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High-intensity, high-brightness polarized and unpolarized beam production in charge-exchange collisions

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HIGH-INTENSITY, HIGH-BRIGHTNESS POLARIZED AND UNPOLARIZED BEAM PRODUCTION IN CHARGE-EXCHANGE COLLISIONS

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Abstract

Basic limitations on the high-intensity H^- ion beam production were experimentally studied in charge-exchange collisions of the neutral atomic hydrogen beam in the Na- vapour jet ionizer cell. These studies are the part of the polarized source upgrade (to 10 mA peak current and 85% polarization) project for RHIC. In the source the atomic hydrogen beam of a 5-10 keV energy and total (equivalent) current up to 5 A is produced by neutralization of proton beam in pulsed hydrogen gas target. Formation of the proton beam (from the surface of the plasma emitter with a low transverse ion temperature ~0.2 eV) is produced by four-electrode spherical multi-aperture ion-optical system with geometrical focusing. The hydrogen atomic beam intensity up to 1.0 A /cm^2 (equivalent) was obtained in the Na-jet ionizer aperture of a 2.0 cm diameter. At the first stage of the experiment H^- beam with 36 mA current, 5 keV energy and ~1.0 cm·mrad normalized emittance was obtained using the flat grids and magnetic focusing.

Polarized proton beams in AGS and RHIC

The polarized beam for RHIC spin physics experimental program is produced in the Optically-Pumped Polarized H^- Ion Source (OPPIS) [1]. The present RHIC OPPIS produces routinely 0.5-1.0 mA (maximum 1.6 mA) current in 400 μs pulse duration. The polarized H^- ion beam (of 35 keV beam energy out of the source) is accelerated to 200 MeV in a linear accelerator for strip-injection to Booster. The H^- ion pulse is captured in a single Booster bunch which contains about $4{\cdot}10^{11}$ polarized protons. Single bunch is accelerated in the Booster to 2.5 GeV beam energy and then transferred to the AGS, where it is accelerated to 24.3 GeV for injection to RHIC. RHIC is the first collider where the "Siberian snake" technique was very successfully implemented to suppress the resonance depolarization during beam acceleration in AGS and RHIC [2]. A luminosity of a $1.6.10^{32}$ cm^{-2} sec^{-1} for polarized proton collisions in RHIC will be produced by colliding 120 bunches in each ring at $2{\bullet}10^{11}$ protons/bunch intensity. The RHIC polarized H- ion source is being upgraded to higher intensity (5-10 mA) and polarization by using a very high brightness fast atomic beam source developed at BINP, Novosibirsk. This beam will be used in the RHIC polarization physics program at enhanced luminosity RHIC operation. The higher beam peak intensity will allow reduction of the transverse beam emittance at injection to AGS (by scraping of beam tails) to reduce polarization losses in AGS. There is also a plan the RHIC luminosity upgrade by using the electron beam lens to compensate the beam-beam interaction at collision points. This upgrade is also essential for future BNL plans for a high-luminosity electron – proton (ion) Collider eRHIC. In addition, a feasibility of high intensity (a few hundred mA), high brightness unpolarized H^- ion beam production will be studied in charge-exchange of high-brightness atomic hydrogen beam in sodium-jet ionizer cell.

A new polarimeter for absolute proton beam polarization measurements at 200 MeV to accuracy better than ±0.5% has been developed as a part of the RHIC polarized source upgrade. The polarimeter is based on the elastic proton-carbon scattering at 16.2° angle, where the analyzing power is large 99.35% and was measured with high accuracy.

OPPIS upgrade with the atomic hydrogen injector

The ECR proton source is operated in high magnetic field. It has low hydrogen gas consumption, which makes possible a dc OPPIS operation with intensity in excess of 1.0 mA. However, the proton beam produced in the ECR source has a comparatively low emission current density and high beam divergence. This limits further current increase and gives rise to inefficient use of the available laser power for optical pumping. In pulsed operation, suitable for application at high-energy accelerators and colliders, the ECR source limitations can be overcome by using instead of ECR a high brightness proton source outside the magnetic field [3-5]. Following neutralization in hydrogen, the high brightness 6.0-10.0 keV atomic H^0 beam is injected into a superconducting solenoid, where both a He ionizer cell and an optically-pumped Rb cell are situated in the same 25-30 kG solenoid field, which is required to preserve the electron-spin polarization. The injected H atoms are ionized in the He cell with 80% efficiency to form a low emittance intense proton beam, which enters the polarized Rb vapour cell (see Fig.1). The protons pick up polarized electrons from the Rb atoms to become a beam of electron-spin polarized H atoms (similar to ECR based OPPIS). A negative bias of about 3.0-7.0 kV applied to the He cell decelerates the proton beam produced in the cell to the 3.0 keV beam energy optimal for the charge–exchange collisions in the Rb and sodium cells. This also would allow the energy separation of the polarized hydrogen atoms produced after lower energy proton neutralization in Rb vapour and residual hydrogen atoms of the primary beam.

Residual higher energy atoms will be neutralized with lower efficiency in Rb cell (due to cross-section decrease at higher energy) and un-polarized component will be further suppressed by lower H^- ion yield at 5.0-8.0 keV atomic beam energy. The H^- ion beam acceleration (by negative -32 kV pulsed voltage applied to the ionizer cell) will produce polarized H^- ion beam of a 35 keV beam energy and un-polarized beam of a 40-43 keV beam energy. Further suppression of un-polarized higher energy ion beam can be done in the LEBT.

Atomic hydrogen beam current of equivalent densities in excess of a 100 mA/cm^2 can be obtained at the Na jet ionizer location (about 200 cm from the source) by using a high brightness fast atomic beam source. Higher polarization is also expected with the fast atomic beam source due to: a) elimination of neutralization in residual hydrogen; b) better Sona-transition transition efficiency for the smaller ~ 1.5 cm diameter beam; c) use of higher ionizer field (up to 3.0 kG), while still keeping the beam emittance below 2.0 π mm·mrad, because of the smaller beam – 1.5 cm diameter. All these factors combined will further increase polarization in the pulsed OPPIS to ~ 90% and the source intensity to over 10 mA.

Charge-exchange collisions

The primary beam energy optimization is an important part of this development. Higher intensity and lower proton beam divergence can be obtained at higher beam energy. The neutralization efficiency in hydrogen cell is about 95% for energies 6-10 keV. The ionization efficiency in He-ionizer cell is 80% at 6 keV and 60% at 10 keV beam energy. The proton beam produced in the He cell is decelerated to 3.0 keV by the negative potential 3-7 keV applied to the cell (see Fig.2). At the 3.0 keV beam energy the H^- ion yield in the sodium ionizer cell is near maximum (~8.4%) and cross-section of polarized electron capture cross-section from Rb atoms is near maximum (~ 10^{-14} cm^2) too. The deceleration is produced by precisely aligned (to reduce beam losses) three-grid system. A small negative bias will be applied to the first grid and cylindrical electrode at the cell entrance to trap electrons in the cell for space-charge compensation. About 40% residual (which passed the He-cell without ionization) atomic beam component of 6-10 keV energy will pass deceleration system, Rb cell (almost unaffected) and ionized in Na-cell producing H^- ion beam. The H^- ion yield at 6 keV is about 5% and at 10 keV it is ~ 2%. This is a significant suppression in comparison with main 3.0 keV beam, but it would be a strong polarization dilution unless further suppression is applied. The H^- ion beam of 3.0 keV energy produced in the Na-jet ionizer cell is accelerated at the exit of cell to 35 keV beam energy by a 32 kV negative pulsed potential, which is applied to the cell. The 6-10 keV un-polarized H^- ion beam component is accelerated to 38-42 keV energy. An effective velocity "filter" was developed for suppression of this high-energy beam component.

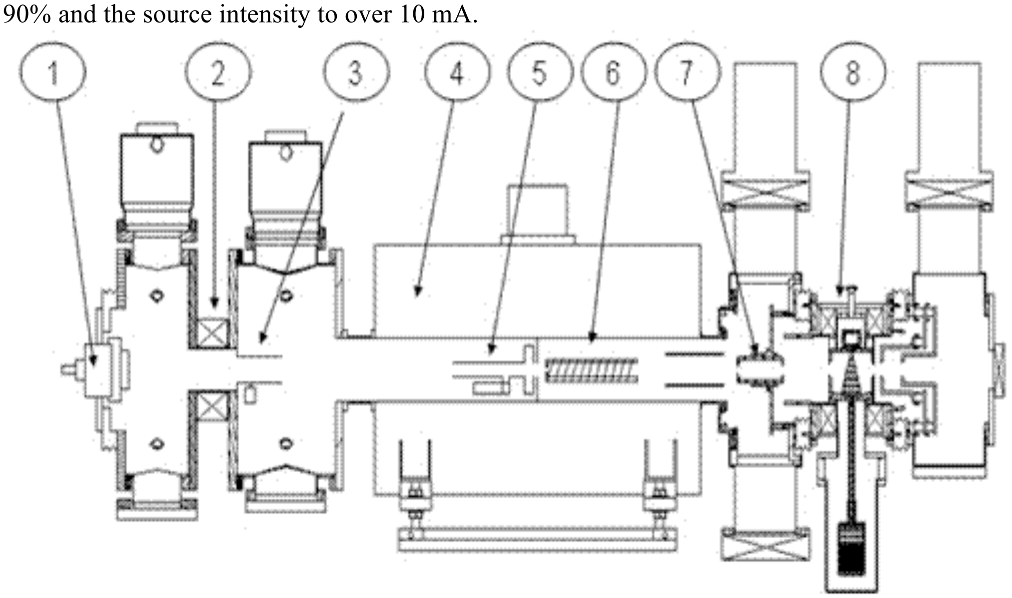

Figure. 1: Layout of the OPPIS with atomic hydrogen injector: 1–high-brightness proton source; 2- focusing solenoid; 3-pulsed hydrogen neutralization cell;4- super conducting solenoid 30 kG; 5-Pulsed He ionizer cell; 6-optically-pumped Rb cell; 7-Sona shield; 8-sodium-jet ionizer cell.

The "filter" is a double Einzel lens system, which is installed in the OPPIS LEBT. A negative potential of about 35 keV is applied to the first lens. This potential decelerates and retards the lower energy (un-polarized) beam component. The second Einzel lens is tuned to compensate the strong focussing of the first lens for optimal beam transmission further for injection to RFQ. This velocity "filter" suppresses not only low energy but also higher energy beam components. For energy difference 7 keV the suppression will be about 100 times and polarization dilution should be less than 0.3 %.

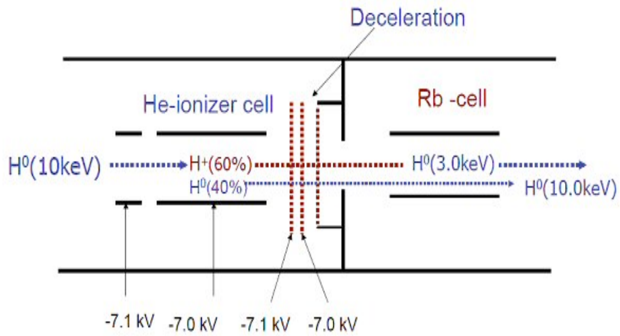

Figure 2: A schematic layout of the He-ionizer cell and deceleration of the proton beam for the energy separation of the residual un-polarized beam component.

Atomic beam source development

The atomic beam injector is being under development at BINP, Novosibirsk. In this injector the proton beam is produced by a four-grid multi-aperture ion extraction optical system and neutralized in the H_2 gas cell downstream from the grids. A high-brightness atomic hydrogen beam was obtained in this injector by using a plasma emitter with a low transverse ion temperature of ~0.2 eV which is formed by plasma jet expansion from the arc plasma generator. The multi-hole grids are spherically shaped to produce "geometrical" beam focusing [6]. The grids are made of 0.2 mm thick molybdenum plates. Holes in the plates (of a 0.4 mm in diameter) were produced by photo-etching technology. An array of 7466 holes is forming a hexagonal structure with the step of 0.55 mm and outer diameter of 5.0 cm.

The focal length of the spherical ion extraction system was optimized for OPPIS application, which is characterized by a long polarizing structure of the charge-exchange cells and small (2.0 cm in diameter) Na-jet ionizer cell, which is located at a 240 cm distance from the source (see Fig. 1). An optimal drift-space length of about 130 cm is required for convergence of the 5 cm (initial diameter) beam to 2.5 cm diameter He-ionizer cell. After ionization in the He-cell the proton beam do not experience angular divergence for about 70 cm from the end of the He ionizer cell to the end of the solenoid and the magnetic field conserves the current density profile and the beam angular divergence. After the solenoid the divergence becomes larger due to addition of the randomized regular radial motion to the initial inherent divergence of the emitter, but the 40 cm expansion remains acceptable. Therefore, with the magnetic field the total current through the Na-jet cell is by a factor of 2.3 larger than the current in the absence of magnetic field in the same geometry.

About 10% (of total neutral injector current of a 4 A) can be transported through the Na-jet cell acceptance (with the magnetic field) by using optimal extraction grid system of a focal length: $F \approx 200$ cm. Taking into account ionization efficiency in He-cell of a 60%, polarized electron capture in the Rb-cell of a 50% and H^- yield in the Na-jet cell of a 8.4% the expected polarized H^- ion beam current is expected to be ~ 10 mA.

Experimental results

Studies of the neutral beam formation and charge-exchange processes are presently in progress at the full-scale Test Bench, which is closely reproduce the OPPIS upgrade Layout (see Fig.1) except the superconducting solenoid, which is replaced by a cylindrical vacuum chamber of 150 mm ID. The proton beam of 3-7 keV energy and total current of 3-6 A is focussed by solenoid lens and then is neutralized in the pulsed hydrogen target. Atomic hydrogen beam is ionized in the Na-jet cell and is deflected by bending magnet and measured by the Faraday cup in the diagnostic box. The maximum H^- beam current of a 12 mA at 7 keV beam energy was obtained in these experiments. Taking into account that H^- ion yield is ~ 4 % at energy 7 keV the total equivalent neutral hydrogen beam intensity was estimated at 300 mA. At present a new extraction system with spherical grid and geometrical focussing was delivered from BINP for beam formation studies and experiments are in progress to assess the extraction system performance and optimization.

Summary

Polarized H^- ion beam current in excess of 10 mA is expected after the OPPIS upgrade with this Atomic Hydrogen Injector developed at BINP, Novosibirsk. Higher polarization is also expected with the fast atomic beam source. The beam emittance will be kept below 2.0 π mm□mrad due to the smaller beam diameter. All these factors combined will increase polarization in the pulsed OPPIS to ~ 85-90%.

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