INVESTIGATION OF ELECTRON CUT-OFF IN A CYLINDRICAL ELECTRODE SYSTEM IN PULSED MAGNETIC FIELD OF AN INDUCTOR

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The effect of electron cut-off from the anode in a cylindrical coaxial electrode system with an inhomogeneity of electric and magnetic fields along the axis is investigated by numerical simulation. The effect is caused by the pulsed magnetic field of the external inductor and the secondary magnetic fields generated by the eddy currents in the electrodes. The inhomogeneity of the fields is due to short length of the cathode and the inductor, and also by the internal protrusion at the anode opposite the cathode for the concentration of the magnetic field. The electrons escape along the axis from the interelectrode gap. To capture them, end cup-shaped collectors are introduced, for which the voltage of up to 300 V is applied when the anode voltage is of 10 kV. The results of the work can be used in designing a high-voltage current interrupter, for analyzing the conditions of magnetic initiation of a magnetron discharge, and the characteristics of magnetron electron guns.

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INTRODUCTION

The effect of electron cut-off takes place in a magnetic field, orthogonal to the electric field, and does not allow the cathode electrons to reach the anode [1, 2]. It finds application in many vacuum and plasma devices: vacuum-magnetrons for microwave generation, gas-magnetrons for electron and ion generation, ion sputtering magnetrons, magnetron-type manometric transducers and gas-discharge switching devices, *etc*. In some devices, this effect creates conditions for the generation of microwave oscillations, charged particles and plasma. In others, it provides interrupting current to the anode in opening devices or switching current from one electrode to the other. The electron cut-off is useful at the post-discharge stage in vacuum arc interrupters, when hot electron-emitting spots rest on the cathode. Fig. 1 demonstrates the cut-off effect in the cylindrical electrode system.

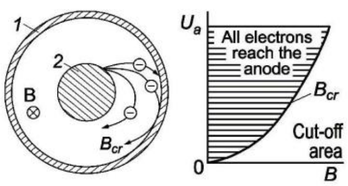


Fig. 1. Electron cut-off effect is at $B \geq B_{cr}$: 1 – anode; 2 – cathode; U_a – anode voltage; B – magnetic induction

The case of electron cut-off in homogeneous crossed fields is considered in the literature [1, 2]. In practice, however, inhomogeneous fields are most often used, and the case of pulsed magnetic control with an external inductor for interrupting or switching current in high-voltage DC circuits, is of great interest. The results of investigation of the electron cut-off in a flat switching diode controlled by pulsed current of a plane inductor are presented in [3]. The effect of electron cut-off in cylindrical electrode systems due to a pulsed magnetic field, taking into account the induction of eddy currents in electrodes and their secondary magnetic fields, was not considered in the literature to the best of our knowledge. Thus, our work is devoted to investigation of the cut-off effect in such systems with help of computer simulation.

1. CONFIGURATIONS OF THE INVESTIGATED ELECTRODE SYSTEMS

Several electrode systems of different configuration have been used for the investigation. They are depicted in Fig. 2. The electrode configurations have been chosen with taking into account the application of the obtained results in the future to the development of a high-voltage opening switch device (a current interrupter) on the base of vacuum arc.

The characteristic dimensions of the systems in millimeters are defined in Fig. 2,d. The electrode material is copper. The cathodes have small diameter (6 mm) and height *h* (10 mm) accordingly to the recommendation [4] for their using in the current interrupter. However, the cathode of the system in Fig. 1,a has also $h = H = 100$ mm for the purpose of verification of the calculations (see this cathode is depicted by dashed lines in Fig. 1,a). The minimal anode diameter opposite the cathodes is 30 mm. All anodes have the vertical split of 1 mm width (at the left in all figures) for better penetration of the pulsed magnetic field, generated by the inductors, through the metal anodes into the "cathode-anode" gaps. Providing anodes in the systems, shown in Figs. 2,b,c,d, with internal projections/protrusions of triangular cross-section solves several tasks: 1) to concentrate the pulsed magnetic field in the "cathode-anode" gaps; such approach, as it is known, successfully works in systems with pulsed magnetic field [4-6]; 2) to extend the anode current during arc discharge over the larger surface; 3) to decrease the part of anode surface disposed closely to the cathode in the order to facilitate vacuum arc extinguishing.

The systems have has been simulated with a code on the base of Comsol Multiphysics software analogously to [3]. The code contains the part for calculation of electric and magnetic fields and eddy currents induced in the bodies of the electrodes as well as secondary magnetic fields of them. The other part of the code was used for electron trajectories calculation. The electron space charge was taken as zero. It was supposed the cathodes emitted electrons with cosinusoidal distribution of emission angles. The DC voltage U_a between the electrodes was 10 kV. The inductors were supplied with alternative current of 44 kHz. Their working regime is determined by ampere-windings (A·w) in the paper. Since cathode electrons reach the system boundary for a few nanoseconds, the trajectories were calculated as for constant magnetic field in the maximum of the inductor current.

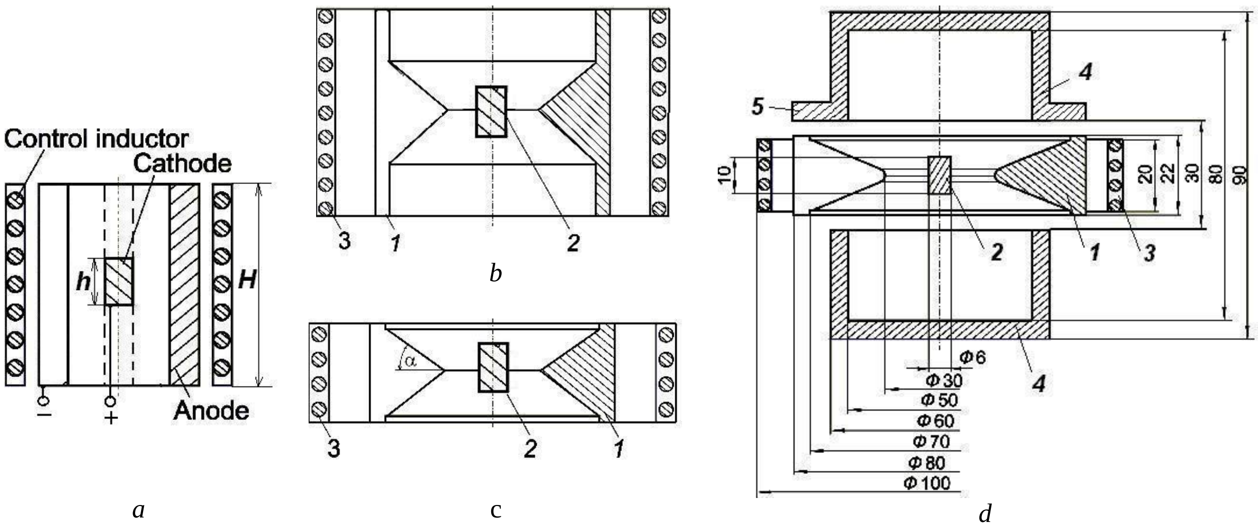


Fig. 2. Configuration of the investigated electrode systems: 1 – anode; 2 – cathode; 3 – control inductor; 4 – electron collectors; 5 – annular cornice-like element

The system, shown in Fig. 2,a, has been used for verification of the simulation code. Our calculations of B_{cr} well agrees with the theoretical calculation for homogeneous crossed fields $B_{cr.theor}$ = 4.7 mT: B_{cr} = = 4.9 mT for $h = H$ = 100 mm and B_{cr} = 5.0 mT for h = 6 mm, H = 100 mm. Here, $B_{cr.theor}$ is determined as in [1]:

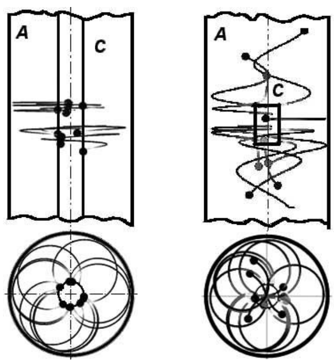
$$B_{cr.theor} = \sqrt{\frac{8m}{e}U_a} \,/\, R_a\left(1 - \frac{R_c^2}{R_a^2}\right),$$

where m and e are the mass and charge of electrons, R_a is the anode radius, R_c is the cathode radius.

2. CALCULATION RESULTS AND DISCUSSION

The typical electron trajectories in the mode of cut-off and at different emission angles are presented in Fig. 3 for two values of length h of the cathode. The black points show the end of calculated parts of the trajectories.

In the case of long cathode the cut-off leads to returning all electrons to the cathode. In the case of short cathode many electrons do not return to the cathode. Moreover, the greater the distortion of the electric field from radial one near the cathode ends and the larger the electron emission angle the faster the electrons go away from the cathode (see Fig. 3,b, where the trajectories show that only electrons, ejected radially, return to the cathode). The inductor length must be equal to H or larger than H for the full cut-off of cathode electrons as it is shown in Fig. 3. Otherwise the anode may capture electrons in the zones with $B < B_{cr}$.



a b

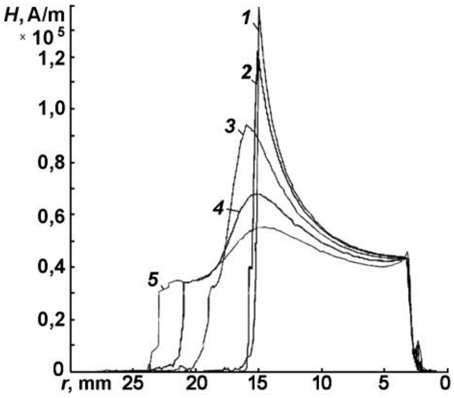
Fig. 3. Electron trajectories with long cathode, h = 100 mm (a), and short cathode, h = 6 mm (b), in the cut-off mode. Inductor – 4 kA·w

The electron trajectories in the system with magnetic field concentration, depicted in Figs. 2,b,c, differ from ones, shown in Fig. 3*b*, by increased rotation radius in the lower and upper parts of the system. The trajectories in the space down and up relatively the cathodes in the systems, depicted in Figs. 2,b,c, are like as an expanding stream.

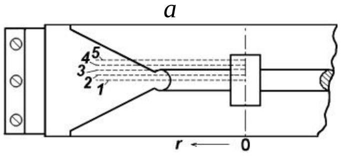
It is interesting to consider the variation of pulsed magnetic field in the gap between the electrodes, especially in the systems with magnetic field concentration. The corresponding calculations have been done and presented below. In the system shown in

Fig. 2,*a* (see or in Fig. 3), the strength of the pulsed magnetic field varies weakly between the electrodes and within the anode in the space removed from the cathode. However, the magnetic field varies considerably within the systems shown in Figs. 2,b,c,d due to change of the anode radius along the vertical axis. The example of such field variation is presented in Fig. 4 for the system depicted in Fig. 2,c. In general, there is the magnetic field, generated by anode eddy current, in the whole space around the anode.

In the order to check the possibility of employing the anode configuration, shown in Fig. 2,b but with a short inductor, we have calculated according electron trajectories and obtained results presented in Fig. 5. One can see the anode does not capture electrons both in the space of magnetic field concentration and within the lower and upper anode parts. The latter is due to larger internal diameters of these parts and if the anode length is not too large. Such property of this configuration allows using the lower and upper anode parts as baffles for the protection of the inductor against arc discharge plasma in the current interrupters.



a



b

Fig. 4. Variation of the strength of the pulsed magnetic field in the "cathode-anode" gap by radius r at various heights (on various planes) over the middle plane. Inductor – 2.2 kA·w

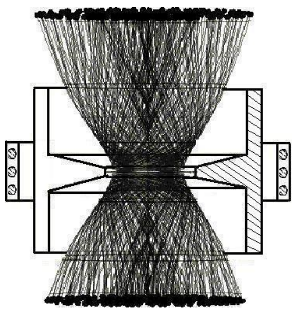


Fig. 5. Electron trajectories with long anode (H = 40 mm) and short inductor (20 mm, 2.8 kA·w)

In the order to investigate the effect of the angle α (see Fig. 2,c) on maximum deflection of electrons from the vertical axis of the system, the electron trajectory have been calculated at various values of α. Fig. 6 demonstrates variation of maximum radial deflection of electrons along the vertical axis for two values of α. One can see the bigger the angle α the less the maximum deflection of electrons. This may be connected with changes in distribution of the induced magnetic field around the anode.

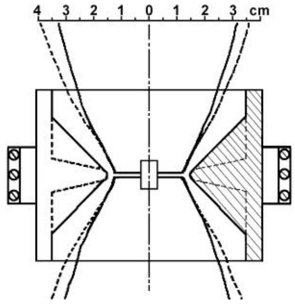


Fig. 6. Maximum radial deflection of electrons for two anode configuration. Inductor – 2.8 kA·w, H = 40 mm

From the above-presented data one can conclude that a real current interrupter must be provided with auxiliary electrodes for collecting the electrons going up and down from the "cathode-anode" gap. As a variant of such approach the configuration depicted in Fig. 2,d has been proposed. The simulation of electron trajectories showed that some group of electrons could pass by the gap between the anode and the collector into the external space of the system. In order to eliminate the leakage of electrons the annular plane element like a cornice has been attached to the lower end of the upper collector and a positive DC voltage U_c relatively the cathode has been applied to the collectors. Fig. 7 presents electron trajectories in the system with collectors.

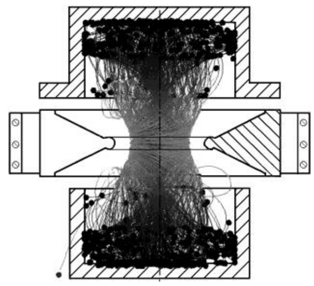


Fig. 7. Electron trajectories in the system with collectors. U_c = +300 V. Inductor – 5 kA·w

The calculations showed that the attaching of the annular element to the collector did not strongly affect the leakage of electrons (it may be seen in Fig. 7 comparing the trajectories in the upper and lower parts). Nevertheless, that element might be useful for protection of the inductor against arc discharge plasma in the current interrupters. Fig. 8 demonstrates the dependencies of relative leakage of electrons by the annular gaps between the anode and the collectors on the collector voltage U_c and the inductor current I_i. Note, the collectors generate the secondary magnetic field, too, due to eddy current induced in their bodies.

One can see that the value U_c = +300 V is enough for minimization of the electron leakage.

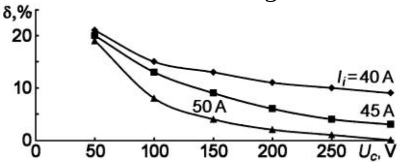


Fig. 8. Relative leakage of electrons through the annular gap between the anode and collector. Inductor – 100 windings

CONCLUSIONS

The computer code on the base of Comsol Multiphysics has been adopted for simulation and investigation of the electron cut-off effect in the cylindrical electrode system in the pulsed magnetic field of the external inductor. The effect of secondary magnetic fields generated by eddy currents in electrodes is taken into account. The successful verification of the numerical results has been proved.

In the system with heterogeneity of geometry, as well as of electric and magnetic fields along the axis (due to the short cathode, the inner projection at the anode opposite the cathode for the concentration of the magnetic field, the short inductor), the cycloid nature of the planar electron trajectories is converted into a spiral ones with the escape of electrons from the interelectrode gap. To obtain the cut-off effect, it is necessary to intercept electrons leaving the interelectrode gap. For this purpose, it is advisable to introduce the end cup-shaped collectors with the positive voltage of 300 V at the anode voltage of up to 10 kV.

The results obtained can be used in designing a high-voltage current interrupter, as well as for analyzing the conditions for the magnetic initiation of a low-pressure magnetron discharge and the characteristics of magnetron electron guns

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ИССЛЕДОВАНИЕ ОТСЕЧКИ ЭЛЕКТРОНОВ В ЦИЛИНДРИЧЕСКОЙ СИСТЕМЕ ЭЛЕКТРОДОВ В ИМПУЛЬСНОМ МАГНИТНОМ ПОЛЕ ИНДУКТОРА

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Исследуется методом численного моделирования эффект отсечки электронов от анода в цилиндрической коаксиальной системе электродов с неоднородностью электрического и магнитного полей вдоль оси. Эффект вызывается импульсным магнитным полем внешнего индуктора и вторичными магнитными полями, генерируемыми вихревыми токами в электродах. Неоднородность полей обусловлена малой длиной катода и индуктора, а также внутренним выступом на аноде напротив катода для концентрации магнитного поля. Имеет место уход электронов вдоль оси из межэлектродного промежутка. Для их улавливания вводятся торцевые чашеобразные коллекторы, на которые подаётся напряжение до 300 В при анодном напряжении 10 кВ. Результаты работы могут быть использованы при проектировании высоковольтного прерывателя тока, для анализа условий магнитного инициирования магнетронного разряда и характеристик магнетронных электронных пушек.

ДОСЛІДЖЕННЯ ВІДСІЧКИ ЕЛЕКТРОНІВ У ЦИЛІНДРИЧНІЙ СИСТЕМІ ЕЛЕКТРОДІВ В ІМПУЛЬСНОМУ МАГНІТНОМУ ПОЛІ ІНДУКТОРА

І. Дрозд, А. Кузьмичев, С. Майкут, Л. Цибульський

Досліджується методом чисельного моделювання ефект відсічення електронів від анода в системі циліндричних коаксіальних електродів з неоднорідністю електричного і магнітного полів уздовж осі. Ефект викликається імпульсним магнітним полем зовнішнього індуктора і вторинними магнітними полями, що генеруються вихровими струмами в електродах. Неоднорідність полів обумовлена малою довжиною катода і індуктора, а також внутрішнім виступом на аноді в області катода для підвищення концентрації магнітного поля. Має місце вихід електронів з міжелектродного проміжку уздовж осі. Для їх уловлювання вводяться торцеві чашоподібні колектори, на які подається напруга до 300 В при анодній напрузі 10 кВ. Результати роботи можуть бути використані при проектуванні високовольтного переривника струму, для аналізу умов магнітного ініціювання магнетронного розряду і характеристик магнетронних електронних гармат.