections is shown in figure 4. It is seen that at all magnetic field values the gyrotron at high voltages operates in the desired $TE^{-}_{34,19}$ mode. Next we assumed that the diamond output window is situated at the exit from the cavity and performed the calculations with real reflection coefficients listed in table 1. Here it was assumed that $R = 0$ for counter-rotating modes, because these modes diverge from the quasi-optical mode converter designed for co-rotating modes. The results of these calculations are presented in figure 5. It is seen that at lower magnetic fields $B = 6.84$ and 6.86 T the gyrotron oscillates in the desired mode, while at the highest magnetic field $B = 6.88$ T gyrotron oscillates in the parasitic $TE^{-}_{33,19}$ mode delivering significantly smaller output power. The calculations were repeated with half of the values of the reflection coefficients for co-rotating modes listed in table 1, which corresponds to reduction of the reflected power by a factor of 4. The results of these calculations are shown in figure 6. It is seen that at high voltages for all three magnetic field values the gyrotron oscillates in the desired mode.

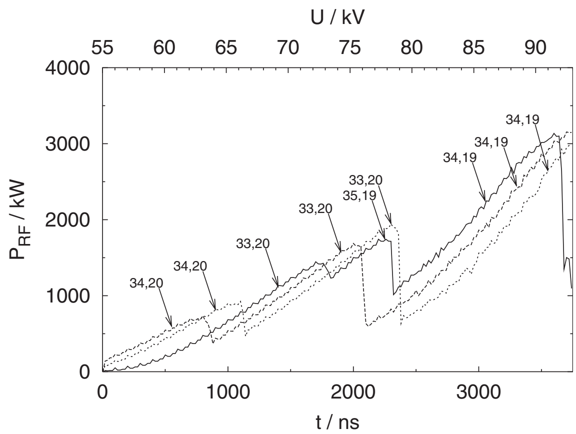

Figure 6. Mode competition scenario in the case of reduced reflections ($|R_s| \rightarrow |R_s|/2$). Other conventions are the same as in figures 4 and 5.

7. Conclusions

The influence of reflections on the operation of the coaxial cavity gyrotron for ITER has been studied. It has been found that

- the gyrotron is sufficiently robust against possible frequency-independent reflections of RF power,
- the amount of reflected power should not exceed 1%,
- the designed diamond window is such that it assures single-mode operation of the gyrotron in the desired $TE^{-}_{34,19}$ mode even if it were placed just at the exit from the cavity.

The difficult question of a complete modelling of reflections in a gyrotron with a radial RF output, i.e. without the assumption that the reflections occur just at the exit from the cavity, is beyond the scope of this investigation.

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