STRUCTURE AND THEORY OF VIRTUAL CATHODE IN MAGNETIC SELF-INSULATED TRANSMISSION LINE

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The possibility of formation of a virtual cathode in a self-insulated magnetic line is shown.
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1. INTRODUCTION

The effect of formation of a virtual cathode (VC) is known from the time of first studies of processes happening in electron tubes [1].

It was revealed that at a large enough current that is flowing between electrodes the potential barrier for electrons is formed not far from cathode. This barrier limits current of an electron beam. The potential barrier together with an electron beam that is dissipated on them also represents a virtual cathode.

Long time VC remained the extremely parasitic phenomena limiting a current of electron devices. The first sensible positive application of VC has found in the generator of short electric (electromagnetic) impulses [2].

One more application of VC is connected to collective ion acceleration. It was established that experiments [3-5], in which the accelerated ions were detected in the presence of an electron beam, could be explained by formation of VC in electron beam and its movement.

VC, which is appeared in REB, was successfully applied for generation of high power RF-radiation. It is associated with the fact that the beam in VC makes electric oscillations near electron plasma frequency that converts VC into a generating element. This direction of VC usage is most successfully realized as virtod [6] - instrument, in which the self-organizing of generation process is realized for reaching high arguments of generated radiation.

All listed above applications of VC deal with VC as quasi-one-dimensional spatial formation. The spatially extended VC calls the more great interest, for example as a generating element. The successful example of creation of such VC is described in [7].

In the present paper the idea is stated and the structure is described for the spatially extended VC that is generated in electron beam, which is propagated in a line with magnetic self-insulation. The feasibility of vircator existence in a magnetic-insulated transmission line (MITL) is demonstrated in this report. We describe some structural peculiarities of vircator formation in such lines and discuss the nature of electron motion in such vircator. Usually, in the line only the potential monotones radial profiles become realizable with zero electric field on the cathode. The pre-supposed vircator existence leaves a possibility of finding solutions, involving the potential trough.

2. STRUCTURE AND PECULIARITIES OF VIRCATOR FORMATION IN MITL

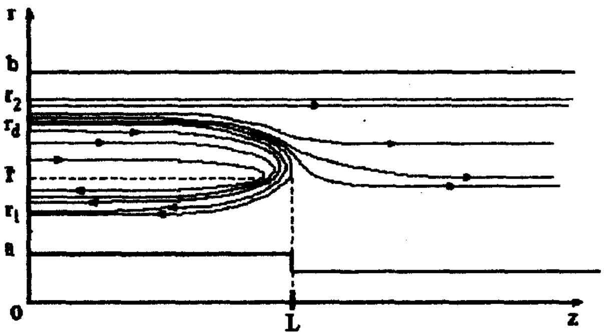
The necessity of ultra-powerful pulsed rf-generation, using comparatively modest energies in drivers, calls for development of such generation schemes that would have high efficiency and reliability. There are several similar schemes in existences that have both rf-seed power generation and REB initial modulation. However, more reliable would be usage of such master-oscillator as the vircator modulator that naturally appears in REB under certain conditions. Yet, feasibility of vircator existence in a MTTL has not been demonstrated to date. Below, we will try to fill the blank and describe some structural peculiarities of vircator formation in such lines.

First of all, let's discuss the nature of electron motion in vircator. In the 1-D case vircator is formed by the interpenetrating counter-streaming "incident" and reflected electron flows. However, the single-stream flows only are permissible in the MITL as constrained by the formula $\upsilon=c(E/H)$ and the unambiquity of the functions E and H. This purports to mean in this case that electron bouncing from the potential barriers, if realizable at all, must follow another path of trajectory.

On the other hand, the vircator problem resolution pre-supposes such possible evolution of the potential relief within the MITL space that would make the reflections quite conceivable. In according with the classic magnetic insulation line theory [1-2] any suitable potential relief in the case is unrealizable. Nevertheless, analysis of the above theory indicates that this impossibility steam from the condition imposed on the cathode-emitted flow to be restricted by space charge. This condition has the form: $E|_{x=a} = 0$. Not being prerequisite for electrodynamics problem used to describe the line, this condition, as an addition, constrains severely any solution for the MITL. In particular, at any Z-coordinate position in the line, only the potential monotones radial profiles become realizable with zero electric field on the cathode. Meanwhile, the pro-supposed vircator existence leaves a possibility of finding solutions, involving the potential well.

The condition $E|_{x=a} = 0$ can be eliminated either in the case of restricted cathode emission, or in the case of transporting along the line of an electron beam with such a large space charge that a sag of the potential appears in the cathode-anode space, causing the electric field $E>0$ to appear near the cathode that would suppress the emission. In the case, the line transports electron beam from an outside source.

As it turns out, it is exactly in this case that vircator becomes possible in the MILO line as vortex formation.



The structure of virtual cathode.

A visual impression of the structure and probable scenario of such vircator can be made from Figure.

The electron beam, injected from an external source, comes into a transmission line, in which the potential U is applied between cathode and anode, propagating along the coordinate $0Z$ until it reaches the region ($z \approx L$) with such impedance variations which preclude propagation of the entire beam at $z>L$. A bit to the right, only a portion of the injected beam can pass, while the remainder must bounce back in the opposite direction.

Parameters for the beam and the line must be chosen such that (he whole system should find itself in a near-threshold state, i.e. when beam slowdown or stopping in a certain region should cause the potential well with $E|_{x \neq a} = 0$ to appear. Such macro perturbation, when appearing mid-line, cannot but propagate to its beginning, forming a trough-shaped potential well. The electric field in its near-anode part ($r_2 > r > \bar{r}$, where $\bar{r}$, r_2 are the well minimum coordinates and beam boundaries, respectively) retains its initial direction, i.e. provides beam propagation to the right, while in its near-cathode part ($\bar{r} > r > r_1$, r_1 is the near-cathode beam boundary) it assumes the opposite direction and provides for the return of the reflected beam portion. In the region $z \geq L$ there is only the passing flow, with the appropriate electric field remaining in its initial direction ($E<0$).

The structure of the forming zero-field formation is such that the injected beam splits into two telescopic parts (one inside the other). The outer, near-anode part forms the passing beam, while the inner part does the reflected beam returning to the near-cathode region. Thus, the MITL-formed vircator is substantially a multidimensional creation.

In the axis-symmetric case (Fig.), vircator is described via the hydrodynamic electron motion equations:

$$\frac{\partial P_r}{\partial t} + \upsilon_r \frac{\partial P_r}{\partial r} + \upsilon_z \frac{\partial P_r}{\partial z} = -eE_r - \frac{e}{c}\upsilon_z H_\theta , \quad (1)$$

$$\frac{\partial P_z}{\partial t} + \upsilon_r \frac{\partial P_z}{\partial r} + \upsilon_z \frac{\partial P_z}{\partial z} = -eE_z - \frac{e}{c}\upsilon_r H_\theta , \quad (2)$$

where $P_r = \gamma m \upsilon_r$, $P_z = \gamma m \upsilon_z$, $\gamma = \left(1 - \upsilon^2/c^2\right)^{-1/2}$, and the Maxwell equations

$$-\frac{1}{c}\frac{\partial H_\theta}{\partial t} = \frac{\partial E_r}{\partial z} - \frac{\partial E_z}{\partial r} , \quad (3)$$

$$4\pi en \frac{\upsilon_r}{c} = \frac{1}{c}\frac{\partial E_r}{\partial t} + \frac{\partial H_\theta}{\partial z} , \quad (4)$$

$$4\pi en \frac{\upsilon_z}{c} = \frac{1}{c}\frac{\partial E_z}{\partial t} - \frac{1}{r}\frac{\partial (rH_\theta)}{\partial r} , \quad (5)$$

$$\frac{1}{r}\frac{\partial (rE_r)}{\partial r} + \frac{\partial E_z}{\partial z} = -4\pi en . \quad (6)$$

The potential and flow structure is one-dimensional at $z >> L$ and $z << L$ being homogeneous along θ and z, while it becomes intrinsically 2-D at $z \approx L$. Next, we derive solution far from the 2-D region.

In the following Chapter we will find solutions for these equations that are now free from the condition $E|_{x=a} = 0$.

3. SPATIAL DISTRIBUTION OF THE BRILLOUIN FLOW MAJOR CHARACTERISTICS WITH THE MITL-FORMED VIRCATOR

Difference of the Brillouin flow theory with vircator in the transmission line from the classical transmission line theory is formally manifested in the rejection of the additional condition $E|_{x=a} = 0$.

This signifies that the principal functional dependencies, derived in [8] remain valid, although the dependencies between the flow-determining parameters are changed.

Thus, the set of equations for determining of ψ, s_0 and s within this context corresponds to the set of equations:

$$\begin{aligned}\gamma_0 &= ch(\psi + D) + 1 - ch(D) + \\ &+ (s-1)\psi\, sh(\psi + D) + s(s_0 - 1)\psi\, sh(D) ,\end{aligned} \quad (7)$$

$$i_c = ss_0 \psi\, ch(D) , \quad (8)$$

$$i_b = ss_0 \psi \left[ch(\psi + D) - ch(D)\right] , \quad (9)$$

where

$$\gamma_0 = 1 + eU/mc^2 ,$$

$$s_0 = \ln(b/a)/\ln(b/r_1) ,$$

$$s = \ln(b/r_1)/\ln(r_2/r_1) .$$

D is a new parameter which, similarly to ψ, is determined by the set (7)-(9). $D = 0$, in the case with additional condition $E|_{x=a} = 0$.

Thus, equations (7)-(9) are determining the depending parameters ψ, D, s_0 (i.e. r_1), if γ_0, i_b, i_c are initial independent parameters. The situation with $D = 0$ have described in [1]. Parameter s_0 is determined by principal of total energy minimum.

Let's write out for the beam, detached from transmission line walls, the radial distributions of potentials, fields, velocities and magnetic field.

In the region $a \le r \le r_1$:

the electric field $\varepsilon_1 = -ss_0\psi\, sh(D)/\rho$,

the potential $\Phi_1 = \Phi_a + ss_0\psi\, sh(D)\dfrac{\ln\left(\frac{r}{a}\right)}{\ln\left(\frac{b}{a}\right)}$,

the magnetic field $h_{\theta 1} = ss_0\psi\, ch(D)/\rho$,

where $\varepsilon \equiv \dfrac{eaE}{mc^2}$, $\Phi \equiv \dfrac{e\varphi}{mc^2}$, $h_\theta \equiv \dfrac{eaH_\theta}{mc^2}\ln\left(\dfrac{b}{a}\right)$, $\rho \equiv \dfrac{r}{a}$.

In the region $r_1 \le r \le r_2$:

$$\varepsilon_2 = -ss_0\psi\,\frac{1}{\rho}sh\left(\psi\,\frac{\ln(r/r_1)}{\ln(r_2/r_1)} + D\right),$$

$$\Phi_2 = \Phi_b - \psi\, sh(\psi + D)\frac{\ln(b/r_2)}{\ln(r_2/r_1)} - ch(\psi + D) + ch\left(\psi\,\frac{\ln(r/r_1)}{\ln(r_2/r_1)} + D\right),$$

$$h_{\theta 2} = ss_0\psi\,\frac{1}{\rho}ch\left(\psi\,\frac{\ln(r/r_1)}{\ln(r_2/r_1)} + D\right).$$

The potential minimum radius in vircator

$$\bar{r} = r_1(b/a)^{-\frac{D}{\psi ss_0}}.$$

Charge density

$$n^* = \left(\frac{\psi ss_0}{\rho}\right)^2 ch\left(\psi\,\frac{\ln(r/r_1)}{\ln(r_2/r_1)} + D\right),$$

where $n^* \equiv \dfrac{4\pi e^2 na^2}{mc^2}\left(\ln\dfrac{b}{a}\right)^2$,

and electron velocity

$$\upsilon = c\,th\left(\psi\,\frac{\ln(r/r_1)}{\ln(r_2/r_1)} + D\right).$$

In the region $r_2 \le r \le b$:

$$\varepsilon_3 = -ss_0\psi\,\frac{1}{\rho}sh(\psi + D),$$

$$\Phi_3 = \Phi_b - ss_0\psi\, sh(\psi + D)\ln(b/r),$$

$$h_{\theta 3} = ss_0\psi\,\frac{1}{\rho}ch(\psi + D).$$

The point r_d in the vircator region separates the passing beam part from the reflected and directed backwards along the cathode. The radius r_d is derived from the condition of flow equality in the vircator region for the case $r_1 < r < \bar{r}$ and $\bar{r} < r < r_d$.

The flow separation radius proves to be

$$r_d = r_1(1 + \xi),$$

where $\xi = \dfrac{2(1 + k\alpha)}{\alpha\,[k(2\alpha - 1) + \alpha - 2]}$, $\alpha = \dfrac{2eI_c}{mc^3 ch(D)}$,

$k = \dfrac{ch(D) + \alpha\, sh(D)}{sh(D) + \alpha\, ch(D)}$, I_c – the cathode current.

4. CONCLUSIONS

This report demonstrates the idea, structure and stationary theory of MITL vircator, which is a substantially multi-dimensional through-shaped vortex creation.

The structure of vircator is such that the injected beam splits into two telescopic parts. The outer, near-anode part forms the passing beam, while the inner part does the reflected beam returning to the near-cathode region. In this case, vircator becomes possible in the MITL as vortex formation.

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