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# Negative ion surface-plasma source development for fusion in Novosibirsk

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**Overview article**

**Résumé.** — Cet article présente une synthèse des travaux effectués à l'Institut de Physique Nucléaire de Novosibirsk sur les sources plasma-surface d'ions négatifs. Il contient la description des performances du planatron, une source qui a produit en 1972 une densité de courant d'ions $H^-$ de 0,75 A/cm$^2$ en hydrogène pur. Les résultats des études de cette source dans sa version 1987, désignée semi-planatron, sont aussi présentés. Les expériences effectuées en ajoutant du césium à la décharge d'hydrogène ont conduit à l'élaboration d'un modèle théorique des sources plasma-surface à cathode à faible travail de sortie. L'optimisation de la production des ions négatifs a permis d'augmenter l'intensité du faisceau à 11 A.

**Abstract.** — This paper is a review of research effected on negative ion plasma-surface sources in the Institute of Nuclear Physics in Novosibirsk. It contains the description of the performances of the planatron, a source which produced in 1972 in pure hydrogen a density of $H^-$ ion current of 0.75 A/cm$^2$. The results of recent studies of this source, in the 1987 version, designated as semi-planatron, are also presented. The experiments effected by adding cesium to the hydrogen discharge lead to a theoretical model of the surface-plasma sources with low work function cathode. The optimization of the negative ion production led to the increase of the beam intensity to 11 A.

The charge exchange method for the fast particles injection is widely used in magnetic plasma confinement systems and in accelerators. In designing the high-energy atom injectors with an energy higher than 100 keV per nucleon it seems to be more efficient to use the neutralization of accelerated $H^-$ ions which easily lose an additional electron in charge exchange target collisions and have a high, close to unity, coefficient of conversion to atoms in a broad range of particle energies. Negative ion sources for the charge exchange injection have been under active study in recent decade.

The work on $H^-$ ion sources at the INP have been under way for about 20-years due to the development of the charge exchange injection of protons to accelerators [1]. Among the sources designed at the INP are the plasma Ehlers-type sources of $H^-$ ions with a pulsed current up to 8 mA as well as the 15 mA charge exchange sources and later on the 100 mA ones. However, the characteristics of these sources did not allow to employ the advantages of charge exchange injection and hindered its efficient application for accelerators.

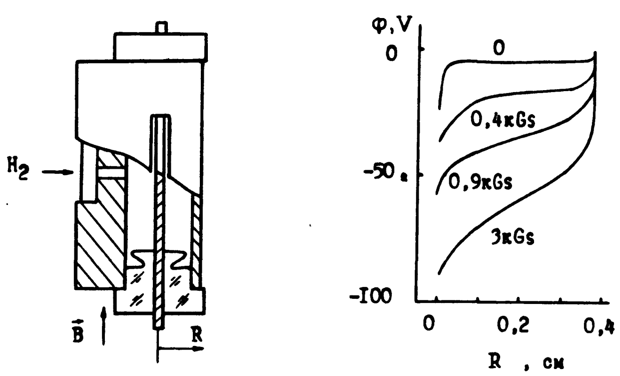
The situation on the production of $H^-$ ion beams has drastically altered just after a new surface-plasma mechanism of the negative ion production in gas discharges was discovered and experimentally studied [2, 3]. This mechanism served as a basis in designing a number of Surface-Plasma Sources (SPS) of negative ions for accelerators. In addition, it seemed to be quite effective to start designing high-power sources of negative ions for the injectors of magnetic high-temperature plasma traps. Multiaperture surface-plasma emitters of negative ions with a beam intensity of 10 A and higher and quasi-steady-state SPS with an about 1 A beam of hydrogen negative ions were studied and developed at the INP in 1977-1986.

A number of the USA Laboratories (Brookhaven, Berkeley, Los Alamos, Oak Ridge, Fermi) and some of the U.S.S.R., Europe and Japan have much contributed to the design of SPS as well. The results were presented in the Proceedings of the International Conferences on negative ion production and neutralization [4-7] and in many other publications.

In this paper we confine ourselves to the results obtained at the INP. Some of them have already been discussed in review papers [8-10].

**Pure hydrogen gas discharge systems of NI generation.**

The INP studies on gas discharge sources of negative ions with the production of negative ions in the plasma volume and its further extraction from a Gas-Discharge Chamber (GDC) were started early in the 60-s. An Ehlers-type [12] source with a Penning-geometry of the GDC was designed and the pulsed 8 mA beam of negative hydrogen ions was produced. Magnetron discharge schemes have been studied in order to obtain suitable for $H^-$ production discharge electric field and electron energy distributions. The experiments were performed with a magnetron source having a cylindrical GDC and a thin wire cathode aligned with a magnetic field up to 3 kG (Fig. 1a). These experiments have revealed that the distribution of the plasma potential along the radius of the discharge channel (Fig. 1b) with high anode potential drop encourages increased yield of $H^-$ ions from the plasma to the extraction region. A cylindrically-shaped magnetron produces a pulsed, about 1 ms, beam of $H^-$ ions at a current up to 7 mA through an emission slit of $10 \times 1$ mm$^2$ area. The optimal for $H^-$ production hydrogen neutral density was about $7 \times 10^{16}$ cm$^{-3}$.




a) b)

Fig. 1. — Cross section of a cylindrically shaped magnetron (a) and electric field distribution (b) in the discharge for various magnetic field values.

To achieve a more efficient utilization of the electrons in the discharge and to reduce electron transport from the plasma to the anode, a device having a planar spool cathode — « the planotron » — has been designed (Fig. 2). The side protrusions

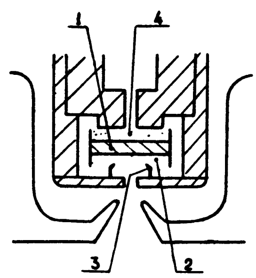



Fig. 2. — Early planotron version.

of the cathode limited the transport of primary and secondary electrons to the anode, while the oscillations of the electrons along the magnetic field lines were provided in the space between these protrusions. Special anode protrusions with variable shape were mounted to create a low density and low temperature near-anode plasma in the region adjacent to the emission slit (Fig. 2).

Negative ions were extracted through the emission slit being perpendicular to the magnetic field, and its width (along the magnetic field) was ranged within 0.1-3 mm. With such orientation of the slit, the flux of accompanying electrons, being extracted together with NI is reduced by a factor of ten due to the electron damping on the side walls of the emission slit. So, in the cylindrically-shaped magnetron with longitudinal, $10 \times 1$ mm$^2$ emission slit and $H^-$ yield of 7 mA the flux of accompanying electrons was 250 mA, while the first planotron with $\Gamma$-shaped anode protrusions and $0.5 \times 10$ mm$^2$ transverse emission slit delivered $H^-$ output of 4.5 mA with a 16 mA flux of accompanying electrons.

The shaped magnet pole tips produced non-uniform magnetic field in NI-extraction area (Fig. 2), so with the negative voltage applied to the GDC body the accompanying and secondary electrons could not oscillate in the extraction gap and they were immediately damped to a grounded extractor or the magnet pole tips. The application of a non-uniform magnetic field hindering the electrons to accumulate enabled one to improve markedly the electric strength of the extraction gap and to carry out the studies on $H^-$ ion extraction for different geometries of the cathode and near-anode regions in a broad range of magnetic fields, hydrogen densities and sizes of the emission slits.

Some of the obtained results and the data on the production of a 22 mA $H^-$ beam with an emission current density up to 270 mA cm$^{-2}$ are given in [13]. The optimal geometry of the near-anode (height and distance between the anode protrusions) was specified and the energy spectra of the produced $H^-$ beams were analysed. The $H^-$ ions formed due to the charge exchange of fast protons on the cathode surface were detected. However, the bulk of $H^-$ ions had an energy corresponding to the anode potential. High emission density of $H^-$ indicated the presence of an intense channel of $H^-$ formation in the plasma volume [14]. The non-single-value nature of the mechanism of intense $H^-$ ion generation in a Pure Hydrogen (PH) mode of planotron-like discharges contributes to the importance of the experimental information and, consequently, most of the new H-Cs surface-plasma sources of $H^-$ ions, designed at the INP, were tested and examined in this PH regime too. So, at the end of 1972, an improved design of the planotron was used in the experiments on $H^-$ extraction from a PH discharge with a view to compare it with the H-Cs regime [2, 14]. It was noticed that as the thickness of the plasma layer of the discharge reduces to 0.5 mm and the cathode is thicker and more massive (with lower operating temperature) the $H^-$ ion yield increased in a broader range of discharge currents. From the $0.4 \times 5\ mm^2$ emission slit the $H^-$ ion beam with 15 mA intensity and with an emission current density up to $0.75\ A/cm^2$ at a discharge current of 150 A was generated ([2.3], the dashed line in Fig. 2 ; [14], p. 2573). The $H^-$ beam increased to 32 mA, when the width of the emission slit was made equal to 1 mm (5 mm length), while the emission current density reduced to $0.64\ A/cm^2$ due to NI destruction on the increased « pillow » of gas escaping through the emission slit. If the planar central section of the cathode was removed from a planotron, the total current of $H^-$ ions decreased. However, due to the vicinity of the « side » cathodes to the emission slit, the emission current density of $H^-$ ions achieved was 0.4-0.5 $A/cm^2$ in such a modified (Penning) geometry.

At that time an emission current density as high as $0.75\ A/cm^2$ was difficult to interpret in terms of ideas and data on elementary processes in a plasma even under the most optimistic assumption on the parameters of the planotron discharge.

The maximum yield of $H^-$ ions from the sources with a planotron and modified-Penning geometry in the PH mode was achieved at the hydrogen molecule density equal to $2 \times 10^{16}\ cm^{-3}$. This value was three times lower as compared with that in a cylindrically shaped magnetron and in the thin-cathode source [13]. This fact indicates a high rate of $H^-$ ion production at low densities of $H_2$ and the suppression of this mechanism (or an enhanced channel of $H^-$ destruction) with adding $H_2$ to discharge.

In the late 70 s, an interest in PH systems for $H^-$ ion generation was stimulated by experimental confirmation of Demkov' prediction (1965) on manyfold increase in the NI production cross-section, when vibrationally-excited molecules dissociate by electron impact [17] :

$$e + H_2(\nu'') \rightarrow H_2^- \rightarrow H^- + H .$$

Several schemes of $H^-$ ion production in hydrogen discharges *via* the vibrationally-excited hydrogen molecules have been proposed and various designs of $H^-$ sources were developed, including those with 1.2 A negative ion output in 0.2 s pulse [7].

At the same time, the emission current density of $H^-$ ions, achieved in these large $H^-$ ion generators was several times lower than that obtained at the PH modes of SPS in 1972 [2]. Additional study on $H^-$ ion production in PH mode of multiaperture SPS with large emission surface was performed in 1987 [18]. The NI were extracted by a multi-slit extractor through the systems of slits or round holes in the anode cover (Fig. 3). The $H^-$ emission was examined in the case of short (0.8 ÷ 3 ms) and long (up to 0.6 s) pulses. The transverse magnetic field 1 ÷ 3 kG separated the beams of extracted $H^-$ ions from heavy impurity ions $O^-$, $OH^-$, $Mo^-$ and from the electrons.

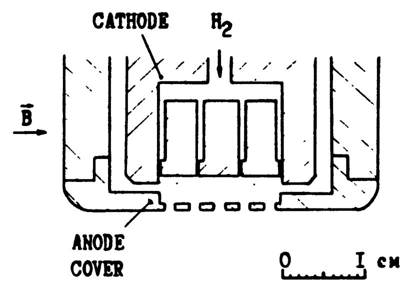



Fig. 3. — The multi-aperture semiplanotron.

A high-current (10 ÷ 750 A) glow discharge was maintained at average hydrogen density in the extended narrow gap of larger than $6 \times 10^{15}\ cm^{-3}$. The discharge voltage was 500 ÷ 700 V and decreased down to 300-400 V after conditioning the electrodes. Figure 4 shows the $H^-$ ion yield from such a multi-aperture semiplanotron in the PH mode *vs.* the discharge current. In the 50-200 A range of discharge currents this yield grew linearly. At 600 A discharge current the intensity of the produced beam of $H^-$ ions was over 1 A and the average density attained $0.5\ A/cm^2$ in 5 emission slits of

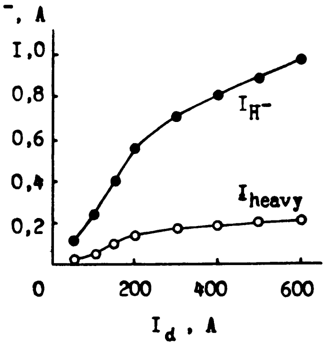



Fig. 4. — $H^-$ yield *vs.* discharge current of semiplanotron PH mode.

$0.8 \times 52\ mm^2$ area. The total extracted current was 1.2 A, but 17 % of the beam were heavy impurity ions.

Beam extraction through 5 round emission holes of 0.72 mm diam has shown that the emission current density of $H^-$ ions, extracted in the pulsed mode of the source was up to 1.1 $A/cm^2$. The tests of this source in the long-pulse mode have indicated that despite the electrodes were heated up to 800 °C, the uniform high-current glow discharge has the same characteristics and $H^-$ capability up to pulse duration 0.6 s and discharge current of 90 A. Further progress was limited by the used power supply systems.

The beam extraction through 90 emission holes of 0.72 mm diam each has shown the linear dependence of $H^-$ output *vs.* discharge current in long-pulsed mode. The $H^-$ yield achieved 0.15 A in the beginning of the pulse, to the end of 0.6 s, 90 A pulse $H^-$ output decreased down to 0.1 A due to overheating of non-cooled electrodes.

The $H^-$ yield has its maximal value at the minimal hydrogen density of $6 \times 10^{15}\ cm^{-3}$, considerably lower than that in the source [2, 11]. Some of non-typical for « volume » sources features were observed [18]. For example, the $H^-$ yield reached its maximal value at optimal electrode temperature (750 K-cathode, 600 K-anode). The $H^-$ yield extracted from « honeycomb » cathode source (Figs. 10, 11) was strongly dependent on relative position of cathode spherical indentations and emission holes even in PH mode. So, the $H^-$ output through the emission hole at geometrical focus of indentation was 5-6 times higher than that obtained through the hole located far from geometrical focus. The results indicate essential contribution of surface processes into $H^-$ production at PH modes of SPS. Under pure conditions the positive ion direct conversion into $H^-$ ions on the molybdenum surface may consist of $I^-/I^+ \sim 1\ \%$ at molecular ion energies 300-400 eV. In this case the main part of reflected and desorbed particles are neutrals, it can be converted to $H^-$ in the volume and on the walls of emission holes. Fast neutrals, like protons, may effectively pump vibrational excitation of molecules and increase $H^-$ production rate in the discharge volume.

The electrode surface can also be an intense source of vibrationally-excited molecules due to high level of molecular ion flux to hydrogen saturated cathode selvage [19]. These fast excited molecules as well as molecule-produced $H^-$ ions can easily penetrate to the extraction area of GDC through a thin plasma layer without destruction.

As a whole one may account that in PH modes of SPS takes place an intense $H^-$ production *via* interaction of plasma particles with electrodes surface.

**Surface-plasma sources with H-Cs discharges.**

In 1969-70s we have tried to increase the $H^-$ output from gas-discharge sources by adding to GDC the hydrogen-containing molecules with the dissociation energies lower than for $H_2$ molecule or ion-binded molecules lower than for $H_2$, thresholds of $H^-$ formation. For example, molecules of $B_2H_6$, LiH, Cs-BH were tested. Simultaneously studies were performed on the secondary-emission method of $H^-$ ion production. The results have shown that the coefficient of secondary emission of $H^-$ ions increased up to 0.8 at $H^-$ emission current density up to 10 $mA/cm^2$ when the surface of the metals was bombarded by Cs atoms in the presence of hydrogen. Cs was also introduced in gas-discharge sources and it was noticed in 1971 that a small amount of Cs-containing substances in the GDC of the planotron (Fig. 2) increased $H^-$ yield from 4.5 mA to 15 mA. Next experiments showed an increase in the $H^-$ yield with decreasing the thickness of the plasma layer between the cathode and the emission hole and with reducing the hydrogen density, as well as a saturation of this yield with the plasma density growth. All this has allowed one to make the assumption that the intense fluxes of $H^-$ ions from the plasma were caused by the emission of these ions from the cathode surface to the discharge and by easy transport of these ions to emission slit without destruction.

Based on this version the optimization of geometry and the discharge mode resulted in increasing the emission current density of $H^-$ ions up to 3.7 $A/cm^2$ and the total $H^-$ current up to hundreds of mA [2]. At that time these values were extremely high for gas-discharge sources. The studies of the energy spectra of ions extracted from the source, the analysis of dependencies of the NI yield on the material of the cathode surface, its profile and on the distance to the emission slit, as well as the experiments with discharge in helium containing hydrogen have furnished the following concept of the surface-plasma formation of negative ions in gas discharges [8, 15].

This mechanism is realizable in gas discharges and plasma devices if the required sequence of processes occur properly (Fig. 3).

A dense plasma layer is generated near the electrode surface. A voltage of several hundreds of V is applied to the gap between the plasma and the electrode, which accelerates the positive plasma ions and provides an intense bombardment of the electrode surface. A dynamically sustained structure of implanted and adsorbed atoms is created in the selvage layer of the electrode. Such an electrode « converts » effectively the incident flux to the inverse flux of fast reflected and sputtered from the selvage particles.

The high exit velocity of the inverse flux particles ($1\text{-}10^2$ eV) contributes to a significant increase in the escaping flux negative ionization, even for the atoms with electron affinity lower than the surface work function [21]. Fast particles « export » an electron at its own affinity level due to kinetic energy acquired upon bombardment. Introducing into a plasma (or directly through the electrode pores) negative ion emission catalysts — the vapours of alkaline metals [22] reduces the surface work function. As a result, the NI formation probability approaches unity at work function of 1.5 eV and electron affinity of 0.75 eV [21] and makes it possible to produce intense fluxes of « hard-to-produce » low electron affinity negative ions ($H^-$, $Li^-$, ...) by surface-plasma method.

**General properties of the SPS with a decreased work function of electrodes.**

A knowledge of the dominant surface-plasma mechanism of NI generation in discharges with a decreased work function of electrodes has enabled one a deliberate designing of the SPS with the required characteristics. Various modifications of the SPS have been designed and studied. In the planotron, semi-planotron, Penning-geometry and multi-aperture SPS [23, 24, 26] the NI emitter is the cathode of a high-current glow discharge. In the SPS with an independent plasma production [8, 25] the gas-discharge plasma is transported to the surface of a specially prepared NI emitter with the potential negative with respect to the plasma.

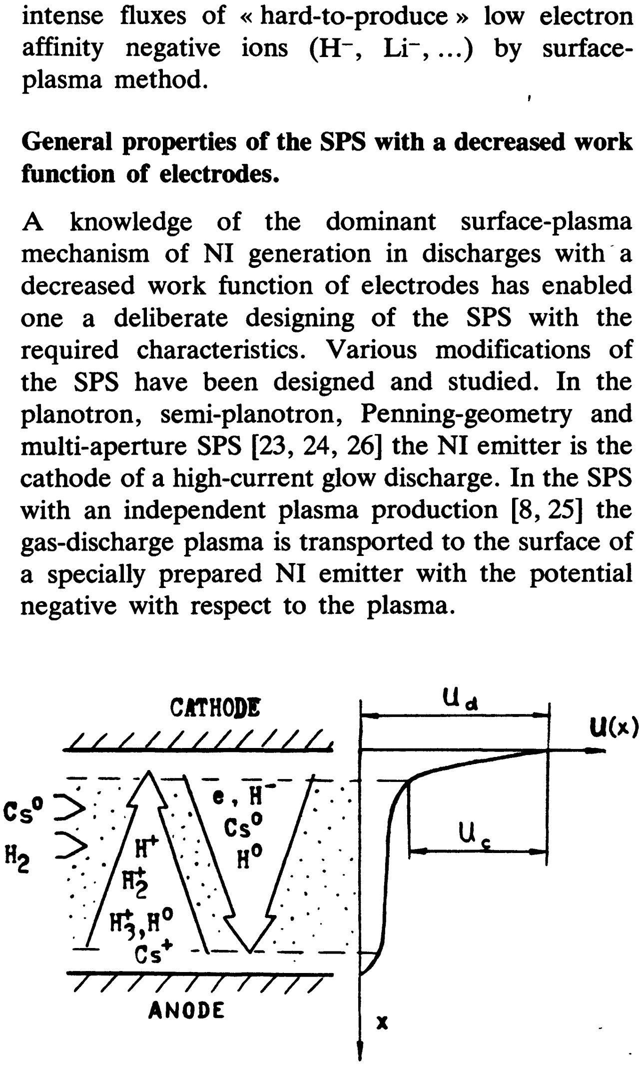



Fig. 5. — Schematic diagram of the surface-plasma mechanism ; on the right-electric field distribution in the inter-electrode gap.

The work function of SPS emitters is predominantly reduced by adding cesium vapour from an external evaporator through the holes or pores to the emitter surface. Several operational modes of SPS, different in the discharge voltage, rate of $H^-$ ion production, level of discharge fluctuations can be obtained by adding Cs to GDC. The effect of emitter surface « activation » has been noticed and analysed. Its essence is a considerable increase of secondary electron and NI emission coefficients from electrodes exposed to plasma [27]. A similar activated structure contained the implanted hydrogen and cesium is supported on the cathodes of SPS during H-Cs discharge. It provides low surface work function of about 1.3-1.4 eV. Fast ionization of Cs in the near-electrode plasma and its return to the emitter by an electric discharge field provides keeping the optimal Cs coverage of the emitter in the intense bombardment conditions. Direct measurements of the Cs ion and atom fluxes through diagnostic holes of SPS have indicated that the cathode Cs ion flux achieves 1-10 % of the total ion current to the cathode, while only a small amount of Cs escapes through the emission slit during the discharge [28]. SPS emitters are usually manufactured of very pure molybdenum. Due to favourable mass ratio it « traps » the Cs ions from the incident flux and ensures a steady low work function Cs coverage in a broad range of ion doses and bombardment energies [8, 29].

NI generation proves to be most effective in the modes when the plasma is enriched by the $H_2^+$ and $H_3^+$ molecular ions [8]. Molecular ions dissociate at the collision with the surface, so a double or triple amount of particles are involved in further motion in the near-surface layer. Consequently, the coefficients of reflection, absorbate sputtering and NI emission are increased.

The negative ionization degree of the particles, leaving the cesiated molybdenum surface $I_{H^-}/I_{exit}$ has rather high value 0.2-0.7 in a broad range of the exit particles velocities $10^6\text{-}10^7$ cm/s [21, 30, 31]. In the intense ion bombardment conditions the dynamic cathode « activation » supports high value of NI secondary emission coefficient $I_{H^-}/I_+ = 0.5 - 0.8$ in terms of incident positive ion. « Deliberate » optimization of the NI production conditions have permitted us to increase the SPS $H^-$ beam intensity up to 0.9 A [3] and later on to 11 A [24]. There are several groups of $H^-$ ions in the energy spectrum of emitted NI [14]. The faster one (III in Fig. 6) is the NI component of reflected flux, post-accelerated by discharge voltage. The « reflected » group is usually small due to large angular spread and low transmission [33]. This group is essential for discharges with non-activated electrodes. With the SPS activated electrodes, the extracted $H^-$ beam contains mainly the $H^-$ ions formed due to sputtering of hydrogen from the emitter selvage (II in Fig. 6) and the slow $H^-$ ions, produced by resonant charge-exchange in near-anode area or at the emission slit walls (I in Fig. 6).

In SPS with the planotron and Penning geometry, the maximum density of hydrogen molecules, necessary to sustain an independent discharge in an

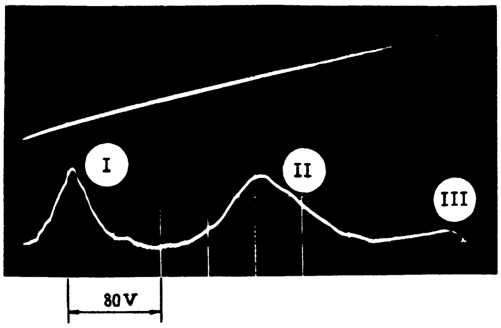



Fig. 6. — The energy spectra of planotron extracted $H^-$ ions (lower trace). Upper trace-scanning voltage of 90° electrostatic analyser.

extended narrow inter-electrode gap was $1-3\times10^{15}\ cm^{-3}$ and depended of the magnitude of the external field and on the GDC geometry. The effect of molecular hydrogen « blocking » in a GDC has been noticed for SPS with a dense ($n_e \gtrsim 10^{13}\ cm^{-3}$) plasma. Due to both the pumping and « blocking » actions of the plasma stream the molecular hydrogen component from SPS reduced by 20-90 % as compared with its former value (Fig. 7). In particular, approximately 30 % of hydrogen particles, escaped from the SPS discharge are negative ions [34].

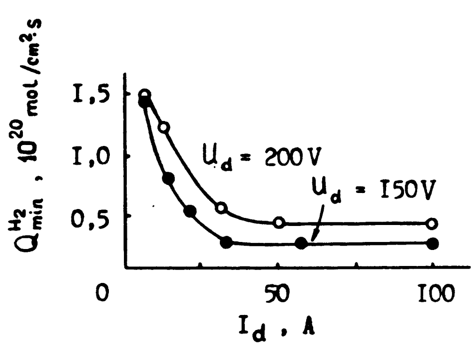



Fig. 7. — A decrease in gas flow from the semiplanotron emission slit *vs*. discharge current in two modes of discharge voltage.

Due to Cs « blocking » in the near-cathode region the escape of Cs from the SPS is small, thereby it is easy to provide a good electric strength of $H^-$ extraction and acceleration systems. Under optimal conditions the Cs escape of Planotron SPS has relatively low value $3\times10^{-3}$ g/A.h without causing any obstacles to high voltage operation of $H^-$ injectors [35].

**SPS with independent negative-ion emitter.**

The use of an external plasma injection to an emitter with independently-controlled negative bias with respect to plasma potential was found to be promising for SPS as early as 1973 [15, p. 74]. In 1976-77 the SPS experiment was performed with independent plasma production and with an independent emitter (IE) [8]. A Penning H-Cs discharge with hollow cathodes were used (Fig. 8), which was itself an effective surface-plasma emitter of $H^-$ ions and made it possible to produce NI beams with emission current density up to 2 A/cm². Applying on IE negative potential increased the emission current density of $H^-$ ions up to 5.4 A/cm² at optimal conditions.

Since the hydrogen and cesium were effectively « blocked » in the hollow cathodes of high-current Penning discharge, the gas efficiency of this SPS was extremely high (> 50 %), so the source operated well in the vacuum chamber without the anode cover (Fig. 8).

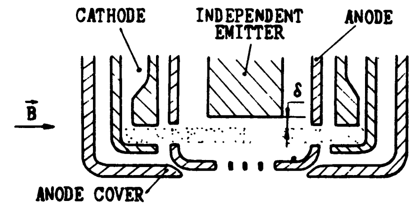



Fig. 8. — Schematic of surface-plasma source with independent emitter and Penning hollow cathodes discharges.

External Cs evaporator or cesiated pellets, placed into the IE body were used for supplying IE with cesium. However, « the return » of sputtered cesium to IE was not efficient, the plasma electric field did not provide rapid return of $Cs^+$ ions to plasma boundary, in contact with IE. Nevertheless, the weakly-activated IE converted to $H^-$ ions up to 3 % of IE current (Fig. 9). This IE circuit current was mainly an ion one (up to 90 %). Most of the IE secondary electrons were returned to IE by magnetic field, parallel to IE surface, and therefore electrons were not measured in IE circuit current.

With an increased supply of Cs or hydrogen, an additional discharge was ignited in the IE region, the electron current increased, while the ion one de-

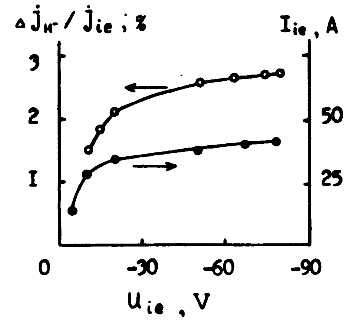



Fig. 9. — The normalized $H^-$ yield (the left scale) and the emitter circuit current (the right scale) *vs*. emitter voltage.

creased. Correspondingly, the NI generation at the IE became less efficient. Under optimal conditions with the IE emitting surface moved up to plasma layer edge and IE voltage of about 100 V the ion current to emitter was roughly equal to one-sixth of main Penning discharge current [8].

In the advanced SPS with independent emitter a significant fraction of the emitter current is transformed into $H^-$ flux. Nevertheless the fact that some negative ions produced on the IE surface failed to get to the emission slit, the multicusp SPS stationary extracted beam of $H^-$ ions has intensity up to 1.25 A and it consists of about 5 % of the IE circuit current [36] due to large amount of molecular ions in plasma.

**SPS with geometric focusing of negative ions.**

With a goal to collect a larger amount of negative ions from the SPS emitters, the sources with a cathode having a concave surface have been tested. In this case, the NI, accelerated by a « concave » layer of the near-electrode voltage drop, were geometrically focused to the emission slit or holes (Fig. 10). In 1978 the experiments were performed dealing with Geometric Focusing (GF) of NI flux, emitted by the cylindrically concave cathode surface to a narrow emission slit [16, 26]. The SPS with a two-dimensional GF of NI emitted by spherical concave surfaces of special indentations on the cathode was tested in 1982 [23]. A close, partially overlapped arrangement of the indentations on the cathode surface of this SPS was of the « honeycomb » structure.

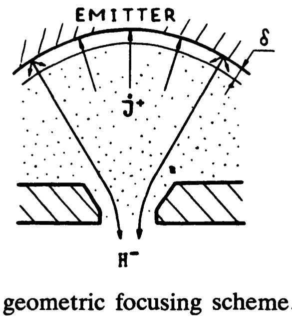



Fig. 10. — NI geometric focusing scheme.

The beam of $H^-$ ions with intensity up to 4 A was produced in the honeycomb SPS with the « useful » cathode area of 10.6 $cm^2$ and multihole extraction system. The local current density of « compressed » beams in the emission hole achieved 8 $A/cm^2$, the average current density after extraction was 0.5 $A/cm^2$. The use of GF increases energy and gas efficiency of NI production and enables one to reduce the sputtering and thermal load of electrodes. In particular, the honeycomb Source with spherical GF gives rather high conversion of the discharge current to the $H^-$ beam up to 5 % at an average thermal load at the cathode up to 1 $kW/cm^2$. Note, that the « sputtered » $H^-$-component is better focused due to smaller angular spread [37].

As has already been mentioned in [9], the surface-plasma sources of $H^-$ ions with ion focusing to emission holes are rather well subject to a simple scaling following from the condition for $H^-$ ions transport through a plasma : with a similar increase in the sizes of a source and plasma volume, the average current density of the extracted $H^-$ ions drops inversely to source linear sizes (the gas efficiency doesn't change). The scaling law mentioned above enables one to decrease the heating and sputtering of the electrodes due to NI current density decrease. In the steady mode it is easy to remove a heat of up to 1 $kW/cm^2$ from electrodes. From this point of view, the $H^-$ ion beams with a density of about 100 $mA/cm^2$ may be produced. The detailed analysis of GF is made in [37].

**Multi-aperture SPS with extended emitting surface.**

In the early design works on SPS it has been revealed that the NI yield is proportional to the emission hole areas. The tests have been performed of the sources with a useful cathode emitting area of $6 \times 40$ mm, and the emission slits of up to $3 \times 20$ mm.

It is beyond doubt that the surface plasma mechanism of NI production is also capable to operate in gas-discharge systems with the enlarged electrode emitting area. In 1979 a multi-aperture SPS was designed with a semiplanotron cathode geometry and cathode emitting area up to 9 $cm^2$ [26]. NI were geometrically focused and extracted through 5 emission slits of 2 $cm^2$ total area. The average $H^-$ current density was up to 0.5 $A/cm^2$, while $H^-$ yield achieved 4 A.

In 1983 a multi-aperture SPS with a honeycomb geometry of electrodes and with a 54 $cm^2$ « useful » area of the cathode was designed (Fig. 11). Owing to the geometrical focusing of NI from 600 spherically-concaved indentations of the cathode such a honeycomb SPS provided the production of a $H^-$ beam with intensity up to 11 A in the pulse mode and at the average emission current density in the beam up to 0.18 $A/cm^2$.

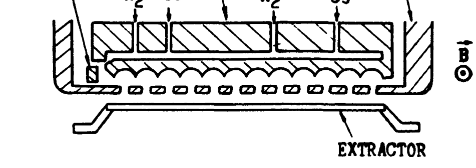



Fig. 11. — Multi-aperture honeycomb source.

The effect of surface active zones has been clearly observed during studying such SPS with extended cathode area. The « self-activation » of cathode area by gas-discharge is shown in figure 12. In spite of homogeneous cesium and hydrogen supply, the H-Cs mode of discharge is « attached » to the ignition area at first. The corresponding $H^-$ emission current distribution is non-uniform either (curve 1 in Fig. 12). The 15-minute pulse discharge conditioning of the cathode made the 0-1.5 cm zone more activated, and some part of the discharge current redistributed from ignition area to this zone (curve 15). The 0-1,5 cm zone completely activated in 25 min, while the discharge current density and $H^-$ yield were however low on cathode section 2-5 cm (curve 25).

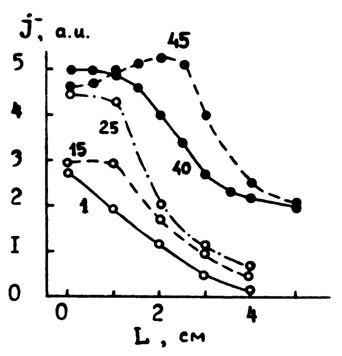



Fig. 12. — The $H^-$-emission density distribution along the extraction gap in 1,15, 25, 40, 45 min of electrode conditioning.

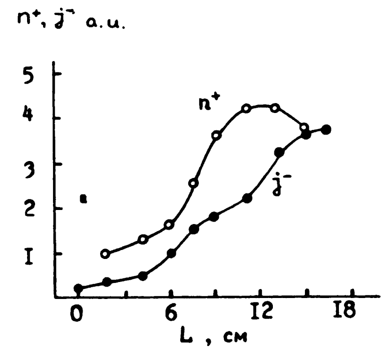



Fig. 13. — Plasma density $n^+$ and $H^-$-emission density $j^-$ distributions after self-activation with uniform supply.

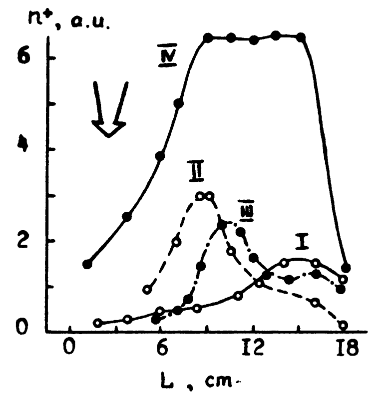



Fig. 14. — Shifting of the activated zone due to forced activation : I — self-activation ; II — with forced fuelling ; III — after forced activation ; I-II — discharge current 100 A ; IV — discharge current 500 A.

The discharge current was increased from 80 A to 120 A at 26-th min with the corresponding increase in area. At 40-th min the 4-5 cm cathode area acquired a relatively high level of emission up to 0.5 that of the ignition zone (curve 40). Note that in 45 min the $H^-$ production decreased in the ignition zone, and 1-2.5 cm sections becomes more activated.

After increasing the discharge current up to 500 A the emission cathode area expanded. The most active zone moved from ignition area towards the plasma $E \times B$ drift. Figure 13 shows the plasma density and $H^-$ emission current density distributions resulted from the « self-activation » with homogeneous fuelling of Cs and $H_2$. There are several ways to compensate for the active area drift. One of them is the non-uniform Cs and hydrogen fuelling into the interelectrode gap. Figure 14 shows the plasma density distribution for various regimes of adding the « fuel »-substance. The initial plasma distribution produced after homogeneous fuelling activation is shown by curve I in figure 14. When fuel feeds only the initial cathode area (the place of maximum supply is indicated by an arrow), the discharge is mainly maintained in the 6-12 cm zone (II in Fig. 14). The repetitive switching on the uniform supply clearly demonstrated the increased and shifted active zone (III in Fig. 14). With an increase in the discharge current up to 500 A this active zone 9-17 cm becomes more uniform (IV in Fig. 14). A steady-stade uniform discharge and $H^-$ emission distributions throughout the whole cathode area have been achieved in large honeycomb SPS with non-homogeneous fuel supply [24].

Another method of plasma drift compensation has been tested by introducing the auxiliary cathode in the beginning region of the discharge (4 in Fig. 11) in 1984 [38]. The pulsed auxiliary discharge with a current of up to 40 A improved the activation of beginning of cathode area. Self-activated cathode provided the low $H^-$ emission output in the initial area (trace 1 in Fig. 15). The upper trace (2 in Fig. 15) was recorded during simultaneous operation of the main and auxiliary discharges. The $H^-$ output increased, especially on the front of the discharge pulse, but to the pulse end the $H^-$ emission was lower due to redistribution of discharge current to activated zones. After a 10 min pulse conditioning the auxiliary discharge was switched off, but the $H^-$

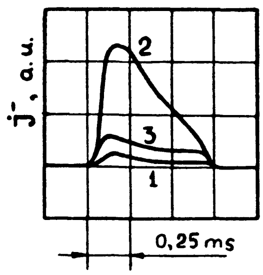



Fig. 15. — The effect of the auxiliary discharge conditioning on $H^-$ production in the weakly self-activated zone (at point $L = 2$ cm).

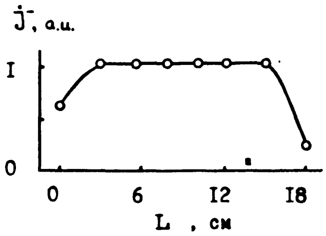



Fig. 16. — The $H^-$-emission current distribution along the SPS length in 90 min of forced auxiliary discharge activation. The main discharge current is 500 A, that of auxiliary one is 30 A.

yield increased to a new higher level of production in the discharge mode (3 in Fig. 15).

The partial return of a plasma to the ignition gap from the tail of the discharge *via* drift closing channels was also a successful way to achieve homogeneous cathode activation (see below).

**Quasi-steadystate models of SPS.**

The long pulsed tests of SPS were performed with honeycomb air-cooled models in 1985 [38]. The diagram of the test model is given in figure 17. The pulsed cathode overheating was reduced by increased cathode height and air-cooling of a cathode body. The emitting cathode surface was covered by spherically-concaved indentations with a 3.5 mm focusing radius. The indentations were placed on the cathode surface in hexagonal or orthogonal arrangement, and their number varied from 97 to 100 in different versions. A portion of the plasma went back from the tail of the discharge to the ignition hollow *via* the electron drift closing channels (Fig. 17) in order to obtain a more uniform activation of the cathode surface. The fuel-hydrogen and cesium were supplied to the discharge through the shaped thin slits in the cathode body. The $H^-$ beam was extracted through a system of profiled emission holes of inner diameter 0.8-0.9 mm.

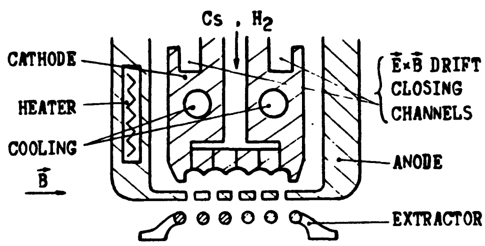



Fig. 17. — The long-pulsed honeycomb SPS model.

A steady-state extracted voltage of up to 18 kV was applied to the GDC body. After the multi-slit extractor heating and short-time conditioning there were no problems to raise the high-voltage operation of the sources. A set of short high-voltage pulses (up to $10^{-3}$ s) with repetition rate up to 100 Hz was also

Table I. — *Parameters of the tested SPS models in the main discharge mode.*

| Arrangement of cathode indentations | | Ortho | Hexa |
|---|---|---|---|
| $H^-$ ion beam current, | A | 0.9 | 0.6 |
| Beam energy | keV | 14 | 18 |
| Pulse duration | s | 0.2 | 0.6 |
| Total emission holes area | $cm^2$ | 0.6 | 0.5 |
| Initial beam cross section | $cm^2$ | 11 | 13 |
| Average $H^-$ current density | $mA/cm^2$ | 60 | 40 |
| Discharge current | A | 50 | 60 |
| Cathode temperature, up to | °C | 800 | 600 |

used for a glance at the emission properties of the models.

Several long-pulsed stable modes of discharge have been revealed, distinctly the discharge voltage, structure and NI production rate. The $H^-$ yield was maximum at 150-130 V discharge voltage (the main stable mode with uniform activated electrodes). In the intermediate mode with the stable discharge voltage of 60-40 V the $H^-$ output was two times lower.

With overheated electrodes we observed a low-voltage (20-30 V) discharge mode with $H^-$ production rate ten times lower.

The table I lists the parameters of tested SPS models for the main discharge mode [38].

**Conclusion.**

The INP studies proved the production of $H^-$ ion beams with the intensity higher than 10 A in the pulse mode and of the order of 1 A in long-pulsed mode of SPS H-Cs mode.

Several tested ways of the forced cathode activation enlarge the uniform activated emission area up to 54 $cm^2$.

The thermostabilization of electrodes ensures the quasistationary operation of SPS. The PH modes of SPS provide pulsed $H^-$ beam production with current intensity of 1 A and emission current density of 1.1 $A/cm^2$. The $H^-$ yield with an intensity of up to 0.15 A was produced in long-pulsed PH mode of SPS.

**References**


[1] BUDKER, G. I., DIMOV, G. I., Proc. of the Intern. Acc. Conf., Dubna, 1963, Moscow (1964) p. 933.

[2] BELCHENKO, Yu. I., DIMOV, G. I., DUDNIKOV, V. G., IVANOV, A. A., *Dokl. AN SSSR* **213** (1973) 1283.

[3] BELCHENKO, Yu. I., DIMOV, G. I., DUDNIKOV, V. G., *Nucl. Fusion* **14** (1974) 113.

[4] Proc. of the Int. Symp. on the production and neutralization of negative hydrogen ions and beams, Ed. K. Prelec (N.Y.) BNL-50727 (1977).

[5] Proc. of the second Int. Symp. on the production and neutralization of negative hydrogen ions and beams, Ed. Th. Sluyters (N.Y.) BNL-51304 (1980).

[6] Production and neutralization of negative ions and beams (3rd Int. Symp., Brookhaven 1983) Ed. K. Prelec, AIP Conf. Proc. N 111 (N.Y.) 1984.

[7] Production and neutralization of negative ions and beams. (4th Int. Symp., Brookhaven 1986) Ed. J. Alessi, AIP Conf. Proc. N 158 (N.Y.) 1987.

[8] BELCHENKO, Yu. I., DIMOV, G. I. and DUDNIKOV, V. G., Proc. Symp. on production and neutralization of negative hydrogen ions and beams, Brookhaven 1977 (N.Y.) BNL-50727 (1977) 79.

[9] DIMOV, G. I., X European conference on contr. fusion and plasma phys., Moscow, 1981, vol. II (1981) 35.

[10] BELCHENKO, Yu. I., DEREVYANKIN, G. E., DIMOV, G. I., DUDNIKOV, V. G., *Zh. Prikl. Mekh. Tekh. Fiz.* **4** (1987) 106.

[11] EHLERS, K. W., *Nucl. Instrum. Methods* **32** (1965) 309.

[12] DIMOV, G. I., TIMOSHIN, I. Ya., SAVCHENKO, O. Ya., *et al.* Proc. of the Nat. Conf. on Charged Particle Accelerators, Moscow, 1968, *VINITI* (Moscow) vol. **1** (1970) 407.

[13] BELCHENKO, Yu. I., DIMOV, G. I., DUDNIKOV, V. G., *Sov. J. Techn. Phys.* **43** (1973) 1720.

[14] BELCHENKO, Yu. I., DIMOV, G. I., DUDNIKOV, V. G., *Izv. AN SSSR Ser. fiz.* **37** (1973) 2573.

[15] BELCHENKO, Yu. I., DIMOV, G. I., DUDNIKOV, V. G., *Sov. J. Tech. Phys.* **45** (1975) 68.

[16] BELCHENKO, Yu. I., DUDNIKOV, V. G., Preprint INP N° 78-95, Novosibirsk (1978).

[17] ALLAN, M., WONG, S. F., *Phys. Rev. Lett.* **41** (1978) 1791.

[18] BELCHENKO, Yu. I., KUPRIYANOV, A. S., Preprint INP N° 88-7 Novosibirsk (1988), also in Production and Application of Light Negative Ions, Proc. 3rd European Workshop (Amersfoort, The Netherlands) 1988, p. 33.

[19] KARO, A. M., HISKES, J. and DE BONI, T. in [7] (1987) p. 97.

[20] BENDER, E. D., DIMOV, G. I., KISHINEVSKY, V. Ye., Proc. of the Nat. Seminar on Secondary Ion-Ion Emission, Kharkov 1975, VINITI, N° 2783-75, (1975) 119, also Preprint INP N° 75-9, Novosibirsk (1975).

[21] KISHINEVSKIY, M. Ye., *Sov. J. Tech. Phys.* **48** (1978) 773.

[22] ARIFOV, U. A., AYUKHANOV, A. Kh., *Izv. AN SSSR, Ser. fiz.-Math. nauk.* **6** (1961) 34.

[23] BELCHENKO, Yu. I., *Fiz. Plasmy* **9** (1983) 1219.

[24] BELCHENKO, Yu. I., DIMOV, G. I., in [6] (1984) p. 367.

[25] EHLERS, K. W., LEUNG, K. N., *Rev. Sci. Instrum.* **51** (1980) 721.

[26] BELCHENKO, Yu. I., DUDNIKOV, V. G., *J. Phys. Colloq. France* **40** (1979) C7-501.

[27] BENDER, Ye. D., KISHINEVSKIY, M. Ye., MOROZOV, I. I. in [4] p. 60.

[28] BELCHENKO, Yu. I., DAVYDENKO, V. I., DEREVYANKIN, G. E., *et al. Pis'ma Zh. Tekh. Fis.* **3** (1977) 693.

[29] TOMPA, G. S., CARR, W. E., SEIDL, M., *Appl. Phys. Lett.* **48** (1986) 1048.

[30] VAN WUNNIK, J. N. M., GEERLINGS, J. J. C., LOS, J., *Surf. Sci.* **131** (1983) 1.

[31] GEERLINGS, J. J. C., VAN AMERSFOORT, P. W., KWAKMAN, Tz., GRANNEMAN, E., LOS, J., *Surf. Sci.* **157** (1985) 151.

[32] BELCHENKO, Yu. I., KUPRIYANOV, A. S., The abstracts of the papers of the 2nd Nat. Seminar on Interaction of Ion Beams with Atoms and Surface of Solids, Novgorod, 1986 (Leningrad) 1988.

[33] WADA, M., BERKNER, K. N., PYLE, R. V., STEARNS, J. W., *J. Vac. Sci. Technol.* **A1** (1983) 981.

[34] APOLONSKIY, A. I., BELCHENKO, Yu. I., DIMOV, G. I., DUDNIKOV, V. G., *Pis'ma Zh. Tekh. Fis.* **6** (1980) 86.

[35] SCHMIDT, C. W., CURTIS, C. D. in [7] p. 425.

[36] KWAN, J. W., ACKERMAN, G. D., ANDERSON, O. A., *et al., Rev. Sci. Instrum.* **57** (1986) 831.

[37] BELCHENKO, Yu. I., KUPRIYANOV, A. S., Preprint INP N° 88-16 Novosibirsk (1988), also in [18].

[38] BELCHENKO, Yu. I., KUPRIYANOV, A. S., VII All-union workshop on ion sources phys. and techn. (Kiev) 1987.