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Polarized ion sources at BNL

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Abstract

The Optically Pumped Polarized Ion Source (OPPIS) is providing polarized H$^-$ to the injector chain of the Relativistic Heavy Ion collider (RHIC), since 2000. The OPPIS had several upgrades. The latest upgrade, completed in 2022, included several improvements. Shorter low-energy beam transport and modifications to the helium, rubidium, and sodium cells were implemented to increase efficiency. These changes resulted in a 15% increase in beam intensity while maintaining similar polarization. A high-brightness primary beam from a fast atomic beam source, combined with optimized charge-exchange processes, led to the production of a high-intensity H$^-$ ion beam with 85% polarization. The high beam brightness and polarization led to impressive results. At 23 GeV, the beam exiting the Alternating Gradient Synchrotron (AGS) maintained 75% polarization. In RHIC, colliding beams achieved polarization levels of 60-65% at energies between 100 and 250 GeV. We are also developing a high intensity (2.10^{11}ions/pulse) ^{3}He^{++} polarized ion source for the future Electron Ion Collider (EIC). This source will use a new technique which is based on the polarization of accumulated high purity ^{3}He gas in high magnetic field by metastability-exchange optical pumping. The existing Electron Beam Ion Source (EBIS) will then ionize the polarized gas using its electron beam. We have developed an infrared laser system for both pumping and measurement within the high-field environment of EBIS. In the test setup, polarization of 80-85% has been achieved for ultra-pure ^{3}He gas in the "Open" cell configuration. Additionally, we are developing a spin-rotator and an absolute nuclear polarimeter for the 6 MeV ^{3}He^{++} beam, enabling precise measurement of the nuclear polarization.

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1.0 Introduction

The Relativistic Heavy Ion Collider (RHIC)is the only operating collider currently which can accelerate polarized proton and collide with 60% polarization [1] and in future Electron Collider (EIC) will be capable of colliding polarized electron and ion (proton, ^{3}He) [2]. The polarized beam for RHIC spin physics experimental program is produced in the Optically Pumped Polarized H^- Ion Source (OPPIS) [3]. Currently RHIC OPPIS produces 0.5-1.0 mA (maximum 1.6 mA) current in 400 μs pulse duration with about 80-85% polarization. The polarized H^- ion beam (of 35 keV beam energy out of the source) is accelerated to 200 MeV in linear accelerator (Linac)for charge exchange injection to Booster. The H^- ion pulse is adiabatically captured in single Booster bunch which contains about $4x10^{11}$ polarized protons. The single bunch is accelerated in the Booster to 2.5 GeV beam energy with almost same polarization as the Linac and then transferred to the Alternating Gradient Synchrotron (AGS), where it is accelerated to 24.3 GeV with about 70% polarization for injection to RHIC. RHIC is the first collider where the "Siberian snake" technique was very successfully implemented to suppress the resonance depolarization during beam acceleration in AGS and RHIC and retain about 60-65% polarization. A luminosity of about $1x10^{32}cm^{-2}sec^{-1}$for polarized proton collisions in RHIC is produced by colliding 120 bunches in each ring at about $2x10^{11}$ protons/bunch intensity.

$^3He^{++}$ polarization can be preserved during acceleration in high-energy synchrotron accelerators such as the AGS and RHIC by using the Siberian snake technique. The nuclear polarization in a polarized $^3He^{++}$ beam is carried mostly by neutrons. Therefore, high-energy collisions of polarized electrons and neutrons can be effectively studied at EIC with the polarized $^3He^{++}$ beam. The RHIC will require about $2x10^{11}$ $^3He^{++}$ ions in the source pulse and about 10^{11} ions in the RHIC bunch. To deliver this intensity in a 20 μs pulse duration for the injection to the Booster, the source peak current must be about 2000 μA, which is 1000 times higher than ever achieved in previous $^3He^{++}$ ion sources. The proposed polarized $^3He^{++}$ ion source is based on the Electron Beam Ion Source (EBIS) [4] currently in operation at Brookhaven National Laboratory (BNL). ^{3}He gas would be polarized within the 5 T field of the first EBIS solenoid via Metastability Exchange Optical Pumping (MEOP) and then pulsed into the EBIS vacuum and drift tube system where polarized ^{3}He will be ionized by the 10 A electron beam. The goal of the polarized ^{3}He ion source is to achieve $2.5x10^{11}$ $^3He^{++}$/pulse at 70% polarization. The polarized ^{3}He ion will be accelerate to 2 MeV/u in Radio Frequency Quadrupole and linac for multiturn-injection in the Booster. We will describe OPPIS status in section 2 and ^{3}He ion source development in section 3.

2.0 Optically Pumped Polarized Ion Source (OPPIS)

The Optically Pumped Polarized Ion Source (OPPIS) has been providing polarized H^- since 2000 for the RHIC spin physics experimental program and gone through several upgrades. The major upgrade are, (a) In 2013, the Electron Cyclotron Resonance (ECR) source was replaced with a Fast Atomic Beam Source (FABS) [5], (b) In 2022, we further improved the source by: (1) Reducing the low-energy beam transport length (LEBT) (see figure 1) by 5 feet, which helped minimize H^- stripping due to residual gas and resulted in roughly 15% increase in intensity. (2) Modifying the helium, rubidium, and sodium cells to enhance both polarization and intensity.

2.1 Components and Depolarization Factors of OPPIS

The upgraded OPPIS comprises of (a) Fast Atomic Beam Source (FABS), (b) pulsed hydrogen neutralization cell, (c) super conduction solenoid at 3 Tesla for polarization, (d) pulse helium

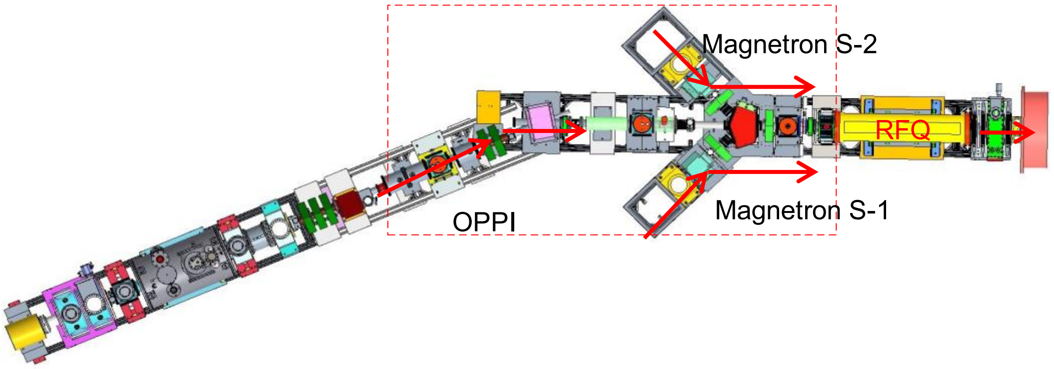

Figure 1: Configuration of the LEBT. Beam from any of these (two high intensity magnetron source, and OPPIS) sources is selected by pulse dipole (red) at rate of 10 Hz.

ionizer cell for efficiently ionize neutral hydrogen atom, (e) optically pumped rubidium cell for transferring electron spin polarization to protons. (f) Sona transition for transferring spin from electron to the nucleus in the polarized hydrogen atom and (g) sodium-jet ionizer cell for efficient conversion of polarized H atoms to H- ions. The high brightness 6 keV proton beam focused by electrostatic spherical grids system goes through in hydrogen cell, where it gets neutralized to H^0. Then it injected into a superconducting solenoid, where both a helium ionizer cell and an optically pumped Rubidium cell are situated in the 25-30 kG solenoid field, which is required to preserve the electron-spin polarization. The injected H atoms are ionized in the Helium cell with 80% efficiency to form a low emittance intense proton beam. Now protons enter in the polarized Rubidium vapor cell (see Figure 2).

Residual higher energy atoms are neutralized with lower efficiency in Rubidium cell, due to cross-section decrease at higher energy, and un-polarized component is further suppressed by lower H^- ion yield in the sodium cell at 5.0- 8.0 keV atomic beam energy. The electron-polarized Hydrogen beam then passes through a magnetic field reversal region, where the electron polarization is transferred to the nucleus, via the hyperfine interaction (Sona-transition). The polarized hydrogen atoms are then negatively ionized in a sodium-jet vapor cell to form nuclear polarized H^- ions. Applying a -32 kV pulse voltage to the ionizer cell accelerate the H^- ion to 35 keV and un-polarized H^- ion to a 40-43 keV. Further suppression of un-polarized higher energy ion beam is done in the LEBT.

Depolarization factors must be carefully managed by continuously controlling relevant parameters to optimize polarization levels. Several factors can contribute to depolarization, each requiring specific control measures: **E_H^0**, Unpolarized beam component with 39 keV energy is separated in the LEBT after the dipole magnet. Affects polarization by approximately 1%. **P_{Rb},** Polarization strongly depends on power, frequency, and linewidth of the pumping laser, which are highly sensitive to temperature.

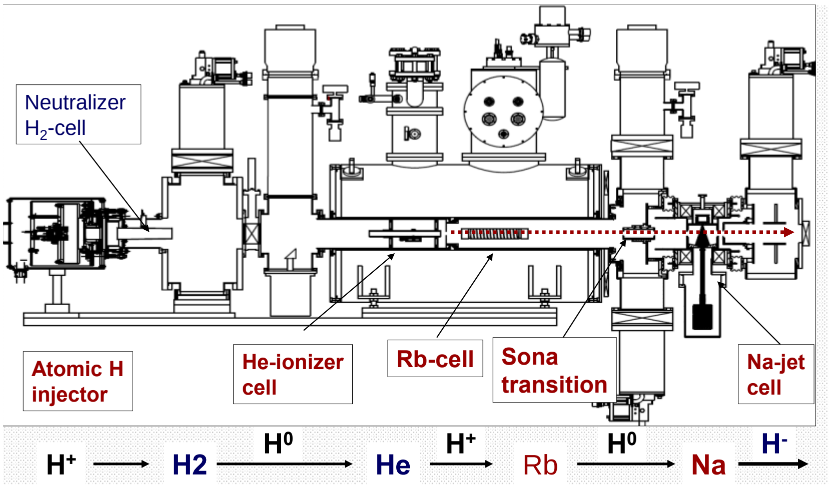

Figure 2: Layout of the OPPIS with atomic hydrogen injector.

Requires precise temperature control of the laser system to minimize depolarization effects (around 1%). **S**, Rubidium polarization and spatial distribution are regulated using optimized collimators. Spatial distribution can impact polarization by 2-3%. **B_{RG},** In the Rb-cell, protons acquire polarized electrons from polarized rubidium atoms, becoming polarized hydrogen atoms. Residual gas in the Rb-cell can neutralize some protons, reducing polarization by an estimated 1-2%. **E_{LS},** Polarization is strongly influenced by the superconducting solenoid's magnetic field, which controls spin-orbital interactions. Affects polarization by about 2%. **E_{ES},** An estimated 1% unpolarized beam component has the same energy (35 keV) as the polarized component and cannot be separated by the LEBT dipole. E_{sona}, Sona-transition efficiency, controlled by 5 correction coils, typically ranges from 96 to 98%. **E_{ion},** Depolarization due to incomplete hyperfine interaction breaking in the ionizer magnetic field, estimated at 1-2%. Taking these factors into account, the estimated achievable polarization is approximately 85-90%.

Figure 3 show the OPPIS performance for last 10 Years. In 2012, the Electron Cyclotron Resonance (ECR) source served as the injector for OPPIS, delivering a polarized H- beam with approximately 80% polarization and 250 microamps of current. OPPIS performance in Run 2023 demonstrates a roughly 15% increase in polarized H- intensity compared to Run 2022, while maintaining consistent polarization at 82%.

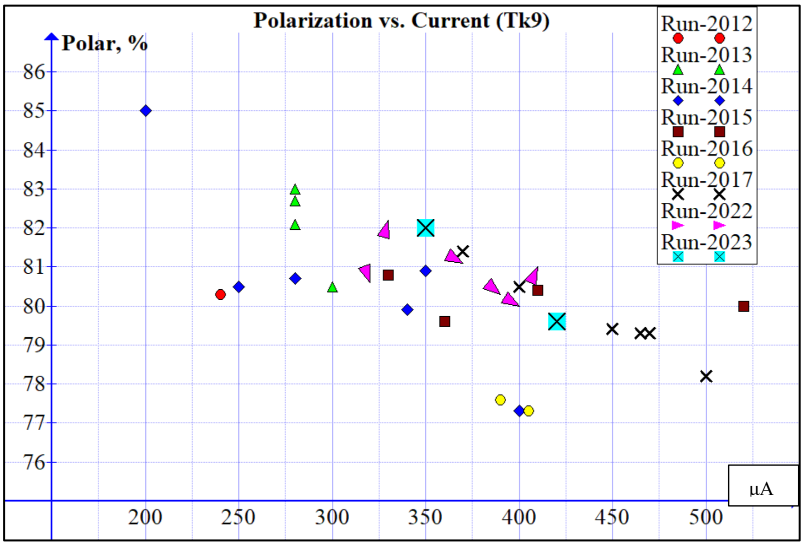

Figure 3: Polarized H- beam current (µA) at 200 MeV verses Polarization measured by 200 MeV polarimeter for last 10 years.

3.0 **Polarized ^{3}He Ion Source**

The proposed polarized $^3He^{++}$ ion source builds upon the existing Electron Beam Ion Source (EBIS) at Brookhaven National Laboratory (BNL) [6,7,8]. It employs a distinct approach for ^{3}He polarization and ionization, outlines as follows. (a) Polarization of ^{3}He atoms: ^{3}He atoms are polarized using the Metastability Exchange Optical Pumping (MEOP) technique [9,10]. This occurs within a glass cell maintained at a pressure of 1-10 mbar. A high-field 5.0 T magnetic field is applied within the EBIS solenoid to facilitate polarization, (b) Injection into EBIS ionizer: The polarized ^{3}He atoms are subsequently injected into the EBIS ionizer, via a innovative Lorenz fast valve (c) Ionization process within EBIS: A high-intensity electron beam (10 A) is generated by an electron gun with a 9.2 mm cathode diameter. This electron beam is injected into the 5.0 T solenoid magnetic field, leading to radial compression to a diameter of approximately 1.5 mm in the ionization region. The compressed electron beam interacts with the polarized ^{3}He atoms, causing ionization. The electron beam then expands before being collected at the end of the EBIS. (d) ^{3}He Ion confinement and extraction: ^{3}He Ions are radially confined by the space charge of the electron beam. Longitudinal confinement is achieved using electrostatic barriers at the ends of the trap region. Ion extraction is performed by raising the potential of the trap and lowering the barrier.

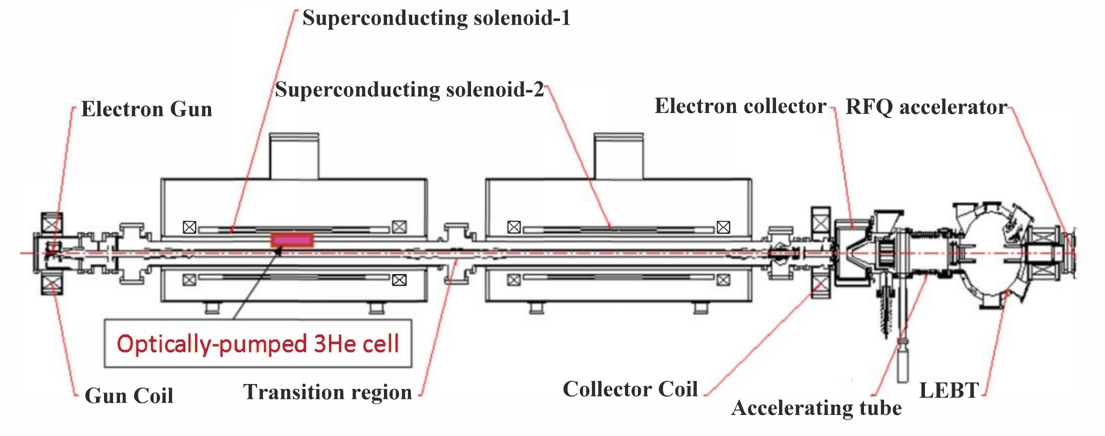

Figure 4: Schematic diagram of the extended EBIS. The polarized ^{3}He gas is injected into the drift tube in the Gas Trap of EBIS. Low Energy Beam Transport (LEBT) transfer the extracted beam from EBIS to the Radio Frequency Quadrupole (RFQ) e accelerator.

The upgraded EBIS features three distinct sections: Gas Trap: to inject gaseous elements and initial ionization, Short Trap and Log Trap: to trap the externally injected or from gas trap low charge state ions and multiply to the desire charge state. The gas trap (40 cm long) and short trap (95 cm long) are in the upstream solenoid and long trap (178 cm long) in the downstream solenoid. The polarized ^{3}He gas will be injected into gas trap to ionized. The resulting $^3He^+$ ions will be trapped in short and long trap. Here, they will undergo further ionization to the desire $^3He^{++}$ state (see Figure 4). The EBIS is estimated to produce and accumulate (2.5–5.0) x10^{11} doubly charged helium ions($^3He^{++}$). The desired beam intensity of 2x10^{11} $^3He^{++}$ ions per pulse can be achieved by extracting and accelerating them during a single 20 μs pulse.

3.1 Development of the 3He source

3.1.1 Optical pumping and polarization Measuremnet

To measure the nuclear polarization, a second probe laser was employed [9]. A 70-mW distributed feedback laser from Toptica was used enabling rapid wavelength tuning through adjustments to the diode temperature and current. The probe laser traversed the pumping cell twice. Second time it was reflected through the cell by a mirror before arriving at a photodiode, which allowed the monitoring of the absorption of the light as a function of laser wavelength. Figure 5 shows a measured ^{3}He absorption spectrum at 3.0 T and includes the probe peaks used for these measurements at 276.76THz. The ratio of peak heights ($r = a2/a1$) of these transition pairs, along with a zero-polarization calibration ($r0$), allows calculating the absolute nuclear polarization M according to the equation: $M = (r/r0 - 1) (r/r0 + 1)$.

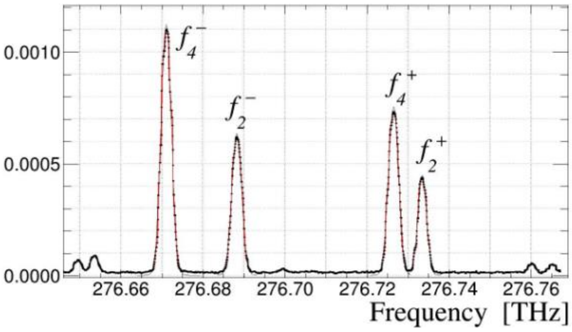

Figure 5: The ^{3}He absorption spectrum in a 2.0 T magnetic field. The f_4^+ transition at 276.726 THz is used for optical pumping and a scan across transitions at 276.760 THz is used for the polarization measurements.

To enhance measurement sensitivity, the 297 Hz amplitude modulation of the RF discharge was routed to a lock-in amplifier, which selectively amplifies the signal at the modulation frequency while suppressing background noise. Integrated into the RHIC control system, the polarimeter DAQ software facilitated spectrum display and performed Gaussian fits on each probe peak to accurately determine peak height and minimize noise. Figure 6 (Left) presents an example of the probe laser absorption signal for the 89% polarization in a sealed 3he cell at 3.0 Torr pressure, compared with a signal at 0%. Figure 6 (right) present polarization build-up vs. time. First 4 minutes the isolation valve is opened (13% polarization), after the valve was closed polarization increased to 80% in 5 minutes, at 22 min. the laser was switched off, and at 29 min. the isolation valve was opened. The best results on optical pumping of ^{3}He gas in the “open” cell configuration at 3.0 Torr.

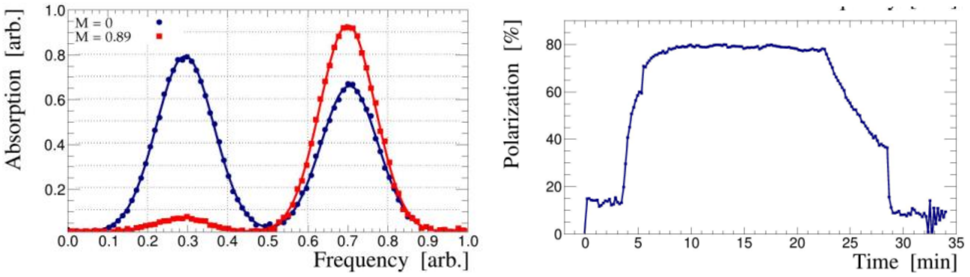

Figure 6: Left: example of the probe laser absorption signal for the 89% polarization in a sealed ^{3}He cell at 3.0Torr pressure, compared with a signal at 0%. Right: polarization build-up vs. time. First 4 minutes the isolation valve is opened (13% polarization), after the valve was closed polarization increased to 80% in 5 minutes, at 22 min. the laser was switched off, and at 29 min. the isolation valve was opened.

3.1.2 ^{3}He Gas Purification and Cell Filling System

Maintaining high gas purity within the 'open cell' configuration is crucial [10]. To achieve this, we developed a novel system based on cryo-pumping. A technique that selectively captures all gas molecules except helium due to their differing condensation temperatures. We have modified a conventional two-stage cryopump by removing half of the cryo-panel (needed for isolation vacuum) and attaching an additional cold vessel filled with charcoal granules, known for its adsorptive properties for gaseous impurities, to the first stage cold head (see Figure 7)

Figure 7: 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.

The pump was connected to the ^{3}He filling system through a flexible vacuum bellows for pressure stabilization (see Figure 7). Operating at frigid 20–25 K, the pump was continuously absorbing and reducing the partial pressures of undesired hydrogen, water, hydrocarbons, and argon to the level below 10^{-7} Torr but this also absorbs quite a significant amount (~100 cm^3) of ^{3}He gas. Fortunately, this absorbed ^{3}He gas can be released by heating the vessel via a built-in cartridge heater. This clever design acts as both a gas reservoir and refueller for the ^{3}He cell, maintaining the optimal pressure (3–5 Torr) for optical pumping. Precise pressure control is achieved through a feedback loop system, where the built-in heater adjusts based on readings from a Baratron MKS-626 pressure gauge.

3.2 The ^{3}He Cell Layout Inside the 5.0T EBIS Solenoid

To deliver polarized ^{3}He gas into the EBIS, we designed a prototype arrangement [11]. A layout for the optically pumped ^{3}He cell inside the 5.0 T EBIS solenoid is presented in Figure 8. The EBIS superconducting solenoid warm orifice diameter is only 215 mm in which we must accommodate the optically pumped ^{3}He cell, injection valve and HV separation insulator in this radially very limited space. Fortunately, laser beams are transported in fibers and are quite compact. To inject polarized ^{3}He gas into the EBIS Drift Tube (Gas Trap), we have developed a unique 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 10–20A passes through the flexible springing plate. The induced Lorentz (Laplace) force 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 achieved at 12 A current through the plate. We also tested operating the valve with four consecutive pulses, spaced 4 ms apart, producing up to $1x10^{13}$ atoms/cycle. Potentially offering an optimal solution for the gas injection distributed over 20 ms, promoting efficient ionization by the EBIS electron beam, while limiting the injection gas cell pressure to $\sim10^{-7}$ Torr. In our setup, the ^{3}He cell and gas preparation and filling system are at ground potential (share the EBIS's high voltage potential, around 100 kV). The drift tube potential is about 20–30 kV. A high-voltage ceramic insulator safely separates the ^{3}He cell and injection valve from the drift tube. Thanks to the minimal gas injected, the pressure within the insulator stays incredibly low, below 10^{-5} Torr. Furthermore, the strong 5 T magnetic field restricts ion movement across the gap, Impacting discharge behavior. To inject unpolarized gas into the EBIS, we developed a pulsed valve with a two-inch ceramic insulator and tested successfully in our EBIS at voltages up to 40 kV.

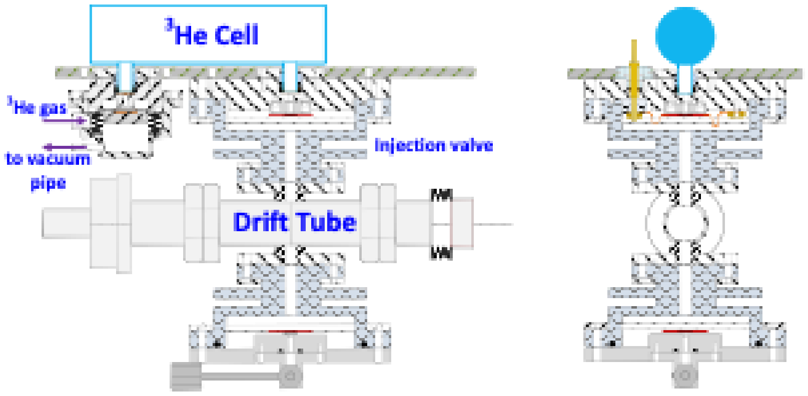

Figure 8: Configuration of the Optically pumped ^{3}He cell inside of the 5 T EBIS upstream solenoid. The warm bore diameter is 215 mm. Left: side view. Right: end view.

4. Chicane for Spin Rotation

After extraction from the EBIS, polarized ^{3}He ions are accelerated by two linear accelerators to an energy of 2 MeV per nucleon. The spin of the ^{3}He direction after the acceleration will be parallel to the beam momentum and need to be rotated to the vertical direction before the injection into the Booster synchrotron. This is accomplished by adding chicane in the EBIS to Booster (EtB) transfer line (see figure 9). The ions first pass through a dipole magnet, which deflects their trajectory by 21.5 degrees. This also causes their spin to rotate by 90 degrees in the horizontal plane, making it perpendicular to their momentum. Next, the ions enter a solenoid, where their spin rotates around the solenoid's axis by either 90 degrees or -90 degrees, depending on the solenoid's field polarity. This crucial step aligns the spin vertically, either upward or downward, as required for injection into the Booster. The deflected ion trajectory is then straightened back to the EtB transfer line by three additional dipole magnets. The arrangement of these magnets forms a trapezoidal chicane, as depicted in Figure 9.

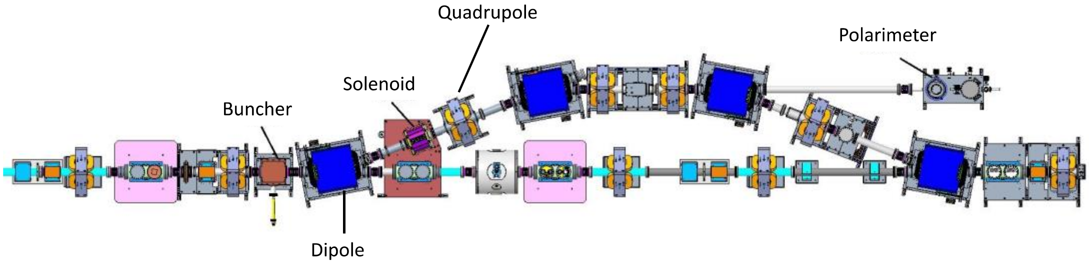

Figure 9: Layout of the Chicane for spin rotation, EBIS to Booster transfer line and 6 MeV Polarimeter. The spin rotation will be accomplished by first dipole and spin flip by the following solenoid in the trapezoidal chicane. By turning of the 3rd dipole, spin measurements will be accomplished.

5.0 Absolute Nuclear Polarization Measuremnet at 6 MeV

The polarization of full stripped ^{3}He^{++} ion at 6 MeV will be verify by a spin asymmetry measurement in scattering from un-polarized ^{4}He gas [12]. The scattering process will reveal information about the ^{3}He ions' spin polarization. A key concept is the "analyzing power" (A_N), a measure of how effectively a scattering process can reveal spin polarization. For spin 1/2 particles like ^{3}He scattering from spinless particles like ^{4}He, A_N can theoretically reach a maximum value of 1, indicating perfect sensitivity to polarization. Previous research [13,14] showed that A_N for 6 MeV polarized ^{3}He ions has a local maximum of over 0.9 at a center-of-mass scattering angle (θ_{CM}) of approximately 96 degrees. By measuring the spin-correlated asymmetry (A_N) as a function of scattered ^{3}He kinetic energy, which is directly correlated with θ_{CM}, researchers can determine the local maximum A_{max} for a given beam energy. Scanning beam energy between 5 and 6 MeV allows finding the absolute maximum A_{max}, which directly reveals the beam polarization, expected to occur around 5.4 MeV.

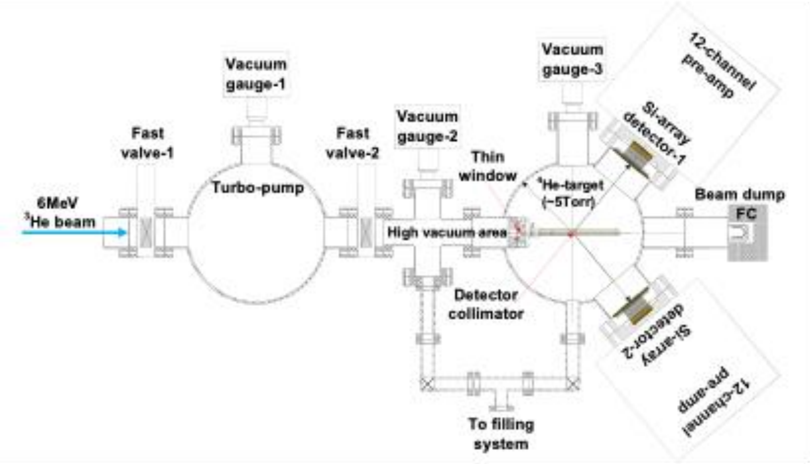

Figure 10: A layout of the ^{3}He-^{4}He polarimeter. The effective target is a 1 cm long collimated part of the 5 Torr ^{4}He gas filled scattering chamber. The scattered ^{3}He and recoil ^{4}He angles, energies and time-of-flight are measured by the Si-strip detectors.

Figure 10 depicts the arrangement of polarimeter: A thin aluminum foil window allows ^{3}He ions to enter the scattering chamber while minimizing energy loss. The chamber is filled with 5 Torr of ^{4}He gas, acting as the scattering target. Collimators restrict the effective target length to approximately 1 cm. Two silicon (Si) detectors are positioned at ±50 degrees in the lab frame, 10 cm from the target's center. The Si detectors offer: A energy resolution: $\sigma_{dE/E} \leq 2\%$ (meaning they can precisely distinguish different ion energies). Time resolution: $\sigma_t \leq 0.2$ ns (enabling accurate timing of scattering events). Potential angular resolution: $\sigma_\theta \sim 0.2$ degrees (due to their strip structure with 1 mm steps). Effective Angular Resolution: While the Si detectors could theoretically achieve $\sigma_\theta \sim 0.2$ degrees, the finite target size (~1 cm) limits the effective angular resolution to ~1.2 degrees. This translates to an effective geometric uncertainty of $\sigma_{geom} \sim 0.1$ MeV in energy measurements. The polarimeter strategically uses scattering and precise detection to analyze ^{3}He ion polarization. The design balances target size with detector resolution to optimize measurement accuracy.

6.0 Summary

Since 2000, OPPIS has played a vital role in the RHIC program by providing polarized protons. It has undergone multiple upgrades, the latest of which achieved a 15% increase in intensity without compromising polarization.

BNL, in collaboration with MIT, has been actively developing an EBIS-based polarized 3He source. The unique challenges of polarizing ^{3}He gas in a 5 T magnetic field led to the innovative development of the Lorenz fast valve and gas purification system. Within the open cell configuration, polarization levels of 80% have been successfully measured in the test setup. The next step involves integrating the ^{3}He cell into the EBIS. Meanwhile, the spin rotator has been successfully commissioned with ^{4}He, and the 6 MeV polarimeter is installed and ready for commissioning with unpolarized ^{3}He in spring 2024. Finally, the upgraded EBIS is expected to receive the final ^{3}He gas injection system by the end of 2024. Upon completion, this system is projected to deliver ^{3}He^{++} ion beam intensities of approximately 2.10^{11} ions per pulse, with a polarization exceeding 70%.

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