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LHEC SPIN ROTATOR

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In addition to the on-going exciting physics program at LHC, there have been quests on expanding LHC to include an LHeC with electron-proton collisions. The potential of studying new physics in high precision QCD, substructure etc. at LHeC requires polarized electrons with spin aligned longitudinally at the collision point [1]. One option for the LHeC is based on an energy recovery linac, for which the electron beam can be generated with 80-90% polarization using a photocathode source. To avoid the polarization loss of the high energy electron beam, the spin vector needs to be aligned vertically during the acceleration in a re-circulating linac and then brought into the longitudinal direction for collision. This paper reports possible design choices for the LHeC spin rotator.

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In addition to the on-going exciting physics program at LHC, there have been quests on expanding LHC to include an LHeC with electron-proton collisions. The potential of studying new physics in high precision QCD, substructure etc. at LHeC requires polarized electrons with spin aligned longitudinally at the collision point [1]. One option for the LHeC is based on an energy recovery linac, for which the electron beam can be generated with 80-90% polarization using a photocathode source. To avoid the polarization loss of the high energy electron beam, the spin vector needs to be aligned vertically during the acceleration in a re-circulating linac and then brought into the longitudinal direction for collision. This paper reports possible design choices for the LHeC spin rotator.

INTRODUCTION

The LHeC physics requires polarized electrons with spin aligned longitudinally at the interaction point (IP) [1]. The motion of the spin vector $\vec{S}$ in an accelerator is governed by Thomas-BMT equation [2]

$$\frac{d\vec{S}}{dt} = \frac{e}{m\gamma}\vec{S} \times [(1+G\gamma)\vec{B}_\perp + (1+G)\vec{B}_\parallel] \quad (1)$$

where e, m and γ are the electric charge, mass and Lorentz factor of the particle. G is the anomalous g-factor. For protons, $G = 1.7928474$ and for electrons, $G = 0.00115$. $\vec{B}_\perp$ and $\vec{B}_\parallel$ are the magnetic field perpendicular and parallel to the particle velocity direction, respectively. In (1) the magnetic field is in the laboratory frame while the spin vector $\vec{S}$ is in the particle rest frame. Eq. (1) implies that, in a perfect circular accelerator with $\vec{B}_\parallel = 0$, a spin vector precesses $G\gamma$ times of the particle orbital rotation in the moving frame. For the electron accelerator of LHeC, which consists of two 10 GeV superconducting linear accelerators linked by six 180° arc paths, the depolarization due to the arcs is negligible if the spin is aligned vertically in the arcs.

Eq. (1) also shows that both dipole field and solenoid field can be used to manipulate the spin motion. However, the effect of a solenoid field on the spin motion goes down linearly with beam energy, while the effect of a dipole field remains almost independent of beam energy.

LHEC SPIN FLIPPER OPTIONS

To produce longitudinally oriented polarization at the final collision point for a 60-GeV electron beam, two options have been explored:

- A low energy spin rotator at the LHeC injector to place the spin vector in a direction that after the precessions from all the arcs becomes the longtiudinal direction at the IP.

- A dedicated high energy spin rotator close to the IP which brings the vertically aligned spin vector into longitudinal direction. For this option, a low energy spin rotator at the injector is also required in order to produce a vertically polarized electron beam for acceleration.

The details of the two options are as follows.

Low energy spin rotator

For the LHeC physics program, the polarization of 60 GeV electron beam needs to be aligned longitudinally at the collision point which is after the last arc and the acceleration. The most economical way to control the spin direction at the collision point is to control the spin direction of the low energy electron beam at the early stage of injector using a Wien Filter, i.e. a traditional low energy spin rotator. Since the spin vector rotates $G\gamma\pi$ each time it passes through a 180° arc, the goal of the Wien Filter is to put the spin vector in the horizontal plane with an angle to the direction of the particle velocity chosen so as to compensate the spin rotations before collision.

For the layout of LHeC, i.e. two linear accelerators linked by two arcs, the spin vector rotates by an amount

$$\phi_{arc} = G\pi[\gamma_i(2n-1) + \Delta\gamma n(2n-1)] \quad (2)$$

during its nth path. Here, γ_i is the initial Lorentz factor of the beam and $\Delta\gamma$ is the energy gain of each linear accelerator. In addition, LHeC also employs a horizontal dipole on either side of the IP to separate the electrons from the protons. These dipoles have a field of 0.3 T and and span 9 m from the collision point. For the 60 GeV electron beam, such bending magnet rotates the spin vector by $\phi_{IP} = 104.4°$. Considering an initial energy of 10 GeV (after the first path through the linac) and for each linear accelerator an energy gain of 10 GeV, Table 1 lists the amount of spin rotation through the arcs and the amount of spin rotation through the final bending dipole at the collision point for a 20, 40 and 60-GeV beam, respectively. Here, the amount of spin rotation at the IP refers to the net spin rotation modulo 2π.

Since the spin rotation is proportional to the beam energy, for a beam of particles with non-zero momentum spread, different amounts of spin rotation generate a spread of spin vector directions. This results in an effective polarization loss due to the associated spread of the spin vector.

beam energy GeV	# of path n	ϕ_{arc} [degree]	ϕ_{IP} [degree]
20	1	8101.8	34.8
40	2	36457.9	69.6
60	3	81017.6	104.4

Figure 1 shows the angle spread of the spin vector for an off-momentum particle at 20, 40 and 60 GeV, respectively. It shows that for a 60-GeV electron beam, a momentum spread of 3×10^{-4} can cause about $(1 - \cos(25°)) \approx 10\%$ effective polarization loss due to the spread of the spin vectors. This level of polarization loss is undesirable and would compromise the physics reach of the LHeC.
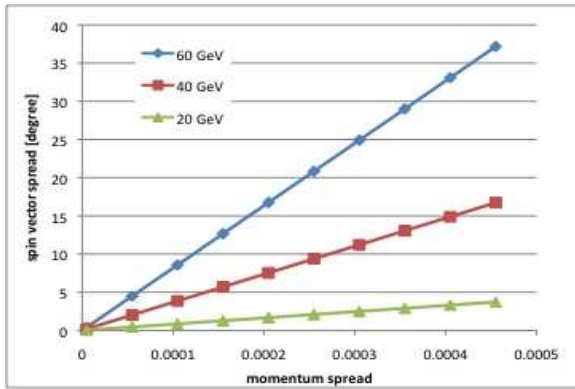

Figure 1: Calculated spin vector spread as function of momentum spread. The effective polarization loss is the cosine of spin vector spread angle, e.g. for an angle of 30 degrees, the effective polarization is 86% of the initial beam polarization

High energy spin rotator

In order to provide the desirable polarization direction without sacrificing polarization, one can adopt the traditional approach of high-energy polarized beams at HERA and RHIC, i.e. rotate the spin vector into the vertical direction before the beam gets accelerated to high energy. Since the spin vector aligns with the main bending magnetic field direction, this prevents the spread of the spin vector due to the momentum spread. For the current compact LHeC final-focusing system (FFS), we propose to use RHIC type spin rotator [3, 4] for the LHeC. Besides saving space by being short, this approach also provides the advantage of an independent full control of the spin vector orientation, as well as a nearly energy-independent spin rotation for the same magnetic field. The four helical dipoles are arranged in a fashion similar to the RHIC spin rotator, i.e. with alternating helicity. Figure 2 shows the schematic layout. Each helical dipole is 3.3 m long and the helicity alternates between right hand and left hand from one helical dipole to

the next. The two inner helical dipoles have the same magnetic field but opposite helicity. The same applies for the two outer helical dipoles.
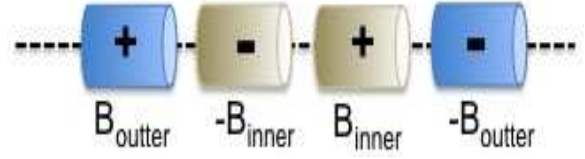

Figure 2: Schematic layout of the LHeC spin rotator, consisting of a total of four helical dipoles with alternating helicity marked as + and -. The polarity of the two outer helical dipole fields is opposite, and so is the polarity of the two inner helical dipoles.

For each helical dipole, the magnetic field is given by

$$B_x = B \cos kz , \qquad (3)$$
$$B_y = B \sin kz , \qquad (4)$$
$$B_z = 0 , \qquad (5)$$

where $B_{x,y,x}$ are the horizontal, vertical and longitudinal components of the magnetic field, respectively, z is the longitudinal distance along the helical dipole axis, while $|k| = 2\pi/\lambda$ and λ are the wave number and the wave length of the helical field, respectively.

For the spin rotator, all helical dipoles are chosen to be one period long, i.e. $\lambda = L$, where L is the length of each helical dipole, and, depending on the direction of the helicity, $k/|k| = \pm 1$. Fig. 3 shows the correlation of the magnetic field for the inner and outer helical magnets of a spin rotator which brings the spin vector from the vertical direction into the horizontal plane. Figure 4 presents the calculated angle of the spin vector for each outer helical magnet field. Both plots show that this design allows for a flexible adjustment for the direction of spin vector by varying the outer and inner helical magnetic fields, respectively.

This rotator will be placed in the straight section between the end of the second linac and the FFS, upstream of the final bending dipole at the collision point as well as of three bends right upstream of the final triplet. As memtioned, the 0.3-T final bending dipole next to the IP rotates the spin vector by 104.4 degrees for a 60-GeV electron beam, while the other, weaker three bends rotate the spin vector by only -1.8 degrees. To align the spin vector of the polarized electrons in the longitudinal direction at the IP the spin rotator must bring the spin vector from the vertical direction onto the horizontal plane at an angle of 102.6 degrees from the longitudinal direction. This requirement then determines the magnetic field of the inner and outer pairs to be 1.92 T and 0.93 T, respectively. The maximum orbital excursion is 17 mm in the horizontal and 8.5 mm in the vertical plane. The fine tuning of the direction of the spin vector can be achieved by empirically adjusting the helical dipole magnetic field strengths based on the measurements of polarimeters installed before and after the collision point.
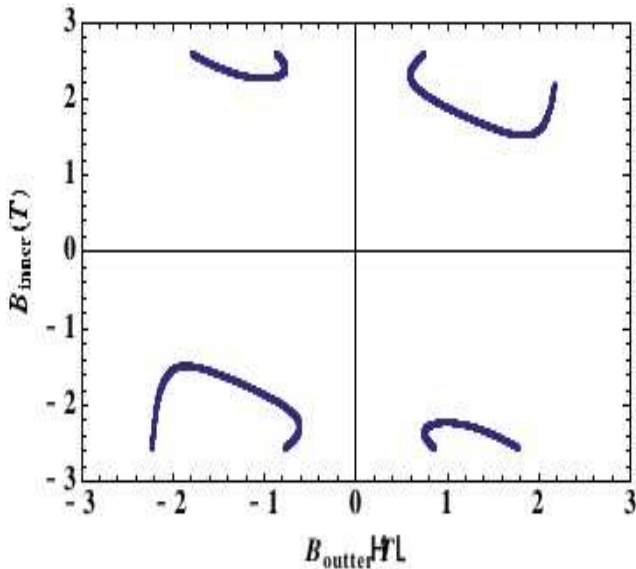
Figure 3: Correlation of the outer and inner helical dipole magnetic field strength for a spin rotator which is designed to bring a vertically aligned spin vector to the horizontal plane.
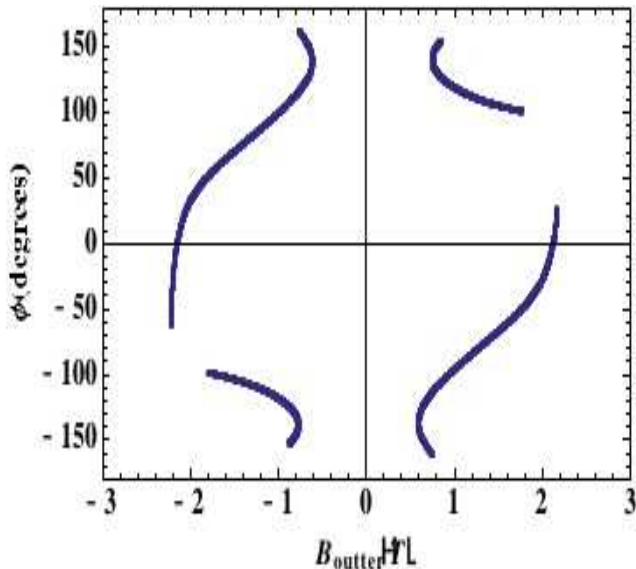

Figure 4: Spin vector direction in the horizontal plane as function of outer helical magnet field strength

POLARIMETRY

To measure the polarization of the high-energy electron beam a Compton polarimeter is foreseen. Such polarimeter detects the electrons and photons produced in Compton scattering of the electron beam off an intense circularly polarized laser beam [5]. A Compton polarimeter requires space to accommodate the laser as well as detectors. For high precision measurements an efficient separation of the Compton-scattered electrons from the main electron beam is required.

The polarimeter could be placed either upstream or downstream of the IP. We tentatively consider two polarimeters, one on either side of the IP, which would allow excluding or quantifying any depolarizing effects in the final focus or due to the collision process. In order to place these polarimeters at locations where the spin direction is longitudinal, we propose installing (or using) additional bending magnets so that the deflection angle by the IP dipoles is exactly compensated and the net spin precession angle between polarimeter and IP equal to zero, also taking into account the small energy change due to synchrotron radiation emitted in these magnets. In this way maximizing the longitudinal polarization at either polarimeter by scanning the field strengths of the two pairs of helical magnets in the upstream spin rotator automatically maximizes the longitudinal polarization at the collision point. The polarization levels measured at the two polarimeters allow deducing the polarization loss in the collision as well as the effective polarization, which is important for particle physics. Figure 5 sketches the overall spin-related layout of the LHeC interaction region (IR).
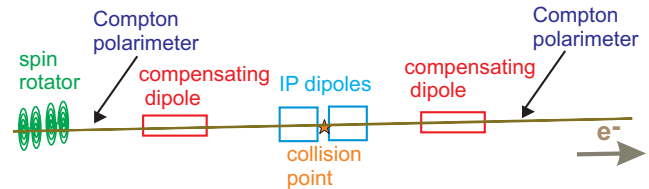

Figure 5: Schematic of spin-related IR layout with spin rotator, two polarimeters, and compensating bends.

CONCLUSIONS AND OUTLOOK

This paper has presented a flexible spin flipper for the LHeC high-energy electron beam. The proposed design based on a group of helical dipoles next to the final collision point, similar to the spin flipper at RHIC, satisfies the requirement of delivering a high-energy electron beam with high longitudinal polarization. It also has the additional merits of being compact and flexible. For this approach, a low energy spin flipper like a Wien Filter as part of the injector is also required to rotate the spin vector into the vertical direction prior to acceleration. Detailed calculations including helical dipole design, orbital and spin tracking of spin rotator are work in progress.

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