SPIN ROTATOR OPTICS FOR MEIC

H. Sayed, Old Dominion University & Jefferson Lab, VA, USA.
S.A. Bogacz, P. Chevtsov, Jefferson Lab, Newport News, VA, USA

Abstract

A unique design feature of a polarized Medium Energy Electron-Ion Collider (MEIC) based on CEBAF is its 'Figure-8' storage rings for both electrons and ions, which significantly simplifies beam polarization maintenance and manipulation. While electron (positron) polarization is maintained vertical in arcs of the ring, a stable longitudinal spin at four collision points is achieved through solenoid based spin rotators and horizontal orbit bends. The proposed MEIC lattice was developed in order to preserve a very high polarization (more than 70%) of the electron beams injected from the CEBAF machine. The otherwise coupled beam trajectory due to solenoids used in the spin rotators was decoupled by design.

A spin matching technique needs to be implemented in order to enhance quantum self-polarization and minimize depolarization effects.

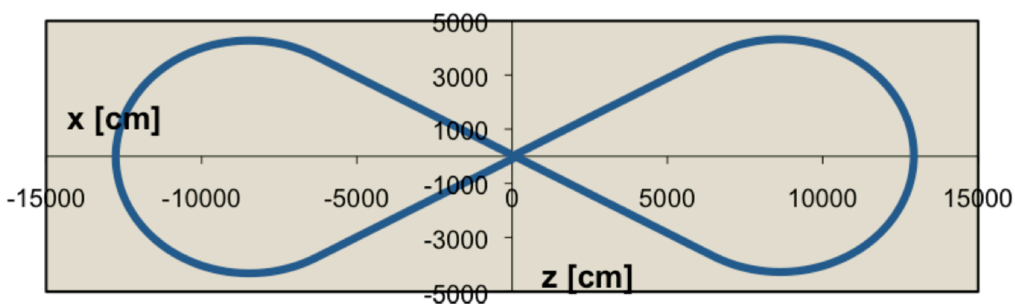

Figure 1: Footprint of figure-8 MEIC electron ring

INTRODUCTION

There is a growing consensus in the international nuclear physics community that further investigations of the quark and gluon structure of matter will require an advanced electron-ion collider with a very high beam polarization (~70-80 %) and extremely high luminosity (~10^{35}).

One such machine, the Medium-energy Electron-Ion Collider (MEIC), is proposed by Jefferson Lab [1] as a future development of the Continuous Electron Beam Accelerator Facility (CEBAF), beyond its 12 GeV upgrade (Fig. 1). The CEBAF accelerator with its polarized electron source will serve as a full energy injector into an electron storage ring providing required electron beam current, energy, and polarization. The electron and ion storage rings, which will be major additions to CEBAF, are designed as figure-8 shaped double rings of about 660 m total length sharing the same tunnel, with the electron ring above the ion ring. Each of these rings consists of two identical arcs connected by two crossing straight beam interaction regions (IR). The electron complex of MEIC will deliver high current (up to 3 A) electron beams of the energy in the range of 3 to 9 GeV with longitudinal polarization at the Interaction Points (IPs) of not less than 70%.

GENERAL POLARIZATION SCEHEME

Longitudinally polarized electrons are generated by a polarized DC photo-injector and then accelerated to the desired energy in the CEBAF. After that, they are injected into the electron storage ring with vertical polarization in arcs and accumulated there until their average current reaches a desired value. The MEIC IPs will accommodate up to four experimental stations, which can operate simultaneously. After beam stacking and accumulation is complete, both storage rings are switched to the collider mode.

Figure-8 storage rings significantly simplify beam polarization maintenance and manipulation. While electron polarization is maintained vertical in arcs of the ring, a stable longitudinal spin at all four collision points required by experiments is achieved through solenoid based spin rotators and horizontal beam orbit bends integrated into some of the used spin rotators. The ions are injected in one of the IR of the ion ring with longitudinal polarization. Three identical Siberian Snakes make the longitudinal polarization periodic in both IRs and provide a very efficient spin tune control.

As it was mentioned above, polarized electrons from the CEBAF accelerator are injected into the figure-8 MEIC electron ring with vertical polarization. To take advantage of the Sokolov-Ternov effect, the direction of the polarization vector in the arcs is opposite to the direction of a beam guiding magnetic field. However, nuclear physics experiments usually require longitudinal beam polarization at the IPs. Special devices, known as spin rotators, are needed to transform spin from original vertical to longitudinal before each IR and then to vertical, opposite to the original spin.

SPIN ROTATORS

A generic spin rotation scheme has been designed to transform the electron spin in the MEIC from vertical in the arcs to longitudinal at all IPs. The scheme, which we call the Universal Spin Rotator (USR), doesn't change the beam orbit for all planned electron beam energies and consists of a combination of superconducting solenoids and horizontal arc dipoles.

One possible implementation of the USR is shown in Fig. 2. The last two equal arc dipole sections, B1 and B2, interleave with two solenoids (Sol1 and Sol2). The rotator works by adjusting spin rotation angles in solenoids depending on the beam energy.

To provide the required spin rotation in the whole (3-9 GeV) energy range, the bending angle of each dipole section is ~ 6.6˚ and the total integral field of each solenoid is ~ 48 Tesla meter. X-Y betatron coupling introduced by solenoids is compensated by the methods based on [2][3], which makes the whole USR optics spin transparent.

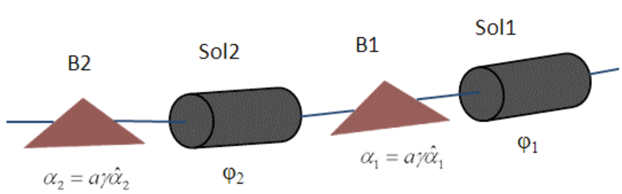

Figure 2: Layout of USR components for MEIC

COMPENSATION OPTICS

X-Y beam coupling introduced by solenoids is compensated locally. Each solenoid is divided into two equal parts and a set of quadrupoles is inserted between them. In order to cancel the orbit coupling the overall transfer matrix of the insert has to have a structure of (M_{COMP}) as described by the following equation

$$M_{COMP} = \begin{pmatrix} M & 0 \\ 0 & -M \end{pmatrix}, \quad (1)$$

where M is a general 2×2 matrix. The overall transfer matrix of two identical solenoids with the insert in between will result in an uncoupled cumulative transfer matrix given by the following form

$$M_{sol} . M_{COMP} . M_{sol} = \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix}, \quad (2)$$

which is independent of the solenoid field strength (A and B are 2×2 matrices).

The solenoid transfer matrix, M_{sol}, is given by the following expression.

$$M_{sol} = \begin{pmatrix} \cos^2\Phi & \frac{\sin 2\Phi}{B} & \frac{\sin 2\Phi}{2} & \frac{2\sin^2\Phi}{B} \\ \frac{-B\sin 2\Phi}{4} & \cos^2\Phi & \frac{-B\sin^2\Phi}{2} & \frac{\sin 2\Phi}{2} \\ \frac{-\sin 2\Phi}{2} & \frac{-2\sin^2\Phi}{B} & \cos^2\Phi & \frac{\sin 2\Phi}{B} \\ \frac{B\sin^2\Phi}{2} & \frac{-\sin 2\Phi}{2} & \frac{-B\sin 2\Phi}{4} & \cos^2\Phi \end{pmatrix}. \quad (3)$$

In which Φ=B L/2; B and L are solenoid field strength and length respectively.

The existence of four spin rotators with relatively long solenoids in MEIC makes preserving the spin rotators modularity and matching to the rest of the ring a challenging task.

Existing schemes involving at least seven normal quadrupoles, and or skew quadrupoles are conceivable [2-3]. Unfortunately they are not compact enough to fit MEIC layout, which leads us to the following new design of the compensating system.

The design involves the minimal required optimization parameters to fulfill four conditions given in equation (1). One could note that the simplicity of the system will reduce those conditions to only three.

A set of two symmetric doublets separated by one quadrupole is designed to meet the three conditions (three knobs to optimize three parameters). The compactness of such a system was incorporated in the optimization process yielding relatively short drifts in between quadrupoles (see Fig. 3).

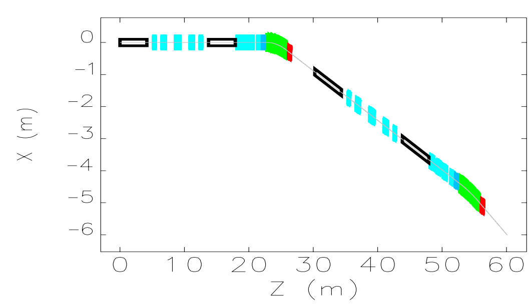

Figure 3: The layout of a spin rotator (solenoids are black, quadrupoles are blue and dipoles are green)

The symmetric insert has the advantage of requiring only four parameters to match the insert to the end of the arc and to the FODO cells of the straight. This will reduces number of matching quadrupoles to four. The β-functions through one of the compensated solenoids are shown in Figure 4. Similarly, β-functions through the whole spin rotator with the horizontal dipoles are shown in Figure 5.

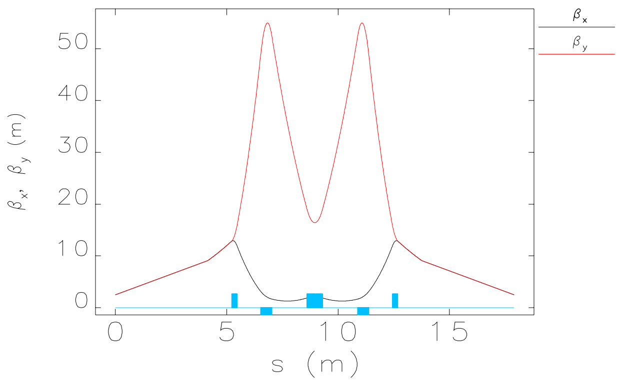

Figure 4: β-functions across symmetric insertion between two identical solenoids.

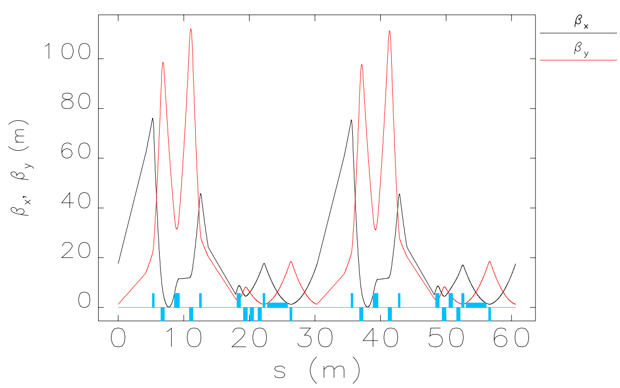

Figure 5: β-functions across the USR.

EMITTANCE DILUTION AND COMPACTION FACTOR

Dipole fields in the USR may lead to an emittance dilution, which could cause a reduction in the delivered luminosity.

Emittance growth due to incoherent synchrotron radiation from the two dipoles in the USR could be estimated by the following equation;

$$\Delta(\gamma\varepsilon_x) = 4\times 10^{-8} E^6[GeV]\int \frac{H(s)}{|\rho(s)|^3}ds, \quad (4)$$

where ε_x and E are the beam emittance and energy, ρ is the radius of curvature and H is defined through the Twiss parameters (α, β, γ, and η) by

$$H(s) = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta'_x + \beta_x (\eta'_x)^2$$

In our case the horizontal emittance dilution is within an acceptable range

$$\frac{\Delta(\gamma\varepsilon_x)}{\gamma\varepsilon_x} = 1.4\times 10^{-7}$$

The momentum compaction factor for the whole spin rotator equals $1.6\mathrm{x}10^{-4}$.

CONCLUSIONS

An overall description of MEIC polarization manipulation was presented; a requirement for a compact modular spin rotator was implemented with an orbit decoupling insert. This insert works for whole energy range by scaling the quadrupole field strength accordingly; it is short and compact to fit within the MEIC electron ring. Emittance dilution and momentum compaction factor were found to be within the acceptable limit.

The compact orbit decoupling insert has a universal nature and can be implemented between any symmetric orbit coupling elements (solenoids, skew quadrupoles, ... etc). It is independent of the coupling rotation angle.

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