Dc tandem surface-plasma source of H^- ions with current up to 100 mA

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The conceptual project of neutral source for the Boron Neutral Capture Therapy at hospitals was developed on the basis of the proton electrostatic tandem accelerator with neutron generation using $^7Li(p,n)^7Be$-reaction [1].

The dc source of ions H^- with current about 50 mA is required for such accelerator for generation of neutron flow of optimal intensity.

The following requirements are made for H^- ion source:

- High reliability, long life.
- The dc current H^- ions is due to exceed the accelerated current, taking into account loss of H^- ions in the low energy transporting channel caused by cutting off the "tails" of beam ions with higher transverse energy and by their destruction in the source output gas before injection into accelerator.
- Normalized emittance (90 %) of the ion beam $\varepsilon_n \sim 0.3\ \pi$ mm mrad.
- H^- ion energy $E_i \geq 35$ keV (the lower growth of emittance caused by space charge effect at higher ion energy).
- Cesium consumption $Q_{Cs} < 5$ mg/hour (otherwise the reliability of the H^- ion source operation will not be high).
- Gas effectiveness $\eta_{gas} \geq 2$ % (otherwise too many H^- ions will lose of electron in the gas flowing out, and high power pumps will be necessary to pump out gas from vacuum chamber of the H^- source).

To satisfy the requirements (especially in emittance, reliability, and the operation endurance) the tandem surface -plasma source (tandem SPS) for H^- ions was proposed [2]. The design of such experimental ion source with current up to 100 mA is shown in Fig. 1 (longitudinal section). The dimensions are: overall height – 54 cm, diameter – 26 cm. Tandem SPS consists of 3 successive separate stages. From the top a multipole plasma driver injects an intensive stream of positive ions into the second stage with low-voltage near-closed Cs/Mo converter generating H^- ions. From the second stage the H^- ion current as usual goes to the ion optical system (IOS) for extraction, acceleration and beam formation (downstairs).

The main advantages of tandem SPS are the following.

1. Full separation of stages
- Allows to better optimize plasma generator, converter for negative ion generation, IOS and magnetic filter for attendant electron flux suppression.

2. Cs density limitation in plasma generator
- Low density of Cs vapors in converter due to its low consumption at low voltage on the converter $U_c \leq 50$V.
- Cs atoms run in the converter $\lambda \sim 1$mm $<< L_c$.
- Cs^+ ions in the converter are reflected at the outlet to plasma generator by electric field in the entrance (connecting) nozzle $\Delta\varphi \sim 3.5$V.

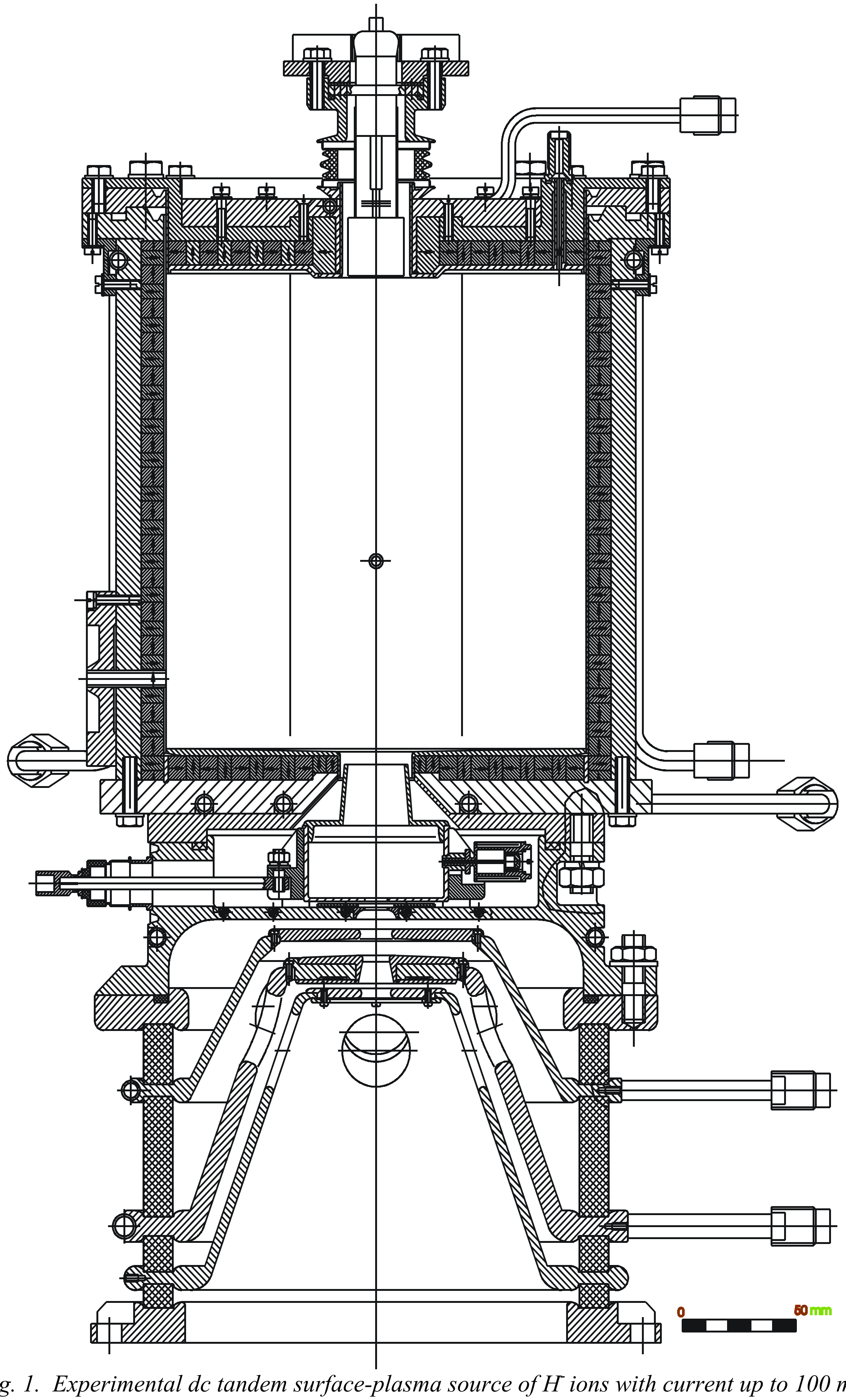

Fig. 1. Experimental dc tandem surface-plasma source of H^- ions with current up to 100 mA (longitudinal section).

3. Converter is almost closed

- Positive ion falling to the wall generates a cascade of reflecting particles in almost closed converter, increasing negative ion H_s^- output from Cs/Mo surface by about 2–2.5 times.
- Dense population of cold H_c atoms is maintained with limited losses.
- The population of cold negative H_c^- ions formed during charge-exchange of flight H_s^- ions on cold H_c atoms is kept in an almost closed electrostatic trap.
- Ionization of hydrogen by accelerated electrons from the walls in the converter generates additional ion flux to walls.
- Hydrogen ionization cross-section is large $\sigma_{ie} \sim 10^{-16}$ cm^2 due to high energy of electrons $E_{eac} \sim$ 50eV. Nevertheless the cross-section of H^- ions destruction by these electrons is $\sigma_{det} \sim 30\ \sigma_i$. But at $n_{H_2} \sim 100\ n_{H^-}$ about 3 additional H^- ions will be generated for one destroyed ion.
- Hydrogen molecules dissociation by fast electrons to Frank–Condon atoms increases density of slow atoms.

4. Keeping cold atoms by walls

- Low sticking coefficient ~ 0.2, $J_{back} \sim 0.8\ J_{ac}$.
- Sputtering of chemisorbed atoms by fast particles $J_{sput} \sim 0.15\ J_{ac}$.
- Exchange desorption of cold atoms from quasi-cluster chemi-states by superbarrier atoms coming from vacuum is $J_{ch} \sim 0.03\ J_{ac}$.
- Atoms incoming into the wall at the expense of H_2 molecules dissociative adsorption, fast atom implantation and associative desorption of atoms as H_2 molecules play a role in balance of atom fluxes.

5. Atoms cooling by walls

- Fast atoms (atomic energy E > bonding energy E_s) penetrate into metal, non-reflected ones cool and come out into chemisorption layer.
- Slow ($E \sim E_s$) and cold ($T \ll E_s$) atoms are partially trapped into the chemisorption layer and loose the energy for heating of the surface, desorption of the trapped atoms, electron emission and irradiation. The rest of them penetrate immediately into metal, cool and return into the chemisorption layer.
- At sputtering from chemisorption layer by fast particles, the average velocity of sputtered atoms increases, but remains lower than the sputtering atoms velocity.
- Atoms getting off into vacuum due to exchange desorption have low average energy $\ll E_s$.

The source of ions H^- design.

From the top of the ion source drawing in Fig. 1 is shown the structure of the first stage of the ion source - plasma driver (longitudinal section). Plasma driver is a magnetic multipole trap for low-temperature plasma. The shape of the trap is close to the cylindrical. Due to its shape the trap doesn't have any docking gaps in the magnetic wall, which usually cause considerable plasma leaks. The magnetic wall is created by permanent NdFeB magnets. Magnets of the wall are set on the inside surface of the pure iron magnet yoke. Flowing water cools down the iron yoke to prevent NdFeB-magnets from overheating by gas discharge in the vacuum chamber. The permanent magnets wall thickness is 10 mm. Magnets of the wall form circular (polygonal) magnetic poles of alternating polarity with a step of 13 mm. The circular poles have width of 5 mm. Circular magnets insertion between the poles have length of 8 mm to reinforce the field in the poles. On the surface of the poles the magnetic field is about 6-7 kG. The multipole magnetic field inside by the magnets wall is ~2 cm of depth and the field in its capacity is 20-30 G.

There is a stainless steel vacuum chamber inside, adjoining the magnets wall. Its thickness is 1mm in its cylindrical part and up to 2 mm in the butt-ends. The upper butt part of a chamber together with a wall of magnets is made as a removable lid, which allows controlling the inner surface of a vacuum chamber.

There is a fixed cathode along the chamber axis, on which gas-discharge voltage of ~150 V is applied. The experimental ion source has a mounting of a LaB_6 -cathode with continuous emissive current up to 20 A. The lifetime of such cathode in vacuum is more than 2000 hours, however lifetime will be significantly less even in pure hydrogen plasma. The operating ion source can use a hollow plasma impregnated cathode, which has the lifetime ~10^4 hours. To limit ingress of plasma into the circular gap near the cathode a magnetic field of ~3.5 kG is established at its entrance. The field of ~2 kG appears on the cathode's surface and expands towards the trap. Electrons leave the cathode along the lines of this field towards the cylindrical surface of the trap, where they enter areas with low magnetic field 20-40 G before a multipolar barrier 5-6 kG. Electrons scattering in gas and losing the adiabatic property in such areas (magnetic wells) have their average transverse energy much larger than radius of energetic holes in the multipolar wall. Then the fast cathode electrons diffuse from cylindrical circumference to the main capacity, continuing to ionize the gas. Gas (hydrogen) itself is injected into the vacuum chamber from the above through the tube.

To let plasma into the second stage, there is a hole in the magnetic wall with diameter of 32 mm along the axis at the bottom. To diminish plasma leaks there is a tangent magnetic field established on the edges of the hole with depth of ~ 5 mm and average value of ~ 1 kG. Magnetic field of ~ 200 G, directed along the axis, correspondingly appears in the main paraxial part of the hole. The ion flux freely leaks out of the magnetic trap without significant losses on the edges of the hole.

The configuration of the total magnetic field in the trap allow to hold generating plasma and fast electrons ionizing gas coming from the cathode. The cathode electrons directly do not come in the bottom hole.

The second stage structure – negative ions generator is shown in the middle of the ion source longitudinal section in Fig. 1. Near-closed cylindrical converter with diameter of 6cm and of 3cm height is situated in the case made of stainless steel. The upper butt part of cylinder is combined with a truncated cone to lead plasma into converter from the magnetic trap of the first stage. The converter is made of vacuum melted molybdenum. It is fixed on the case through four ceramic isolators. Through the ceramic feedthrough isolator from the left the negative potential ~ 45 V is connected to the converter from the power supply by direct current of up to 8 A. Expected power emerging in the converter is ~ 300 W. Main heat elimination is realized by four ceramic insulators. The working temperature of the Cs/Mo converter is about 200^{o}C. The second stage structure provides the temperature control using thermocouple.

The dispenser for inflow cesium vapor in the converter is connected to it from the right (it will displace from the inside to the outside of the case in operating ion source). Cesium vapors density has to allow keeping ~ 0.6 of cesium monolayer on the surface of molybdenum. Here cesium consumption will be less than 1mg/hr. The cesium dispenser is a small cylindrical oven, which the extruded cesium chromate and titanium mixture pellets are put in. After the oven is heated up to ~ 700^{o}C pellets extract cesium and the oven can let it out heated to ~ 200^{o}C.

The double emissive hole in the bottom of the converter and in the case (11 mm in its diameter) serves for letting the negative H^- ions generating in the converter out. The emissive molybdenum electrode, which is the first electrode of the following IOS, is pressed in around the emissive hole in the case.

To limit the accompanying electrons getting into the IOS, there is a magnetic filter fixed around the emissive hole on the inner surface of the case under the converter. The filter consists of a 1mm thick iron screen with aperture hole 60 mm × 16 mm and thin SmCo-magnetized plates 90 mm long and 0.5 mm in thickness. The magnetized plates are fixed underneath on the iron screen. The magnetic filter generates the transverse magnetic field ≥ 50 G in the double emissive hole limiting its sagging into the converter at < 1 cm. Electrons are removed mainly along the magnetic field.

Downstairs of the ion source drawing in Fig. 1 IOS is shown. It is constructed as accelerator tube for 35 keV. The upper flange, which the second stage of the source with the first emissive electrode is fixed to, is under negative potential 35 kV with respect to the lower grounded flange.

Positive potential ~ 10 kV with respect to the first electrode is applied to the second extracting electrode. The third accelerating electrode is under positive potential ~ 1 kV with respect to the earth. It serves to capture the accelerated electrons and reflect positive ions, which are generated in the outgoing negative ion beam and compensate their space charge. The fourth electrode is under the earth's potential; it is isolated from the earth in order to control the IOS operation.

All electrodes are made sectional. The paraxial parts are made of molybdenum. The main peripheral parts of the second and third electrodes are made of copper in order to achieve good heat conductivity, because these electrodes will be used to catch accompanying electrons, and the permanent SmCo-magnets are installed into the third electrode. The outer circular parts of the third and fourth electrodes in the atmosphere are cooled down by the flowing water.

For the purpose of increasing the electrical durability of the IOS and reinforcing of the electrons outgo sideways from accelerator channel, magnetic field has to be increased from the emissive hole along the accelerator channel till the third electrode. The two SmCo-magnetized plates 65 mm × 17 mm and 1.5 mm thick, installed on the back side of the third electrode along the plates of the magnetic filter after the converter, serve for. The overall transverse magnetic field increases and on the third electrode achieves the value ~ 200 G. In this field the H^- ions move along the curve and in the hole of the third electrode they shift across ~ 0.5 mm, which can even be non-compensated by the corresponding hole-shift.

We hope to obtain the next results.

- Ion density in the driver (mainly molecular H_2^+, H_3^+) ~ 3×10^{12} cm^{-2}.
- Current of the molecular ions injection from plasma generator ~ 3 A.
- Positive ion current due to ionization of hydrogen in the converter ~ 3 A.
- Expected density of flight H_s^- ions in converter from the surface > 10^{11} cm^{-3}.
- Expected density of cold atoms H_c in the converter ≤ 10^{14} cm^{-3}.
- Expected density of cold negative H_c^- ions in the converter ~ 2×10^{12} cm^{-3}.
- Expected temperature of cold H_c atoms and H_c^- ions ~ 0.3 eV.
- Expected current density of the negative H_c^- ions ≥ 100 mA cm^{-2}.
- The H^- ion beam current > 50 mA.
- Normalized emittance (90 %) of the H^- ion beam ε_n < 0.5 π mm mrad.
- Gas efficiency ≥ 2 %.

Fig. 2. Photograph of the plasma driver on measuring vacuum chamber.

At the present time the plasma driver is fabricated, assembled and vacuum tested. In Fig. 2 the plasma driver installed on the measuring vacuum chamber is shown.

Second stage – generator of H^- ions is fabricated. Geometry of the ion optical system is optimized for H^- ion beam with current 60 mA. Working drawings of the accelerating tube with IOS are elaborated.

In presented development of this H^- ions source took an active part following co-workers: Vobly P.D. – optimization and calculation of magnetic trap and magnetic filter of electrons and technology of the permanent magnets walls; Novikov V.A. – technology of the permanent magnets walls and of the plasma driver assemblage; Belov V.P. – elaboration of the H^- ions source design; Tiunov M.A. – optimization and calculation of the IOS geometry; Razorenov V.V. – preparation for experimental study of the plasma driver.

For the operating source of H^- ions it is possibly to decrease the dimensions of the magnetic multipole plasma trap and the Cs/Mo converter.

References

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