Solenoidal Compensation Scheme for an Interaction Region of an Electron-Positron Collider

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Abstract

Solenoidal fields of detectors in colliders are compensated usually with the 4 skew quadrupole method, which is not optimal for Φ-factories. In DAΦNE the Rotating Frame Method [1] has been adopted. An alternative compensation scheme, with a small superconducting solenoid, providing also final focusing at the interaction point, is described. The optical aspects of a possible application to one of the DAΦNE Interaction Regions are discussed.

1. INTRODUCTION

In high energy rings experimental detectors need often solenoidal fields which must be compensated to avoid coupling between horizontal and vertical oscillations [1,2,3].

When the beam energy is relatively low, like in Φ-factories, the coupling introduced by the experimental solenoid may be so strong that it becomes one of the main optical characteristics of the ring.

In DAΦNE [1,4] rotation of each low beta quadrupole and compensating superconducting solenoids provide cancellation of coupling outside the interaction regions (IRs).

In the Novosibirsk Φ-factory project [5] the solenoidal coupling is not compensated but used specifically to generate emittance in the two transverse phase spaces and to focus the round beam.

We present here a new idea for a compensating method which we have applied as an example to the DAΦNE IR which houses the detector of the FI.NU.DA. [6] experiment.

2. THE NEW COMPENSATION SCHEME

The basic idea of this scheme starts from the observation that the total optical effect of a rectangular field model solenoid can be split in two completely different effects (see Appendix). The first one is a rotation of the transverse plane by the angle:

$$\theta_r = \frac{B_z L_s}{2B\rho} \tag{1}$$

where L_s is the solenoid length, B_z its longitudinal field, and $B\rho$ the magnetic rigidity of the beam. The second one is a focusing quadrupole effect on both planes characterized by the quadrupole constant K_s:

$$K_s = \frac{B_z}{2B\rho} \tag{2}$$

The focusing properties of a quadrupole for each plane are determined by the element A_{21} of the 2x2 transport matrix. For a solenoid (see Appendix):

$$A_{21} = -K_s \sin\theta_r \approx -\frac{\theta_r^2}{L_s} \tag{3}$$

The last formula is the key point. For the same longitudinal field integral, proportional to θ_r, the focusing effect is inversely proportional to the solenoid length.

The new scheme can be imagined as derived from the DAΦNE scheme [1] by interchanging the positions of the quadrupoles and the compensator. The compensator placed inside the detector very near to the Interaction Point (IP) can have a small radius. Furthermore its length can be very small to increase its focusing properties on both planes.

An advantage of this scheme is that the coupling vanishes at all energies within the beam energy spread.

On each side of the IP two quadrupoles instead of four are enough to properly focus the beam at the crossing point and match the optical functions to the arcs outside the detector. Of course they do not need any rotation and can be realized as conventional electromagnets.

The solution studied for FI.NU.DA. is based on the preliminary experiment design parameters, recalled in the following table.

Table I - FI.NU.DA. detector characteristics

Total integrated field ($B_z L_s$, Tm)	3
Maximum field (B_{max}, T)	1.1
Total length (L_s,m)	2.7
Total rotation angle (θ_r ,deg)	50.05

The FI.NU.DA. detector needs a region free from machine components defined by two 45° half aperture cones with the vertex at ~20cm from the IP, outside which the compensator solenoid can be housed.

Computations have been performed on a 22 cm superconducting coil . The inner radius is 6 cm and the outer 7 cm, corresponding to ≈550 A/mm^2 current density. The required beam stay clear aperture inside the compensator is a circle of 3.5 cm radius, based on the assumption of $10\sigma_x$ (off coupling) and $10\sigma_y$ (full coupling) as a limit for good quantum lifetime [7], crossing angle ±15 mrad, vertical separation @ IP of ±2.5 mm. Therefore there are 2.5 cm left for the vacuum chamber and helium circulation.

The optical functions behaviour in half IR is shown in Figure 1 together with the beam trajectory for a crossing angle of ±10 mrad. The longitudinal magnetic field inside the detector is plotted in Figure 2, together with the rotation angle of the betatron oscillation planes.

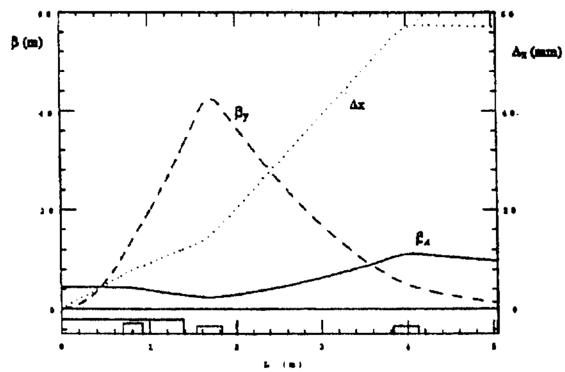

Figure 1. Optical functions and beam central trajectory in half IR

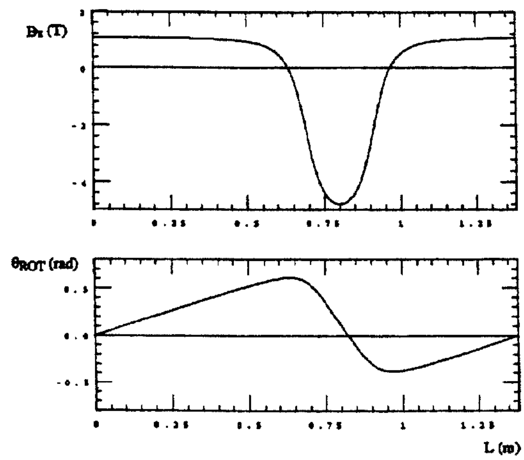

Figure 2. Total longitudinal magnetic field in the detector region and total rotation angle

If the detector field is changed to follow experimental requirements, the compensating solenoid field has to be changed accordingly to maintain the compensation (this is not possible in the previous scheme with quadrupoles unless each one can be rotated independently inside the detector). From the optics point of view the focusing effect is an increasing function of the ratio between the detector field and the beam rigidity. The quadrupoles are therefore used to compensate the variation of the detector-compensator focusing in order to keep the IP β functions and matching the ring arcs constant. The natural chromaticity of the whole ring is, however, lower at high solenoid and compensator fields and the dynamic aperture is larger as well. On the contrary the IR optics is almost unperturbed if the detector is switched off. The two compensating solenoids must be oppositely powered, at a field $|B|=|B_c|-|B_d|$ where B_c and B_d are the nominal operating fields of the compensator and the detector respectively.

3. MAGNETIC FIELD ANALYSIS

The analysis of the magnetic properties of the detector plus compensator system has been carried out, under the assumption of a constant field in the main detector solenoid with the compensator coil superimposed without any iron contribution.

Due to the cylindrical symmetry of the model the magnetic field is two-dimensional and therefore its effect on the lattice can be estimated more accurately than in the standard rectangular approximation.

The longitudinal and radial magnetic field profiles of the compensator are shown in Figure 3 along half main detector solenoid. The plots show the field on axis and on concentric surfaces of different radius. It can be observed that the longitudinal field decreases rapidly with the distance from the axis: B_z is of the order of 10% of the value on axis at r = 10 cm. The magnetic lines of force for half IR are shown in Figure 4: it is clear that the detector field is not affected inside the 45° cone.

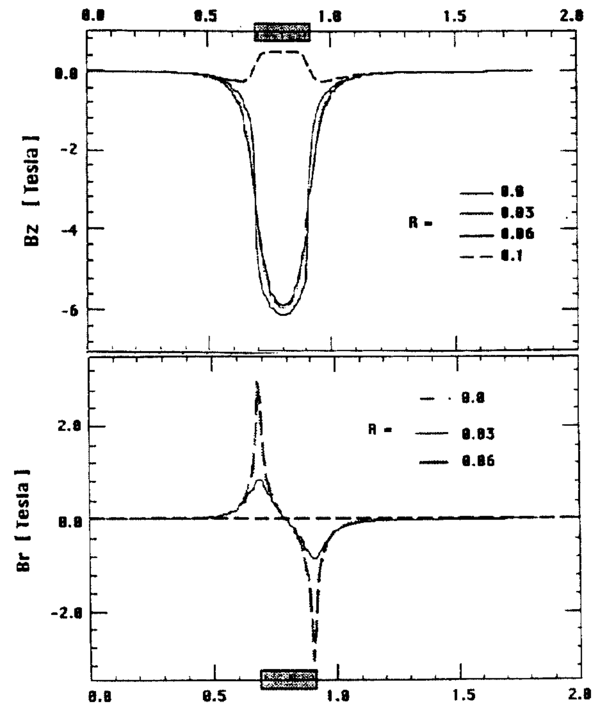

Figure 3. Longitudinal and radial magnetic field of the compensating solenoid along the detector length

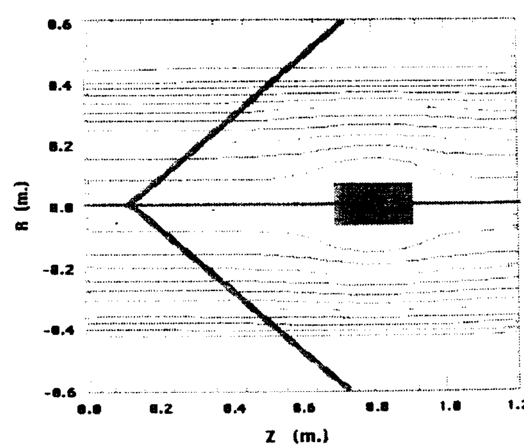

Figure 4. Magnetic lines of force with main detector and compensator solenoids

4. ANALYTICAL COMPUTATIONS

A tracking code has been developed where the particle trajectories are computed as solutions of the three-dimensional equations corresponding to the motion of relativistic particles inside the total magnetic field.

In order to solve the equations, the Jacobian around the particle trajectory has been computed and used as the transport matrix corresponding to the whole detector zone. This matrix, whose simplecticity has been checked, can be used in kick codes. A similar result can be found by multiplicating many matrices, each representing a very small solenoid chunk. We found a good agreement between the two different approaches.

The analysis of the Jacobian around the axis verifies (as expected) that the horizontal and vertical oscillations are uncoupled. The Jacobian around the actual particle trajectory, which makes an angle of 12.5 mrad with respect the magnet axis at the IP, shows a small coupling never exceeding the project value of 1%.

APPENDIX - OPTICAL PROPERTIES OF SOLENOIDS

Defining:

$$K_S = \frac{B_z}{2B_r} \tag{4}$$

and

$$\theta_r = K_S L_s \tag{5}$$

the transport matrix corresponding to the rectangular model solenoid can be written for both transverse planes as:

$$Q_S = \begin{vmatrix} \cos\theta_r A & \sin\theta_r A \\ \sin\theta_r A & \cos\theta_r A \end{vmatrix}$$

where A is the 2x2 matrix:

$$A = \begin{vmatrix} \cos\theta_r & \dfrac{\sin\theta_r}{K_S} \\ -K_S\sin\theta_r & \cos\theta_r \end{vmatrix}$$

Defining matrices **R** and **F** as:

$$R(\theta_r) = \begin{vmatrix} \cos\theta_r \mathbf{I} & \sin\theta_r \mathbf{I} \\ -\sin\theta_r \mathbf{I} & \cos\theta_r \mathbf{I} \end{vmatrix}$$

$$F(L_S,\theta_r) = \begin{vmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{0} & \mathbf{A} \end{vmatrix}$$

we can also write:

$$Q_S = \mathbf{R}\ \mathbf{F} = \mathbf{F}\ \mathbf{R} \tag{6}$$

The conclusion is that a solenoid has focusing and rotating effect in both planes. Its contribution to the chromaticity is larger by a factor 2 with respect to a quadrupole with the same length and the same focusing strength, because of the different energy dependence.

Expressing the integrated solenoid focusing strength as a function of the rotation angle:

$$K_S^2 L_S = -\frac{\theta_r^2}{L_S} \tag{7}$$

we notice that while θ_r depends only on the integrated B_Z, the focusing strength, at a given θ_r, is inversely proportional to L_S. This explains why the focusing properties of the small compensating solenoid are so relevant while those of the main detector with the same absolute value of θ_r are negligible.

This rectangular model is exact only in the limit of a uniform field shape, which is true when the ratio between the internal radius and the total length is small, or when the magnetic field is clamped by the iron joke (like in the DAΦNE detectors).

In a more general case the optical effects of a longitudinal magnetic field can be computed or by tracking or by decomposing it in thin slices, each represented in the rectangular model.

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