LONGITUDINAL EXTRACTION OF H^- IONS FROM PENNING DISCHARGE WITH METAL-HYDRIDE CATHODE

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In the paper the emitting ability of negative hydrogen ions H^- in longitudinal direction from Penning discharge with metal-hydride cathode is investigated. This effect is possible due to mutual influence of activated hydrogen desorbed from metal-hydride on discharge properties. In order to separate negative ions from extracted current of charged particles an electromagnetic filter is applied. The efficiency of the filter is carried out experimentally and optimal external parameters for H^- ions separation are determined. The experimental results about negative ions extraction along an external magnetic field from Penning discharge are given. The beam current of H^- ions is got on the level of 5 μA.

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INTRODUCTION

The interest in sources of negative hydrogen ions H^- is caused by high efficiency of their neutralization in the energy range of 0.15…1 *MeV* [1]. Therefore, H^- ions are widely used for corpuscular heating and plasma diagnostic, for doubling the particles energy in tandem accelerators [2] and for extracting them from cyclotrons without using a deflector [3]. Currently, such accelerators are widely applied in the production of a number of medical radionuclides for diagnosis and for contact radiotherapy [2-4].

Typically, the initial injection of H^- beam is realized by cesium surface plasma sources [5] that limits their wide application. For the mass application the most preferred are the sources with bulk H^- ions formation and without cesium adding [6, 7]. In such sources H^- ions is generating due to dissociative attachment of thermal electrons to vibration-excited hydrogen molecules H_2^*, which have the main electronic state $X^1\Sigma_g^+$ [1, 8]. Increasing the vibration quantum number v from 0 to 5 makes the cross section of dissociative attachment rise by five orders of magnitude up to the value of 10^{-16} cm^2, but the energy threshold of the process reduces from 3.73 *eV* (at $v = 0$) to 1.45 *eV* (at $v = 5$) [9, 10].

The necessary concentration of H_2^* achieves mainly by cascade way of vibration states occupation due to radiative transitions from the singlet electronically excited states of molecules H_2 [10]. For the efficient states occupation it is typically used an electron beam with the energy of $\varepsilon_{be} \geq 50$ *эВ*. But here it should be noted that electrons with energy more then few electron volts intensively destroy H^- ions, so vibration-excited hydrogen molecules should be taken away from the area with low-energy electrons. As a rule, such sources are double-chambered that invariably entails the loss of H_2^* molecules and reduces system efficiency.

Fortunately, there is an original division of the areas with fast and slow electrons in Penning discharge: in anode layer electrons are heated to the required energy by diocotron instability, and in cathode region there is a large number of slow electrons got both due to secondary emission processes, and due to reflection and scattering as well [11]. The H^- ions extraction from Penning discharge traditionally realizes from cathode region perpendicular to the external magnetic field and that is often causes a number of intractable constructive problems. Therefore, more preferred would be a source with an axial extraction of H^- ion beam.

1. PROBLEM STATEMENT

With this regard the metal-hydride technology is of great interest. When one of the cathodes in Penning discharge is replaced on metal-hydride one (MH-active cathode) the properties of the discharge significantly changes. It appears an additional mode of operation (III) (Fig. 1), when at discharge voltage $U_d > 3.5$ *kV* the negative current begins flowing in the axial direction along the external magnetic field (curve 1) [12, 13]. (Using conventional cathodes (curve 2) is registered no negative current).

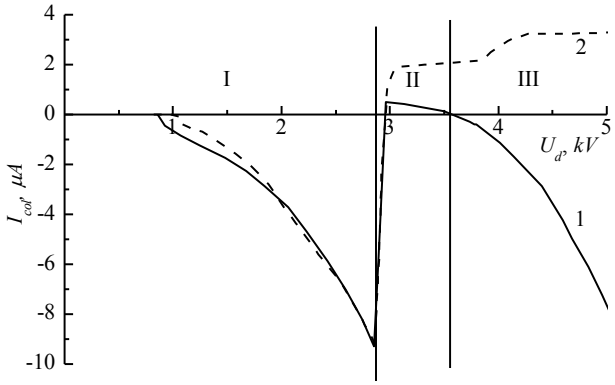

Fig. 1. Dependence of collector current I_{coll} on discharge voltage U_d (H_{zo0} = 800 Oe, $p = 5 \cdot 10^{-6}$ Torr), 1 – MH-cathode; 2 – copper cathodes

The negative current is caused by electrons output due to both addition energy appearance in unstable anode layer and reduction of space potential at the axis of the discharge as well, i.e. decreasing of cathode potential barrier for negatively-charged particles [12]. The voltage drop when discharge is reorganized as well as collector current might slightly vary depending on the geometry of a cell and other external factors. However, if a MH-cathode applies there is always mode III of the discharge.

An important advantage of the active MH-cathode is the forming of H_2^* molecule directly by the surface due to metal-hydride activation of desorbed hydrogen [10]. Those, exactly in the area where the largest amount of thermal electrons is contained! This opens up an additional powerful incoming channel of vibration-exited

H_2^* molecules that is beneficial to increase of H^- ions formation.

Thus, MH-cathode applying in Penning discharge will not only significantly increase the efficiency of H^- ions formation, but also will provide the conditions for the longitudinal output of negative ions from the cell. The problem that arises here is the necessity of H^- ions separation from the total flow of charged particles output longitudinally. Removing of positive ions H_2^+ could be done with an electric field by introducing delayed grid with positive potential, and electrons could be removed with a magnetic filter installed behind the cathode.

2. EXPERIMENTAL SETUP

The scheme of Penning discharge with MH-cathode and with electromagnetic filter is shown in the Fig. 2.

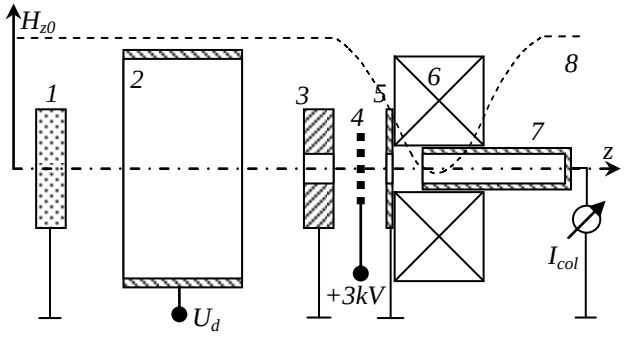

Fig. 2. The scheme of experiment, 1 – active MH-cathode; 2 – anode; 3 – passive copper cathode with an aperture; 4 – cutoff grid; 5 – electron current collector; 6 – magnetic filter coil; 7 – collector; 8 – resulted magnetic field H_z when the magnetic filter is switched on

The discharge cell was composed of an active water-cooled MH-cathode 1, a tubular anode 2 and a copper passive cathode 3 with a central aperture. Behind the aperture in the passive cathode an electromagnetic filter was set. It included a grid 4 for positive ions cutting off, a magnetic coil 6 to divert electrons, a collector of diverted electrons 5 and a collector of extracted axial beam 7.

The cell was placed in external uniform longitudinal magnetic field $H_{z0} = 0…1000$ *Oe*. The coil 6 was switched such a way to create between the cathode 3 and the collector 7 the reverse magnetic field H_{z0} enough to divert electrons on the collector 5.

The MH-cathode 1 had the form of a disc 0.5 c*m* thick and 2.0 c*m* in diameter. It was produced by pressing of saturated with hydrogen powder $Zr_{50}V_{50}H_x$ with copper binder. The initial hydrogen saturation degree was about 900 cm^3 at normal conditions. In order to stabilize the rate of hydrogen desorption the MH-cathode had a water-cooling unit. Its temperature in the experiments did not exceed 20 ^{0}C, that sufficiently lower than temperature of thermal decomposition of hydride phases. Therefore, H_2^* desorption was determined only by the discharge current and was provided mainly by ion-stimulated processes on the surface of metal-hydride [13].

In the center of passive copper cathode 3 the same size as MH-cathode was an aperture 0.5 *cm* in diameter for charged particles extraction. Both cathodes were placed at 1.0 *cm* from cutting edge of the anode 2 2.0 *cm* long and 3.7 *cm* in diameter. In the electromagnetic filter the distances between the cathode 3, grid 4, collector 5 were identical and were 0.5 *cm*. The collector 7 installed that way to have the same distance to electron current collector 5 of 0.5 *cm*.

The cathodes 1 and 3, the electron current collector 5 and the collector 7 had ground potential. The anode 2 was under positive voltage up to +5 *kV*. On the grid 4 was supplied +3 *kV* good enough for cutting off positive ions in the range of anode voltage applied.

The parameters of magnetic coil 6 were selected from the condition to obtain a magnetic field topology ensuring to divert the electrons and keep the straight movement of negative hydrogen ions. It was evaluated with the equation of paraxial trajectories using numerical simulation by the Runge-Kutta fourth-order method.

3. RESULTS AND DISCUSSION

Preliminary experimental verification of electromagnetic filter efficiency was carried out with an additional electron source modeled the electron flow specific for a given discharge cell [12]. The electron source was installed instead of the MH-cathode and created a cylindrical electron beam 0.6 *cm* in diameter, 10 μA of current and 100 *eV* of energy.

The collector current dependence on the magnitude of resultant magnetic field H_{z0} in the center of the filter coil 6 was determined. The results are shown in Fig. 3.

One can see, the electron beam is diverted almost entirely without reaching the collector 7 at zero resultant magnetic field $H_{z0} = 0$. It kept only a small group of paraxial particles. It proved the efficiency of electromagnetic filter for separation of electrons from output flow.

In the carried out experiments decreasing the electron beam current on the order of magnitude is achieved at values of resulted field $H_{z0} \approx -50$ *Oe* in the center of the filter coil that corresponds to a zero field in the cutting edge of the collector 7. For ease readability, this optimal distribution H_{z0} is shown in Fig. 1 as a curve 8.

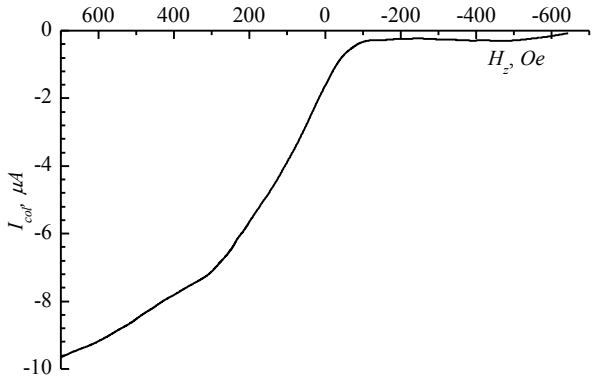

Fig. 3. Electron beam on collector depending on resulted magnetic field at the center of filter magnetic coil H_{z0}, H_{z0} = 800 Oe, p = 5·10^{-6} Torr

Fig. 4 shows the Penning discharge operation as an axial source of negative hydrogen ions. In this figure, dependence of collector current I_{col} on discharge voltage U_d at electro-magnetic filter switched off (curve 1) and at switched on one (curve 2) are shown. (The magnetic filter had optimal distribution of H_{z0} (curve 8 in Fig. 2), while the cutting off grid was supplied with 3 *kV*.)

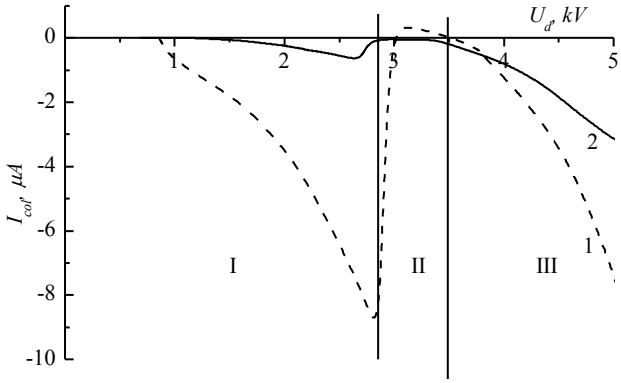

Fig. 4. Dependence of collector current I_{coll} on discharge voltage U_d (H_{z0} = 800 Oe, $p = 5 \cdot 10^{-6}$ Torr), 1 – without magnetic filter, 2 – with magnetic filter

One can see the negative current at filter switched on (curve 2) is registered only in those modes, when the total extracted current (curve 1) also takes negative values. It is the resultant current of electrons, positive and negative hydrogen ions. And each of these components has its own dependence on the discharge voltage U_d.

Thus, in mode I (U_d = 0.75…3 *kV*) the negative current more than 10 times higher than one when the electro-magnetic filter is switched on. Basically this is electron current, which successfully suppressed by magnetic filter. Small amount of positive ions are successfully retarded by grid 4.

In mode II (U_d = 3…3.5 *kV*) there is positive current. The discharge operates as an ion source and there is no negative particles being extracted.

And finally, in mode III (U_d > 3.5 *kV*) the large negative current appears again. And in this case, electrons are effectively removes by the filter. As it was mentioned above, the mode III is due to MH-cathode applying.

Thus, it could be assumed that curve 2 when electromagnetic filter is switched on corresponds mainly to the current of negative hydrogen ions.

The purification efficiency from electrons demonstrates Fig. 5. It is shown the dependence of collector current I_{col} on the resulted magnetic field at the center of the filter coil H_{z0}. The curves in Fig. 5 are correspond to discharge voltage U_d = 2.5 *kV* (I mode), U_d = 3.5 *kV* (transition from II to III mode) and U_d = 5.0 *kV* (III mode) at external magnetic field of 800 *Oe*.

One can see from the figures since the reverse magnetic field of the filter coil growths (resulted field H_{z0} decreases) the collector current reduces. The rate of the reduction is not permanent. First (at the part of 700 … 0 *Oe*) there is a relatively fast current recession, and then (in the area from 0 to 100…-400 *Oe*) current reduction slows down (even with the plateau), then the decay of the current increases again.

The vertical dash line here is pointed the values corresponds to optimal resulted magnetic field distribution (see curve 8 in the Fig. 2).

It should be noted that collector current changing along the reverse magnetic field growth is not associated with a change in discharge conditions, since the location of the filter coil provided its magnetic field decreasing on 95 % in the plate of the cathode edge. In other words, it was specially chosen that whole reverse magnetic field had been concentrated outside the discharge cell.

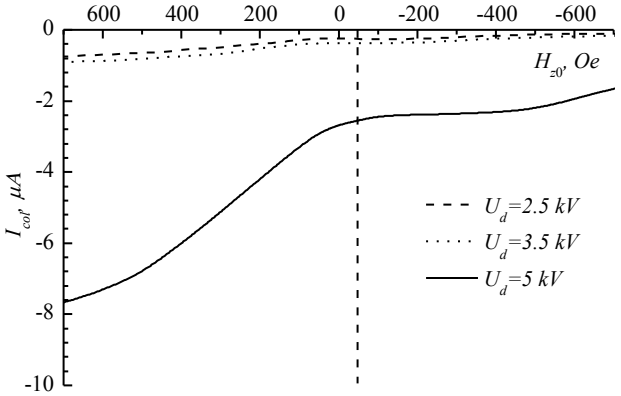

Fig. 5. Collector current depending on magnetic field at the centre of magnetic coil of the filter at different discharge voltages (H_{z0} = 800 Oe, $p = 5 \cdot 10^{-6}$ Torr)

The negative collector current in the initial part of the curves reduces due to electrons diverting from the output flow. When the resulted field on the collector edge is about zero (the values pointed with vertical dash line) practically all the electrons are removed. Subsequent plateau means that the field H_{z0} is still not large enough to divert negative ions. And only at high reverse magnetic fields negative hydrogen ions obviously starts diverted from the flow.

Thus, the electromagnetic filter behind the Penning discharge with MH-cathode quite good manages with purification of the negative hydrogen ions flow from electrons and positive ions.

CONCLUSIONS

The paper shows the possibility of creating a negative hydrogen ions source with longitudinal extraction based on the Penning discharge with metal-hydride cathode. Hydrogen desorption of vibration-excited molecules H_2^* from metal-hydride cathode leads to intensive formation of H^- ions. Low residual pressure ($p = 5 \cdot 10^{-6}$ *Torr*) provides H^- ions for unimpeded output in longitudinal direction together with electrons and positive ions.

Successful purification of the flow from the electrons and positive ions is made with electro-magnetic filter installed behind the discharge. Positive ions are retarded by electric field and electrons are diverted by magnetic field. When the discharge voltage up to 5 *kV*, there is enough 3 *kV* on the grid for positive ion cutting off. For optimal electrons diverting the best configurations of the magnetic field is achieved when it is about zero on the edge of the collector.

The obtained current of negative hydrogen ions is of 5 *μA* at discharge current of 1 *mA* and discharge voltage of 5 *kV*. The described way of H^- ions formation and extraction may be of interest in high-vacuum devices, which require injecting continuous type beams.

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ПРОДОЛЬНОЕ ИЗВЛЕЧЕНИЕ ИОНОВ H^- ИЗ РАЗРЯДА ПЕННИНГА С МЕТАЛЛОГИДРИДНЫМ КАТОДОМ

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Исследуется способность пеннинговского разряда с насыщенным водородом металлогидридным катодом эмитировать отрицательные ионы водорода H^- в продольном направлении. Это становится возможным благодаря взаимному влиянию активированного водорода, десорбируемого из металлогидрида, на свойства разряда. С целью сепарации отрицательных ионов из извлекаемого потока заряженных частиц применяется электромагнитный фильтр. Эффективность работы фильтра исследована экспериментально и определены оптимальные внешние параметры для сепарации ионов H^-. Приведены экспериментальные данные по извлечению отрицательных ионов вдоль магнитного поля из пеннинговского разряда. Получен ток пучка ионов H^- на уровне 5 *мкА*.

ПОЗДОВЖНЄ ВИТЯГУВАННЯ ІОНІВ H^- З РОЗРЯДУ ПЕНІНГА З МЕТАЛОГІДРИДНИМ КАТОДОМ

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Досліджується здатність пеннінговского розряду з насиченим воднем металогідридним катодом емітувати негативні іони водню H^- в поздовжньому напрямку. Це стає можливим завдяки взаємному впливу активованого водню, що десорбується з металогідриду, на властивості розряду. З метою сепарації негативних іонів з потоку заряджених частинок, що витягається, застосовується електромагнітний фільтр. Ефективність роботи фільтра досліджена експериментально і визначені оптимальні зовнішні параметри для сепарації іонів H^-. Наведено експериментальні дані по вилученню негативних іонів уздовж магнітного поля з пеннінговского розряду. Отримано струм пучка іонів H^- на рівні 5 *мкА*.