Study of direct current negative ion source for medicine accelerator

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Status of dc H^- ion source development for tandem accelerator of boron capture neutron therapy is described. Upgrade and study of the Penning surface-plasma source with hollow cathodes was continued. Results of source optimization, of ion optic computer simulation, and of emittance measurement are presented. The upgraded source delivers dc H^- beam with energy 25 kV, current 8 mA, 1rms emittance $\epsilon_X \sim 0.2\ \pi$ mm·mrad, $\epsilon_Y \sim 0.3\ \pi$ mm·mrad at discharge power ≤ 0.5 kW.

I. BACKGROUND

A dc negative ion source delivering H- beam with intensity >10 mA is under development at Budker Institute for use at the tandem accelerator of boron neutron capture therapy (BNCT) device. It is important to have a long-term stability and an easy maintenance for the source. The surface-plasma source, based on the Penning discharge with hollow cathodes, can provide an efficient dc operation[1,2]. Experimental dc surface-plasma source, delivering 8 mA beam reliably, was developed recently[3]. The results of experimental source study and upgrade is presented below.

II. EXPERIMENTAL SOURCE

The scheme of experimental surface-plasma source for BNCT accelerator is shown in Fig.1. Negative Ions (NI) are extracted from plasma of the Penning discharge. Gas-discharge chamber consists of the cylindrical anode box with the massive cathode body enclosed. Penning discharge is supported by electron oscillations between the cathode protrusions in the horizontal magnetic field, produced by external electromagnet. The source uses no heated cathodes. Two hollow cathode bushes with small apertures (schematically shown in Fig.2) are inserted into the massive cathodes of Penning discharge. The hydrogen and small amount of cesium was fed to the discharge through the hollow cathode apertures.

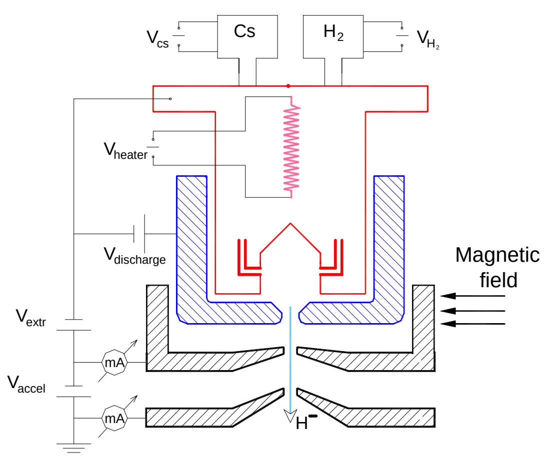

Fig. 1. Experimental source scheme (*cross section along magnetic field lines)*

The plasma injection from hollow cathodes supplies the high current Penning discharge operation at lower gas pressure and at smaller cesium consumption, as compared with the conventional cold cathode Penning SPS. Hollow cathode arc provides the Penning discharge stabilization: localization in the emission aperture vicinity, long term stability and the decreased level of fluctuations. In turn, electron confinement in the Penning area favors the hollow cathode arc ignition.

The water cooling of discharge electrodes is applied for keeping an optimal temperature of the anode. Negative Ions (NI) are produced on the cesiated anode surface and by charge-exchange of surface-produced ions[1]. Both NI groups are extracted from the discharge through the emission aperture with diameter 3 mm, made in the anode bottom. The axisymmetrical ion-optical system is applied for beam extraction and acceleration. Solid bars at the extractor sides (Fig. 1) are used for the co-extracted electron flux interception at extractor potential. The experimental source is wholly located in a vacuum box. It improves the outgoing gas pumping from all the sides.

Experimental source operation was described in details before[3]. Maximal H^- production was realized at the following source parameters: hydrogen feed 0.1 LTor/s, discharge voltage 80-90 V, anode temperature in the emission area 300-400 ^oC, cesium feed <1 mg/h. Beam current is increased proportionally to the emission aperture area growth and to the arc current increase while keeping the optimal anode cesium coverage. NI beam with current up to 8 mA was obtained with emission aperture diameter of 3 mm and discharge power 0.7 kW. The ohmic heater inside the cathode body provides the easy source start. The full extraction voltage and the acceleration voltage of about 7-10 kV are applied at the start. The acceleration voltage is increased to values up to 25 kV within the next 3-5 minutes after the discharge on.

III. SOURCE OPTIMIZATION

Source experimental optimization and parameters enhancement were done recently. Both the triode and the tetrode ion optical system (shown in Fig.2) were studied and optimized. Independent cesium feed to each of hollow cathode units was applied for cesium consumption decrease. Enhancement of H^- production with gas admixture to hydrogen was obtained and studied.

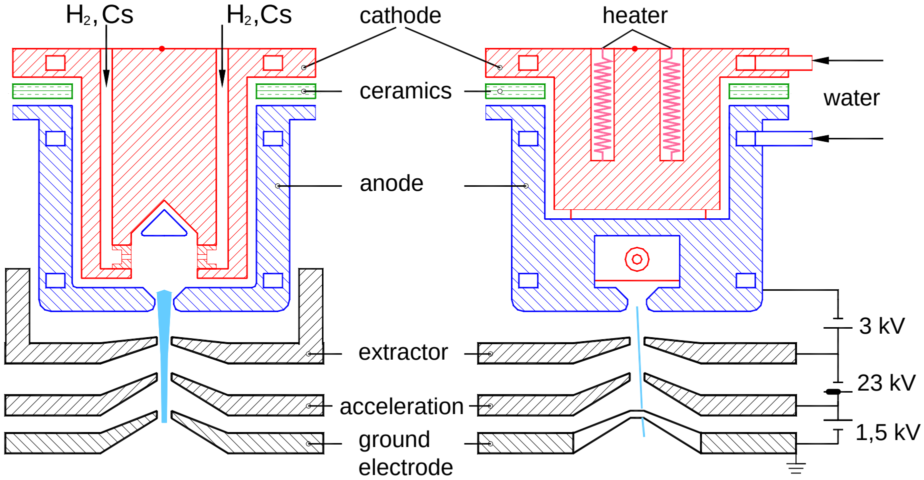

Fig. 2. Layout of experimental source with tetrode ion-optical system and independent cesium feed.
right- cross section along magnetic field lines, left- cross section across magnetic field

Improved source parameters at 8 mA H^- beam production are listed in the Table 1. Data of Table 1 were obtained at lower values of discharge current, magnetic field, cesium and gas feed, as compared with the previous source version[3], but with the same emission aperture diameter. The power efficiency of H^- production is increased to value of about 19 mA/kW, gas efficiency – to value of about 1 %.

TABLE 1. Improved Source parameters.

H^- beam current (aperture 3 mm)	8 мA
Beam energy	25 (2 + 23) keV
Discharge voltage	60 - 80 V
Discharge current	6 A
Magnetic field	0.8 kGs
Cesium feed	< 0.5 mg/h
Gas feed	0.07 L Tor/s

Dependence of H- beam current vs acceleration voltage for the optimized triode ion-optical system is shown in Fig.3. Corresponding optimal values of the extraction voltage is shown in Fig. 3 by crosses. H^- beam current intensity is saturated at the acceleration voltage 18 kV (for 6.2 A discharge current and 0.7 kGs magnetic field). Optimal extraction voltage increases with the extraction voltage growth.

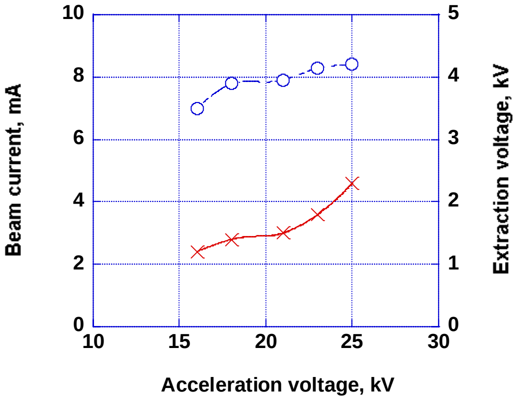

Fig. 3. H- beam current (circles) and optimal extraction voltage (crosses) vs acceleration voltage.
Discharge current 6.2 A, voltage 80 V, magnetic field 0.7 kGs, gas feed 0.07 L Tor/s.

IV. EMITTANCE

Movable emittance scanner was applied for the emittance measurement in X (along magnetic field) and Y (across magnetic field) directions across the beam. The scanner had the entrance collimator with an aperture 0.4 x 0.4 mm. The divergence of small elementary beam jet, formed by collimator, was analyzed at the 23 cm long flight base by the slit collectors with the help of electrostatic deflectors[3]. The scanner was shifted across the beam in order to determine the emittance diagram. An elementary beam jets have an elliptical cross section while moving in the 90% beam area, and its current density distribution have the Gaussian waveforms in X and Y directions. The typical beam cross section and XX' diagram (along magnetic field) for 8 mA, 25 kV beam are shown in Fig. 4. Measured widths of Gaussian distribution in cross section of elementary beam jets are shown by oblique lines in Fig. 4

(solid lines – for 90% of elementary beam jet, dashed lines – at FWHM of elementary beam distribution). Corresponding normalized 1rms XX' emittance has the value ~ 0.2 π mm·mrad.

The larger local divergence was measured for beam in Y direction (across magnetic field), as it is shown in Fig. 5 for 8 mA, 21 kV beam. The Y beam size is narrower, so the normalized 1rms YY' emittance has a value of ~ 0.3 π mm·mrad.

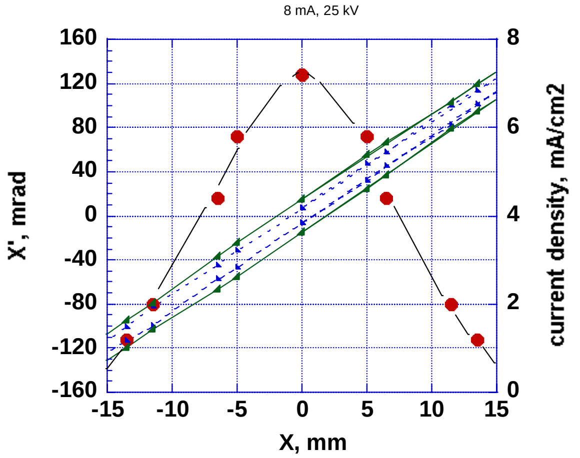

Fig.4. Beam current density distribution (circles) and XX' diagram for 8 mA, 25 kV beam.
XX'- solid lines – 90% of elementary beam,
dashed lines - FWHM of elementary beam

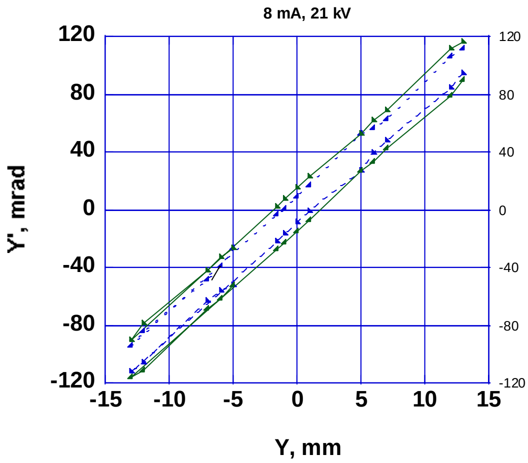

Fig.5. YY' diagram for 8 mA, 21 kV beam.
solid lines – 90% of elementary beam,
dashed lines - FWHM of elementary beam

V. RELIABILITY

The experimental source dc operation was tested for 4-6 hours per day during about two months study. Two of vincible problems in a long-term operation are shown in the Fig. 6 and 7. Molybdenum, sputtered at low rate from the cathode was deposited and flaked at the anode plate (Fig. 6). The metal deposition to the cathode-anode insulator is shown in Fig. 7. Molybdenum sputtering could be depressed by prevention of poor-cesium discharge modes (with voltage > 100-120 V).

Fig.6. Molybdenum flakes deposition on the anode (after one month of experiments)

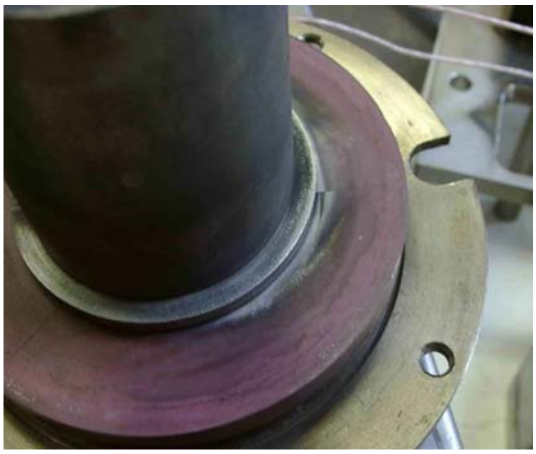

Fig.7. Metal deposition to cathode-anode insulator

VI. BEAM FORMATION SIMULATION

PBGUNS computer program was used for axisymmetrical 3D computing of beam extraction, formation and transport. It uses a fine matrix in the emission region, and computes the plasma boundary position with the self-consistent model of transient plasma sheath, modified for NI extraction. More than 100 parameters, including emitted NI drift energy and temperature, electron and positive ion density and temperature in the emission region can be interactively controlled.

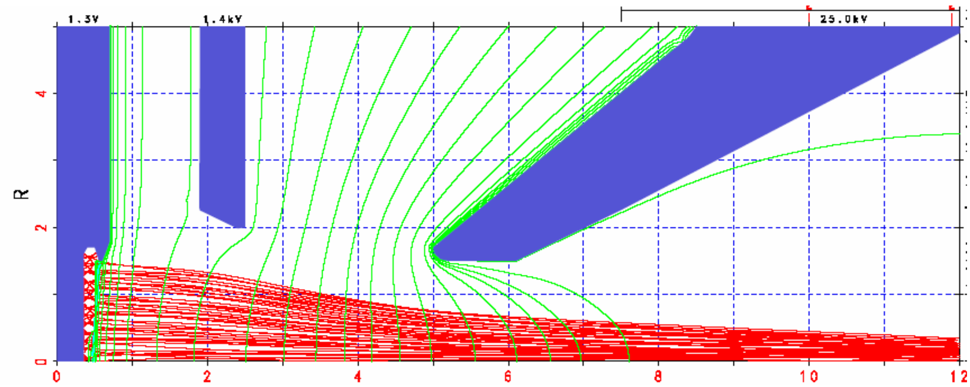

Fig. 8. PBGUNS output data for 10 mA H^- beam formation

Two types of plasma emission (uniform plasma emitter and emitter with the Maxwellian angular distribution) were tested and applied for simulation of H^- beam extraction from the source. Beam formation with various emission, plasma and ion-optical system parameters were simulated. An example of PBGUNS output data for 10 mA H^- beam formation by the triode ion-optical system is shown in Fig. 8. The simulated data were used for the purposely experimental optimization of the source ion-optical system.

VII. FLANGE SOURCE DESIGN

Flange Source to be installed at the test bed and at the low-energy beam transport line of BNCT accelerator is under manufacturing at BINP. The flange source has several novel features to be tested: most outside parts of the source (gas-discharge electrode flanges, discharge insulator, cesium system) will contact with air; source differential pumping will be produces from the source bottom only.

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