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EFFECT OF ARGON ADDITION ON H^- ION YIELD IN PENNING DISCHARGE WITH METAL HYDRIDE CATHODE IN DC REGIME

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The influence of argon addition to the hydrogen plasma in a Penning discharge with a metal hydride cathode on H^- ion generation is investigated experimentally. It was shown that argon addition weakly impacts on the H^- ion yield in contrast to the previous results due to the localization of efficient H^- production area within a narrow layer near the metal hydride cathode surface, so the rest of H^- ions formed in the plasma volume largely ineffective in contributing to the extracted current. Experiments also showed slight expansion of the electron distribution function towards higher energies in case of argon injection along with the suppression of low-energy electrons.

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INTRODUCTION

Negative hydrogen ions (H^-) continue to play a crucial role in various fields such as nuclear fusion [1], atomic physics and the production of medical radionuclides [2], primarily due to their high neutralization efficiency even at energies exceeding 100 keV per nucleon [1]. More recently, H^- ions have gained relevance in the study of dusty plasmas and in the fabrication of thin films and nanostructures [3]. These ions can be generated both within the plasma volume and on the surfaces in contact with the plasma.

In the plasma volume, the main pathway for H^- ion generation is dissociative attachment, where low-energy electrons attach to vibrationally excited hydrogen molecules $H_2(v)$. The efficiency of this process increases significantly with the vibrational quantum number (v), with the cross-section peaking around 3×10^{-16} cm^2 when $v > 5$ [4]. Surface-based H^- ion production typically employs the surface-plasma method, where cesium is deposited on the electrode to reduce the surface work function from 4…5 eV to as low as 1.2…2 eV [4]. Although volume production of negative ions generally yields lower ion densities compared to surface methods, volume sources are advantageous for being more compact, cost-effective, and cesium-free, making them environmentally safer.

An early effort to merge volume and surface production techniques utilized LaB_6 cathodes in cesium-free Penning discharges [4]. There have also been reports that thin tantalum films applied to discharge electrodes enhance H^- ion production [5]. Hence, the development of alternative electrode materials for cesium-free ion sources remains a critical research area.

Alternatively, stable getter alloys like ZrV hydrides show great potential due to their low equilibrium hydrogen pressure, high sorption/desorption rates, and significant thermal effects during hydrogen isotope interactions [6].

The ZrV alloy has been successfully utilized as a cathode material for H^- ion generation within a Penning discharge setup. In this configuration, negative hydrogen ions are primarily produced through dissociative electron attachment to vibrationally excited hydrogen molecules $H_2(v)$ released from the hydride cathode. This molecular hydrogen emission is triggered by the impact of ion currents from the plasma [6]. A key advantage lies in its ability to operate under ultra-low-pressure conditions (below 0.6 mPa), with hydrogen flow self-regulated by the discharge current, eliminating the need for external gas feeds. Subsequently, we explored several methods to enhance the source's productivity, including applying an electric bias to the cathodes [7] and implementing a pulsating discharge regime [8]. Another well-established method to enhance negative ion yield involves injecting argon into a hydrogen plasma. This technique has been shown to increase H^- ion production, primarily by influencing the electron energy distribution and boosting the population of low-energy electrons [9].

In this study, we present experimental results examining the impact of argon addition on H^- ion generation in a Penning discharge setup utilizing a metal-hydride cathode.

1. EXPERIMENTAL METHODS

The experimental investigations were conducted using a discharge cell in a Penning configuration, placed within a longitudinal magnetic field $B_0 = 0…0.1$ T. (Fig. 1). The electrode assembly was mounted inside a quartz cylinder. The cell featured a cylindrical anode (4) with a diameter of 5.6 cm and a length of 3 cm. The anode was centrally positioned between two cathodes spaced 1.5 cm apart.

The metal hydride cathode (1) was fabricated as a disk with a diameter of 2 cm and a thickness of 0.5 cm. These cathodes were pressed from a powder mixture composed of $Zr_{50}V_{50}H_x$ alloy, pre-saturated with hydrogen, and a copper binder. The initial hydrogen saturation of the material was approximately 860 cm^3 under standard conditions. The discharge was initiated by applying a positive potential to the anode, with an optional negative electrical bias applied to the metal hydride cathode. The copper cathode was under ground potential.

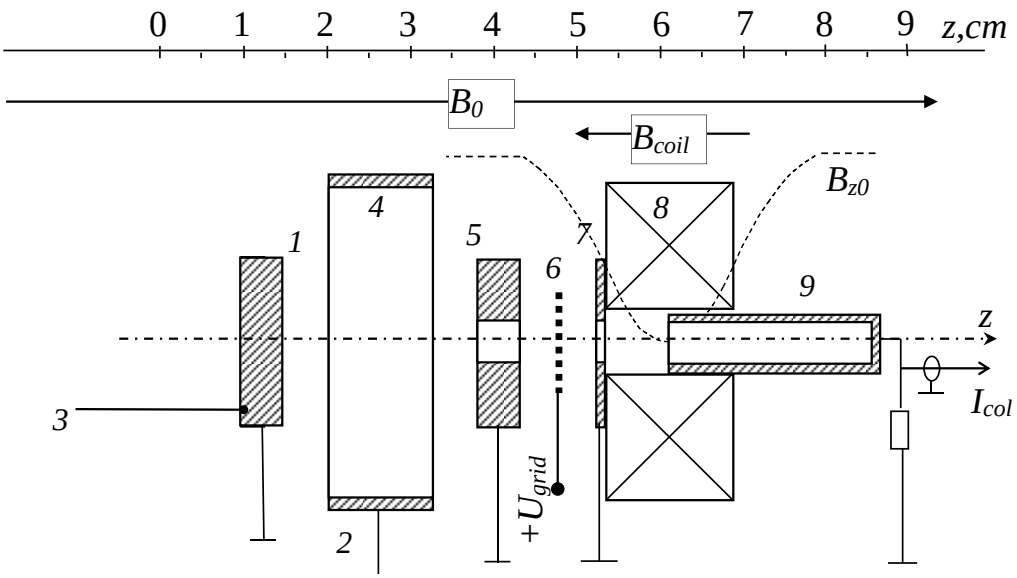

Fig. 1. The scheme of a Penning cell:
1 – metal hydride cathode; 2 – to anode power unit; 3 – thermocouple; 4 – anode; 5 – copper cathode with an aperture; 6 – reflecting grid U_{grid} = +1.6 kV; 7 – electrons collector; 8 – filter magnetic coil; 9 – H^- ion collector; B_0 – main axial Penning magnetic field (B_0 = 0…0.1 T); B_{coil} – reverse magnetic field of the filter

To maintain pressure stability during discharge operation, the metal hydride cathode was mounted in a water-cooled copper holder. The cooling system ensured temperature stabilization of the metal hydride below the threshold for thermal decomposition of the hydride phases. This allowed the desorption of activated hydrogen molecules to occur predominantly through ion-stimulated processes, concentrated in the near-cathode region.

Negatively charged particles, along with positive ions, exit the discharge region through an aperture in the cathode (5), moving along the external magnetic field. The separation of H^- ions is achieved using an electromagnetic filter, which comprises several components: a grid (6) that retards positive ions, a magnetic coil (8) that deflects electrons, an electron collector (7) for the diverted beam, and a collector (9) for the extracted axial H^- ion beam.

The residual pressure in vacuum chamber did not exceed 0.3 mPa. The working pressure during discharge was determined by the combined contribution of gas supplied from the ballon and hydrogen released from the metal hydride cathode.

2. RESULTS AND DISCUSSION

In a Penning cell, the spatial potential distribution for electrons along the axial direction forms a potential well, causing electrons to oscillate between reflective cathodes within an axially symmetric magnetic field. Radially, electrons are confined by the magnetic field, making extraction difficult both along and across magnetic field lines. Axial extraction is hindered by the cathode potential drop, while transverse extraction is obstructed by the magnetic field itself. However, at low pressures and high magnetic fields, electron currents can still pass through apertures in the cathode, especially in the central region, despite the potential drop.

Negative hydrogen ions primarily form via dissociative attachment, where low-energy electrons (1…2 eV) attach to vibrationally excited hydrogen molecules ($v > 5$) [4]. Efficient ion production requires both a reliable source of low-energy electrons and mechanisms to retain them longer in the interaction zone to increase attachment probability. In a Penning discharge, this region is near the cathode, where electrons lose energy due to their oscillatory motion.

Electron loss to the cathodes typically originates from the region adjacent to the anode sheath, where the space potential is minimal or zero. This low-potential zone usually forms under high discharge voltages and magnetic fields and is influenced by cell geometry and the type of gas used. Therefore, negative ions generated near the cathodes may be extracted in the longitudinal direction, accompanying the electron current through the cathode aperture.

The yield of H^- ions is enhanced when a negative electrical bias is applied to the metal hydride cathode. This bias creates a pushing effect that directs the generated ions along the axis. Figs. 2 and 3 illustrate the behavior of the negative ion current as a function of the applied negative electrical bias.

When pure hydrogen is used as the working gas, negative ions can exit the discharge even when both cathodes are grounded. However, in the case of argon injection, the current is predominantly composed of positive ions. This behavior can be attributed to two factors: the higher energy of positive ions, and the increased axial potential, which acts as a barrier preventing the negative ions from leaving the discharge. Nevertheless, the application of a negative electrical bias effectively pushes the negative ions out of the discharge region. A characteristic inflection in the H^- ion current curve, previously reported in [7], was attributed to electron depletion near the cathode. This depletion results from the reflection of electrons by the negative potential ($-U_{MH}$), which reduces the rate of dissociative electron attachment. However, secondary ion-electron emission from the surface of the metal hydride cathode mitigates

this depletion by providing an additional source of slow electrons in the cathode region – becoming more significant than the contribution from reflected plasma electrons.

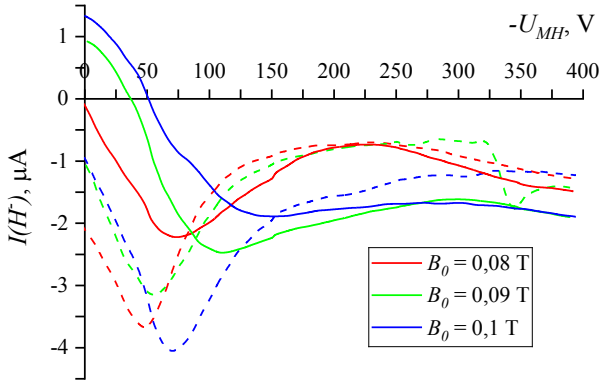

Fig. 2. H^- ion current via negative electrical bias of metal hydride cathode at P = 2.6 mPa; U_d = 4 kV. Solid curve – argon addition, dashed – pure hydrogen supply

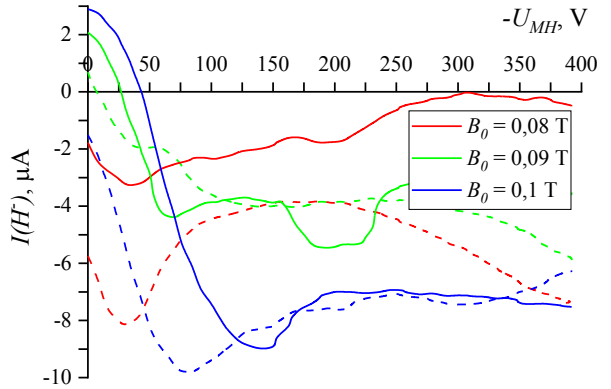

Fig. 3. H^- ion current via negative electrical bias of metal hydride cathode at P = 10 mPa; U_d = 4 kV. Solid curve – argon addition, dashed – pure hydrogen supply

The inflection point observed in the H^- ion current curve corresponds to the plasma electron temperature (T_e), which rises with external magnetic field B_0 [7]. Therefore, an alternative explanation for the current behavior could involve an elevated T_e or the presence of multiple electron populations with different temperatures.

In our experiments, the addition of argon did not lead to an increase in H^- ion yield (Fig. 4), contrary to the results reported in [9]. This discrepancy may be explained by the localization of the efficient H^- ion production zone, which appears to be concentrated in a narrow layer near the surface of the metal hydride cathode, where the maximum amount of vibrationally excited hydrogen molecules together with low energy electrons are concentrated. And the dissociative attachment process is considerably enhanced in this zone. As a result, a small amount of H^- ions formed in the plasma volume have minimal influence on the overall extracted current.

The maximum possible current of negative ions can be roughly estimated using an approximation based on the free outflow of ions from their formation region [10]. According to this model:

$$j_{H^-} = \Delta l e \frac{dn_{H^-}}{dt} = n_e n_{H_2(v)} (\sigma_- v_e) \Delta l e, \quad (1)$$

where $\Delta l = 6\times10^{-4}$ m is the width of the region providing of H^- outcoming [10], $v_e \approx 10^6$ m/s is the electron velocity, $\sigma_- \approx 10^{-20}$ m^2 is the cross-section of dissociative attachment, $n_{H2(v)} \approx 0.05\times2.6\times10^{18}$ m^{-3} is the concentration of excited molecules at p = 10 mPa (the coefficient 0.05 was taken from [10]), $n_e = 0.8\times10^{14}$ m^{-3} is the electron density measured in [11]. Substituting the following data into Eq. (1) gives 10 μA, which is almost identical to the experimental one (see Fig. 4) and proved the last statement about the narrow area of efficient negative ion production.

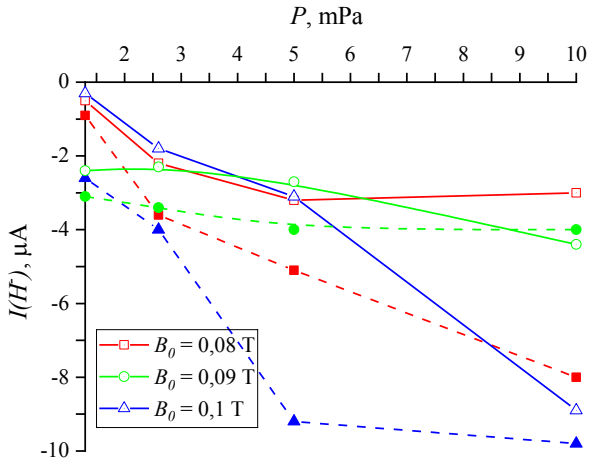

Fig. 4. H^- ion current via working pressure at U_d = 4 kV. Solid curve – argon addition, dashed – pure hydrogen supply

The distribution functions of axial electrons in the cell for hydrogen and argon injection are presented in Figs. 5 and 6.

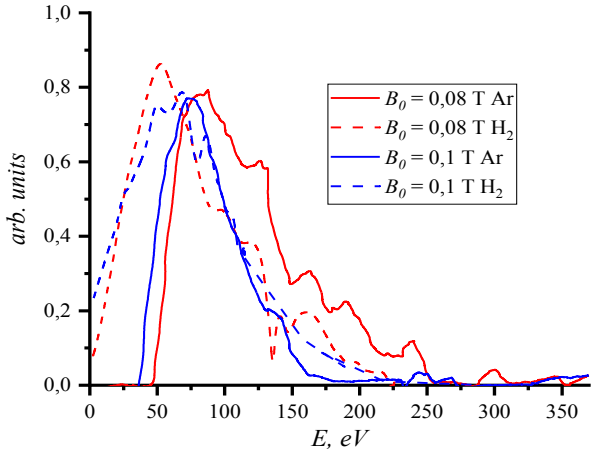

Fig. 5. Electron energy distribution function at P = 2.6 mPa; U_d = 4 kV

The results indicate that there is no substantial difference in the axial electron energy between hydrogen and argon injection. The only noteworthy feature is the suppression of low-energy electrons observed during argon injection, which is attributed to an increased axial potential that acts as a barrier, preventing electrons from reaching the cathode. This plays a decisive role in reducing the efficiency of negative ion formation, as indicated in Fig. 6.

The instability of the anode layer, where electrons gain additional energy, also plays an important role.

This may explain the presence of several less pronounced subgroups of electrons in addition to the main group with the highest intensity.

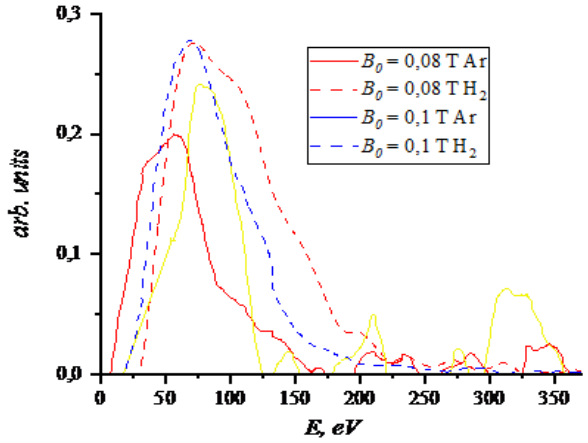

Fig. 6. Electron energy distribution function at P = 10 mPa; U_d = 4 kV

CONCLUSIONS

The hydrogen-saturated metal hydride cathode plays a crucial role in establishing the axial flux of H^- ions along the external magnetic field in a Penning cell. Negative ions are predominantly generated near the surface of the metal hydride that faces the plasma. This occurs through the dissociative attachment of thermal electrons to vibrationally excited hydrogen molecules released from the cathode.

Contrary to the earlier findings, the introduction of argon did not enhance the yield of H^- ions. This discrepancy can be attributed to the spatial confinement of efficient H^- ion production. The process appears to be limited to a thin region adjacent to the metal hydride surface, where vibrationally excited hydrogen molecules and low-energy electrons are most densely concentrated. Within this narrow zone, the dissociative attachment mechanism is significantly more effective. Consequently, H^- ions formed elsewhere in the plasma contribute minimally to the overall extracted ion current.

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ВПЛИВ ДОДАВАННЯ АРГОНУ НА ВИХІД ІОНІВ H^- У РОЗРЯДІ ПЕННІНГА З МЕТАЛОГІДРИДНИМ КАТОДОМ У РЕЖИМІ ПОСТІЙНОГО СТРУМУ

І.М. Середа, Я.О. Гречко, М.О. Азарєнков

Експериментально досліджено вплив додавання аргону до водневої плазми в розряді Пеннінга з металогідридним катодом на генерацію іонів H^-. Показано, що додавання аргону слабо впливає на вихід іонів H^-, на відміну від попередніх результатів, через локалізацію ефективної області утворення іонів у вузькому шарі поблизу поверхні металогідридного катода, тому решта іонів H^-, що утворюються в об'ємі плазми, значною мірою є неефективними для внеску у виведений струм. Експерименти також показали незначне розширення функції розподілу електронів у бік вищих енергій у разі інжекції аргону разом із придушенням електронів низької енергії.