https://doi.org/10.46813/2024-154-053

INFLUENCE OF DISTANCE BETWEEN ANODE – METAL HYDRIDE CATHODES ON YIELD OF H^- IONS FROM PENNING DISCHARGE

I.M. Sereda[1], Ya.O. Hrechko[1], O.G. Vorobiev[2]

[1]V.N. Karazin Kharkiv National University, Kharkiv, Ukraine;
[2]Ivan Kozhedub Kharkiv National Air Force University, Kharkiv, Ukraine

E-mail: igorsereda@karazin.ua

The behavior of extracted axial current of H^- ions formed in plasma volume of Penning discharge with different distances between metal hydride cathodes and an anode is discussed. The discharge operation is ensured on hydrogen locally injected from metal hydride cathodes due to ion current impact from plasma. Efficient formation of H^- ion is achieved due to high vibrational excitation of hydrogen molecules because of nonequilibrium desorption process. It has been shown that at high magnetic field an increase of the H^- ion current is registered at the negative electric bias supply on a cathode. At low magnetic field H^- ions are pushed out by the negative space charge of anode layer which expands towards the axis. The optimal anode-cathode distance for effective yield of H^- ions was found.

PACS: 29.25.Ni

INTRODUCTION

Hydrogen negative ion sources are important for high-intensity neutral beams production for plasma heating and diagnostics [1], for thin-films and nanostructures production [2], for dusty plasma investigation [3] and as proton beams for producing a number of medical radionuclides used in diagnosis and contact radiation therapy [4]. Initial beam of negative ions is produced by using sources with surface or volume ionization. In the first case, significant intensity of negative ion beam is achieved by cesium addition [5]. In the second case, H^- ions are formed in the plasma volume by the mechanism of dissociative attachment of low-energy electrons to ro-vibrationally excited molecules of hydrogen. These sources are more reliable, compact and environmentally friendly (cesium free). Unfortunately, the brightness of the volume source is extremely low and does not meet modern needs.

The application of ZrV metal hydrides as the electrodes of plasma devices is known to increase the efficiency of negative ion formation in plasma volume [6]. Excited H_2* molecules are formed due to the activation of desorbed hydrogen directly at metal hydride surface followed by the formation of H^- ions by dissociative electron attachment. Original separation of regions with fast (in an anodic layer) and slow electrons (by the cathodes) makes a Penning discharge attractive for use as a volume source of negative ions. Moreover, at low pressure (< 0.01 Pa) and high magnetic field (> 0.07 T), the electron current predominates in the central region of the cathodes, which allows for axial extraction of negatively charged particles including negative ions [7]. The electron beam is deeply modulated at the frequency of potential oscillations in the anode layer, then for negative ions such a phenomenon was not observed [8].

Unlike the standard perpendicular extraction, this approach simplifies the source design by the unification of used parts. In negative ion volume sources with ion extraction along a magnetic field accompanied electron current is large negative ion current up to a hundred times [5]. But using magnetic separation along with numerical calculation of motion equation solves this task [6]. Subsequently, it was made various attempts to increase the productivity of the source by the electric bias of the cathodes [9] or pulsating regime implementation [10]. In this paper we describe the behavior of H^- current extracted in axial direction from Penning discharge with different distances between metal hydride cathodes and an anode.

1. EXPERIMENTAL SETUP

The scheme of a Penning cell used in experiments is shown in Fig. 1. It includes a metal hydride cathode (1), a copper cathode (5) which could be optionally changed on a metal hydride one and a tube-shaped anode 40 mm in diameter (4) placed in longitudinal magnetic field H_{zo0} = 0…0.1 T. The metal hydride cathode was produced from hydride-forming alloy $Zr_{50}V_{50}$ stored with hydrogen at a level of 800 cm^3 at atmospheric pressure and room temperature. Destruction of hydride phase due to ion current impact from plasma ensures activated hydrogen H_2* desorbtion locally to the cathode region. Negatively charged particles together with positive ions yielding along the external magnetic field through an aperture in the cathode (5). The separation of negative ions H^- is performed by electromagnetic filter, which consists a grid (6) for positive ions retarding, a magnetic coil (8) to divert electrons, a collector of diverted electrons (7) and a collector of extracted axial beam of H^- ions (9). The coil (8) creates a reverse magnetic field H_{coil}. The required values of the resulting field H_{z0} and grid potential (U_{grid} = 1 kV) in the filter is calculated from the analysis of electrons and H^- ions trajectories by numerical solution of a motion equation in axially symmetric electric and magnetic fields [4]. Calculations show that the electron beam is diverted almost completely and only a small group of paraxial particles (about 10%) passes through.

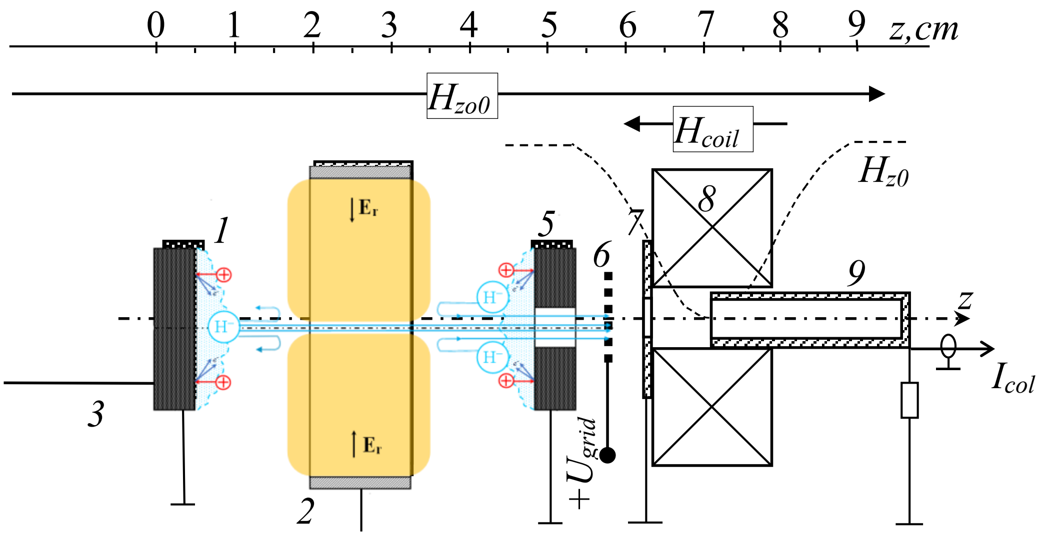

Fig. 1. The scheme of a Penning-type ion source:
1 – metal hydride cathode; 2 – Rogowski coil; 3 – thermocouple; 4 – anode; 5 – copper / metal hydride cathode with an aperture; 6 – reflecting grid U_{grid} = +1.6 kV; 7 – electrons collector; 8 – filter magnetic coil; 9 – H^- ion collector; H_{zo0} – main axial Penning magnetic field (H_{zo0} = 0…0.1 T); H_{coil} – reverse magnetic field of the filter

The grid (6) in addition to the retarding function for positive ions accelerates electrons and H^- ions to approximately the same energy followed by the successful separation in the magnetic field H_{z0} of the filter.

The discharge operation is ensured by applying a positive potential to the anode. There was no external supply of hydrogen, and all experiments were carried out on hydrogen, which was desorbed from the metal hydride cathode. The residual pressure in the vacuum chamber was $1.5 \cdot 10^{-6}$ Torr.

2. RESULTS AND DISCUSSION

The ability of Penning source of emitting negative particles in longitudinal direction is typical at low pressure, high discharge voltage and high magnetic field [5]. In this case a negative space charge placed close to an anode followed by a field-free plasma region formation around the axis. The main part of applied voltage drops in an anode layer, and it keeps low by the cathodes.

If the cathodes are made from hydride ZrV alloy, H^- ions will be produced near the metal hydride surface due to the dissociative attachment of slow electrons (2…4 eV) to pre-excited hydrogen molecules H_2*, which are released from the cathode due to the influence of ion current from plasma. Hydrogen working pressure in the cell is set on the level which is automatically determined by the discharge current.

The dimensions of the electrodes of Penning cell sufficiently impacts on the behavior of extracted axial current. For instance, the reduction of anode length resulted in significant decline of the current of positive ions outgoing in the axial direction and allowed for the reduction of the retarding grid potential [7]. In the same time, in our previous experiments we used one metal hydride cathode (the second one was from coper) and clear results were obtained only at high magnetic field [4, 6, 7].

Introduction of second metal hydride cathode into discharge cell does not practically impact on discharge current, but sufficiently changes the features of H^- ions extraction (Fig. 2). At high magnetic field H^- ions produced nearby the opposite metal hydride cathode, so application of negative cathode bias significantly improves extraction of negative ions. The role of the second metal hydride cathode (with aperture) is limited. At low magnetic field thick anode layer of negative space charge pushes H^- ions formed by the second metal hydride cathode (with aperture). And now, on the contrary, the role of the first metal hydride cathode is reduced, because formed negative ions there retain by negative space charge of anode layer.

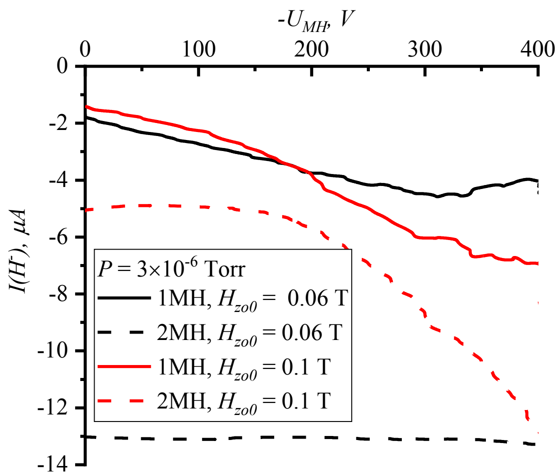

Fig. 2. The current of negative ions versus the electrical bias of opposite cathode at U_d = 5 kV, $I_d \approx$ 2 mA and the anode cathode distance of 12 mm

Figs. 3 and 4 show the behavior of H^- current at different distance between the anode and the cathodes. At low magnetic field the current of negative ions does not depend on the bias potential of opposite cathode and increases with the elongation of anode-cathode distance.

But at a distance exceeding 12 mm the part of positive ions in axial flux significantly rises and the current of negative particles, on the contrary, decreases. This makes it already ineffective for the extraction of negative ions. The behavior of the negative ion current at low magnetic fields is described in [11] and concerns with the spreading of the negative space charge of anode layer towards the axis. The negative electric bias of opposite cathode in this case has weak effect. Only a small amount of paraxial negative ions formed by the opposite cathode could overcome the layer of negative space charge. So, in case of single metal-hydride cathode using H^- current kept low and had been not impacted by $-U_{MH}$ bias.

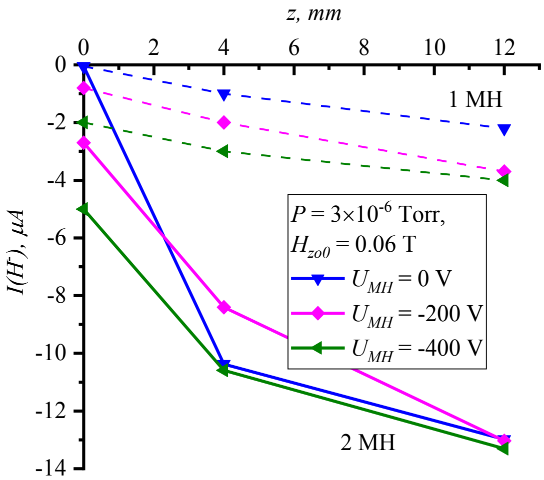

Fig. 3. The current of negative ions versus the anode-cathode distance at U_d = 5 kV, $I_d \approx$ 2 mA and low magnetic field

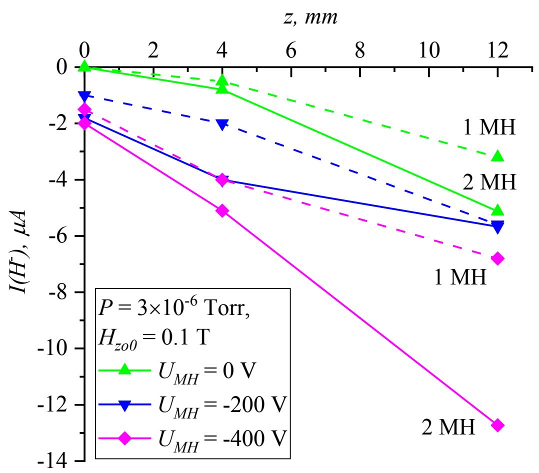

Fig. 4. The current of negative ions versus the anode-cathode distance at U_d = 5 kV, $I_d \approx$ 2 mA and high magnetic field

The drop of H^- current along the decreasing of anode-cathodes distance is mainly due to the distortion of the area of negative ions formation near the cathode layer.

At high magnetic field the anode layer is thin and a field-free plasma placed around the axis of the cell. So, H^- ions extraction can be enhanced by the supply of negative electric bias of opposite cathode. The main contribution to H^- current are negative ions which are pushed out by negative electric bias $-U_{MH}$ from the opposite side of the cell [11].

There is also a shift in energy of oscillating electrons at the change of anode-cathode distance (Figs. 5 and 6). This may be due to the existence of a virtual cathode region in the interelectrode space, which limits the output of low-energy oscillating electrons over long interelectrode distances. At the anode cut line there are electrons up to thermal energies (see A-C 0 mm in Figs. 5 and 6), and as we move away from the anode cut line, electrons of higher energies were recorded [12].

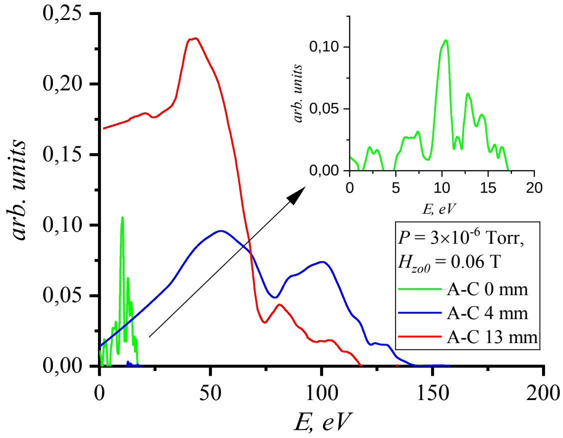

Fig. 5. Electron energy distribution function at U_d = 5 kV and at low magnetic field

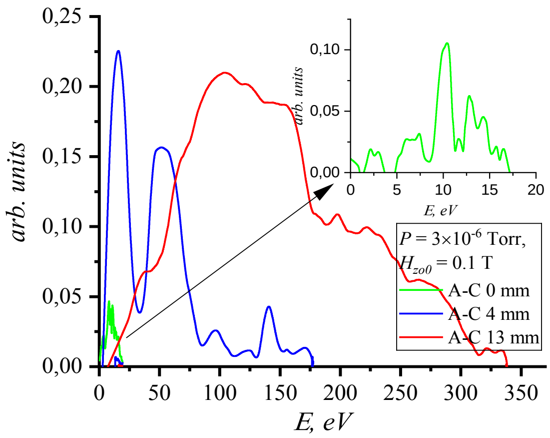

Fig. 6. Electron energy distribution function at U_d = 5 kV and at high magnetic field

A possible reason for the electrons to gain additional energy is the oscillations of the negative space charge in the discharge and deep modulation of the electron flux on corresponding frequency. At high magnetic field the amplitude of oscillation is higher, therefore the electron energy spread increases.

Thus, the use of low magnetic fields is more attractive for H^- production, because more favorable conditions for H^- formation are established. The are lower energy of axial electrons and self-pushing effect of formed negative ions by negative space charge of thick anode layer. In other words, one can get the same H^-current at lower energy consumption.

CONCLUSIONS

The application of metal hydride cathodes in Penning cell allows for the formation of axial H^- ion flux along the external magnetic field. It sufficiently increases the efficiency of H^- ion formation due to excluding the stage of H_2 molecule excitation in plasma. The separation of H^- ions from electrons and positive ions was made with electro-magnetic filter. Positive ions are retarded by electric field of the grid and electrons are diverted by magnetic field with efficiency of about 90%. The generation of negative ions occurs nearby the surface of metal hydride facing the plasma due to the dissociative attachment of thermal electrons to hydrogen molecules which are released in vibrationally excited state. It sufficiently increases the efficiency of H^- ion formation due to excluding the stage of H_2 molecule excitation in plasma. H^- ions migrate then in axial direction inside the field-free central plasma which is limited by the anode layer and could be extracted through the central aperture in the cathode. At high magnetic field the current of negative ions can be enhanced by the supply of negative electric bias on opposite cathode. At low magnetic field negative ions are pushed out by the negative space charge of expanded anode layer. The best anode-cathodes distance has been found through the experiments for efficient negative ions formation and extraction corresponds to 12 mm.

REFERENCES

1. R.S. Hemsworth, D. Boilson, P. Blatchford, M. Dalla Palma, G. Chitarin, H.P.L. de Esch, F. Geli, M. Dremel, J. Graceffa, D. Marcuzzi, G. Serianni, D. Shah, M. Singh, M. Urbani, and P. Zaccaria. Overview of the design of the ITER heating neutral beam injectors *// New J. Phys.* 2017, v. 19, p. 025005. https://doi.org/10.1088/1367-2630/19/2/025005

2. V. Lisovskiy, A. Minenkov, S. Dudin, S. Boga-tyrenko, P. Platonov, and V. Yegorenkov. Synthesis of Nanoparticles and Theoretical Model of Their Retention in Plasma of RF Capacitive Discharge with Vertically Arranged Electrodes in Acetylene // *ACS Omega*. 2022, v. 7, N 51, p. 47941-47955. https://doi.org/10.1021/acsomega.2c05846

3. I.B. Denysenko, M. Mikikian, N.A. Azarenkov. Modeling results on the dust charge distribution in a plasma afterglow // *Phys. Plasmas*. 2022, v. 29, p. 093702. https://doi.org/10.1063/5.0100913

4. P.W. Schmor. Review of Cyclotrons for the Production of Radioactive Isotopes for Medical and Industrial Applications *// Rev of Accelerator Sci and Tech*. 2011, v. 4, p. 103-116. https://doi.org/10.1142/S1793626811000574

5. M. Bacal and M. Wada. Fundamental Processes of Hydrogen Negative Ion Production in Ion Source Plasma Volume // *Physics and Applications of Hydrogen Negative Ion Sources, SSAOPP*, v 124, (Springer, Cham., 2023), p. 1-27. https://doi.org/10.1007/978-3-031-21476-9

6. I. Sereda, A. Tseluyko, N. Azarenkov, D. Ryab-chikov, Ya. Hrechko. Effect of metal-hydride hydrogen activation on longitudinal yield of negative ions from PIG // *Int. J. Hydrogen Energy*. 2017, v. 42, p. 21866-21870. http://dx.doi.org/10.1016/j.ijhydene.2017.07.129

7. I. Sereda, Ya. Hrechko, M. Azarenkov. Modulation of negatively charged particle flux from Penning discharge with metal hydride cathode // *Problems of Atomic Science and Technology. Series "Plasma Physics" (29).* 2023, № 1(143), p. 71-73. https://doi.org/10.46813/2023-143-071

8. W. Schuurman. Investigation of a low pressure Penning discharge // *Physica*. 1967, v. 36, p. 136-160. https://doi.org/10.1016/0031-8914(67)90086-9

9. I.N. Sereda, Ya.O. Hrechko, D.L. Ryabchikov, A.F. Tseluyko, N.A. Azarenkov. The increasing of H– current from Penning ion source with electrically biased metal hydride cathode *// Vacuum*. 2019, v. 162, p. 163-167. https://doi.org/10.1016/j.vacuum.2019.01.046

10. I. Sereda, Y. Hrechko, I. Babenko, M. Azarenkov. The emission of H^- ions from Penning-type ion source with metal hydride cathode in pulsating regime *// Vacuum*. 2022, v. 200, p. 111006. https://doi.org/10.1016/j.vacuum.2022.111006

11. I. Sereda, Y. Hrechko, M. Azarenkov. Expulsion of hydrogen negative ions by the anode layer of negative space charge from Penning discharge with metal hydride cathodes // *Phys. Plasmas*. 2024, v. 31, p. 053516. https://doi.org/10.1063/5.0202579

12. A.A. Petrushenya. *Formation and dynamics of negative charged particles in plasma electromagnetic traps:* PhD thesis in phys. and math.: 01.04.08, V.N. Karazin Kharkiv national university, Kharkiv, 2005.

Article received 30.09.2024

ВПЛИВ ВІДСТАНІ МІЖ АНОДОМ ТА МЕТАЛОГІДРИДНИМИ КАТОДАМИ НА ВИХІД ІОНІВ H^- З ПЕННІНГОВОГО РОЗРЯДУ

І.М. Середа, Я.О. Гречко, О.Г Воробйов

Обговорюється поведінка виведеного аксіального струму іонів H^-, що утворюються в об'ємі плазми розряду Пеннінга за різних відстанях між металогідридними катодами та анодом. Розряд горить на водні, що локально інжектується з металогідридних катодів за рахунок дії іонного струму з плазми. Ефективне утворення іона H^- досягається за рахунок високого коливального збудження молекул водню внаслідок нерівноважного процесу десорбції. Показано, що збільшення струму іонів H^- реєструється при подачі від'ємного електричного зсуву на катод у сильному магнітному полі. При низькому магнітному полі іони H^- виштовхуються негативним просторовим зарядом анодного шару, який розширюється до осі. Знайдено оптимальну відстань анод-катод для ефективного виходу іонів H^-.