Has a magnetron abnormal anode current?

Oleksandr Nikitenko
Measurement and Technical Expertise department
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
nikonxipe@gmail.com

***Abstract*—In this article two model of crossed-field devices: magnetron and magnetron diode was described. For magnetron diode one equilibrium point was found and it is potential energy minimum. Therefore electrons that have lost kinetic energy move to potential minimum forming space charge. For magnetron two equilibrium points was found one of them is potential energy minimum and other is potential energy maximum. Therefore electrons that have lost kinetic energy move to potential minimum forming anode current. Thus magnetron has no abnormal anode current.**

***Index Terms*—magnetron, magnetron diode, equilibrium point, current, potential energy.**

I. Introduction

A magnetron is one of the first and the most wide propagating microwave oscillators. In these oscillators electrons move in crossed statical electrical and magnetic fields and interact with RF electromagnetic fields.

Constructively modern magnetron consist of three parts:

- cathode;
- anode with cavity resonators;
- RF energy output joint.

Theoretical and experimental investigations of magnetrons leaded to many discrepancies and paradoxes

All theoretical works asserted that an abnormal anode current should not exist in magnetron at pre-oscillation mode for example [1]–[4].

Practically anode current exist in magnetron always.

What is the matter?

This work purpose is discussed why so-called abnormal anode current exist in magnetron.

II. Theoretical Basis

Theoretically magnetrons' behaviour described by motion, Poisson and excitation equations.

Here we used motion equations only.

In general case the motion equations in polar coordinates (s, φ) is Cauchy problem and described such equations

$$\begin{aligned} &\frac{d^2 s}{dt^2} - s\left(\frac{d\varphi}{dt}\right)^2 = \eta\left(E_s + Bs\frac{d\varphi}{dt}\right) \\ &s\frac{d^2\varphi}{dt^2} + 2\frac{ds}{dt}\frac{d\varphi}{dt} = \eta\left(E_\varphi - B\frac{ds}{dt}\right), \end{aligned} \tag{1}$$

where s — dimensionless radius r/r_c;

$\eta = 1.76 \cdot 10^{11} C/kg$ — the specific charge of electron;

B — axial magnetic field density;

E_s — electrostatic field density along the radial coordinate;

E_φ — electrostatic field density in azimuthal coordinate.

with initial conditions

$$\begin{aligned} &s(0) = 1; \quad \left.\frac{ds}{dt}\right|_{t=0} = 0; \\ &\varphi(0) = 0; \quad \left.\frac{d\varphi}{dt}\right|_{t=0} = 0. \end{aligned} \tag{2}$$

Future system (1) are considered as dynamical system for two construction: magnetron diode and magnetron.

To obtain dynamical system property we must at least define equilibrium points in such system and analysed their.

A. Magnetron Diode

A magnetron diode consists of two coaxial cylinder between which an electric field is applied.

For a magnetron diode electrostatic field density define as

$$E_s = \frac{b}{s},$$

where $b = \dfrac{\eta U_a}{r_c^2 \omega_H^2 \ln s_a}$;

U_a — anode voltage;

r_c — cathode radius;

ω_H — cyclotron frequency;

s_a — dimensionless anode radius

and $E_\varphi = 0$.

Taking into account the above mentioned system (1) for a magnetron diode transform to

$$\begin{aligned} &\frac{d^2 s}{dt^2} = -\frac{s}{4} + \frac{b}{s} + \frac{1}{4s^3} \\ &\frac{d\varphi}{dt} = \frac{1}{2}\left(1 - \frac{1}{s^2}\right). \end{aligned} \tag{3}$$

To define equilibrium points coordinate we must equal to 0 right hand side of equations (3).

As results from second equation of (3) we obtained φ is anyone that is an angle does not matter.

From first equation of (3) we obtained [5], [6]

$$s_0 = \sqrt{2}\sqrt{b + \sqrt{b^2 + 1}}.$$

Thus for a magnetron diode we have equilibrium radius $r_0 = s_0$.

To find out the system behaviour (3) near equilibrium point it is necessary to determine this point type. To do this we should build characteristics matrix

$$[M] = \begin{bmatrix} -\lambda & 1 \\ -\left(\frac{1}{4} + \frac{b}{s_0^2} + \frac{3}{4s_0^4}\right) & -\lambda \end{bmatrix}.$$

Then characteristics equation look like

$$\lambda^2 + \left(\frac{1}{4} + \frac{b}{s_0^2} + \frac{3}{4s_0^4}\right) = 0.$$

This equation roots were purely imaginary thus the equilibrium point is "centre".

Such equilibrium point means that system (3) had a oscillatory movements near this point.

The potential energy minimum of dynamical system (3) placed in this point and in interaction space of magnetron diode.

When we have a determination coefficient α is not equal to zero, electrons had lost kinetic energy by different cases.

In this case electrons that have lost kinetic energy move to potential minimum forming space charge in interaction space of magnetron diode and anode current not exist.

B. Magnetron

A magnetron interaction space was shown in fig. 1.

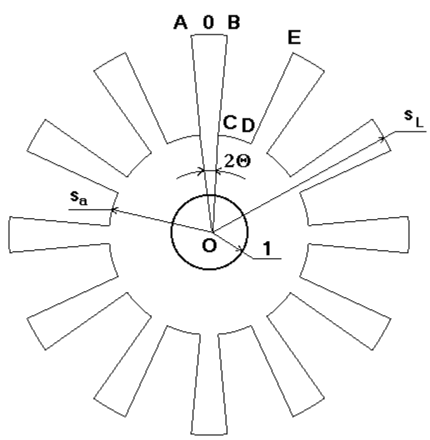

Fig. 1. Magnetron interaction space.

Analysing magnetron volt-ampere performance (fig. 2) we can saw anode current exist always.

For a magnetron electrostatic field density from (1) [7], [8]

$$E_s = \frac{A}{s}\left(1 - 2N \ln\frac{s_L}{s_a}\sum_{n=1}^{\infty} n a_n cors^{Nn} \cos Nn\varphi\right)$$

$$E_\varphi = -\frac{2AN}{s}\ln\frac{s_L}{s_a}\sum_{n=1}^{\infty} n a_n sirs^{Nn} \sin Nn\varphi$$

where $A = \dfrac{\eta U_a}{\left(\frac{N\theta}{\pi}\ln\frac{s_L}{s_a} + \ln s_a\right) r_c^2 \omega_H^2}$

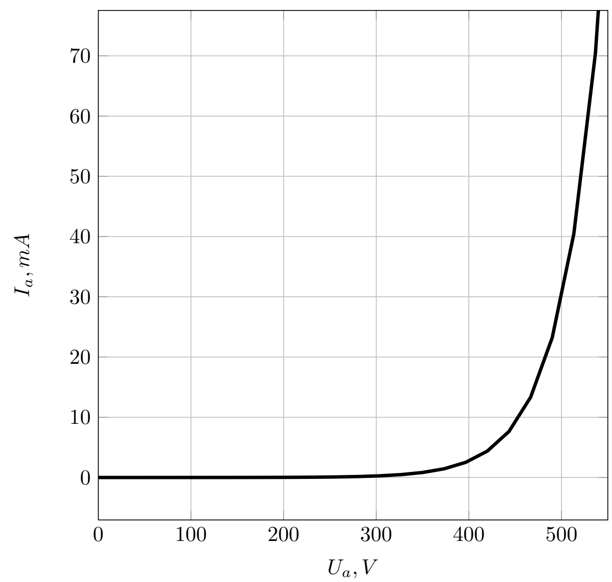

Fig. 2. Volt-ampere performance.

$$a_n = \frac{\sin Nn\theta}{(Nn\theta + \sin 2Nn\theta)(sirs_L^{Nn} - sirs_a^{Nn}) + \pi sirs_a^{Nn}}.$$

Taking into account the above mentioned system (1) for a magnetron transform to

$$\begin{aligned} &\frac{d^2 s}{dt^2} + \left(1 - \frac{d\varphi}{dt}\right)\frac{d\varphi}{dt} s = E_s \\ &\frac{d^2\varphi}{dt^2} + \frac{1}{s}\frac{ds}{dt}\left(2\frac{d\varphi}{st} - 1\right) = E_\varphi. \end{aligned} \tag{4}$$

To define equilibrium points coordinate we must equal to 0 right hand side of equations (4).

As results we obtained two roots: $s_0^{(1)} < 1$ and $s_0^{(2)} > s_L$.

To find out the system behaviour (4) near equilibrium points it is necessary to determine these points type. To do this we should build characteristics matrix

$$[M] = \begin{bmatrix} -\lambda & 1 & 0 & 0 \\ \alpha & -\lambda & 0 & -s_0 \\ 0 & 0 & -\lambda & 1 \\ 0 & \frac{1}{s_0} & -\alpha & -\lambda \end{bmatrix},$$

where $\alpha = \dfrac{AN \ln\frac{s_L}{s_a} a_1}{s_0^2} sirs_0^N \cos N\varphi$.

Then characteristics equation look like

$$\lambda^4 + \lambda^2 - \alpha^2 = 0.$$

This equation roots were two real roots with difference signs and two purely imaginary. In this case we have two equilibrium points $s_0^{(2)}$ is "centre" point placed into anode (potential energy minimum) and $s_0^{(1)}$ is "saddle" point placed into cathode (potential energy maximum) [5], [6].

Electrons that have lost kinetic energy move to potential minimum forming anode current in magnetron.

III. Results

It is well known electron moved along the similar to cycloid trajectory both in magnetron diode (fig. 3) and in magnetron (fig. 4) in pre-oscillation mode. These trajectories are solutions of the move equation (3) for magnetron diode and one (4) for magnetron. This does not contradict the generally accepted notions about the trajectory of charged particles in crossed electrical and magnetic fields.

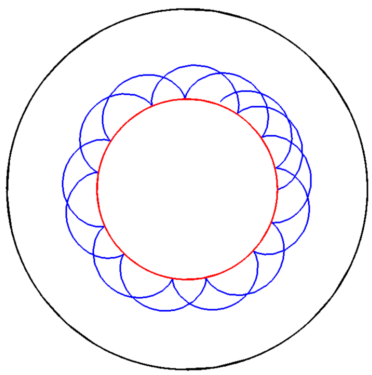

Fig. 3. Electron trajectory in magnetron diode.

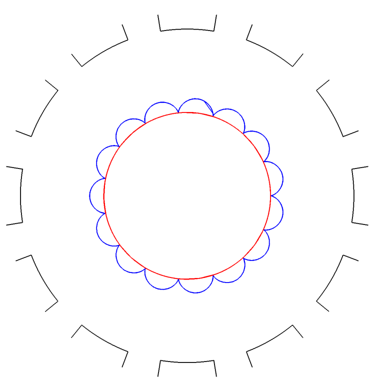

Fig. 4. Electron trajectory in magnetron.

During motion electrons lost kinetic energy. Thus their trajectories transformed from cycloid like trajectory to circular one for magnetron diode (fig. 5) and to helix like trajectory for magnetron (fig. 6) [5], [6].

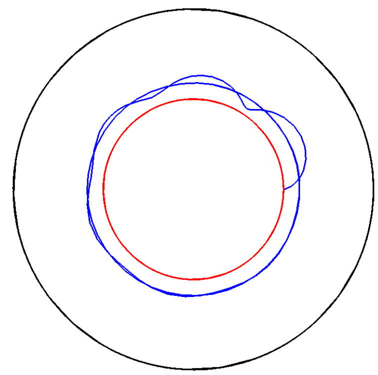

Fig. 5. Electron trajectory in magnetron diode with dissipation.

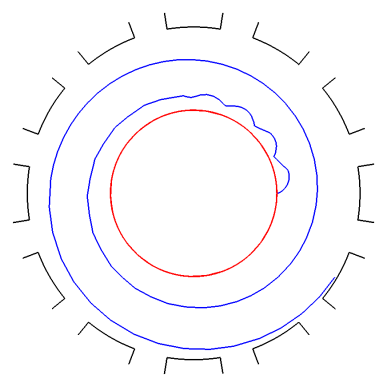

Fig. 6. Electron trajectory in magnetron with dissipation.

IV. Discussion

To simulate magnetron operating researchers frequently used as electrostatic potential distribution a magnetron diode model. This model allowed to explain many interesting properties taken place during magnetron operation.

However, there is still no clear explanation for the mechanism of space charge accumulation and abnormal current in the pre-oscillation mode.

Based on system (3) it was defined that in magnetron diode interaction space was one equilibrium point named ”centre” where placed potential energy minimum.

During magnetron operation electrons lost kinetic energy by different cases moved to potential minimum. Such motion leaded to space charge accumulation and future influence to other processes and mechanisms.

When we transformed electrodes’ configuration in magnetron diode forming a magnetron (fig. 1) we get space bifurcation.

In this case the equilibrium point ”centre” takes place in magnetron diode transmute to two equilibrium points: ”saddle” point into cathode (potential energy maximum) and ”centre” point into anode (potential energy minimum).

Based on system (4) it was defined that in magnetron were two equilibrium points one of them named ”centre” where placed potential energy minimum is into anode and other named ”saddle” where placed potential energy maximum is into cathode.

As in the case with a magnetron diode electrons lost kinetic energy by different cases moved to potential minimum. Such motion leaded to named abnormal current (fig. 2).

V. Conclusion

Thus we explained why space charge was formed when we used a magnetron diode electrostatic potential distribution to simulation magnetron operating.

On the other hand we explained why exist named ”abnormal” anode current when we used a magnetron electrostatic potential distribution to simulation magnetron operating. In dissipative case electrons that have lost kinetic energy move to anode.

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