MAKARA, SAINS, VOL. 6, NO. 3, DESEMBER 2002

REFLECTION INFLUENCE ON OUTPUT FREQUENCY SPECTRUM AT SUBMILLIMETER FREQUENCY TUNABLE GYROTRONS

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Abstract

Influence of output window reflections on oscillatory processes in gyrotrons has been studied. The processes in a gyrotron have been modeled numerically, and enhancement of the spectrum signal in the presence of reflections has been studied. Dependencies of output power versus time and frequency spectrum for different value of reflection coefficient are given. Possibilities of significant increasing of output spectrum are demonstrated experimentally. The results demonstrate significant influence of reflections on operation stability and composition of the output radiation of the gyrotron.

Keywords: gyrotron, tunability, reflections, oscillation regime, radiation spectrum

1. Introduction

The development of gyrotrons is proceeding in two directions. One is the development of high power: millimeter wave gyrotrons as the power sources for electron cyclotron heating of plasmas and electron cyclotron current drive of tokamaks and for ceramic sintering [1-2]. The second direction is the development of high frequency: medium power gyrotrons as millimeter to submillimeter wave sources for plasma scattering measurements, ESR (Electron Spin Resonance) experiments and so on [3]. Gyrotrons developed in Fukui University belong to the second group [4]. A high frequency, medium power gyrotrons covering a broad frequency bands in millimeter and submillimeter wavelength regions have been developed. For diagnostics applications, a narrow frequency spectrum of output radiation is required.

Gyrotrons electrodynamic system may contain different types of reflections of transmitted microwave power. A strong influence of the reflection power on the generation regimes discussed at the works [5-7]. Due to special optimization of output taper and waveguide, reflections from inhomogenious wall are small and the strongest reflections can be observed from output window at some frequencies. The influence of external microwave fields must be the strongest in gyrotrons without quasi-optical isolation between the interaction space and the window for microwave power output, where the reflected signal gets directly into the resonator thus making the conditions for interaction of the electron beam with the RF (Radio Frequency) field worse. This paper is mainly concentrated on the influence of reflections on output frequency spectrum in tunable gyrotrons.

2. Methods

In order to solve this problem, an axially symmetric model of the gyrotron was used with no account for a spread of electron velocities and radii of leading centers of electron orbits in a tubular beam, as well as for fields of the spatial charge. The resonator cavity can be excited not only by the current through the cavity volume, but also by any field getting into the cavity from the outside. Hence the RF field excitation factor is represented as a sum of the factor of cavity excitation by the electron beam in the absence of reflections and by the term in proportional to the reflected signal getting into the cavity. Non-stationary processes in a gyrotron with several reflector points are described by a self-consistent system of equations (see, e.g. reference [8]), which consists of the good known shortened equation for electron motion in the external magnetic field and the field of the mode existing in the gyrotron:

(1)

Equations for mode excitation, which at presence of reflected signal, have the following form [5] :

(2)

and an expression that determines complex value **,** the factor of mode excitation by the electron beam, is represented by following equation :

(3)

The value of the electron current is described by parameter that proportional to the constant component of the beam current. The complex value a^* describes a variation of the energy and phase of rotational motion of electrons affected by the RF field with amplitude *F*, phase , and distribution *f.* The other parameters are detailed in [8]. Integration over the reduced longitudinal coordinate is performed along the total length of the interaction, is a dimensionless component of the velocity, is frequency of generated oscillations, and is eigenfrequency of the resonator. The conditions for removal of the energy by the decelerating phase of the RF field from the electron beam are provided by choosing , i.e. the mismatch of the cyclotron resonance, *n* is a number of the cyclotron harmonic. Positions of electrons at the entrance to the interaction space are described by their initial phase **.**

The perturbation introduced by the reflected signal is set by value j- - the gain of the phase of the reflected signal after its passing to the reflection point and back, and by parameter . *R* is an amplitude of the reflection coefficient and T_j is a delay time for the reflected signal.

The value of the reflection coefficient for a simplest gyrotron window can be calculated using formula for reflections microwave radiation from a dielectric plate. For a single mode operation the minimum of reflections is obtained by the variation of window size - (1,2,3...), there is the Brilluen angle of the mode. For tunable gyrotrons of different modes, the reflection coefficient is different due to different values of the wavelength and the dielectric parameter . For calculations, only a real part of the reflection coefficient was used due to

. The main window and cavity parameters of the experimental gyrotron FU (Fukui University) IV are given at the Table 1 [4].

The reflection coefficient (without account the mode transformation) can be found by formula :

(4)

where is a reflection coefficient, is a phase variation and can be described as follows :

(5)

Table 1. The gyrotron FU IV parameters

Window material	Quartz
Window width, mm	2.1
Window diameter, equal to output waveguide diameter, mm	20
Dielectric parameter:	3.8
Cavity diameter, mm	3.23
Cavity length, mm	14.5
Operating voltage, kV	12-15
Beam current, mA	100

In order to model the processes in the gyrotron numerically, the real longitudinal structure of the RF field in the cavity was approximated by a close Gaussian function, **,** where is a reduced length of the cavity. The dependence of output power versus time ( ) for two modes with different reflection coefficient are shown in Figure 1. The delay time for the reflected signal from the output window is ,

where . When there are no mode transfor-mations for main operating modes, at $L \approx 1$ m, d $\approx$ 5 , the delay time is several nanoseconds, which correspond to the power variation period in Figure 1. For the mode with a highest reflection coefficient value more strong fluctuation of output power was observed together with a more lowly efficiency. The gyrotron operate at regime of self-modulating oscillations and the depth of the modulation becomes greater as the reflection coefficient grows. With increasing the modulation level, extensions of the frequency spectrum are observed at calculation in reference [7], which corresponds to the increase of the integral power at the frequencies different from the carrier. This fact illustrated by results of Fourier harmonics calculation in Figure 2. For TE_{42} mode – mode with high reflections - the spectrum is approximately two times larger.

The character of the system behavior depends essentially on the value of the current parameter. However, in this case, for all modes, which excite at experiment, the starting currents are approximately same – several times less then the operating current.

3. Results and Discussion

The frequency spectrum was measured by a heterodyne detection system consisting of a sweep oscillator, a frequency counter, a harmonic mixer and a modulation domain (more detail see reference [9]). The detected signal was mixed with a high harmonic of the local oscillator. The frequency resolution of the detected system is 10 kHz. The calculation curve for the reflection coefficient value and the measurement results of the frequency spectrum for different modes are given in Figure 3.

For all cases the mode with small reflections have narrow frequency spectra and the mode with strong reflections possess wide spectra. The main reason for it is the additional instabilities (fluctuations) of output power, which produced by influence at reflected signal. The experimental dependencies of output power are shown in Figure 4 (compare with Figure 1). The measured frequency spectrums for TE_{42} and TE_{13} modes are presented in Figure 5. The scale of the fluctuation time is larger than the calculation results (see Figure 1b). But, it may be as a result of digital oscilloscope measured time limit (about several tens ns). A comparison between the measured frequency spectrums for TE_{13} and TE_{42} modes and the results of Fourier-analyze reveal that the TE_{42} have near two times wider spectrum in all cases.

(a)

(b)

Figure 1. The dependence of output power versus time ( ) for two modes with different reflection coefficient (R_{13}=0.1, R_{42}=0.25)

Figure 2. The additional to carrier frequency Furie harmonics at gyrotron radiation spectrum for TE_{13} and TE_{42} modes. Significant extension of the spectrum for TE_{42} mode with large reflection coefficient is observed

Figure 3. **The calculated reflection coefficient (window width *d*=2.07 mm) and results ofrequency spectrum measurements for different operating mode at Gyrotron FU IV.**

Figure 4. **The measured dependence of output power versus time for TE_{13} and TE_{42} modes with different reflection coefficient (R_{13}=0.1 R_{42}=0.25)**

Figure 5. The measured output frequency spectrum for TE_{42} and TE_{13} modes with different reflection coefficient (R_{42}=0.25, R_{13}=0.1). Approximately two times increasing of frequency spectrum for TE_{42} mode with strong reflections observed.

4. Conclusion

The experimental results demonstrate a significant influence of the reflections on an operation stability and a frequency spectrum of the output radiation of the gyrotron. As the reflected signal becomes stronger, the generation regimes have as results oscillations with lower efficiency and much more extended spectrum of the output radiation. The calculation results with a fixed longitudinal structure of the RF-field and the experimental results have a high correlation to each other. So, the presented method can be used for analysis of the generation regimes at frequency tunable gyrotrons. To reduce the reflection influence of the gyrotrons with quasi-optical converters the Brewster window can be used, but for the gyrotrons with direct output of microwave power, other possibilities must be found. One of them can be "night mouth eye window" which discussed at [10] for medium power frequency tunable gyrotron.

Acknowledgement

The authors are deeply grateful to M. Glyavin, V.E.Zapevalov and N.S.Ginzburg (IAP RAS) for for valuable discussions.

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