ION POLARIZATION IN THE MEIC FIGURE-8 ION COLLIDER RING*

V.S. Morozov#, Ya.S. Derbenev, Y. Zhang, Jefferson Lab, Newport News, VA, USA
P. Chevtsov, Paul Scherrer Institut, Villigen, Switzerland
A.M. Kondratenko, M.A. Kondratenko, Sci. & Tech. Laboratory Zaryad, Novosibirsk, Russia
Yu.N. Filatov, MIPT, Dolgoprudny, Russia & JINR, Dubna, Russia

Abstract

The nuclear physics program envisaged at the Medium-energy Electron-Ion Collider (MEIC) currently being developed at the Jefferson Lab calls for collisions of 3-11 GeV/c longitudinally polarized electrons and 20-100 GeV/c, in equivalent proton momentum, longitudinally or transversely polarized light ions. In this paper, we present a scheme based on figure-8 shaped booster and collider rings that provides the required ion polarization arrangement in the MEIC's ion collider ring.

INTRODUCTION

The nuclear physics program [1] of MEIC [2] sets the following requirements on the ion polarization: high polarization (>70%) for light ions (p, d and $^3H^{++}$), availability of both longitudinal and transverse polarizations at all interaction points (IP), adequate polarization lifetime during beam storage, and fast-rate spin flipping.

In principle, delivering a highly polarized light ion beam is challenging. Unlike electrons, which can acquire polarization through synchrotron radiation, ion polarization has to be generated in polarized sources and then preserved all the way to the collider ring during acceleration and storage. This is challenging because, during acceleration in a synchrotron ring, ion beams cross a large number of depolarizing resonances [3] arising due to magnet errors (imperfection resonances) and the beam's natural betatron motion (intrinsic resonances).

One technique for preserving the ion polarization is to stabilize the spin motion using a Siberian snake [4]. It is a special magnetic insertion made of dipoles or a solenoid that rotates the spin by 180° about an axis in the horizontal plane. This makes the spin tune equal to ½ independent of the beam energy, therefore, effectively eliminating all imperfection and most intrinsic spin resonances. However, there is still a problem with using presently available snakes for medium-energy ions because the orbital distortions caused by dipole-based helical (transverse) snakes are too large while the required magnetic fields of solenoid-based (longitudinal) snakes become impractical.

In the MEIC design, to deliver highly-polarized ion beams, we adopted a figure-8 shape for all booster and collider rings. In this paper, we present this new scheme and show how, with help of Siberian snakes or other special magnetic insertions, the spin tune is made energy independent and adjusted to an optimal value while the polarization orientations of proton, $^3He^{++}$ and deuteron beams are aligned in the desired directions at multiple IPs. In the last section, we provide a brief discussion of spin flipping.

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# morozov@jlab.org

FIGURE-8 DESIGN

The figure-8 geometry [2, 5] of the MEIC rings is a very elegant way to preserve the ion polarization during acceleration and storage and to significantly simplify the spin control tasks. The spin rotation in one half of the figure-8 ring is exactly cancelled in the other half so that the net spin rotation is zero. The spin motion is degenerate, and any polarization direction is periodic. As a consequence, it is possible to control and stabilize the polarization in any desired orientation by using relatively small magnetic fields, as long as their spin rotation is a few times greater than the strength of the zero-harmonic imperfection resonance.

For protons and $^3He^{++}$ ions, the figure-8 design is especially advantageous for the MEIC booster rings where the polarization can be stabilized using a partial Siberian snake or a special spin rotating device described below. Unlike in a circular ring, even a partial snake in a figure-8 ring can make the spin tune energy independent. Even though, for protons and $^3He^{++}$, one could employ full Siberian snakes in the collider ring, the ring's figure-8 design makes its polarization schemes more flexible as discussed below.

Another important advantage of the figure-8 design is that it allows acceleration and storage of polarized deuterons for collision. This is not possible in a conventional circular synchrotron since the required Siberian snakes would be impractical due to the deuteron small anomalous magnetic moment. The figure-8 design presently is the only practical way to preserve the deuteron polarization up to the medium range collision energies. As with protons and $^3He^{++}$, the deuteron polarization can be stabilized in any desired orientation in the MEIC booster and collider rings using a partial solenoidal or transverse-field Siberian snake or a device rotating the polarization by a small angle around the vertical axis.

POLARIZED PROTONS AND HELIUM-3

The tasks of accelerating polarized protons and $^3He^{++}$ in MEIC are conceptually very similar. At the same energy, the spin resonances are generally stronger for $^3He^{++}$ than for protons due to the larger anomalous magnetic moment of $^3He^{++}$. However, the top $^3He^{++}$ energy in MEIC is lower and, since the strengths of the spin resonances are generally proportional to energy, this makes the problems of preserving the proton and $^3He^{++}$ polarizations rather comparable. Therefore, below we will focus our discussion on the proton polarization schemes.

The first spin configuration we consider is the longitudinal proton polarization at all IPs, i.e. in both straights of the figure-8 ring. If a full Siberian snake with a longitudinal axis is inserted in one of the straights, it stabilizes the longitudinal polarization in that straight. However, the stable polarization in the other straight is still energy dependent. To make the polarization in the second straight also longitudinal, two additional Siberian snakes with longitudinal axes are placed in the middle of the arcs. This configuration is illustrated in Fig. 1a. The stable spin direction is longitudinal in both straights at all energies with the spin tune still equal to ½ (not always the case with multiple snakes) and energy independent.

The second polarization configuration required at MEIC is the transverse polarization in both experimental straights. This can be attained by placing two full Siberian snakes in the middle of the arcs with the snake axes perpendicular to each other, as illustrated in Fig. 1b. The stable polarization is vertical in both straights, and the spin tune is again ½ and energy independent. In fact, this configuration can be realized using the same hardware as in the longitudinal polarization configuration described above. To go from the longitudinal to transverse polarization, the snake located in the straight is switched off, and the axes of the arc snakes are rotated to form a 90° angle. In case of a helical Siberian snake, one can manipulate the snake's axis orientation simply by adjusting currents in the snake windings [6]. Thus, no physical movement or replacement of the hardware is required.

The three-snake configuration also allows one to obtain the longitudinal and radial polarizations in the opposite straights. A longitudinal snake in one straight provides the longitudinal polarization in that straight while the radial polarization in the other straight can be obtained by adjusting the axes of the arc snakes to the same 45° angles as shown in Fig. 1c.

When using a longitudinal snake in Figs. 1a and 1c, the stable polarization in the arcs lies in the orbit plane. At high energies, the spin makes a large number (hundreds) of turns in the arcs, which may have a significant effect on the spin motion stability. Figure 2 shows an alternate control scheme, in which the polarization is always vertical in the arcs for any combination of polarization orientations in the straights. This avoids spin rotation in the arcs. As shown in Fig. 2, the polarization is controlled in each straight independently using a pair of rotators, which turn the vertical polarization into longitudinal or radial before the IP and restore it back to vertical at the end of the straight. With the rotators off, the polarization is vertical in the straights. The helical rotators developed at BNL [6] can be used as such rotators. The spin tune in this scheme is determined by the rotators and is energy independent. It can be adjusted to a desired operational value between 0 and ½ using a special insert rotating the spin around the vertical axis [7].

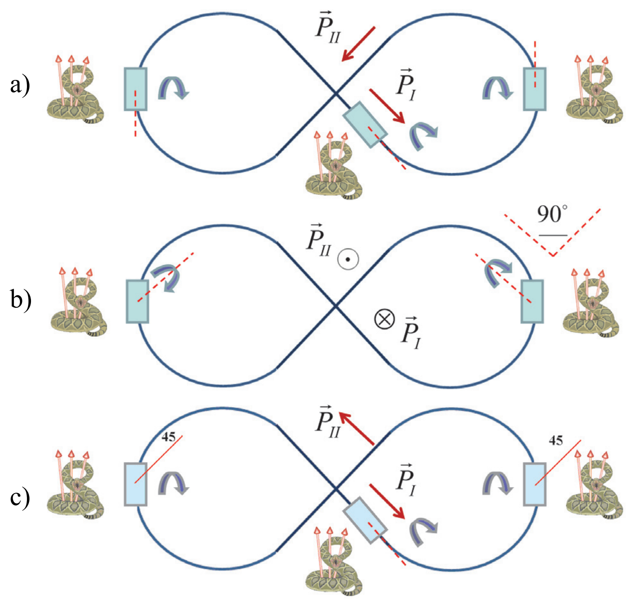

Figure 1: Schemes for the longitudinal (a), transverse (b) and longitudinal/radial (c) proton/$^3He^{++}$ polarizations in the two figure-8 straights.

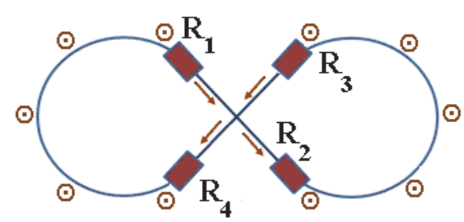

Figure 2: Polarization control scheme using rotators R_1, R_2, R_3, and R_4 with the polarization vertical in the arcs.

POLARIZED DEUTERONS

The nuclear physics goals require the capability of providing highly polarized deuterons with both the longitudinal and transverse polarizations in the MEIC experimental straights. It is clear that full Siberian snakes are not feasible for deuterons due to their exceptionally small anomalous magnetic moment. However, the figure-8 design allows one to control the deuteron stable spin orientation using magnetic inserts that rotate the deuteron spin by only a small angle around a certain axis. The polarization is then stable and points along the rotation axis at the insert's location, as long as the spin rotation angle exceeds the Fourier harmonics of the spin perturbing fields in the figure-8 structure.

The longitudinal deuteron polarization can be stabilized in one of the figure-8 straights by inserting a spin rotating solenoid in that straight, as shown in Fig. 3a. The spin tune ν_s in this case is given by $\nu_s = \phi / 2\pi$ where ϕ is the spin rotation angle in the solenoid. The stable deuteron

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polarization in the second straight lies in the horizontal plane with its orientation depending on the energy. For a discrete set of energies, the polarization is also longitudinal in the second straight.

The vertical deuteron polarization can be provided in both straights by placing one or more magnetic inserts [8], which rotate the spin by a small angle around the vertical axis, anywhere in the ring, as illustrated in Fig. 3b. Figure 4 shows placement of solenoids and radial-field dipoles along a new fixed orbit inside the insert. Such an insert produces a spin tune shift $\nu_s = 2\varphi_x\varphi_z/\pi$ where φ_x denotes the spin rotation around the radial axis, and φ_z is the spin rotation around the longitudinal axis. Thus, if the solenoidal fields are fixed and the dipole fields are ramped together with the energy, the spin tune is energy independent, and the orbit excursion remains constant with energy. One advantage of this scheme is that one can then use strong super-conducting solenoids producing a large spin rotation, and they do not have to be ramped with energy, which would have been problematic. Another advantage is that, since the two solenoidal fields point in opposite directions, such an insert introduces essentially no coupling.

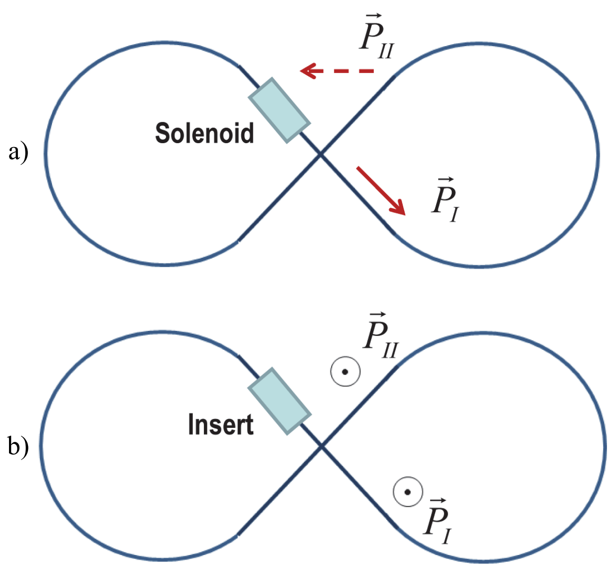

Figure 3: Schemes for the longitudinal deuteron polarization (a) in one of the figure-8 straights and the transverse deuteron polarization (b) in both straights.

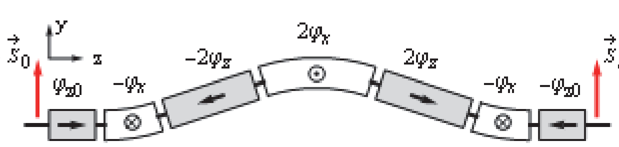

Figure 4: Schematic of magnet placement along the reference orbit inside the insert.

SPIN FLIPPING

Fast-rate spin-flipping of both colliding electron and light ion beams is critical to suppress systematic errors in polarized asymmetry experiments. There are two options to provide the required spin flipping for ions. One option is to change the beam polarization at the source to produce bunch trains with alternating polarization at the required frequencies. A potential problem with this technique is the presence of systematic differences in the polarization magnitudes of the different spin states produced by the source. The other option is to flip the polarization of an already stored beam using rf magnetic fields. We briefly discuss this option below.

In general, the polarization of a stored beam can be manipulated using rf fields with frequencies correlated with the spin precession frequency. The conventional approach to spin-flipping a stored polarized beam employs an adiabatic spin reversal by sweeping the frequency of an rf magnet through a harmonic of the spin precession frequency.

There are also some novel and rather promising spin-flipping techniques, which may be employed. A specialized frequency sweep pattern such as multiple crossing of a spin resonance can flip the polarization with a greater efficiency and in a shorter time than the conventional approach by taking advantage of the interference of the spin precession phases between consecutive resonance crossings. A stable spin state characterized by reversal of the polarization every turn or every few turns around the ring can be created [9] by trapping the spin with an rf field. These new techniques still need to be studied in more detail and tested experimentally to demonstrate their feasibility.

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