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OPTICALLY-PUMPED POLARIZED H$^-$ AND 3He^{++} ION SOURCES DEVELOPMENT AT RHIC

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Abstract

The RHIC Optically-pumped Polarized H$^-$ Ion Source (OPPIS) upgrade with the atomic beam hydrogen injector and the He-ionizer cell was commissioned for operation in the Run-2013. The use of the high brightness primary proton source resulted in higher polarized beam intensity and polarization delivered for injection to Linac-Booster-AGS-RHIC accelerator complex. The proposed polarized 3He^{++} acceleration in RHIC and future electron- ion collider (eRHIC) will require about $2 \cdot 10^{11}$ ions in the source pulse. A new technique had been proposed for production of high intensity polarized 3He^{++} ion beam. It is based on ionization and accumulation of the 3He gas (polarized by optical-pumping and metastability-exchange technique in the high magnetic field of a 5.0 T) in the Electron Beam Ion Source (EBIS). We present a status of the 3He^{++} ion source development.

INTRODUCTION

The RHIC is the first high-energy accelerator-collider complex where the "Siberian Snake" technique was successfully implemented to avoid the resonance depolarization during the beam acceleration and obtain 60 % polarization for colliding beams. The high-intensity polarized H$^-$ ion source combined with charge exchange injection allowed the maximum possible intensity and luminosity limited by beam-beam interaction [1]. During Run-2017, the polarized H$^-$ ion beam current of a 0.5-1.0 mA was delivered for the injection to the Booster in 300 µs Linac pulse (this beam intensity corresponds up to 10^{12} H$^-$ ions/pulse).

The nuclear polarization in polarized 3He^{++} beam is carried mostly by neutrons. The 3He^{++} polarization can be preserved during acceleration in high-energy synchrotron accelerators like AGS and RHIC by using the "Siberian snake" technique. Therefore, the high-energy polarized neutron beam can be readily available for the fundamental studies in collisions of the polarized electrons with polarized protons and 3He^{++} beams. The proposed polarized 3He^{++} acceleration in RHIC will require about $2 \cdot 10^{11}$ ions in the source pulse and about 10^{11} ions in the RHIC bunch. To deliver this intensity in a 20 us pulse duration for the injection to the Booster, the source peak current has to be about 2000 µA, which is 1000 higher than ever achieved in existed 3He^{++} ion sources. We have proposed the concept for a polarized ^{3}He^{++} ion source based on the existing EBIS at Brookhaven National Laboratory (BNL) [2]. The ^{3}He atoms are polarized via the Metastability Exchange Optical Pumping (MEOP) technique [3-4] in a glass cell at a pressure of 1-10 mbar in a 5.0 T magnetic field inside the EBIS solenoid and then are injected into the EBIS ionizer. In the EBIS the 3He^{++} an estimated (2.5-5.0)1011 3 He++ ions can be produced and accumulated in 1.5 m EBIS trap region with a capacity of about 10^{12} total charge based on the total electron beam charge, and a neutralization factor between 0.5 and 1.0. The required beam intensity of $2 \cdot 10^{11}$ 3He^{++}/pulse can then be obtained during extraction and acceleration in the single beam pulse. Successful tests of polarizing ^{3}He in a high magnetic field [5] have led to the development of the Extended EBIS concept. This upgrade will also improve the heavy ion and gas species production. The Extended EBIS upgrade is now an approved Accelerator Improvement Project at BNL with the primary purpose of increasing the Au^{32+} intensity, but it will provide essential infrastructure for the polarized ^{3}He ion source.

HIGH-INTENSITY OPTICALLY-PUMPED POLARIZED ION SOURCE AT RHIC

The primary proton source in OPPIS during Runs 2000-2012 was the dc Electron Cyclotron Resonance (ECR) source [6]. The proton beam produced in the ECR source had the comparatively low emission current density and the high beam divergence. The OPPIS upgrade with the high-brightness atomic hydrogen injector and the He-ionizer cell (which effectively works as the proton source inside the high magnetic field) was completed for the Run-2013. Practically all OPPIS systems were modified during the upgrade: the new neutral hydrogen injector, the new superconducting solenoid, the new He-ionizer cell with pulsed He-injection by the new pulsed electro-magnetic gas valve. The vacuum system upgrade includes turbo-molecular pumps for helium gas pumping. The LEBT was modified to reduce losses of the high-intensity beam and increase the energy resolution for the better suppression of the residual un-polarized beam component. In the first year of operation, the upgraded source performance exceeded the old ECR-based source parameters.

The primary proton beam (in the atomic hydrogen beam source) is produced by the four-grid multi-aperture Ion Optical System IOS) and is neutralized in the pulsed H_2 gaseous cell downstream of the IOS. The multi-hole grids were spherically shaped to produce geometric beam focusing. The focal length of the spherical IOS was optimized for OPPIS application and is characterized by the long polarizing structure of the charge-exchange cells and small (2.0 cm in diameter) Na-jet ionizer cell aperture (see Figure 1). The drift-space length of about 100-140 cm is required for

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convergence of the 5.0 cm (the IOS diameter) beam to 2.5 cm diameter of the He-ionizer cell.

The new IOS was developed and manufactured at BINP, Novosibirsk for use in the Run-2017 [7]. The grids geometry was optimized for the long focal length to match the OPPIS charge-exchange cells acceptances. The new IOS produced 2.5A. The converging proton beam at 6.5 keV energy, which was neutralized with 90% efficiency in the hydrogen neutralizer cell. The atomic beam envelope waist is located at 100 cm distance from the source. The FWHM of the beam profile is 2.3 cm. The He-ionizer cell is a 30 cm long stainless steel tube with an inside diameter of 25.4 mm. The pulsed electro-magnetic valve for He-gas injection to the cell was developed for operation in the 25-30 kG solenoid field. The proton beam produced in the He-cell was decelerated from 6.5 keV to 2.5 keV by the pulsed (to reduce probability of sparking) negative potential of 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 (~ 8.4%) and cross-section of the polarized electron capture cross-section from Rb atoms is also near maximum at about $0.8 \cdot 10^{-14}$ cm^2. The deceleration is produced by the precisely aligned (to reduce beam losses) three wire-grid system. The H^- ion beam acceleration at the exit of Na-ionizer cell (by the negative 32.5 kV extractor voltage applied to the cell) produces polarized H^- ion beam at 35.0 keV beam energy and un-polarized beam at 39.0 keV beam energy. The un-polarized beam component was 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.

The equivalent intensity of the primary atomic hydrogen beam (at 6.5 keV beam energy) through the He and the Na-jet ionizer cells exceeded 115 mA. It was 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). This intensity was measured in Faraday Cup after the bending magnet (after 6 m transport in the LEBT with large intensity losses) and is a low limit on intensity.

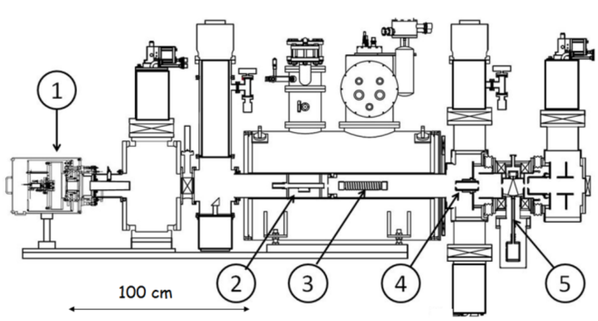

Figure 1: Layout of the OPPIS with atomic hydrogen injector: 1–high-brightness neutral hydrogen injector; 2- helium ionizer cell; 3-optically-pumped Rb cell; 4-Sona transition region; 5-sodium-jet ionizer cell.

The He-cell and Rb-cell were turned off for these measurements. About 70% of this atomic H beam is ionized in the He-cell to proton beam and decelerated to 2.5 keV. About 70% of this proton beam is neutralized back to atomic beam by polarized electron capture from Rb atoms. This beam was ionized to the H^- ion beam in the Na-jet cell with efficiency of ~ 8.4%. Therefore, the expected polarized beam intensity is in excess of 4.0 mA. Beam deceleration by the three grid IOS may introduce additional beam divergence and cause additional losses. The beam acceleration at the exit of Na-ionizer cell was essential for reduction of the space-charge effects during the high intensity beam transport.

POLARIZED $^3He^{++}$ ION SOURCE

The EBIS currently produces high charge state ions for injection to the RHIC and will remain the primary source of charged ions from P to U for the eRHIC. In the EBIS, the high intensity (10 A) electron beam is produced by the electron gun with cathode diameter 9.2 mm and injected into the 5.0 T solenoid magnetic field. The electron beam is radially compressed by the magnetic field to the diameter of about 1.5 mm in the ionization region and then expanded before dumping into the electron collector at the other end. Ions are radially confined by the space charge of the electron beam and longitudinally trapped by electrostatic barriers at the ends of the trap region. The ions are extracted by raising the potential of the trap and lowering the barrier [8]. A second 5.0 T solenoid has been constructed as the part of the extended EBIS upgrade. The polarized 3He gas will be injected and ionized in the upstream solenoid, and $3He^+$ ions will be trapped and further ionized to the $3He^{++}$ state in the downstream solenoid (see Figure 2).

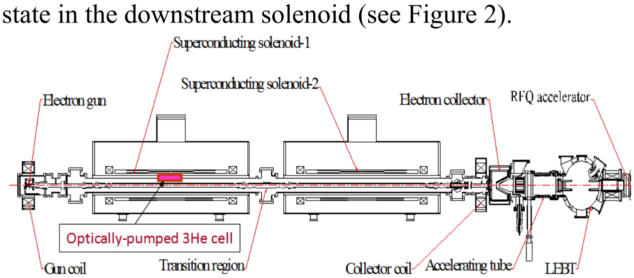

Figure 2: Schematic diagram of the extended EBIS. The polarized 3He gas is injected into the drift tube of the new "injector" EBIS part.

The 3He gaseous cell will be placed inside the EBIS "injector" solenoid and the pulsed gas valve (similar to OPPIS valve) will be used for the gas injection into the centre of the EBIS drift tube system to minimize depolarization and increase ionization efficiency. The second "injector" EBIS section allows using differential pumping between the "gas injector" and the main EBIS. This is especially beneficial for gas species production (including the 3He gas). An isolation valve between the two EBIS sections will simplify the 3He polarizing apparatus maintenance. The ionization in the EBIS is produced in a 5.0 T magnetic field, which preserves the nuclear 3He polarization while in the intermediate single-charged $3He^+$ state. The number of ions is limited to the maximum charge, which can be confined in the EBIS. From experiments with Au^{32+} ion production,

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one expects more than $2.0 \cdot 10^{11}$ $^3He^{++}$ ions/pulse to be produced and extracted for the subsequent acceleration and the injection in the RHIC. After the $^3He^{++}$ beam acceleration to the energy 6 MeV/nucleon the absolute nuclear polarimeter based ^3He-^4He collisions will be used for the polarization measurements.

The high ^3He nuclear polarization in excess of 80% was achieved by the metastability-exchange technique in the sealed glass cell in the high 2.0-4.0 T magnetic field. In these measurements, the ^3He gas at 1.0-3.0 torr pressure was contained in the glass cell and the weak RF discharge was introduced to populate the meta-stable states. Meta-stable atoms in the 2 $^3S_1$ state was polarized by optical pumping with circularly polarized (2^3S_1 - 2^3P_0) 1083 nm laser light. Any contamination in the helium gas cell (hydrogen, water vapor etc.) reduces the 3He polarization due to meta-stable states quenching. In the polarized source, the optically pumped cell has to be connected to the valve for gas injection to the drift tube and the line for the gas refill. To eliminate the contaminations and maintain the necessary gas purity we developed the system for 3He gas purification and filling based on the cryo-pump, which pumps all gases except for helium. We installed inside the conventional CTI-8 cryo-pump the additional cold vessel (attached to the cold head of the cryo-pump) filled with charcoal granules. It was connected to the 3He filling system by the thin wall tube. At a temperature of 46 K the pump continuously absorbing and reducing partial pressures of hydrogen, water, hydrocarbons, and argon to the level below 10^{-7} torr. This pump absorbs also quite a significant amount of 3He gas (of about 100 sccm). The absorbed gas is released by the pump vessel heating. This provides gas storage and supply for 3He-cell operation at the optimal pressure value.

The optically pumped 3He glass cell was attached to the gas filling system with a 200 cm long stainless tube. The cell and filling system were mounted on a movable support and inserted inside superconducting solenoid. To prevent 3He atoms depolarization due to travel through the solenoid gradient field we installed an additional isolation valve close to the cell in the homogeneous field region. We used a remotely controlled (pneumatic) non-magnetic brass valve and copper coupling adapter between the glass cell and the isolation valve.

For the polarization measurements, we used the technique of the probe laser absorption [9]. The best results on optical pumping of 3He gas in the "open" cell were 73% with the closed isolation valve and 20% with the open isolation valve at 3.0 torr pressure.

We have studied a new EBIS drift-tube configuration to increase the gas efficiency (minimize amount of injected 3He gas for the EBIS trap saturation). The 3He gas will be injected into the small diameter (10-20 mm ID) drift tube by the pulsed valve. The estimations show that a very small amount of 3He gas of about $(5\text{-}10) \cdot 10^{12}$ atoms will be required to be injected into the drift tube for ~50 % EBIS trap neutralization. We are developing the pulsed valve for the 3He-gas injection into the EBIS drift tube, which operates in the 2.0-5.0 T solenoid field. In this valve, the pulsed current of 10-20 A passes through the flexible springing plate (made of phosphorus bronze with a thickness of 0.12 mm). The sealing Kalrez circular pad (5 mm in diameter 1.0 mm thick) was attached to the plate. The induced Lorentz (Laplace) force: $\mathbf{F} = eL\,[\mathbf{I}\times\mathbf{B}] = 2\text{-}5$ N (for L=5 cm long plate) bends the plate and opens the small (0.1 mm in diameter) hole for the gas injection into the drift-tube. The valve prototype was tested in the 2.0 T solenoid field. The gas flow as low as $2 \cdot 10^{12}$ atoms /pulse was measured at 12 A current through the plate. The valve was also operated with the four consecutive pulses 4 ms apart, producing up to 10^{13} atoms/per cycle. This might be an optimal mode for the gas injection distributed over 20 ms for the effective ionization by the EBIS electron beam, while limiting the injection gas cell pressure to $\sim 10^{-6}$ mbar.

The studies of the possible depolarization effects during polarized ^3He gas injection and multi-step ionization process in the EBIS, the optimization of the materials, the valve, and the 3He-cell geometry will be required to determine the maximum attainable polarization. The expected $^3He^{++}$ ion beam intensity is about $2 \cdot 10^{11}$ ions/pulse with polarization 70%.

CONCLUSION

After the upgrade, the RHIC optically pumped polarized H^- ion source produces high beam intensity and high polarization sufficient to fill the RHIC (eRHIC) storage rings to the full capacity. The extended EBIS operation for the Au^{32+} ion beam production is planned for the Run-2019. The next step will be integration of polarizing 3He apparatus. The development of the 3He polarizing apparatuses, the spin-rotator, and the nuclear polarimeter at the $3He^{++}$ ion beam energy 6.0 MeV (in the high-energy beam transport line after the EBIS drift-tube Linac) is funded by the DOE Research and Development Funds for the Next Generation Nuclear Physics Accelerators Facilities.

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