Development of a Polarized ^{3}He Ion Source for RHIC using the Electron Beam Ion Source

C.S. Epstein* and R.G. Milner†
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA

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A polarized ^{3}He beam in RHIC would enable new, unique, high energy QCD studies of neutron structure with existing polarized proton beams. In addition, it could be used for important tests of the Standard Model in a future electron-ion collider. A source of polarized ^{3}He^{++} ions utilizing the new Electron Beam Ion Source (EBIS) at BNL is under development. ^{3}He atoms can be polarized using metastability exchange optical pumping (MEOP) and the atoms transferred to EBIS. Fully stripped ^{3}He^{++} ions would be extracted from EBIS and their polarization measured at low energies. The concept for the ion source is presented and the plan for the development described. Research supported by DOE Office of Nuclear Physics.

I. INTRODUCTION

A current problem of great interest is the study of the spin structure of the nucleon. Through experiments at SLAC, CERN, and DESY, it has been determined that quarks contribute only about 25% of the nucleon's spin; current experiments such as those at RHIC-spin are testing the contributions of gluons. A useful tool in these studies has been the polarized proton; however, it is vital to have two isospin configurations of the nucleon. The polarized neutron provides a different configuration of quarks with supposedly the same distribution of gluons. A polarized neutron beam at RHIC-spin would allow an additional independent determination of the nucleon spin structure. [1]

Presently, as highly polarized free neutrons are not readily available in nature, polarized deuterons or ^{3}He have been used as targets in a variety of experiments. However, there are problems with the use of a deuteron in the formation of a beam because of its low magnetic moment, as the spin of the proton and neutron are aligned and the magnetic moments cancel almost completely. This makes spin manipulation difficult. With ^{3}He, however, the spins of the protons are in opposite directions and thus the magnetic moments of the protons cancel, causing the overall magnetic moment to be similar to that of the free neutron. This allows spin manipulation in accelerators such as RHIC. Thus a high-intensity source of highly polarized ^{3}He is of great interest. [1]

I.1. Polarizing ^{3}He

A number of polarized ^{3}He sources have been developed in the past. At the University of Birmingham, UK, a Lamb shift polarized ^{3}He source was developed that reached a current of 50 particle nA at 65% polarization [2]. A Rice University - Texas A&M collaboration developed a 11% polarized ^{3}He source using metastability exchange optical pumping at 8 particle μA [3]. At Laval University, Canada, a source was developed using the Stern Gerlach method that provided 100 particle nA with 95% polarization [4]. Our goal is to produce a high-current source of polarized ^{3}He ions of approximately 500 particle nA with at least 70% polarization.

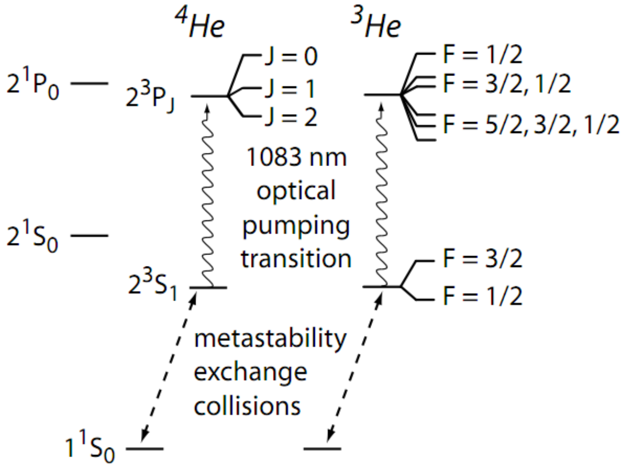

FIG. 1. Atomic energy levels of ^{4}He and ^{3}He

It is planned to polarize the ^{3}He atoms using metastability exchange optical pumping (MEOP), in which a weak RF discharge excites atoms into the metastable state, where they are pumped from the 2^3P to 2^3S states via 1.083 μm circularly polarized light (Fig. 1). Metastability exchange collisions transfer this spin configuration to ground-state atoms. Previous experiments successfully performed MEOP using a Nd:YAG system that included a flashlamp pumped Nd:LMA, and provided 2×10^{17} ^{3}He atoms/sec at 50% polarization. [1]. Advances in laser technology have improved the efficiency of MEOP. Recently, using ytterbium fiber lasers, highly-polarized high-current sources have been formed; the

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* cepstein@mit.edu; http://he3.xvm.mit.edu
† milner@mit.edu

University of Mainz has demonstrated a flow rate of 8×10^{18} ^{3}He/sec at polarizations over 70% [1]. We have purchased two 10W Keopsys commercial fiber lasers and are in the process of setting up a lab to optically pump ^{3}He.

I.1.1. Measuring the Polarization in the Pumping Cell

In order to measure the polarization in the pumping cell we plan to use a pump-probe technique. A circularly polarized probe laser is directed transverse to the pumping cell, and the ratio of the transmitted power of transverse to longitudinally polarized light is measured [5]. This gives the ratio of populations in the two 2^3S sublevels. The scaling of the equilibrium population densities as a function of polarization is known, thus allowing the nuclear polarization to be inferred [5].

I.1.2. Reversing the Polarization

An important capability is the ability to reverse the sign of the polarization of the ^{3}He^{++} ions extracted from EBIS. We plan to do this by simultaneously reversing the polarization of the atoms in the pumping cell by adiabatic fast passage NMR and by reversing the circular polarization of the light from the 1.083 μm pump laser. This would allow the polarization of the atoms fed to be EBIS to be reversed in sign within about one second.

Adiabatic fast passage (AFP) [6, 7] is a technique used to reverse the direction of the macroscopic magnetization of a system with respect to a static magnetic field. To understand this technique, consider the effect of an oscillating rf magnetic field $\mathbf{B}_x = 2\mathrm{B}_1\cos(\omega \mathrm{t})\mathbf{i}$ applied to a magnetized sample that is immersed in a static magnetic field $B_0\mathbf{k}$. A useful transformation takes us from the laboratory frame ($\mathbf{i}$, $\mathbf{j}$, $\mathbf{k}$) to a frame ($\mathbf{i}'$, $\mathbf{j}'$, $\mathbf{k}' = \mathbf{k}$) rotating at the rf frequency ω. In this rotating frame, decomposing B_x into two rotating fields yields one field that is stationary and a second that rotates at the frequency 2ω. The effective field in the rotating frame is given by

$$\mathbf{B}_e = \left[B_0 - \frac{\omega}{\gamma}\right]\mathbf{k}' + B_1\mathbf{i}'$$

where γ is the gyromagnetic ratio: for ^{3}He $\frac{\gamma}{2\pi} = 3.24$ kHz/G. If the static field is initially far enough away from $\frac{\omega}{\gamma}$ so that $\left|B_0 - \frac{\omega}{\gamma}\right| >> B_1$, then $\mathbf{B}_e$ and the magnetization $\mathbf{M}$ are oriented nearly along $\mathbf{k}'$ in the rotating frame. If the static field is ramped towards resonance $\left(B_0 = \frac{\omega}{\gamma}\right)$, $\mathbf{B}_e$ rotates away from the $\mathbf{k}'$ axis towards the $\mathbf{i}'$ axis and carries the magnetization along with it. At resonance, $\mathbf{B}_e = B_1\mathbf{i}'$. If the static field is ramped far past resonance, both $\mathbf{B}_e$ and $\mathbf{M}$ will reverse direction. If the sweep rate $\frac{dB_0}{dt}$ is slow enough (*adiabatic* condition) so that

$$\left|\frac{dB_0}{dt}\right| << \gamma B_1^2$$

then the magnetization follows the effective field. The *fast* condition requires that the effects of relaxation must be negligible during the time of passage through resonance, *i.e.*

$$\frac{1}{B_1}\left|\frac{dB_0}{dt}\right| >> \frac{1}{T_1}, \frac{1}{T_2}$$

where T_1 and T_2 are the longitudinal and transverse relaxation times, respectively. T_2 is dominated by depolarization effects due to transverse gradients in B_0. However, if $B_1 >> \Delta B_0$, where ΔB_0 is the inhomogeneity in B_0 across the sample, transverse relaxation due to gradients can be neglected.

As $\mathbf{M}$ slowly reverses direction, it is also rapidly precessing in the laboratory frame at the rf frequency ω. For a pickup coil in the xz plane, this precessing magnetization induces an AC voltage of amplitude E, given by

$$E = -NQ\frac{d\Phi}{dt} = -NQ\omega\Phi,$$

where Φ is the magnetic flux through the pickup coil with N turns and Q is the quality factor of the tuned pickup circuit. The AFP line shape is

$$E(B_0) = E_0\frac{B_1}{\left[B_1^2 + (B_0 - \frac{\omega}{\gamma})^2\right]^{1/2}},$$

where E_0 is the amplitude of the induced voltage at resonance.

Here, $B_0 \approx 1000\ G$ is provided by the solenoidal field of EBIS so, to implement reversal of the ^{3}He polarization in the pumping cell via AFP, the EBIS field would need to be slowly ramped through resonance. The resonance frequency is $\nu_r = \frac{\omega_r}{2\pi} = 3.24$ MHz. There are a number of conditions which must be satisfied:

- We require that $\Delta B_0 << B_1$, which sets the scale for B_1. $\Delta B_0 \sim \Delta_t B_0 \cdot l$, where $\Delta_t B_0$ is the transverse gradient in the holding field and l is the transverse size of the pumping cell. Here $\Delta_t B_0 \approx 2$ G cm^{-1} and $l \approx 5$ cm. Thus, 10 G $<< B_1$, i.e. $B_1 \approx 100G$. The rf magnetic field $B_1\mathbf{i}$ would be provided by a pair of Helmholtz coils with the axis in the $\mathbf{i}$ direction. Two rectangular coils in the $\mathbf{j}$ direction can be used to pickup the signal.

- The field B_0 needs to be ramped in about 1 second from below resonance to above resonance. Once can sweep from either below or from above the resonance. The width of the resonance depends on the noise. However, based on previous experiments at low fields [7], it is likely one will need to sweep from about 20 G below resonance to about 20 G above resonance. This demands a sweep in field of about 4% in 1 second. With $B_1 \approx 100G$, the *adiabatic* condition above is satisfied.

- Also, this would give $\frac{1}{B_1}\left|\frac{dB_0}{dt}\right| \approx 0.4$ s^{-1}, which satisfies the *fast* condition above.

High efficiency reversal depends on the degree to which the conditions for AFP are satisfied. However, because the atoms in the cell are immediately pumped with a strong laser, small inefficiencies should be tolerable. Note that we may not need the pickup coil as we can measure the polarization in the pumping cell using the pump-probe technique.

II. RHIC ELECTRON BEAM ION SOURCE

As an alternative to the Tandem Van de Graff ion sources at RHIC, an Electron Beam Ion Source (EBIS) has been developed and is operational as of 2010 [8]. EBIS is a 1.5 meter ion trap with a 15 keV electron beam surrounded by a 5T superconducting solenoid (Figues 2, 3). The desired flow rate into EBIS is approximately 3×10^{14} ^{3}He/sec, with approximately 10^{12} ^{3}He^{++} ions extracted per second. ^{4}He has been successfully flowed into EBIS, indicating the possibility of ionizing ^{3}He indicates at the desired rate.

II.1. EBIS Ion Trap Properties

In the following, a number of properties of the EBIS ion trap are addressed. These include the operating pressure, ion trapping mechanisms, average time spent in the trap, and energy deposition by the electron beam.

II.1.1. Pressure Inside EBIS

An important figure to estimate is the operating pressure inside EBIS. Assuming a pumping speed of 100 l/s = 10^5 cm^3/s at the trap, then P = Q/S =

$$= \frac{3 \times 10^{14}\ s^{-1}}{10^5\ cm^3 s^{-1}} = 3 \times 10^9\ cm^{-3} \rightarrow \sim 10^{-7}\ \text{torr}$$

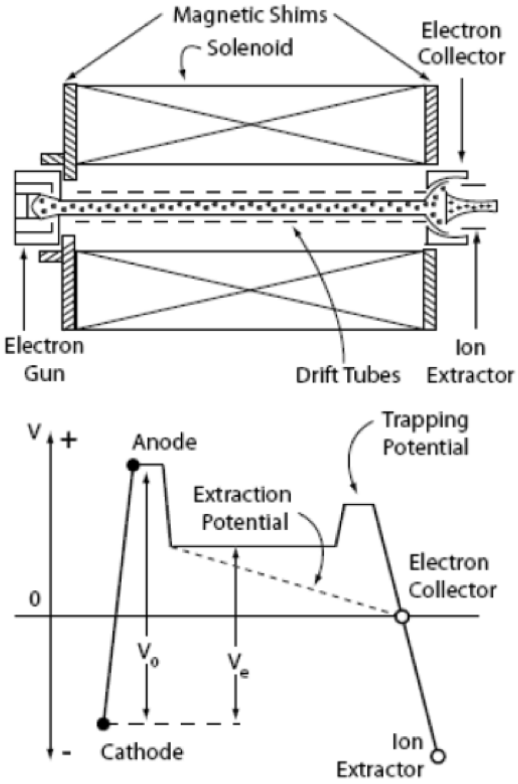

FIG. 2. Top: a schematic of EBIS. Below: the electric potential along the length of EBIS.

II.1.2. Ion Trapping

We note that in EBIS, the ions are trapped in a 5T field, and thus the radius of curvature of their motion is given by

$$Bqv = \frac{mv^2}{r}$$

With B = 5T, q = 1.6×10^{-19} C, v = 10^3 m/s (thermal), m = 5×10^{-27} kg, it is calculated that $r \approx 6 \times 10^{-6}$ m. Along with the negative charge of the electron beam, this effectively pins the ^{3}He^{++} ions in the trap.

II.1.3. Time Spent in Trap

Another important figure is the approximate time spent in the trap. First, the equilibrium number of atoms in the trap is estimated. With a trap length of 1.5m and an approximate diameter of 5cm, the volume of gas in the trap is

$$\frac{25\pi}{4} \cdot 150\ cm^3 = 2945\ cm^3 \approx 3,000\ cm^3$$

Then,

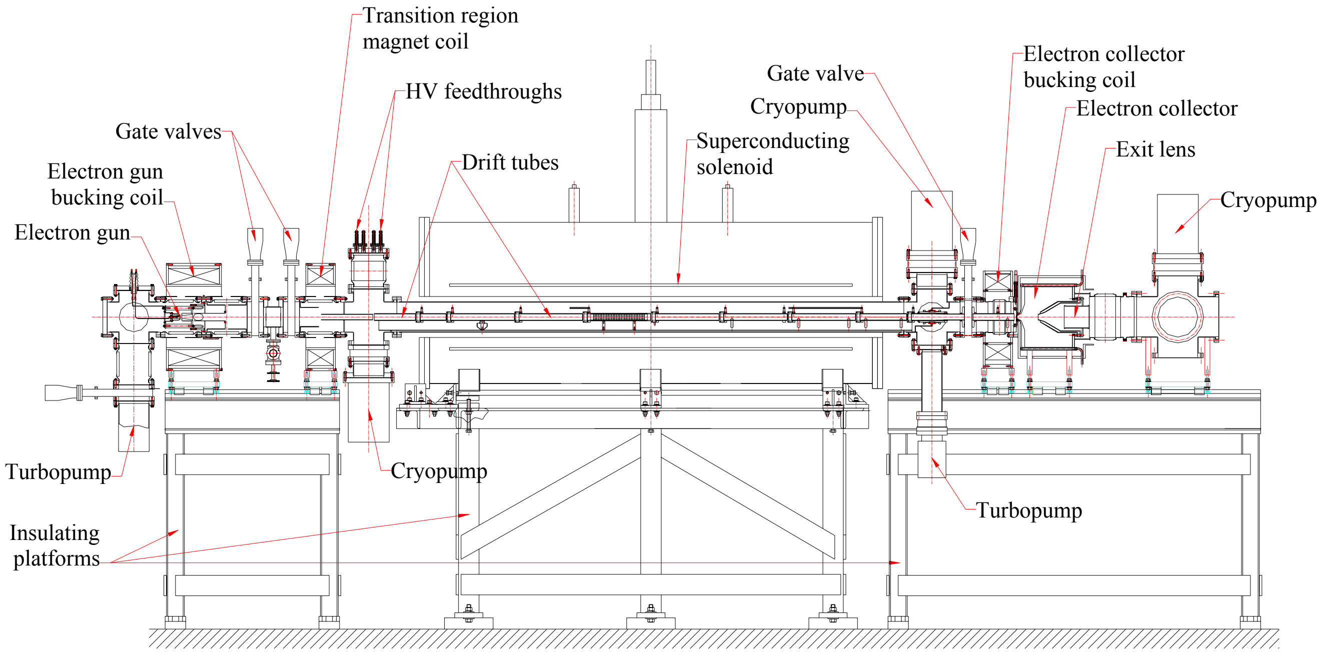

FIG. 3. A detailed schematic of EBIS

$$3 \times 10^{9}\ cm^{-3} \cdot 3 \times 10^{3}\ cm^{3} =$$

$= 9 \times 10^{12}$ atoms inside EBIS at equilibrium. Then the average time the atoms spend in the trap is

$$\frac{9 \times 10^{12}}{3 \times 10^{14}}\ s \approx 30\ ms$$

This is useful to reference with polarization relaxation times for various processes inside EBIS, all of which seem to occur over longer time scales.

II.1.4. Ionization in EBIS

It is possible to estimate, theoretically, the energy deposited by an electron beam through various materials. The following equation relates the stopping power of a charged particle to the properties of the medium [9]:

$$-\frac{1}{\rho}\left(\frac{dE}{dx}\right) = \frac{0.153536}{\beta^{2}}\frac{Z}{A}B(T)$$

where $\beta = v/c$, Z is atomic number, A is atomic weight, and

$$B(T) = B_0(T) - 2\ln\left(\frac{I}{mc^{2}}\right) - \delta$$

where I is the mean excitation energy of the medium ($41.8eV$ for Helium), mc^2 is the rest mass of the electron ($0.511MeV$), δ is the plasma density effect correction, and

$$B_0(T) = \ln(\tau^{2}(\tau+2)/2) + [1+\tau^{2}/8-(2\tau+1)\ln 2]/(\tau+1)^{2}$$

where $\tau = T/mc^2$. T is the kinetic energy, which in EBIS is 15 keV. Evaluating this yields $B_0(T) = -6.79$.

Since the parameter $X = \frac{1}{2}\log_{10}(\tau(\tau+2)) = -0.6125$ is less than the value $X_0 = 2.191$ for Helium, then $\delta = 0$.

Thus,

$$B(T) = 12.0$$

And therefore,

$$-\frac{1}{\rho}\left(\frac{dE}{dx}\right) = 21.9\ \frac{MeV}{g\ cm^{-2}}$$

With $\rho = 10^{10}$ atoms$/cm^3 \rightarrow 4.98 \times 10^{-14}\ g/cm^3$,

$$-\frac{1}{\rho}\left(\frac{dE}{dx}\right) = 1.09 \times 10^{-12}\ MeV/cm$$

With 6×10^{19} electrons passing over the length of EBIS ($190\ cm$) per second, the rate of energy deposition is $1.24 \times 10^{10}\ MeV/sec$. 79 eV are necessary to fully ionize a ^{3}He atom; an extraction rate of 3×10^{12} ions/sec requires about $2.4 \times 10^{8}\ MeV/sec$. Thus, more than enough energy is provided by a factor of $\sim 10^2$.

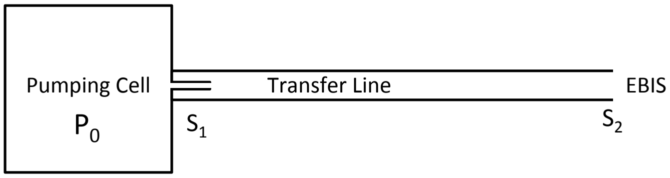

FIG. 4. Schematic layout showing definition of variables

III. SYSTEM SETUP OVERWIEW

The fringe magnetic fields of the RHIC EBIS are strong enough to allow polarization of ^{3}He without additional field coils. ^{3}He atoms are polarized in a pumping cell in the fringe field of EBIS (Fig. 5). A transfer line brings the polarized atoms to the entry port of EBIS, where they travel through a final transfer line into the trap where they become ionized. Ions are extracted at the opposite end of the EBIS.

III.1. Flow from the Pumping Cell to EBIS

Polarized ^{3}He atoms must be transferred from the pumping cell at $P_0 \approx 1$ torr to EBIS at $\sim 10^{-7}$ torr (Fig. 4). A calibrated leak at 10^{-5} atm-cc/sec at the pumping cell and a capillary tube to EBIS will provide the necessary flow rate, as shown in detail in technical note #2 [10]. In summary, from [11, p. 65];

$$\frac{1}{C} = \frac{1}{S_1} - \frac{1}{S_2}$$

where $S =$ pumping speed and C is the conductance. The pumping speeds at the entrance and exit of the transfer line, S_1 and S_2, respectively, are calculated to be approximately 8×10^{-6} l/s and 8×10^{1} l/s. This corresponds to a total necessary conductance between the pumping cell and EBIS of approximately 8×10^{-6} l/s.

To ensure low pressure in the transfer line, i.e., molecular flow, and therefore few collisions, most of the conductance must be located near the pumping cell in the form of a precision capillary leak. If the conductance is uniformly distributed through the transfer line, the pressure directly outside of the pumping cell will be too high.

To check to ensure the flow through the transfer line is molecular, the mean free path at the entrance, λ_0, is set to a factor of 10 higher than the diameter of the line, which is to be determined. For helium, $\lambda = 9.26{\times}10^{-3}/P$ in centimeters [11, p. 32]. The mean free path will be the shortest at the entrance to the transfer line as the pressure is the highest, thus, if flow is molecular at that point then it will continue to be molecular.

The necessary flow rate of the leak is 10^{-5} atm-cc/sec. If the pumping cell leak is in the form of an aperture, the necessary diameter is 5.6×10^{-4} cm. The uneconomic nature of manufacturing an aperture with such a diameter to high precision necessitates the use of another form of flow control. We plan to use a calibrated capillary leak in order to provide a comparable flow rate. This allows the diameter of the transfer line to be on the order of 0.2 cm. In this configuration the mean free path will be at least an order of magnitude greater than the tube diameter and thus the flow will be molecular, keeping collisions and depolarization low. Additionally, the approximate time each atom will spend in the transfer line is approximately 1 m / 10^3 $m/sec = 10^{-3}$ sec.

III.1.1. Measuring the Polarization of the ^{3}He Atoms in EBIS using NMR

To verify the concept described here, it is proposed to collect a sample of order 10^{15} ^{3}He atoms at the end of the feed line in the EBIS solenoid and measure their polarization using NMR [6]. In a few seconds one could trap this number of atoms in a glass cell. By comparing with previous experience with NMR measurement on protons at low field of order 30 G [7] and at high field of order several Tesla [12], it is estimated that the signal-to-noise ratio should be sufficient. The cell should have a valve to a pumping system so that the cell can be evacuated. The polarization in the sample cell can be compared directly with the polarization in the pumping cell. This can be measured as a function of sampling time. In addition, the reversal capability can be studied and optimized.

IV. CONSIDERATION OF POSSIBLE DEPOLARIZATION PROCESSES

IV.1. Processes Inside EBIS

There are a number of processes that take place inside EBIS that may lead to depolarization. They include:

- Charge exchange. $^3\text{He}^+ + {}^3\text{He}^{++} \rightarrow {}^3\text{He}^{++} + {}^3\text{He}^+$

  This has a cross section of $\sigma \approx 10^{-16}$ cm^2, and is thus thought to occur at a low rate.

- Recombination. $^3\text{He}^+ + e \rightarrow {}^3\text{He}$; $^3\text{He}^{++} + e \rightarrow {}^3\text{He}^+$

  This is a 3-body process and thus thought to be unlikely. The cross section is lowered by a factor of α^2, thus $\sigma < 10^{-20}$ cm^2

- Spin-exchange collisions. These are thought to occur at a low rate. The cross section for neutral Hydrogen spin-exchange collisions is approximately 10^{-14} cm^2; for ^{3}He ions it is expected to be even lower. It is expected that due to coulomb interactions, the ions will not even approach close enough for spin-exchange to occur.

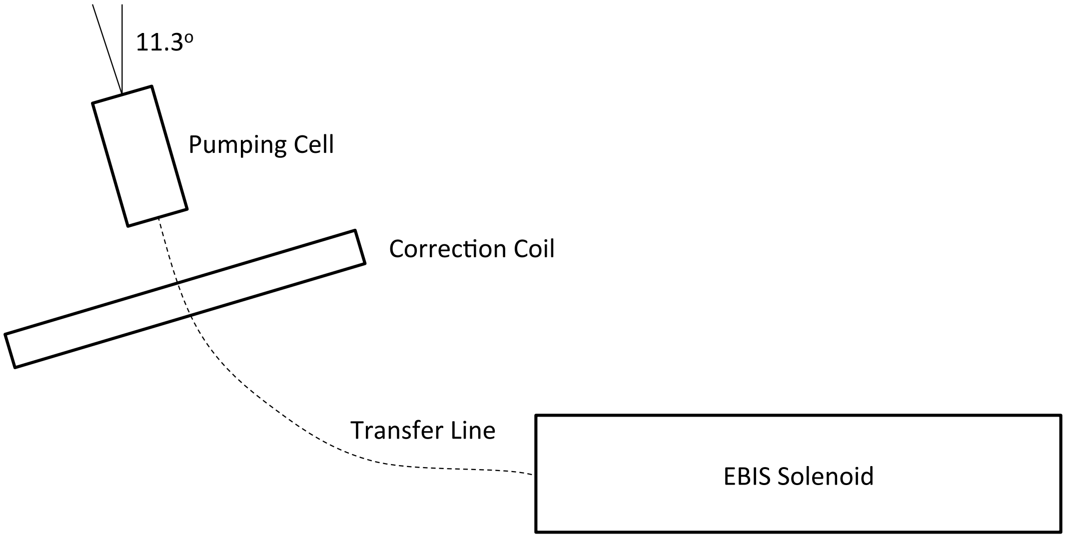

FIG. 5. Setup schematic (not to scale)

- Wall depolarization of atoms inside EBIS. This is thought to be low because of the low probability of depolarization in a wall collision.

IV.1.1. Charge Exchange

It is important to investigate charge exchange because ^{3}He$^+$ has a free electron which can depolarize, and then cause the nucleus to depolarize via hyperfine coupling. If a ^{3}He$^+$ and a ^{3}He^{++} ion undergo charge exchange, depolarization can propagate to the ^{3}He^{++} ions.

We approximate the rate of charge exchange as $\rho_1\rho_2\bar{v}\sigma V$, where ρ_1, ρ_2 are the densities of singly and doubly ionized ^{3}He, $\bar{v}$ is the average velocity, $\sigma = 10^{-16}\ cm^2$ is the charge exchange cross section, and V is the volume. We approximate the densities as both being $3\times10^7\ cm^{-3}$, which implies 1% of the gas being ionized. Then the rate is

$$\begin{aligned}(3\times10^7\ cm^{-3})(3\times10^7\ cm^{-3})\cdot 10^5\ cm\ s^{-1}\\ \times10^{-16}\ cm^{-2}\cdot 3\times10^3\ cm^3\\ = 2.7\times10^7\ s^{-1}\\ \approx 3\times10^7\ s^{-1}\end{aligned}$$

Since the rate of ion extraction is approximately $10^{12}\ s^{-1}$, it is thought that even if singly-charged ions depolarize and undergo charge exchange, the effects will be small.

IV.2. Processes in Pumping Cell and in Transport to EBIS

IV.2.1. Magnetic Field Gradients

The fringe fields of EBIS are on the order of 10^{-1} Tesla (1000 Gauss), which is strong enough for polarization. However, they contain strong gradients. A strong transverse magnetic field gradient can cause depolarization if it appears to oscillate in the particle's rest frame near the Larmor frequency [13]. The polarization relaxation time of the ^{3}He is related to the strength of the transverse magnetic field gradients by the equation [13]:

$$\frac{1}{\tau} = \frac{2}{3}\frac{|\Delta B_t|^2}{|B_l|^2}\langle v^2\rangle\frac{\tau_c}{\omega_0^2\tau_c^2+1}$$

where for our system, $\omega_0 = 3.24\ |B_l|\ kHz/Gauss$ and $\tau_c \approx 2.2\times10^{-7}p^{-1}$, where p is in torr.

IV.2.1.1. Gradients Along Transfer Line The optimal way to transfer the ^{3}He atoms into EBIS would be to align the transfer line along a magnetic field line, however this is not always possible due to the EBIS configuration. The internal transfer line in EBIS from the entry port to the electron beam has two straight sections connected at a right-angle. Depolarization there was calculated to be negligible, especially given the small time each atom spends in the transfer line.

IV.2.1.2. Gradients In Pumping Cell Since a longitudinal field is necessary for polarization, the pumping cell is aligned along a field line in the EBIS fringe field; however, there are transverse field gradients. In order to correct this, a rectangular coil is placed on the same axis as the pumping cell. Thus the longitudinal direction of the field is maintained, as is the approximate magnitude

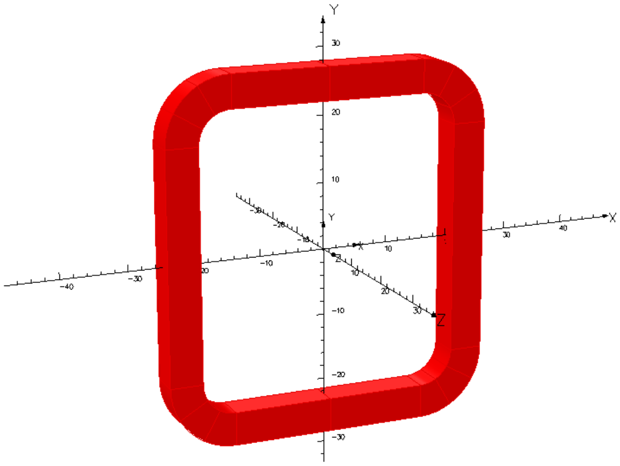

FIG. 6. Correction coil visualized in VectorFields Opera-3D software

of 0.08 T. A program was developed to calculate relaxation times across a pumping cell; running this program provided a number of possible configurations of coil location and geometry that allow the necessary relaxation times.

One possible configuration places the pumping cell 158cm behind the center of EBIS, and 84cm above (Fig. 5). At this location, an angle of 11.3 degrees relative to the vertical is necessary. The coil (Fig. 6) is rectangular with dimensions 45cm by 50cm. The coil is located 13cm in front of the pumping cell. The coil cross section is a 5cm square with a current density of 240 A/cm^2 (1500 A/in^2); the total current is 6,000A. This is low enough to allow air coiling. The average depolarization time is approximately 757 seconds, with a median of approximately 667 seconds.

IV.2.2. Wall Bounces

In [14], the relaxation time of ^{3}He was measured on various surfaces. In an enclosed space with surface area A, such as the pumping cell, the number of wall collisions per unit time is given by $\frac{1}{4}\rho\bar{v}A$, where ρ is the density and $\bar{v}$ is the average velocity. With a measured relaxation time T, the probability to depolarize per collision is approximately

$$P \approx \frac{1}{T\frac{1}{4}\rho\bar{v}A} \approx 10^{-20}$$

With an average number of collisions of 10^6, the expected depolarization is 1 part in 10^{14}, which is negligibly small.

V. SUMMARY

A system for polarizing ^{3}He in a pumping cell in the fringe fields of EBIS and then transporting the atoms to the ion trap has been developed. Possible depolarization processes have been considered; only magnetic field gradient-related depolarization was found to be significant and this has been addressed with a correction coil for the pumping cell. A scheme for reversing the polarization in the pumping cell in ∼1s using adiabatic fast passage has been integrated into the design. Two 10W Keopsys fiber lasers have been acquired and the setup of a lab to construct the source is underway.

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