PENNING TRAPS FOR CONFINEMENT AND COOLING OF CHARGED PARTICLES

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The parameters of confinement of trapped charged particles are compared for self-consistent electromagnetic traps and for traditional and electromagnetic traps. The possibilities to control the trapped particles dynamics are found, which allows more effective particle confinement. The main attention is paid to methods of controlling the dynamics of charge particles in the trap. Resistive cooling of particles is considered as the main cooling mechanism.

PACS: 52.27.Jt

INTRODUCTION

The main parameters of confinement and cooling of trapped charged particles are compared for dynamic electro-magnetic traps and for more traditional magnetic and electrostatic traps [1, 2]. For the first case the possibilities to control the trapped particles dynamics are found, what allows more effective particles confinement and cooling.

We consider a self-consistent electro-magnetic trap as one of the most promising implementation of the mentioned above concept. Different methods of controlling the dynamics of charge particles in the trap are analyzed. In particular the opportunity of controlling the trapped particles dynamics by introducing an additional spatial electrostatic potential is considered. Resistive cooling of particles is considered as the main cooling mechanism [3, 4].

It is noted that different variants of self-consistent electro-magnetic traps can be realized in conditions of the Earth atmosphere and space.

In our work, the experimental results on capture and confinement of non-neutral particles are reviewed during the passage of a pulse electron beam through the drift space. In the previous publications, during the injection and drift of electron beam with broad distribution by velocities ('hot beam') in the drift chamber, situated in homogeneous magnetic field, the accumulation and confinement of particles in central part of the drift space were observed. This could be detected by measuring the relaxation time of particles in this region after the pulse of injection had finished. The capture and the confinement of particles in homogeneous longitudinal magnetic field happen due to the formation of the non-stationary virtual cathode and, as a consequence, double sagging of the potential. Due to the dynamics of particles in the drift space a potential pit is formed into which the 'coldest' particles are captured. We report results of experimental research of properties of the dynamic trap that is a modification of Penning-Malmberg trap.

EXPERIMENTAL SETUP

The scheme of experimental setup is shown on Fig. 1. The main beam was generated by the electron gun. Such gun consists from indirectly heated cathode and anode metal grid. The injection of electron beam was provided by applying of negative voltage pulse (injection pulse) to the cathode. The form of anode grid was chosen specially for obtaining the required form of electron beam (hollow cylinder). The main beam was injected into the drift space (a brass tube of length L = 150 cm and diameter D = 4 cm) at whose entrance and exit were flat metal grids. The tube was cut parallel to the generatrix into two equal halves and was made up of two sectors of angular extent 180º (π-electrodes). Both sectors were attached to the leads and used for diagnostic purposes. The thickness of injected beam was Δ = 1…2 mm and its diameter was d = 2 cm. The beam energy was 20…80 eV. The constant longitudinal magnetic field had a strength of H = 100…2000 Oe. The magnetic field varied over the length of the drift tube by less than 5% so we assumed it to be uniform inside the drift tube. It is also necessary to note that injector is located near the entrance to the drift tube at the area of non-uniform magnetic field. The range of working pressures was $10^{-4}…10^{-7}$ Torr.

Diagnostic measurements of axial distribution of electrostatic potential were made by high-frequency Langmuir probe. The probe was placed on the mobile carriage together with a multigrid electrostatic analyzer. The occurrence and evolution of diocotron oscillations was detected by π-electrodes. In this experiments we generated diocotron modes with the azimuthal wave number l = 1. In this case the oscillations of current induced on each of the π-electrodes are in opposite phases. The flat grids located at the entrance and exit of the drift tube were used for measuring of current input and output.

The distributions were obtained with the Langmuir probe, the probe being under floating potential. The beam current being $I_B = I_{CR}$ = 15 mA, distribution of potential in longitudinal direction has typical shape for velocity spread electron beams [4], distribution of 'bell'type. Such a potential distribution leads to the accelerated extractions of electrons from the drive space caused by electric fields of the spatial charge of the beam. Radial localization of the direct flow of electrons coincides with that of the reverse flow in the drive space. The beam current being increased

$I_B > I_{CR} = 17$ mA, the form of potential in the drive space essentially changes with formation of a potential pit for electrons in the drive space center (Fig. 2, curve 1). Transformation of the potential distribution in longitudinal direction is accompanied by excitation of the oscillations of the beam's density, which have been identified in as the diocotron oscillations with $l = 1$ mode [5, 6].

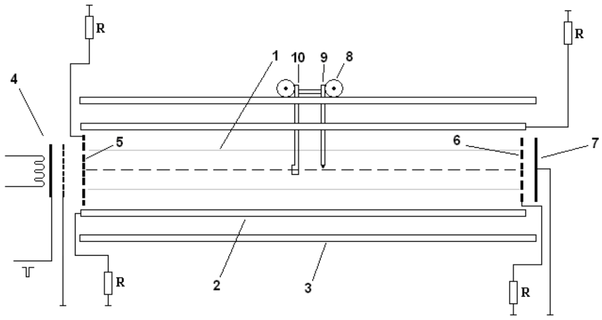

Fig. 1. Schematic of the experimental setup:
1 – electron beam; 2 – drift tube; 3 – vacuum chamber;
4 – electron gun; 5 – entrance grid; 6 – exit grid;
7 – collector; 8 – carriage; 9 – high-frequency Langmuir probe; 10 – electrostatic analyzer

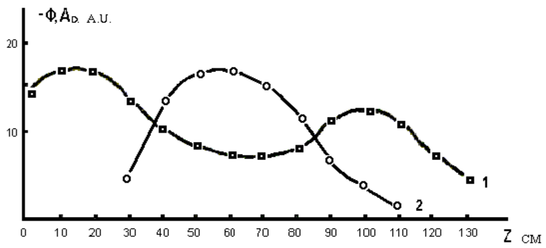

Fig. 2. Distributions potential (1), and diocotron oscillations (2) in the drive space,
$U_B = 30$ V, $I_B = 17$ mA, H = 1 kOe

DYNAMICS OF PARTICLES EJECTION DEVELOPMENT

The ejection of charged particles across the magnetic field was observed during the transportation of cylindrical electron beam through the space of drift. Such beam had a strong dispersion in velocities.

The space of drift was limited axially by two π-electrodes and radially by two measuring grids. Figure represents the oscillograms of signals obtained from π-electrodes. This oscillograms displays the dynamics of particles ejection process and diocoron instability development.

Fig. 3 displays the signals obtained in the absence of instability. Asymmetrical pulses were observed due to non-symmetrical beam injection in the drift chamber. The occurrence of diocotron oscillations was always preceded by the ejection process. Such process arises initially at the end of the injection pulse as a small pulse of voltage. In case of beam current increasing the ejection pulse moves towards the first front injection pulse. During such movement the pulse of ejection becomes shortened. It is also necessary to note that the diocotron oscillations were not only observed during the pulse of injection. So called "tails" of damped diocotron oscillations were formed after the pulse of injection. In case of beam current or energy increasing the duration of such tails grows together with the injection pulse amplitude. Finally "tail" duration may exceed the length injection pulse. Further growth of the injection pulse amplitude reduces to transition of the diocotron oscillations into a noise mode [7].

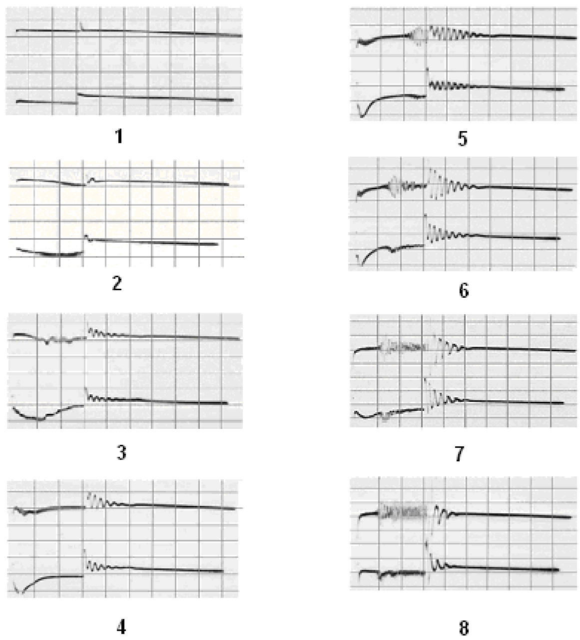

Fig. 3. Oscillograms of signals from π-electrodes. Sensitivity – 0.05 V/div; broach – 0.2 ms/div; H=1 кOe. Amplitudes of injection impulses: U_1=20 V; U_2=21 V; U_3=23.5 V; U_4=25 V; U_5=27.5 V; U_6=30 V; U_7=32.5 V; U_8=35 V

THE DYNAMICS OF LONGITUDINAL AND CROSS CURRENTS

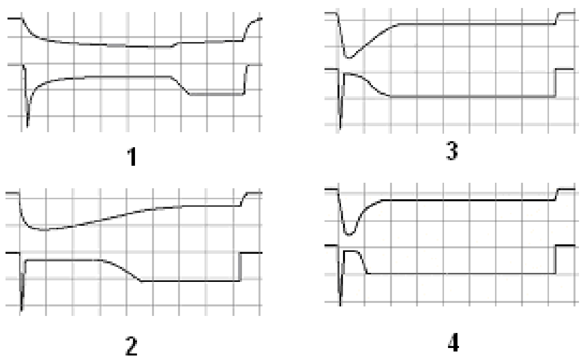

Fig. 4. Signals obtained from π-electrode and measuring grid. Sensitivity of the top trace – 0.5 V/div; sensitivity of the bottom trace – 2 V/div; broach – 0.1 ms/div; H=1кOe

There is a strong connection between variations of longitudinal and cross currents during the injection pulse energy changing. The oscillograms of such currents are presented on Fig. 3. Here the top traces represent the signal from π-electrodes while the bottom traces represent the signal from the measuring grid. It is easy to notice from given oscillograms (Fig. 3(1)) that the ejection pulse is followed by the stage of longitudinal output current growth. Fig. 3(2), 3(3) displays the time shortening of signals observed on π-electrodes. From Fig. 3(4) one can conclude that the longitudinal output current growth stage is followed by satiation stage. After the electrons cross-ejection the amplitude of π-electrode signal is also established on the certain level which does not change during the pulse of injection. Fig. 4 gives a rough idea about dynamics of longitudinal and cross currents in considered system.

PENNING TRAP WITH A CENTRAL ELECTRODE

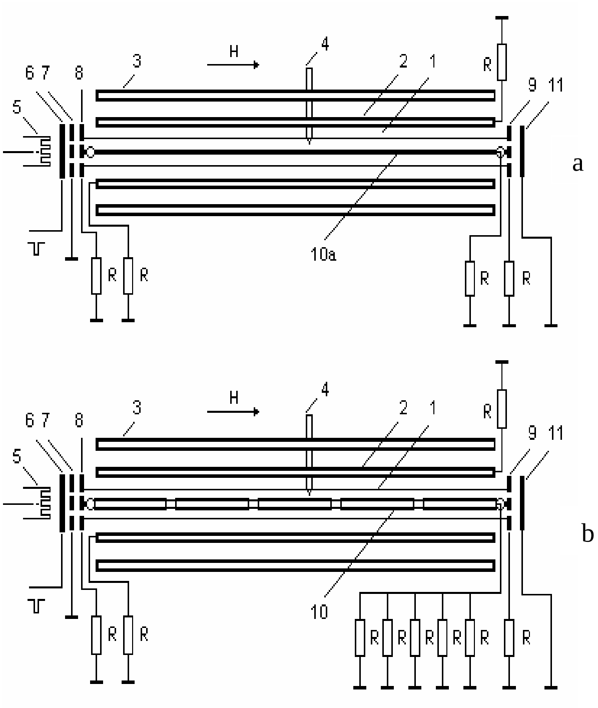

Fig. 5. The scheme of experimental setup: a – modification with an axial electrode as a metal string; b – modification with an axial multielement electrode

In case Fig. 5,a an axial electrode as a filament is connected with a corps through the resistor of loading of R. Executed functions as an active electrode (on him potential was given) so diagnostic. In case Fig. 5,b axial electrodes were used on one axis. Every electrode is connected with a corps through the resistor of R and also could be used as an active electrode or diagnostic.

STUDIES WITH A SINGLE AXIAL ELECTRODE

Fig. 6 shows the injection current pulses observed on the entrance grid of the drift tube, fluctuations registered by π-electrodes, different polarity voltage pulses applied to the central electrode. The negative polarity pulse with amplitude U_1 =-10 V was applied to the central electrode at the same time with the beam injection pulse. Then during the time period much shorter than diocotron oscillation period it was changed up to value U_2 =+20 V. After the ending injection pulse the central electrode voltage was supported on the certain level U_1 during the time period t_3. After that it was rapidly declined to the value U_3 = -20 V. In this experiment the sum $t_1 + t_2 + t_3$ was constant.

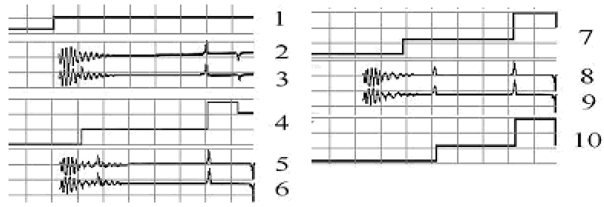

Fig. 6. The oscillograms of current Iin on the entrance grid (1), current I_1 and I_2 on π-electrodes (2, 3, 5, 6, 8, 9) and negative pulses on the central electrode (4, 7, 10): ***4*** *– t_1 = 0.6 ms, U_1 = -20 V, t_2 = 1.0 ms, U_2 = -14 V, t_3 = 0.25 ms, U_3 = 0 V;* ***7*** *– t_1 = 0.75 ms, U_1 =-20 V, t_2 = 0.85 ms, U_2 =-14 V, t_3 = 0.4 ms, U_3 = 0 V;* ***10*** *– t_1 = 0.6 ms, U_1 =-20 V, t_2 = 1.0 ms, U_2 =-14 V, t_3 = 0.25 ms, U_3 = 0 V. Broach – 0.2 ms/point; sensitivity – 0.01 V / point (2, 3, 5, 6, 8, 9), 10 V/point (4, 7, 10)*

The presence of positive polarity voltage pulse on the central electrode does not excites the diocotron instability. And the variation of the pulse duration does not affect on the qualitative picture of observed phenomena. Thus one could conclude that the appliance of positive polarity voltage pulse suppresses the diocotron instability.

STUDIES WITH A MULTIELEMENT AXIAL ELECTRODE

The experimental study was provided for two regimes of setup operation:
- positive polarity voltage pulse was applied to the axial electrode element 3 with the certain delay after injection beginning. Other elements were grounded through the certain resistance (Fig. 7,a);
- positive polarity potential was applied to the axial electrode elements 2 and 4. Other elements were grounded (Fig. 7,b)

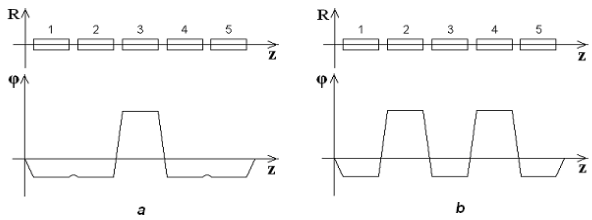

Fig. 7. The distributions of potential on the axial electrode elements

The signal was obtained from π-electrodes using oscillograph. The oscillograms were similar to displayed on Fig. 8 for both of observed regimes. The oscillations detected by π-electrodes were antiphased. Together with the fact of oscillations frequency dependence on the magnetic and electric field intensities, this fact allows to conclude that these oscillations have a diocotronic character in a mode with *l*=1.

Fig. 8 displays that the diocotron oscillations are excited by the main pulse. The appliance of long duration additional positive polarity pulse on the axial electrode elements results in the diocotron frequency increasing which corresponds to a particles density increasing.

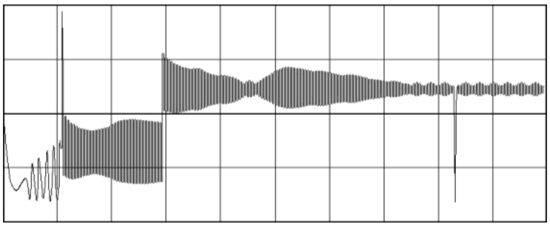

Fig. 8. The diocotron oscillations on π -electrodes at submission of positive polarity voltage pulse on the axial electrode element. Broach – 1 ms/point, sensitivity – 0.01 V/point

The oscillations frequency varies poorly during the whole pulse. Also during this pulse the amplitude modulation was observed. After the end of stimulation pulse the diocotron oscillations frequency and amplitude damps very slowly. This testifies that confined electrons are rather cold and after the stimulating pulse termination they spread slowly along the magnetic field. Given configuration of charged particles drift differs from one with a single electrode and allows confining electrons for a much longer time period [8].

CONCLUSIONS

1. Upon the injection of an electron beam with a broad velocity distribution into the drift space with a longitudinal magnetic field the majority of the particles experiences a reorganization of their movement: they start moving in the azimuthal direction, having lost their axial velocity.

2. Such reorganization promotes the occurrence of sagging of the spatial potential and a virtual cathode as a consequence, thus changing the dynamics of particles particles in drift space.

3. An inverse flow of the electrons takes place and a certain part of particles leave in a radial (ejection).

4. As a result, during the time corresponding to the front of increase of the current of injection, between two saggings of the potential a dynamic trap is formed that can capture 'slow' electrons that are situated in the drift space upon the occurrence of double sagging.

5. Charged particles (electrons) ejection across the magnetic field is followed by the process of non-stationary virtual cathode formation.

6. This formation occurs as result of longitudinal current limiting provided by the spatial charge of injected beam.

7. It was noticed, that studied phenomenon always precedes the formation of potential double sagging followed by the coherent diocotron oscillations excitation in the space of drift.

8. Single axial electrode configuration utilization allows to suppress the diocotron instability due to influence of cross electric field.

9. Self-consistent electron confinement in the space of drift may be stimulated using the axis electrode configuration.

10. The application of multielement axial electrode allows to accumulate and confine electrons in drift space for a long enough time period.

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Article received 01.12.2014

ЛОВУШКИ ПЕННИНГА ДЛЯ УДЕРЖАНИЯ И ОХЛАЖДЕНИЯ ЗАРЯЖЕННЫХ ЧАСТИЦ

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Производится сравнение параметров удержания заряженных частиц в конфигурациях самосогласованной электромагнитной ловушки и традиционных электромагнитных ловушек. Показаны возможности управления динамикой удерживаемых частиц, что позволяет более эффективно удерживать и охлаждать их. Основное внимание уделено методам контроля динамики заряженных частиц в ловушке. В качестве основного рассматривается резистивный механизм охлаждения частиц.

ПАСТКИ ПЕНІНГА ДЛЯ УТРИМАННЯ І ОХОЛОДЖЕННЯ ЗАРЯДЖЕНИХ ЧАСТИНОК

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Робиться порівняння параметрів утримання заряджених частинок у конфігураціях самоузгодженої електромагнітної пастки і традиційних електромагнітних пасток. Показані можливості управління динамікою утримуваних частинок, що дозволяє ефективніше утримувати і охолоджувати їх. Основна увага приділена методам контролю динаміки заряджених частинок у пастці. В якості основного розглядається резистивний механізм охолодження частинок.