ELECTRON POLARIZATION IN THE ERHIC RING-RING DESIGN*

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Abstract

High electron beam polarization (70-80%) is required in the future electron-ion collider eRHIC over the whole electron beam energy range from 5 GeV to 20 GeV. This paper analyses important aspects for achieving a high electron polarization level in the Ring-Ring design option of eRHIC and presents the design of spin rotators required to generate the longitudinal polarization orientation at the interaction point. Experiment considerations require bunch spin patterns with both spins up and down. A highly polarized beam will be produced by a photo-injector, accelerated to full collision energy by an injector accelerator and injected into the storage ring. Beam depolarization time in the storage ring has to be minimized in the presence of spin rotators, detector solenoid and damping wiggler, which establishes specific requirements for the ring lattice.

ACHIEVING HIGH POLARIZATION

The Ring-Ring design option has been recently under detailed consideration for the future electron-hadron collider eRHIC [1]. It will use polarized electrons in the energy range from 5 to 20 GeV stored in a new storage ring placed in the existing RHIC tunnel to collide with polarized protons and ions accelerated in RHIC. One important issue for the Ring-Ring option is to show that high polarization of electrons (> 70%) with longitudinal orientation in an experimental detector can be reliably achieved.

The evolution of beam polarization in electron storage rings is defined by two processes related to synchrotron radiation: Sokolov-Ternov self-polarization and depolarization caused by synchrotron radiation quantum emission. The self-polarization process leads to a slow build-up of electron polarization in the direction opposite to the vertical guiding field, up to a maximum level of 92.4% in an accelerator without spin rotators and with sufficiently weak spin resonances. However, the presence of spin rotators, wigglers, as well as strong spin resonances reduces the achievable polarization level. An important quantity is also the self-polarization time, which has a strong dependence on the beam energy, scaling like E^{-5}. The self-polarization time for an eRHIC storage ring placed in the present RHIC tunnel is shown in Figure 1 for the energy range of interest. The self-polarization time is very long over the entire energy range, except approaching 20 GeV where it drops to about 30 minutes. This demands a full energy polarized electron injector, so that the electron beam is injected into the storage ring with high polarization – 70% to 80%. One benefit of the long self-polarization time is that spin patterns containing bunches of opposite polarization orientation can be used.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.

The main challenge of spin dynamics in the storage ring is to preserve the high polarization level of the injected beam, at least at energies that are far from spin resonance conditions. The required timescale of polarization preservation is defined by the time interval between electron beam re-injections. Depolarizing effects are dominated by spin diffusion caused by the quantum nature of synchrotron radiation emission. In the presence of synchrotron radiation related spin diffusion the equilibrium polarization is described by the Derbenev-Kondratenko formula [2].The depolarizing time τ_{dpl} is defined by the diffusion rate of beam energy spread and the sensitivity of the stable spin solution n to the particle energy:

$$\frac{1}{\tau_{dpl}} \approx \frac{1}{2}\langle\left|\gamma\frac{\partial \boldsymbol{n}}{\partial\gamma}\right|^2 \frac{d\left({}^{\delta\gamma}/_{\gamma}\right)^2}{dt}\rangle_\theta$$

where γ is the relativistic factor and the averaging inside angle brackets is done over the accelerator azimuth θ and, in general, over the beam phase space.

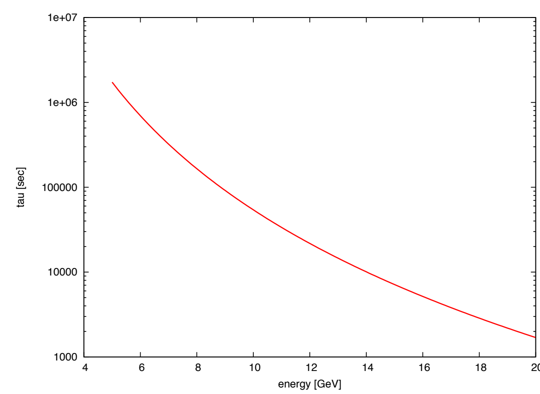

Figure 1: Sokolov-Ternov polarization time in the eRHIC electron storage ring as a function of energy.

The strength of depolarizing effects generally increases as E^7, thus making it more difficult to maintain high polarization in storage rings at higher energies. Nonetheless, Figure 2 shows that several accelerators operating above 10 GeV have demonstrated high electron polarization levels, exceeding 60% [3]. The accelerator technology used to achieve high polarization at high energies included highly efficient orbit correction, beam-based alignment of Beam Position Monitors relative to quadrupole field centers, and harmonic spin matching [4]. These tools mitigate the effects of imperfection spin resonances and their synchrotron sidebands.

In addition, the intrinsic resonances must be narrow enough to preserve high polarization, at least at energies far enough away from spin resonance conditions. Betatron coupling and unmatched spin rotator insertions can considerably widen the spin resonances, decreasing the achievable polarization. Thorough spin simulation studies have yet to be performed to determine the tolerances on the closed orbit and betatron coupling control, and the required efficiency of spin matching and correction techniques. The eRHIC storage ring uses damping wigglers to increase the damping decrement at lower energies. Wiggler-enhanced synchrotron radiation increases the spin diffusion rate. Thus, careful attention must be paid to the possibility of enhanced depolarization at lower energies. Similarly, the effect of beam-beam interactions on polarization needs attention, since large electron beam tune spreads would effectively widen the intrinsic spin resonances.

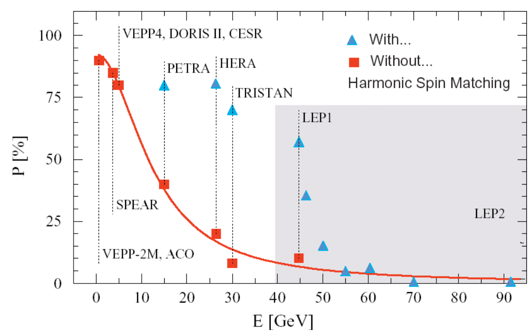

Figure 2: Electron polarization levels achieved in various electron storage rings [3].

SPIN ROTATORS

Spin rotators are needed to convert the vertical polarization of the electron beam in the arcs to a longitudinal polarization at the experimental detector. The state-of-the-art electron spin rotator that was used in the electron-proton collider HERA (DESY, Germany) [5] employed a sequence (~ 56 m long) of interleaved vertical and horizontal dipole magnets to transform the vertical spin of 27 GeV electrons to the required orientation in the horizontal plane. The vertical orbit excursion inside the spin rotator was quite large – about 20 cm – thus requiring some of the rotator magnets to be shifted vertically from the plane of the HERA electron ring.

Spin rotators based on helical magnets have been successfully used for polarized protons in RHIC [6]. The helical magnet design leads to smaller orbit excursion compared with the design based on common dipoles. Helical magnet design of electron spin rotators has been proposed for LHeC [7].

The eRHIC spin rotators must operate over a large energy range, from 5 GeV to 20 GeV. Since the orbit excursion in the dipole magnets (common-type or helical) scales inversely with the beam energy, a HERA-type rotator leads to 1 m orbit excursions of 5 GeV electrons. Furthermore the synchrotron radiation power (per meter) produced by 20 GeV eRHIC electrons is considerably larger than the 27 GeV electrons in HERA, due to the much large electron current. Reducing the linear power load requires further increasing the rotator length and, correspondingly, the orbit excursion. Therefore, the most practical solution consists of a spin rotator based on strong solenoid magnets. Solenoidal Siberian Snakes have been used in electron accelerators operating in the 0.5 GeV to 1 GeV range [8].

A solenoid-based scheme for eRHIC using two rotators on each side of the interaction region is shown in Figure 3. The combination of rotators (rot1 and rot2) and bending arcs (bend1 and bend2) allows to realize the exact longitudinal orientation of electron spins in the whole energy range from 5 GeV to 20 GeV. Optimization of solenoidal spin integrals led to the parameters listed in Table 1. Figure 4 shows the dependence of solenoidal field integrals on the electron energy. The spin rotator will be based on superconducting solenoid magnets with magnetic fields in the 7 T to 10 T range. High-temperature superconducting technology might be considered to produce even higher fields.

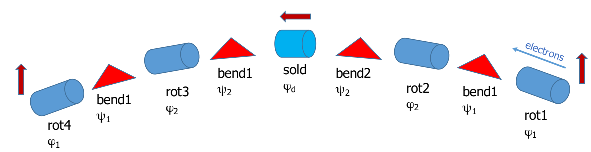

Figure 3: Schematic layout of the electron spin rotators.

Table 1: Spin rotator parameters.

Parameter	rot1	rot2
Field integral range [Tm]	2 – 40	0 – 127
Solenoid length (at 7 T max field)	5.7	18.1
Bending angle from the IP [mrad]	92 $=\psi_1+\psi_2$	46 $= \psi_2$
Location in the RHIC tunnel	D9 – D10	D6 – Q8

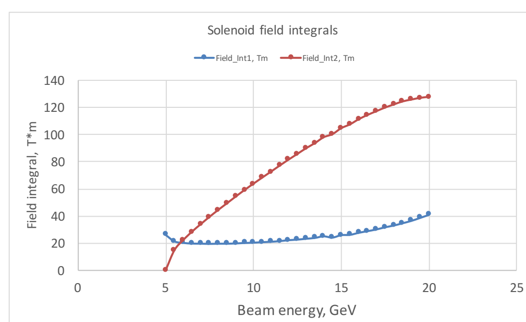

Figure 4: Solenoidal field integral of 1st and 2nd rotators.

Each of the spin rotators, rot1-4, includes two solenoids and several quadrupole and skew quadrupole magnets to compensate for betatron coupling and vertical dispersion, as well as to satisfy, when required, the spin matching conditions. The optics of the rotator insertion on one side of the IR is shown in Figure 5. The set of beta-functions describing this coupled case is given in Mais-Ripken parameterization [9]. Betatron coupling functions and vertical dispersion excursions are limited to the rotator insertions.

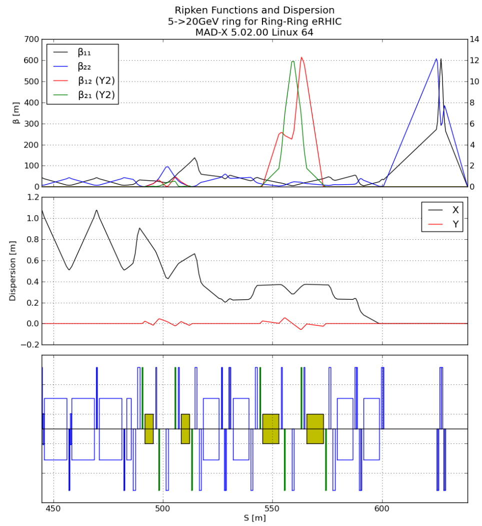

Figure 5: Optical functions through the rotator insertions on one side of the interaction region. The interaction point is at the right side of the plot. Blue lines are normal quadrupoles, while green lines are skew quads. Blue and light green boxes present dipole bending and solenoidal magnets respectively.

SPIN MATCHING CONDITIONS

In order to minimize the depolarization effects caused by synchrotron radiation induced diffusion the spin matching conditions on the rotator optics have to be satisfied. The spin conditions for solenoidal spin rotators can be obtained using general expressions for $F_5 = \gamma\, \partial \boldsymbol{n}/\partial\gamma$ function [10]. Taking into account that the betatron coupling and vertical dispersion are fully compensated for each individual rotator insertion, one gets the following conditions to nullify $\gamma\, \partial \boldsymbol{n}/\partial\gamma$ outside of the rotator area (in the bending arcs of the storage ring):

$$\nu_0 H(D') + \sum_{rot:j=1,2} \varphi_j k_{sj} - \nu_0 \sum_{bends:j=1,2} \psi_j k_{yj} \quad = 0$$

$$H(f_1') = 0 \; and \; \; H(f_1'^{*}) = 0$$

where

$$H(a) = \frac{\varphi_1}{2}\left(I_{1ent}(a) + I_{1ex}(a)\right) + \frac{\varphi_2}{2}\left(I_{2ent}(a) + I_{2ex}(a)\right)$$

$$I_{n\, ent/ex}(a) = (k_x a_x + k_y a_y)_{n\, ent/ex}$$

Here, $\nu_0 = G\gamma$ and the solenoidal and bending angles φ_i and ψ_i are as defined in Figure 3. Indexes x, s, y correspond correspondingly to horizontal, longitudinal and vertical components. D is the dispersion function and f_I is the eigen function of betatron motion corresponding to the horizontal motion in the arcs (with betatron phase advance μ_I). Its components are: $f_{1x} = \sqrt{\beta_{11}} e^{i\mu_1}$ and $f_{1y} = \sqrt{\beta_{12}} e^{i\mu_1}$, where β_{11} and β_{12} through the rotator insertion are shown in Figure 5. The functions $I_{1,2}$ are calculated at the entrance and exit of the solenoidal magnets of first and second rotator, right after or right before the solenoid edge. The spin motion in this formulas are described by components of spin eigen vector $\boldsymbol{k} = \boldsymbol{l} - i\boldsymbol{m}$, where $\boldsymbol{l}$ and $\boldsymbol{m}$ are spin solutions on the design orbit orthogonal to the stable spin solution $\boldsymbol{n_0}$ and to each other.

The spin matching conditions are obviously energy dependent, and the first goal is to satisfy them at 20 GeV where, if not taken care of, the depolarization time can be reduced at minimum by factor 3 as compared with the Sokolov-Ternov time. Work on improving the rotator optics for spin matching is underway. We also need to include the effect of detector solenoid, including induced betatron coupling.

SPIN PATTERN AND INJECTORS

To realize arbitrary spin patterns in the electron beam, electron bunches with spins up and down need to be injected into the eRHIC electron storage ring. Assuming that depolarization caused by fluctuations of synchrotron radiation is minimized (that is $\gamma \frac{\partial \boldsymbol{n}}{\partial \gamma} \ll 1$) the depolarization rate for bunches with spin “down” is defined by the Sokolov-Ternov time constant shown in Figure 1. It gives the timescale on which entire bunches (or bunch trains) need to be replaced on a regular basis.

With the shortest Sokolov-Ternov polarization time of about 1600 seconds at an energy of 20 GeV, continuously replacing single bunches at 1 Hz would take 6 minutes for a 360-bunch fill. In reality it is sufficient to only replace those bunches with spin “down”, which would only take 3 minutes. This is sufficiently short compared to the Sokolov-Ternov polarization time, so that depolarization of those bunches is small even at 20 GeV.

An injector system capable of providing polarized bunches at the required rate can be based either on a recirculating linac, which can operate in pulsed mode, or on a rapid cycling synchrotron with highly symmetric structure, which eliminates strong intrinsic resonances [11].

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ISBN 978-3-95450-147-2