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PROGRESS OF POLARIZED ION SOURCES AT BNL*

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Abstract

The OPPIS has undergone multiple upgrades since 2000, with the most recent completed in 2022. Improvements to the Rb and Na cells have reduced vapor dispersion in the beamline, significantly lowering consumption and improving source stability. Plasmatron modifications extended component lifetimes. These upgrades enabled reliable Run-24 operation, with a mean current of 350 µA, 300 µs pulse width, and ~80% polarization delivered at the 200 MeV linac exit.

Development is also underway for a high-intensity (2×10^{11} ions/pulse) polarized $^3He^{++}$ source for the future EIC. The approach uses metastability-exchange optical pumping of high-purity ^3He gas in a strong magnetic field, followed by ionization in EBIS. In tests with an “open” cell, 80–85% polarization has been achieved. The final gas cell configuration is now being tested with a 5 T EBIS solenoid magnet.

INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) is currently the only operational collider capable of accelerating and colliding polarized proton beams, achieving ~60% polarization [1]. The upcoming Electron-Ion Collider (EIC) will extend this capability to polarized electron–ion collisions, including $^3He^{++}$ beams [2]. Polarized protons for RHIC are produced using the Optically Pumped Polarized H^- Ion Source (OPPIS) [3], which provides 0.5–1.0 mA (up to 1.6 mA) in 400 µs pulses with 80–85% polarization. The polarized H^- beam is accelerated to 200 MeV in the Linac, then injected into the Booster, where it is adiabatically captured in a single bunch of $\sim4\times10^{11}$ protons. The bunch is accelerated to 2.5 GeV, transferred to the Alternating Gradient Synchrotron (AGS), and further accelerated to 24.3 GeV, delivering ~70% polarization to RHIC. The use of Siberian Snakes in AGS and RHIC effectively suppresses depolarizing resonances, preserving 60–65% polarization through the full acceleration cycle.

Preserving polarization during acceleration will again rely on Siberian Snakes. To meet EIC requirements, the ion source must deliver $\sim2\times10^{11}$ $^3He^{++}$ ions in a 20 µs pulse, implying a peak current of ~2000 µA—about 1,000× higher than past $^3He^{++}$ sources. The proposed source is based on the Electron Beam Ion Source (EBIS) at Brookhaven National Laboratory (BNL) [4]. Polarized ^3He gas will be produced via Metastability Exchange Optical Pumping (MEOP) in a 5 T solenoidal field, then injected into EBIS where it will be ionized by a 10 A electron beam. The goal is to achieve 2.5×10^{11} $^3He^{++}$/pulse at ~70% polarization, followed by acceleration to 2 MeV/u using a Radio Frequency Quadrupole (RFQ) and IH linac for injection into the Booster.

OPPIS

The proton polarization techniques employed in the Optically Pumped Polarized H^- Ion Source (OPPIS), as detailed in [5, 6], are structured into five core functional components: the Fast Atomic Beam Source (FABS), helium cell (He-cell), rubidium cell (Rb-cell), Sona transition region, and the sodium (Na) jet ionizer and extraction system. Both the He-cells and the Rb-cell operate within the 3 T magnetic field provided by a superconducting solenoid (Fig. 1).

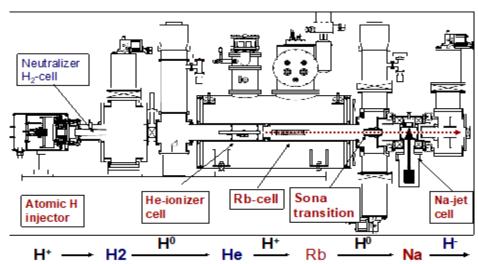

Figure 1: Layout of the OPPIS.

The FABS cathode underwent a redesign that included the addition of a small nozzle and an increase in the outer rim thickness to 3.2 mm. This new nozzle geometry enhances gas flow shaping into the discharge channel and promotes a more uniform wear pattern on the cathode. These changes significantly extended cathode lifetime—eliminating typical blistering and clustering effects seen previously. While the older cathodes averaged two months of operation, the current plasmatron design has now run for 29 weeks without failure.

For Run-24, a new Rb-cell design was implemented. In contrast to the earlier configuration (Fig. 2a, left), where the Rb reservoir was directly exposed to the beam channel, vessel that holds the liquid Rb, which then diffuses evenly through four lateral slits into an inner copper cylinder (Fig. 2c). To improve thermal regulation, a cooling groove was added to the stainless vessel (Fig. 2a), and a copper shield was mounted above it to ensure uniform temperature distribution (Fig. 2b).

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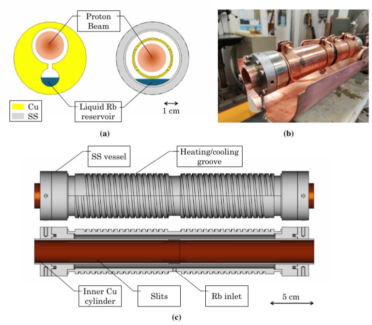

Figure 2: (a) Sections of the two different concepts of the Rb-cell; photo (b) and sketch (c) of the newly designed Rb-cell assembly.

Modifications to the Na-cell targeted the reservoir and cooling line. The container volume was reduced from 500 mL to 230 mL, and heater coupling was improved to enhance thermal efficiency. These changes extended the operating time of the Na-jet ionizer to over six months without requiring a reservoir refill.

The Low-Energy Beam Transport (LEBT) section (Fig. 3), which connects OPPIS to the 750 keV RFQ, also received upgrades in 2022. The distance between the Na-jet ionizer and the 23.7° dipole magnet was shortened by ~2 meters, and electrostatic Einzel lenses were replaced with magnetic quadrupoles. These improvements led to a 10% gain in transmission efficiency, primarily by reducing beam losses due to stripping. Additionally, the reduced length improved the delivery of the pumping laser beam into the source.

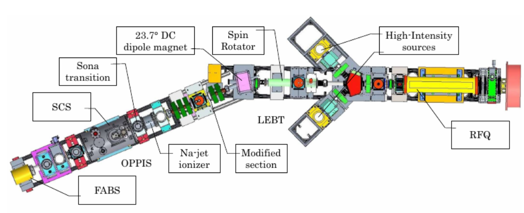

Figure 3: Configuration of LEBT with High intensity sources.

Together, these upgrades enhanced the performance, reliability, and safety of OPPIS during Run-24. A beam current of 350 μA was consistently delivered, fully meeting Booster injection requirements over a six-month uninterrupted operational period. System stability was demonstrated by an average arcing rate of 2%, indicating the OPPIS power supplies and He grid system can reliably support extended pulse widths after proper conditioning. However, a slight reduction in average polarization was noted during the run. Preliminary analysis suggests the increased longitudinal size of the new Rb-cell may contribute to this effect, though further investigation is ongoing.

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) [7-10]. 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 [11-12]. 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 (Fig. 4)

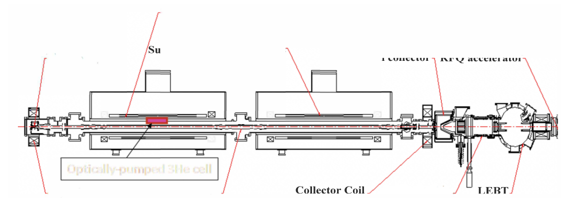

Figure 4: Schematic diagram of the extended EBIS. The polarized ^{3}He gas is injected into the drift tube in the Gas Trap of EBIS. Low Energy Beam Transport (LEBT) transfer the extracted beam from EBIS to the Radio Frequency Quadrupole (RFQ) e accelerator.

The 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. A gas purification system detailed in [13] 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 ^{3}He gas. An internal heater is used to release ^{3}He 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.

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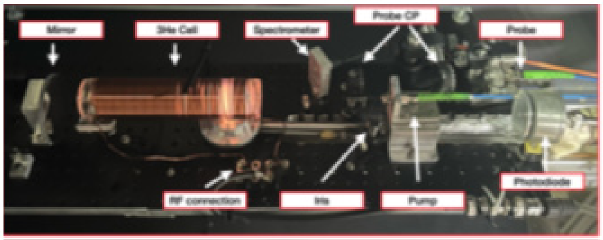

Figure 5: The compact optical polarization and polarimetry setup just outside of the solenoid bore. The probe passes through circularly polarizing optics before traversing the plasma discharge in the cell and reflecting into a photodiode. The pumping laser freely expands to saturate the cell.

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 Fig. 5. Centrally aligned to the cell is a fiber optic carrying the pumping laser which operates at 1064 nm, typically between 2 and 4 Watts. 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 as shown in Fig. 6.

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 ^{3}He into the drift chamber for ionization [13]. The valve uses the same operating principle as the valve currently used to inject unpolarized ^{3}He into EBIS.

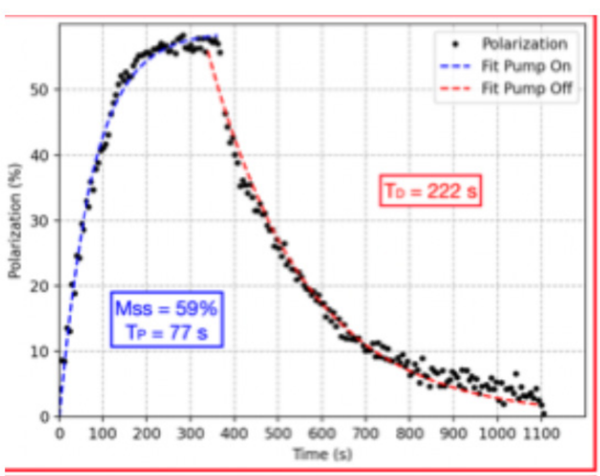

Figure 6: Polarization data taken with the compact optical setup at 3 Tesla showing steady state polarization near 60% and relaxation time close to 4 minutes.

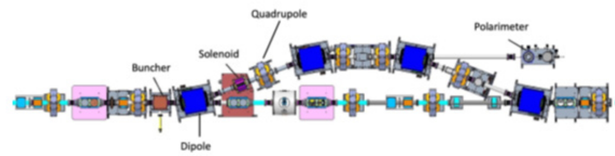

Figure 7: Spin-manipulation chicane along to Ebis to Booster transfer beam line.

Current efforts aim to refine the optical layout to achieve the 70% polarization target for integration into EBIS during the June 2026 shutdown. A spin-manipulating chicane (Fig. 7) has been designed and tested for beamline integration to control $^3He^{++}$ spin orientation downstream of EBIS. An absolute nuclear polarimeter based on ^{3}He–^{4}He elastic scattering has also been designed for installation in early 2026, preparing for future polarization characterization tests.

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