STUDIES OF SURFACE-PLASMA NEGATIVE ION SOURCES AT NOVOSIBIRSK

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The recharging method is often used to control particle flows in accelerator technology and magnetic controlled thermonuclear synthesis systems. This method permits use of a change in particle charge state to control motion in electric and magnetic fields, change the magnitude and direction of particle acceleration, "switch on" and "switch off" the action of macroscopic fields, affect particle distribution in phase space, etc.

G. I. Budker produced a significant contribution to the development of the recharging method for control of accelerated particle flows. He prosposed the use of dissociation of rapid molecular ions upon collisions with residual gas and plasma to fill magnetic hot plasma traps in his first study of mirror traps in 1954. At his initiative the Nuclear Physics Institute of the Siberian Branch, Academy of Sciences of the USSR developed a recharging method for proton injection into cyclical accelerators and accumulators [1, 2], together with physical bases for producing intense atomic beams of high energy hydrogen isotopes for injection into thermonuclear traps [3-6].

A convenient method for producing high energy hydrogen particles is stripping of accelerated negative hydrogen ions which easily lose their "excess" electron in collisions on the recharging target and have a high (0.6-0.9) coefficient of conversion into atoms over a wide range of particle energies.

Studies of H^- ion sources at the Nuclear Physics Institute of the Siberian Branch, Academy of Sciences of the USSR were begun in connection with development of the recharging method for proton injection into accelerators. For this purpose plasma sources were developed at the Institute (Elers type sources) with pulsed current up to 8 mA, together with recharging sources first at a current of 15 mA, later up to 100 mA. However the characteristics of these sources did not permit complete realization of the advantages of recharging injection so that the latter were not widely used in accelerators.

The situation with respect to production of negative ion beams improved radically after observation and experimental study of a new surface-plasma mechanism for negative ion formation in gas discharges [3]. Using this mechanism a number of surface-plasma H^- ion sources were developed for accelerators. Moreover, the surface-plasma method proved so effective that it could be used for development of high power negative ion sources for controlled thermonuclear synthesis.

Major contributions to development of surface-plasma sources were also made by laboratories in the USA (Brookhaven, Berkeley, Los Alamos, Oak Ridge, Fermi Lab), a number of laboratories in the Soviet Union, Europe, and Japan. These results are reflected in the proceedings of the International Symposium on Production and Neutralization of Negative Ions [7-9], accelerator conferences, and many other publications.

In the present study we will briefly consider the results obtained at the Nuclear Physics Institute of the Siberian Branch, Academy of Sciences of the USSR. Some achievements of these studies were considered in [4, 5, 10, 11], which offer citations of the original literature involved.

Studies of the Physical Basis of the Surface-Plasma Method for Producing Negative Ion Beams. The first major results which served as a base for development of the surface-plasma method for generating negative ion beams and surface-plasma sources were obtained at the Institute in 1970. At that time note was made of the possibility in principle of forming H^- ions due to secondary emission of negative ions upon bombardment by ions of surfaces with a reduced work function. Experiments performed revealed that upon bombardment of metal

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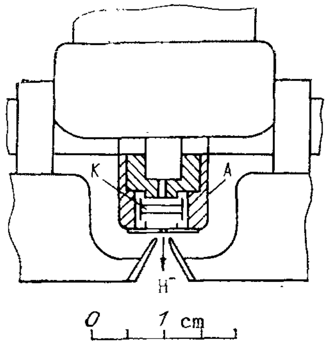

Fig. 1

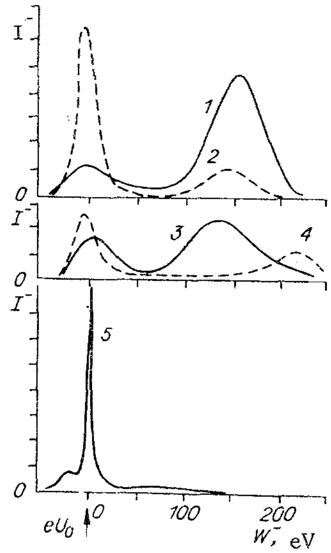

Fig. 2

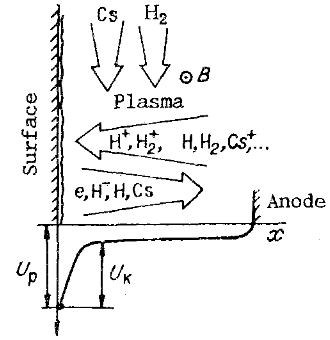

Fig. 3

surfaces by cesium ions in a hydrogen atmosphere the coefficient of secondary H^- ion emission can increase to 80%, with H^- ion current densities up to 10 mA/cm^2 [12].

At the same time techniques were perfected for extraction and formation of H^- ion beams with a magnetic field from high current glow discharges in gas discharge cells with planar magnetron (planotron) geometry. The important fact of reduction by several orders of magnitude of the flow of accompanying electrons extracted together with the beam from the emission slot was noted experimentally. For this to occur it is necessary that the size of the emission slot along the magnetic field be minimized, with the slot itself being oriented in the direction perpendicular to the magnetic field.

A plasma planotron is shown schematically in Fig. 1. Such a planotron has produced H^- ion beams with intensity <10 mA, but its construction served as the basis for subsequent surface-plasma sources. Thus, in 1971 it was found that upon addition of cesium vapor to the planotron gas discharge chamber, negative ion emission increased. Empirical optimization of the source led to an ion output up to 0.2 A with current density up to 1.5 A/cm^2. These values were improbably high for that time.

The picture was clarified by studies of the energy spectrum of negative ions extracted from the sources. Examples of such spectra are shown in Fig. 2. For low hydrogen density in the gas discharge chamber (curve 1, Fig. 2) the majority of ions in the H^- spectrum have an energy greater than that which corresponds to the voltage established across the discharge. With increase in hydrogen supply (spectrum 2) the fraction of accelerated ions becomes small. With increase in cesium supply to the discharge (transition from curve 4 to 3) the voltage the discharge decreased, the peak in the H^- ions accelerated by the full voltage shifted correspondingly, and the fraction of H^- ions within this peak increased. In spectra from a Penning cell (with the central plate of the planotron cathode K, Fig. 1, removed) ions with increased energy were not observed, and the energy spread was significantly less (curve 5).

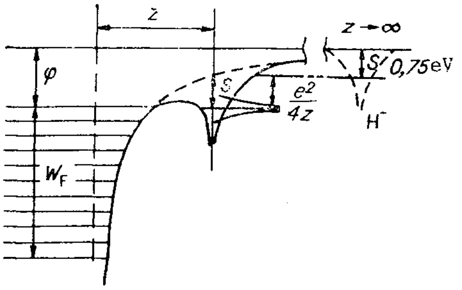

Fig. 4

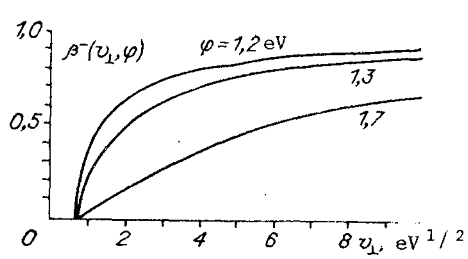

Fig. 5

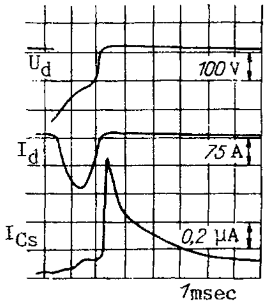

Fig. 6

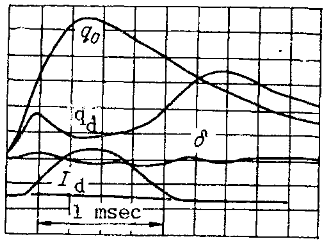

Fig. 7

From the results of these experimental studies the concept of the surface-plasma mechanism for negative ion formation in gas discharges was formulated, as illustrated by Fig. 3:

– in the gas discharge plasma positive hydrogen and cesium ions are formed;

– these ions are accelerated in the electrode space-charge layers and bombard the surface of the cathode or an additional electrode, a portion of the atoms of the working substances are adsorbed on the surface in states which favor subsequent emission in the form of negative ions;

– upon exchange of momentum between bombarding and adsorbed particles the latter escape the surface with superthermal velocities;

– as a result of electron exchange between the emitter and electron affinity levels of the deposited and reflected particles a portion of the latter (with high velocities away from the surface) depart beyond the surface barrier in the form of negative ions; with decrease in the surface work function due to adsorption of cesium the probability of negative ion formation increases significantly;

– the negative ions formed are accelerated by the electrical field in the electrode layer and can pass through the relatively thin plasma and gas layer to the beam formation system, while the remaining portion of the accelerated negative ions is destroyed and transformed to rapid atoms;

– the negative ions which fall into the electrical field of the formation system are accelerated and focused into a beam.

Since negative ion formation is controlled by a set of interrelated processes occurring within the plasma and on the electrode surface this mechanism has been called surface plasma. We will note that the high efficiency of negative ion formation by this mechanism is retained even under extremal conditions, with a discharge current density at the cathode greater than 100 A/cm^2.

The high (~ 1) degree of negative ionization of the desorbed hydrogen particles leaving the cesium-activated surface in experiments with surface-plasma sources did not agree with theoretical concepts which then existed. Thus it was assumed that for a surface work function $\varphi \sim 1.5$ eV and ion electron affinity $S = 0.75$ eV the probability of negative ion formation on the surface should be exponentially small, $\exp(S - \varphi)/kT$. A theoretical justification of the high rate of negative ionization was presented in [13], which called attention to the fact that upon approach of an atom to the surface its electron affinity level decreases and may prove to be lower than the Fermi level within the metal, as shown in Fig. 4 (W_f, Fermi level; φ, vacuum work function; z, ion's distance from metal). Under such conditions the electron affinity level is filled with electrons from the metal and upon rapid removal of the atom from the surface the "excess" electron may not be able to return into the metal.

Thus the rapid particle "carries off" an electron in its electron affinity level because of the kinetic energy imparted during bombardment. As a result, the probability of negative ion formation approaches unity for a work function of 1.5 eV and electron affinity of 0.75 eV, as existed in the H^- surface-plasma source. Further decrease in work function then makes possible formation of negative ions from particles with thermal velocities. The features of this mechanism were discussed in greater detail in [4].

Example calculations of the degree of ionization as a function of work function and the velocity of particle removal from the surface are presented in Fig. 5 (β^- is the degree of negative ionization of the departing flow; $v_\perp$, velocity of negative ion departure normal to surface).

After further optimization of conditions for negative ion formation the intensity of beams produced in surface-plasma sources in 1974 increased to 0.9 A, with emission current density up to 3.7 A/cm^2. Ion current density was increased to 6 A/cm^2 [4].

Study of surface-plasma source characteristics has shown that addition of cesium to the ion source gas discharge chamber leads to a reduction in voltage drop across the discharge from 400-600 to 100-200 V. Effective values of the secondary electron emission coefficient then increase from 0.1-0.2 to 5-6, while values of the negative ion secondary emission coefficient increase from 0.01 to 0.6-0.8 for H^- ions for single bombarding ions, a significant fraction of which are molecular ions.

Study of surface-plasma source characteristics revealed that the cesium atoms desorbed from the electrode surface are rapidly ionized in the plasma and transferred to the cathode in the form of ions. Thus, for burning of a discharge, the cesium is effectively confined in a thin cathode layer, which aids maintenance of a low work function and high efficiency of negative ion formation for high discharge current density. This effect is shown in Fig. 6 (U_d is the discharge voltage; I_d, discharge current, I_{Cs}, cesium current through the source emission slot). During the course of the discharge pulse the cesium removal is small, the cesium is "confined" to the cathode layer. Switchoff of the discharge voltage leads to an ejection of cesium, but the total quantity of cesium in the volume is small and after switchoff of the discharge voltage it rapidly deposits on the wall of the gas discharge chamber. In the final reckoning the cesium output from the surface-plasma source proves insignificant [14].

The above is also true of hydrogen, which is effectively confined by the plasma in the gas discharge chamber [15]. Figure 7 illustrates the hydrogen confinement effect (q_0 is the hydrogen flux from the source with discharge switched off, q_d, with discharge on at current I_d). In particular, for discharge in a surface-plasma source with planotron geometry up to 30% of the hydrogen exits through the emission slot in the form of negative ions.

In 1978 geometric focusing of the flow of negative ions emitted by the cylindrical surface of a plasma-surface source with semiplanotron geometry was accomplished [16]. This permitted increased energy efficiency, economy in negative ion gas generation, and decrease in specific cathode bombardment power.

In 1982 the ions emitted by spherical surfaces of special recesses in the cathode were geometrically focused [9, 17], increasing energy and gas efficiency of the plasma-surface source still more. In particular, to produce an H^- ion beam with current of 2.5 A in such a source with geometric focusing the energy expenditure was 10 kW.

With sufficient thickness of the plasma and gas target between the emitter and emission orifice, negative ions emitted from the surface and accelerated by the potential difference between the emitter and the plasma are effectively destroyed, being converted into accelerated atoms.

Direct recording of an accelerated atom flow from a surface-plasma source was performed in 1978. By recharging the atoms into H^- atoms their energy spectrum was measured. These spectra proved to be completely analogous to the high energy portions of the spectra shown in Fig. 2. The efficiency of accelerated atom production is comparable to the efficiency of H^- ion production. Thus, the surface-plasma mechanism for formation of negative ions can serve as an effective means of producing moderate energy fast atoms (100-200 eV).

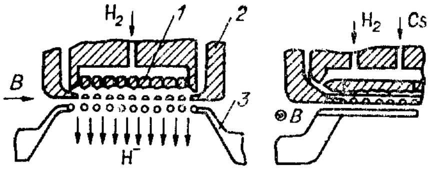

Fig. 8

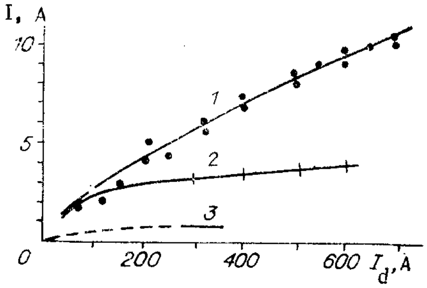

Fig. 9

In the surface-plasma source the atoms formed by destruction of primary negative ions can again be converted to H^- ions on surfaces with cesium. This effect can be clearly observed in a surface-plasma source with Penning geometry of the gas discharge chamber, in which rapid atoms bombard the emitting cathode surface at the same level as positive ions. As a result the negative ion output from these sources grows linearly with discharge current at a discharge current density up to 300 A/cm^2. The analogous dependence for a planotron reaches a maximum at a current density of 60-80 A/cm^2 and then falls off.

The results presented reliably confirm the dominant role of the surface-plasma mechanism in efficient production of negative ions. At present there is a good understanding of the basic processes involved in formation and destruction of negative ions in surface-plasma sources for controlled thermonuclear synthesis and high brightness beams for accelerators.

Development of Surface-Plasma Sources. After studies of the basic surface-plasma mechanism for negative ion formation were completed, they served as a basis for "conscious" design of surface-plasma sources. Improvements in source construction and supply systems, and development of methods for hydrogen and cesium feed permitted increasing the reliability of surface-plasma sources to the level required for application.

Studies of surface-plasma sources at the Institute led in two directions.

1. Various types of high current surface-plasma sources were developed for the controlled thermonuclear synthesis program. Special attention was given to achieving high level specific negative ion generation characteristics. Significant progress was achieved in realizing geometric focussing of negative ions at the emission orifice in the anode. Sources with cylindrical and spherical focussing produced H^- beams with currents up to 4 A at a mean current density in the extraction gap of 0.5 A/cm^2. In this case the local current density with spherical focussing (at the emission orifice) reaches 8 A/cm^2.

Good geometric focussing makes possible use of multiaperture formation systems. Thus, in a multiaperture honeycomb source with spherical focussing an H^- ion beam ∿12 A was obtained at a discharge current of 700 A, ion energy 20 keV, and pulse duration of 1 msec. The construction of this source is shown schematically in Fig. 8 (1, honeycomb cathode; 2, anode; 3, multiaperture extraction electrode). Figure 9 shows its emission characteristic (curve 1). For comparison, also shown is the H^- current from a honeycomb source with small cathode area and from a source without geometric focussing (lines 2 and 3). High current surface-plasma sources were considered in greater detail in [9, 17].

2. In designing surface-plasma sources for accelerators, together with questions of stability and reliability of operation, the question of obtaining high brightness in the beam is also important. Energetic efficiency is not of dominant importance. The majority of known surface-plasma source types operate in a region with direct extraction of the ions formed on the emitting surface. Since negative ion emission from the surface is the result of bombardment of the latter by particles from the discharge with an energy of ∿100 eV, the emitted ions have wide energetic and angular scattering. As a result, the effective temperature of the negative ions at the emitter comprises ∿10 eV. Beam brightness is proportional to the ion current emission density and inversely proportional to the ion temperature. From this it is clear that design for high beam brightness in sources of this type is not possible, and that the geometric focussing discussed above gives no gain in brightness.

The situation is different in a Penning geometry source (PGS). Its basic construction is shown in Fig. 10, where 1 is the lid of the gas discharge chamber, which serves as the anode; 2 is the gas discharge chamber body; 3 is the anode insert, on which the cathode module is mounted, consisting of the cathode itself 4, its cooler 5, and ceramic cathode insulators 6,

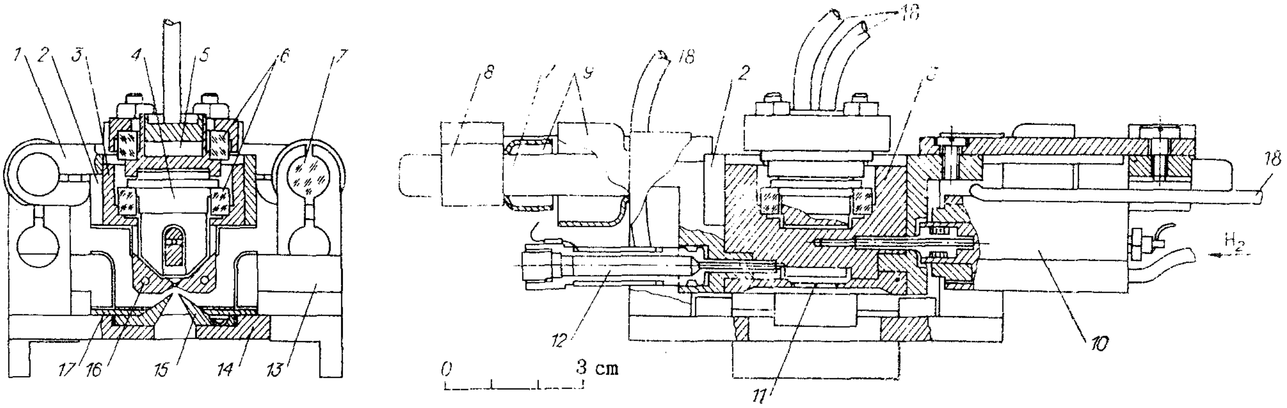

Fig. 10

7, which are high voltage insulators; 8 is the gas discharge chamber holder; 9, screens; 10, electromagnetic valve for hydrogen supply; 11, emission orifice (slot); 12, container with cesium; 13, magnet pole; 14, base; 15, extraction electrode; 16, cooling channels; 17, iron inserts; 18, water cooling tube.

In this source it is very difficult (geometrically) for ions formed on the emitting cathode surface to exit through the emission orifice into the extraction gap. The ion beam is essentially formed of negative ions produced in the vicinity of the emission orifice due to resonant recharging of rapid primary negative ions in the atomic gas. Numerous studies have shown that the ion temperature does not exceed 0.5-1 eV. In any case (see Fig. 2) the energy spectrum for a PGS is significantly narrower than for a planotron.

Since the section for resonant recharging is less than the section for ion destruction in the plasma, such a reduction in ion temperature is accompanied by a reduction in source output. However in the range of emission current density of practical interest, $\sim$1 A/cm^2, this reduction in output is fully compensated by the increase in beam brightness in the PGS.

In accordance with the above, for the Academy meson production project the Institute developed a PGS with nominal H^- beam intensity of 0.1 A, energy of 25 keV, with pulse duration of 250 μsec, repetition rate 100 Hz, with operation for up to 10^8 pulses [18]. This source realizes a normalized beam brightness of $3 \cdot 10^7$ A/(cm$^2 \cdot$rad^2). Oscillograms of voltages and currents characterizing source operation are shown in Fig. 11, where I_0 is the total current in the extraction gap circuit; I^- is the H^- ion beam current; U_d is the discharge voltage; I_d is the discharge current; U_0 is the extraction voltage.

A source with increased output was developed for purposes not requiring high beam brightness. It uses semiplanotron geometry with geometric focussing of the H^- ions on the emission slot [19]. This source is characterized by good stability of operation without fluctuations in discharge parameters. An H^- ion current of 0.1 A is reached at a discharge current of $\sim$20 A. Therefore when operated at a frequency of 50 Hz it does not require forced cathode cooling.

To produce low intensity H^- ion beams (up to 30 mA) a PGS was developed with circular emission orifice 1.5 mm in diameter. This source also requires no forced cooling at a duty cycle of ~300 and realizes a brightness of $2 \cdot 10^7$ A/(cm$^2 \cdot$rad^2) in a regime with fluctuating discharge.

It should be noted that PGS is characterized by a low content of heavy impurities in the ion beam (<1%), while plasma-surface sources of other types may have an impurity content of 7-10%.

Formation of a High-Brightness Beam. Conditions for formation of a high-brightness ion beam in a surface-plasma source were considered in [11, 20]. We will present their major results. A shaper system with one-dimensional beam focussing in a rotating magnet with falloff index $n \simeq 1$ was developed for convergence of a ribbonlike diverging beam into a parallel one. It is now generally used in the majority of plasma-surface sources.

1. A generalized characteristic of ion quality is its normalized brightness

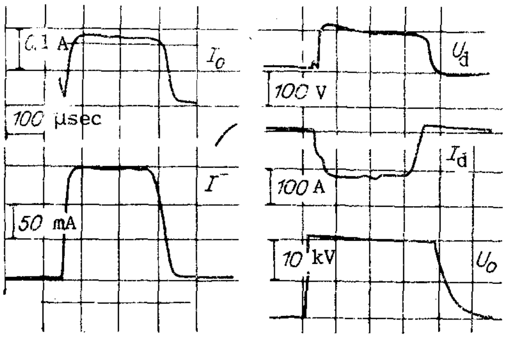

Fig. 11

$$B = \frac{2I^-}{\pi^2 E_x E_y} = \frac{2j^- Mc^2}{\pi^2 T_i},$$

where I^-, j^-, and T_i are the beam current, beam density, and ion temperature in the plane of the emission orifice; E_x, E_y, normalized beam emittence. A method for determining emittence is described in detail in [19]. Here we will only note that the width of the corresponding distributions was calculated from the 0.1 level to the maximum.

The expression on the right above defines the beam brightness which can be obtained under hypothetically ideal conditions. In reality additional heating of the beam always occurs, and consequently we must deal with the question of how great this heating is, and how much it can be reduced. A convenient characteristic of this additional beam heating, obtainable from emittence measurements, is the scattering of the energies of transverse ion motion, referenced to the emission orifice:

$$\Delta W_{0x} = \frac{2Mc^2E_x^2}{\delta^2}, \quad \Delta W_{0y} = \frac{2Mc^2E_y^2}{L^2}.$$

Here $\delta = 0.5$ mm is the size of the source emission slot along the magnetic field (the transverse x-coordinate in the beam section); $L = 10$ mm is the length of the emission slot (transverse y-coordinate).

2. An indispensable condition for minimization of additional heating is extraction of a stable beam with low fluctuation level (<1%). This in turn requires maintenance of a stable discharge in the course.

Aside from plasma instabilities, the oscillatory properties of a plasma-surface source discharge are affected significantly by fluctuations in the cathode emissivity caused by nonconstancy and inhomogeneity in the density of the cesium coating. These questions have yet to be completely clarified. It has been established experimentally that in sources with Penning and semiplanotron geometries it is necessary to decrease the magnetic field as much as possible and increase the supply of hydrogen and cesium.

3. Efforts to increase the brightness of intense beams ($\gtrsim$0.1 A) using high emission current density affect additional heating caused by aberrations in the extraction gap. Studies have shown that this heating for slot optics remains acceptable (0.1-0.3 eV) for a current density of 1-2 A/cm^2 and beam space charge related to emission current density by the "3/2" law.

If the magnetic field is not too high (<0.1 T) such a relationship is possible in a PGS, in which the form of the plasma emission boundary in the plane of the emission orifice is determined essentially by the space charge of the negative ions. The effect of this relationship is illustrated by Fig. 12. In other types of plasma-surface sources achieving this relationship is difficult. In such sources the plasma boundary is essentially determined by the space charge of electrons, since negative ions impinge on the boundary with a high directional velocity (energy of ∿100 eV). As a result, for them the plasma boundary is a highly nonlinear lens.

Another powerful heat source is related to the space charge of the negative ion beam. It can be compensated by positive ions of the residual gas, ionized by the beam. In the

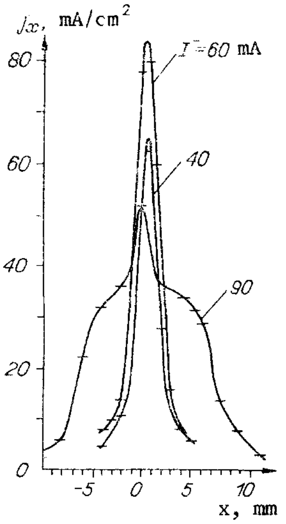

Fig. 12

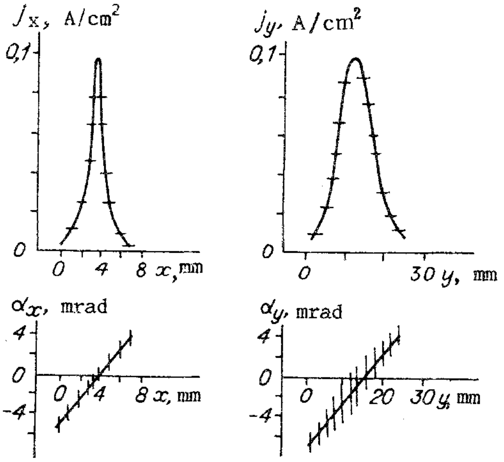

Fig. 13

case of hydrogen this requires a pressure of $0.5\text{-}1\cdot10^{-2}$ Pa. The compensation time then comprises 30-15 μsec. If the gas pressure is sufficiently high, achievement of an overcompensated state (gas focussing) is possible. For a beam with a high level of intensity fluctuations (20%), gas focussing improves emittence by a factor of 2-3 times. However for a stable beam it is better to maintain an undercompensated state, for in the opposite case oscillations can develop rapidly, producing a significant increase in emittence.

Forming a diverging beam into a quasiparallel one is accompanied by expansion, so that the local scattering in energy of transverse ion motion (the transverse temperature) should decrease to very small values of $\sim10^{-3}$ eV. However electric field fluctuations hinder achievement of such deep cooling. The residual energy scattering of $\sim10^{-2}\text{-}10^{-1}$ eV is equivalent to multiple heating of the beam. This has an especially great effect on increase in ΔW_{0x}, since the initial beam size in the x-direction is very small (0.5 mm).

We will note that even in a stable H^- ion beam fine scale fluctuations in current density with transverse dimension of ~0.1 mm develop, producing fluctuating transverse electric fields. Therefore, to maintain high brightness in an H^- ion beam during transport minimal transverse beam dimensions must be maintained, at which residual scattering in energies of transverse motion significantly exceeds the scattering produced by electric field fluctuation.

Having optimized beam formation conditions it was possible to reduce additional heating effects to a minimum. As a result an H^- ion beam was obtained with current of 40 mA, energy 22 keV, $E_x \simeq 7\cdot10^{-7}$ cm·rad, $E_y \simeq 1.4\cdot10^{-3}$ cm·rad, $B \simeq 8\cdot10^{8}$ A/(cm²·rad²), $\Delta W_{0x} \simeq 0.4$ eV, $\Delta W_{0y} \simeq 0.3$ eV. Current density distribution and phase diagrams of this beam are presented in Fig. 13.

The basic achievements of the studies performed are the following: 1) an effective surface-plasma mechanism for generation of multiampere currents of negative hydrogen ions was discovered and studied; 2) physical processes in several types of surface-plasma negative ion sources were studied; 3) surface-plasma ion sources were developed for accelerators with high brightness and current of the order of 100 mA; 4) a prototype pulsed negative hydrogen ion source was developed for atomic injectors in thermonuclear devices with a current of the order of 10 A.

All experimental studies and development were performed with small scale (portable) apparatus. There is no doubt that stationary D^- ion sources with currents of 10-20 A can be developed, which would allow production of atomic beams at power levels of the order of 10 MW for controlled thermonuclear synthesis purposes. However that task will require creation of large-scale high-power experimental modules.

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