REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 73, NUMBER 2 FEBRUARY 2002

Tandem surface–plasma source: A new concept for a dc negative ion source

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(Presented on 6 September 2001)

The newly developed tandem surface–plasma source (SPS) concept is expected to break new ground in the production of high-current, high-brightness H^- ion beams. The tandem SPS consists of three successive separate stages: the multipole plasma driver; the H^- ion generator with a low-voltage closed converter, and the ion extraction and beam formation system. To date the plasma driver stage has been designed, and is anticipated to produce an intense plasma stream with high efficiency (low energy-per-ion expenditure). The atomic processes in the second stage have been analyzed, the anticipated result is a dense population of H^- ions with a very low temperature. The tandem SPS source is expected to produce dc beams of H^- ions with currents up to 50 mA and pulsed H^- beams at large duty factors with currents up to 100 mA. [DOI: 10.1063/1.1432468]

Surface–plasma sources (SPS) of H^- ions are distinguished in the way of plasma generation. There are three main kinds: magnetron (planatron) SPS, Penning SPS which were originated by Belchenko, Dimov, and Dudnikov,[1] and multicusp with a converter developed by Ehlers and Leung.[2] Later Leung *et al.*[3] and Okumura *et al.*[4] discovered that the H^- output was enhanced many times by seeding cesium into a volume source. Seidl *et al.*[5] proposed a superthermal H-atom source of H^- ions with an external cesiated converter.

There are difficulties with dc one-aperture H^- ion sources for accelerators with long-term operation. In a magnetron SPS and multicusp with an internal converter, large amounts of cesium are consumed, and its accumulation leads to a breakdown of the sources. The Penning SPS works at high hydrogen pressure in the discharge, and its operation time is limited by the erosion of electrodes. Use of hollow cathodes in the Penning SPS (Ref. 6) may essentially increase its lifetime.

The proposed tandem SPS can operate for a long time in a dc regime. It consists of successive separate stages (see Fig. 1): a multipole plasma driver and a H^- ion generator with a closed Cs/Mo converter and, as usual, an ion extraction and beam formation system. Thanks to small consumption in the converter at low voltage $\sim$25 V,[7] a cutoff potential drop between the driver and converter plasmas, and very small cesium ionization length in the converter $<10^{-4}$ cm, the cesium vapor cannot pass into the driver. The absence of cesium in the driver makes sputtering of a hot cathode there very weak, and one may use a tablet of heated LaB_6.[8] Full separation allows for better optimization of plasma generation in the driver, H^- ion generation in the converter, and ion extraction system with a magnetic filter for suppression of the electron escape. Near-cylindrical systems of permanent NbFeB magnets form a good multipole magnetic trap for hydrogen plasma confinement in the driver. This allows one to hopefully obtain an intense ion flux with high-energy efficiency.

The plasma comes into the second stage from the driver through a pass hole with the magnetic field existing only near a wall. A cylindrical top part of the converter is 2.9 cm in diameter and is inserted into this hole (see Fig. 1). Some ions from the driver will strike this pass cylinder and reflect as H atoms and H^- ions. The main ion flux will come into the converter. Before the pass hole, we anticipate to obtain plasma with a density $\sim 5\times 10^{12}$ cm^{-3}, temperature of the molecule ions of 0.5–1 eV, and electron temperature $\sim$3 eV. The plasma will come into a confuser collisionally with a magnetic wall and outflow with the velocity of the ion sound at the critical cross section into a flow nozzle diffuser. Since the time of energy exchange between the ions and electrons is very large, each stream of the ions and electrons is isentropic. In our model the ion stream consists of ${H_2}^+$ ions only. From the energy and Bernoulli equations we find the following parameters in the cross section: ion density 3.3×10^{12} cm^{-3}, H_2^+ ion energy 2.5 eV, and H_2^+ current $I_j = 3.43$ A. At the exit from the pass cylinder the density and electron temperature fall, H_2^+ ion energy becomes $E_j = 4.5$ eV. The electrons are confined in the pass cylinder by the electrostatic potential φ. From the Bernoulli equation for the electrons $ed\varphi = kT_e dn/n$, where T_e is the electron temperature and n is the ion density. The potential drop in the pass cylinder is $\Delta\varphi = 3.5$ V.

When the injected H_2^+ ions fall to the converter, a primary flight (hot) atom flux originates with the current, which is 1.6 times larger than the injected ion current $I_j(\langle E_{1a}\rangle \approx 10\text{ eV})$ and H^- ion flux is generated. Many hot atoms originate when the H^- ions hit the converter. The H_2 molecules and atoms are ionized by the rapid electrons and fall on the converter with the nucleon current I_{ni} and originate from the hot atom flux, too. The primary atoms fall on the converter, the majority of them are reflected with the loss of

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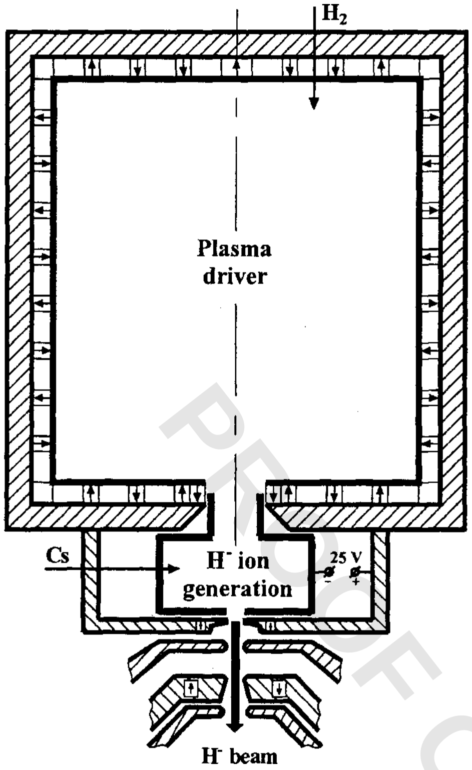

FIG. 1. Schematic diagram of the tandem SPS.

their energy $\sim$30%. The cascade of subsequent reflections of atoms from the converter leads to a decrease in their energy down to binding energy $E_s = 2.7$ eV, and the atom flux decreases due to losses through the pass cylinder. An experiment on the interaction of deuterium with niobium ($E_s = 2.5$ eV) demonstrated a fast decrease in reflection at energies $\leqslant E_s$.[9] Probably, the slow atoms with energy $\leqslant E_s$ lingered on the surface and were cooled. They could not linger very long, because the surface was irradiated by a large flux of fast atoms and ions. Cold atoms come from the surface with delay and form a population with low-temperature $T_{\mathrm{ac}} \leqslant 1$ eV in the converter.

Measurements of the temperatures of the atoms T_{ac} and H^- ions $T_{\mathrm{H}_c^-}$ in the Penning SPS (Ref. 10) showed that $T_{\mathrm{ac}} \approx T_{\mathrm{H}_c^-}$, and with dc discharges $T_{\mathrm{H}_c^-} < 0.4$ eV. Probably, the cooled atoms originated when particles hit the electrodes. In our case the temperature of the atoms confined in an almost closed volume by the cooling walls will possibly not exceed 0.5 eV. From the analytic study of the atom generation in a spherical converter, it follows that the summary hot atom current $I_{\mathrm{ah}} = 7I_j + 3I_{\mathrm{ni}}$, and the slow atom current which is not reflected and leads to the cold atom accumulation is $I_{\mathrm{ac}} = 1.4I_j + 0.75I_{\mathrm{ni}} + I_{\mathrm{FC}}$.

When the ions hit the converter, the potential ion–electron emission appears. Regardless of the energy, 0.2 electrons are emitted per proton.[11] In the experiments[5] on irradiation of a Cs/Mo surface by thermal atoms with temperature 0.23 eV, electron emission was observed with a current of 0.7 of the emission H^- ion current. The H^- ions may be generated on the surface only when the energy of the incident atoms is $>(\Phi - S) \approx 1$ eV.[6] Here, Φ is the work function and S is the electron affinity. Probably, hydrogen atoms with the energy $E_a > \Phi - S$ produce electrons as a result of many-particle Auger transitions in the $\mathrm{H} \rightarrow \mathrm{H}^- \rightarrow \mathrm{H}$ processes close to the surface. For fast ions and fast atoms ($E_a > 3$ eV), we took the electron yield about 0.2 electrons per nucleon, but for the Maxwellian tail of the cold atoms with energy >1 eV and Frank–Condon (FC) atoms, we took the yield 0.02 electrons per atom, which is close to the yield of the H^- ions evaluated from its energy dependence.[11] Emission electrons from the converter will be accelerated in the Debye layer, fly from the converter with the energy $E_{\mathrm{efl}} \geqslant 25$ eV, and come to the opposite wall causing SEE with the coefficient $\gamma_{\mathrm{se}} \sim 0.4$.[12] Subsequent SEE of the secondary electrons will lead to multiplication of the primary rapid electrons by the factor γ.

When the injected H_2^+ ions hit the converter with the energy 30 eV, the flight H^- ion flux originates from the current $0.4I_j$ (Ref. 11) ($\langle E_{1\mathrm{H}^-} \rangle = 35$ eV). When the primary hot atoms hit the converter, the flight H^- ion flux originates from the current $0.32I_j$ (Ref. 11) ($\langle E_{\mathrm{H}^-} \rangle = 32$ eV). The ionized H_2 molecules and H atoms with energy of 25 eV, which fall on the converter, cause origination of the flight H^- ion flux. Some flight H^- ion flux originates by secondary, tertiary, and charge-exchange fast atoms. The analytic study of the H^- ion generation in the spherical converter by injected ions made it possible to evaluate the flight H^- ion current by the value $1.08I_j$. The Frank–Condon atoms and Maxwellian tail cold atoms ($T_{\mathrm{ac}} = 0.5$ eV) produce about 2% and 3% of H^- ions, respectively.

The current of the rapid electrons can be determined by the relation

$$I_{\mathrm{cr}} = \frac{2\gamma k_r(1+a_j)I_j + \gamma k_a I_{\mathrm{amt}} + \gamma k_r(1+a_i)I_{ni}}{1 - 2\gamma k_a \sigma_d I \nu n_{\mathrm{H}_2} + (n_{\mathrm{H}_2}\sigma_{\mathrm{ir}} + n_{\mathrm{ac}}\sigma_{\mathrm{irc}}) l \nu/2}, \qquad (1)$$

where k_r is the electron yield per nucleon for the fast ions and atoms ($E_a > 3$ eV), k_a is the electron yield per nucleon for the Maxwellian tail of the cold atoms ($E_a > 1$ eV), $I_{\mathrm{aml}} = \eta_{\mathrm{ac}} \langle v_{\mathrm{ac}} \rangle V/l$ is the current of the Maxwellian tail cold atoms ($E_a > 1$ eV) to the walls, η is their portion in the population, $\langle v_{\mathrm{ac}} \rangle$ is the average velocity of the cold atoms, a_j is the summary yield of the fast atoms $E_a > 3$ eV per nucleon for the injected ions, a_i is the summary yield of the fast atoms per nucleon for the ionized H_2 and H_c, σ_{ir} and σ_{ira} are the cross sections of ionization of H_2 and H_c by rapid electrons, σ_d is the cross section of dissociation of H_2 by rapid electrons, ν is the increase factor of the rapid electron lifetime by scattering of the electrons on the H_2 molecules, n_{H_2} is the density of the H_2 molecules, V is the volume of the converter, and l is the average path between the converter walls for the flight particles. The nucleon current of the ionized hydrogen

$$I_{\mathrm{ni}} = (2n_{\mathrm{H}_2}\sigma_{\mathrm{ir}} + n_{\mathrm{ac}}\sigma_{\mathrm{ira}}) l \nu I_{\mathrm{er}}. \qquad (2)$$

The density of the cold atoms is calculated from the following equation:

$$n_{\mathrm{ac}} = (2/V)[c_j I_j + c_i I_{\mathrm{nt}} + n_{\mathrm{H}_2}\sigma_d l \nu I_{\mathrm{er}}]\tau_{\mathrm{ac}}, \qquad (3)$$

where c_j is the yield of the slow atoms per nucleon for the injected ions, c_i is the yield of the slow atoms per nucleon for the ionized H_2 and H_c, and $\tau_{\rm ac}$ is the lifetime of the cold atoms.

Equations (1) and (3) allow us to determine the values of $I_{\rm er}$ and $n_{\rm ac}$ without taking into account the production of the Franck–Condon atoms by the reaction: $e+H_2^+\rightarrow 2H$. The density of the rapid electrons with the initial velocity $v_{\rm er}$

$$n_{\rm er}=\frac{l\nu}{\nu_{\rm cr}}\frac{I_{\rm er}}{V}. \tag{4}$$

The density of the warm electrons formed by ionization of hydrogen

$$n_{\rm ew}=\frac{8(n_{H_2}\sigma_{\rm ir}+n_{\rm ac}\sigma_{\rm ira})l\nu I_{\rm er}}{\langle v_{\rm ew}\rangle S_p}, \tag{5}$$

where $\langle v_{\rm ew}\rangle$ is the average velocity of the warm electrons and S_p is the cross section of the pass cylinder. The initial average energy of the warm electrons is about 5 eV, and their maximum energy is 10 eV. The time of the energy exchange of the warm electrons is close to the time of the energy loss on H_2 excitation and is larger than its lifetime. The density of flight H^- ions

$$n_{H^-_{\rm fl}}=[2g_jI_j+g_iI_{\rm ni}+2Y_{\rm FC}\sigma_d l\nu n_{H_2}I_{\rm er} + Y_{\rm at}\eta\langle\nu_{\rm ac}\rangle n_cV/l]\,\frac{1-\exp(-n_{\rm ac}\sigma_{\rm tr}l)}{n_{\rm ac}\sigma_{\rm tr}\langle\nu_{H^-_{\rm fl}}\rangle V}, \tag{6}$$

where g_j is the total yield of the flight H^- ions per nucleon for the injected ions, g_i is the total yield of the flight H^- ions per nucleon for the ionized H_2 and H_c, $Y_{\rm FC}$ is the yield of the flight H^- ions per nucleon for the Frank–Condon atoms, $Y_{\rm at}$ is the yield of the flight H^- ions per atom for the Maxwellian tail of the cold atoms ($E_a>1$ eV), $\langle v_{H^-_{\rm fl}}\rangle$ is the average velocity of the flight H^- ions, and $\sigma_{\rm tr}$ is the cross section of the charge-exchange $H^-_{\rm fl}+H_c$.

The density of the cold H^- ions originating in the charge exchange of the flight H^- ions with the cold atoms is determined by the equation

$$n_{H^-_c}=\frac{\langle n_{H^-_{\rm jt}}\rangle n_{\rm ac}K_{\rm tr}}{n_{i+}K_{\rm rec}+n_{\rm er}K_{\rm de}+n_{\rm ew}K_{\rm dew}+n_{\rm ac}K_{\rm ad}+1/\tau_{H^-_c}}, \tag{7}$$

where $K_{\rm tr}$, $K_{\rm rec}$, $K_{\rm dc}$, $K_{\rm dew}$, and $K_{\rm ad}$ are the reaction rates $\langle\sigma v\rangle$ of the charge exchange, recombination, detachment by the rapid electrons, detachment by the warm electrons, and associative detachment, respectively; n_{i+} is the summary density of the positive ions; $\tau_{H^-_c}$ is the lifetime of the cold H^- ions determined by their escape through the pass cylinder. The cold H^- ions are collisional ($\lambda_d\approx 0.4$ cm), therefore, they flow out with the velocity of the ion sound at the pass cylinder entrance.

From the condition of quasineutrality it is necessary that $n_{i+}=n_{H^-_c}+n_{H^-_{\rm fl}}+n_e$. If the densities of the ${H_2}^+$ and H^+ ions are inadequate, their lifetimes increase due to confinement of the slow ions in a potential well of small depth (~1 eV). Such a potential well is formed in a self-acting way in the converter. The positive ion density should not be allowed to increase (by decreasing the hydrogen density) in order not to let the electron density increase.

The lifetime of the hot atoms with average energy of 4.5 eV is determined by their average time of flight. Their density is more than ten times smaller than the cold atom density. In the charge exchange of the flight H^- ions on the hot atoms, a population of hot H^- ions is formed. The hot ion density is determined by an equation similar to Eq. (7). But, here the influence on the hot H^- ion lifetime of the secondary charge-exchange process between the originated hot H^- ions and cold atoms prevails. As a result, the majority of hot H^- ions are substituted by cold H^- ions. The hot H^- ion density becomes very small, less that 1% of the cold H^- ion density.

We have adopted the converter in the second stage in the form of a cylinder with the height equal to its radius $r_c=3$ cm. The converter volume is $V=85\ {\rm cm}^3$. From our estimation $l=r_c$. We take $n_{H_2}=2\times10^{14}\ {\rm cm}^{-3}$ (5.6 mTorr).

From Eqs. (3) and (1) we find $n_{\rm ac}=6\times10^{13}\ {\rm cm}^{-3}$ and $I_{\rm er}=1.5\times10^{20}\ {\rm s}^{-1}$. From Eqs. (4) and (1) we obtain $n_{\rm er}=0.9\times10^{11}\ {\rm cm}^{-3}$. From Eqs. (5) and (1) we find $n_{\rm ew}=2.8\times10^{11}\ {\rm cm}^{-3}$, Thus, $n_{\rm e}=n_{\rm er}+n_{\rm ew}=3.7\times10^{11}\ {\rm cm}^{-3}$ if density of cold electrons (from plasma driver) $n_{\rm ec}\ll n_{\rm ew}$. From Eq. (6) we obtain $\langle n_{H^-_{\rm fl}}\rangle=1.5\times10^{11}\ {\rm cm}^{-3}$. From Eq. (7) we obtain $n_{H^-_c}=1.45\times10^{12}\ {\rm cm}^{-3}$ and $n_{i+}=2\times10^{12}\ {\rm cm}^{-3}$ (together with the quasineutrality condition). The hot H^- ion density ($\langle E\rangle\approx4.5$ eV) is $10^{10}\ {\rm cm}^{-3}$.

Thus, it seems possible to form a population of cold H^- ions ($T\sim0.5$ eV) with a density $\sim1.5\times10^{12}\ {\rm cm}^{-3}$ in the second stage. The hydrodynamic current density of the cold H^- ions can be up to 135 mA/cm^2. In order to obtain a high-quality H^- ion beam, it is necessary to exclude the presence of escaping flight H^- ions ($\langle E\rangle\sim30$ eV) at LEBT.

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