Development of a polarized 3He++ ion source for the EIC

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Development of a Polarized 3He++ Ion Source for the EIC

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The capability of accelerating a high-intensity polarized ^{3}He ion beam would provide an effective polarized neutron beam for new high-energy QCD studies of nucleon structure. This development is essential for the future Electron Ion Collider, which could use a polarized ^{3}He ion beam to probe the spin structure of the neutron. The proposed polarized ^{3}He ion source is based on the Electron Beam Ion Source (EBIS) currently in operation at Brookhaven National Laboratory. ^{3}He gas would be polarized within the 5 T field of the EBIS solenoid via Metastability Exchange Optical Pumping (MEOP) and then pulsed into the EBIS vacuum and drift tube system where the ^{3}He will be ionized by the 10 Amp electron beam. The goal of the polarized ^{3}He ion source is to achieve 2.5×10^{11} ^{3}He^{++}/pulse at 70% polarization. An upgrade of the EBIS is currently underway. An absolute polarimeter and spin-rotator is being developed to measure the ^{3}He ion polarization at 6 MeV after initial acceleration out of the EBIS. The source is being developed through collaboration between BNL and MIT.

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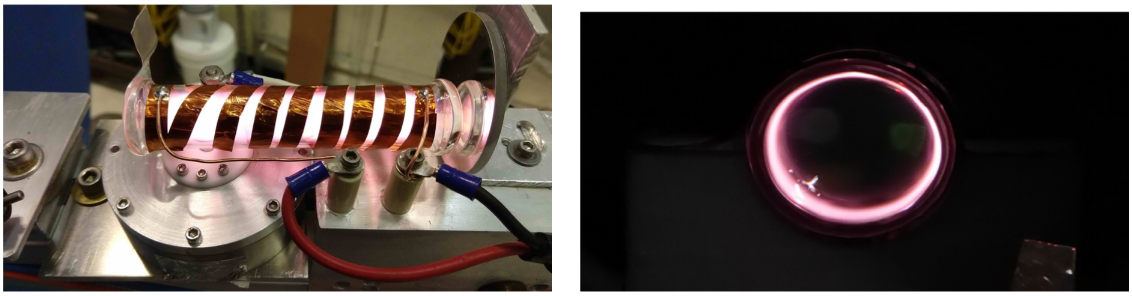
1. Introduction

The Electron Ion Collider (EIC) will enable the study of the spin structure of protons and neutrons with unprecedented precision. However, this statistical precision requires high intensity hadron beams with high polarization. RHIC has the capability to create polarized proton beams, but the study of polarized neutrons requires a suitable proxy for use in an accelerator. The ^{3}He nucleus has an 88.6% probability of being in its spatially symmetric S-state, where the protons form a singlet and the neutron carries the nuclear spin, which makes it a viable surrogate for a polarized neutron beam. However, an EIC will require a much higher intensity and polarization than achieved by previously developed polarized ^{3}He ion sources [1, 2, 3]. For this reason, development of a polarized ^{3}He ion beam has been identified as an R&D priority for the EIC [4, 5, 6], and the BNL-MIT polarized ^{3}He ion source collaboration has pursued this R&D [7, 8, 9, 10, 11, 12, 13]. The design goal of the polarized ^{3}He ion source is 2.5×10^{11} ^{3}He^{++}/s with 70% polarization in a 20 μs pulse, which equates to a peak current of $\approx$4 mA.

2. ^{3}He Polarization at 5 Tesla

Before ionization, ^{3}He gas at 1-5 mbar is polarized in a cylindrical glass polarization cell within a 5 T magnetic field with the technique of metastability exchange optical pumping (MEOP) [14, 15]. During MEOP, an RF excitation is induced in the ^{3}He gas to populate the 2^3S metastable state, which is optically pumped by circularly polarized 1083 nm light, and the nuclear spin state is simultaneously polarized by hyperfine coupling. A ^{3}He cell with an RF discharge can be seen in Fig. 1a, and Fig. 1b shows how the RF discharge is localized around the parameter of the ^{3}He polarization cell in high magnetic fields. The relatively new technique of high-field MEOP is similar with the additional complication that the spectra lines of the ^{3}He are Zeeman shifted by the 5 T field, as can be seen in Fig. 2. The pumping laser used to polarized the ^{3}He gas is a 5 W Lumibird fiber laser. The laser's central frequency is targeted at the C0 resonance line of ^{3}He 276769.46 GHz with a 300 GHz thermal tuning range, so that all four of the Zeeman shifted pump lines at 5 T can be reached. The laser also has a 2 GHz linewidth, which is matched to the thermal Doppler broadening of the resonance lines. The ^{3}He gas polarization is measured by monitoring the transmission spectrum of a weak probe beam from a 1083 nm Toptica diode laser at either of the pair small spectral peaks shown in Fig. 2 at -125 GHz or 155 GHz.

We are developing an open cell ^{3}He polarizing system complete with ^{3}He gas purification. A ^{3}He cryo-purification system built from a modified cryopump effectively removes contaminants from the ^{3}He gas such that at a temperature of 46 K the cryo-purifier completely eliminates hydrogen, water, hydrocarbons, and argon from the gas spectrum. Additionally, adjusting the cyro-purifier temperature enables fine control of the ^{3}He pressure. This cryo-purifier will allow routine operation of a flowing system to provide a continuous polarized ^{3}He^{++} ion beam to the EIC. The open ^{3}He polarization cell has a relaxation time of about 30 s, which is limited by the metal surfaces of valves and gas contamination. Tests with polarization cells attached to the gas handling system and cryo-purifer in a 3 T field have consistently achieved polarizations greater than 80% in the 1-3 mbar range.



(a) ^{3}He polarization cell.

(b) RF discharge in 5 T.

Figure 1: Images of ^{3}He polarization cells with an RF discharge in a 5 T magnetic field.

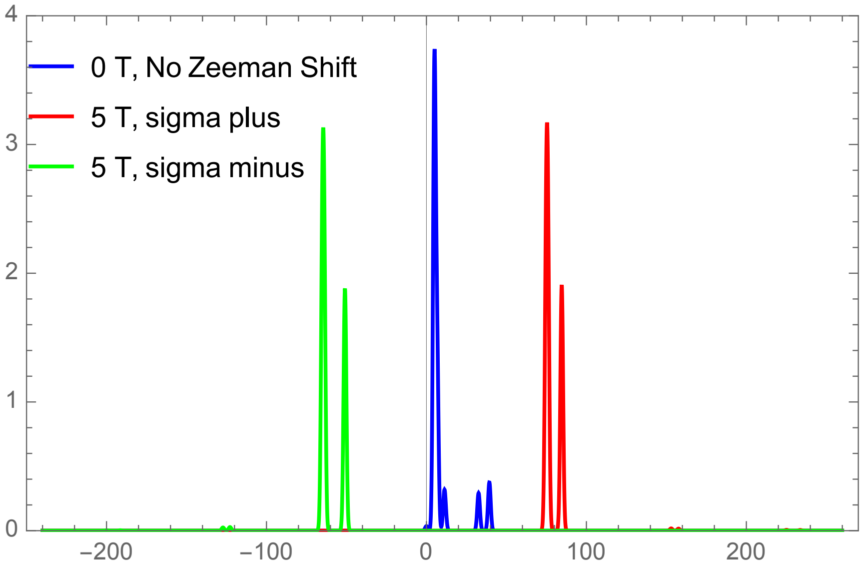


Figure 2: The Zeeman shifted spectra of ^{3}He relative to the C1 frequency at 0 T in units of GHz. The four large red and green peaks can all be used to optically pump ^{3}He. The small resonance peaks at -125 GHz and 155 GHz are used with the probe laser polarimeter.

3. RHIC EBIS & Extended EBIS Upgrade

The Electron Beam Ion Source (EBIS) is the primary source of charged ions from D to U for the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab [16]. The EBIS is currently being upgraded to enable ion production from gas injection and to increase the ion trap capacity. The primary purpose of the gas injection system is for the injection of polarized ^{3}He gas to produce ^{3}He^{++} ions. The EBIS consists of a 10 A electron beam that is compressed by a 5 T solenoidal magnetic field. Low charge state ions are injected into the EBIS axially along the electron beam where they are radially confined by the space charge of the electron beam and longitudinally confined by electrostatic barriers at either end of the trap region within the solenoid. Ions are held in the trap until successive electron impact ionization breeds the desired charge state, and then the ions are ejected towards the downstream accelerator system. The EBIS can produce pulse trains of ions of a specific charge to mass ratio at a rate of 5 Hz, while a change in element or charge state requires 1 s for adjustment of magnetic components in the downstream beam transport line. The charge capacity of the EBIS trap is a function of the electron beam current, electron energy, and the length of the trap according to the equation

$$C = \frac{I}{e} \times l \times \sqrt{\frac{m_e}{2E}}.$$

The Extended EBIS upgrade will include the addition of a second superconducting solenoid to effectively double the length available for gas injection, ion transfer, and ion trapping as shown in Fig. 3. A system for ^{3}He polarization and gas injection will be installed in the upstream portion of the new solenoid. A conceptual illustration of the proposed ^{3}He ion source is shown in Fig. 4. The ^{3}He ion source will consist of a glass polarization cell adjacent to a narrow vacuum chamber, which serves as an ionization cell for efficient gas ionization. The polarization and ionization cells will be connected by a high speed pulsed valve designed to operate in a 5 T magnetic field similar to the valve used to pulse ^{4}He for the RHIC Optically-Pumped Polarized H$^-$ Ion Source (OPPIS) [17]. A differential pumping scheme will surround the ionization cell to maintain an ultra-high vacuum in the rest of the EBIS vacuum system. The pressure in the polarization cell will be in the range of 1-3 mbar. However, the amount of ^{3}He injected will be small enough that after injection into the ionization cell, the ^{3}He will quickly expand to pressures below 10^{-6} mbar, which is necessary to preserve the electron beam quality and prevent discharges from the electron beam to the ionization cell walls.

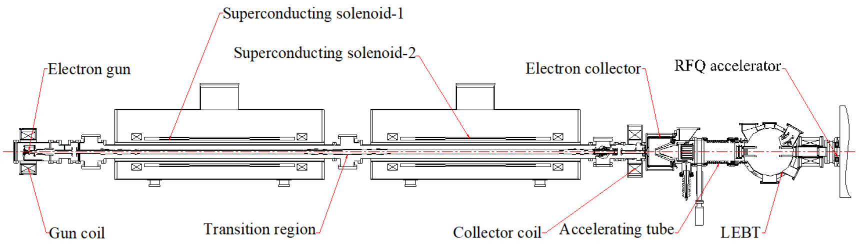


Figure 3: The Extended EBIS will consist of two 5 T solenoids to increase the ion trap length with additional pumping to improve the vacuum quality. Infrastructure for direct gas injection into the EBIS will be installed in the upstream solenoid.

Excluding the ionization cell, an ultra-high vacuum in the range of 10^{-10} mbar is required for the production of high-charge state ions, and residual ^{3}He gas could lower the maximum achievable polarization because ^{3}He in the EBIS vacuum will depolarize over time and can be ionized during later EBIS fills. Therefore, it is necessary to minimize the amount of ^{3}He injected into the EBIS vacuum both to preserve the limited supply of ^{3}He and to maintain the ultra-high vacuum conditions in the EBIS trap. The narrow diameter of the ionization cell reduces the volume that is filled with injected ^{3}He, and the constrictions on either end of the ionization cell help confine the ^{3}He in the ionization cell where it is more likely to be ionized by the electron beam.

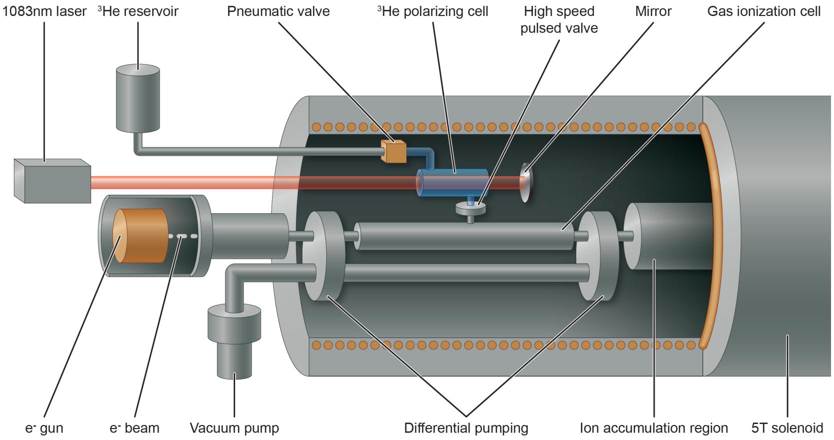


Figure 4: Conceptual illustration of the proposed ^{3}He ion source to be installed in the upgraded RHIC EBIS.

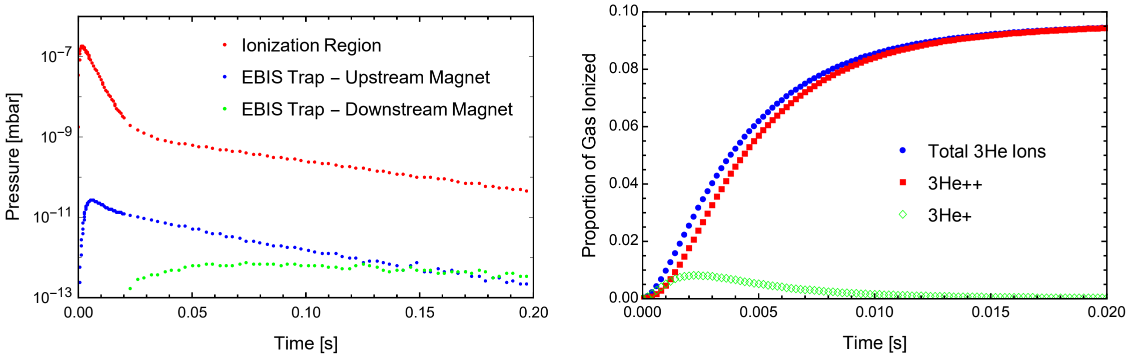
4. ^{3}He Injection & Ionization Simulations

Expanding on the preliminary results reported in 2017 [12], the entire Extended EBIS vacuum system has been modeled (see Fig. 5) to estimate the vacuum performance of the gas injection system and the efficiency of the gas ionization. In addition to testing the feasibility of gas injection, various design options including the dimensions of the ionization cell are tested to optimize the final design. Since the pressures in the EBIS vacuum will be below 10^{-6} mbar, the vacuum is in the molecular flow regime, and MolFlow is used to create the EBIS model [18, 19]. Molflow models consist of several 2-dimensional facets that represent the surfaces of vacuum chambers as well as the locations of vacuum pumps and gas injection.

Figure 5: Model of the entire Extended EBIS vacuum structure in MolFlow. Internal structures are colored red for contrast.

The electron beam of the EBIS acts as an ion pump on the EBIS vacuum by ionizing gaseous atoms and trapping them in the beam. Thus the electron beam can be modeled in MolFlow by a set of facets that make a long narrow cylinder with the radius of the electron beam. The facets of the electron beam are semi-transparent pumps with a opacity equal to the probability of a gas atom being ionized while traversing the electron beam. Thus simulated atoms are either ionized and removed from the simulation or traverse the electron beam without any change in their trajectory. The probability of ionization upon hitting the electron beam facets is equal to the ratio of the average distance traveled through the electron beam, which is equal to the diameter of the electron beam, and the mean free path of gas atoms in the electron beam, and when these values are determined in the electron rest frame, the ionization probability per facet hit can be given by

$$R = \frac{16 I \sigma}{3 \pi^2 e r_e v_{gas}}$$



(a) ^{3}He pressure in the EBIS trap.

(b) Populations of ^{3}He$^+$ and ^{3}He^{++} ions.

Figure 6: Results from simulations of gas injection into the Extended EBIS.

where I is the electron beam current, r_e is the radius of the electron beam in the MolFlow model, v_{gas} is the average thermal speed of the gas, and σ is the electron-impact ionization cross-section, which is determined as a function of electron energy from Eq. 4 in [20] using parameters from [20, 21, 22]. The average gas speed is modified by a factor of $\frac{3\pi}{8}$ to account for the fact that faster gas molecules will hit the electron beam facets more often in the simulation. This simplified model of the electron beam will accurately simulate a real electron beam with a nonuniform distribution of electrons because the electron beam radius dependence in the ionization probability R cancels with the radius in the model geometry, and thus simulations results are independent of the radius chosen.

Results from the ^{3}He injection and ionization simulations are encouraging for the feasibility of an operational polarized ^{3}He^{++} ion source. Fig. 6a shows that the ^{3}He pressure at various locations in the Extended EBIS trap drops to below the 10^{-10} mbar level necessary for efficient high-charge state ion production within 200 ms, which is significantly less than the 1 s timing between switching ion species. Fig. 6b shows the proportion of injected ^{3}He atoms ionized into the ^{3}He$^+$ and ^{3}He^{++} charge states by the electron beam for the final ionization cell design chosen for the Extended EBIS upgrade. The actual number of ^{3}He^{++} ions produced will depend on the amount of ^{3}He gas injected, which is highly dependent on the pulsed valve design and the ^{3}He pressure in the polarization cell. The operation of the pulsed valve also has to be optimized including timing and number of pulses per fill. However, these ionization results imply that achieving the goal of 2.5×10^{11} ^{3}He^{++} ions per pulse is achievable. Time scales for the production of ^{3}He^{++} ions and operation of the EBIS with the final ionization cell design are shown in Table 1, and all of the time results are indicative of a successful design.

5. Conclusion

Progress is steadily being made on the development of a polarized ^{3}He^{++} ion source for the EIC. Installation of the Extended EBIS upgrade is scheduled for the end of the summer of 2020, and installation of components for polarization and injection of ^{3}He is scheduled for the summer of 2021. In parallel with development of a ^{3}He^{++} ion source, a spin-flipper and polarimeter are being developed to test the feasibility of the ion source after the ^{3}He^{++} ions have been accelerated to

Step sequence	Time
^{3}He gas injection	0.5 ms
Diffusion into ionization cell	2 ms
Injected gas pressure falls 50%	5 ms
Ionization of ^{3}He to ^{3}He$^+$	$\sim$10 ms per gas injection
Time constant for ^{3}He$^+ \rightarrow {}^3$He^{++} conversion	1 ms
Pump down to 10^{-9} mbar	$\sim$30 ms
5 Hz EBIS pulse repetition rate	200 ms
Switching time between species	1 second

Table 1: EBIS polarized ^{3}He^{++} ion production with a 10 Amp, 20 keV electron beam.

6 MeV. Successful measurement of greater than 70% polarization at 6 MeV will confirm the ability to provide polarized ^{3}He^{++} ions to the EIC to study the nuclear spin structure of the neutron.

Acknowledgments

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