EFFECT OF NEGATIVE SHIFT OF METALHYDRIDE CATHODE ON THE EMISSION OF H^- IONS FROM PENNING DISCHARGE

I. Sereda, A. Tseluyko, Ya. Hrechko
V.N. Karazin Kharkiv National University, Kharkiv, Ukraine
E-mail: igorsereda@karazin.ua

On the basis of numerical calculations, the experimental results obtained by the authors in the study of the source of negative hydrogen ions of the Penning type with a metal hydride cathode are explained. It was shown that the yield of negative ions depends on the potential at the metal hydride cathode and is determined by the temperature of the plasma electrons. The dependence of this potential on the electron temperature is calculated numerically to ensure the maximum current of negative ions.

PACS: 52.80.Sm

INTRODUCTION

The development of negative ion sources for high-power ion beams is a significant challenge for world science and are pursued in fusion research institutes worldwide, e.g., IPP Garching [1] (Germany), Consorzio RFX [2] (Padova, Italy), JAEA [3, 4] and NIFS [5] (Japan). This is due to the neutralization efficiency of negative hydrogen ions, that remains acceptable at higher kinetic energy and is nearly independent on beam energy above 100 keV/nucleon. Since high heating power (up to 33 MW) of atomic beams are required in fusion research, the need for producing intense negative ion beams becomes urgent. The main problem that arises here is the insufficient current of negative ion beams for heating the plasma in tokamaks up to the burning temperature. For instance, in ITER, negative ion current should be more than 40 A to produce intense neutral beam with reasonable pulse duration for effective plasma heating.

Another application area of negative ions beams is producing a number of medical radionuclides used in diagnosis and contact radiation therapy [6]. Beams of high energy (hundreds MeV) and small average current (from 20 μA to several A) are used here depending on the type of therapy [6]. All these force the intensive development of negative hydrogen ion sources, which are traditionally based on two types of processes: H^- formation in the plasma volume [7], and on surfaces [8]. In the first case negative ions are formed by dissociative attachment of slow electrons to vibrationally/ rotationally excited hydrogen molecules H_2^* and H^- current usually does not exceed tens mA at several kW of a discharge power in a pulse. In the second one – by the interaction between hydrogen plasma and caesiated surface facing the plasma. Using cesium sufficiently increases the intensity of negative ions, but complicates ion source operation and requires a careful stabilization of cesium injection and discharge parameters [8]. These sources are usually set separately from acceleration complexes to avoid operational risks associated with cesium flow. Maximum H^- current on the level of 2 A has been achieved there. On the contrary, volume sources possess much low intensity of H^- beam (tens mA), but they are more reliable, compact and environmentally friendly (cesium free). They could be inserted inside an acceleration complex that sufficiently reduces dimensions and cost of the equipment. Achieved low current of negative ions is caused by hydrogen pressure limitation in the source volume, because raising it more than 10^{-2} Torr increases the destruction processes of negative ions [7]. So, if one could increase the intensity of H^- beam from volume source, it would be the best way to produce high-power negative ion beams for fusion and accelerators.

In our previous work we obtained the H^- ion current of 10 μA at an input power of 6 W from Penning type ion source with metal-hydride cathode [12]. Maximum extracted current was observed at electrical bias of metal-hydride cathode. The purpose of the paper is to explain carried out results and to giveadvices on increasing the extracted current.

1. EXPERIMENTAL SETUP

Experimental results [12] were obtained on a device shown in Fig. 1. It shows a schematic illustration of the Penning type H^- ion source with metal hydride cathode and electromagnetic filter.

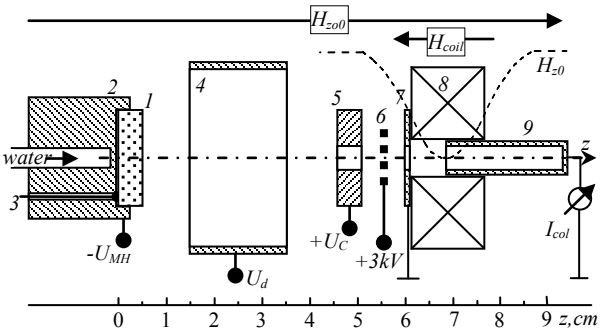

Fig. 1. The scheme of the Penning type H^- ion source: 1 – metal hydride cathode; 2 – cathode-holder with water-cool; 3 – thermocouple; 4 – anode; 5 – copper cathode-reflector with an aperture; 6 – reflecting grid; 7 – electrons collector; 8 – filter magnetic coil; 9 – H^- ion collector, H_{z0} – main axial Penning magnetic field (H_{z0} = 0…1000 Oe)

Hydrogen plasma was formed inside a tubular anode 4 and between a metal hydride cathode 1 and a copper cathode-reflector 5. Behind the central aperture in the cathode-reflector 5 an electromagnetic filter was set. It consists of a grid 6 for positive ions reflecting, a magnetic coil 8 for electrons diverting, a collector of diverted electrons 7 and a collector of extracted axial beam of H^- ions 9.

The metal hydride cathode 1 was produced from hydride-forming alloy $Zr_{50}V_{50}$. The quantity of hydrogen stored in the cathode is $\sim 9\times10^{-3}$ m^{-3} under normal at-

mospheric conditions. For pressure being stabilized, the metal hydride cathode had got a water-cool and its temperature was not exceed 20°C, that much lower than the temperature of thermal destruction of hydride phases. Therefore, H_2^* desorption was determined only by a discharge current and is provided mainly by ion-stimulated processes from the surface of metal hydride [11].

2. RESULTS AND DISCUSSION

Fig. 2 shows the experimental results [12] of the total collector current (I_{col}) of outgoing particles behavior depending on the value of metal hydride cathode bias. The growth of axial total current with an increase in negative bias on the metal hydride cathode (U_{MH}) may be attributed to the repulsive force to the electrons by the extra cathode potential.

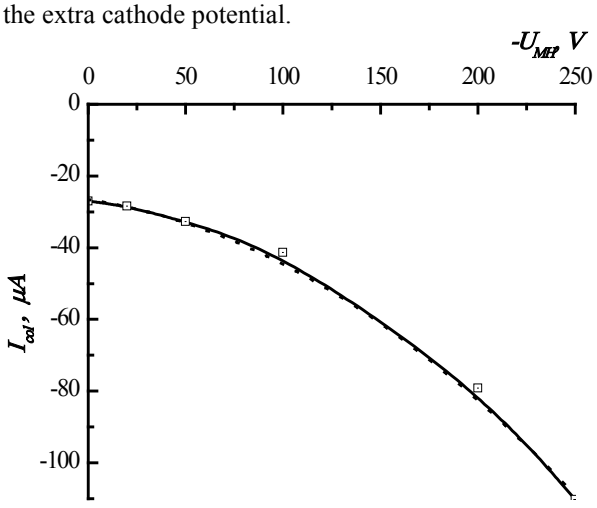

Fig. 2. The dependence of total current on negative electric bias on the metal hydride cathode at U_d = 4 kV, H_{z0} = 1000 Oe, p = 5×10^{-6} Torr

On the other hand, an increase in the H^- ion current (I_{H^-}) (Fig. 3) is observed only to the values of U_{MH} of -50 V.

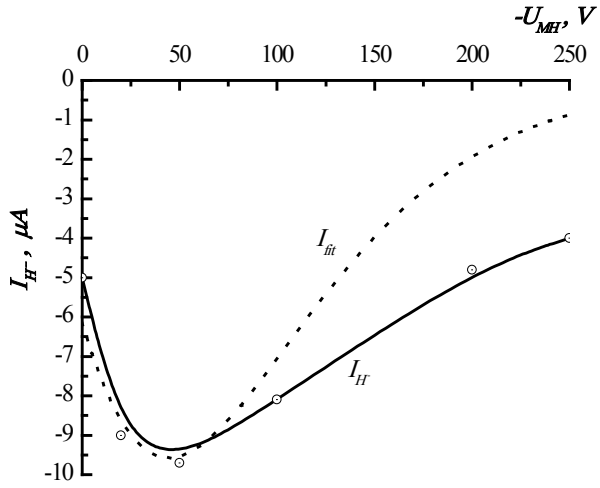

Fig. 3. The dependence of H^- ion current on negative electric bias on the metal hydride cathode at U_d = 4 kV, H_{z0} = 1000 Oe, p = 5×10^{-6} Torr

To explain this behavior, we assume that the electron concentration near the cathode is described by the Boltzmann distribution. Thus, the dependence of I_{H^-} current on U_{MH} can be approximately described as:

$$I_{H^-} = aI_0 e^{-b(|U_{MH}|)}, \qquad (1)$$

where I_0 is the current of outgoing charged particles, which we do not associate here with any particular physical process, but simply approximate it up to a constant i to fit the experimental curve I_{col} in Fig. 2.

$$I_{fit} = I_0 - i = -c\left(|U_{MH}| + U_0\right)^2. \qquad (2)$$

This additional term i is related to the initial current of negatively charged particles from the whole cell volume at $U_{MH} = 0$ and was not included in the equation (1) because it concerns only the cathode region.

Substituting the following values of $a = 3.85$, $b = 0.0237$, $c = 0.001$, $i = 25$, and $U_0 = 40$ one can be sure of the good match of calculations (dot curve) with experiment (solid curve) in Fig. 3 at $|U_{MH}| \le 50$ V. So, an increase in the H^- ion current is due to the growth of the total collector current.

The coincidence of the H^- yield maximum with the calculated curve is a result of the parameter a in Eq. (1) fit and does not help as physical interpretation. But the factor b is responsible for the inflection point of the curve I_{H^-} in Fig. 3 and depends on the temperature of plasma electrons (T_e). If the factor $b = \frac{e}{kTe}$, one could see, that T_e should be 42 eV, which is in good agreement with experiments carried out in [11]. Higher values of b correspond to a decrease in T_e and a shift of the inflection point towards smaller values of $|U_{MH}|$. One can see this dependence from Fig. 4, which is calculated from Eq. (2).

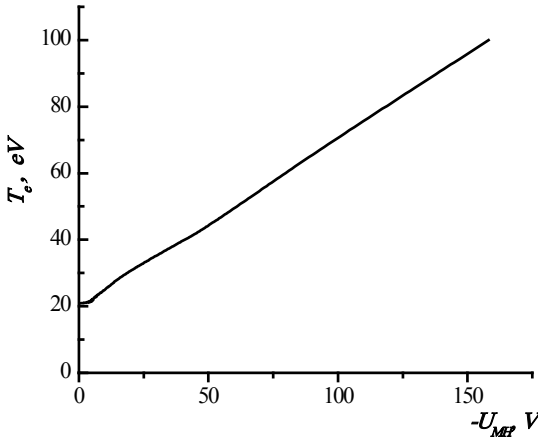

Fig. 4. The dependence of metal-hydride electric bias on temperature of plasma electrons

A further significant decline in the calculated I_{H^-} curve (dot curve) is obviously due to electrons depletion in the cathode region reducing the rate of the dissociative electron attachment. Since in our experiments the reduction of H^- current (solid line) is not so strong, as it predicted by Boltzmann distribution, we suppose that at least three more physical phenomena are responsible for the I_{H^-} curve behavior in Fig. 3. These are secondary ion-electron emission, which slows down the depletion of electrons, reduction in the efficiency of accelerated electron dissociative attachment to H_2^* molecules and the destructive impact of energetic electrons on H^- ions.

The dissociative attachment rate coefficients can be as high as 10^{-8} cm^3·s^{-1} at $T_e \approx 1…2$ eV when the molecules are in the highest vibrational states [7]. But an

increase in the electron temperature even to 5 eV leads to a decrease in the rate coefficients by 4 orders of magnitude. So, high bias supply on metal hydride U_{MH} can sufficiently reduce the efficiency of electron dissociative attachment to H_2^* molecules. Destructive impact of accelerated electrons on H^- ions appears only at high plasma density $n_e > 10^{17} m^{-3}$ [7] that much higher, than in our experiments ($n_e = 3\times10^{15}$ m^{-3}) [17]. Thus, the maximum H^- yield is apparently due to the effect of these competing processes.

CONCLUSIONS

Thus, the current of negative ions depends on the potential at the metal-hydride cathode and is determined by the temperature of the plasma electrons. To increase the H^- current one should supply a negative potential on metal hydride cathode, with sufficient values to deflect plasma electrons. In our experiments $T_e \approx 40$ eV, and the maximum value of H^- current is achieved by applying a negative bias to 50 V. The higher values of electric bias leads to decreasing in the efficiency of H^- ions formation due to electrons depletion in the cathode region and reduction in the dissociative attachment rate coefficients.

REFERENCES

1. P. Franzen, U. Fantz, D. Wünderlich, B. Heinemann, R. Riedl, W. Kraus, et al. Progress of the ELISE test facility: results of caesium operation with low RF power // *Nucl. Fusion*. 2015, v. 55, p. 053005.
2. V. Antoni, D. Aprile, M. Cavenago, G. Chitarin, N. Fonnesu, et al. Physics design of the injector source for ITER neutral beam injector (invited) // *Rev. Sci. Instr.* 2014, v. 85, p. 02B128.
3. M. Kashiwagi, N. Umeda, H. Tobari, A. Kojima, M. Yoshida, M. Taniguchi, et al. Development of negative ion extractor in the high-power and long-pulse negative ion source for fusion application // *Rev. Sci. Instr.* 2014, v. 85, p. 02B320.
4. N. Umeda, M. Kashiwagi, M. Taniguchi, H. Tobari, K. Watanabe, M. Dairaku, et al. Long-pulse beam acceleration of MeV-class H^- ion beams for ITER NB accelerator // *Rev. Sci. Instr*. 2014, v. 85, p. 02B304.
5. Y. Takeiri, K. Tsumori, M. Osakabe, K. Ikeda, K. Nagaoka, H. Nakano, et al. Development of intense hydrogen-negative-ion source for neutral beam injectors at NIFS // *AIP Conf. Proc*. 2013,v. 1515, p. 139.
6. Th. Stammbach, S. Adam, A. Mezger, P.A. Schmelzbach, P. Sigg. Cyclotron performance and new developments // *Proc. of the 8-th Europ. Part. Acc. Conf.* Paris, 2002, p. 159.
7. M. Bacal, G.W. Hamilton. H^- and D^- Production in Plasmas // *Phys. Rev. Lett.* 1979, v. 45, 1538.
8. V. Dudnikov. Thirty years of surface plasma sources for efficient negative ion production // *Rev. Sci. Instr.* 2002, v. 73, p. 992.
9. Yu.F. Shmal'ko, M.V. Lototsky, V.V. Solovey, V.A. Yartys', A.P. Strokach. Application of metal hydrides in hydrogen ion sources // *Z. Phys. Chem*. 1994, v. 183, p. 479.
10. V. Borgun, D.L. Ryabchikov, I.N. Sereda, A.F. Tseluyko. PIG charged particle source with hydrogen supply from a metal-hydride cathode // *J. Phys. Conf. Ser*. 2014, v. 514, p. 012051.
11. I. Sereda, A. Tseluyko, N. Azarenkov, D. Ryabchikov, 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.
12. I.N. Sereda, Ya.O. Hrechko, D.L. Ryabchikov, A.F. Tseluyko. Method of increasing the longitudinal current of H^- ions from PIG with metal hydride cathode // *Problems of Atomic Science and Technology. Series "Plasma Physics"*. 2019, № 7, p. 190-192.

Article received 17.05.2019

ВЛИЯНИЕ ОТРИЦАТЕЛЬНОГО СМЕЩЕНИЯ МЕТАЛЛОГИДРИДНОГО КАТОДА НА ЭМИССИЮ ИОНОВ H^- ИЗ РАЗРЯДА ПЕННИНГА

И. Середа, А. Целуйко, Я. Гречко

На основе численных расчетов объяснены экспериментальные результаты, полученные авторами при исследовании источника отрицательных ионов водорода типа Пеннинга с металлогидридным катодом. Показано, что выход отрицательных ионов зависит от потенциала на металлогидридном катоде и определяется температурой электронов плазмы. Зависимость этого потенциала от температуры электронов рассчитывается численно для обеспечения максимального тока отрицательных ионов.

ВПЛИВ ВІД'ЄМНОГО ЗСУВУ МЕТАЛОГІДРИДНОГО КАТОДА НА ЕМІСІЮ ІОНІВ H^- З РОЗРЯДУ ПЕННІНГА

І. Середа, О. Целуйко, Я. Гречко

На основі чисельних розрахунків пояснені експериментальні результати, які отримані авторами при дослідженні джерела негативних іонів водню типу Пеннінга з металогідридним катодом. Показано, що вихід негативних іонів залежить від потенціалу на металогідридному катоді і визначається температурою електронів плазми. Залежність цього потенціалу від температури електронів розраховується чисельно для забезпечення максимального струму негативних іонів.