DEVELOPMENT H^- SOURCES FOR THE MEDICINE ACCELERATORS

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In the work two versions of H^- ion source (without additives of cesium) for a neutron capture and fast neutron therapy were considered. The results of researches of a high current pulse H^- source and a three-chambered discharge section for a stationary H^- ion source are submitted.

Key words and phrases: high current pulse source of negative ion hydrogen, neutron capture and fast neutron therapy.

Introduction

One of the important tasks in creation of the medical equipment of neutron capture and fast neutron therapy based on accelerators is the development of effective sources of negative ions. These sources, depending on the installation on which they will be used, should function either in pulse or stationary modes of operation [1].

So the installation for therapy by fast neutrons, which is based on the pulse small-sized accelerator, requires a source of H- ions with a current in some mA functioning in a pulse mode with duration of a pulse from 1 up to 10 ms.

Neutron capture therapy requires use of electrostatic tandem accelerator, for which the source working in a quasi-stationary mode with a current in tens mA and duration of an exposition in tens of minutes is necessary.

In both versions to the ion source such requirements as an extremely high reliability, a large lifetime, a high readiness, simplicity of supply and service are demanded.

On the basis of the analysis of a modern condition of works on generation of negative ions and their sources it is possible to make such conclusion.

1. A high reliability and a large lifetime of the source are possible to achieve on the basis of the following concept:

1.1. Using of plasma systems with the cold cathode (without additives of cesium);

1.2. Removing all isolators using in a design of the discharge chamber outside of the direct irradiation from plasma;

1.3. Creating of designs of magnetic system of a source, in which the field of magnetic filter is generated by magnets placed outside of plasma and, hence, are not exposed to the large thermal loadings.

2.High readiness for use it is possible to reach due to inclusion into the mechanism of generation of negative ions only those elementary processes, which do not require applications of vapors of alkaline materials, and also due to exception of elements which need to be heated from a design of the discharge chamber.

At reception of necessary vacuum conditions at the input into the accelerator there is a serious problem of a reduction of a gas flow from the ion source into the area of a beamline. This problem has a principal character at limitation of sizes of evacuation systems.

Besides the efficiency of use of a concrete ion source will depend on a degree of suppression of an electron component in a flow of negative ions.

In this work the constructive schemes are submitted and physical characteristics of two versions (pulse and stationary) of a source of negative hydrogen ions developed at the Institute of Applied Physics National Academy of Science of Ukraine are given, in our opinion they in general satisfy above requirements.

Pulse source of H^- ions

The design scheme of ion source is shown in Fig.1. It is a source with volume generation of negative ions (without additives of cesium).

In it the two-step dissociative attachment of thermal electrons to vibrationally excited molecules H_2 is used [2]. The cross-section of this process quickly grows up to a significant size ($>10^{-17}$ cm^2) with growth of oscillatory quantum number at electron energy of several eV. The basic contribution to the generation of H^- ions is brought by H_2 molecules exited on levels $v = 5$-11. The formation of the vibrationally excited H_2 molecules is carried out basically by fast electrons ($E> 10$ eV). The optimization of conditions for vibrating excitation of molecules and for the following formation of negative ions in this source is realized due to creation of discharge system generating two areas of plasma in the discharge chamber: peripheral, with rather large fraction of fast electrons and paraxial with cold electrons.

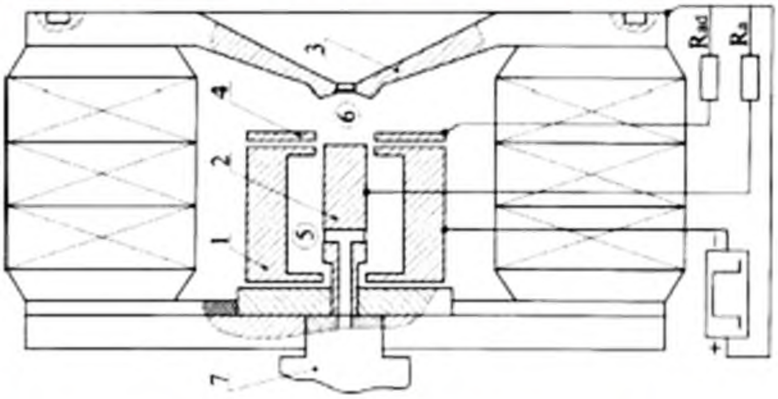

Figure 1. Schematic of ion source with a magnetron discharge in longitudinal magnetic field. 1- cathode; 2- anode; 3- plasma electrode; 4- intermediate electrode; 5- discharge chamber, 6- emission chamber; 7- gas valve.

The ion source functions as follows. The discharge chamber 5 consisting of the cathode 1 and anode 2 represents inverse gas magnetron which works on the basis of glow discharge in crossed ExH fields. The electromagnetic valve 7 supplies gas magnetron with working gas [3]. Under submission of a pulse of a voltage onto electrodes of the discharge chamber, plasma of a tubular configuration is generated. Under the certain conditions plasma penetrates through an annular slot into the emission chamber 6 and reaches the emission electrode 3. For stable current transmission, the additional electrode 4 is placed near a face part of magnetron, on which voltage higher than potential of anode is applied.

Due to formation of double layer before a narrow annular slot at magnetron output delivering fast electrons to the area of its volume, in peripheral plasma favorable conditions for vibrational excitation of molecules are created.

Internal paraxial plasma, formed by diffusion of peripheral tubular plasma across a magnetic field, will contain the vibrationally excited molecules and the enriched fraction of slow electrons, while the fraction of fast electrons does not penetrate here because of the action of magnetic filter [4]. Thus, in the internal plasma there are necessary conditions for effective realization of a finishing phase of two-step process of formation of negative ions.

It is necessary to note, that in the presented source, the magnetic field of a filter coincides with a magnetic field of discharge and, accordingly, is created by general magnetic system. The magnetic system is executed on the basis of permanent Sm-Co5 magnets, which create a field with magnetic induction $B_z = 0{,}09 - 0{,}12T$ in the interpolar gap.

The design of discharge system provides the existence of differential pressure in its various parts caused by resistance of the convergent channels. The design of a source also allows to pump out unionized working gas from the emission chamber past by the emission aperture. At that the gas conductivity of the additional channel of pumping-out can be made much above conductivity of the emission aperture. It allows to reduce essentially the pressure of gas in the field of primary formation of ion beam and thus to reduce the neutralization of negative ions along the channel of acceleration.

Extraction of ions from a source is made from paraxial zone of the emission chamber. Suppression of accompanying electrons occurs due to their moving along a magnetic field onto the emission electrode serving as the anode of a source.

The tests of this ion source were carried out with orientation of its use in high current injector of the accelerator. The results of tests are given in the table:

Ion beam current I_i	~ 50 mA
Ratio I_e/I_i	~ 3 – 6
Ion beam energy	10 – 100 keV
Emission current density	~ 0,22 A/cm^2
Impurity ions	~ 3 %
Pulse duration	~ $(10^{-4} - 10^{-3})$ s
Repetition rate of pulses	~ (1 – 10) s^{-1}
Gas flow	3 – 10^{-2} cm^3 Pa / pulse
Gas flow through emission aperture	3,7 – 10^{-3} cm^3 Pa / pulse
Life time of source	~ (1-2) 10^6 pulses

The lifetime of a source is determined mainly by a resource of the electromagnetic valve.

From the table it is visible, that the basic parameters of the ion source in some times exceed those which are necessary for installation of therapy by fast neutrons, but there are also those which need to be improved, for example, gas flow from the source and a lifetime of the electromagnetic valve.

The gas flow from the source working at pulse duration of ion current equal to some micro seconds is basically determined by the minimal duration of a gas pulse, which can generate the gas valve and by geometry (diameter and length) of channel between the valve and discharge chamber.

We hope to solve this task with the help of the fast-acting valve, developed by us [5]. The design of this valve allows to feed working gas directly to the discharge chamber of ion source, and to exclude completely the integration of a gas pulse.

Experimental researches of gas discharge in direct current H^- source

The work of volume sources in a stationary mode is especially important, as the existing now powerful surface plasma sources, with use of vapors of alkaline metals, work in a range up to 10 ms and at the further increase of duration of a pulse there are complexities.

As a result of our thermal-physical researches we obtained a power flux ~ 1 kW/cm^2 (on different areas of the discharge chamber) giving the basis for development of a source of quasi-continuous action, on the basis of pulse source described above.

For use of glow discharges in the dc ion sources it is necessary to decrease gas pressure in the discharge chamber. This fact is especially important in the sources of negative ions, where negative ions are collected from all volume of their generation, therefore the mean free path of a negative ion in the emission area should be large. For minimization of negative ion neutralization it is necessary to reduce the pressure in front and behind of the emission aperture, where the velocity of negative ions is small and cross section of their neutralization in collisions with gas is large.

Decrease of gas feed into discharge system with cold cathode leads to sharp increase of ignition and burning voltage of the glow discharge. To increase both ignition voltage and working gas pressure we were able due to the auxiliary discharge at high pressure [6]. The auxiliary discharge feeds a flow of penetrating plasma into the chamber of low pressure and works as the plasma cathode, which gives primary electrons for maintenance of basic discharge here.

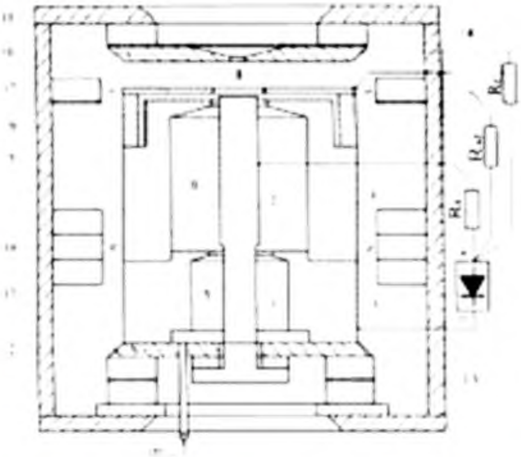

Figure 2. Schematic diagram of three-chambered discharge system. 1,2 – anode; 3,4 – cathode; 5,6 -discharge chambe ; 7,9 – convergent ring channels; 8- emission chamber; 10- intermediate electrode; 11- emission electrode; 12 – magnetic pole; 13- framework; 14 – 17 – $SmCo_5$ magnets.

The design of a source is schematically shown on Fig. 2. Its discharge system consists of three chambers with a dosed supply of gas between them. The copper anode (1 and 2) and copper cathode (3 and 4) are made of two parts. Part 3 of the cathode and part 1 of the anode create the first discharge chamber 5 (with high pressure), and part 4 of the cathode and part 2 of the anode create the second discharge chamber 6 (with low pressure). Chamber 5 is connected with chamber 6 by convergent ring channel 7, and the discharge chamber 6 is connected with the third emission chamber 8 with the help of another convergent ring channel 9. Due to gas flow resistance of the convergent ring channels, the decrease of pressure in each following chamber is obtained. An additional decrease of working gas pressure due to its expansion to the large volume and due to radial differential pumping is obtained in the emission chamber 8. $SmCo_5$ magnets (14 and 15) is established between the emission electrode 11 and a magnetic pole 12. The framework 13 of the discharge system, which is a component of magnet system, has a form of six-sided box. The ~ 35 mm gaps between the longitudinal sides of the box provide the radial pumping of inter-electrode space. High-pressure chamber is supplied with the working gas through the bottom tube.

The electrode system, forming discharge chambers 5 and 6, represents two-chambered inverse gas magnetron, which works as E x H glow discharge. Both discharge chambers are connected to one power supply, as shown in Fig. 2. The voltages on the electrodes were distributed with the help of the resistive divider.

Dependence of ignition voltage $U_з$ of magnetron as a function of gas pressure P_e in the emission chamber is shown at Fig. 3 by curve (gas flow is proportional to the pressure P_e). The maximal voltage applied was 800 V. At this voltage (800V) the discharge ignites when pressure is $P_e \approx 1{,}7\cdot10^{-3}$ Pa, and it ignites at lower pressure with the gas flow increase. Experiment has shown, that in a range of gas pressure $P_e = (1{,}7 - 3)\cdot10^{-3}$ Pa the discharge glows only in the first chamber, and at $P_e \geq 3\cdot10^{-3}$ Pa the discharge begins to glows in the second chamber, at ignition voltage $U_3 = 560$ V (as it follows from the diagram).

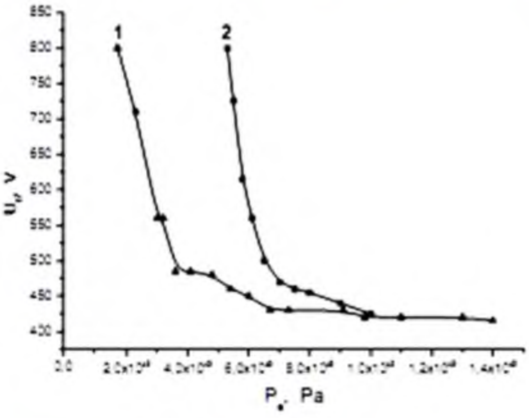

Figure 3. Dependence of ignition voltage discharge in two-chambered (1) and one-chamber (2) gas magnetron on pressure in the emission chamber.

A similar dependence for the single-chamber gas magnetron is shown in the same figure (curve 2) for comparison. In this case, chamber 5 was filled with a copper insert. The outside surface of this insert adjoined tightly to the internal surface of the cathode 3, and a ring channel with width $\Delta r \sim 0{,}8$ mm was left between the anode 1 and the internal surface of insert for gas delivery into the chamber 6.

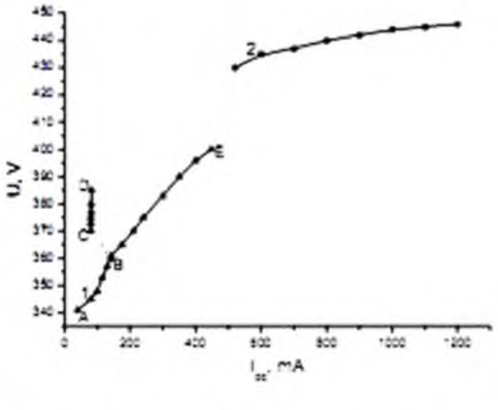

Figure 4. Volt-ampere characteristic of discharge in the gas magnetron (1) and discharge in the emission chamber (2) at $P_e = 1{,}5\cdot10^{-2}$ Pa.

The discharge ignition voltage in the chamber 6 was 560 V, and it occurs at pressure $P_e \approx 6\cdot10^{-3}$ Pa, two times higher as compared with that of the two-chamber magnetron.

Fig. 4 shows a volt-ampere characteristic of the magnetron discharge (curve 1) and of the discharge in the emission chamber (curve 2) at the following characteristics of the gap: $\Delta r = 1{,}5$ mm; $P_e = 1{,}5\cdot10^{-2}$ Pa; $\Delta l = 0{,}4$ mm; $l_e = 0{,}7$ cm. After the discharge initiation, a voltage between cathode and anode falls from value U_b to the value designated by a point A on curve 1. Further a volt-ampere characteristic corresponds to AB segment of this curve. At obtaining of the certain current (point B) a discharge initiation occurs in the emission chamber, and then the dependence of a current in the anode circuit from a voltage corresponds to CD segment. When the emission electrode is disconnected, then a volt-ampere characteristic corresponds to ABE curve. The change of gas pressure in the emission chamber results in the point B shift: point B is shifted to larger currents with pressure decrease, and to smaller current with pressure increase. The dependence of a current in the circuit of the emission electrode vs voltage (after voltage breakdown in the gap) is shown by curve 2.

The carried out experiment also has shown, that after discharge ignition in the gap, the pressure P_e can be decreased down to ~ $8 \cdot 10^{-3}$ Pa at the same discharge current and with the same stability of discharge burning. In other words, a discharge ignition occurs at a little bit higher pressure than its stable burning.

Conclusions

On the basis of the received experimental data it is possible to make the following conclusions.

1. In a pulse volume source of H- ions on a base of magnetron tubular discharge with a quasi-differential pumping out of emission chamber, the optimum conditions for reception of record values of the emission density of a current were carried out.

2. The pulse source has shown the high physical-technical and operational characteristics. The ion source readiness time for use ~ 1min. The basic construction of a source satisfies the principal requirements of the concept declared above.

3. The change of operation regime of the ion source from pulse to stationary was made. A stable ignition and burning of the charge at a rather low voltage and pressure in the emission chamber was obtained.

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РАЗРАБОТКА ИСТОЧНИКА ОТРИЦАТЕЛЬНЫХ ИОНОВ ВОДОРОДА ДЛЯ МЕДИЦИНСКИХ УСКОРИТЕЛЕЙ

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В работе представлено две версии H^- ионного источника (без добавок цезия) для нейтронозахватной терапии и терапии быстрыми нейтронами. Представлены результаты исследований сильноточного импульсного источника H^- и трех камерной разрядной ячейки для работы источника H^- в стационарном режиме.

Ключевые слова и фразы: сильноточный импульсный источник отрицательных ионов водорода, нейтронозахватная и терапии быстрыми нейтронами