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THE PLASMA PARAMETERS OF PENNING DISCHARGE WITH NEGATIVELY BIASED METAL HYDRIDE CATHODE AT LONGITUDINAL EMISSION OF H⁻ IONS†

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The enhancement of negative ion production in a volume Penning based source could be performed by the application of metal hydride cathode. Hydrogen isotopes are stored there in a chemically bound atomic state and desorbed from the metal hydride under the discharge current impact. Highly vibrationally / rotationally excited molecules H_2* are formed by recombination of H-atoms at the metallic surface, which then can be easily converted to H^- by dissociative electron attachment without the pre-excitation of a H_2 molecule in plasma. Changing the discharge properties opens the way of source design simplification by negative ions extraction along the external magnetic field in comparison with traditional volume sources, where the extraction is performed perpendicular to magnetic field. The separation of negative ions from the extracted in longitudinal direction flux of charged particles was performed by an electromagnetic filter basing on numerical calculations of particles trajectories. The dependence of electron temperature and plasma density on the bias potential is carried out by Langmuir probe method. The measurement of electron energy was performed by an electrostatic energy analyzer. It was shown that the yield of H^- ions depends on the electrical bias on the metal hydride cathode with strong dependences on the plasma electrons temperature. The estimation of the bias potential versus T_e was performed under the assumption of electron Boltzmann distribution near the cathode. The presence of additional groups of electrons with higher energies distorts the behavior of H^- current, but generally the experimental results are in good agreement with estimation based on the physics behind the Boltzmann distribution. The optimum for the effective extraction of H^- ions was revealed, when the metal hydride cathode had been electrically biased at -20V and higher, and plasma density reaches the maximum value to 2×10^9 cm^{-3}.
Keywords: negative ions, hydrogen, Penning type ion source, metal hydride
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In 1963 Ehlers et al. [1] extracted a beam of negative deuterium ions through the apertures in the anode with a current of 0.5 mA from a Penning discharge with cold cathodes at a discharge voltage of 3 kV. Further, sources of this type were developed and studied in many laboratories [2]. It can easily be built into the center of cyclotrons and was used in many cyclotrons for accelerating negative ions. It had been used until 1987 in the TRIUMF cyclotron, but the source was installed outside [3]. The Ehlers type source was also used in a Van de Graaf accelerator which accelerated H– ions up to 1.5 MeV with the current of 1 mA and the pulse duration of 1.5 ms [4]. Then some basic understanding of the operation of the Penning type H– ion source was presented.

Today there are two known methods for increasing the current of negative ions from a volume source without cesium using. This is an increase in pressure and plasma density, but this way is limited by destruction of H– ions in plasma [5]. The second method is the choice of the electrode's material [6], which indicates the decisive role of processes on the surface facing hydrogen plasma.

Hydride-forming getter materials based on Zr-V alloys are a promising base for the manufacture of such electrodes [7]. They are characterized by high hydrogen storage capacity and low activation temperatures. They easily uptake hydrogen when heated to moderately elevated temperatures. This circumstance determines the high efficiency of hydrogen pressure adjusting according to the scheme of "adjustable parameter – thermal effect." Hydrogen uptake is accompanied by it excitation with following reduction of ionization potential by 0.3 - 0.5 eV and an increase in cross section for the dissociative attachment of slow electrons to neutral hydrogen molecules [8].

So, the application of metal hydrides as the electrodes of plasma devices opens the possibility of increase the efficiency of negative ion formation in plasma devices and provides an internal local hydrogen supply directly into a gas-discharge cell. The features of metal hydride application in hydrogen plasma of Penning discharge were carefully described in [9].

Highly rotationally/vibrationally excited molecules H_2* are formed by recombination of H-atoms at the metallic surface, which then can be easily converted to H^- ions by dissociative electron attachment. The efficiency of H^- ion production sufficiently increases, because one does not need any more wasting energy on the pre-excitation of a H_2 molecule [10].

Activated hydrogen desorbed from a metal hydride cathode impacts on the Penning discharge properties [11]. It was cleared that at high discharge voltages negative ions along with electrons and positive ions starts outgoing along the external magnetic field through an aperture in the cathode. So, the simple replacement of a cathode by a metal hydride one and the reverse of polarity on pulling electrodes could make a negative ion source from traditional positive one.

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In [13] the H^- ion current of 10 μA at an input power of 6W from Penning type ion source with metal-hydride cathode has been obtained. Maximum extracted current of H– ions was observed at negative electrical bias of metal hydride cathode to 50 V. The purpose of the paper is to investigate the discharge properties in order to explain carried out results and to give advices on increasing the extracted current.

EXPERIMENTAL SETUP

Experimental investigations were performed on a device shown in Figure 1. This is a H^- ion source based on Penning discharge with metal hydride cathode equipped with an electromagnetic filter for H^- ions separation from extracted charged particle flux. Between a metal hydride cathode *1* and a copper cathode-reflector *3* a tubular anode *2* made from stainless steel was set. The positive potential U_a was supplied to the anode. On the metal hydride cathode there was a possibility of supplying a negative electric bias. An electromagnetic filter for negative ions separation was set behind the central aperture in the cathode-reflector. It includes of a grid *7* for positive ions reflection, a magnetic coil *9* for electrons divertion, a collector of diverted electrons *8* and a collector of extracted axial beam of H^- ions *10*.

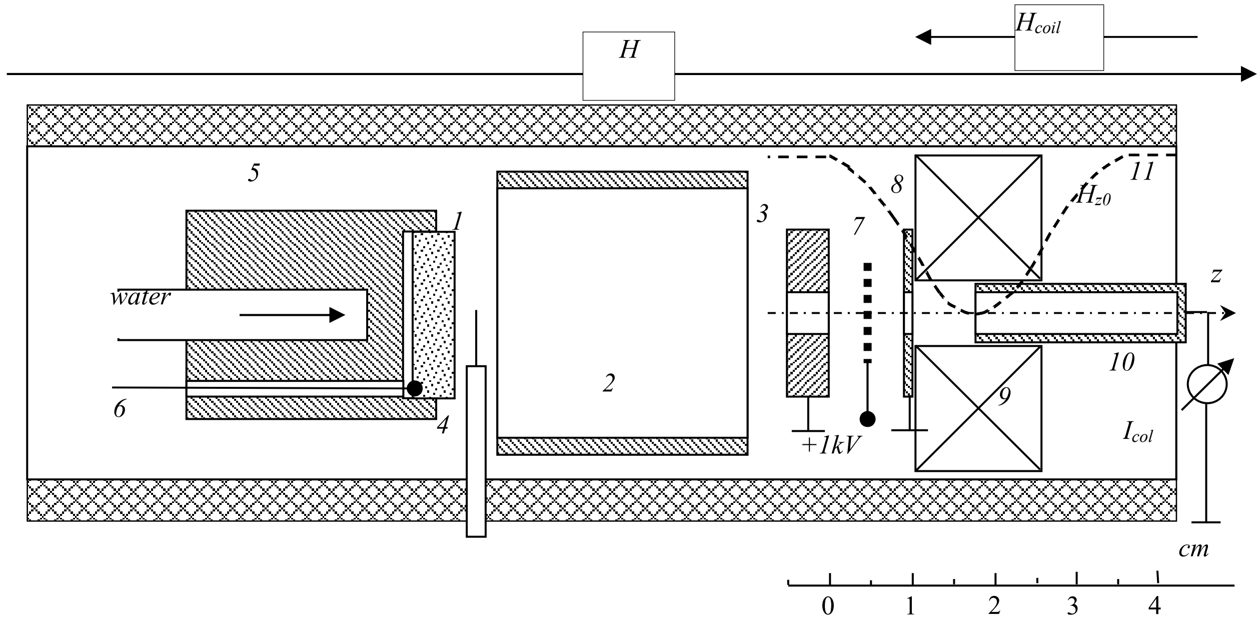

Figure 1. The scheme of discharge cell
1 – metal hydride cathode, 2 – anode, 3 – copper cathode with an aperture, 4 – Langmuir probe, 5 – cathode-holder, 6 - thermocouple, 7 – retarding grid, 8 – electrons collector, 9 – coil of magnetic field H_{coil}, 10 – H^- ion collector, 11 – distribution of the magnetic field H_{z0} in the filter

The metal hydride cathode *1* was pressed from a powder of hydride-forming alloy $Zr_{50}V_{50}$ with a copper binder by a method including melting of the alloy, its activation and filling with hydrogen. The quantity of hydrogen stored in the cathode was ~ 870 cm^3 under normal atmospheric pressure and room temperature. The metal hydride cathode had a water-cool and its temperature (~ 20 ^{0}C) was much lower than the minimal temperature of thermal desorbtion of hydrogen (~ 80 ^{0}C). So, H_2^* uptake was determined only by a discharge current and is provided mainly by ion-stimulated processes from the surface of metal hydride [12]. Langmuir probe *4* made from tungsten wire and embedded in ceramic insulator was set perpendicular to discharge axis on the half distance between anode and metal hydride cathode. The working area of the probe was a cylinder 0.35 mm in diameter with the length of 4 mm faced the center of the cathode. The discharge worked only in desorbed from metal hydride hydrogen at initial residual pressure of 1.5×10^{-6} Torr without any external gas injection.

RESULTS AND DISCUSSION

Previously we reported about the possibility of enhancement of H^- ions yield by the application of a negative electric bias on metal hydride cathode [13]. Following decreasing in inter electrode distance induced significant modification in the negative ions current behavior under the negative electrical bias on metal hydride cathode [14]. More detailed results carried out within the frame work of the paper is shown in Figure 2. One can see, the inflection of H^-current is observed only at low magnetic fields (to 0.06 T) and is already not so pronounced. And when the electric bias -U_{MH} and magnetic fields take higher values the H^- current does not decrease, as it was in [13], but on the contrary it grows.

In [13] a decrease in the H^- current was explained by electrons depletion by the metal hydride cathode owing to their reflection by -U_{MH} potential which is reduced the rate of the dissociative electron attachment. The neglection of secondary ion-electron emission from the surface of the cathode, which was slowed down the electrons depletion, caused a moderate discrepancy between experiment and calculation.

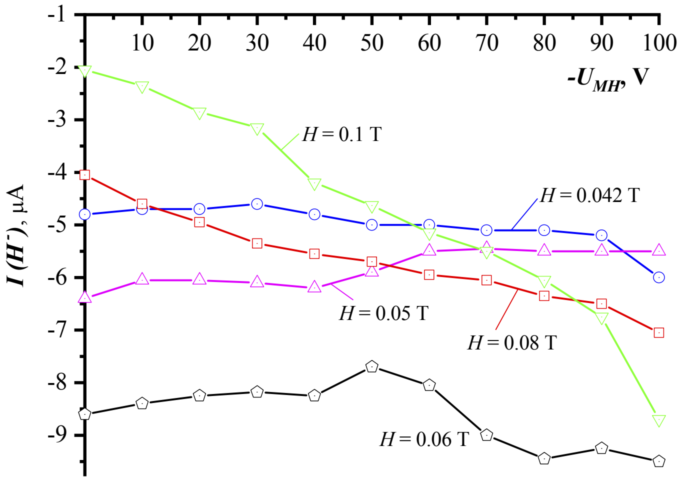

Figure 2. H^- ion current versus negative electric bias on metal hydride cathode at $U_a = 5$ kV, $P = 5\times10^{-6}$ Torr

The typical volt-ampere characteristics measured by cylindrical Langmuir probe is shown in Figure 3. The calculation of plasma density n was performed from Bohm current. The electron temperature T_e was calculated from transition section of volt-ampere characteristic near the point of floating potential using standard methodic. The applicability of this technique for determining the electron temperature for moderate magnetic fields has been confirmed in [15], mainly because of large (~1 cm) Larmor radius of H_2^+ ion compared with probe dimension.

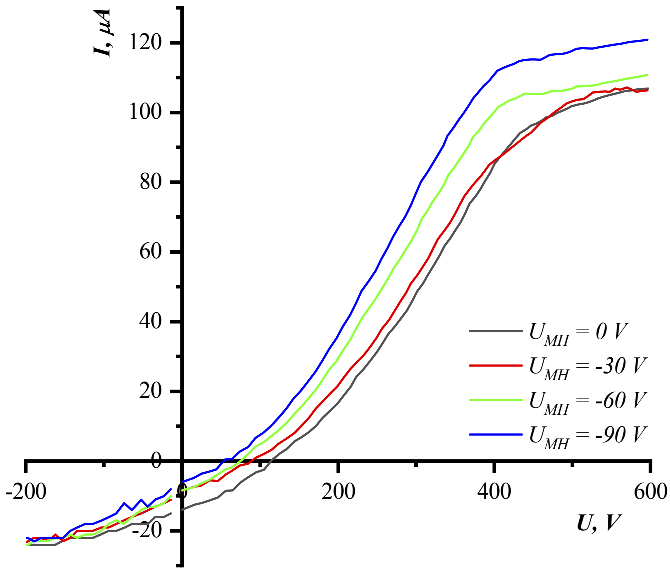

Figure 3. The typical volt-ampere characteristics measured by cylindrical Langmuir probe at $U_a = 5$ kV, $I_d = 0.8$ mA, $H = 0.1$ T, $P = 5\times10^{-6}$ Torr

The plasma parameters measured on the axis of discharge cell close to metal hydride cathode is shown in Figure 4. Negative electrical potential on metal hydride cathode $-U_{MH}$ impacts the density and plasma electron temperature. It is seen they behave in the same way at low electric bias. The density surely grows since the bias potential increase to -20 V. T_e drops wherein and takes the value of approximately from 14 eV to 28 eV depending on the magnetic field.

In [13] it was suggested that the inflection point of $I(H^-)$ in the Figure 2 corresponds to plasma electron temperature T_e. And the more T_e, the closer electron reflects from the metal hydride cathode which is under negative bias potential. Figure 4 has primarily proved this statement. At low magnetic field, when the inflection of H^- current is observed under the bias potential of -40 V, the electron temperature takes smaller value, and electrons could be easily reflected reducing the value of H^- current. If T_e takes larger values, there is no H^- current inflection, or it is not so pronounced.

Plasma density and electron temperature T_e takes on increased values when the pressure raises. But it depends in the same way as for those shown in Figure 4 and does not specially represented in the paper.

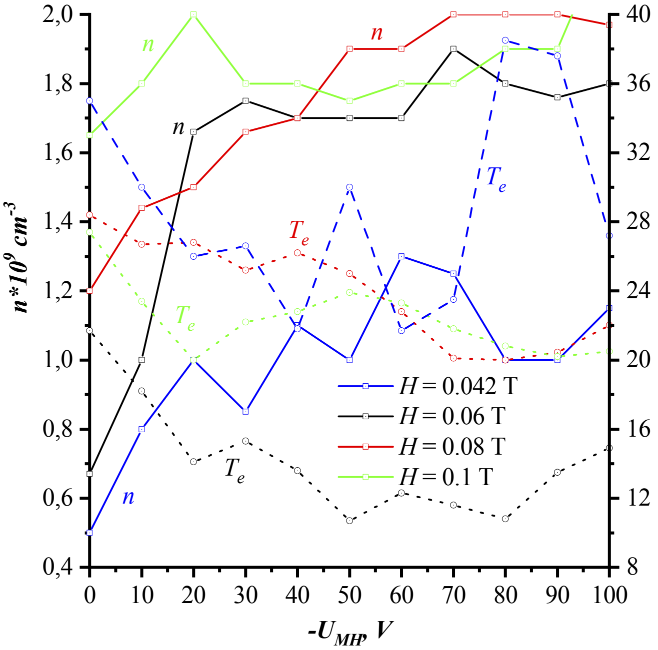

Figure 4. Plasma density and electron temperature on the axis of discharge cell by metal hydride cathode at $U_a = 5$ kV, $I_d = 0.8$ mA, $P = 5\times10^{-6}$ Torr

Another explanation of H^- current behavior could be the existence of electrons groups with different higher energy. To test this assumption, the electromagnetic filter was replaced with an electrostatic energy analyzer, which was used to measure the electron energy that outgoes in longitudinal direction (Figure 5).

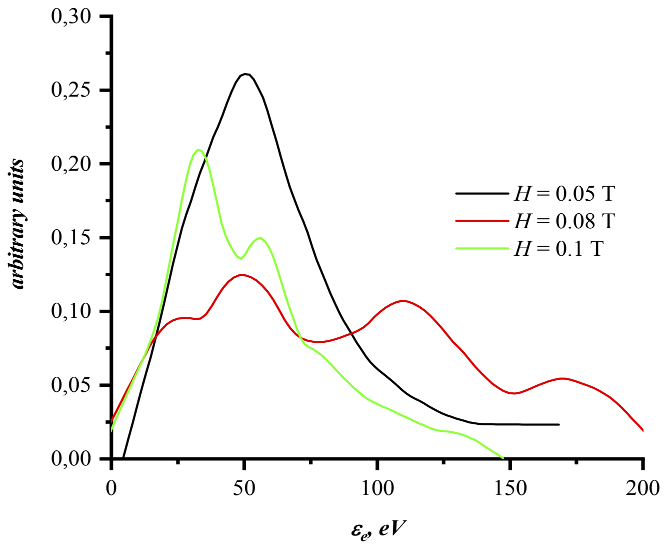

Figure 5. Electron energy at $U_a = 5$ kV, $I_d = 0.8$ mA, $U_{MH} = -20$ V, $P = 5\times10^{-6}$ Torr

As seen from Figure 5 the groups of high-energy particles appear in the spectrum of registered electron current at high magnetic field and distribution function strongly distorted by the “non-Maxwellian” tail of high-energy electrons with energies more than 100 eV. But the studies carried out in [16] pointed out, that in the central region of the discharge it close to the Maxwellian one, what determines the applicability of Langmuir probe set on the axis of the cell.

The highest value of electron energy there is much bigger, than the electric bias of metal hydride cathode, which could explain the increase of H^- current at high bias potential (Figure 2).

If we assume that decline in the H^- current is explained by electrons depletion by the metal hydride cathode because of the physics behind the Boltzmann distribution, then the factor e/T_e will be responsible for the inflection point of the H^- current. The higher values of T_e, the closer the inflection point to the cathode surface and higher values of $|U_{MH}|$ needed. This dependence was calculated in [14] and presented in Figure 6 (solid line).

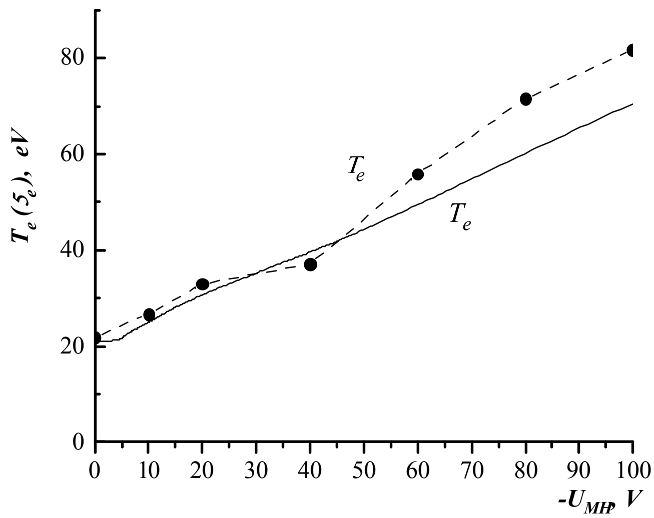

Figure 6. The dependence of needed metal-hydride electric bias on plasma electrons temperature (calculated) and electron energy (measured) at $U_a = 5$ kV, $I_d = 0.8$ mA, H = 0.1 T, P = 5×10^{-6} Torr

The electron energy ε_e is measured by energy analyzer. The presented data (dash line) correspond to the dynamic of the first maximum in distribution function, which is agreed with previously calculated values for T_e. It is, obviously, the group of electrons which are oscillated along the axis of Penning cell. The groups of electrons with higher energies appear due to heating on the instability of the anode layer. The characteristic dependence of the oscillation frequency on the magnetic field indicates on a diocotron type instability (Figure 7).

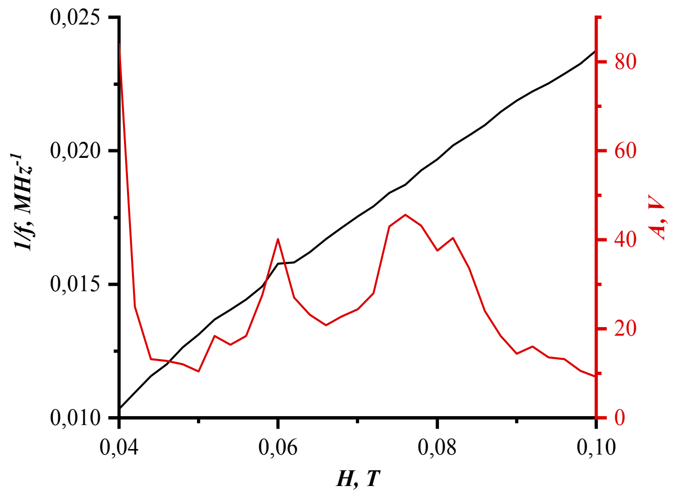

Figure 7. The dependence of frequency and arbitrary amplitude of oscillation in anode layer on magnetic field at $U_a = 5$ kV, $I_d = 0.8$ mA, P = 5×10^{-6} Torr

So, the presence of additional groups of electrons with energies significantly exceeding T_e distorts the behavior of H^- current in Figure 2 in comparison with the results obtained in [13]. Considering that the arbitrary amplitude of oscillation in anode layer is irregular, the behavior of H^- ion current in Figure 2 is irregular as well. The only clear fact here is that at low magnetic field the distortion of distribution function takes minimal value and weekly impact on H^- ion current behavior at negative electric bias of metal hydride cathode.

CONCLUSION

Thus, the application of metal hydride cathode in the Penning type ion source allows for producing axial H^- ion flow along the external magnetic field. The production of negative ions takes place in the near-cathode region caused by the dissociative attachment of thermal electrons to vibrationally / rotationally excited hydrogen, desorbed from metal hydride. The large mean free path of the H^- ions ensures their unimpeded yield together with an axial flow of charged particles. The configuration of the discharge electrodes, electromagnetic filter and electrical field of the discharge ensures the registration of only the paraxial group of particles. For increasing the H^- current a negative potential on metal hydride cathode should be supplied. The plasma density by metal hydride cathode surely grows since the bias potential increase and T_e drops. The smaller T_e, the far electron reflects from the metal hydride cathode which is under negative bias potential. At low magnetic field, when the inflection of H^- current is observed under the bias potential of -40 V, the electron temperature takes smaller value (~15 eV), and electrons could be easily reflected reducing the value of H^- current. If T_e takes larger values, there is no H^- current inflection, or it is not so pronounced. The existence of electron groups with higher energies heated on anode layer instability sufficiently impacts the H^- current behavior and explains discrepancy between experiments and calculation results. The optimum bias potential for the effective extraction of H^- ions is -20V and higher, when plasma density reaches the maximum value to 2×10^9 cm^{-3}.

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REFERENCES

[1] K.W. Ehlers, B.F. Gavin, and E.L. Habbard, Nucl. Instrum. Methods, **22**, 87 (1963). https://doi.org/10.1016/0029-554X(63)90232-5
[2] K. Jimbo, K. Ehlers, K. Leung, and R. Pyle, Nucl. Inst. Methods, **248**(2-3), 282 (1986). https://doi.org/10.1016/0168-9002(86)91009-0
[3] G.I. Dimov, Review of Scientific Instruments, **67**, 3393 (1996). https://doi.org/10.1063/1.1147513
[4] G.I. Dimov, G.V. Roslyakov, Pribory i Tekhnika Ehksperimenta, **1**, 29 (1967), https://inis.iaea.org/search/searchsinglerecord.aspx?recordsFor=SingleRecord&RN=5144624 (in Russian)
[5] M. Bacal, R. McAdams, and B. Lepetit, in: *Second International Symposium on Negative Ions, Beams and Sources, AIP Conf. Proc.*, (vol. 1390, 2011), pp.13.
[6] T. Inoue, Y. Matsuda, Y. Ohara, Y. Okumura, M. Bacal, and P. Berlemont, Plasma Sources Sci. Technol. **1**, 75 (1992). https://doi.org/10.1088/0963-0252/1/2/001
[7] M.V. Lototsky, V.A. Yartys, Ye.V. Klochko, V.N. Borisko, R.I. Starovoitov, V.M. Azhazha, P.N. V'yugov, J. Alloys Compounds, **404-406**, 724 (2005). https://doi.org/10.1016/j.jallcom.2005.02.086
[8] Yu.F. Shmal'ko, Ye.V. Klochko, and N.V. Lototsky, Int. J. Hydrogen energy, **21**(11-12), 1057 (1996), https://doi.org/10.1016/S0360-3199(96)00040-7
[9] I. Sereda, A. Tseluyko, and N. Azarenkov, in: *Hydrides: Types, Bonds and Applications,* edited by Patrick C. Dam. (New York: Nova Science Publishers Inc, 2018), pp. 149-192.
[10] M. Bacal, and M. Wada, Applied Physics Reviews, **2**, 021305 (2015). https://doi.org/10.1063/1.4921298
[11] Ie.V. Borgun, D.L. Ryabchikov, I.N. Sereda, and A.F. Tseluyko, J. Phys. Conf. Ser. **514**, 012051 (2014), https://doi.org/10.1088/1742-6596/514/1/012051
[12] I. Sereda, A. Tseluyko, N. Azarenkov, D. Ryabchikov, and Ya. Hrechko, International Journal of Hydrogen Energy, **42**(34), 21866-21870 (2017). https://doi.org/10.1016/j.ijhydene.2017.07.129
[13] I. Sereda, A. Tseluyko, D. Ryabchikov, Ya. Hrechko, and N. Azarenkov, Vacuum. **162**, 163 (2019), https://doi.org/10.1016/j.vacuum.2019.01.046
[14] I. Sereda, D. Ryabchikov, Ya. Hrechko, Ie. Babenko, Problems of atomic science and technology. Series: Plasma Physics, **6**(26), 107 (2020), https://vant.kipt.kharkov.ua/ARTICLE/VANT_2020_6/article_2020_6_107.pdf
[15] J.R. Sanmartin, Phys. Fluids, **13**(1), 103 (1970), https://doi.org/10.1063/1.1692776
[16] A.A. Petrushenya, Ph.D. dissertation, V.N. Karazin Kharkiv National University, 2005.

ПАРАМЕТРИ ПЛАЗМИ РОЗРЯДУ ПЕННІНГА З НЕГАТИВНО-ЗМІЩЕННИМ МЕТАЛОГІДРИДНИМ КАТОДОМ ПРИ ПОЗДОВЖНІЙ ЕМІСІЇ ІОНІВ H^-

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Підвищення ефективності формування негативних іонів в об'ємному джерелі іонів на основі Пеннінговського джерела може бути здійснено за допомогою застосування металогідридного катода. Ізотопи водню зберігаються там у хімічно зв'язаному атомарному стані та десорбуються з металогідриду під впливом струму розряду. Коливально / обертально збуджені молекули H_2* утворюються шляхом рекомбінації Н-атомів на металевій поверхні, які потім можуть бути легко перетворені в іони H^- шляхом дисоціативного прилипання електронів без попереднього збудження молекули H_2 у плазмі. Зміна властивостей розряду відкриває шлях для спрощення конструкції джерела шляхом екстракції негативних іонів вздовж зовнішнього магнітного поля в порівнянні з традиційними об'ємними джерелами, де екстракція здійснюється перпендикулярно магнітному полю. Відокремлення негативних іонів від витягнутого в поздовжньому напрямку потоку заряджених частинок здійснювалося електромагнітним фільтром базуючись на чисельних розрахунках траєкторій заряджених частинок. Залежність температури електронів та щільності плазми від потенціалу зміщення проводилося методом зонда Ленгмюра. Вимірювання енергії електронів проводилося електростатичним аналізатором енергії. Було показано, що вихід іонів H^- залежить від потенціалу зміщення на металогідридному катоді і визначається температурою електронів плазми. Оцінка потенціалу зміщення від T_e проводилася за припущення розподілу електронів по Больцману поблизу катода. Наявність додаткових груп електронів з вищими енергіями спотворює поведінку струму H^-, але загалом результати експерименту добре узгоджуються з оцінкою, заснованою на фізиці, що лежить в основі розподілу Больцмана. Було виявлено оптимальне значення потенціалу зміщення металгідридного катода для ефективного вилучення іонів H^- на рівні -20 В та вище, коли щільність плазми досягає максимального значення до 2×10^9 см$^{-3}$.

Ключові слова: негативні іони, водень, джерело іонів типу Пеннінга, металогідрид