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PIG charged particle source with hydrogen supply from a metal-hydride cathode

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Abstract. We present the results of an experimental investigation of a Penning-type charged-particles source with a metal-hydride cathode. The main characteristic of the experiment is internal hydrogen supply from the metal-hydride cathode under the conditions of ion-stimulated desorption; we studied its influence on the source’s emissive characteristics. An additional mode of source operation was observed involving axial electron emission; the decisive effect was revealed of the desorbed hydrogen on the axial electron emission. The ion energy distribution function was measured and its dependence on the external discharge parameters was determined.

1. Introduction

The use of metal-hydride cathodes (MH) based on Zr-V alloys in hydrogen plasma devices is of interest for modern science and technology. These materials are capable of storing hydrogen isotopes followed by desorption through heating with a uniform gas release in a wide range of working temperatures. In the case of using MH as a cathode material, desorption is caused by both heating and the discharge current. A distinctive characteristic of these compounds is a decrease of the ionization potential of desorbed hydrogen by 0.3 eV – 0.5 eV due to recombination of hydrogen atoms at the metal-hydride surface followed by desorption of the molecules in an excited and thermodynamically non-equilibrium state. This results in an increase of the hydrogen ionization cross-section by a factor of 1.3 to 1.5 as compared to common molecular hydrogen [1]. Additional advantages of using a MH-cathode are its compactness and safe hydrogen storage, as well as the possibility to realize local gas supply where necessary in the plasma device.

The early experiments with a Penning-type ion source using a MH-cathode revealed several particularities. One of them was an additional mode at a high discharge voltage and a low pressure [2]. In this mode, electrons were detected in an output axial flux from the cathode-reflector side (the side opposite to the MH-cathode), whereas an ion flux was only maintained on the MH-cathode side. The negative current increased with the discharge voltage and at some point exceeded the ion current. Another effect was the strong dependence of the hydrogen pressure on the MH-cathode temperature, which made it difficult to stabilize the discharge mode.

This is why the work reported here was devoted to solving the problem of stabilizing the pressure and revealing the factors responsible for the axial electron emission from the discharge.
2. Experimental setup

The experiments were carried out using a Penning-configuration discharge cell in a longitudinal magnetic field (figure 1). Three types of cathodes were used. The first one was an ordinary MH-cathode; the second type was the same MH-cathode with forced cooling, and the third one was a copper cathode with hydrogen supplied in order to simulate hydrogen desorption (figure 2).

![Figure 1](image1.png)

**Figure 1.** Schematic of the discharge cell:
1 – anode, 2 – MH-cathode, 3 – cathode holder, 4 – thermocouple, 5 – cathode reflector, 6 – collector.

The MH-cathode (2) was a disk with a diameter of 2 cm and a thickness of 0.5 cm. It was pressed from a powder mixture of Zr50V50Hx alloy and copper saturated with hydrogen. The initial saturation of the MH-cathode with hydrogen was about 900 cm³ under normal conditions. In order to stabilize the MH-cathode temperature, it could be placed in a water-cooled copper cathode holder (3) with a diameter of 2.5 cm. To ensure a good thermal contact of the MH-cathode with the cathode holder, its surface was covered by heat-conducting grease. The MH-cathode temperature was controlled by a thermocouple (4). The copper cathode reflector (5) had a diameter of 2 cm and a thickness of 0.5 cm with a 0.5-cm diameter hole at the center. A collector (6) was placed behind the hole with the purpose of measuring the axial charged-particles current. An electrostatic energy-analyzer was used to study the energy spectrum of the axial charged-particles flux (it could mounted instead of the collector). To separate the electrons or ions in the flux, a potential of +3 kV or −0.2 kV was applied.

The cylindrical anode had a diameter of 3.7 cm with a length of 3 cm. The cathode-anode distance was 1 cm. The entire electrode system was fixed inside a quartz cylinder to prevent the ignition of a parasitic discharge in the vacuum chamber. The cathode was kept at ground potential, while a positive potential was supplied to the anode.

In the simulation experiments, a copper cathode of special design was used (figure 2). Hydrogen was fed from a balloon through small holes on the cathode’s working surface, thus simulating hydrogen desorption. The ratio between the local and the additional fluxes of hydrogen, as well as the intensity of the external magnetic field, were the same as in [2], where an axial electrons output was registered in a discharge with a MH-cathode. Solid copper cathodes were used in the check experiments.

The residual pressure in the vacuum chamber did not exceed 5×10⁻⁶ Torr. The investigations were carried out at pressures within 10⁻⁶ Torr – 10⁻⁴ Torr. The working pressure was varied via the initial supply of hydrogen from a balloon into the vacuum chamber.

3. Results and discussion

Figure 3 shows typical dependences on the discharge voltage of the current through the collector placed behind the central hole in the cathode reflector for all cathode types used.

One can see three working modes taking place in succession as the discharge voltage is raised. The first one ($U_d \leq 1.6$ kV) with axial electrons output and the second one ($U_d \geq 1.6$ kV) with ions output have been known for a long time and have been observed irrespective of the electrode material and the working gas type [2]. The third mode ($U_d > 3$ kV) only arose when a MH-cathode saturated with
hydrogen was used. In the case of the MH-cathode without cooling, the third mode started at 3.0 – 3.5 kV (curve 1 in figure 3), and at approximately 3.0 kV or less (curve 2 in figure 3), in the case of the water-cooled MH-cathode. The higher voltage needed for the onset of the third mode in the case of the MH-cathode is obviously due to the ion contribution to the total output current. In the simulation experiment, the current through the collector diminished in the same way (curve 3 in figure 3). But if the current reduction in the case of MH-cathodes was caused by the electron contribution to the output flux, then measurements in the simulation experiments by the retarding field method showed that there were no electrons in the flux. Thus, no third mode took place in the simulation and in the check experiments. This fact is indicative of the decisive role played by desorbed hydrogen in the processes of axial electron emission.

Moving in an axial direction against an electric field, the electrons can take up energy from a HF-field in a HF-instability of a diocotron type. As was shown in [3], the transition to the third mode is followed by a step-wise increase of the HF-oscillation frequency and amplitude. Taking into account the well-known ratio for the frequency of diocotron oscillations \( f \sim E_r / H \) [4], the rise in the oscillation frequency is obviously due to the increase of the radial electric field \( E_r \) related to a redistribution of the axial \( E_z \) and radial \( E_r \) electric fields leading to an extension of \( E_r \) (the potential on the axis of the system drops). The distributions of the radial \( E_r \) and axial \( E_z \) electric fields are thus established in such a way that the primary ionization occurs in the anode layer. The comparison between the MH-cathode experiments and the simulation experiment reveals that the additional hydrogen flux from the cathode affects the axial electric field \( E_z \) distribution in the gap and the formation of the \( E_z \) gradient [3].

Thus, the decisive factor for the appearance of the axial electron flux emission is a HF-instability developed under the conditions of a non-equilibrium hydrogen desorption from the MH-cathode. The electron output from one side only is obviously caused by the \( E_z \) gradient that appears due to the drop in the potential barrier induced by the cathode-reflector [3]. When the hydrogen stored in the MH-cathode is exhausted, the third mode vanishes and the discharge behaves as in the case of ordinary cathodes. Thus, activated hydrogen desorbed from MH-cathode not only brings about the appearance of an axial electron flux, but also causes a redistribution of the electrical field in the gap.

However, another problem in implementing a working hydrogen source is the strong dependence of the desorbed hydrogen flux on the MH-cathode temperature, which makes it difficult to stabilize the discharge mode. As was shown in [5], forced MH-cathode cooling stabilizes the working discharge pressure and eliminates the hydrogen kick due to uncontrolled thermal decomposition of hydride phases. A low MH-cathode temperature (lower than that leading to decomposition of hydride phases) ensures hydrogen desorption by ion-stimulated processes only and would thus allow one to control the hydrogen desorption rate by controlling the discharge current. While in previous experiments with a MH-cathode in a Penning discharge, additional hydrogen was provided from an external source (a balloon), it is reasonable to investigate the behavior of a discharge that works only on hydrogen desorbed from the MH-cathode, thus eliminating the necessity of an external plasma-forming gas supply.

Figure 4 shows typical dependences of the collector current on the discharge voltage in the case of a water-cooled MH-cathode. Curve 1 registered at \( P = 5 \times 10^{-6} \) Torr corresponds to the initial residual pressure in the vacuum chamber without hydrogen supply with the discharge working only on desorbed
hydrogen. The other curves refer to an initial hydrogen supply in the vacuum chamber. One can see that there are no sufficient differences in the discharge behavior as the pressure is varied.

The source is characterized by an axial electron emission both when hydrogen is added from a balloon (curves 2 and 3) and when hydrogen is desorbed from the MH-cathode only (curve 1). Therefore, how hydrogen is supplied does not affect the discharge behavior. This gives one an opportunity to work with hydrogen desorbed from the MH-cathode only, with water-cooling of the MH cathode used to stabilize the pressure via its influence on the discharge current [4].

The analysis of the energy spectra of axially-moving charged particles revealed a number of particularities. Figure 5 shows the ion energy distribution function (IEDF) for all cathodes used in the discharge gap. Figure 5(a) refers to \(U_d = 2.5\) kV corresponding to the second discharge mode with an axial ion flux output; figure 5(b), to \(U_d = 3\) kV corresponding to the transition to the third mode (electrons in the output flux start appearing); and figure 5(c), to the third discharge mode (the output axial current has a negative sign).

One can see that, as the discharge undergoes a transition to the third mode, the distribution function shifts and widens towards the lower energy values. This is caused by the widening of the intensive ionization field from the anode layer to the discharge axis at lower values of the space potential. This is observed most distinctly when a MH-cathode without water-cooling is used (curve 3), when intensive hydrogen desorption in a non-equilibrium state occurs under the conditions of thermal hydride phases decomposition brought about by the discharge current.

The intensive desorbed hydrogen flux leads to intensification of the ionization by the MH-cathode so that and ions are detected generated along the low-potential. Therefore, the widening of the IEDF is caused by hydrogen desorption followed by ionization intensification along the axis. In the case of hydrogen desorption due only to ion-stimulated processes (curve 4), the situation is the same but the flux of desorbed hydrogen is is reduced and the number of ions generated along the axis drops.

The differences of the simulation experiments results (curve 2) as compared with the other cases studied are due to the constant ratio between the local and the additional flux of hydrogen in the whole range of discharge voltages. The addition balloon hydrogen flux was chosen the same as in [2], when axial electrons output was registered corresponding to \(U_d \approx 3.5\) kV. At lower \(U_d\), the desorbed hydrogen flux was considerably lower than in the simulation experiment.
The studies on the electron energy distribution function showed that the average electron energy was about 20 eV and did not depend substantially on the hydrogen desorption.

4. Conclusions
The possibility is shown of a discharge to operate with hydrogen desorbed from a MH-cathode due to ion-stimulated processes only. This hydrogen does not influence substantially the discharge emissive characteristics, which gives one the opportunity to use data reported in previous experiments.

The decisive factor determining the axial electron flux emission is a HF-instability developing under the conditions of non-equilibrium hydrogen desorption from the MH-cathode. The axial electron current from one side only is due to the additional neutral hydrogen flux from the cathode side. When the hydrogen stored in the MH-cathode is exhausted, the third mode of operation disappears and the discharge behaves as in the case of copper cathodes.

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