# NOVEL MODES OF VACUUM DISCHARGE IN MAGNETIC FIELD AS THE BASE FOR EFFECTIVE ION GENERATION

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New properties of vacuum discharges in magnetic field with unconventional discharge gaps at low pressure up to high vacuum are briefly described. Both single- and multi-charge ion sources may be developed on basis of such new discharge modes. Such ion sources may have advantages in comparison with conventional ones. The main advantages are the long lifetime due to the absence of filaments and arc spots, high energy and gas efficiency due to high plasma electron temperature. The development of the discharge research and recent results are discussed.

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## 1. INTRODUCTION

It is known that ion sources have very low power efficiency as compared to energy necessary for ionization. Also in addition powerful ion sources are featured by short lifetime. Such features of ion sources are largely depend upon one another. It is related to properties of electric discharges used for ionization. With increasing of a discharge power and accordingly extractive current it is necessary to increase pressure of ionized gas or vapour and to apply additional means such as heated cathodes for increasing the current of a discharge (magnetic fields and also high-frequency fields). It is noticed at the same time that the most power efficient of sources without cathode spots is observed in the vicinity of the low bound of pressure of the discharge initiation [1]. It was known before only one type of the discharge the maintenance of which is possible at the most lowest pressure. It is magnetic insulated glow discharge [2]. However, such discharge has relatively high voltage of initiation at low pressure ($\sim 10^3\,V$ and more) that is unacceptable due to considerable energy spread of an extracted ion beam. Nevertheless at relatively high pressure the sources of such type (gas-magnetron and Penning) found wide enough application. As a result of long-term researches were discovered which differ substantially from traditional magnetic insulated discharge. These properties allow hoping to increase power and gas efficiency of sources substantially and to increase their lifetime.

## 2. DESCRIPTION OF NEW MODES OF THE DISCHARGE

### 2.1. Magnetic insulated discharge with an additional high-frequency feed

The electrode system of such discharge is like the Penning and differed only by an additional hollow anode. An additional anode can have the same design as the first one is placed along direction of the magnetic field axially with the first one. The plot of such discharge gap is shown on Fig.1.

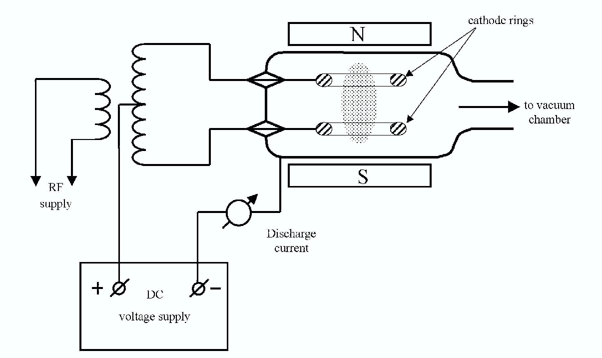


***Fig.1.*** *Double Penning vacuum cell with additional RF supply*

If both anodes are fed by identical positive potential relatively to flat cathodes then such system has the same properties as the ordinary single-anode Penning cell with the large height of an anode. However, if anodes are fed by relatively small radio-frequency voltage of tens of volts then properties of the discharge are changed substantially [3-5].

- The voltage of the discharge initiation decreases an order of magnitude.
- The application of alternating voltage to an already initiated discharge increases the discharge current by an order of magnitude.
- The current of the discharge has maximum value depending on pressure.
- The discharge goes out and not passes to the arc with increasing of pressure.

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These properties specify on high efficiency of ionization processes in such system that has to provide high power efficiency. The possibility of maintenance of the discharge at low voltage will allow decreasing energy spread of extracted beam. Low energy of ions bombarding cathodes will allow increasing the lifetime of the source. Table shows the increasing of the discharge current due to affect of relatively low alternating voltage. It should be noted here that in the gas-discharge ion sources based on the Penning's discharge the ion beam current is proportional to the discharge current at high enough extracting voltage. The model of similar source was developed and tested at low currents. It has the ratio of the beam current to the discharge current of 2.5%.

*Discharge current increasing by applied radio frequency*

| DC voltage, V | RF voltage, V | Frequency, MHz | Pressure of Nitrogen, Pa | The current mA | The current with RF, mA | Increasing ratio |
|---|---|---|---|---|---|---|
| 700 | 50 | 5.28 | 0.01 | 0.081 | 0.156 | 1.9 |
| 250 | 90 | 13.56 | 4 | 4.8 | 48 | 10(!) |

Thus, one may hope to achieve ion currents of a milliampere order in the mode corresponding to the bottom line of the Table.

### 2.2. Secondary-emission discharge in cross fields

The possibility of maintenance of such discharge is not related with the presence of gas in a discharge gap. An electron cloud hold by set of electric and magnetic field generates electrons with an excess energy. Bombarding a cathode these electrons provide the considerable secondary emission [6]. Electrons can be extracted across the magnetic field under application of the high-frequency electric field of a split anode as in RF magnetron with a cold, secondary-emission cathode providing transformation of energy of a constant field to a high-frequency field. Electrons may be also extracted from a discharge along the magnetic field providing the generation of powerful electron beam as in a magnetron gun with secondary emission [7-9]. There is a deep high-frequency modulation of electron beam at certain conditions [10-12]. Thus, frequencies of generation may be in a frequency range, where the effect of increasing of ionization efficiency under application of the high-frequency field is observed [11]. At the same time, in a difference to the first discharge type additional actions are needed for the discharge initiation. The discharge should be initiated by creating preliminary a dense electron cloud in the cross fields.

## 3. RESULTS OF RECENT EXPERIMENTS

During first experiments with a magnetron gun in the secondary emission mode the excitation of the self-sustained emission was achieved due to a falling of a voltage pulse [7, 8, 11]. Thus, the amplitude of the pulse should exceed tens of kilovolts for providing of the excitation. Beam current at such voltage values achieved tens of amperes. So high power is unacceptable and so high voltage is uncomfortable for many ion sources. The possibility of excitation of such discharge was recently tested due to the small increasing of pressure in a vacuum system [13]. In such conditions characteristic for ion sources a self-sustained secondary emission discharge is excited at considerably lower voltage of units of kilovolts. Thus, the electron beam current is 0.1...10 $A$.

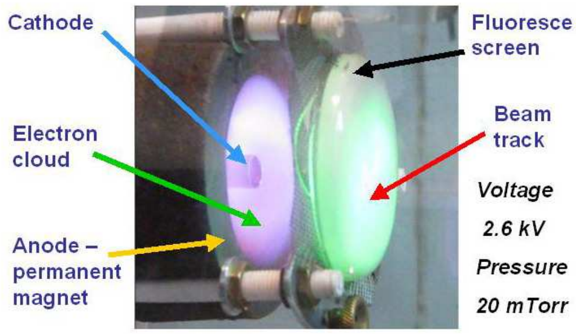
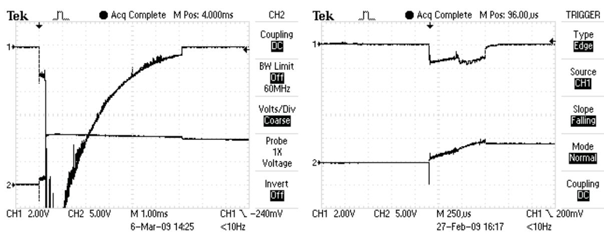



***Fig.2.*** *Operating gun*

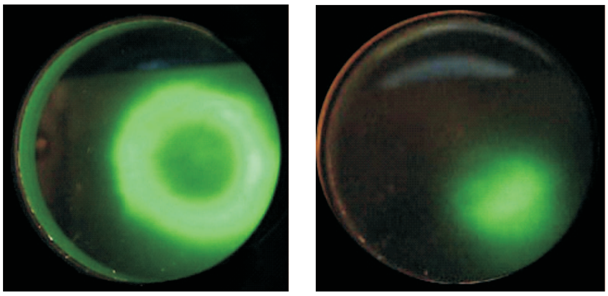
The picture of operating gun is shown with track of beam on a fluoresce screen on a Fig. 2. It should be noted here that in case of not enough cleared and degassed electrodes such discharge passes easily to arc mode when voltage in a discharge gap falls and the generation of electron beam is terminated. This situation is illustrated on the Fig.3,a where oscillograms of collector current and gun voltage obtained, on the upgraded installation "Rassvet" [13] are shown.



*a)* *b)*

***Fig.3.*** *Oscillograms of the operating gun*

One may see on the figure the sharp growth of the collector current determined by the value of a protective resistor. At the same time the gun voltage is decreased sharply. As the current and voltage are negative, the y-axis is directed downward. Heating up of cathode by an internal heater to the temperatures about 400°$C$ during few hours with subsequent cooling off and discharge training results in suppression of an arc mode development. This is shown on the oscillogram (Fig.3,b). The pictures of the hollow beam on the luminescent screen for the same mode were taken on the installation "Rassvet" (Fig.4,a). As in a number of applications such hollow beam can appear unsuitable, the focusing system, allowing transformation of a hollow beam into continuous one, was used. The spot of the continuous beam is shown on the Fig.4,b.



*a)* *b)*

***Fig.4.*** *Beam traces*

A storing condenser of small capacity was set to avoid the damage of the luminescent screen by high energy pulses. For the magnetic field creation the permanent magnet with the magnetic field strength of $0.03\,T$ was used here in a difference from the installation "Rassvet". The gun together with the magnet was set in a glass chamber. The insufficient magnetic field did not allow exciting a secondary emission discharge at so low pressures as in the installation "Rassvet". The pressure was increased approximately up to $3\,Pa$ in order to get discharge excitation. At this point we detected the excitation of intense high-frequency oscillations with frequency about $10\,MHz$ and magnitude up to $5\,A$ in the collector circuit. The corresponding oscillogram is shown on Fig.5.

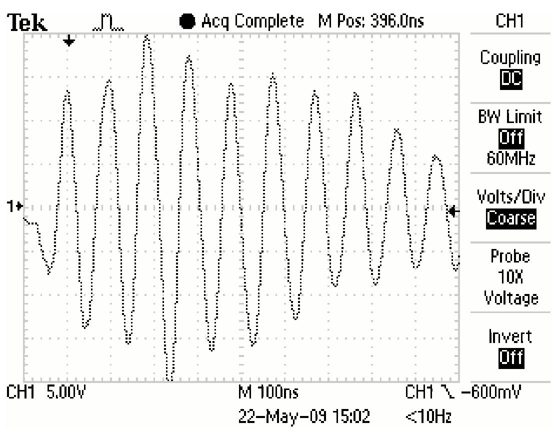



***Fig.5.*** *High-frequency oscillations*

The presence of bipolar oscillations on the collector indicates an origin of dense enough plasma in vicinity of the collector. The electron current in similar case must be of single polarity. High-frequency modulation of the beam in a magnetron gun was observed before [10, 12]. Besides, the supposed amplitude of the beam current is lower substantially than the collector current. Therefore, the intense build-up of oscillations takes place in plasma. The frequency of these oscillations corresponds to the mode of excitation of waves, absorbed intensively by plasma. These frequencies are well absorbed by in gas-discharge plasma put in a magnetic field. Such phenomenon was noticed both in our experiments [4, 5] and in later works [14-16]. Here one has not only injection of electron beam, ionizing gas, but also the excitation of oscillations of plasma and heating the last one by these oscillations. Thus, transition of the energy from a beam to plasma becomes considerably more effective. It will allow reducing operating pressure of a filled gas and increasing plasma electron temperature. All of these will increase the degree of ionization and efficiency of ion source. Decreasing the pressure and increasing the length of the beam interaction with plasma with corresponding increasing of beam power, and also increasing magnetic field it might be possible to obtain the effective generation of multicharge ions.

## 4. PROBLEMS IN REALISATION OF THE PROPOSED CONCEPTION

Structurally an ion source with such an operation principle can be of the same design as one of the most wide-spread sources with oscillating electrons, or a source with ionization by electron beam. It is sufficient to apply corresponding voltage to a device that is similar to the gun test installation. Ions can be extracted along magnetic field direction through holes in a cathode or in a collector. The extraction of ions is possible across magnetic field direction. A choice will be depend on required parameters and a function of a source. However, cathode emission in such source will not demand heating up of the cathode and gas or vapour injection in to space in vicinity of the cathode for the neutralization of electron space charge, in to limiting a current. Therefore, the design may provide such admission or pumping-down so that a cathode could be in a high vacuum and its dispersion both thermal and ion would be suppressed. All these means will provide the generation of plasma with high temperature of electrons and with desirable element composition. For the realization of such source the set of problems should be solved:

- Excitation of Secondary Emission Discharge;
- Suppression of arc excitation;
- Increasing of pulse duration;
- Beam compression;
- RF generation control;
- Control of gas or vapour input;
- Plasma stability.

The part of these problems is successfully solved during the described experiments. Thus, the ways of their solving are outlined in the developing ion sources.

## 5. COMPARISION OF EXISTING ION SOURCES AND DISCUSSION

The proposed conception occupies the intermediate position among the set of types of ion sources. The presence of electron gun moves it to the electron-beam sources [17-18] differed only by the type of an electron gun. The possibility of excitation of high-frequency oscillations and transition of their energy in to plasma moves it to high-frequency sources [14-16, 19-21]. It will be differed by simple design from last ones. Ion sources utilizing gas-discharge plasma, in particular, are difficult for calculations. Therefore, the choice of parameters and sizes of designs is often determined by the operating experience of ones with similar operation principle and parameters. Therefore, it is necessary carefully to study the experience of the developing and operation both electron-beam and high-frequency sources before the development of ion sources on the indicated principles. Foremost, those high-frequency sources that have close parameters of frequency plasma excitation. The so-called gelicon sources [14-16] presenting one of the most advanced directions in development of ion sources belong to them. The possibility of operation at very low pressures and the cleanness of generated plasma will close in them with other advanced direction of sources on electron-cyclotron resonance [20, 21]. A difference will be the simplicity of design and the absence of rigid reference of operating frequency to magnetic field. The large efficiency due to low efficiency of corresponding microwave sources of high-frequency feed with a very small wavelength may become another difference. All these conditions will provide the cheapness of production and operation of ion sources on the proposed principles. Recently achievement of current level up several kilo ampere was reported for the secondary emission mode in cold-cathode magnetron gun [22]. It was at voltage up to several hundred kilovolts. This current and electron energy may be enough for transferring of all elements up to heaviest to pure (singled) nucleuses.

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## НОВЫЕ РЕЖИМЫ ВАКУУМНОГО РАЗРЯДА В МАГНИТНОМ ПОЛЕ КАК ОСНОВА ДЛЯ ЭФФЕКТИВНОЙ ГЕНЕРАЦИИ ИОНОВ

***С.А. Черенщиков***

Кратко описаны новые свойства вакуумных разрядов в магнитном поле с нетрадиционными разрядными промежутками при низких давлениях вплоть до высокого вакуума. На базе таких новых режимов разряда могут быть созданы ионные источники, включая источники многозарядных ионов. Такие ионные источники могут иметь преимущества по сравнению с более традиционными. Главные преимущества: большой срок службы благодаря отсутствию нитей накала и катодных пятен; высокая энергетическая и газовая эффективность благодаря высокой электронной температуре плазмы. Обсуждаются новые результаты автора и развитие исследований разряда.

## НОВІ РЕЖИМИ ВАКУУМНОГО РОЗРЯДУ В МАГНІТНОМУ ПОЛІ ЯК ОСНОВА ДЛЯ ЕФЕКТИВНОЇ ГЕНЕРАЦІЇ ИОНІВ

***С.О. Черенщиков***

Стисло описано нові властивості вакуумних розрядів в магнітному полі з нетрадиційними розрядними проміжками при низькому тиску аж до високого вакууму. На базі таких нових режимів розряду можуть бути створені іонні джерела включаючи джерела багатозарядних іонів. Такі іонні джерела можуть мати переваги понад більш традиційними. Головні переваги: великий термін служби завдяки відсутності ниток розжарювання і катодних плям; висока енергетична і газова ефективність завдяки високій електронній температурі плазми. Обговорюються нові результати автора і розвиток досліджень розряду.