Electron Dynamics in the Process of Mode Switching in Gyrotrons

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Abstract—**The present paper is devoted to the analysis of electron interaction process in the course of gyrotron switching from one mode to another. This analysis is based on the use of the Hamiltonian formalism that allows one to construct Poincare plots for different instants of switching time. The study is carried out for a 170 GHz MW-class gyrotron for ITER.**

I. Introduction and Background

In recent years, the attention of gyrotron developers is primarily focused on the design of MW-class gyrotrons with the use of available numerical codes and on gyrotron manufacturing, assembling and testing. In addition to this mainstream, there are also some continuing efforts (see, e.g., [1-3]) aimed at better understanding the physics of electron interaction with microwave fields in gyrotrons. One of the issues which still need better explanation is the electron dynamics in the process of gyrotron switching from one mode to another. An example of such switching in the process of voltage rise in a 1.2 MW, 170 GHz European gyrotron which is currently under development for ITER is shown in Fig. 1.

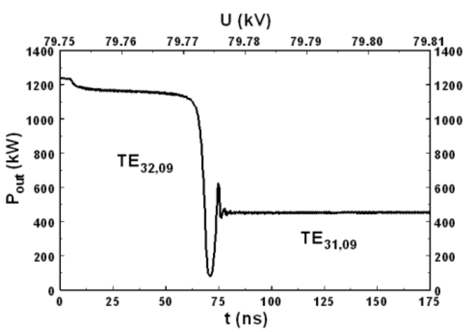


Fig. 1. Switching from the operating $TE_{32,09}$ mode at 170.027 GHz to the parasitic $TE_{31,09}$ mode at 166.985 GHz. Here B=6.76 T, I=42 A, Rel=9.50 mm, and α=1.3.

Below we analyze electron interaction with the fields of the two modes during the time of switching, i.e., from 70 ns up to 74 ns.

II. Formalism

Our analysis is based on the use of known non-stationary gyrotron equations [4]:

$$\begin{aligned}&\frac{\partial p}{\partial \varsigma}+i(|p|^2-1)p=i\sum_s f_s\exp[i(\Delta_s\varsigma+\psi_s)]\\&\frac{\partial^2 f_s}{\partial \varsigma^2}-i\frac{\partial f_s}{\partial \tau}+\delta_s f_s=I_s\frac{1}{4\pi^2}\int_0^{2\pi}\int_0^{2\pi}pd\vartheta\exp[-i(\Delta_s\varsigma+\psi_s)]d\phi\end{aligned}\tag{1}$$

The equation for electron motion in a single-mode case can be rewritten [3] in action-angle variables with the Hamiltonian

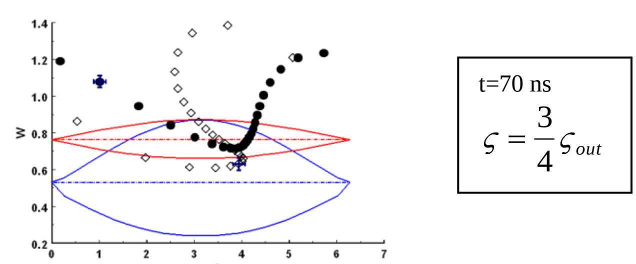
$$H(w,\theta)=\frac{w^2}{4}-w_r\frac{w}{2}+\sqrt{w}\,\mathrm{Im}(e^{i\theta}f)\tag{2}$$

where $w=|p|^2$, $w_r=1-\Delta$ and $\theta=\arcsin(\mathrm{Re}\,p/\sqrt{w})$. Here Δ is proportional to the difference between the mode frequency and the electron cyclotron frequency. A similar formula can be written for a two-mode case. From $H(w,\theta)=H(w_r,0)$ the equation for separatrix follows

$$w=w_r\pm 2\sqrt{\sqrt{w_r}\,\mathrm{Im}\,f-\sqrt{w}\,\mathrm{Im}(e^{i\theta}f)}\tag{3}$$

III. Results

In solving Eq. (1) we used 25 electrons with entrance phases ϑ and 7 azimuthal phases ϕ uniformly distributed between 0 and 2π. In the following figures we show Poincare plots at two cross sections of the resonator $\varsigma=3\varsigma_{out}/4$ and $\varsigma=\varsigma_{out}$ for two azimuthal phases: $\phi=2\pi/7$ (black dots) and $\phi=2\pi\cdot 4/7$ (white diamonds). Crosses mark the electron number one, whose entrance phase is $\vartheta=2\pi/25$. Here the lower cat's eye shows the separatrix of the operating mode and the upper cat's eye shows the separatrix of the parasitic mode.



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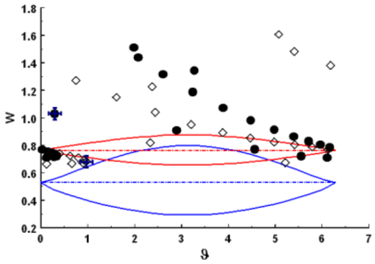
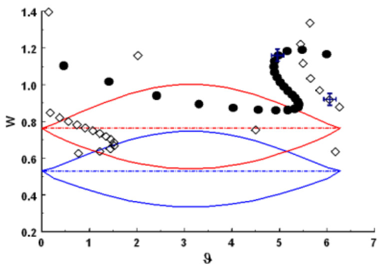


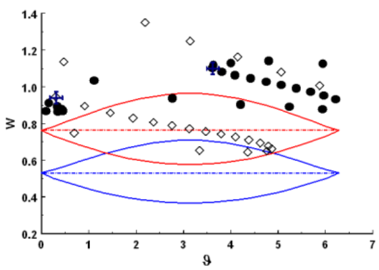
t=70 ns

$\varsigma = \varsigma_{out}$



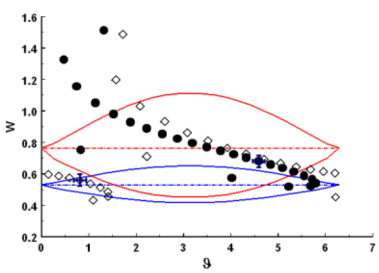
t=72 ns

$\varsigma = \frac{3}{4}\varsigma_{out}$



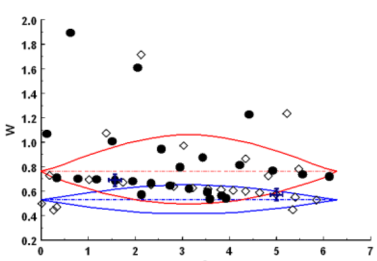
t=72 ns

$\varsigma = \varsigma_{out}$



t=74 ns

$\varsigma = \frac{3}{4}\varsigma_{out}$



t=74 ns

$\varsigma = \varsigma_{out}$

IV. CONCLUSIONS

The first conclusion which can be drawn from these figures relates to the possibility of the second mode excitation. When the voltage rise results in fulfillment of self-excitation conditions for this mode, the first mode operates with a high efficiency where the difference between the frequency of this mode and the electron cyclotron frequency is rather large. For the second mode with a lower frequency this difference is smaller. Therefore, electrons, which enter the interaction region with the initial value of w equal to one, in the process of their deceleration by the first mode first enter the region occupied by the separatrix of the second mode and, hence, interact with this mode in spite of the presence of the first mode. This gives the preference to the second mode and so it starts to grow.

Secondly, as the amplitude of the second mode grows, electron interaction with this mode leads to significant disturbances in the electron distribution in the phase space. Therefore, when electrons enter the region occupied by the separatrix of the first mode they have much less free energy to be transformed to the first mode radiation. Thus, the first mode starts to decay.

Third, while in the process of single-mode operation electrons with different azimuthal phases of electron beamlets exhibit the same behavior in the phase space, in the process of mode switching where two modes are present electron dynamics depends on the azimuthal coordinate of the guiding center. This can be explained by the fact that the phase difference of these modes is azimuthally dependent. This conclusion is illustrated by the figure showing electron distribution at the exit for t=72ns: here the lowest value of w for black dots is larger than 0.8, while a corresponding minimal value for white diamonds is about 0.5. When the switching process is rather slow, this azimuthal non-uniformity in the energy of spent electrons can be important for collector operation.

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REFERENCES

[1] G. S. Nusinovich, R. Ngogang, T. M. Antonsen, Jr., and V. L. Granatstein, Phys. Rev. Lett., **93**, 055101 (2004).
[2] Y. Kominis, O. Dumbrajs, K. A. Avramides, K. Hizanidis, and J. L. Vomvoridis, Physics of Plasmas, **12**, 113102 (2005).
[3] O. Dumbrajs, Y. Kominis, K. A. Avramides, K. Hizanidis, and J. L. Vomvoridis, IEEE Trans. Plasma Sci., **34**, 673 (2006).
[4] N. A. Zavolsky, G. S. Nusinovich and A. G. Pavelyev, in "Gyrotrons", a book of collected papers, Gorky, USSR, 1989, p. 84.

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