The RHIC Polarized Source Upgrade

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Abstract—The RHIC polarized H\(^{-}\) ion source is being upgraded to higher intensity and polarization for use in the RHIC polarization physics program at enhanced luminosity RHIC operation. The higher beam intensity will allow reduction of the longitudinal transverse beam emittance at injection to AGS to reduce polarization losses in AGS. There is also a planned 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. The basic limitations on the high-intensity H\(^{-}\) ion beam production in charge-exchange collisions of the neutral atomic hydrogen beam in the Na-vapor jet ionizer cell were experimentally studied.

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OPPIS UPGRADE WITH THE ATOMIC HYDROGEN BEAM INJECTOR

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 0.5–1.0 mA current in 300 \(\mu\)s 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 is accelerated in the Booster and then transferred to the AGS, which 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.

The Electron Cyclotron Resonance (ECR) is used as a primary proton in the present operational polarized source. The ECR source is operated in high magnetic field. 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 fact only about 15% of the electron-spin polarized hydrogen atoms produced in Rb cell is within the ionizer cell acceptance.

In pulsed operation, suitable for application at high-energy accelerators and colliders, the ECR source limitations can be overcome by using a high brightness proton source outside the magnetic field instead of ECR source [2, 3]. Following neutralization in hydrogen, the high brightness 6.0–8.0 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 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 60–80% efficiency to form a low emittance intense proton beam, which enters the polarized Rb vapor 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 3.0–5.0 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 allows energy separation of the polarized hydrogen atoms produced after lower energy proton neutralization in Rb vapor and residual hydrogen atoms of the primary beam.

Residual atomic H beam (of about 20–40%, which is not ionized in the He-cell) of 6.0–8.0 keV will be converted to H\(^{-}\) ion un-polarized beam with lower yield (3–4% at 6.0–8.0 keV atomic beam energy). The H\(^{-}\) ion beam acceleration (by \(-32\) 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 38–40 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$^2$ was obtained at the Na jet ionizer location (about 250 cm from the source) by using a high brightness fast atomic beam source which was developed in collaboration with BINP, Novosibirsk. The estimated polarized H$^-$ ion beam current of about 5–10 mA is expected in this source after upgrade completion (in assumption 50% ionization efficiency in He-cell and 50% neutralization efficiency in the optically-pumped Rb-vapor cell). This was tested in experiments at TRIUMF, where more than 10 mA polarized H$^-$ and 50 mA proton beam intensity was demonstrated [2]. The beam losses at proton beam deceleration introduce additional losses. 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). All these factors combined should increase polarization in the pulsed OPPIS to over 85% [3].

**ATOMIC BEAM SOURCE DEVELOPMENT**

The atomic hydrogen beam source was developed 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 [4]. The multi-hole grids are spherically shaped to produce “geometrical” beam focusing. The grids are made of 0.4 mm thick molybdenum plates. Holes in the plates (of a 0.8 mm in diameter) were produced by photo-etching techniques. The holes array is forming a hexagonal structure with the step of 1.1 mm and outer diameter of 5.0 cm. The grids were shaped by re-crystallization under pressure at high temperature. They are welded to stainless steel holders by pulsed CO$_2$ laser. At emission current density of a 470 mA/cm$^2$ an angular divergence of the produced beam is ~10–12 mrad.

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 140 cm is required for convergence of the 5 cm (initial diameter) beam to 2.5 cm diameter He-ionizer cell. About 20% (of total neutral injector current of a 3.5 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. Three spherical IOS were tested at the test-bench at BNL.
The results are presented in table.

The focusing lengths of IOS #1 and #2 are 145 cm and 250 cm which will allow study of optimal beam formation. IOS#2 produces about 500 mA equivalent atomic H beam within 2.0 cm (in diameter) Na-jet ionizer acceptance (at the distance 240 cm from the source) and 16 mA H– ion beam current.

| IOS  | I_{beam}, A | F, cm | α, mrad | H–, mA |
|------|-------------|-------|---------|--------|
| #1   | 3.4         | 145   | 10.5    | 12.5   |
| #2   | 3.6         | 250   | 10      | 16     |
| #3   | 3.6         | 156   | 13      | 11     |

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HE IONIZER CELL. BEAM ENERGY SEPARATION

He-ionizer cell is a 40 cm long stainless steel tube with inside diameter 25.4 mm (see Fig. 2). A new fast “magnito-dynamic” valve for He gas injection to the cell was developed for operation in 30 kG solenoid field. In this valve a pulsed current of about 100 A is passed through the flexible springing plate (made of beryllium bronze foil of a 0.5 mm thickness). The Lorentz force: \( F = eL[I \times B] = 15 \text{ N} \) for a \( L = 5 \text{ cm} \) long plate. The plate is fixed at one end. This force bends plate and opens the small (0.5 mm in diameter) hole which is sealed with Viton O-ring. The pulsed current rise-time is ~50 us.

The proton beam produced in the He cell is decelerated to 3.0 keV by the negative potential 4 keV applied to the cell. 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 (~0.8 \times 10^{-14} \text{ cm}^2) too. The deceleration is produced by precisely aligned (to reduce beam losses) three wire-grid system. A small negative bias is applied to the first grid at the cell entrance and second grid at the cell exit to trap electrons in the cell for space-charge compensation.

About 40% residual (which passed the He-cell without ionization) atomic beam component of 7.0 keV beam energy will pass deceleration system and Rb cell (almost unaffected) and ionized in Na-cell producing H– ion beam. The H– ion yield at 7 keV is about 4%. 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 acceleration (by ~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 39 keV beam energy. Further suppression of un-polarized higher energy ion beam is done in the LEBT and RFQ. The un-polarized 39 keV beam component is well separated after the 24 degree magnetic bending magnet in LEBT. A 30 mm in diameter collimator after the bend eliminates this beam almost completely and additional suppression is achieved after RFQ (see Fig. 2). In these measurements the beam energy was varied by accelerating voltage applied to the Na-jet ionizer cell. At 32 keV accelerating voltage (where the polarized beam component of 3.0 keV beam energy accelerated to 35.0 keV optimal for injection to RFQ) the transmission of residual 7.0 keV un-polarized beam component is strongly suppressed (to less than 2% of polarized beam component).

EXPERIMENTAL RESULTS

The energy-separated beam intensity vs. Rb-cell thickness is presented in Fig. 3. The beam intensity

![Fig. 2. Beam transmission efficiency vs. acceleration voltage applied to Na-jet ionizer cell. Squares are primary 7.0 keV energy beam. Diamonds are polarized (decelerated for 4.0 keV) beam.](image)

![Fig. 3. Polarized beam intensity and polarization vs. optically-pumped Rb-vapor thickness.](image)
was measured in FC after the 24 degree bending magnet. At low Rb-vapor densities the residual (un-polarized H\(^{-}\)) ion beam current produced by neutralization on residual gas is less than 0.03 mA. This is less than 2% polarization dilution factor. Maximum current was measured 1.4 mA so far. About 60–80% of this beam can be accelerated to 200 MeV. This current can be further improved by opening collimator diameter in front of He-ionizer cell. It was reduced to 20 mm to for initial tests of energy deceleration system. Basic limitations on the high-intensity polarized H\(^{-}\) ion beam production and transport were experimentally studied in charge-exchange collisions of the neutral atomic hydrogen beam in the Na-vapor-jet ionizer cell. The energy dependence of space-charge effects on the beam instabilities and losses were studied and described in the model of “synthetic” H\(^{+}\)–H\(^{-}\) beam transport /see F. Podolyako et al., paper at this Conference/. The proton polarization of H\(^{-}\) ion beam was measured in Lamb-shift polarimeter. The polarization values are similar to best numbers observed with ECR-based source (see Fig. 3). The polarization dependence is rather flat up to very low Rb vapor thickness. This confirms the expectation of lower neutralization on residual gas in comparison with ECR-based source. The Lamb–shift polarimeter has large systematic errors and is used for relative polarization measurements. The accurate absolute calibration measurements will be done by using a 200 MeV polarimeter in December 2012.

REFERENCES
1. A. Zelenski, et al., Rev. Sci. Instr. \textbf{73}, 888–891 (2002).
2. A. Zelenski, et al., SPIN 2002 Proc. AIP Conf. Proc. \textbf{675}, 881 (2003).
3. A. Zelenski, et al., “The RHIC polarized source upgrade,” J. Phys.: Conf. Ser. \textbf{295}, 012147 (2011).
4. V. I. Davydenko and A. A. Ivanov, Rev. Sci. Instr. \textbf{72}, 1809 (2004).