MECHANISMS OF AN ELECTRON STREAM SELF-BUNCHING IN MAGNETRON GUNS

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Various processes of self-bunching of reentrant electron cloud nearby a distributed cylindrical cathode in crossed fields are investigated theoretically using particle-in-cell (PIC) simulation algorithms. As most probable mecha nisms of formation of an azimuthally heterogeneous electron beam, tangential eigenmodes (i.e., natural tangential oscillations) of the electron cloud, secondary-emission bunching of one and true solitons generation in the beam are considered and compared. Illustrations of all just listed bunches as well as of some other turbulence phenomena at the electron hub are given, and their possible influence on the magnetron guns performance is discussed.

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1. INTRODUCTION

The magnetron guns are very promising sources of high perveance electron beams for particle accelerators. However, some undesirable physical phenomena take a place in a reentrant electron cloud (so-called hub) moving nearby a distributed cylindrical cathode in crossed fields. This is, mainly, the cloud "self-bunching" resulting in formation of an azimuthally heterogeneous electron hub. Those phenomena were staying unclear long time, even after the first computer simulations of magnetron devices [1]. The reason is that the azimuthal periodicity of the bunches is of 2π, as a rule. Only development of "full-format" particle-in-cell (PIC) codes in beginning of the 1980s ([2]–[4]) have enabled ways to all-round examinations of the beam formation mechanisms in the magnetron diodes (smooth-bore magnetrons) that are similar to the magnetron guns.

In most cases, the primary aim of such investigations performed by the author was explanation of the causes of an increased noise level in crossed-field devices (CFDs), because there is no still a clear comprehension of physical phenomena generating the extra noises in these tubes. Nevertheless, some accumulated results might be useful for understanding of negative phenomena in the magnetron guns, like to the electron beam improper formation, violation of the magnetic insulation, and the cathode erosion. The phenomena described in this paper have been discovered and/or examined with 2D PIC simulations using the TULIPgm code intended for full-format transient modeling of CFDs.

According to a modern conception, there are three main mechanisms of the reentrant electron cloud self-bunching nearby the distributed-emission cathode in crossed fields: (i) tangential eigenmodes of the electron hub; (ii) secondary-emission bunching of one; and (iii) true solitons in the electron cloud. These phenomena are considered in detail in sections 2–4. Abbreviations are used in the figures captions: r_c and r_a are the radii of the cathode and the anode respectively in mm; B is the magnetic induction in T; U is the anode voltage in kV. Rotation of the hub is clockwise in all the figures.

2. THE TANGENTIAL EIGENMODES

The tangential eigenmodes (i.e., natural oscillations) of the hub in crossed fields have been known from an analytical consideration long before the computer simulations. However, in computational experiments they are hard to detect because of their "frailty". These oscillations (see Figs.1,2) can be observed only if the secondary emission from the cathode is negligibly small. Their formation period is too long (tens or hundreds of the cyclotron periods) and they might degenerate later into other bunches, usually, into solitons (see Fig.3 where a first stage of such degeneration is shown).

Typical number of the space charge wavelengths contained by the hub perimeter is 3…7. This number is a function of the magnetic induction and the anode voltage for each construction of the magnetron diode. Found in the computational experiments frequencies of the rippled hub rotation are close to both experimentally measured frequencies of the magnetron diodes noises (see, for example, [5]) and calculated under the Buneman-Hartree formula values.

Because the electron cloud in the magnetron guns drifts continuously in the axial direction (in contrast to the magnetron diode), the tangential oscillations are inessential for these devices, as it seems. Nevertheless, ones can exist in the gun rear space, where the drift velocity is small.

3. THE SECONDARY-EMISSION BUNCHES

Unlike the tangential eigenmodes of the electron cloud, secondary-emission bunches in crossed fields nearby the distributed-emission cathode have been discovered in beginning of the 1980s during simulations of CFDs with first "full-format" PIC codes (e.g., such bunches are visible in Fig.4 of [2]). Unfortunately, because of those times diagnostics low resolution (see, for example, Fig.4 that had been obtained by the author in 1984 using a character printer), they initially were mistakenly recognized as solitons [6]. Later, after observations of true solitons, the distinction between both grouping mechanisms has been ascertained.

There are two typical shapes of the bunches: ordinary (rounded) ones (see Fig.5) and clots having a thin layer of the space charge nearby the cathode, which moves ahead of the "main" bunch (as in Fig.6).

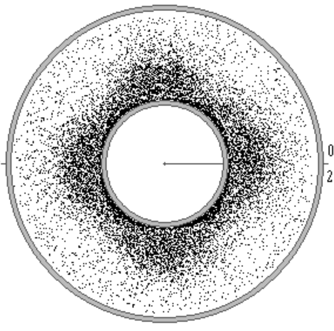

Fig. 1. $r_c = 4; r_a = 9.5$
$B = 0.0675; U = 2.02$

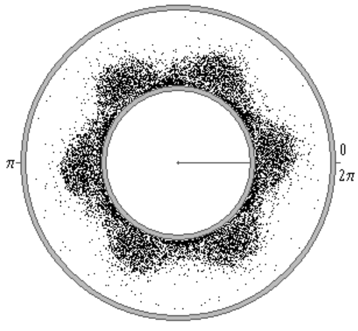

Fig. 2. $r_c = 1.625; r_a = 3.175;$
$B = 0.211; U = 1.5$

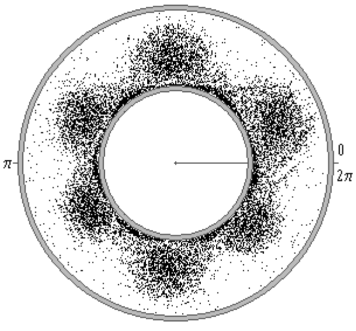

Fig. 3. $r_c = 1.625; r_a = 3.175;$
$B = 0.211; U = 1.5$

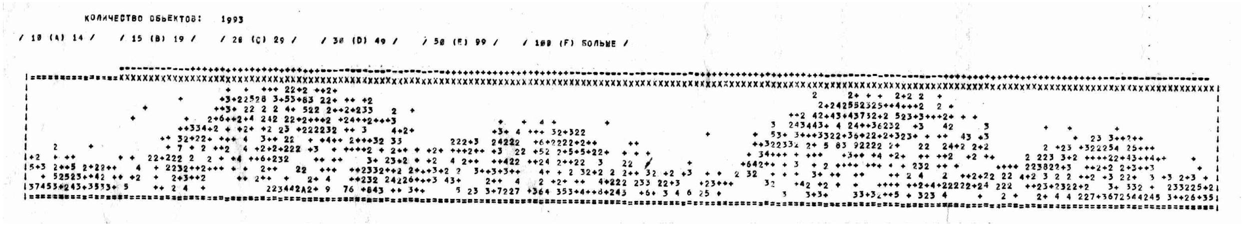

Fig.4. Two the secondary-emission bunches in the disturbed by a RF signal hub of the cathode-driven CFD
$r_c = 9; r_a = 16.2; B = 0.19; U = 48$

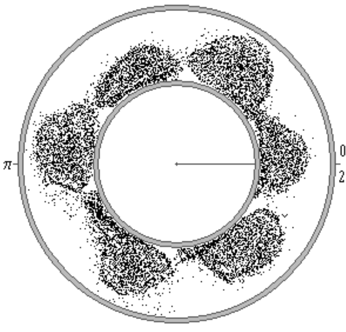

Fig. 5. $r_c = 9; r_a = 16.2;$
$B = 0.19; U = 48$

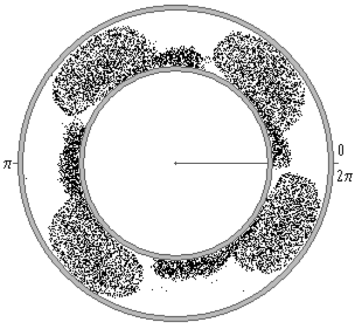

Fig. 6. $r_c = 9; r_a = 14;$
$B = 0.14; U = 15$

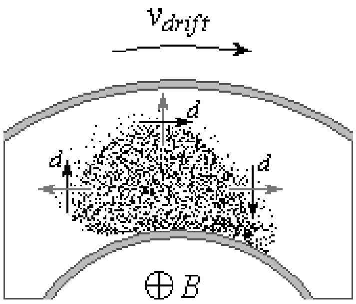

Fig. 7. $r_c = 9; r_a = 16.2;$
$B = 0.19; U = 48$

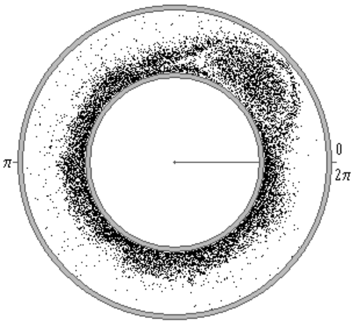

Fig. 8. $r_c = 0.865; r_a = 1.45;$
$B = 0.3; U = 0.55$

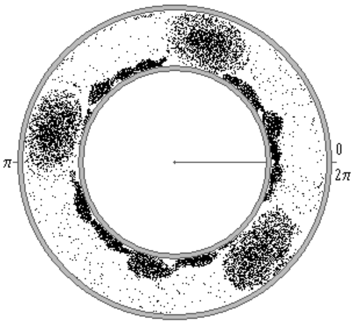

Fig. 9. $r_c = 9; r_a = 14;$
$B = 0.2; U = 15$

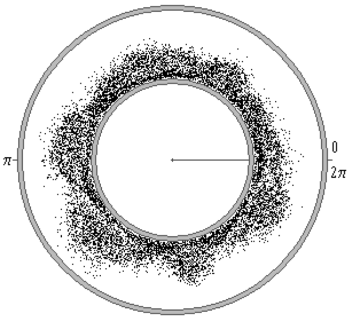

Fig. 10. $r_c = 9; r_a = 16.2;$
$B = 0.19; U = 48$

In the contemporary conception, the secondary-emission bunches are concerned with a non-uniform secondary-emission feeding of an inhomogeneous in the azimuthal direction electron stream. Accelerated by Coulomb's repulsion electrons at the bunch front border, after their twisting by the magnetic field, bombard the cathode surface. Emitted here secondary electrons feed the bunch and cause rotation of one like to a rolling "water sack".

A possible mechanism of the secondary-emission bunch formation is explained more explicitly by Fig.7, where one of bunches is extracted. The grey arrows indicate the Coulomb's repulsion forces that affect the electrons moving along the bunch perimeter. The black arrows with "*d*" characters are extra drift velocity components that appear in addition to the bunch "main" drift velocity v_{drift} (marked by the large arrow in the top of the picture). The additional drift velocity components are perpendicular to the Coulomb's forces as well as to the magnetic induction vector marked in the bottom of the picture. They cause lowering of the bunch front edge and lifting of its rear border. As it can be seen, the highest electron density nearby the cathode surface takes a place at the fore half of the bunch, as a rule. This area is the most intensive source of the secondary electrons for the bunch buildup.

Unlike the tangential eigenmodes, the secondary-emission bunches are very "aggressive". They arise too fast (during a few the cyclotron periods) and appear every time as secondary emission from the cathode is appreciable. The most effective method for these bunches destruction is intensive thermionic emission from the cathode.

Although formation of the secondary-emission bunches has been confirmed later in computational experiments of other authors ([7], [8]), their actual existence in magnetron diodes is doubtful yet. The main argument "contra" is that a permanent bombardment of the cathode (to ensure a secondary emission) demands significant energy consumption. In particular, these bunches are observed in numerical experiments at far supercritical magnetic fields. They cause appreciable currents through the diode that are never registered in actual experiments. Therefore, an experimental confirmation of the simulations results is needed.

4. THE SOLITONS AND OTHER BUNCHES

True soliton instability of the electron hub is a more "robust" oscillation than the tangential eigenmode. The solitons in the hub can arise independently (see Fig.8) or because of degeneration of the tangential eigenmodes or the secondary-emission bunches (as in Fig.9). One or several solitons distributed uniformly over the tube perimeter are observed usually. A feeding of an elevated above the hub soliton is performed, as a rule, through a narrow "umbilical cord" that enlaces one.

The solitons are, probably, more usual for the magnetron diodes and guns than the tangential eigenmodes. This follows from both computational experiments and experimentally measured noise spectra in the magnetron diodes (see, for example, [9]). In fact, all lowest harmonic of the hub rotation frequency are presented in the spectra with approximately equal amplitudes. This might mean existence of a one essential irregularity of the electron cloud, like to shown in Fig.8.

In addition to the electron hub classified instabilities, other oscillations of the electron cloud in crossed fields occur quite often. These are various turbulences and bunches like to shown in Fig.10 for pure thermionic (i.e., non-secondary-emission) cathode, which cannot be referred to anyone abovementioned phenomena with certainty. A combination of several modes described above (e.g., the tangential oscillation along with the soliton) can be also observed sometimes.

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МЕХАНИЗМЫ САМОГРУППИРОВКИ ЭЛЕКТРОННОГО ПОТОКА В МАГНЕТРОННЫХ ПУШКАХ

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Теоретически исследованы процессы самогруппировки замкнутого электронного облака вблизи распределенного цилиндрического катода в скрещенных полях. Наиболее вероятными механизмами группировки являются собственные тангенциальные колебания, вторично-эмиссионные сгустки и истинные солитоны.

МЕХАНІЗМИ САМОГРУПУВАННЯ ЕЛЕКТРОННОГО ПОТОКУ В МАГНЕТРОННИХ ГАРМАТАХ

О.В. Грицунов

Теоретично досліджено процеси самогрупування замкненої електронної хмари поблизу розподіленого циліндричного катода в схрещених полях. Найбільш ймовірними механізмами групування є власні тангенційні коливання, вторично-емісійні згустки та справжні солітони.