The Coaxial Vircator with an Asymmetric Electron Beam

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Abstract – This work is presented the results of theoretical research of the vircator of coaxial configuration with asymmetric radially convergent beam. The fields structure of the vircator electrodynamic system was regarded. It was carried out the research of an influence of geometry system and electron-beam parameters on virtual cathode forming and radiation characteristics. Numerical modeling was carry out using 3 dimensional particle-in-cell code KARAT.

1. Introduction

The high power microwave radiation can be generated from the virtual cathode systems when the current of intense relativistic electron beam exceeds the space charge limiting current [1–6]. There are exists two types of vircators. One of it has cylindrical beam and flat electrodes, and other one is coaxial vircator with radially convergent beam. The power level more than 10% was reached in the vircator with flat electrodes [1]. In a coaxial vircator symmetrical radially convergent electron beam interacts with the symmetric modes and achieved radiation performance levels does not exceed 5% [2, 4]. Low efficiency of radiation is connected primarily with the problem of axial symmetry of the beam and the deep electrons modulation issues.

Azimuthally asymmetric waves are interacted with the beam with no axial symmetry more efficiently. Currently, much attention is paid to coaxial vircator with two opposed emitting surfaces [6–7]. Virtual cathode is formed in the drift space, i.e. in a cylindrical anode. The obtained values of the radiation efficiency are not more than 3% in such systems.

In this paper, the coaxial vircator with an asymmetric electron beam is considered. The vircator scheme is presented in Fig. 1. The accelerating voltage is applied to the anode, a cathode and an external resonator is under ground potential. Virtual cathode is formed in a retarding electrostatic field, so there is no need for two opposed emitting surfaces to exclude the drift electrons. In this paper the virtual cathode formation and excitation of electromagnetic oscillations in the vircator of coaxial configuration with asymmetric radially convergent beam (Fig. 1) are studied.

2. Numerical simulation

Investigation of the virtual cathode formation and excitation of electromagnetic oscillations in a coaxial vircator was carry out using particle-in-cell method in a relativistic package KARAT (three dimensional particle-in-cell code). Investigation of the fields structure of the vircator electrodynamic system carried out applying the package COMSOL Multiphysics.

Electrodynamic system of coaxial vircator is non-simply connected in the region of interaction between the beam and a system field. The anode-grid and anode holder are internal conductors, and a cylindrical chamber is an external conductor. Free anode edge in a reflex triode (Fig. 1) plays the role of right wall of non-simply resonator. In the region of beam-field interaction waves of type H, E, and TEM can be excited. The reflex triode own fields structure presented in the scheme of Figure 1 was investigated numerically. Therefore, the Helmholtz equation with appropriate boundary conditions was numerically solved. The coaxial vircator geometric dimensions are following: the radius and width of the emission region $R_C = 7.2$ cm and $h = 6$ cm, the radius of the external resonator $R = 11$ cm, the radius and width of the anode $R_A = 5.4$ cm and $L_A = 7$ cm, length of the anode arc $l = 12$ cm.

Fig. 1 shows the field structure (electric component) of the first higher modes $H_{11}$ and $H_{21}$ in cross-section plane. From Fig. 2 it is visible that the radial components of these wave types interacts with an asymmetrical electron beam more effectively. Numerical calculations have shown the transverse wave number in the vircator electrodynamic structure for the wave $H_{11}$ equals $k_\perp = 16.67$ m$^{-1}$ (when a resonator length $L = 0.5$ m), and $k_\perp = 16.31$ m$^{-1}$ when $L = 0.3$ m. For comparison, in a smooth circular cavity
$k_l = 16.72 \text{ m}^{-1}$. The excitation resonant frequency of wave $H_{11}$ is determined from the formula 

$$f = c \left( k_l^2 + (p \pi / L)^2 \right)^{1/2} / 2 \pi,$$

where $p$ is quantity of half-waves $\lambda = \pi / L$ along $L$.

Length of the inner conductor, i.e. length of anode $L_A$ must also be a multiple of half-waves number. Figure 3 presents the solution of the Helmholtz equation for the wave $H_{11}$ with $L = 0.3$ m: the 6 half-waves fit in the longitudinal direction, resonance frequency of the wave $H_{11}$ is $f = 3.1 \text{ GHz}$. The resonant frequency of the wave TEM in this geometry is equal $f = 2.99 \text{ GHz}$.

Investigation of the virtual cathode formation and excitation of electromagnetic oscillations in a coaxial vircator carried by particle-in-cell method with the help of a relativistic package KARAT. Figure 4 shows a configuration portrait of the beam in different projections.

The dependence of the diode current on the width of the emission surface $h$ is performed in Figure 5. When the beam width increases from 5 to 10 cm diode current $I_d$ changes from 19.5 to 25.5 kA. A insignificant increase of $I_d$ is due to the diode current is limited by the beam magnetic field.

Current limitation in the vircator can be reduced by electrons that are reflected from the virtual cathode and returned to the anode-cathode area. Dependence of current in a coaxial vircator (anode transparent equals 0.7) on the accelerating voltage is shown in Fig. 6. The frequency of microwave generated in coaxial vircator is direct proportional to square root of diode voltage, i.e. $f \propto \sqrt{U}$. Numerical calculations show, that when the voltage changes from 350 to 600 kV frequency $f$ varies from 3 to 3.8 GHz.
High Power Microwaves

However, the current reduction is not proportional to the reduction of area, i.e. the reduction of \( l \). Symmetrical vircator current is equal \( I = 25 \text{kA} \), and it takes value \( I = 20 \text{kA} \) when the emitting surface area (\( l = \pi r \) and \( \theta = \pi \)) decreases by half. This phenomenon is due to the influence of boundary effects and the beam own fields.

At decreasing of central angle \( \theta \) limitation of beam current by eugen magnetic field in anode-cathode gap decrease, therefore linear dencity of charge on anode \( j_A \) increase and respectively anode–virtual cathode gap \( R_{A–VC} \) reduce [8]. At that frequency of electron oscillations and vibration of vircator grow (Fig. 8). The most effective interaction of the beam with a electrodynamic structure field occurs in two cases: when \( v_r \gg v_\perp \) and when the eigenfrequency of the resonance system coincides with the virtual cathode oscillation frequency \( f_{VC} \) [2, 7]. The frequency of electron oscillating in an asymmetric potential well \( f_{os} \sim f_{VC} \) in this case. This is consistent with the findings of analytical studies that have shown that \( f_{os} = f_{VC} = f_w + \zeta N^3 \), where \( \zeta \) is growth rate of the instability of following magnitude: parameters of the beam and the system, excited wave type, variation in velocity and oscillation amplitude [2, 7].

Taking into account the oscillator energy changing with changing amplitude we can estimate the radiation efficiency \( \eta = \frac{\delta W}{W} \):

\[
\eta = \frac{2}{\sqrt{3}} \frac{\zeta}{f_w} \left( \frac{1}{K} \right)^2 \left[ \frac{2\gamma_0 - 1}{\gamma_0} + 2K \right],
\]

where \( \gamma_0 = 1 + U/511 \), \( K = (\partial \Omega / \partial \chi)_{\gamma_0} / (c^2 / \Omega_0^2) \) is the nonlinearity parameter of oscillation movement, \( \chi \) is the square amplitude of electron oscillation, \( \Omega = 2\pi f_w \).

### Conclusion

Coaxial vircator with axially asymmetric electron beam is a generator of electromagnetic oscillations. Vircator electrodynamic structure is non-simply. Resonant interaction with mode TEM and with asymmetric mode \( H_{11} \) can be performed in the beam region. As \( f_{os} \) and \( f_{VC} \) frequencies depend upon beam parameters, therefore there is a possibility to control a radiation frequency by changing an accelerating voltage, as well as by geometry of electrodes and beam.

### References