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Impact of the Tilted Detector Solenoid on the Ion Polarization at JLEIC*

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Abstract. Jefferson Lab Electron Ion Collider (JLEIC) is a figure-8 collider "transparent" to the spin. This allows one to control the ion polarization using a universal 3D spin rotator based on weak solenoids. Besides the 3D spin rotator, a coherent effect on the spin is produced by a detector solenoid together with the dipole correctors and anti-solenoids compensating betatron oscillation coupling. The 4 m long detector solenoid is positioned along a straight section of the electron ring and makes a 50 mrad horizontal angle with a straight section of the ion ring. Such a large crossing angle is needed for a quick separation of the two colliding beams near the interaction point to make sufficient space for placement of interaction region magnets and to avoid parasitic collisions of shortly-spaced 476 MHz electron and ion bunches. We present a numerical analysis of the detector solenoid effect on the proton and deuteron polarizations. We demonstrate that the effect of the detector solenoid on the proton and deuteron polarizations can be compensated globally using an additional 3D rotator located anywhere in the ring.

1. Spin Transparency of the JLEIC Collider

Jefferson Lab Electron Ion Collider (JLEIC) is designed to provide high polarizations of both ion and electron colliding beams. The figure-8 JLEIC collider is "transparent to the spin". In such a collider, effect on the spin of one arc is compensated by the other arc. Thus, effect of "strong" arc fields on the spin is reduced to zero. Any spin direction repeats itself after each particle turn, i.e. the collider has no preferred spin direction [1-3].

Colliders transparent to the spin offer a unique opportunity to efficiently control the ion polarization using small magnetic field integrals. In such a collider, any small perturbation has a strong effect on the beam polarization. To stabilize the spin direction, one must introduce a 3D spin rotator based on 'weak' solenoids, which "shifts" the spin tune by a small value ν and sets the necessary orientation of the polarization. The "weak" solenoids have essentially no effect on the beam's orbital characteristics.

For polarization stability, one must ensure that the spin tune ν induced by the 3D spin rotator significantly exceeds the strength of the zero-integer spin resonance: $\nu \gg \omega$. Our calculations show

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that, for stable control of the ion polarization, it is sufficient to use 3D spin rotators, which allow one to induce spin tunes of 10^{-2} for protons and 10^{-4} for deuterons.

The resonance strength consists of two parts: a coherent part ω_{coh} arising due to additional transverse and longitudinal fields on the beam trajectory deviating from the design orbit and an incoherent part ω_{emitt} associated with the particles' betatron and synchrotron oscillations (beam emittances). In practice, the coherent part significantly exceeds the incoherent one: $\omega_{coh} \gg \omega_{emitt}$. The coherent part does not cause beam depolarization and only results in a simultaneous rotation of all particles' spins. In principle, the direction and magnitude of the coherent part of the resonance strength can be measured and compensated by an additional 3D spin rotator. To preserve the polarization, it is then sufficient to satisfy a weaker condition: $\nu \gg \omega_{emitt}$.

Experiments require insertion of additional magnetic elements into the collider lattice. When integrating an experimental insertion into the lattice, one must make sure that the insertion does not violate the spin transparency of the collider. This is related to the fact that, besides the 3D spin rotators, an additional coherent effect on the spin can be caused by the magnetic elements of the insertion.

Let us next consider influence of the detector solenoid on the ion polarization.

2. Crab crossing scheme of the JLEIC collider

Effect of the detector solenoid on the ion polarization is determined by specific details of the interaction region design of the JLEIC collider. To obtain a high luminosity of the colliding electron and ion bunches, the collider employs a crab crossing scheme illustrated in Fig. 1.

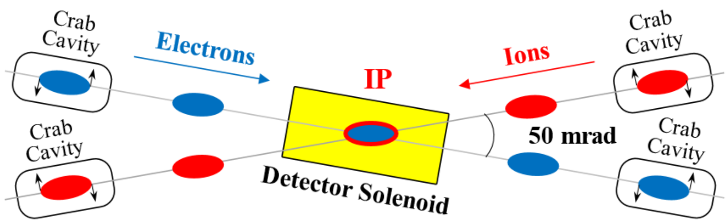

Figure 1. Schematic of the detector solenoid placement in the JLEIC ion collider ring.

The JLEIC interaction region design has a crossing angle of 50 mrad for a rapid separation of the colliding beams near the IP in order to create sufficient space for placement of interaction region magnets, eliminate harmful parasitic collisions under a high (476 MHz) bunch repetition frequency and enable detection of outgoing small-angle particles. To avoid luminosity loss associated with non-head-on collisions, following the success of the KEK B-factory, a scheme of crab crossing [4] utilizing SRF crab cavities is employed for restoring head-on collisions [5,6]. A 4 m detector solenoid is aligned with a straight section of the electron ring and makes a 50 mrad horizontal angle with a straight section of the ion ring.

3. Calculation of the proton and deuteron spin dynamics in the JLEIC ion collider ring including the detector solenoid

The detector solenoid in the JLEIC collider is oriented at an angle of 50 mrad to the ion trajectory and therefore has both transverse and longitudinal magnetic field components along the trajectory. Figure 2 shows a scheme of the detector solenoid placement in the JLEIC ion collider ring [7,8]. The interaction point divides the tilted detector solenoid into two parts with a length ratio of $1.6\ \text{m} : 2.4\ \text{m} = 2 : 3$ and lies at the crossing point of the electron and ion straight sections when the solenoid is off. When the field of the detector solenoid is on, the ions are affected not only by the longitudinal field component but by the radial field component as well, which shifts the ions vertically away from the interaction point. To stabilize the interaction point and correct the ion orbit at the exit and entrance of the Final Focusing Quadrupole (FFQ) triplets, there are a pair of dipole correctors on each side of the detector solenoid: the first and second correctors are directly to the left of the solenoid and the third and fourth correctors on the right-hand side of the solenoid are separated by a detector dipole with vertical field. Each dipole corrector has vertical K_{yi} and radial K_{xi} components of the transverse field.

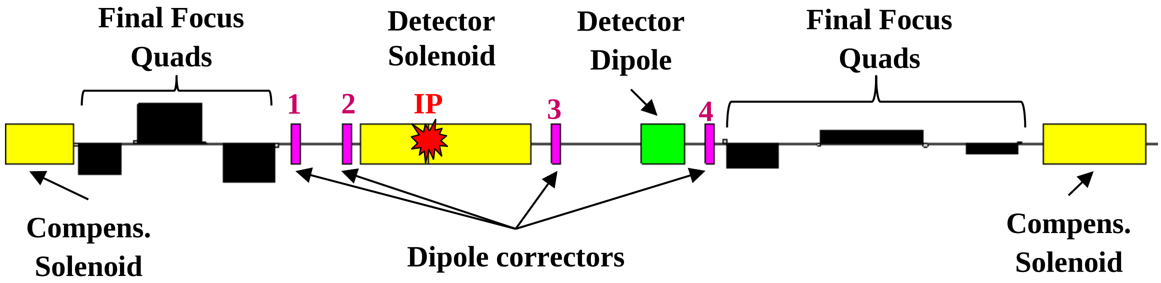

Figure 2. Schematic of the detector solenoid placement in the JLEIC ion collider ring.

To compensate betatron oscillation coupling introduced by the detector solenoid, 1.6 m and 2.4 m anti-solenoids are placed on the two sides of the detector solenoid. The axes of the anti-solenoids are aligned with the axes of the ion beam lines.

The ion orbital and spin motions in the tilted detector solenoid are calculated using the linear approximation. Its accuracy depends on the choice of the reference orbit. If one uses the straight trajectory, which particles follow when the field of the detector solenoid is off, then the deviation of a particle trajectory from the reference orbit is mainly determined by the excursion of the closed orbit. It is proportional to the crab-crossing angle α_{crab} and, for a solenoid of a length L_{sol} is about:

$$\Delta r \sim \alpha_{crab} K_{sol} L_{sol}^2.$$

The deviation of a trajectory can reach values of up to a few mm. If one considers that a particle trajectory in a tilted solenoid is a spiral and uses it as a reference orbit then the deviation of a particle trajectory from the reference orbit is determined by the betatron beam size σ, which is a few μm. In this case, the accuracy of calculations in the linear approximation improves by 2-3 orders of magnitude. Later in our calculations, we use the spiral trajectory as the reference orbit.

Figure 3 shows the vertical excursion of the ion beam trajectory caused the detector solenoid field of 3 T at the beam momentum of 100 GeV/c. As we can see, the new orbit is completely restored at the exit and entrance of the FFQ triplets. To stabilize the interaction point, the transverse components of the kickers in units of the magnetic rigidity must take the following values:

$$K_{x1} \approx -3.3 \cdot 10^{-3} \text{m}^{-1},\ K_{y1} \approx 2.9 \cdot 10^{-5}\ \text{m}^{-1},\ K_{x2} \approx 6.9 \cdot 10^{-3}\ \text{m}^{-1},\ K_{y2} \approx -5.5 \cdot 10^{-5}\ \text{m}^{-1},$$
$$K_{x3} \approx 7.9 \cdot 10^{-3}\ \text{m}^{-1},\ K_{y3} \approx 9.2 \cdot 10^{-5}\ \text{m}^{-1},\ K_{x4} \approx -3.1 \cdot 10^{-3}\ \text{m}^{-1},\ K_{y4} \approx -4.\cdot 10^{-5}\ \text{m}^{-1}.$$

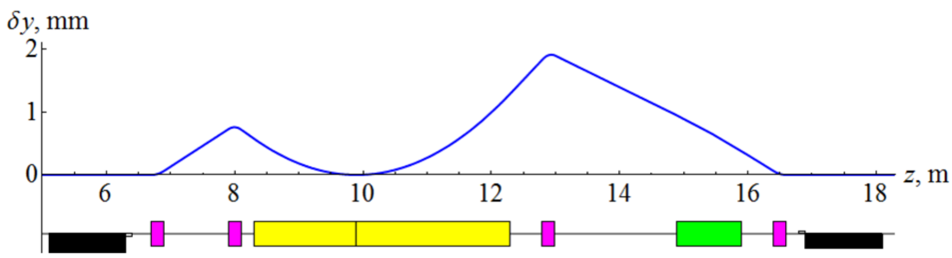

Figure 3. Vertical deviation of the ion beam from the axis of the ion straight section. The field of the detector solenoid is 3 T. The beam momentum is 100 GeV/c.

Besides the 3D spin rotator, a coherent effect on the spin is produced by a detector solenoid together with the dipole correctors and anti-solenoids compensating betatron oscillation coupling. Figure 4 shows the influence of the detector solenoid insertion on the proton and deuteron spin dynamics as a function of momentum. The calculations assume that the beam orbit is stable and corresponds to the beam parameters shown in Fig. 3.

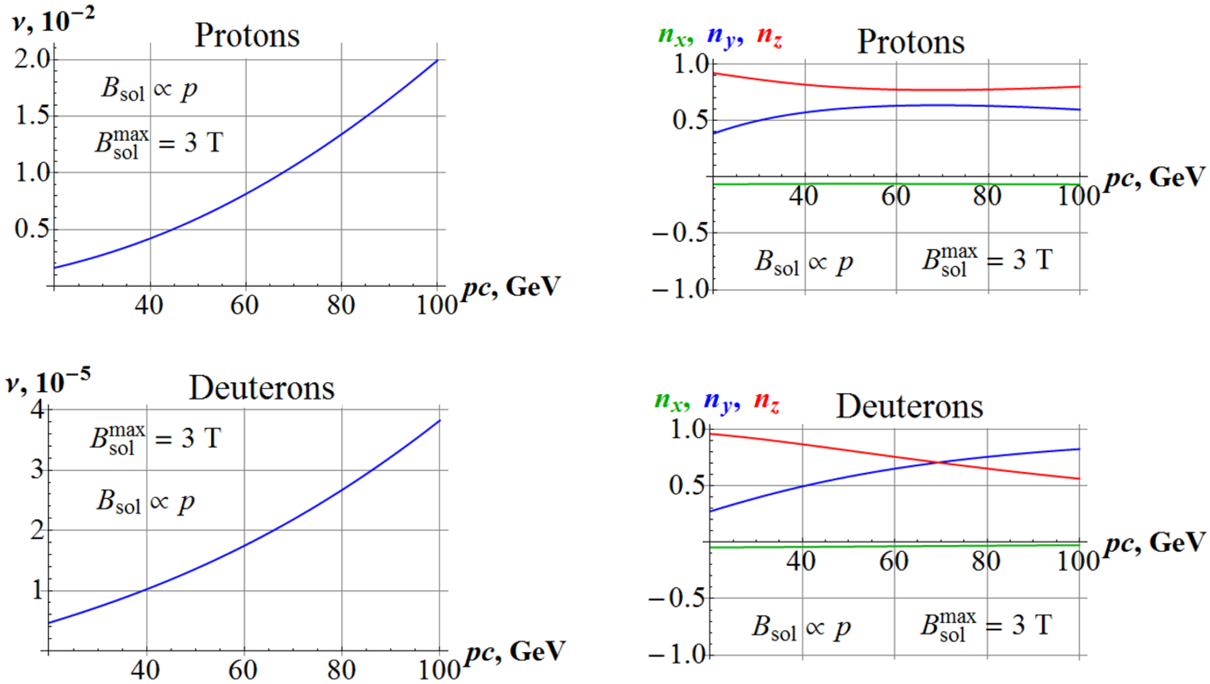

Figure 4. Momentum dependence of the spin tune and $\vec{n}$ – axis components induced by insertion of the detector solenoid for protons (top) and deuterons (bottom). In these calculations, the solenoid field scales proportionally to the beam momentum and reaches 3 T at the maximum beam momentum of 100 GeV/c.

4. Conclusions

The calculations presented above show that the spin tune induced by the detector solenoid insertion does not exceed the value of $2 \cdot 10^{-2}$ for protons and $4 \cdot 10^{-5}$ for deuterons when the field of the detector solenoid changes from 0 to 3 T in the whole momentum range of the JLEIC collider. Influence of the detector solenoid insertion on the proton and deuteron polarizations can be compensated using an additional 3D rotator, which can be placed in any available space in the collider. The above analysis shows that the influence of a tilted detector solenoid on the ion polarization depends on locations of the correcting dipoles and compensating anti-solenoids. In principle, it is possible to optimize the scheme for stabilization of the bunch collision point on the basis of correcting dipoles and anti-solenoids so that the spin transparency condition is automatically satisfied.

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