THE RHIC POLARIZED SOURCE UPGRADE

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Abstract

A novel polarization technique has been successfully implemented for the upgrade of the RHIC polarized H^- ion source to higher intensity and polarization. In this technique, a proton beam inside the high magnetic field solenoid is produced by ionization of the atomic hydrogen beam (from an external source) in the He-gas ionizer cell. Proton polarization is produced by the process of polarized electron capture from the optically-pumped Rb vapor. Polarized beam intensity produced in the source exceeds 4.0 mA. Strong space-charge effects cause significant beam losses in the LEBT (Low Energy Beam Transport, 35.0 keV beam energy) line. The LEBT was modified to reduce losses. As a result, 1.4 mA of polarized beam was transported to the RFQ and 0.7 mA was accelerated in linac to 200 MeV. A maximum polarization of 84% (in the 200 MeV polarimeter) was measured at 0.3 mA beam intensity and 80% polarization was measured at 0.5 mA. The upgraded source reliably delivered beam for the 2013 polarized run in RHIC at √S=510 GeV. This was a major factor contributing to the increase in RHIC polarization to over 60 % for colliding beams.

OPPIS UPGRADE WITH THE ATOMIC HYDROGEN BEAM INJECTOR

The polarized beam for the RHIC spin physics experimental program is produced in the Optically-Pumped Polarized H^- Ion Source (OPPIS) [1].

An Electron Cyclotron Resonance (ECR) ion source was used as the primary proton source in the old operational polarized source. The ECR source was operated in a high magnetic field. The proton beam produced in the ECR source had a comparatively low emission current density and high beam divergence.

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 the ECR source. In this technique (which was implemented for the first time at INR, Moscow [2]), the proton beam is focussed and neutralized in a hydrogen cell producing the high brightness 6.0-8.0 keV atomic H° beam. The atomic H^0 beam is injected into the superconducting solenoid, where both the He ionizer cell and the optically-pumped Rb cell are situated in the 25-30 kG solenoid field. The solenoid field is produced by a new superconducting solenoid with a re-condensing cooling system. The injected H atoms are ionized in the He cell with 60-80% efficiency to form a low emittance intense proton beam and then enter the polarized Rb vapour cell (see Figure 1). The protons pick up polarized electrons from the Rb atoms to become a beam of electron-spin polarized H atoms (similar to the ECR based OPPIS). A negative bias of about 3.0-5.0 kV applied to the He cell decelerate the proton beam produced in the cell to the 3.0 keV beam energy, optimal for the charge– exchange collisions in the rubidium and sodium cells. This allows energy separation of the polarized hydrogen atoms produced after lower energy proton neutralization in Rb-vapour and residual hydrogen atoms of the primary beam.

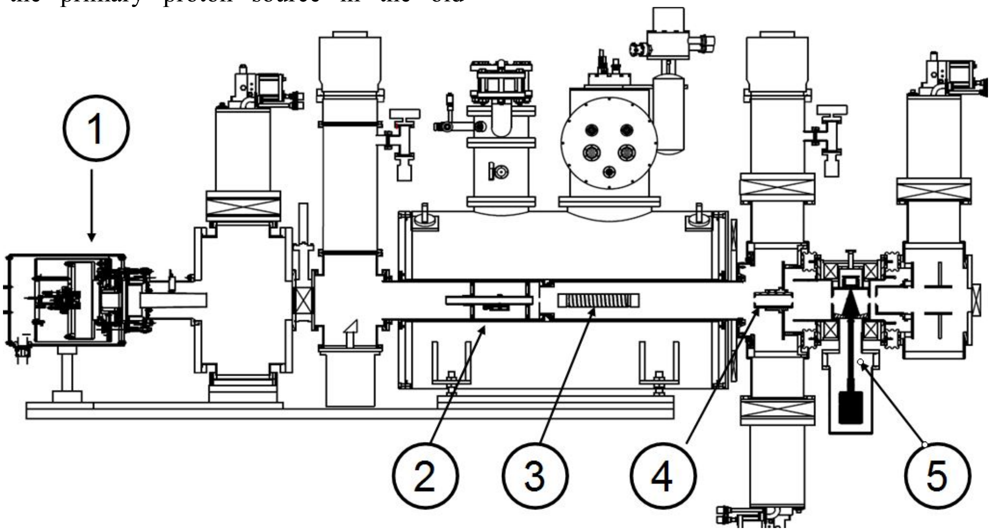

Figure 1: A new polarized source layout: 1–atomic hydrogen injector; 2–pulsed He –gaseous ionizer cell; 3–optically-pumped Rb-vapour cell; 4–Sona-transition; 5–Na-jet ionizer cell.

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Residual atomic H beam is converted to un-polarized H^- ion beam with lower yield (3-4% at 6.0-8.0 keV atomic beam energy). The H^- ion beam acceleration (by applying a pulsed -32 kV voltage to the ionizer cell) produces polarized H^- ions with beam energy of 35 keV and un-polarized beam with energy of 38-40 keV. Further suppression of un-polarized higher energy ion beam is produced by magnetic separation in the LEBT.

Atomic hydrogen beam currents of equivalent densities in excess of a 100 mA/cm^2 were obtained at the Na jet ionizer location (about 240 cm from the source) by using a high brightness fast atomic beam source which was developed in collaboration with BINP, Novosibirsk. Estimated polarized H^- ion beam current of about 5-10 mA is expected in this source after upgrade completion (assuming 50% ionization efficiency in He-cell and 50 % neutralization efficiency in the optically-pumped Rb-vapour cell). In feasibility studies of this technique (performed at TRIUMF) in excess of 10 mA polarized H^- and 50 mA proton beam intensities were demonstrated [3]. The beam losses during proton beam deceleration introduced 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 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%.

ATOMIC BEAM SOURCE DEVELOPMENT

In the atomic hydrogen beam source the primary 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 about 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 (0.8 mm diameter) in the plates were produced by photo-etching techniques. The hole array form a hexagonal structure with a step of 1.1 mm and outer diameter of 5.0 cm. The grids were shaped by re-crystallization under pressure at high temperature and were welded to stainless steel holders by a pulsed CO_2 laser. At an emission current density of 470 mA/cm^2, the angular divergence of the produced beam was measured to be ~ 10-12 mrad.

The focal length of the spherical ion extraction system was optimized for the OPPIS application, which is characterized by a long polarizing structure of the charge-exchange cells and small (2.0 cm diameter) Na-jet ionizer cell, which is located 240 cm from the source (see Figure 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 the total beam intensity (~3.5 A) can be transported through the Na-jet cell acceptance by using the optimal extraction grid system with a focal length: $F \sim 200$ cm. Three spherical IOS were tested on the test-bench at BNL. The focusing lengths of IOS #1 and #3 were ~150 cm and for IOS#3 F~250 cm, which allowed study of optimal beam formation. IOS#2 produced about 500 mA equivalent atomic H beam within the 2.0 cm diameter Na-jet ionizer acceptance (at the distance 240 cm from the source) and 16 mA H^- ion beam current.

HELIUM IONIZER CELL. BEAM ENERGY SEPARATION

The He-ionizer cell is a 40 cm long stainless steel tube with an inside diameter 25.4 mm. A new fast "electro-dynamic" valve for He-gas injection to the cell was developed for operation in the 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 with a thickness of 0.5 mm). The Lorentz force: $\mathbf{F} = eL\,[\,\mathbf{I}\times\mathbf{B}] = 15$ N for a L=5 cm long plate. The plate is fixed at one end and this force bends the plate and opens the small (0.5 mm diameter) hole which is sealed with a Viton O-ring. The pulsed current rise-time is ~ 50 μs and gas pressure rise time is about 100 μs

The proton beam produced in the He cell is decelerated from 6.0 keV to 2.5 keV by a negative potential of 3.5 keV applied to the cell. At the 2.5 keV beam energy, the H^- ion yield in the sodium ionizer cell is near maximum (~ 8.4%) and the polarized electron capture cross-section from Rb atoms is also near the maximum of ~ $0.8\cdot10^{-14}$ cm^2. The deceleration was produced by a precisely aligned (to reduce beam losses) three wire-grid system. A small negative bias was 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. Fine tuning of the grids voltages is required for the polarized beam current optimization and total current reduction of the He-cell pulsed power supply.

About 40% residual (which passed the He-cell without ionization) atomic beam component at 6.0 keV energy will pass through the deceleration system and Rb cell and be ionized in Na-cell producing H^- ion beam. The H^- ion yield at 6 keV is about 4%. This is a significant suppression in comparison with the main 2.5 keV beam, but it would be a strong polarization dilution unless further suppression is applied. The H^- ion beam acceleration produce polarized H^- ion beam with 35 keV beam energy and un-polarized beam with 38.5 keV energy. The un-polarized 38.5 keV beam component is well separated after the 24 degree bending magnet in the LEBT. In measurements of beam separation, the beam energy was varied by the accelerating voltage applied to the Na-jet ionizer cell. At 32.5 keV accelerating voltage (where the polarized beam component of 2.5 keV beam energy accelerated to 35.0 keV, optimal for injection into the RFQ) the transmission of residual 6.0 keV un-polarized beam component is strongly suppressed (to less than 2 % of polarized beam component).

EXPERIMENTAL RESULTS

The beam polarization was measured in the precision absolute polarimeter at 200 MeV beam energy after the Linac [5]. The polarization and H^- beam current measurements (after acceleration to 200 MeV in the Linac) vs. Rb-vapor thickness is presented in Figure 2.

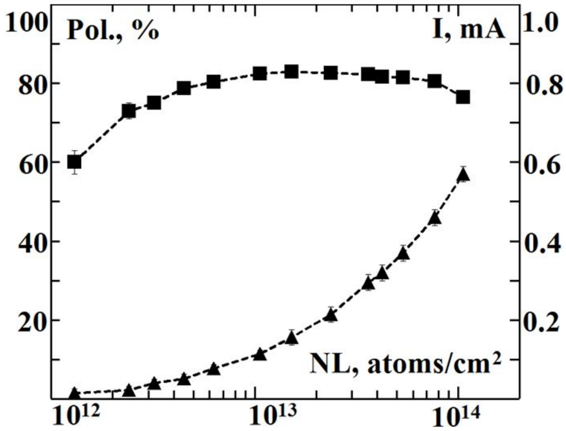

Figure 2: Polarization (squares at the left axis) and beam intensity (triangles- in mA at the right axis) vs. Rb-vapour thickness.

At low Rb-vapor densities, the residual (un-polarized) H^- ion beam current produced by neutralization in residual gas and incomplete energy separation is less than 0.01 mA. Therefore, the polarization dilution due to these factors does not exceed ~ 2%. There was observed some polarization drop at **NL** $\geq 10^{14}$ atoms/cm^2 (**N** ~ $3 \cdot 10^{13}$ atoms/ cm^3, Rb-cell length - **L**=30 cm). Depolarization due to "radiation trapping" is small (at this density Rb-vapor), but some polarization losses may occur due to reduced polarization near the cell walls. This limits the proton beam size and requires good matching between the beam and the Rb-cell diameter. These losses depend on atomic beam intensity and were reduced by laser tuning and atomic beam parameters optimization.

Polarized beam intensity produced in the source exceeds 4.0 mA. The H^- ion beam produced in the sodium-jet ionizer cell is accelerated to 35 keV. This energy increase is essential for the high intensity beam transport. Strong space-charge effects cause significant beam losses in the LEBT line. 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 LEBT was modified to reduce losses and 1.4 mA of polarized beam (after energy separation in the bending magnet and after 6 m in LEBT) was transported to the RFQ and ~ 0.7 mA of beam was accelerated in the Linac to 200 MeV. This current can be further increased by increases in the atomic beam intensity and reduction of the beam losses in LEBT.

Electron depolarization due to spin-orbital interaction in exited (2S, 2P) states of hydrogen atoms should be suppressed by high magnetic field in the Rb-cell [6]. Polarization dependence on magnetic field in the Rb-cell is presented in Figure 3. At every field set-point, the Sona-transition field distribution was optimized by correction – coil tuning. The polarization saturation was observed at super-conducting solenoid fields ≥ 25 kG.

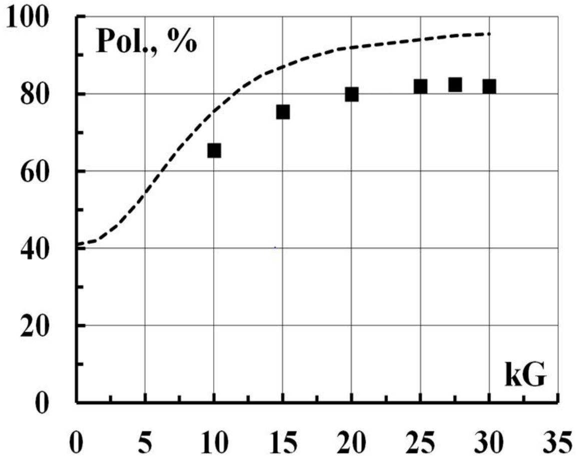

Figure 3: Squares-polarization vs. magnetic field in the Rb-cell. Dashed line–calculations [6].

SUMMARY

The performance of the new source in Run 13 is presented in Table 1 (Rb-cell thickness **NL**$\times 10^{13}$ atoms/cm^2. Linac pulse duration-300 µs. Booster input $\times 10^{11}$ ions/pulse):

Table 1: New Source Performance in Run 13

Rb-cell thickness, **NL**	3.6	5.3	7.6	10.6
Linac Current, µA	295	370	430	570
Booster Input $\times 10^{11}$	4.9	6.2	7.3	9.0
Pol. %, at 200 MeV	84	83	80.5	78

Very reliable operation and reduced maintenance time was demonstrated. In the first year of operation, the new source performance exceeded the old ECR-based source parameters. This was a major factor contributing to the polarization increase to about 60 % for the RHIC colliding beams.

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