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DISCLAIMER

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Abstract. Production of H^- beam for accelerators applications by charge exchange of high brightness hydrogen neutral beam in a sodium jet cell is experimentally studied in joint BNL-BINP experiment. In the experiment, a hydrogen-neutral beam with 3-6 keV energy, equivalent current up to 5 A and 200 microsecond pulse duration is used. The atomic beam is produced by charge exchange of a proton beam in a pulsed hydrogen target. Formation of the proton beam is performed in an ion source by four-electrode multiaperture ion-optical system. To achieve small beam emittance, the apertures in the ion-optical system have small enough size, and the extraction of ions is carried out from the surface of plasma emitter with a low transverse ion temperature of ~0.2 eV formed as a result of plasma jet expansion from the arc plasma generator.

Developed for the BNL optically pumped polarized ion source, the sodium jet target with recirculation and aperture diameter of 2 cm is used in the experiment. At the first stage of the experiment H^- beam with 36 mA current, 5 keV energy and ~0.15 cm·mrad normalized emittance was obtained. To increase H- beam current ballistically focused hydrogen neutral beam will be applied. The effects of H^- beam space-charge and sodium-jet stability will be studied to determine the basic limitations of this approach.

Keywords: H- beam, charge exchange, sodium jet target
PACS: 29.25.Ni, 29.25.-t, 41.75.i

INTRODUCTION

Intense beams of hydrogen negative ions with enough high efficiency can be obtained by charge exchange of protons and hydrogen atoms in supersonic jets of alkaline and alkaline-earth metal vapors. Cross sections of charge exchange processes and equilibrium fractions of hydrogen negative ions in the targets are well known. For sodium maximal H- yield is 9% and achieved at 1-2 keV beam energy (8.4% at 3keV).

BINP and BNL now develop intense optically pumped polarized ion source with high brightness atomic beam injector and decided also to study production of high brightness H^- beam for accelerator applications by charge exchange method in joint experiment. Developed for the BNL optically pumped polarized ion source, sodium jet target with recirculation is used in the experiment. BINP prepare intense high brightness focused atomic beam injector with 3-5 keV beam energy. Experiment is curried out at well equipped experimental test stand at BNL.

In the paper description of the sodium jet target, results of initial experiments on H^- beam production, study and design of the atomic beam injector and discussion of interaction of intense hydrogen beam with target jet are presented.

SODIUM JET TARGET

Transverse sodium jet charge-exchange cell with the recirculation and 2 cm aperture [1] is used for charge exchange ionization of hydrogen beam. Scheme of the target is shown in Figure 1.

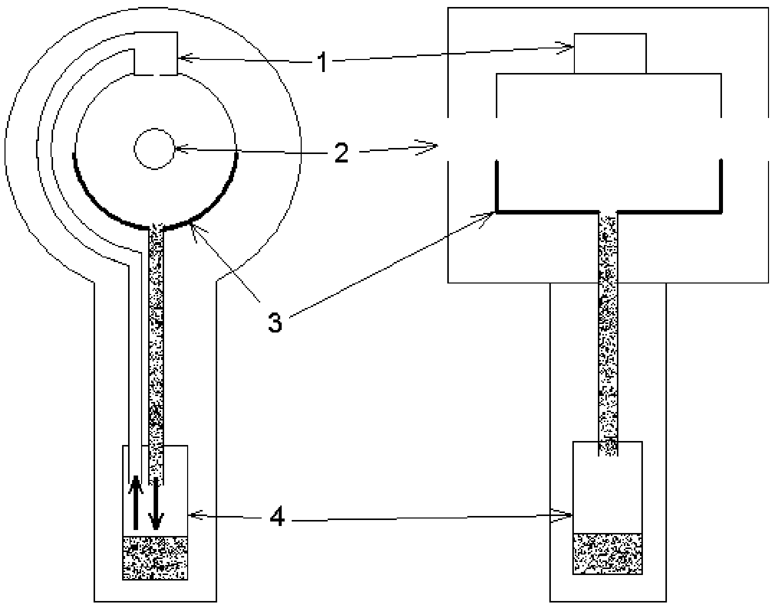

FIGURE 1. Scheme of the sodium jet target. Front and side views are shown. 1-jet nozzle, 2- beam aperture, 3- collector, 4 - reservoir.

The reservoir of the target is loaded with 150 g of sodium metal, and both the reservoir and jet nozzle are operated at a temperature of 505 °C. At this temperature the sodium vapor density is ~10^{17} atoms/cm^3 resulting in a vapor jet with an effective thickness of ~$5\cdot 10^{14}$ atoms/cm^2, sufficient for saturation of the H^- yield. The sodium vapor condenses on the collector walls, which are cooled to 120 °C (above melting point) by hot water circulation. Liquid sodium flows down the return tube and back to reservoir. The return tube temperature is kept at 150 °C by an attached cooling line with controlled hot water flow. Backstreaming vapor flow through the return line is negligible due to the low conductance at 150 °C. Sodium in the jet cell circulates along the path reservoir–nozzle–collector–return line–reservoir and the system provides continuous, stable operation for hundreds of hours with 150 g sodium.

FIRST STAGE OF EXPERIMENT ON H^- BEAM PRODUCTION

Scheme of the initial experiment on H^- beam production is shown in Figure 2. Proton beam is extracted by small-size four electrode multi-slit ion optical system of acceleration-deceleration type from the surface of the plasma emitter with a low transverse ion temperature, formed as a result of the expansion of the plasma jet from the arc plasma generator [2]. The formed proton beam with energy of 3-6 keV, current of 3-5 A and 200 microsecond pulse duration is first focused by magnetic lens and after that is neutralized in pulsed hydrogen target. Obtained beam of hydrogen atoms passes through the Na target located at 75 cm distance from the ion-optical system. Produced in result of charge-exchange in the target beam of H^- is deflected by bending magnet and measured by Faraday cup.

In Figure 3 dependence of measured of H^- current on the beam energy is presented. Maximal current of H- beam is 36 mA and is achieved at 4.5-5.5 keV beam energy. Dependence of determined by the negative ions equilibrium yield total current of hydrogen particles beam through the target on beam energy is shown in Figure 4. About 10% of the obtained atomic beam passes through the Na-jet cell.

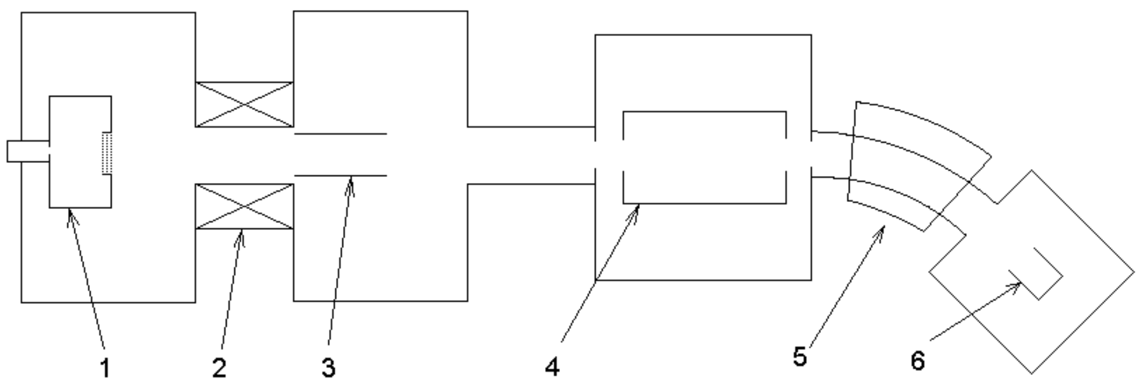

FIGURE 2. Scheme of the experiment on H^- beam production. 1- proton source, 2 - magnetic lens, 3 - neutralizer, 4 - sodium target, 5 – bending magnet, 6 - Faraday cup.

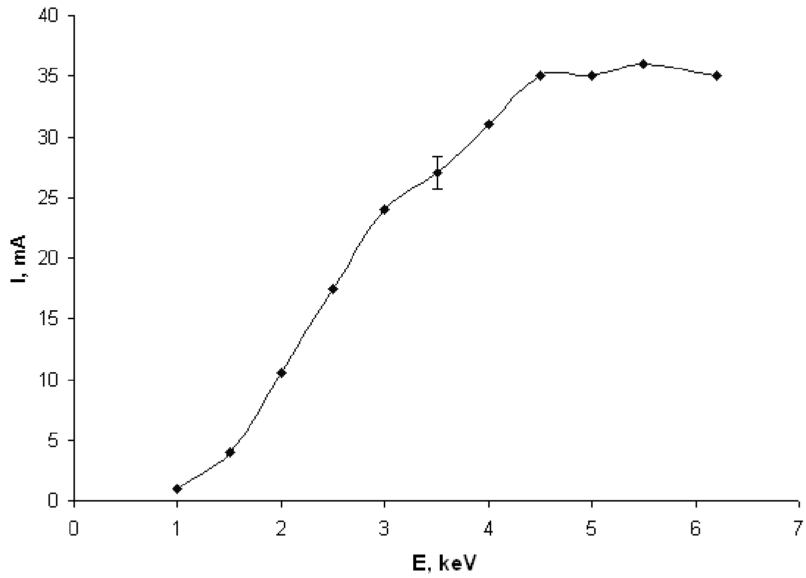

FIGURE 3. Dependence of H^- beam current on the beam energy.

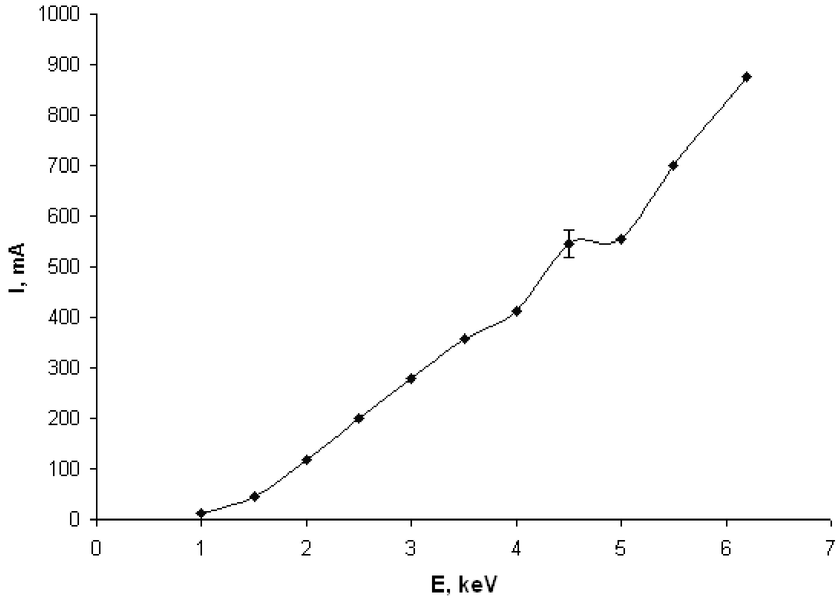

FIGURE 4. Equivalent current of hydrogen particles beam through the target versus beam energy.

Angular divergence of the formed atomic beam is ~$1.5 \cdot 10^{-2}$ rad and normalized emittance of the produced H^- beam is estimated as 0.15 cm·mrad.

The distance between ion optical system and sodium target was increased to 175 cm and obtained dependences of produced H^- current with and without magnetic focusing of proton beam are shown in Figure 5. Maximal H^- beam current with focusing is 9.5 mA, without focusing is 5.5 mA. Magnetic focusing increases H^- beam only twice.

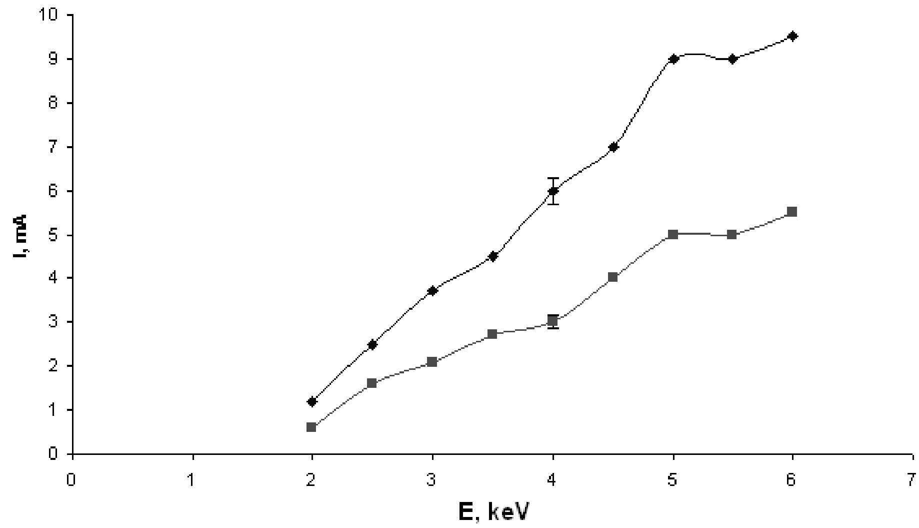

FIGURE 5. Dependence of H^- beam current on the beam energy at 175 cm distance to the sodium jet. Upper curve - with magnetic beam focusing, lower curve – without focusing.

Magnetic beam focusing at low beam energies was studied in BINP and TRIUMF experiments [3,4]. These experiments have shown that at energy below 4 keV the magnetic focusing of ion beam is reduced due to insufficient beam space charge compensation by secondary electrons in the magnetic lens.

ATOMIC BEAM INJECTOR WITH GEOMETRICAL FOCUSING

To avoid problem of proton beam compensation at low energies, ballistic or geometrical focusing of atomic beam will be applied instead of the magnetic one. In this case the proton beam is focused by spherically formed grids of ion optical system and neutralized at a target short distance downstream from the grids [2,5] . The ion optical system the atomic injector should be operated at low energies. In this case thin electrodes with small diameter apertures should be used.

Elementary cell of small size four electrode ion optical system acceleration-deceleration type was optimized by the PBGUNS code [6]. Ion trajectories and equiponential lines in the optimized version of the elementary cell with 0.2 mm electrode thickness and 0.4 mm apertures are shown in Figure 6. Initial ion temperature is 0.2 eV. The emittance diagram of the formed elementary beam is presented in Figure 7. At emission current density of 470 mA/cm^2 angular divergence of the formed beam is 15 mrad. Electric field in accelerating gap is about 50 kV/cm that is low than 70 kV/cm experimental limitation of electric field.

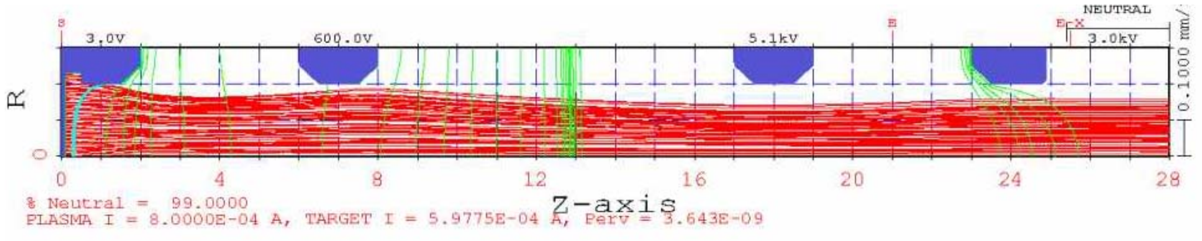

FIGURE 6. Ion trajectories and equipotentials plot for 3 keV ion beam formation

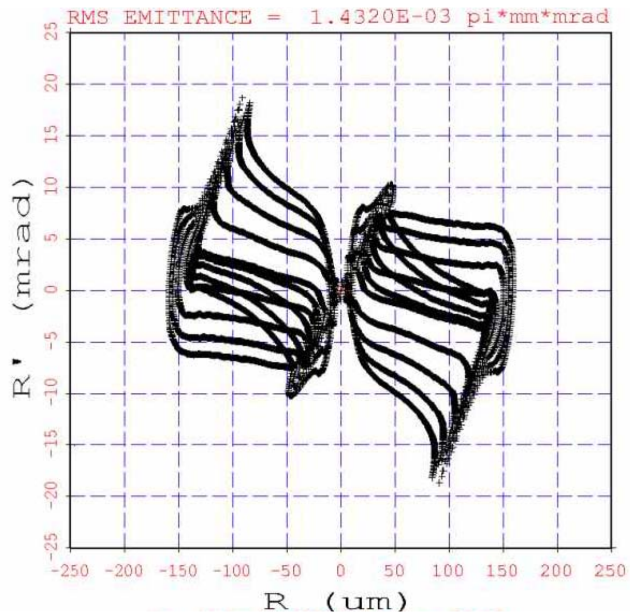

FIGURE 7. Emittance diagram of formed 3 kev elementary beam.

The ion beam formation with 4.0 A current is executed by 7466 apertures which forming hexagonal structure with the step of 0.55 mm and outer diameter of 5 cm. The grids were made of 0.2 mm thick pure molybdenum. Photo-etching technology was applied for holes production. The grids were subsequently shaped by re-crystallization under stress at high temperature. The grids were welded to stainless steel holders by pulse technological CO_2 laser.

Atomic beam injector with geometrically focused beam is shown in Figure 8. Focal distance of the formed atomic beam is 60 cm. The sodium jet cell will be installed in beam focus region. The atomic beam intensity through Na cell aperture 2 cm in diameter should be of 3 A that corresponds to 360 mA current of ions H^- .

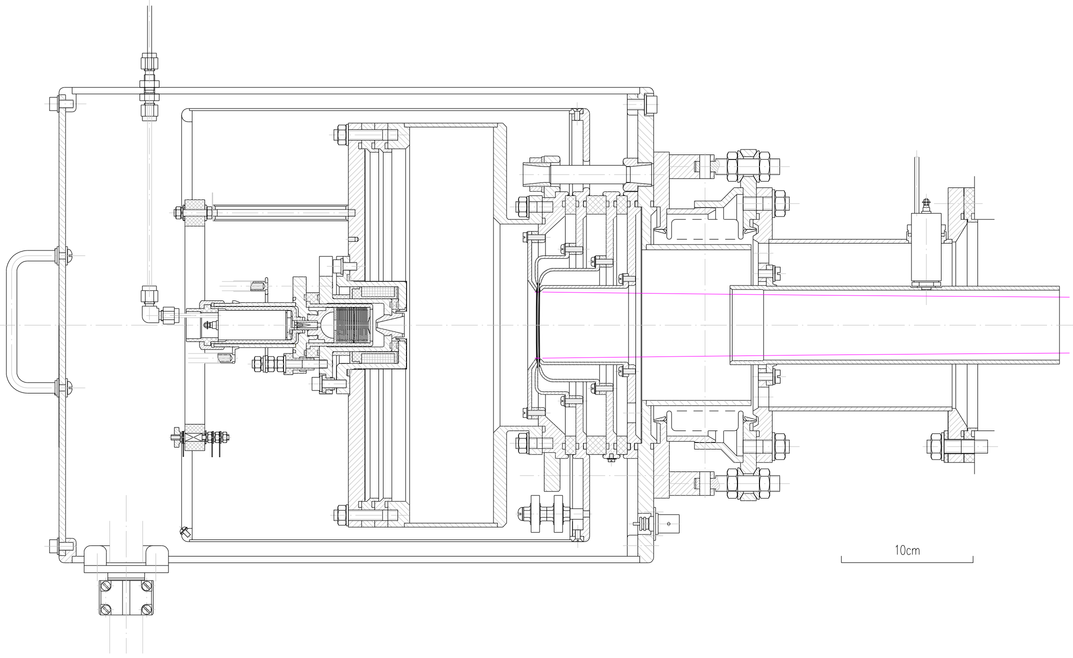

FIGURE 8. Atomic beam injector with geometrical focusing.

INTERACTION OF HIGH-INTENSITY HYDROGEN BEAM WITH NA-JET CELL

Critical problem of the charge exchange method is interaction of intense beam with target jet. Secondary plasma arising in result of the interaction causes slowing down and heating of the jet that leads to increase in vapor carrying out from the jet and to deterioration of pumping out and protecting jet characteristics. According to paper [7] influence of secondary plasma on a stream current is determined by parameter $\alpha = J\sigma_i /(ev_0)$, where J beam current on unit of length of target, σ_i – cross-section of ionization of atoms of a target, v_0 - speed of a stream. The parameter α is the ratio of flux density of sodium ions generated by hydrogen beam in not disturbed jet to density of flux of atoms in initial jet. Direct ionization of sodium atoms by hydrogen particles with energy 3-4 keV is small, ionization cross section apparently less than 10^{-16} cm^2, the basic ionization of sodium in jet is caused by transfer of electron from sodium atom to hydrogen particles. The cross section of charge exchange of protons on sodium atom has value of $1.2\cdot10^{-14}$ cm^2, electron capture cross section of hydrogen atom at sodium atom of $5\cdot10^{-16}$ cm^2. At beam current on unit of length $J \approx 1.5$ A/cm and beam proton fraction ~ 5% at sodium target entrance the factor α for target ionization by proton charge exchange is ~0.04, for ionization sodium target as a result of negative ions origin α has value ~ 0.04.

According to results of the paper [7] at the estimated values of α the secondary plasma can impacts on of the transverse jet flow. Critical value of α is ~ 0.06. To reduce Na ionization in the cell, it is desirable to remove protons by magnetic field after beam exit from the neutralizer target.

In these experiments, the effects of interaction between a hydrogen beam and a target will be studied. The linear density of the incoming beam ion current is supposed to be varied through the change of the hydrogen beam neutralization degree. The maximum line density of the incoming beam proton current at the switched-off charge-exchange hydrogen target will be ~1.5 A/cm.

Also in the experiments, the accompanying electron current in the H^- ion beam will be measured and the compensation and transportation of the produced H^- ion beam will be studied. These measurements will provide the data necessary for the production of more intense H^- beams by use of the charge exchange technique.

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