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The RHIC polarized source upgrade

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Abstract. A novel polarization technique has been successfully implemented for the Relativistic Heavy Ion Collider (RHIC) polarized H^- ion source upgrade to higher intensity and polarization. In this technique, the proton beam is produced, inside the high magnetic field solenoid, 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 this 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 the BNL linear accelerator (Linac) to 200 MeV. A maximum polarization of 84% (in the 200 MeV polarimeter) was measured at a beam intensity of 0.3 mA and 80% polarization at 0.5 mA. The source reliably delivered beam for the 2013 polarized run in RHIC at $\sqrt{S}$=510 GeV. This was a major contribution to the RHIC polarization increase to over 60 % for colliding beams.

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1. Introduction

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) source was used to produce the primary proton beam 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 an 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^0 beam which 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. The magnetic 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, which enters 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 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 2.0-3.0 keV beam energy, optimal for the charge–exchange collisions in the Rb and Na cells. This allows energy separation of the polarized hydrogen atoms produced after lower energy proton neutralization in the Rb-vapour and the residual hydrogen atoms of the primary beam. The residual atomic H beam is 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 a pulsed voltage of negative 32-33 kV applied to the sodium ionizer cell) produce polarized H^- ion beam with an energy of 35 keV and un-polarized beam with 38-40 keV of beam energy. Further suppression of un-polarized higher energy ion beam is provided by magnetic separation in the LEBT.

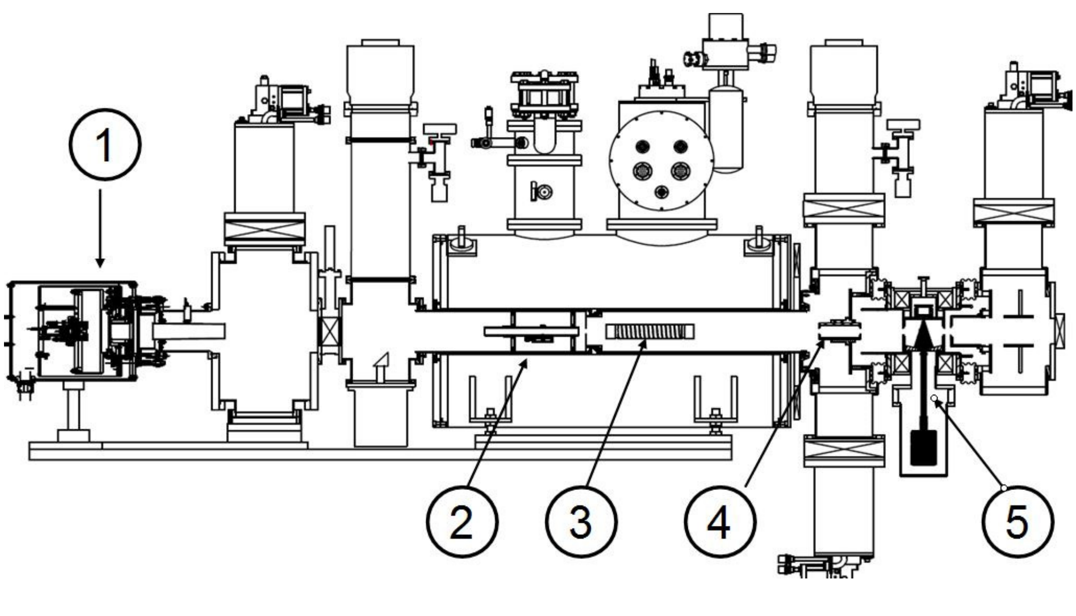

Figure 1: A new polarized source layout: 1-atomic hydrogen source; 2- pulsed He –gaseous ionizer cell; 3 -optically-pumped Rb-vapor cell; 4- Sona-transition; 5-Na-jet ionizer cell

Atomic hydrogen beam current of equivalent densities in excess of a 150 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. The estimated polarized H^- ion beam current of about 5-10 mA is expected in this source after completion of the upgrade (assuming 50% ionization efficiency in He-cell and 50 % neutralization efficiency in the optically-pumped Rb-vapour cell). In feasibility studies of this technique at TRIUMF, in excess of 10 mA polarized H^- and 50 mA proton beam intensity were demonstrated [3]. 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%.

2. 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 ~ 0.2 eV. This was formed by plasma jet expansion from the arc plasma generator [4]. The reliability of long term (2-3 weeks) plasmatron operation at 1 Hz repetition rate in continuous 24/7 operation at RHIC was a primary concern. Original copper cathode in this cold cathode high-current (~ 500 A arc current) lasted only a few days (~$5{\cdot}10^5$ arc pulses). The use of Molybdenum cathode greatly improved the lifetime to ~ $5{\cdot}10^6$ arc pulses. 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 0.8 mm diameter) 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. They were welded to stainless steel holders by pulsed CO_2 laser. At an emission current density of a 470 mA/cm^2, the angular divergence of the produced beam was ~ 8-12 mrad. The schematic layout of atomic hydrogen source is presented in Figure 2.

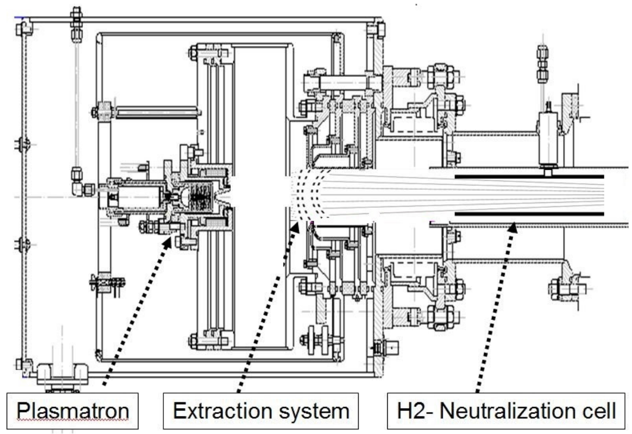

Figure 2. Atomic beam source with geometrical focusing.

The focal length of the spherical Ion Optical System (IOS) 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 250 cm distance 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 2.0 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 optimal extraction grid system of a focal length: F ~ 250 cm. Three spherical IOS were tested at the test-bench at BNL. The beam intensity profiles were measured by secondary emission monitors at two distances 79 cm and 167 cm from the source. The IOS focal length and beam angular divergence which were calculated using these measurements are presented in Table I.

In these calculations we assumed that atomic beam width δr evolution along the drift path L can be expressed using IOS parameters as follows:

$$\delta r^2 = \delta\alpha^2 \times L^2 + a^2 \times \left(\frac{L}{F} - 1\right)^2$$

where δr – beam half-width at 1/e level at distance *L*, $\delta\alpha$ – beam angular divergence, *F* – IOS focal length, a = 2.5 cm is IOS grid radius. By measuring the δr of the beam at two points, it is possible to solve a system of equations and find the focal length and angular divergence.

Table 1:

IOS	I_0, A	F, cm	α, mrad	H^0, mA	H^-, mA
#1	3.5	170	12	270	9
#2	3.2	300	7	730	22
#3	3.0	280	8	650	20

The intensity of atomic beam H^0 within the ionizer acceptance of 2.0 cm diameter at the distance of a 250 cm from the source was calculated from these measurements. This atomic beam was ionized in the Na-jet ionizer cell. The H^- ion yield in the Na-cell is about 3.0% at beam energy 8.0 keV. The produced H^- ion beam intensity (deflected by a dipole magnet to a Faraday Cup) is also presented in Table I.

3. Helium ionizer cell

The He-ionizer cell is a 40 cm long stainless steel tube with an inside diameter of 25.4 mm. A new fast "electro-magnetic" 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 of 0.5 mm thickness). The Lorentz force: **F** = eL [**I**×**B**] **=** 15 N for the L=5 cm long plate. The plate is fixed at one end. This force bends the plate and opens the small (0.5 mm in diameter) hole which is sealed with a Viton O-ring. The pulsed current rise-time is ~ 50 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 kV 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 polarized electron capture cross-section from Rb atoms is also near maximum of about ~ $0.8 \cdot 10^{-14}$ cm^2. The deceleration is produced by a precisely aligned (to reduce beam losses) three wire-grid systems. A small negative bias (relatively to He-cell bias) is applied to the first grid at the cell entrance and the second grid at the cell exit to trap electrons in the cell for space-charge compensation.

About a 40% residual (which passed the He-cell without ionization) atomic beam component of the 6.0 keV beam energy will pass through the deceleration system and Rb cell and be ionized in the Na-cell producing an 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 after the Na-jet ionizer cell [1] produce polarized H^- ion beam with beam energy of 35 keV and un-polarized beam with 38.5 keV beam energy. The un-polarized 38.5 keV beam component is well separated after the 24 degree magnetic bending magnet in LEBT. In the measurements of beam separation, the beam energy was varied by changing 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 is accelerated to 35.0 keV which is 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).

4. Superconducting Solenoid development

A new super-conducting solenoid has been constructed for the OPPIS upgrade by Cryomagnetics, Tennessee. This is a persistent current solenoid with a cold iron yoke and a room temperature bore of 154 mm in diameter. The pulse tube cooling head provides cooling of the two layers of thermal shield and helium re-condensation in a 50 l liquid He vessel. There was no helium loss in 18 months of operation, actually the cooling head provides about 0.6 W extra cooling power at 4 K which is compensated by built in heater and used for feedback system control of the He-gas pressure in the vessel. Five independently energized coils allow solenoid operation in two different modes. In the Atomic Beam Mode, a long flattop 3.0 T field of 70 cm long is produced for operation with neutral beam injection and He-ionizer cell as discussed above. In the ECR mode, the field shape optimal for 29.2 GHz ECR-primary proton source operation [1] is produced with an additional set of coils. The magnetic field shape in the Sona-transition region is carefully adjusted and optimized by solenoid positioning, an additional soft steel plate attached to the solenoid vacuum chamber, one large correction coil which produces field in the opposite direction to the superconducting solenoid and three small correction coils for fine field tuning inside the soft steel cylinder- "Sona-shield" (of 100 mm diameter and 120 mm length). The fine correction coil field tuning is done by measuring polarization vs. coil current.

5. 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 Linac) vs. Rb-vapor thickness is presented in Figure 2.

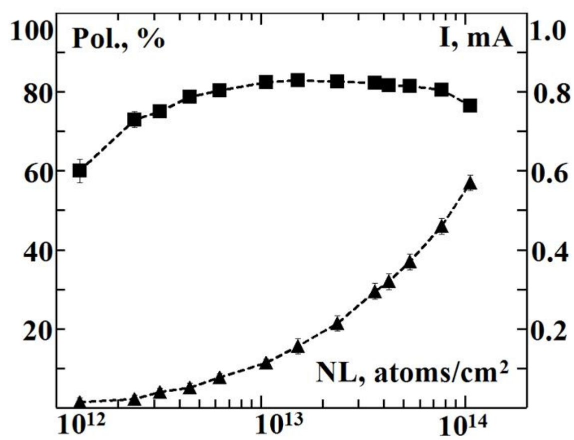

Figure 2: Polarization (squares at the left axis) and beam intensity at 200 MeV after the Linac (triangles- in mA at the right axis) vs. Rb-vapor thickness.

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 factor due to these factors does not exceed ~ 2%. There was observed some polarization drop at **NL** ≥ 10^{14} atoms/cm^2 (**N** ~ $3\cdot10^{13}$ 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 polarized beam (after energy separation in the bending magnet and 6 m of transport in the LEBT) was transported to the RFQ and ~ 0.7 mA beam current was accelerated in the Linac to 200 MeV. This current can be further increased by increasing 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 the super-conducting solenoid field: B ≥ 25 kG.

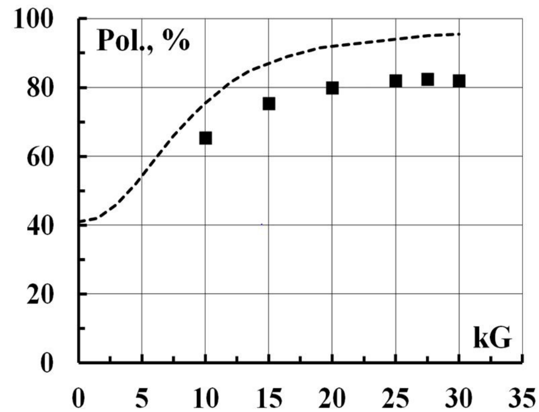

Figure 3: Squares-polarization vs. magnetic field in the Rb-cell. Dashed line–calculations [6].

6. Summary

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

Table 2:

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 contribution to the RHIC polarization increase to ~ 60 % for colliding beams.

References

[1] A. Zelenski, et al., ICIS 2001 Proc., Rev.Sci.Instr., **73**, p.888, (2002)
[2] A. Zelenski et al., NIM **245**, p.223, (1986)
[3] A. Zelenski et al., Hyperfine Interaction, **127**, p.475, (2000)
[4] V.I. Davydenko, A.A.Ivanov, Rev. Sci. Instr., **72**, p.1809, (2004)
[5] A. Zelenski et al., SPIN 2010 Conf.Proc., J.Phys.Conf.Ser., 295012132, (2011)
[6] E. Hinds et al., NIM **189**, p.599, (1981)