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Negative Ion Surface Plasma Source Development for Plasma Trap Injectors in Novosibirsk*

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Abstract

Work on high-current ion sources carried out at the Novosibirsk Institute of Nuclear Physics (INP) is presented. The INP investigations on "pure plasma" planotron and "pure surface" secondary emission systems of H^- generation, which preceded the surface-plasma concept developed in Novosibirsk, are described. The physical basis of the surface-plasma method of negative-ion production is considered. The versions and operating characteristics of different surface-plasma sources including the multi-ampere ($\geq$ 10A) source are discussed. Research on efficient large-area ($\sim 10^2 cm^2$) negative ion surface-plasma emitters is described. The INP long-pulse multiaperture surface-plasma generators, with a current of about 1A, are described.

In systems with magnetic plasma confinement and accelerators, the charge-transfer method of injecting fast particles is widely used. In developing injectors of high-energy atoms, with energies greater than 100keV per nucleon, it is preferable to employ stripping of accelerated negative hydrogen ions, which easily lose the "extra" electron in collisions in a charge-transfer target and have a high, close to 1, conversion coefficient to atoms in a wide range of particle energies. In the last decade the intensity and volume of research on negative-ion sources for charge-transfer injection has significantly increased.

At the Institute of Nuclear Physics, Siberian Branch, Academy of Sciences of the USSR, work on H^- ion sources has been carried out over more than two decades and was begun in connection with the development of a method of charge-transfer proton injection into accelerators. For charge-transfer injection at the Institute, plasma sources of H^- ions of the Ehlers type, with a pulsed current up to 8mA, were developed, along with charge-transfer sources, initially with a current up to 15mA, and subsequently up to 100 mA. However, the characteristics of these sources did not allow realization in full measure of the advantages of charge-transfer injection, and did not guarantee their wide use in accelerators.

The situation, as far as storing negative-ion (NI) beams,was radically improved after the discovery and experimental investigation of a new surface-plasma mechanism of forming negative ions in gas discharges.[2,3] On the basis of this surface-plasma mechanism a series of surface-plasma sources (SPS) of H^- ions were developed for accelerators.

Most of all, the surface-plasma method has been sufficiently efficient to initiate the development of high-power negative-ion sources for the injectors of magnetic traps for high-temperature plasma. In 1976-1986, the INP carried out studies and created multiaperture surface-plasma sources of negative ions with pulsed beam intensity of more than 10A, and quasistationary SPS with a ~1A H^- beam

A large contribution to the development of SPS has also been made by the national laboratories of the USA (Brookhaven, Berkeley, Los Alamos, Oak Ridge, Fermilab), and a number of laboratories in the Soviet Union, Europe and Japan. These results have been reflected in the International Symposia on obtaining and neutralizing negative ions[4-7] and many other publications.

In this work we will dwell only on the results obtained at the Institute of Nuclear Physics, Siberian Branch, Academy of Sciences of the USSR. Some results of this research have been discussed in review articles.[8-10]

Pure-Hydrogen Gas-Discharge Systems for NI Generation

Work on "gas-discharge" NI sources, with negative ions generated in a plasma volume and subsequently extracted from the gas-discharge chamber (GDC), was begun at the INP at the onset of the sixties. An Ehlers-type source[11] was developed with a Penning geometry of the GDC from which a pulsed H^- beam with a current up to 8mA was obtained. Research was carried out on magnetron designs for NI generation, in which we hoped to obtain a better distribution of electric field intensity in the plasma and a more favorable electron speed distribution for H^- generation. A magnetron source with a cylindrical GDC geometry and a thin wire cathode coaxial with the external magnetic field up to 3kG was tested (Figure 1).

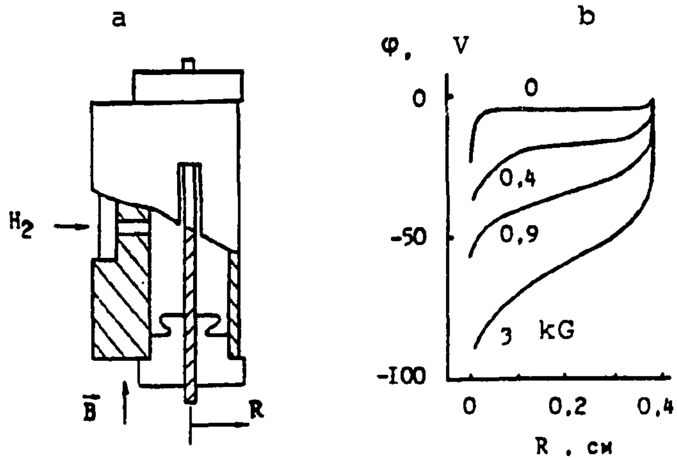


Figure 1. Design of the cylindrical magnetron (a) and potential distribution along the radius of the discharge channel for different values of the magnetic field (b).

The investigations showed that the plasma potential distribution along the radius of a discharge channel (Figure 1b) with a large anode drop is favorable for driving H^- ions from the plasma in the extraction region. From the cylindrical magnetron a pulsed (1ms) H^- beam was obtained with a current up to 7mA through an emission gap of 10x1mm. The optimal hydrogen pressure for output of H^- ions had a value of $7x10^{16}cm^{-3}$.

With the idea of increasing the efficiency of electron use in the discharge and decreasing the exit speed of electrons from the plasma to the anode, a design was created with a flat "spool-shaped" cathode - the planotron (Figure 2). The side projections of the cathode limited the exit of primary and secondary electrons to the anode; in the space between the side projections of the cathode electron oscillations occur along the force lines of the magnetic field. In order to create in the area adjacent to the emission gap an anodal plasma with a reduced density and electron temperature, special anode flanges (Figure 2) were installed, the height and shape of which were varied.

Extraction of NIs took place across the emission gap, oriented perpendicular to the magnetic field; the width of the gap (along the magnetic field) varied in the range 0.1-3mm. For such an orientation of the emission gap the flux of accompanying electrons, extracted along with the NIs due to electron withdrawal on the lateral wall of the emission gap, decreased ten times. Thus, if in the cylindrical magnetron with a longitudinal emission gap of 10x1 mm, for an H^- ion current of 7mA, the flux of accompanying electrons had a value of 250mA, then in one of the first variants of the planotron with -shaped anode flanges (Figure 2), an H^- beam with a current intensity of 4.5mA and a flux of accompanying electrons of 16mA was obtained across a transverse emission gap of 0.5x10mm.

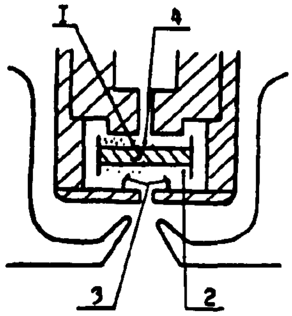


Figure 2. An early modification of the planotron: 1- spool-shaped cathode; 2- electron oscillation zone; 3- -shaped flanges; 4- zone of electron drift cutoff.

By designing the shape of the magnetic polar terminals in the zone of NI extraction, an inhomogeneous magnetic field was generated, so that upon supply of a negative voltage to the body of the GDC to pre-accelerate the NIs, the accompanying and secondary electrons cannot oscillate in the extraction gap, but immediately are dumped onto the grounded extracting electrode or the polar terminals of the magnet. Use of such an inhomogeneous magnetic field, preventing electron accumulation, allows a dramatic improvement in the electrical stability of the extraction gap and permits investigations of the extraction of H^- ions for different cathode and near-anode geometries of the discharge area in a wide range of magnetic field, hydrogen densities and sizes of emission gaps.

Results of these studies and data on obtaining a H^- beam of intensity up to 22mA with an emission current density up to 270mA/cm^3 were partially presented in Ref.13. The optimum geometry was established for the near-anode region (height and distance between anode flanges), and the energy spectra of the H^- ion beams obtained were studied. H^- ions were detected which were formed by charge transfer of fast protons on the cathode surface; however, an overwhelming portion of the H^- ions had an energy corresponding to the anode potential. The high H^- ion current density testified to the increased speed of H^- formation in the plasma volume.[14] The ambiguity of the mechanism for such intense H^- ion generation in the pure-hydrogen regime of planotron discharge increased the value of the experimental information; therefore the majority of the new cesium-hydrogen surface-plasma H^- sources created at the INP were also studied in the pure-hydrogen regime. Thus, at the end of 1972 experiments were repeated on extraction of H^- ions from a pure-hydrogen discharge in an improved planotron source for comparison with the cesium-hydrogen regime.[2,14] It was observed that on decreasing the width of the plasma discharge layer to 0.5mm and with a thicker and more massive (with a lower working temperature) cathode, the output of H^- ions grew over a wider range of discharge current. From an emission gap of 0.4x5mm, a beam of H^- ions was obtained with an intensity of 15mA and an emission current density up to 0.75A/cm^2 for a discharge current of 150A (Ref.2,3 - dashed line in Figure 2, Ref.14, p.2573). Upon increase of the width of the emission gap to 1mm (length of 5mm) the H^- beam grew to 32mA; however, the emission current density decreased somewhat to 0.64A/cm^2 due to stronger NI disintegration on the gas emergent through the emission gap. If the flat central part of the cathode was removed from the planotron in general, the total H^- ion current was decreased. However, thanks to the proximity of the "lateral" cathodes to the emission gap the emission current density of H^- ions in such a modified (Penning) geometry reached 0.4-0.5A/cm^2.

Such a high emission current density of H^- ions as 0.75 A/cm^2 was hard to interpret in the framework of existing models and information at that time on elementary processes in a plasma for the most optimistic assumptions on the discharge parameters in a planotron.

The maximum H^- ion outflow from the planotron[2] and Penning sources in the pure-hydrogen regime was three times lower than in the cylindrical magnetron and source with a thin cathode[13] and a density $2x10^{16}cm^{-3}$ of hydrogen molecules. This fact testifies to the high rate of generation of H^- ions for low H_2 densities, and to the suppression of this mechanism (or the strengthening of additional channels of H^- decay) for increased H_2 admission to the GDC.

At the end of the seventies interest in pure-hydrogen systems of H^- ion generation grew in connection with experimental confirmation of the prediction of Demkov (1965) on the manifold increase in formation cross-section for negative ions upon dissociation of vibrationally-excited molecules by electron impact[17]:

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

Several plans were realized for generating H^- ions in hydrogen discharges through vibrationally-excited hydrogen molecules; various modifications of bulk generators of H^- ions were worked out, including one with a NI current up to 1.2A of 0.2s duration.[7]

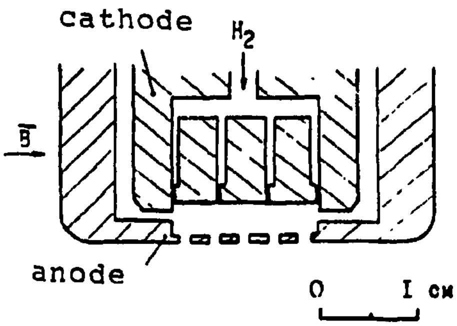
Moreover, the emission current density of H^- ions achieved in such bulk generators was several times lower than those obtained from the pure-hydrogen regime SPSs even in 1972.[2]

For full-scale confirmation of the efficiency of surface-plasma sources in the pure-hydrogen regime, experiments were carried out at the INP in 1987 on H^- ion extraction from a multiaperture SPS with a large emitter surface and a half-planotron cathode geometry. NI extraction was carried out with the aid of a multigap extracting electrode through a multigap or multihole system of emission apertures in the anode (Figure 3). The emission of H^- ions was investigated in the regime of short (0.8-3ms) and long (up to 0.6s) pulses. An external 1-3kG source magnetic field separated the beam of extracted

H^- ions from the heavy impurity ions O^-, OH^-, Mo^-, etc., and from the electrons, very well.

A high-current glow discharge of voltage 500-600V (after conditioning at 300-400V) was maintained in the extended narrow gap between the flat cathode and the anode for a hydrogen density no less than $6x10^{15}cm^{-3}$. As in the rest of the half-planotron constructions, to ensure ignition of the discharge at such a low pressure, an ignition region was made on one end of the cathode, with lateral projections increased up to 3mm and improved electron confinement. From the ignition region, by drift in crossed poles, the plasma exits into the interelectrode gap. As in the source of Ref.2, an anode slot was formed. The dependence of the output of H^- ions from the pure-hydrogen (PH) regime of a multiaperture half-planotron on discharge current is presented in Figure 4. In the range 50-200A of discharge current the H^- ion output grew linearly. For a discharge current of 600A (an average discharge current density at the cathode of $60A/cm^2$) a beam of H^- ions was obtained from five emission gaps of 0.8x52mm with an intensity of more than 1A and an average emission current density up to $0.5A/cm^2$. The total extracted NI current had a value of 1.2A; however, up to 17% of the beam consisted of heavy impurity ions.

The extraction of a H^- ion beam through five circular holes of 0.72mm diameter showed that in the pulsed regime such a source achieves an emission current density up to $1.1A/cm^2$ of H^- ions.



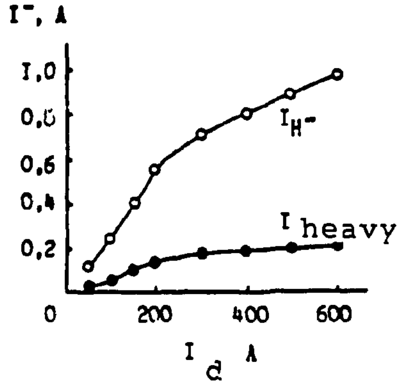


Figure 3. Multiaperture half-planotron.

Figure 4. Dependence of H^- ion output on discharge current in the pure-hydrogen regime of a multiaperture half-planotron.

Trials of this source in the long-pulse regime showed that, aside from electrode heating up to 800C, a uniform high-current glow discharge has the same characteristics and preserves the ability to emit H^- ions with a high emission density right up to discharge currents of 90A and duration 0.6s. Further progress was limited by the systems used to supply the discharge current.

For extraction through 90 emission apertures the H^- ion current increased linearly with discharge current and for a discharge current of 90A reached 150mA at the beginning of the pulse. Toward the end of the 0.6s pulse, the H^- ion output decreased to 100mA due to electrode overheating.

In contrast to the planotron of Ref.2 and the source with reflecting discharge of Ref.11, the output of H^- ions was maximum for minimal hydrogen input into the discharge and a hydrogen molecule density of $6 \times 10^{15} cm^{-3}$, several times less than in Ref.2 and 11. Other relationships,[18] not characteristic of "bulk" sources, were also observed. Thus, the output of H^- ions was maximum at the optimal electrode temperature (750K for the cathode, 600K for the anode).

Variation of the temperature by ± 100K from the optimal led to a 30-40% reduction in H^- ion output. Upon using a honeycombed cathode (Figures 10,11) the H^- ion output in the PH-regime depended substantially on the positions of the emitter holes relative to the geometric foci of the spherically-concave cathode holes. Thus, the output of H^- ions from emission holes at the points of geometric focus of a lune was 5-6 times larger than from holes situated far from geometric foci. The facts presented testify to the substantial contribution of surface processes to H^- generation even in PH-regimes of SPSs. However, in PH-regimes, due to the high electrode work function, a small part (~1%) of the primary intensive flux of gas-discharge particles "converts" immediately at the cathode to NIs. In this regime a large part of the reflected and sputtered particle flux from the cathode flies off in the form of fast neutral particles.

Fast atoms can "convert" to H^- ions upon collisions with plasma particles and on the walls of the emission holes. In addition to the excitation of molecules by electrons, fast atoms (like protons) can efficiently pump up the vibrationally-excited degrees of freedom of molecules and, consequently, increase the rate of NI generation in the bulk discharge.

Besides direct conversion to H^- ions, the electrode surfaces in PH-discharges can be intense sources of vibrationally-excited molecules, from which H^- ions are subsequently formed in the plasma volume. The high content of molecular ions in the particle flux incoming on the hydrogen-enriched near-surface cathode layer is favorable for the process of pumping vibrationally-excited molecules on the surface.[19] According to our measurements 60-70% of the ion flux on the cathode consists of H_2^+ and H_3^+ ions.[18]

Due to the small thickness of plasma between the cathode and the emission holes fast vibrationally-excited molecules from the cathode and the H^- ions formed at them can exit to the emission region almost without decay.

On the whole we can say that even in the PH-regime of a SPS intense NI generation takes place due to interaction of plasma particles with the cathode surface.

Surface-Plasma Sources with Hydrogen-Cesium Discharges

During 1969-70, attempts were undertaken at the INP to increase the negative-ion output from gas-discharge sources by feeding the discharge hydrogen-containing molecules with lower dissociation energies than H_2 or molecules with an ionic bond for which the threshold of H^- ion formation is less than for H_2. In particular, supplying the discharge with diborane, lithium hydride, and cesium boron hydride was tried. At the same time research was conducted on obtaining H^- ions by secondary-emission methods Work carried out showed that under bombardment of metal surfaces by cesium ions in a hydrogen atmosphere the coefficient of secondary emission of H^- ions increased[20] to 0.8 for an H^- emission current density up to 10mA/cm^2. Experiments were conducted on cesium introduction into gas-discharge sources and in 1971 it was observed that upon admission of small quantities of cesium-containing material into the gas-discharge chamber of a planotron (Figure 2), the output of H^- ions increased from 4.5 to 15mA. In subsequent experiments an increase in H^- output was observed with a decrease in thickness of the plasma layer between cathode and emission holes and with a decrease in hydrogen density, as well as a saturation of this output with an increase in plasma density. All this allows us to suppose that intense H^-

ion fluxes from a plasma are due to emission of these ions in the discharge from the cathode surface and travel to the emission hole without decay.

An optimization, based on this version, of the geometry and discharge process led in 1972 to an increase in H^- ion current density from the emission gap to $3.7 A/cm^2$ for a total current in the hundreds of mA[2]. These values were anomalously large for gas-discharge sources of that time. Experiments carried out on the energy spectra of the ions flowing from the source, analysis of the dependence of NI output on the material of the cathode surface, its profile and the distance to the emission gaps, experiments with discharges in helium with hydrogen admixture, all allowed formulation of the subsequent concept of a surface-plasma mechanism for forming negative ions in gas discharges.[8,15]

The surface-plasma mechanism is realized in gas discharges and plasma installations if the following set of processes is ensured (Figure 5).

Near the electrode surface a layer of dense plasma is generated. Between the plasma and the electrode, a voltage in the hundreds of volts is applied, which accelerates the positive ions of the plasma and provides intense bombardment of the electrode surface. In the layer near the surface of the electrode a dynamically maintained structure of implanted and adsorbed atoms is created. Such an electrode effectively "converts" the flow of incident ions into a reverse flow of fast particles reflected and sputtered from the layer.

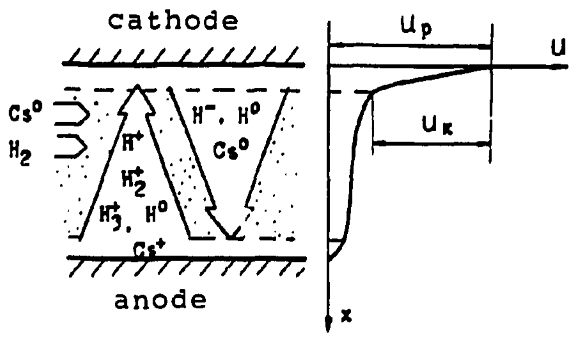


Figure 5. Schematic of surface-plasma generation of intense secondary fluxes; to the right, the distribution of potential in the interelectrode space.

The high speed of the particles leaving the surface (1-100eV) favors a higher degree of negative ionization of the flux flying off, even if the affinity of the atoms for the electron is lower than the work function of the surface[2]. A fast particle "withdraws" an electron at its level of electron affinity due to the kinetic energy imparted to it upon bombardment. Introduction into the plasma (or directly through the pores of the electrode) of a catalyst of negative-ion emission - alkali metal vapor[22] - decreases the work function of the surface. As a result the probability of NI formation approaches unity for a work function of 1.5eV and an electron affinity of 0.75eV, and allows one to obtain intense fluxes of "almost unobtainable" negative ions with a low electron affinity, such as H^-, Li^- and others, by the surface-plasma method.

General Properties and Characteristics of SPSs with a Reduced Electrode Work Function

The establishment of a dominating surface-plasma mechanism for intense NI generation in discharges with reduced electrode work functions allows one to "deliberately" build SPSs with the necessary characteristics. Different modifications of SPSs have been developed and investigated. In the planotron, half-planotron, modified Penning and multiaperture SPSs cited[23,24,26] the NI emitter is the cathode of a high-current glow discharge. In SPSs with an independent plasma generator[8,25,26] the gas-discharge plasma is fed onto the surface of a specially prepared NI emitter under a negative potential.

To reduce the work function of SPS emitters, cesium is primarily used, fed from an external evaporator through holes or pores in the emitter surface. Upon cesium supply to the discharge, several working regimes of SPSs are realized, differing in the discharge voltage, the intensity of H^- ion generation, and the level of fluctuations in the discharge. The effect of emitter surface activation, consisting of a significant increase in the coefficients of secondary electron and negative-ion emission upon electrode treatment by a hydrogen plasma[27], was observed and investigated. As a result of a similar activation in a hydrogen-cesium SPS discharge, a structure is formed on the cathode from implanted hydrogen and cesium; the work function is 1.3-1.4eV. Maintaining the optimal cesium coverage of the emitter in conditions of intense bombardment enables fast cesium ionization in the near-electrode plasma and its recovery by the electric field on the emitter. Direct measurements of the fluxes of ions and atoms of cesium through diagnostic holes in the cathode and anode of the SPS showed that the flux of cesium atoms returning to the cathode reaches 1-10% of the total ion current on the cathode, whereas the transport of cesium through the emission gap during the discharge is insignificant.[28] SPS emitters are usually prepared from especially pure molybdenum, which because of the favorable mass relationship "traps" cesium ions well from the incoming flux and ensures stable cesium coverage with a low work function in a wide range of doses and bombardment energies.[8,29]

The most effective NI generation is in processes when the plasma is ignited by the molecular ions[8] H_2^+ and H_3^+. Upon a fast impact on the surface the molecular ion dissociates, and in further motion in the near-surface layer twice or three times the number of particles with lower energies participates. As a result the coefficients of reflection, sputtering of adsorbed hydrogen and negative-ion emission from the surface grow.

The degree of negative ionization of particles leaving the cesium-treated molybdenum surface, I_{H-}/I_{out}, has the high value of 0.2-0.7 in a wide range of particle departure speeds from the surface from 10^6-10^7cm/s.[21,30,31] In conditions of intense bombardment dynamic "activation" of the cathode ensures a high coefficient of H^- secondary ion emission, $I_{H-}/I_+ \simeq 0.5$-0.8, on the scale of the incident positive ion. A "deliberate" optimization of NI generation conditions permitted increases of intensity obtained from SPS H^- beams up to 0.9A[3], and later even up to 11A.[24]

In the energy spectrum of emitted NIs there are several groups of H^- ions. The faster ions, having been formed by reflection of primary particles from the emitter, are barely noticeable in the energy spectra for activated SPS electrodes (peak III in Figure 6). Due to the large angular scatter of the ions of the "reflected" component after preacceleration of the NI flux by the near-electrode voltage drop and transport through the plasma, only a fraction of the "reflected" NIs enter in the region of beam formation.[33]

In the regime of activated SPS electrodes H^- ions dominate in the beam composition, having been formed as a result of hydrogen sputtering from the near-surface emitter layer (peak II, Figure 6).

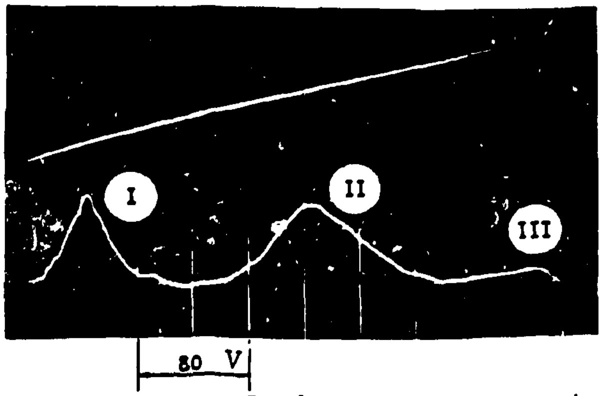
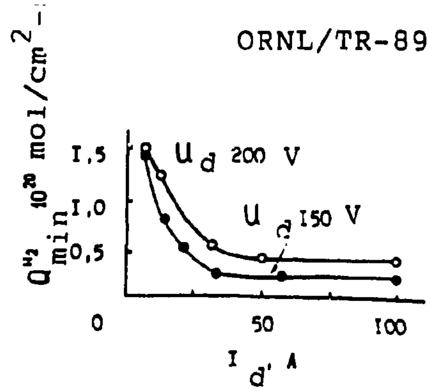


Figure 6. Oscillogram of the energy spectrum of negative hydrogen ions from the planotron SPS (lower ray).Upper ray-scanning voltage 90° of the electrostatic analyzer. I-"anode" group; II - "sputtered" NI; III - "reflected" H^- ions.

The group of slow H^- ions (peak I on Figure 6) contains H^- ions formed as a result of resonant charge transfer on atoms in the near-anode region and on the walls of the emission holes. Resonant charge exchange in the slow H^- ions allows one to significantly reduce the energy spread of H^- ions extracted from the SPS and increase the sharpness of the H^- ion beam for accelerator applications.

Figure 7. Decrease in gas flux from the emission gap for increased discharge current for two half-planotron regimes. The location of the hydrogen intake is far from the emission gap; the H^- supply is minimized.



In planotrons and Penning SPSs the minimal density of hydrogen molecules necessary to sustain a self-maintaining discharge in the narrow elogated interelectrode space has the value $(1\text{-}3)\times10^{15}cm^{-3}$ and depends on the value of the external magnetic field and the GDC geometry. In similar SPSs with a dense ($\simeq 10^{13}cm^{-3}$) plasma, a cutoff effect for molecular hydrogen in the GDC was observed.[34] Due to the evacuating and cutoff action of the plasma layer, the molecular component of the hydrogen from the SPS decreases by 20-90% from its initial value (Figure 7) upon ignition of the high-current discharge. In particular, for large discharge currents in a SPS with a planotron geometry, up to 30% of the hydrogen leaves the emission gap in the form of negative ions.[34]

Due to the "cutoff" of cesium in the region of the near-electrode voltage drop and on the emitter surface, cesium is hardly carried out of the SPS; this ensures good electrical stability of the extraction system and of the H^- ion beam acceleration and is not an obstacle to the normal operation of the high-voltage circuits of the H^- injectors.[35] In optimal conditions for H^- generation the consumption of cesium in planotron SPSs has the value 3×10^{-3}g/A-hr.

SPSs with an Independent Negative Ion Emitter

In 1973 it was noted that external injection of a plasma on an emitter with an independently controlled negative potential, relative to the plasma, was a possible means of generating negative ions in an SPS (Ref.15, p.74). In 1976-77 experiments were carried out on an SPS with independent plasma generation and an independent emitter (IE).[8] A Penning cesium-hydrogen discharge with full cathode (Figure 8) which in itself was an efficient surface-plasma H^- ion emitter and permitted one to obtain NI beams with emission densities up to 2A/cm^2, was used as a plasma generator. Inclusion of a negative shift on the IE, approximating a plasma layer, doubled the H^- output; the H^- emission current density achieved from the SPS had a value of 5.4A/cm^2.

Due to the efficient cutoff of gas and cesium in the full cathodes of the high-current Penning discharge the gas efficiency of such a SPS was anomalously high (~50%), so that the source operated normally in the vacuum chamber upon removal of the anode cover (Figure 8).

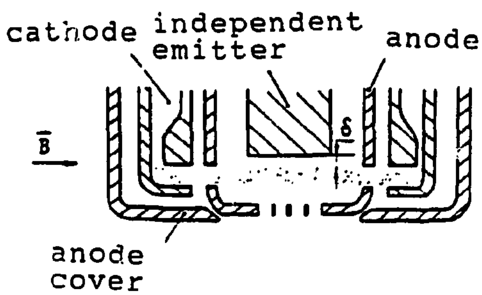


Figure 8. Surface-plasma source with an independent emitter. The plasma generator is a Penning discharge with full cathodes.

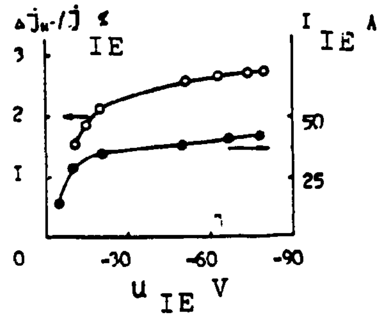


Figure 9. Dependence of the "reduced" (on the scale of the emitter current) H^- ion output (left scale) and the current on the emitter (right scale) on the independent emitter voltage.

To reduce the IE work function additionally cesium was supplied in the IE region from an external evaporator or from tablets placed in the body of the IE. However, the "recovery" mechanism for the cesium sputtered from the IE surface was less efficient; the electric field in the plasma did not provide a quick recovery of Cs^+ ions on the plasma boundary in contact with the IE. None the less, on the surface of the weakly activated IE, up to 3% of the current was successfully "transformed" into the H^- beam (Figure 9). The current recorded in the emitter circuit was basically ionic (up to 90%). The larger part of the secondary electrons knocked off the IE surface were returned to the IE by the magnetic field and did not generate a current in the emitter circuit. For an increased supply of hydrogen or cesium in the IE region a self-maintaining discharge was ignited; the electronic component of the IE current increased, and the ionic decreased. Correspondingly, the efficiency of NI generation on the IE surface decreased. In optimal conditions when the IE was 0.1mm from the edge of the plasma layer limited by the magnetic field and the voltage on the IE was near 100V, the ionic current on the emitter was about a sixth of the current of the basic discharge (Figure 9).

In the present SPSs with an independent emitter a more substantial part of the emitter current is successfully transformed into an H^- beam. Notwithstanding the incomplete collection of negative ions formed on the IE surface in the SPS with the peripheral magnetic field, the steady-state extracted H^- beam of 1.25A current is 5% of the current in the IE current[36], which is due to higher content of molecular ions in the current on the IE.

SPS with Geometric Focusing of Negative Ions

With the goal of more complete collection of negative ions formed on the SPS emitters, sources were tested with a concave surface, in which NIs accelerated by the "concave" layer of the near-electrode voltage drop were geometrically focused on the emission gaps or holes (Figure 10). In 1978, geometric focusing (GF) of a negative ion flux was experimentally accomplished with a cylindrical-concave cathode surface on a narrow emission gap.[16,26] In 1982 a SPS was developed with two-dimensional geometric focusing of NIs emitted by spherically-concave surfaces of special lunes on the cathode.[23] The close-packed arrangement, with partial overlap, of the lunes on the cathode surface of such a SPS had a "honeycomb" structure. We note that, basically, H^- ions formed upon sputtering of the "hydrogenated" near-surface layer, having a small energy and angular spread, are geometrically focused. From the honeycomb SPS with a useful cathode area of $10.6 cm^2$ a beam of H^- ions of current up to 4A was obtained through a multihole extraction system, with an average H^- current density in an extracting gap of 0.5 A/cm^2. The local current density in an emission hole of the honeycomb source reached $8 A/cm^2$. Use of GF raises the energetic and gas efficiency of the SPS and allows reduction of the power density on the cathode. In particular, in a honeycomb source with spherical GF the efficiency of discharge current conversion into an H^- beam reached a value of $I_{H^-}/I_d \simeq 5\%$ for an average thermal load on the cathode of $1 kW/cm^2$.

As noted in Ref.9, surface-plasma sources of H^- ions with ion focusing in emission holes conform rather well to a simple similarity law coming from the conditions of propagation of the H^- ions through the plasma: with a similar increase in the dimensions of the source and the volume occupied by the plasma, the average current density of extracted H^- ions falls directly in proportion to the linear dimensions (the gas efficiency should not vary).

The similarity rule mentioned allows, due to the reduction of negative ion current density, a reduction in heating and electrode sputtering. In the steady-state regime it is not difficult to achieve heat removal from the electrodes of up to $1kW/cm^2$. From this point of view it is safe to obtain H^- ion beams with density of order $100mA/cm^2$.

More detailed factors influencing the efficiency of geometric focusing in SPSs are analyzed in Ref.37.

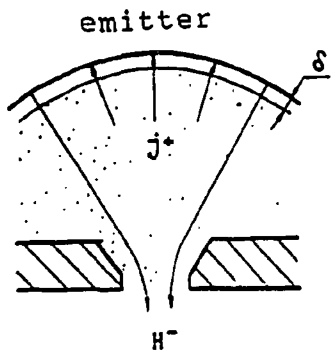


Figure 10. Design for geometrical focusing of a flux of negative ions with a concave cathode surface on the emission gap or hole.

Multiaperture SPSs with Increased Emitting Surface

Even in the first modifications of the SPS it was observed that the NI output from a discharge was proportional to the area of the emission holes. Sources were tested with a useful emitting part of the cathode of 6x40mm, with emission gaps of dimensions up to 3x30mm.[8]

There was no doubt that the surface-plasma mechanism of NI generation was capable of working in gas-discharge systems and with large emitting electrode surfaces. In

1979[26] a multiaperture SPS was developed with a half-planotron GDC geometry and one-dimensional geometric focusing, and a usable cathode emission surface of $9cm^2$. NI extraction took place through 5 emission gaps of a total area of $2cm^2$. The "reduced" average H^- current density from the cathode had a value of $0.5A/cm^2$, and the total extracted H^- ion current was up to 4A.

In 1983, a multiaperture SPS with a honeycomb electrode geometry and a usable cathode surface of $54cm^2$ (Figure 11) was created. By means of geometric focusing of NIs from 600 spherically concave lunes in the cathode on the emission holes the total area of $4cm^2$ of the honeycomb SPS provided a H^- beam of total current greater than 11A with an average current density in the beam up to $180mA/cm^2$.

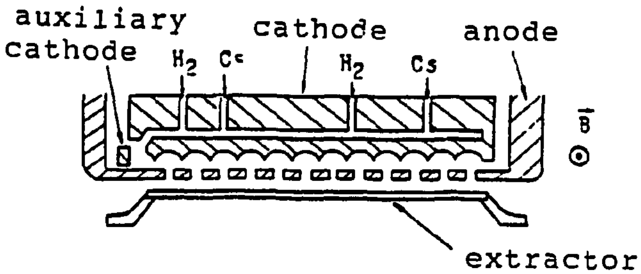


Figure 11. Multiaperture honeycomb source.

Upon investigation of such SPSs with increased cathode area, there appeared a definite activation effect of the separate zones on the surface upon treatment by the hydrogen-cesium discharge. The influence of such an effect is shown in Figure 12, where the distributions of H^- ion current density from sections of the discharge differing in length of interelectrode spacing, for uniform cesium supply to the discharge, are pictured. At the beginning of the discharge in the hydrogen-cesium regime, the discharge is "attached" to the ignition channel, and quickly decreases according to distance from it. The corresponding distribution of current density is also nonuniform along the length of the emission gap (curve 1). During 15 minutes of pulsed operation of the discharge the initial section of the cathode 0-1.5cm is activated; a part of the discharge current is redistributed from the ignition channel to this section (curve 15); after 25 minutes of operation the discharge completely activates the initial section 0-1.5cm; however, on the sections 2-5cm the density of discharge current and H^- ion output are low. If at the 26th minute the discharge current is increased from 80 to 120A, then after a subsequent 15-20 minute activation the zone of uniform discharge combustion is expanded (curves 40 and 45); at the 45th minute a decrease in H^- generation is noted in the initial region, the 1-3cm segment becoming more active. Further, on increase of the discharge current to 500A, the active zone on the cathode surface is widened, and shifts in the direction of plasma drift from the ignition channel. The distribution of plasma density along the length of the interelectrode gap established as a result of "self-activation" for uniform supply of the working material in the discharge, and the analogous distribution of H^- ion current density are distinctly inhomogeneous (Figure 13). To compensate the drift of the active region and to improve the distribution of the emission current density several methods can successfully be used, including profiling the supply of cesium and hydrogen in the discharge. In Figure 14 we show the variation of distribution of plasma density in different regimes of working substance supply. On supplying additional cesium to the discharge (the location of maximum supply is marked by the arrow) and decreasing the supply of hydrogen in the region 13-18cm, the discharge is maintained basically in the zone 6-13cm (curve II in Figure 14). After including forced supply of cesium and increasing the hydrogen supply in the tail of the discharge for small discharge currents, additional activation of the zone 9-12cm appears distinctly (curve III in Figure 14). Upon increase of the discharge current to 500A , the 9-17cm part of the cathode is activated (curve IV).

Profiling the hydrogen and cesium supply in the discharge ensures uniform combustion of the discharge and uniform emission of H^- ions over the whole cathode area.[24]

Another method of uniform activation of the cathode and compensation of the active zone drift was tested with the help of an auxiliary discharge. In this method, an additional cathode was installed near the ignition region of the basic cathode (Figure 11). Inclusion of a pulsed auxiliary discharge with a current up to 40A improved activation of the initial part of the cathode (Figure 15). With an auxiliary discharge and a "self-activated" cathode the discharge current and H^- ion current (lower ray 1 in the oscillogram of Figure 15) from the initial part of the source are small.

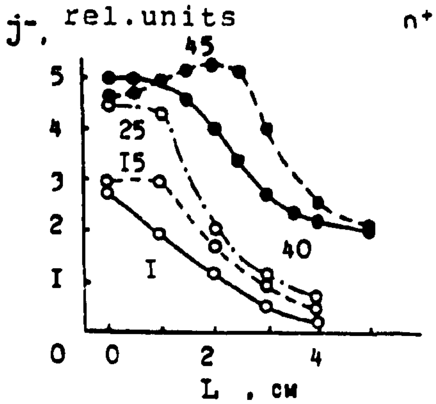


Figure 12. Distribution of H^- ion current density along the length of the emission region at the beginning of the cathode: 1, 15, 25, 40, 45 are after 1,15,25,40 and 45 minutes of conditioning by the discharge. At 26 minutes the discharge current is increased from 80 to 120 A.

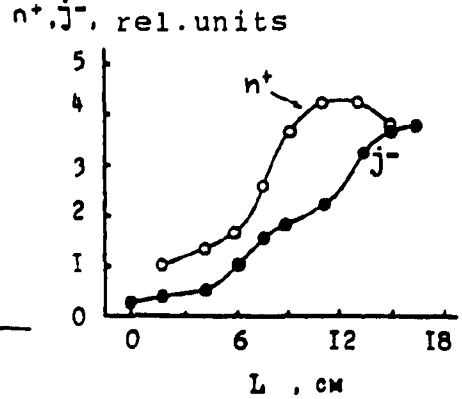


Figure 13. Distribution of plasma density n_+ and H^-ion emission current density j_- along the gas-discharge interval as a result of cathode self-activation for uniform supply of hydrogen and cesium.

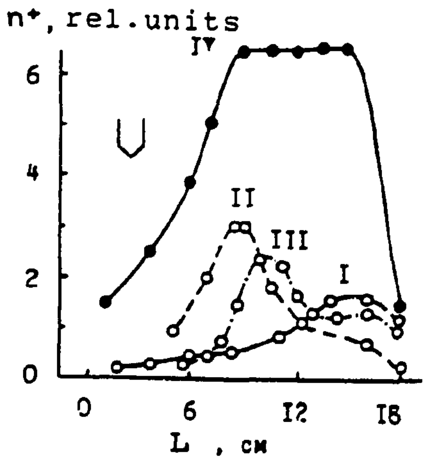


Figure 14.Shift of the active zone as a result of forced activation by profiling the supply of cesium and hydrogen:I-"self-activated" zone for uniform supply of hydrogen and cesium; II-distribution of plasma density along the interelectrode space upon forced supply of cesium and hydrogen;III-upon uniform supply after forced activation;I-III:100A discharge current;IV- after forced activation, 500A discharge current.

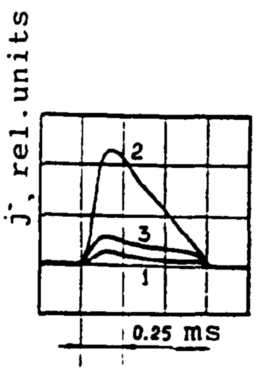


Figure 15. Influence of an auxiliary discharge on H^- current density in a weakly-activated zone (L = 2cm).

Upon inclusion of an auxiliary discharge the NI current grows (ray 2). After a 10-minute pulsed activation and inclusion of an auxiliary discharge the H^- current density in the initial part of the source reaches a new level of more intense generation (ray 3 in Figure 15).

In Figure 16 we show the stable maintained distribution of H^- current density from a multiaperture honeycomb SPS, obtained after 1.5 hours of activation with the aid of an auxiliary discharge of 25A current. Another successful method was uniform activation of the cathode surface by partial plasma recovery from the tail of the discharge along a drift cutoff channel in the ignition channel (see below).

Quasistationary SPS Models

In 1985 trials were carried out of honeycomb SPSs in the long-pulse (up to 0.6s) regime.[38] Construction of one of the models applied is shown in Figure 17.

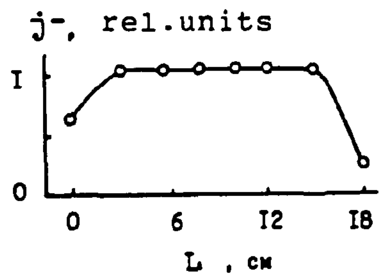


Figure 16. Distribution of H^- current along the length of the source after a 1.5- hour forced cathode activation by an auxiliary discharge. The current of the basic discharge is 500A; of the auxiliary, 25A.

To reduce pulsed overheating the cathode was made more massive and compressed air was passed through it along internal channels. The emitting surface of the cathode was covered by spherical holes with a radius of focus of 3.5mm. The holes were arranged on the cathode surface in a hexagonal or orthogonal ordering. The number of holes in the different variations ranged from 97 to 100. For more uniform activation of the cathode surface, a portion of the plasma along the drift cutoff channels (Figure 17) was recovered from the tail section of the discharge in the ignition channel. The operating substance - hydrogen and cesium - was supplied to the discharge through shaped thin slits in the body of the cathode. Extraction of the H^- ion beam was carried out through round emission holes of diameter 0.8-0.9mm.

A steady-state extracting voltage up to 18kV was applied to the body of the source. Extraction by a packet of short pulses of 1ms in length, of repetition frequencies up to 100GHz, was also applied. After a short period of treatment and heating the extracting electrode up to 800C, the difficulties with electrical stability of the extracting gap did not arise.

It was observed that in the regime of activated electrodes and uniform distribution of discharge current over the cathode surface, there exist several stable discharge modes, differing in the discharge voltage, discharge structure, and level of NI generation.

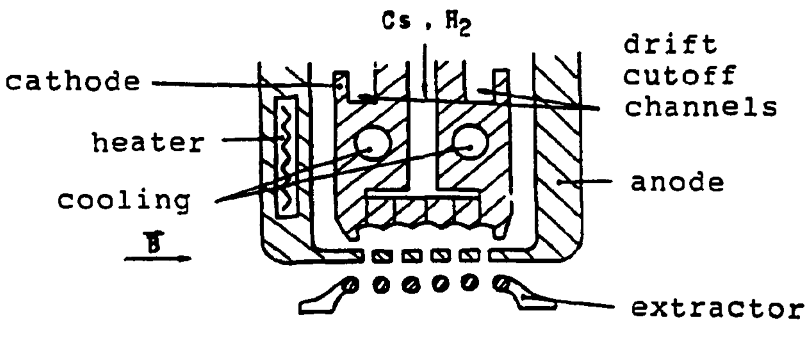


Figure 17. Model of a honeycomb SPS with electrode cooling and with electron drift cutoff channels.

The output of H^- ions is maximum for a discharge voltage of 150-130V (fundamental regime). In the intermediate regime with a discharge voltage of 60-40V the output of H^- was two times lower. Upon transition to the low-voltage mode of self-maintained discharge of 30-20V, the H^- output from the source decreased by a factor of 10 (for the same discharge currents). The low-voltage mode was observed upon electrode overheating.

A summary of the parameters of the models of honeycomb SPSs with orthogonal and hexagonal distribution of holes on the cathode for the fundamental regime is presented in the table[38]:

Arrangement of Holes	Ortho	Hexa
H^- ion beam current, A	0.9	0.6
Beam energy, keV	14	18
Pulse length, s	0.2	0.6
Total area of emission holes, cm^2	0.6	0.5
Beam cross-section in the ion-optic system, cm^2	2x5.5	2x6.6
Average density of H^- current in the beam, mA/cm^2	60	40
Discharge current, A	50	60
Cathode temperature, C	to 800	to 600

Conclusions

Research and development carried out at the Institute of Nuclear Physics, Siberian Branch, Academy of Sciences of the USSR, resulted in beams of negative hydrogen ions with a current intensity greater than 11A in the pulsed regime and of the order of 1A in long-pulse regimes for hydrogen-cesium SPS discharges. The basic problems of maintaining the surface-plasma mechanism on emitting surfaces of large area are solved by forced cathode activation with an auxiliary discharge or by drift cutoff channels. A quasistationary operating regime of such SPSs is successfully maintained by cooling and cathode thermostabilization.

Pure-hydrogen SPS regimes generate pulsed H^- ion beams with a 1A current and emission current density up to 1.1 A/cm^2. In the quasistationary pure-hydrogen regime an H^- beam with current up to 150mA is obtained.

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Note:

Expression in brackets [ ]* represents translator's best guess for meaning of abbreviation.