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Investigation of various electron ring concepts for the ENC with regard to depolarising effects

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Abstract. This investigation covers first feasibility studies for an electron ring in the tunnel of the High Energy Storage Ring (HESR) of the Facility for Antiproton and Ion Research (FAIR). This electron ring should accumulate and store polarised electrons at an energy of 2.8 - 3.3 GeV and should provide for collisions of longitudinally polarised electrons with the longitudinally polarised protons at the PANDA detector and at a centre-of-mass of around 14 GeV. Electron-ion collisions would also be possible.

In order to attain longitudinally polarised electrons in the interaction region, two different concepts have been considered and the optical constraints and depolarising effects have been analysed numerically. Both concepts use spin rotators based on solenoids. For the first concept the polarisation is in the horizontal plane, while in the second concept the polarisation is vertical in the arcs. The electrons would be pre-polarised before injection. The aim is then to obtain the highest possible depolarising time.

1. Introduction

The collision of ultrarelativistic, charged and spin-polarised particles has become a global topic of research. Several facilities have pursued fundamental research or foresee to do it using colliders with polarised beams [1]. In this context, studies have been undertaken for building an Electron-Nucleon Collider (ENC) at the Facility for Antiproton and Ion Research (FAIR)[3][4]. This collider should enable experiments to be carried out with longitudinally polarised electron and nucleon beams at a centre-of-mass energy of 14 GeV and would use the High Energy Storage Ring (HESR) at FAIR as well as the PANDA detector. This would require continually providing longitudinally polarised electrons with an energy of about 3 GeV from a superconducting linear accelerator, or accumulation of pre-polarised electrons in a normal conducting ring. In order to avoid high costs, an electron ring is the preferred option. In this case, the electron ring would be installed inside the HESR tunnel and the electrons would be accumulated in the ring. For this, the polarisation vector of the injected beam would have to be parallel to the direction

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[1] To name only an arbitrary selection (see also [1] [2]): HERA, RHIC – successful now and in the past, and eRHIC, ELIC, LHeC, C-tau factory, ILC... – planned for the future
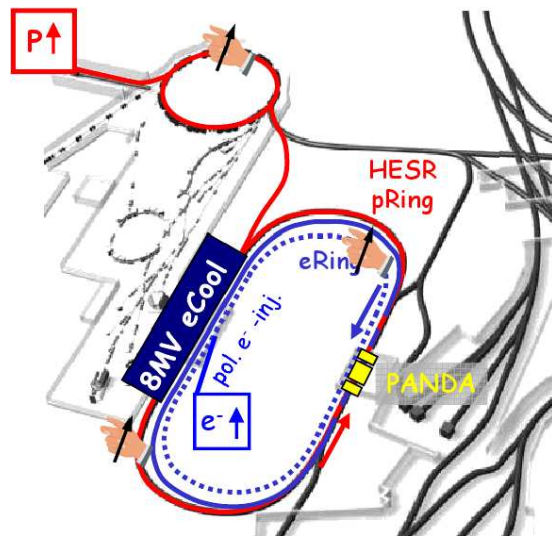
Figure 1. ENC overview (coloured) within FAIR (black): A part of the research facility is shown in black in the background. The HESR with a momentum up to 15 GeV/c is shown in red. The PANDA detector is marked in yellow. The polarisation at the interaction point should be longitudinal for the HESR as well as for the electron ring (blue).

of the equilibrium polarisation of the ring (the vector $\hat{n}_0$ [5]) at the injection point and the depolarising time would have to be maximised. At this energy self-polarisation in the ring by the Sokolov-Ternov effect would take too long [5]. Figure 1 shows an overview of FAIR including the main components of the ENC.

Installing the electron ring inside the existing HESR tunnel entails strong limitations on the design in comparison with the use of a green-field solution. As well as the geometric boundaries given by the tunnel, the electron ring design is constrained by the physical characteristics of the HESR and the need for high luminosity. In order to allow us to focus only on the design parameters of the ring, these constraints are listed in Table 1 and can be compared to the properties of the HESR in the second column.

Table 1. Design parameters of HESR compared to the resulting parameters of Concepts 1 and 2 of the electron ring (eRing).

	HESR	eRing Concept 1	eRing Concept 2
lattice type	FODO with missing magnet	FODO with missing magnet	hextuple bend achromat
bending radius [m]	29.35	29.35	21.96
ϵ_{norm} (ϵ_x, ϵ_z) [mm mrad]	(2.3,2.3)	(2.14,2.14)	(3.8,3.12)
I (beam current) [A]	0.6	2	2
L (luminosity) $\left[\mathrm{cm}^{-2}\mathrm{s}^{-1}\right]$		$(2-6) \cdot 10^{32}$	

Two different concepts have been investigated. The main characteristic of Concept 1 is a Siberian Snake [6] mounted in the straight section opposite the interaction point. The snake consists of a solenoid which rotates spins by 180° around the beam axis. With this scheme the equilibrium (i.e. periodic) polarisation vector is in the horizontal plane. In contrast, Concept 2 utilises two 90°-solenoids installed directly in the arcs. The stable optical solutions then have $\beta_x = \beta_z$ at the solenoids[2]. With strong solenoids the optics are usually decoupled with skew quadrupoles or with a scheme of upright quadrupoles. For these studies, we decided to apply

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[2] Mœbius-accelerators[7]

the condition $\beta_x = \beta_z$ right from the start and to attain this by a suitable design of the cell structure. In this scheme the equilibrium polarisation vector is vertical in the arcs.

For the first evaluations, nonlinear motion and nonlinear magnetic elements have been neglected. Linear particle motion can be described via a 6-dimensional matrix formalism. This formalism can be extended by two additional dimensions to describe the linearised spin motion in an appropriate rotating coordinate system (SLIM formalism [5]). Then the spin-orbit motion is described by 8×8 matrices and for one turn:

$$\bar{u}_8(s_0 + C) = \begin{pmatrix} \mathbf{M}_{6\times6} & \mathbf{0}_{6\times2} \\ \mathbf{G}_{2\times6} & \mathbf{D}_{2\times2} \end{pmatrix} (C) \cdot \bar{u}_8(s_0) \qquad ; \qquad (1)$$

where C is the circumference and $\bar{u}_8$ is the 8-component spin-orbit vector depending on the position s around the ring. The first six elements of $\bar{u}_8$ describe the canonical particle coordinates and the last two describe the spin motion. Stern-Gerlach forces acting on the particles are neglected since they are so small. Magnet misalignments are included by adding extra magnetic fields to the standard fields and the extra fields are chosen according to gaussian distributions with the tails cut. We now present simulations for the rates of depolarisation for both concepts. These were done using the code SLICKTRACK [8].

2. Polarisation studies of Concept 1
As mentioned above, in the Concept-1 lattice the equilibrium polarisation is the horizontal plane. Figure 2(a) gives an impression of the s-dependence of the polarisation on the design orbit. The resulting fractional spin tune is 1/2. The full coupling of the lattice results in only
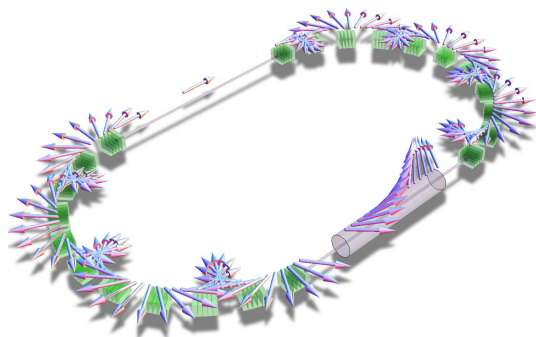
(a) Periodic spin motion on design orbit.
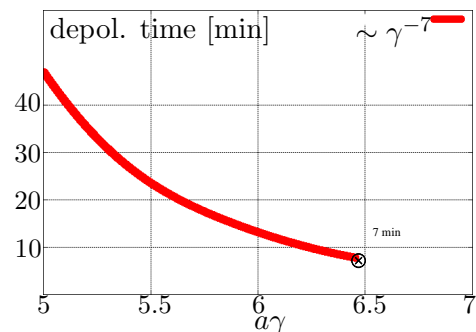
(b) Simulated depolarising time versus $a\gamma$ where $a = 0.00115965$ is the gyromagnetic anomaly or the electron and γ is the Lorentz factoro.

Figure 2. Fundamental design approach of concept 1.

one transverse emittance. Thus, the ansatz of sparing a decoupling scheme for the solenoid leads on the one hand to a sensible optical solution, but on the other hand one obtains a high luminosity by having transverse emittances with the same magnitude in both planes. Inside the arcs the structure of the electron ring can be copied from the HESR lattice. This gives an arc design with 11 dipoles per arc and the familiar FODO structure. The dispersion is suppressed via a missing magnet design as in the HESR. Thus, this concept is best suited for geometric reasons.

However, the horizontally orientated polarisation leads to strong depolarisation with the depolarising rate increasing approximately as γ^7 (see figure 2(b)). In [2] it is shown that the

depolarising time for higher energies depends on the number of spin rotators. The higher the number of spin rotators the higher is the depolarising time in the desired energy range. Even so, for the electron ring in the ENC there is no possibility of installing more than one 180°-solenoid due to geometric constraints. As the result, in the foreseen energy range, the solution of Concept 1 does not maintain the polarisation for a sufficient time.

3. Polarisation studies of Concept 2

Concept 2 is based on an equilibrium polarisation which is vertical in the arcs. Therefore, two spin rotators are needed to give longitudinal polarisation at the interaction point. Including two 90°-solenoids in a ring without decoupling the optics presents big problems for designing the optics. As in Concept 1, stable optical solutions are obtained by setting $\beta_x = \beta_z$ at the solenoids. A missing-magnet structure for suppressing the horizontal dispersion is not feasible because the rotators needs one dipole and one solenoid directly inside the arcs. Hence, the cells in the arc have to provide equal beta functions, vanishing alpha functions and vanishing horizontal dispersion at the cell boundaries. These constraints lead at least to 4 different kinds of quadrupoles and to six dipoles per cell so that each arc contains 30 dipoles.

Figure 3(a) shows the periodic spin motion on the design orbit. Figure 3(b) shows the Courant-Snyder functions for a single cell, the so called twin peaks design. The SLIM-formalism
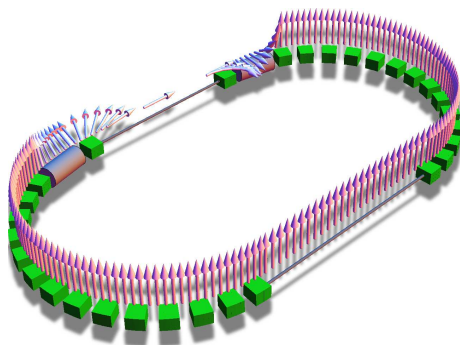
(a) Periodic spin motion on design orbit.
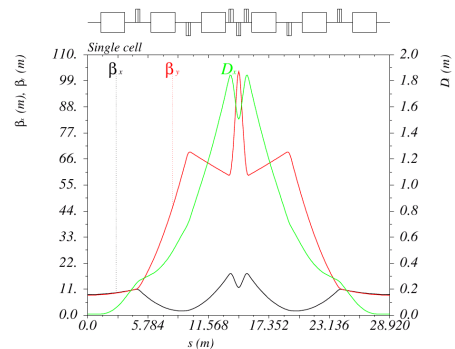
(b) Optical functions β_x, β_z and dispersion D_x for a single cell (twin peaks design).

Figure 3. Fundamental design approach of Concept 2.

shows that the depolarising time depends, among others things, on the quadrupole strengths which are included in the $\mathbf{G}_{2\times6}$ matrix and on each optical tune $Q_{x,z,s}$[5]:

$$\tau_{\mathrm{dep,lin}} = \tau_{\mathrm{dep,lin}}\left(\mathbf{G}_{2\times6}, Q_{x,z,s}, \ldots\right) \qquad . \tag{2}$$

These dependencies offer a rough but very effective way to influence the depolarising time of the lattice. For sure, both parameters (**G** matrix and tune) cannot be varied independently. The variation of the tunes effects the strength of each quadrupole and thus effects the entries of the **G** matrix or vice versa. The variation of the tunes was made by a matching code implemented in MAD-X and this matching does not lead to a unique solution. Nevertheless, the lattice can be enhanced towards higher depolarising times and this is therefore a good tool for a first-time approach of the present concept. The depolarising time was increased in this manner during these first studies, from a few seconds up to several minutes. Figure 4(b) shows the dependence of the depolarisation on tunes Q_x and Q_z at the foreseen particle energy. The maximum depolarising times are reached close to an optical resonance with about 100 minutes (figure 4(a)) compared to the initial lattice state with about 7 seconds (not shown in the plot). The maximum depolarising times are close to fractional spin tunes of 1/2, i.e. away from spin-orbit resonances.
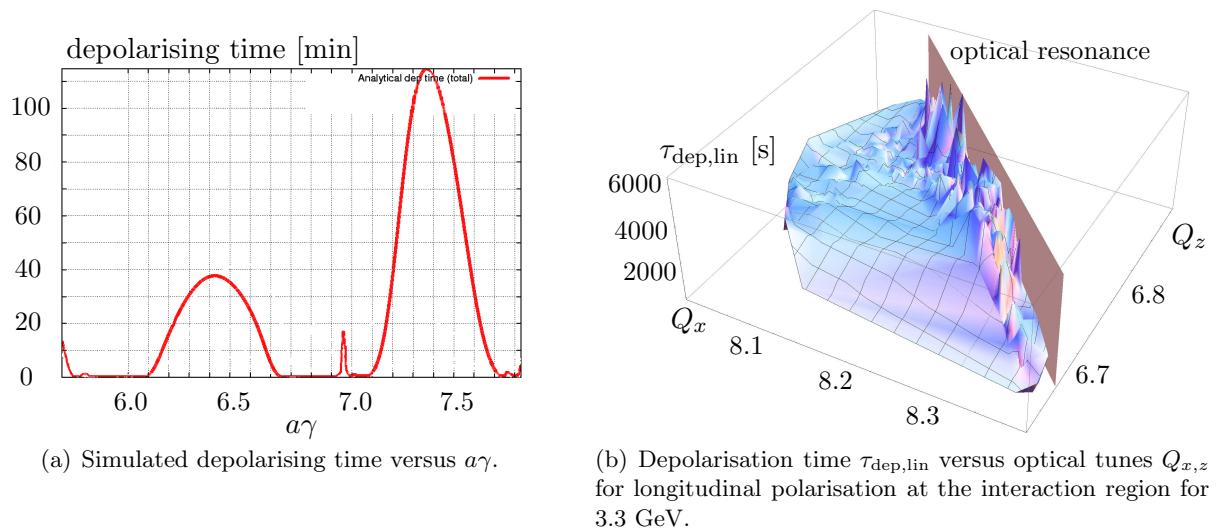
(a) Simulated depolarising time versus $a\gamma$.

(b) Depolarisation time $\tau_{\text{dep,lin}}$ versus optical tunes $Q_{x,z}$ for longitudinal polarisation at the interaction region for 3.3 GeV.

Figure 4. Fundamental design approach of concept 2.

4. Conclusion and outlook

This first investigation of the electron ring for the ENC gives reasonable results for the lattice of Concept 2 with a depolarising time in the range of 100 minutes. On the contrary, for Concept 1, with its horizontal polarisation in the arcs, the polarisation is only conserved for a few minutes. In order to increase the depolarising time of the lattice of Concept 2, detailed spin matching is essential. The lattice has to be modified, such that the $\mathbf{G}_{2\times6}$-matrix vanishes for one evolution and the spin motion is decoupled from the particles' motion[5]. In the present case, for an optically sensible solution with $\beta_x = \beta_z$, this kind of spin matching is a demanding task. In parallel, other lattice concepts with a decoupling scheme for the solenoids should be reconsidered.

5. Acknowledgments

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