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Progress on a Polarized 3He++ Ion Source at BNL

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A high intensity (2 x 10ˆ11 ions per pulse) polarized 3He++ ion source is being developed at BNL for use at the future Electron Ion Collider (EIC). The helium gas will be polarized using a novel technique based on metastability-exchange optical pumping (MEOP) in the 5T field of the existing Electron Beam Ion Source (EBIS), where it can be ionized and prepared for injection into the Booster. An infrared laser system has been developed for optical pumping and measuring the polarization of the gas inside of the EBIS field. Previous results in a test setup have shown up to 80% polarization for ultra-pure 3He in an "open" cell configuration, with isolation valve and refilling tubes closed. Now, the setup has been moved into an exact copy of the EBIS magnet to prepare for final integration and injection into the Booster. An absolute nuclear polarimeter and spin-rotator has been constructed to measure the 3He polarization near 6 MeV in the EBIS to Booster transit line. The ion source will be an essential component of future polarized neutron studies at the planned Electron Ion Collider (EIC).

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1. Introduction

The planned Electron Ion Collider (EIC) will open new avenues to study the spin structure of nucleons and provide important information on the three dimensional spatial and momentum distributions of the partons. A polarized neutron beam will be essential to a successful EIC physics program. The small magnetic moment of deuterium poses severe challenges to its spin manipulation in the Relativistic Heavy Ion Collider (RHIC) and the planned EIC, however polarized 3He is an attractive alternative. 3He is predominantly found in its spatially symmetric S-state where the proton spins are anti-aligned, and the nuclear spin is carried by the neutron. The larger magnetic moment of 3He has also been determined to be compatible with RHIC spin manipulation[1]. The development of a 3He ion source at the RHIC Electron Beam Ion Source (EBIS) has been aggressively pursued by a collaboration between Brookhaven National Lab and MIT, with plans to integrate the ion source at EBIS during the November 2025 shutdown period.

1.1 Source Design

The 3He++ ion source design[2] at BNL uses the Metastability Exchange Optical Pumping (MEOP) scheme to polarize 3He inside of the bore of the superconducting solenoid in the existing EBIS[3]. A compact optical scheme has been developed to provide polarization and polarimetry for a glass cell of ultra-pure 3He mounted directly above the EBIS drift tube, shown schematically in Figure 1.

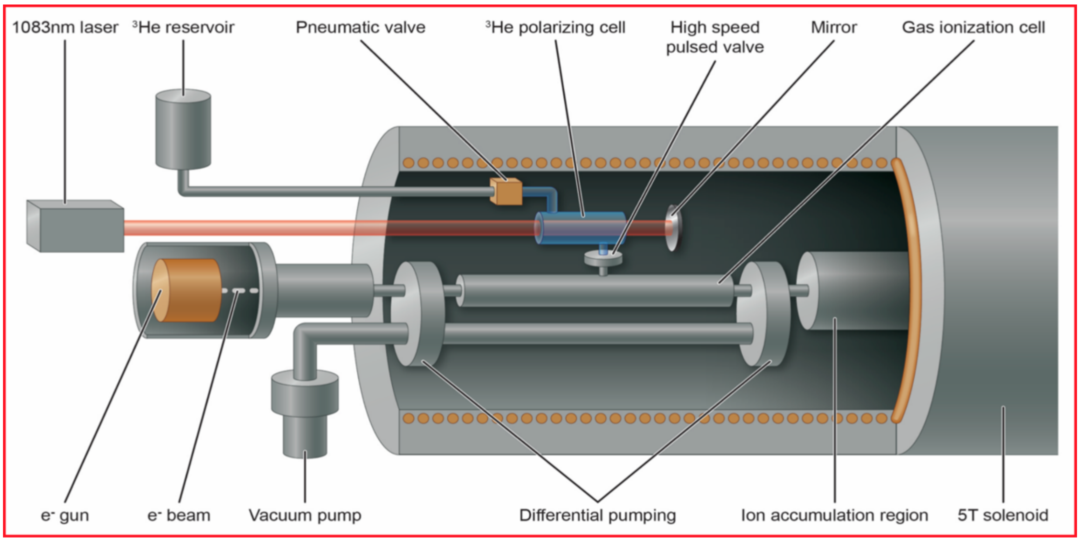

Figure 1: A schematic diagram of the 3He polarization cell inside of the EBIS bore.

After polarization, the 3He is injected through a pulsed valve into the drift tube, where the gas is ionized by a 10 A electron beam before being extracted near 6 MeV for transport to the Booster or the absolute polarimeter. The design goal of the source is to provide 70% polarized 3He with 2.5 x 10^{11} ions per 20 microsecond pulse for a peak current near 4 mA.

The MEOP polarization technique[4] utilizes an RF discharge to excite a small population (about one part in a million) of the 3He atoms from the ground into the 2S metastable state. Circularly polarized laser light near 1083 nm pumps the metastable atoms in the 2S to 2P transition, imparting angular momentum to the system and building up a net polarization in the metastable state. This polarization is transferred to the ground state by metastability exchange collisions allowing the entire sample to become polarized. This technique had traditionally been believed to be viable only in low magnetic fields around 50 G and pressures below 1 Torr. New advances in polarized 3He for medical applications have recently demonstrated that the MEOP technique can be employed in multi-Tesla fields and at higher pressures[5]. In addition, the polarization can be measured optically, making it possible to provide polarization and polarimetry in a compact setup which can fit inside of the EBIS bore. Previous studies[6] have shown the viability of this technique and polarizations greater than 80% have been achieved in the 3 Tesla field of the Optically Pumped Polarized Ion Source at BNL. Relaxation times close to 30 minutes had also been measured, sufficiently long for ionization and acceleration in the ring.

1.2 Absolute Polarimeter

A chicane has been designed for attachment to the existing straight line between the EBIS injector and Booster synchrotron to divert polarized 3He++ ions for spin rotation and direct measurement of the polarization in an absolute nuclear polarimeter. A diagram of the chicane can be seen in Figure 2, where spin rotation is accomplished by the labeled dipole and the spin can be flipped by the following solenoid.

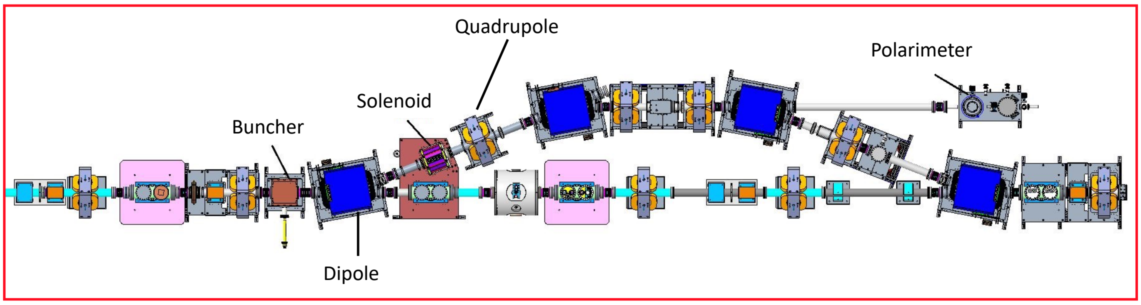

Figure 2: A three-dimensional drawing of the chicane and the main beamline from EBIS to booster.

This manipulation rotates the 3He spin, which is polarized along the beam (EBIS) axis, into the transverse plane.

The absolute nuclear polarimeter measures a spin asymmetry in the elastic scattering of polarized 3He from unpolarized 4He. Previous measurements[7] have shown an analyzing power close to 100% for a 6 MeV polarized 3He beam at a center-of-mass scattering angle close to 96°. The polarimeter layout is shown in Figure 3. The polarized 3He beam enters through a thin aluminum foil window and scatters from a 5 Torr 4He gaseous target region. Two silicon detectors are placed 100° from each other in the lab frame, covering center-of-mass angles from 69° to 100°. Preliminary estimates give an expected systematic error for absolute 3He polarization measurements below 1%.

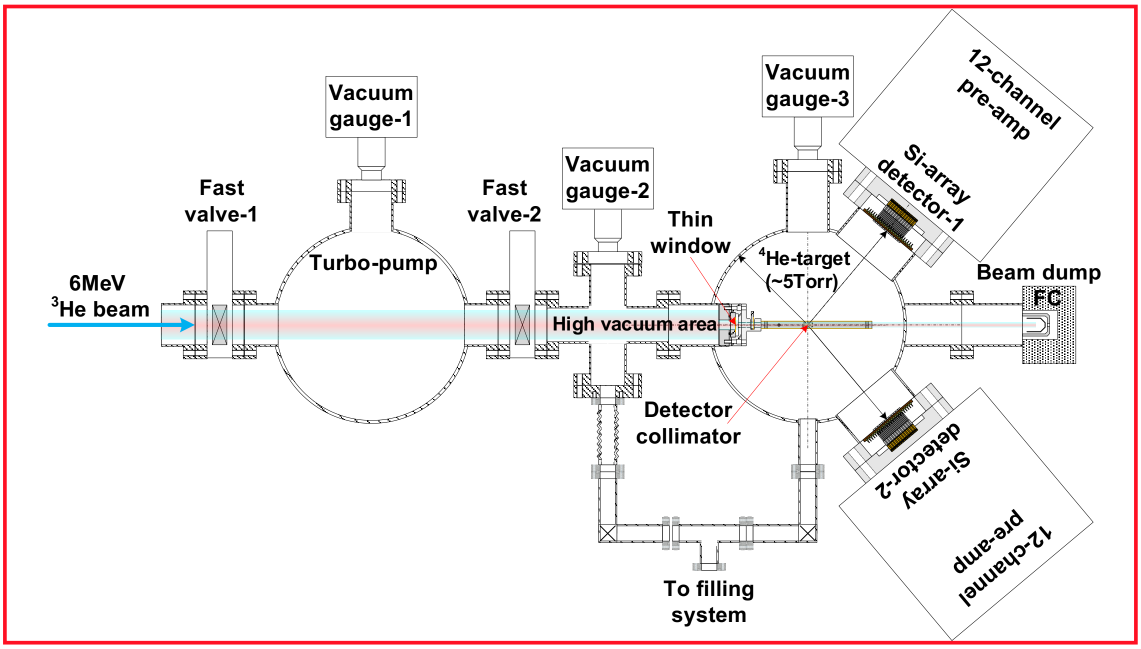

Figure 3: A schematic diagram of the absolute nuclear polarimeter. The 6MeV 3He beam enters from the left and scatters elastically from the 4He target on the right into two symmetric silicon detectors.

2. Current Progress

Development on the 3He++ source was paused after 2022 and has recently been resumed. A gas purification system detailed in[8] has been moved into a test lab along with an identical copy of the EBIS solenoid. The gas purification system uses a modified cryopump capable of pumping hydrogen, water, hydrocarbons, and argon to a level below 10^{-7} Torr. The pump also stores around 100 cm^3 of 3He gas. An internal heater is used to release 3He from the pump and controls the gas pressure in the polarization cell. The cryopump is connected to the polarization cell using a bellows-operated isolation valve which can be operated to purify and cycle the gas mixture.

A compact optical polarization and polarimetry setup has been developed which fits entirely within the solenoid bore. The layout of the optics can be seen in Figure 4. Centrally aligned to

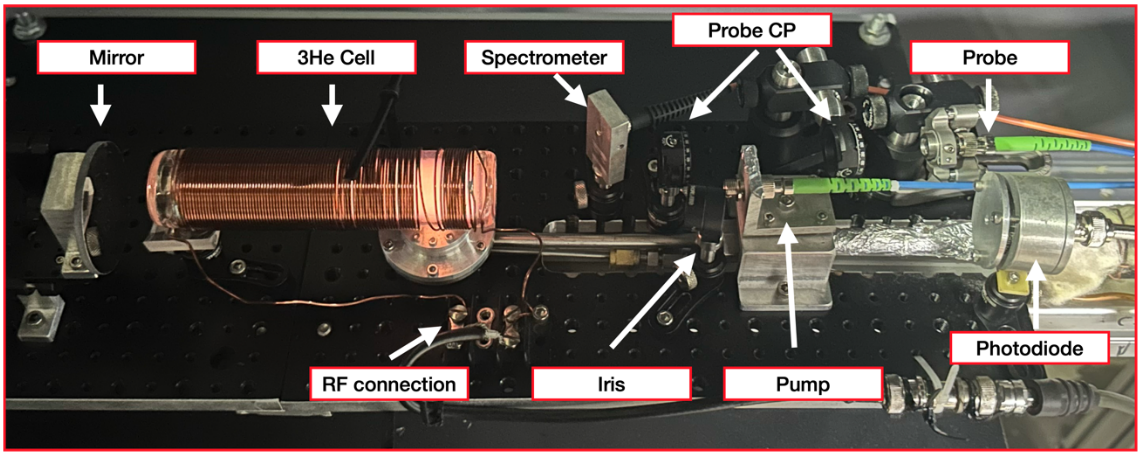

Figure 4: The compact optical polarization and polarimetry setup just outside of the solenoid bore. The probe passes through circularly polarizing optics before traversing the plasma discharge in the cell and reflecting into a photodiode. The pumping laser freely expands to saturate the cell.

the cell is a fiber optic carrying the pumping laser which operates at 1064 nm, typically between 2 and 4 Watts. To save space, there are no polarizing or shaping optics and the pump is allowed to diverge freely from the fiber port. A mirror placed behind the polarization cell improves polarizations by allowing the pump to address a larger sample of atoms in the Doppler broadened plasma. A probe laser, spatially offset from the pump, traverses the cell and is reflected from the mirror into a photodiode. The probe frequency is also close to 1064 nm and is operated at typical powers of a few mW. To identify the small probe signal in a noisy background, the plasma is amplitude modulated close to 260 Hz and the photodiode is connected to a lock-in amplifier where the signal is downmixed. Steady state polarizations close to 60% have been achieved at 3 T using the compact optical setup shown in Figure 5. While pumping times are comparable to previous

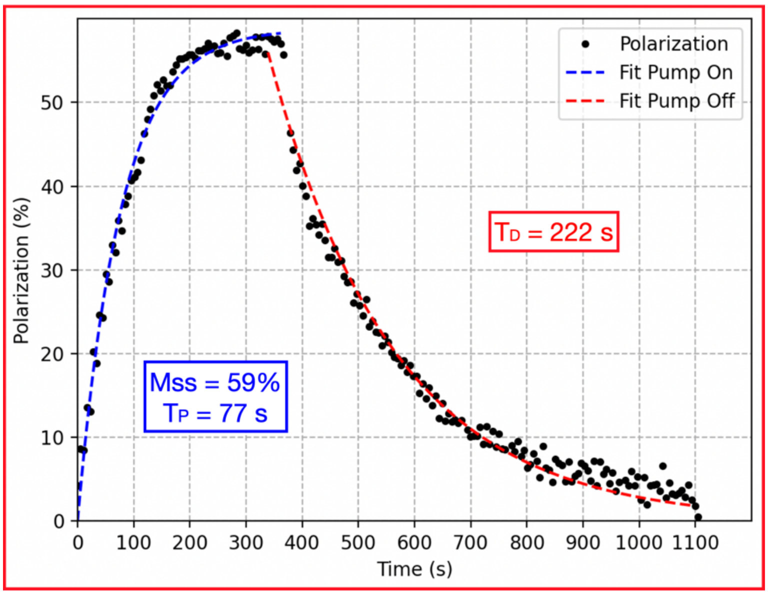

Figure 5: Polarization data taken with the compact optical setup at 3 Tesla showing steady state polarization near 60% and relaxation time close to 4 minutes.

results[8], the relaxation time is only a few minutes which suggests the possible influence of transverse magnetic field gradients which are under investigation. We are currently focused on the optimization of the polarization and refinement of the optical layout with a focus on development of the final geometry which will rest on top of the drift tube inside of EBIS.

Finally, a pulsed valve is being developed for the injection of the polarized 3He into the drift chamber for ionization. The valve uses the same operating principle as the valve currently used to inject unpolarized 3He into EBIS. After the glass-metal connection of the cell to the valve, there is a small (several hundred micron) pore connected to the drift tube. A strip of copper holds a rubber face against the pore, sealing the cell. To open the valve, a 10 A current is pulsed through the copper strip for several microseconds. The Lorentz (Laplace) force produced through the interaction of the large current in the strip and the EBIS magnetic field opens the valve for a controllable length of time to inject gas into the chamber. The pulsed valve has been designed and is currently under construction.

3. Conclusion

The 3He++ polarized ion source at BNL has been revived with a new compact optical layout in an identical copy of the EBIS solenoid. With minimal optimization, polarizations of 60% have been achieved in the refillable cell at 3T. Ongoing work is focused on optimizing the polarization to the design target of 70%, working closely with BNL designers to refine the final optical layout for installation in EBIS during the November 2025 shutdown period. A chicane has been designed and installed on the EBIS to Booster beam transport line to manipulate the extracted 3He++ spin just downstream of EBIS. An absolute nuclear polarimeter based on 3He-4He elastic scattering has been designed and will be installed in the next year in anticipation of polarization tests in early 2026.

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