Analytical theory of low frequency oscillations in gyrotrons

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***Abstract*—Low frequency oscillations attributed to reflected electrons bouncing adiabatically between the electron gun and the interaction space have been observed in many gyrotrons. An analytical model is considered which allows one to apply space-charge wave theory to the analysis of these oscillations. In the framework of the small signal theory, the regions of low frequency oscillations, the oscillation frequency and the temporal and spatial growth rates of low frequency oscillations are determined in the parameter relevant space. These results are consistent with some experimental data. They also allow recommending some means for suppressing low frequency oscillations.**

I. INTRODUCTION

In principle, the gyrotron efficiency can be improved by increasing the ratio of electron orbital to axial velocity components. However, by increasing this ratio in the presence of velocity spread, electrons with large transverse (and correspondingly, small axial) velocities can be reflected from the magnetic mirror in the beam compression region. The reflected electrons can be trapped and accumulated in the region between the reflection plane, which is usually close to the cavity entrance, and the electron gun. When the amount of trapped electrons becomes large enough, parasitic low-frequency oscillations (LFOs) can be excited at frequencies close to the frequency of electron axial oscillations in the trap [1-4].

In this paper, we propose an analytical model applying the space-charge wave theory [5] to the analysis of such low-frequency oscillations. In this model shown in Fig. 1 electrons confined by a strong, constant magnetic field, stream between two reflection points. There are three groups of electrons: 1) beam electrons which are born at z=0 and stream through the beam compression without reflection, 2) forward moving trapped electrons and 3) backward moving trapped electrons. At the right boundary (z=L) forward trapped electrons start moving backward, while at the left boundary (z=0) backward trapped electrons start moving forward. All these electrons contribute to the space charge density.

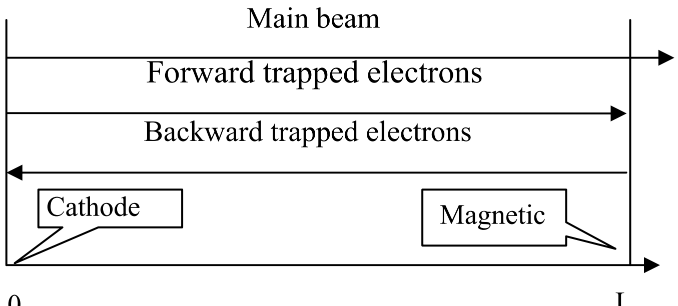

Figure 1. The model of three beam components in the trap region.

II. Formulation

Assume that in the trap region a strong magnetic field is uniform and the electrons perform one-dimensional motion; then the situation can be formulated in terms of one-dimensional fluid equations. In particular, each group of electrons is described by a continuity equation and the electron motion is described by a one dimensional cold fluid Euler equation. Since the frequency of LFO is well below the gyrofrequency of electrons, and the resonant frequency of electromagnetic modes in the gun region, the fields are electrostatic. So the electrostatic potential is determined by the beam space charge density and Poisson's equation. In the framework of small-signal theory all equations describing the model can be represented as a superposition of unperturbed values and small perturbations. Then these equations can be linearized and written to first order in the perturbed quantities. The resulting system is a set of six first order partial differential equations, along with the linearized Poisson's equation through which the different species are coupled. Application of the boundary conditions and linearized equations describing the model then results in a system of a 6×6 matrix equation that determine the mode oscillation frequency and the instability growth rate. These equations contain the following parameters: the unperturbed beam velocity v_{b0} and unperturbed trap beam velocity v_{t0} describe the main beam and trap electrons motion. The quantity of sound speed $C^2_s = q\sigma_{b0}\Delta/\varepsilon_0 m$ (Δ is clearance between the beam and wall) and the ratio of the density of trapped electrons to that of the main beam $F=\sigma_{t0}/\sigma_{b0}$ describe the space charge density. The length L between the reflection planes to describe the trap length.

II RESULTS

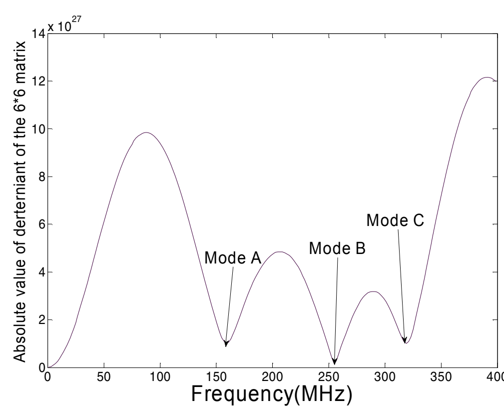

Figure 2. Quasi-period character of oscillation frequency (v_{b0}/c=0.3, v_{t0}/c=0.27, $(C_s/v_{b0})^2$=0.2, F=0.3, L=0.2m)

Result shown in Fig 2 indicate that oscillation frequencies calculated by our model have a quasi-period character and their

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values correlate with the frequency of trapped electrons moving back and forth in the trap.

In Fig .3, contours of the equal growth rate of LFO are shown in the plane of parameters "the square of sound speed to the beam velocity ($c^2{}_s / v^2{}_{b0}$) versus ratio of the density of trapped electrons to the electron beam density (F)". Corresponding frequency of LFO varies from 100MHz to 200 MHz.

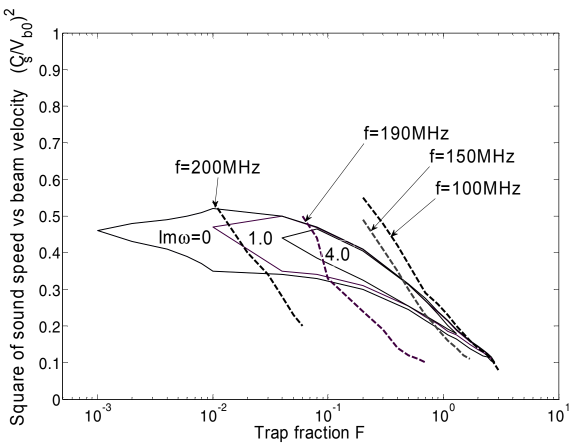

Figure 3 Contours of equal growth rates ($\mathrm{Im}\,\omega \bullet 10^{-5}$) and oscillation frequencies in the plane of parameters "the square of sound speed to the beam velocity ($c^2{}_s / v^2{}_{b0}$) versus ratio of the density of trapped electrons to the electron beam density (F)" (v_{b0}/c=0.3, v_{t0}/c=0.27, L=0.2m)

Results shown in Fig.3 indicate that low-frequency oscillations can be suppressed when either the trap fraction F is minimized, which is obvious, or, that is less obvious, the ratio of the square of sound speed to the beam velocity $(C_s / v_{b0})^2$ lies outside of the instability region bounded by $\mathrm{Im}\,\omega = 0$. This means that in practice, for a given beam density value, this ratio $(C_s / v_{b0})^2$ can be varied by varying the sound speed $C^2{}_s$ which depends on the clearance between the beam and the wall (Δ).

In gyrotrons with depressed collectors, electrons with small axial velocities at the resonator exit can be decelerated and then reflected back when the voltage depression is stronger than magnetic decompression of the beam which transforms part of the orbital energy into the energy of axial motion. Such trapped electrons can also form a cloud of trapped electrons. Moreover, some of them can even propagate through the interaction region and go back to the cathode, so such trapped particles will oscillate between the gun and the depressed collector. To avoid this instability the shape of metallic walls in the region of depressed collector should be properly optimized. Also, as shown in Ref. 6, backscattered electrons emitted from the collector may contribute to this instability.

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