Office of Science Final Report

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Facilities and Project Management Division

Proposal Name: Development of a Polarized ^{3}He Ion Source for RHIC
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The goal of the project is to develop a polarized ^{3}He ion source that will meet the polarization and luminosity requirements of the Electron-Ion Collider (EIC). This development is essential for the EIC science program to study the spin structure of the neutron.

The initial design of the polarized ^{3}He source planned to polarized ^{3}He gas via meta-stability exchange optical pumping (MEOP) at low field in the fringe field of the 5 T Electron Beam Ion Source (EBIS) solenoid field, and then transfer the gas into the EBIS solenoid along a magnetically shielded path that follows the field lines of the EBIS solenoid's fringe field. The ^{3}He gas would then be injected into the EBIS vacuum and ionized by the 10 Amp, 20 keV electron beam.

Work on the low-field concept primary took place from 2012-2015. To study the feasibility of this design, a ^{3}He laser lab was established at MIT to optically pump ^{3}He, and a ^{3}He cell filling station was commissed at the Bates Research and Engineering Facility. Fig. 1 shows the optical pumping setup in the MIT ^{3}He laser lab. Several ^{3}He cells were filled at Bates and a compact polarimeter, which determined the ^{3}He polarization by measuring the circular polarization of 667 nm discharge light, was assembled to measure the ^{3}He cell's polarization. The design of the polarimeter was published in Ref. 1. Polarizations of 70% were measured in several sealed cells.

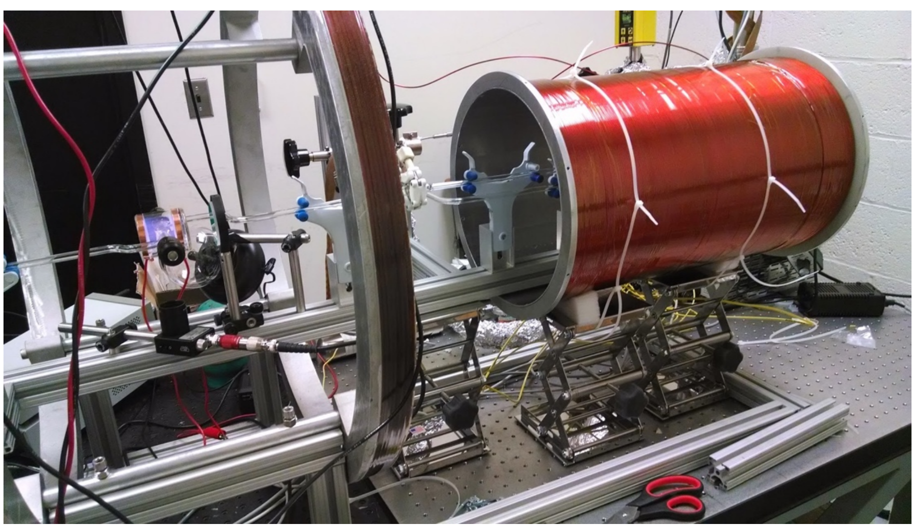

Figure 1. The ^{3}He laser lab at MIT. The ^{3}He is being optically pumped in the Helmholtz field on the left side and will be transferred through glass tubing to the solenoid field.

To study the diffusive transfer of polarized ^{3}He gas, a double cell system with two magnetic field regions was created. Using two cells in two magnetic fields, separated by a region of depolarizing gradients, ^{3}He was polarized in one cell, while monitoring the polarization in both cells. This experiment showed a significant amount of depolarization during diffusive transfer across field gradients as shown in Fig. 2, which agreed with calculations, and the results have been published in Ref. 2.

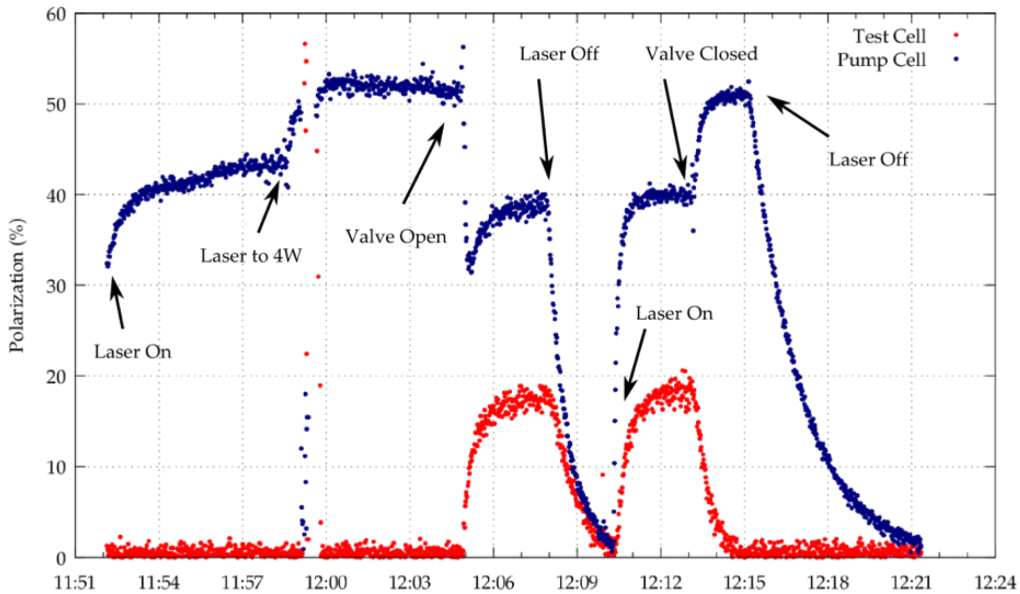

Figure 2. The ^{3}He polarization measured in the pump cell and the test cell in the solenoidal field shown in Fig. 1.

In the MIT laser lab, a probe laser polarimeter was created that could measure the ^{3}He polarization at high magnetic fields to facilitate studies in a high field region. A superconducting solenoid that serves as a spare EBIS solenoid was recommissioned at BNL to test optical pumping in the stray field of the solenoid, polarized ^{3}He gas transfer into a high magnetic field, and the feasibility of polarizing directly in a high magnetic field. Results for polarizing in the stray field with the solenoid at 1 T were between 30-38% with an additional holding field and 17-26% with just the stray field. Initial tests polarizing ^{3}He in a high field (2, 3, & 4 T) achieved 80% polarization in cells that often struggled to reach 60% at low field. The results of high field ^{3}He polarization with l torr cells are being prepared for publishing in Ref. 3.

Successful tests polarizing ^{3}He at high magnetic fields above 1 T and the expected depolarization during polarized ^{3}He gas transfer from low field prompted a re-design of the polarized ^{3}He ion source. In the new design, the ^{3}He is polarized in a second 5 T solenoid in an extended EBIS design. Fig. 3 shows the design of the Extended EBIS, and Fig. 4 is a conceptual illustration of the high field polarized ^{3}He ion source. The Extended EBIS Upgrade was approved as an Accelerator Improvement Project at BNL with the primary purpose of increasing the Au32+ intensity, and it will provide essential infrastructure for the polarized ^{3}He ion source.

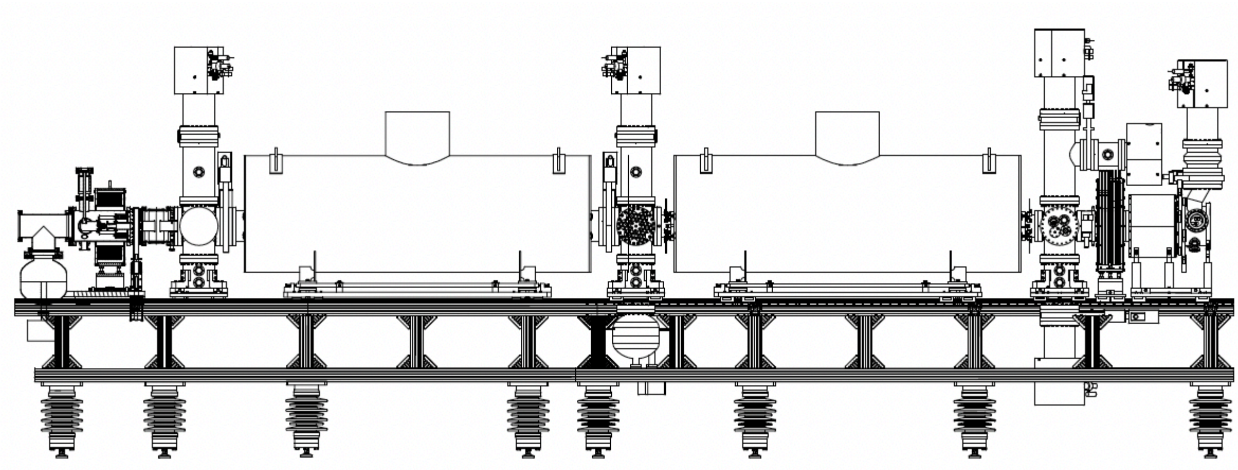

Figure 3. The Extended EBIS Upgrade design. The ^{3}He will be polarized and injected in the upstream solenoid on the left-hand side.

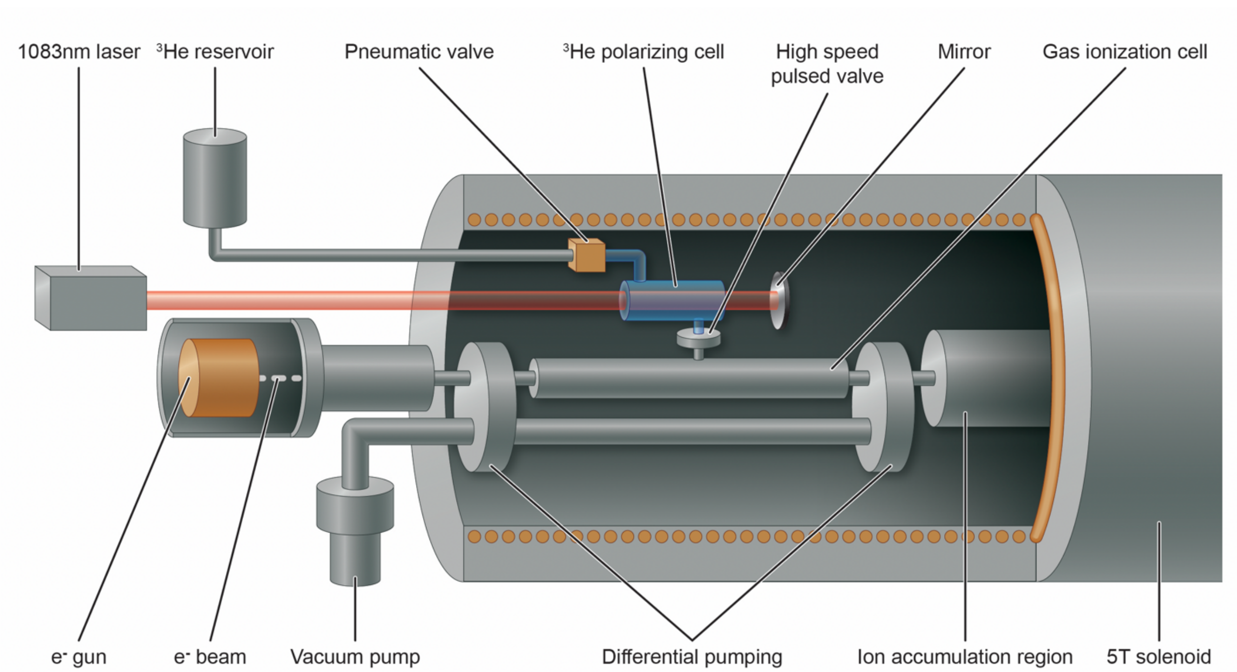

Figure 4. A conceptual illustration of the parts of the ^{3}He polarization and injection systems to be installed in the Extended EBIS Upgrade.

A ^{3}He test lab was established at BNL to continue necessary R&D. From 2015-2017 this lab was equipped with the 5 T EBIS spare solenoid until it had to be sent back to the manufacturer for reinforcement for the Extended EBIS Upgrade. The ^{3}He test lab is now being recommissioned for low field studies, and the Optically Pumped Polarized H- Ion Source (OPPIS) solenoid was converted into a high field ^{3}He test station during the summer of 2017 because there were no polarized proton runs planned for RHIC in 2018.

At magnetic fields above 1 T, improvements in the maximum polarization have been achieved with a narrower cell design to account for formation of the RF discharge around the periphery of the cell at high field, as well as ^{3}He cell fabrication improvement, increased laser power, and improved RF discharge characteristics. These improvements also applied to ^{3}He polarizations in open cell systems attached to a gas handling manifold. Maintaining gas purity in open cell systems often limited the maximum polarization; however, the BNL team has constructed a specialized cryopump gas purification system that when operated at a temperature of 46K will selectively pump all gases except helium. Recently, ^{3}He polarizations above 80% have been regularly achieved with different open cell configurations at 3 T.

The polarized ^{3}He ion source in EBIS is expected to have a narrow gas ionization region with constrictions and differential pumping on either end to efficiently ionize gas while maintaining high vacuum conditions in the rest of the EBIS vacuum system. This concept is shown in Fig. 4. Gas injection simulations with MolFlow have allowed us to estimate the gas injection and pump out times. The ionization rate of ^{3}He and accumulation of ^{3}He++ ions was also calculated in the MolFlow model by using the electron impact ionization cross sections of ^{3}He to determine the pumping rate of the electron beam. The simulations are ongoing and are expected to also provide insights on ^{3}He depolarization and general vacuum improvement for the Extended EBIS. Initial model results of various time parameters are shown in Table 1, and Fig. 5 shows a plot of ^{3}He++ ion accumulation within the electron beam trap. All of these timing results are encouraging and are within necessary constraints.

Step sequence	Time
^{3}He gas injection	0.5 ms
Diffusion into ionization cell	2 ms
Injected gas pressure falls 50%	3 ms
Ionization of ^{3}He to ^{3}He$^+$	~10 ms per gas injection
Time constant for ^{3}He$^+ \rightarrow {}^3$He^{++} conversion	1 ms
Pump down to 10^{-9} torr	100-150 ms
5 Hz EBIS pulse repetition rate	200 ms
Switching time between species	1 second

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

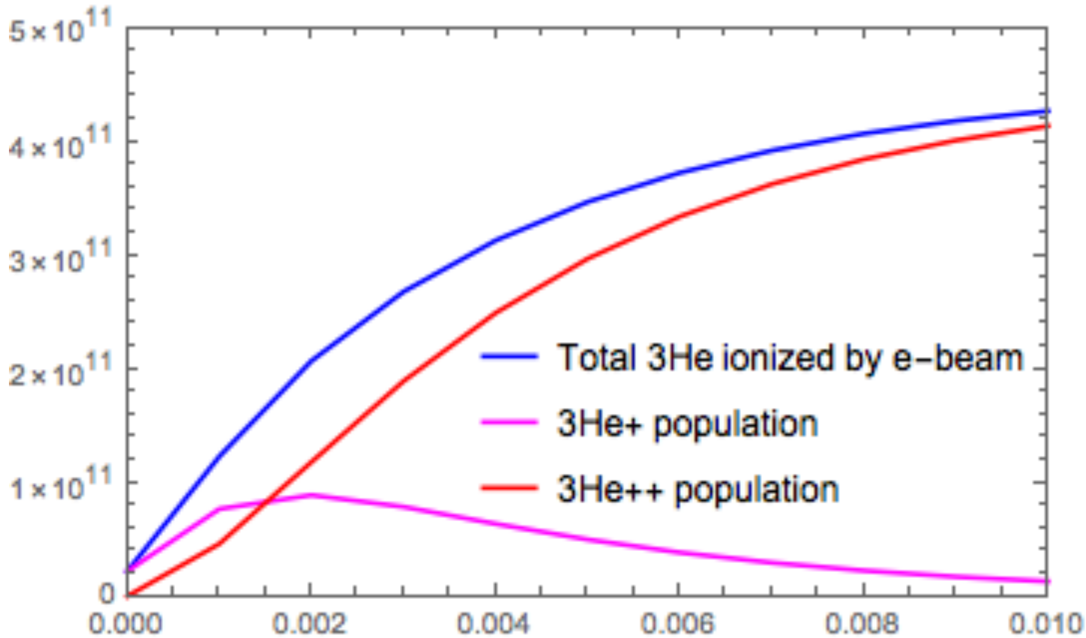

Figure 5. Calculation of the charge accumulation of ^{3}He ions in the EBIS electron beam trap. The abscissa is in units of seconds.

Extended EBIS solenoids were delivered in February 2018 and are shown in Fig. 6. These solenoids are now in the TestEBIS experimental area where the Extended EBIS will be constructed before commissioning as an injector for RHIC.

Figure 6. The reinforced 5 T superconducting solenoid magnets for the Extended EBIS Upgrade.

A prototype high speed pulsed valve has been developed for polarized ^{3}He injection, which opens by the Lorentz force when a current is pulsed through a conductive plate in a high magnetic field. The prototype is shown in Fig. 7. This valve has been successfully tested in the 5 T field of the Extended EBIS solenoids and the 3 T field of the OPPIS solenoid. The valve appears to maintain a good vacuum when closed. Valve development is ongoing to reduce the valve size and optimize the quantity of ^{3}He gas injected.

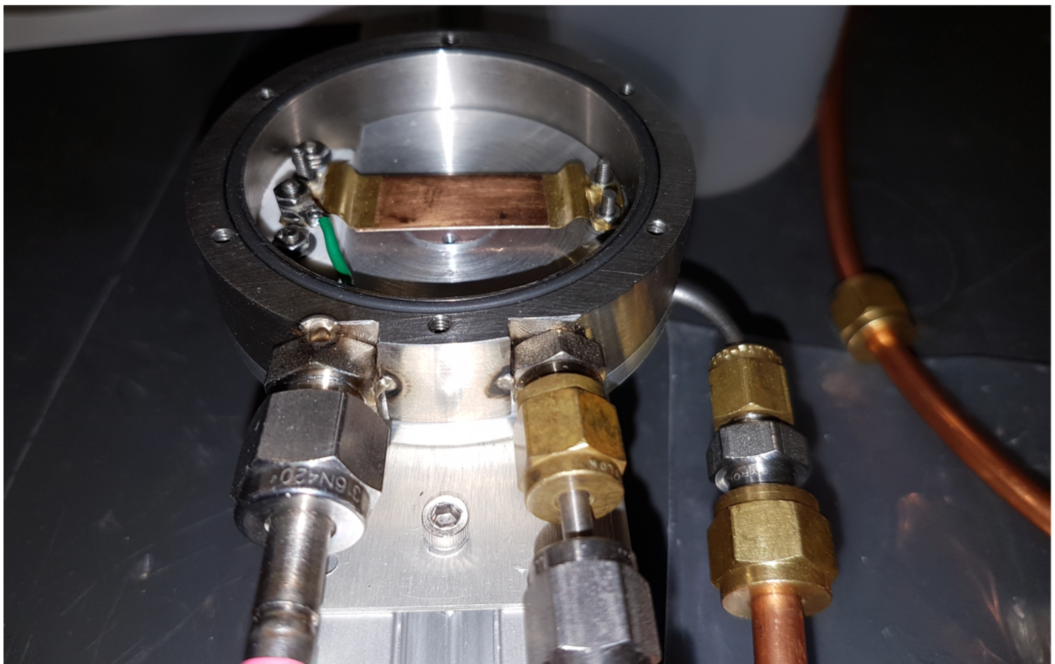

Figure 7. The prototype high speed valve for injection of ^{3}He gas into the EBIS vacuum system.

After successful polarization measurements at high field, plans were made to calibrate the probe laser polarimeter with NMR. However, NMR was not possible in any of the superconducting solenoids available at BNL, because the size of the field gradients results in a T2 relaxation time too small to resolve with NMR. A new plan to calibrate the probe laser polarimeter in an NMR magnet were made and progress has been made acquiring the necessary equipment, including a high frequency lock-in amplifier and a second probe laser. However, with the start of work on the Extended EBIS Upgrade, the NMR calibration has been delayed. The measurement will now be continued with funds from DE-SC0012704.

Initial plans, when the ^{3}He was going to be polarized at low field, were to design the ^{3}He polarization system semi-independently of the Extended EBIS Upgrade. However, space restrictions within the EBIS solenoid have complicated the design, and construction will have to proceed in tandem with the design of the Extended EBIS Upgrade in the solenoid bore. This project will be continued with DE-SC0012704 funds as the Extended EBIS Upgrade progresses. Grant funding was awarded to MIT and BNL to develop a 6 MeV ^{3}He polarimeter to measure the ^{3}He polarization after it is ejected from the EBIS. This work is ongoing and is proceeding with the Extended EBIS Upgrade.

We do believe that several systems necessary for a polarized ^{3}He ion source that meets the requirements for an Electron-Ion Collider (EIC) have been successfully tested. The experience gained from developing the various systems discussed within this report will be necessary for the completion of an operational polarized ^{3}He ion source based on the EBIS. With continued support for the Extended EBIS Upgrade and the 6 MeV ^{3}He polarimeter, a feasibility study of a polarized ^{3}He ion source should be completed in a few years. The results of this research have been presented at several international conferences Ref. 4-17.

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