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Optically Pumped Polarized ^{3}He^{++} Ion Source Development at RHIC

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The proposed polarized ^{3}He^{++} acceleration in RHIC and the future Electron-Ion Collider will require about 2×10^{11} ions in the source pulse. A new technique had been proposed for production of high intensity polarized ^{3}He^{++} ion beams. It is based on ionization and accumulation of the ^{3}He gas (polarized by metastability-exchange optical pumping in the 5 T high magnetic field) in the existing Electron Beam Ion Source (EBIS). A novel ^{3}He cryogenic purification and storage technique was developed to provide the required gas purity. The status of the Extended EBIS upgrade project is presented.

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1. Introduction

The proposed polarized ^{3}He^{++} acceleration in the Relativistic Heavy Ion Collider (RHIC) will require about 2×10^{11} ions in the source pulse and about 10^{11} ions in the RHIC bunch. To deliver such an intensity, we have proposed the concept for a polarized ^{3}He^{++} ion source based on the existing Electron Beam Ion Source (EBIS) [1] at Brookhaven National Laboratory. The ^{3}He atoms are polarized via the Metastability Exchange Optical Pumping technique [2, 3] in a glass cell at a pressure of 1–10 mbar in a 5.0 T magnetic field inside the EBIS solenoid and then will be injected into the EBIS drift tube. In EBIS, an estimated $(2.5–5.0) \times 10^{11}$ ^{3}He^{++} ions can be produced and accumulated in the 1.5 m trap region with a capacity of about 10^{12} total charge based on the total electron beam charge and a neutralization factor of about 0.5. The required beam intensity of 2×10^{11} ^{3}He^{++} ions/pulse can be obtained after extraction and acceleration of the accumulated ions in a single beam pulse. Successful tests of ^{3}He polarization in a high magnetic field [4–7] have led to the development of the Extended EBIS concept, in which adding of the second solenoid (see Fig. 1) extends the trap length and provides space for the ^{3}He polarization apparatuses. This upgrade will also improve the heavy ion and gas species production. The Extended EBIS construction is now in progress with the primary purpose to increase the Au^{32+} intensity, but it will also provide the essential infrastructure for the polarized ^{3}He ion source.

2. Polarized ^{3}He^{++} ion beam production in the Extended EBIS

In the EBIS, the high intensity (10 A) electron beam is produced by the electron gun with cathode diameter 9.2 mm and is 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 the electrostatic

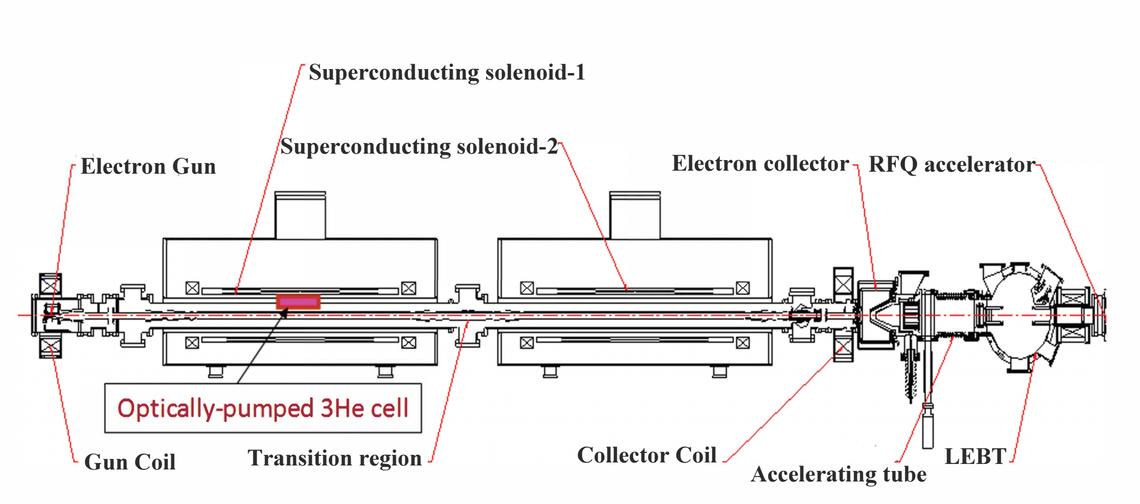

Figure 1: Schematic diagram of the Extended EBIS. The polarized ^{3}He gas is injected into the drift tube of the new "injector" EBIS section.

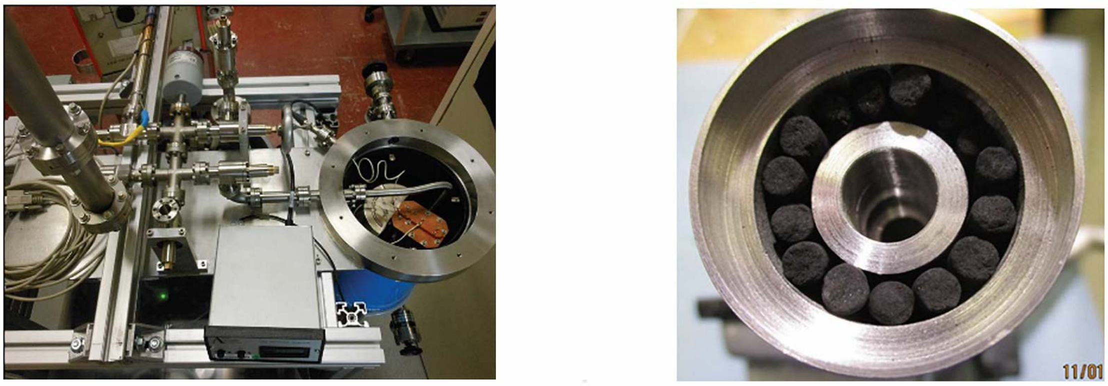

Figure 2: Left: the cryogenic ^{3}He purification and filling system. Right: the vessel filled with charcoal granules is attached to the cold head of the cryo-pump.

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 part of the Extended EBIS upgrade. The polarized ^{3}He gas will be injected in the extended drift tube and ionized in the upstream solenoid, and ^{3}He$^+$ ions will be trapped and further ionized to the ^{3}He^{++} state in the downstream solenoid (see Fig. 1).

The ^{3}He gaseous cell will be placed inside the EBIS "injector" solenoid and the pulsed gas valve will be used for the gas injection into the 30 cm long, small diameter of a 16 mm drift tube, which works like a "storage cell", increasing the effective ^{3}He target thickness and ionization efficiency. The ionization in the EBIS is produced in a 5.0 T magnetic field, which preserves the nuclear ^{3}He polarization while the ions are in the intermediate single-charged ^{3}He$^+$ 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, one expects more than 2×10^{11} ^{3}He^{++} ions/pulse to be produced and extracted for the subsequent acceleration and injection in RHIC. After the ^{3}He^{++} beam acceleration to the energy 6 MeV/nucleon the absolute nuclear polarimeter based on ^{3}He^{4}He collisions [9] will be used for the polarization measurements.

2.1 ^{3}He gas purification and cell filling system

The gas purity in the sealed cell was achieved by an elaborate glass cell cleaning, baking, outgassing procedure and use of a sophisticated gas purification system. In the polarized source, the optically pumped cell must be connected to the valve for gas injection to the drift tube and the line for the gas refill. To eliminate contamination and to maintain the necessary gas purity in this "open cell" configuration, we developed a system for ^{3}He gas purification and filling based on the technique of cryo-pumping, which pumps all gases except helium. In a conventional CTI-8 cryopump, we cut away half of the cryo-panel (the second part is required to maintain the isolation vacuum) and installed the additional cold vessel (attached to the cold head of the cryo-pump) filled with charcoal granules (see Fig. 2).

It was connected to the ^{3}He filling system by a thin vacuum bellows (see. Fig. 2). At the operational temperatures of 20–25 K, the pump was continuously absorbing (and reducing the partial pressures of hydrogen, water, hydrocarbons, and argon) to the level below 10^{-7} Torr. This

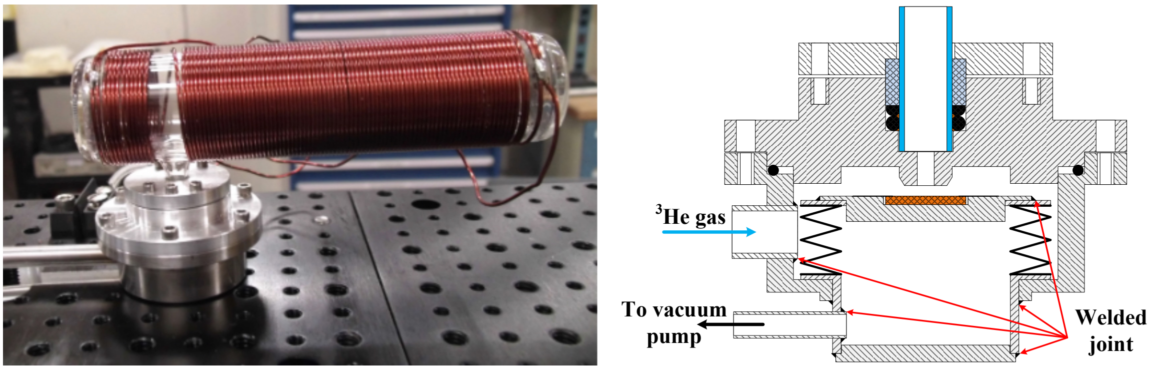

Figure 3: Left: “Open” ^{3}He gas cell (30 mm in diameter) with the isolation (filling) valve (IV) attached. Right: A new custom built pneumatic (bellows-based) isolation valve.

pump also absorbs quite a significant amount of ^{3}He gas (about 100 cm^3). The absorbed gas is released by the vessel heating with a built-in cartridge heater. This provides gas storage and supply for ^{3}He-cell operation at the optimal optical-pumping pressure of 3–5 Torr. The pressure stability is maintained with the heater feedback system on the gas pressure measured by the Baratron MKS-626 pressure transducer.

The optically pumped ^{3}He glass cell is 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 the superconducting solenoid. To prevent ^{3}He atom 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 developed a remotely controlled (pneumatic) valve with a small bellows. To open the valve, it is connected to a vacuum pump and it is closed by atmospheric pressure. The valve coupling to the ^{3}He cell is designed to minimize the contact surface to aluminum surfaces and silicon sealing O-rings (see Fig. 3).

In the ^{3}He gas handling system, we use all-metal bakeable valves, an oil free turbomolecular pump, and a residual gas analyzer. After extensive baking and pumping, the cryo-module is cooled down and the system is filled with about 100 standard cm^3 of ^{3}He gas, which initially is absorbed by the cryo-pump and then released by heating the vessel to about 20 K to produce 3–5 Torr He gas pressure in the cell and gas supply manifold. The RF-discharge in the ^{3}He-cell is induced by inductive coupling with the 100 turns coil (see Fig. 3). This inductive coupling works better than capacitive coupling for the cell in the high magnetic field. The inductive coupling produces a more homogeneous plasma density distribution across the cell volume (in contrast to the capacitive coupling where the discharge is mostly induced near the cell walls). We use the master oscillator and a 60 dB broadband RF-amplifier to induce the discharge. The RF frequency is tuned for the best matching to the coil impedance. Typically, the RF-power is operated at about 44 MHz frequency. The He gas purity in the RF-induced discharge in the cell is monitored by the measurement of the relative brightness of the hydrogen Balmer-alpha line at 656 nm and adjacent ^{3}He spectral line at 668 nm. With the cryo-pumping, the hydrogen contamination from residual gas equilibrium pressure in the cryo-pump, or water dissociation by RF-discharge in the cell is the main contamination and it is well monitored by the optical spectrometer. It was experimentally established that for production of high ($>80\%$) ^{3}He polarization, the relative hydrogen Balmer-alpha line brightness must be less than 2% of the He-line. After the extensive He-filling system pumping, baking and ^{3}He cryogenic purification, the hydrogen line was almost completely eliminated and high ^{3}He polarization can be maintained for several (3–5) hours with the isolation valve closed (which is required for high polarization production).

We have studied a new EBIS drift-tube configuration to increase the gas efficiency (minimize amount of injected ^{3}He gas for the EBIS trap saturation). The ^{3}He gas was injected into the small (inner diameter 10–20 mm) drift tube by the pulsed valve. Estimates show that a very small amount of ^{3}He gas of about $(5–10)\times10^{12}$ atoms will be required to be injected into the drift tube for $\sim$50% EBIS trap neutralization. The total number of ^{3}He atoms in the 50 cm^3 at 3 Torr pressure is about 5×10^{18} atoms and only a small fraction will be used for the future Electron-Ion Collider fill.

The EBIS superconducting solenoid warm orifice diameter is 215 mm. Therefore, we have to place the optically-pumped ^{3}He cell, injection valve and HV separation insulator in this radially very limited space. We developed a pulsed valve for the ^{3}He-gas injection into the EBIS drift tube, which operates in the 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 silicon rubber circular pad (6 mm in diameter, 1.0 mm thick) was attached to the plate. The induced Lorentz (Laplace) force: $\boldsymbol{F} = eL\,[\boldsymbol{I}\times\boldsymbol{B}]$ = 2–5 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. A gas flow as low as 2×10^{12} atoms/pulse was measured at 12 A current through the plate.

3. ^{3}He cell optical pumping and polarization measurements

A high $\sim$ 90% polarization for the optical pumping of ^{3}He gas in the high magnetic field 2.0–4.0 T was reported earlier for the sealed cell configuration at 1 Torr pressure [7]. For the ^{3}He optical-pumping studies in the "open cell" configuration, we used a 3.0 T solenoid of the Optically Pumped Polarized Ion Source with warm aperture of 152 mm. For the polarization measurements, we used the technique of the probe laser absorption, which was described in detail in our paper [7]. For polarization measurements the probe laser frequency was scanned across side transitions at 276.77 THz. From the evolution of the sub-level populations, the polarization of the ^{3}He ground states can be directly deduced.

For the measurements of the small absorption signals, we used the conventional technique of RF discharge modulation and lock-in amplifier signal measurements. The polarimeter DAQ was integrated into the common RHIC control system. The best results of the optical pumping of the ^{3}He gas in the "open cell" were $\sim$ 25% with the open isolation valve and $\sim$ 80% with the closed isolation valve at 3.0 Torr pressure.

The Extended EBIS completion and operation for the Au^{32+} ion beam production is planned for the RHIC Run 2023. The next step will be the integration of the ^{3}He polarizing apparatuses in the EBIS operation. The spin-rotator and the nuclear polarimeter (at 6 MeV beam energy) construction is in progress for completion in 2023–24. The studies of the possible depolarization effects during the polarized ^{3}He gas injection and multi-step ionization process in the EBIS, the optimization of the materials, the valve, and the ^{3}He-cell geometry will be required to determine the maximum attainable polarization. The expected ^{3}He^{++} ion beam intensity is about 2×10^{11} ions/pulse with polarization of 70%.

References

[1] A. Zelenski and J. Alessi, *Prospects On High-Intensity Optically-Pumped Polarized H$^-$, D$^-$, and ^{3}He^{++} Ion Source Development*, vol. **30** of *ICFA Beam Dynamics Newsletter*, pp. 39–42 (2003), https://icfa-usa.jlab.org/archive/newsletter/icfa_bd_nl_30.pdf.

[2] M. Abboud, A. Sinatra, X. Maître, G. Tastevin and P.-J. Nacher, *High nuclear polarization of ^{3}He at low and high pressure by metastability exchange optical pumping at 1.5 Tesla*, *EPL* **68** (2004) 480.

[3] K. Batz, S. Baeßler, W. Heil, E.W. Otten, M. Abboud, D. Rudersdorf et al., *^{3}He Spin Filter for Neutrons*, *J. Res. Natl. Inst. Stand. Technol.* **110** (2005) 293.

[4] J. Maxwell, C. Epstein, R. Milner, J. Alessi, E. Beebe, A. Pikin et al., *Development of a Polarized Helium-3 Source for RHIC and eRHIC*, *Int. J. Mod. Phys. Conf. Ser.* **40** (2016) 1660102.

[5] A. Zelenski, G. Atoian, E. Beebe, D. Raparia, J. Ritter, J. Maxwell et al., *Optically-pumped Polarized H$^-$ and ^{3}He^{++} Ion Sources Development at RHIC*, *PoS* **SPIN2018** (2018) 100.

[6] A. Zelenski, G. Atoian, E. Beebe, J. Maxwell, R. Milner, M. Musgrave et al., *Optically-pumped Polarized H$^-$ and ^{3}He^{++} Ion Sources Development at RHIC*, in *9th International Particle Accelerator Conference (IPAC'18), Vancouver, BC, Canada, April 29 – May 4, 2018*, (Geneva, Switzerland), pp. 644–646, JACoW Publishing, June, 2018, DOI.

[7] J.D. Maxwell, J. Alessi, G. Atoian, E. Beebe, C.S. Epstein, R.G. Milner et al., *Enhanced polarization of low pressure ^{3}He through metastability exchange optical pumping at high field*, *Nucl. Instrum. Meth. A* **959** (2020) 161892 [`1812.06139`].

[8] J.G. Alessi, D. Barton, E. Beebe et al., *The Brookhaven National Laboratory electron beam ion source for RHIC*, *Rev. Sci. Instrum.* **81** (2010) 02A509.

[9] G. Atoian, A. Zelenski and A. Poblaguev, *Precision absolute polarimeter development for the ^{3}He^{++} ion beam at 5.0–6.0 MeV energy*, *PoS* **PSTP2019** (2020) 045.