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The RHIC Polarized H^- Ion Source

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Abstract. A novel polarization technique had been successfully implemented for the RHIC polarized H^- ion source upgrade to higher intensity and polarization. In this technique, a proton beam inside the high magnetic field solenoid is produced by ionization of the high-brightness atomic hydrogen beam injected in the He-gas ionizer cell. Further proton polarization is produced in the process of polarized electron capture from the optically-pumped Rb vapor. Polarized H^- ion beam intensity out of the Linac at 200 MeV increased in Run-2017 up to 1.0 mA with a new high-current IOS (Ion Optical System) optimized for polarized source acceptance. This corresponds to $1.8 \cdot 10^{12}$ H^- ion for the Linac pulse. High beam brightness and polarization resulted in 70-75% polarization at 23 GeV out of AGS and 60-65% beam polarization at 255 GeV colliding beams in RHIC in Run 2017.

INTRODUCTION

The goals of the 14 weeks of polarized proton on proton collisions at a beam energy of $\sqrt{s}=510$ GeV were studies of scale evolution of the Sivers effect by measurements of analyzing power in W, Z-boson and Drell-Yan process with transversally polarized colliding beams. The integrated luminosity of 350 pb^{-1} for the W,Z- production exceeded maximum Run-17 goal.

The RHIC is the first high-energy accelerator-collider complex, where the “Siberian snake” technique successfully implemented to avoid resonance depolarization during beam acceleration in the AGS and RHIC and high-intensity polarized H^- ion source combined with the charge –exchange injection allowed to achieve maximum possible intensity and luminosity limited by beam-beam interaction [1]. A luminosity of $1.6 \cdot 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ for polarized proton collisions in RHIC produced by colliding 110 bunches in each ring at $2 \cdot 10^{11}$ protons/bunch intensity. In Run-17, the polarized source produced up to 1.6 mA H^- ion beam current in 300-400 μs long pulses at 82-85% polarization. After losses in a Low Energy Beam Transport (LEBT) line and in the Linac, polarized H^- ion beam current of a 0.5-1.0 mA delivered for injection to the Booster (this beam intensity corresponds up to 10^{12} H^- ions/pulse). Since one source pulse accelerated and transformed to one RHIC bunch (by multi-turn injection of 200 MeV Linac beam to The Booster ring), there is plenty of intensity out of the source to charge the RHIC to its full capacity (limited by the beam-beam interaction) in spite of losses along the accelerator chain. In addition, an intentional beam scraping of about 70% occurs during dynamic beam collimation after the Booster, to reduce beam emittance in AGS and RHIC. The polarization direction switched in the source, by changing laser beam circular polarization and frequency according to the required bunch spin direction pattern in the RHIC.

In previous Runs strong space-charge forces at injection to Booster caused the emittance growth and did not allow of taking full benefits of high polarized source and linac pulse intensity. In Run 2015-17, a different capture scheme implemented which defocuses the center of the bunch longitudinally and reduces the peak current. The resulting transverse emittances at AGS extraction and in RHIC were 20% smaller than in previous runs owing largely to this improvement. The higher brightness Booster and AGS beam allowed polarization losses reduction and resulted in significant increase of the integrated beam luminosity.

The Electron Cyclotron Resonance (ECR) used as a primary proton in the old operational polarized source in Run 2000-2012 [2,3]. In pulsed operation, suitable for application at high-energy accelerators and colliders, the ECR source limitations was overcome by using a high brightness proton source outside the magnetic field instead of ECR source. In this technique, which implemented for the first time at INR, Moscow [4], the primary proton beam focused and neutralized in hydrogen cell, producing the high brightness 6.0-6.5 keV atomic H^0 beam. Then atomic

FIGURE 1. Layout of the OPPIS with atomic hydrogen injector: 1–high-brightness neutral hydrogen injector; 2- helium ionizer cell; 3-optically-pumped Rb cell; 4-Sona-transition; 5-sodium-jet ionizer cell.

hydrogen beam injected into a superconducting solenoid, where a He ionizer cell and an optically-pumped Rb cell are situated in the 25-30 kG solenoid field (see Fig.1). The injected H atomic beam ionized in the He cell with 60-80% efficiency to form a low emittance intense proton beam, which is decelerated to 2.0-2.5 keV for energy separation from primary beam and then enters the polarized Rb vapor cell, where protons capture the polarized electrons from Rb atoms producing electron-spin polarized atomic hydrogen beam [5,6].

The un-polarized higher energy beam component well separated and is strongly suppressed by beam collimation after the bending magnet in the LEBT line. Atomic hydrogen beam current of equivalent densities in excess of a 100 mA/cm² obtained at the Na jet ionizer location (about 240 cm from the source) by using a high brightness fast atomic beam source, which developed in collaboration with BINP, Novosibirsk [7,8].

ATOMIC BEAM SOURCE BRIGHTNESS INCREASE WITH A NEW 4-GRID IOS

In the atomic hydrogen beam source the primary proton beam produced by a four-grid multi-aperture ion extraction optical system and neutralized in the pulsed H_2 gaseous cell downstream from the grids. A high-brightness atomic hydrogen beam 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 [8]. The multi-hole grids spherically shaped to produce “ballistic” beam focusing. At emission current density of a 470 mA/cm² an angular divergence of the produced beam is ≤ 10 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). A drift-space length of about 100-140 cm is required for convergence of the 5 cm (initial diameter) beam to 2.5 cm diameter He-ionizer cell. At 6.5 kV extraction voltage, the total proton beam current is 3.5 A and after neutralization in hydrogen neutralizer cell $\sim 20\%$ of this atomic hydrogen beam intensity can be transported through the Na-jet cell acceptance by using optimal extraction grid system of a focal length: $F \sim 200$ cm.

Three new sets of ion-optical system were developed and manufactured at BINP and studied at test bench for the Run-2017. The grids geometry were optimized for long focal length to match the OPPIS charge-exchange cells acceptances. A new grid alignment procedure developed, which greatly improved accuracy and reproducibility of

IOS assembly for the highest beam brightness operation. At the test-bench, the atomic beam intensity profiles were measured by movable secondary emission beam profile monitors at distances of 40-180 cm from the source (see Fig.2). The focal distance 200 cm and beam divergence ~ 10 mrad calculated by fitting this beam envelope. As a result, the average OPPIS beam intensity increased for at least 20%, and contributed to higher polarization in a trade of intensity for polarization.

Figure 2. Atomic hydrogen beam profile: Y- half-width (at 1/e-level) measured vs. distance (X) from the proton source. Beam profile FWHM is equal 1.67 Y. Blue squares-a new IOS, which produced higher brightness primary atomic hydrogen beam in Run-2017. Red diamonds the old IOS with larger beam divergence.

Also at the test-bench the H^- ion beam current measurement produced in the H_2 neutralizer cell were used for the source tuning and parameters optimization. The H^- ion beam current measured in Faraday Cup after the 10 degrees bending magnet. A 75 mA H^- ion beam current was obtained at 10.0 keV beam energy at the distance 200 cm from the source (see Fig. 3). The total primary proton beam current was 4.7 A. The H^- ion beam yield in the H_2 neutralizer cell at 10 keV beam energy is ~ 2.0 % and total H^- ion beam current cannot exceed 94 mA, therefore H^- ion beam transport efficiency is very high. It is actually higher, than neutral beam transport efficiency. To resolve this puzzle, the second H_2 charge-exchange cell was installed at the distance of 200 cm from the source and H^- beam production from neutral hydrogen beam (H^- ions from neutralizer cell were deflected by bending magnet) was measured. In these measurements, we got agreement in between atomic beam intensity calculated from beam profile measurements and H^- ion beam current in assumption of the 2.0 % yield. However, with the cell empty and deflecting field off H^- ion beam intensity increased 2.5 times. This means that H^- ion beam produced in the neutralizer cell has smaller divergence than neutral beam. Additional H^- ion beam focusing can be produced by residual H^+ ion beam co-propagating with H^- ion beam. The Monte-Carlo simulations of the three components beam transport confirm these observations [9]. The residual H^+ beam intensity at 10 keV is about 8 % of the primary beam and space charge field of this beam focuses H^- ion beam.

FIGURE 3. The H^- ion beam current -75 mA (magenta); extractor beam voltage-10 kV (green); total proton beam current-4.7A (blue). Time scale is 100 us/div.

An energy dependence of the H^- ion beam yield drops to 1.8% at 20 keV (and 1.4% at 30 keV). The primary proton beam current strongly increases with the beam energy (from 3,2 A at 8.0 keV to 4.7 A at 10 keV) and H^- ion beam current increases from 50 to 75 mA. Therefore, it is expected at 20-30 keV beam energy it is possible to produce a few hundred mA of the H^- ion beam intensity (in Cesium-free source), which might be used for some accelerator applications. The source operated at 1Hz, 24 hours and 7 days a week continuously for 2-3 months, with little performance degradation. The source continuous operation duration limited by arc-plasma generator erosion. The whole plasma generator replacement takes about one hour during the planned maintenance time.

ATOMIC H BEAM IONIZATION IN THE HELIUM IONIZER CELL

The He-ionizer cell is a 30 cm long stainless steel tube with inside diameter 25.4 mm. A new fast “electromagnetic” valve for He-gas injection to the cell developed for operation in 25-30 kG solenoid field. The proton beam produced in the He-cell is decelerated from 6.5 keV to 2.5 keV by the pulsed negative potential 4.0 keV applied to the cell. At the 2.5 keV beam energy the H^- ion yield in the sodium ionizer cell is near maximum ($\sim 8.4\%$) and cross-section of polarized electron capture cross-section from Rb atoms is also near maximum of about $0.8 \cdot 10^{-14} \text{ cm}^2$. The deceleration is produced by precisely aligned (to reduce beam losses) three wire-grid system. A small negative bias 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 (see Fig. 4). An intermediate potential of a 2-3 kV applied to the second grid and positive potential of $\sim 100 \text{ V}$ to the third grid to prevent positive Rb-ion flow. A fine-tuning of these voltages is required to minimize space-charge effects in the He-cell and during beam deceleration and reduce beam divergence. About 40% of primary atomic beam of 6.5 keV beam energy will pass deceleration system and Rb cell and ionized in Na-cell producing H^- ion beam.

FIGURE 4. A schematic layout of the He-ionizer cell and deceleration system for the polarized beam energy separation.

The H^- ion beam acceleration for 32.5 keV at the exit of Na-ionizer cell (by the extractor voltage applied to the cell) produces polarized H^- ion beam of a 35 keV beam energy and un-polarized be of 39.0 keV beam energy. The un-polarized 39.0 keV beam component well separated after the 23.7 degrees bending magnet and beam collimation system in the LEBT. The suppression factor of about 50 times (for the 200 MeV beam out of the Linac) was measured by scanning of the extractor voltage. Therefore, the residual un-polarized beam strongly suppressed to less than 2 % of polarized beam component.

Equivalent intensity of primary atomic H beam (at 6.5 keV beam energy) through He and Na-jet ionizer cells exceeds 100 mA. It is estimated from measured direct H^- ion beam intensity of 5.2 mA using the known H^- ion yield in Na-vapor of a 4.5% at 6.5 keV beam energy. He and Rb-cells turned off for these measurements. About 50-60% of this atomic H beam ionized in He-cell to proton beam and decelerated to 2.5 keV. About 50% of this proton beam neutralized back to atomic beam by polarized electrons capture from Rb atoms. This beam ionized to H^- ion beam in the Na-jet cell with efficiency of $\sim 8.4\%$. Therefore, the expected polarized beam intensity is $\sim 4.0 \text{ mA}$. Beam deceleration by three grid IOS may introduce additional beam divergence and cause additional losses. Some beam loss expected due to space-charge effects at 2.5 keV in presence of ionizer solenoid 1.5 kG magnetic field. The H^- ion beam produced in the sodium-jet ionizer cell 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 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 1.6 mA polarized beam (after energy separation in the bending magnet after 6 m transport in the LEBT) was transported to the RFQ and up to 1.0 mA H^- ion beam current of a 80 % polarization was accelerated in the Linac to 200 MeV . This current can be further increased by atomic beam intensity increase and reduction of the beam losses in LEBT.

POLARIZED SOURCE PERFORMANCE IN RUN-2017

The new source with atomic beam hydrogen injector and He-ionizer was developed in 2010-12 and commissioned for operation in Run-2013 [5,6]. It produces significantly higher brightness primary proton beam, which resulted in higher polarized beam intensity and polarization delivered for injection to Linac-Booster-AGS-RHIC accelerator complex. Very reliable operation and reduced maintenance time was demonstrated. Already in the first 2013 year of operation, the new source performance exceeded the old ECR-based source parameters and performances further improved in Runs 2014-17 [12]. The beam polarization measured in the absolute polarimeter at 200 MeV beam energy after the Linac. After upgrade, the polarized source produces 0.5-1.0 mA current in 300 μ s long pulses (which corresponds to about 10^{12} H^- ions/pulse) at 82-85% polarization as measured after the Linac at 200 MeV beam energy. The source current is significantly higher (up to 5.0 mA) and large beam losses occurs during 35 keV beam transport in the long LEBT line and energy separation process. These losses can be reduced by ongoing optimization of LEBT line.

Polarization losses in AGS depend on beam emittance and corresponding bunch intensity. When extrapolated to zero intensity (small emittance) polarization numbers are consistent with absolute 200 MeV polarimeter measurements. The AGS bunch intensity for injection to RHIC was about $2.0 \cdot 10^{11}$ protons/bunch and polarization 70-72% optimized for best RHIC performance for STAR experiment operation. The beam polarization in RHIC measured with absolute H-jet polarimeter [10]. As a result of recent Atomic Beam Source, detectors, DAQ upgrades and ongoing systemic errors analysis, the statistical accuracy for the single RHIC fill measurement reduced to less than $\pm 3\%$ and systematic error for absolute polarization value to $<0.5\%$. The steady source and AGS performances resulted in production of high average beam polarization at 255 GeV. The polarization for colliding beams is actually even higher (see Ref.[11] for corrections due to polarization beam profiles) and exceeded 60% for the good fraction of fills.

High beam current, brightness and polarization produced in the source resulted in polarization increase out of AGS to 70-72% (due to beam emittance reduction by strong beam scraping at extraction from Booster) and 60-65% beam polarization at 100-250 GeV colliding beams in RHIC.

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