IMPACT OF THE HERA LUMINOSITY UPGRADE ON THE ELECTRON SPIN POLARIZATION

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Abstract

The planned luminosity upgrade of the proton-electron (positron) collider HERA is a challenge for both engineers and machine physicists. The redesign of the interaction regions (IRs) presents many problems – one of them is to preserve a high $e^{-/+}$ spin polarization. In order to reduce the beta-functions at the interaction points (IPs), combined function magnets will have to be introduced inside the detector solenoids of the experimental stations. This unconventional layout will create a complicated field picture in the close vicinity of the IPs and affect the orbits of both beams as well as the spin polarization of the $e^{-/+}$ beam. Various techniques to model the situation will be described. To achieve good polarization certain conditions on the optics must be fulfilled (so called spin matching conditions) and depolarizing resonances have to be avoided. Methods for modelling the complicated field configurations, for calculating the resulting spin-orbit trajectories and for calculating the polarization are discussed.

1 INTRODUCTION

The HERA p/$e^{-/+}$ collider is a unique machine in many respects. One is that it is the only high energy accelerator that can deliver longitudinally polarized $e^{-/+}$ to a particle physics target (the HERMES experiment).

Stored $e^{-/+}$ beams can become vertically polarized through synchrotron radiation emission via the Sokolov-Ternov effect [1], however polarized beams can best be exploited if the beam is longitudinally polarized. In HERA the natural vertical polarization is brought into the longitudinal direction in the straight section around the HERMES experiment by means of a pair of spin rotators of the Buon-Steffen type [2], that form the ends of the arcs. According to the Luminosity Upgrade plans (for more details on the Luminosity Upgrade, see [3, 4]) two more rotator pairs will be installed around the North and South interaction regions, serving the H1 and Zeus experiments.

It is very important that the planned upgrade geometry does not spoil the polarization that can be delivered to the experiments. This requires that special care is taken when designing the $e^{-/+}$ optics and that good tools be developed to analyze the new situation.

To achieve a higher luminosity in HERA the transverse beam sizes will be squeezed at the IPs and to achieve this the low-beta magnets have to move in closer to the experiments. Hence, the space available for necessary correction magnets will be smaller than it is today. Two important consequences for the polarization result:

1) the experimental solenoids will not, as at present, be compensated by anti-solenoids; 2) the experimental solenoids must overlap with some of the machine magnets.

In the current HERA layout the compensating anti-solenoids have two important tasks: to compensate for the betatron coupling and to compensate for the distortion of the closed solution of the T–BMT spin precession equation [5], $\hat{n}_0$, generated by the solenoids themselves. With no anti-solenoids these effects must be corrected in another way. The H1 solenoid has a higher integrated field strength then Zeus, it is longer and will have the largest overlap with the innermost machine magnets in the new lattice. Moreover, the H1 solenoid is longitudinally off centre with respect to the IP. Our main concern has therefore been to analyze the effects from this solenoid.

In the new lattice, the design orbit inside the solenoid is curved in the horizontal plane due to the bending action of the machine magnets. (See Fig. 1). This will lead to disturbances both to the $e^{-/+}$ orbit and to the spin.

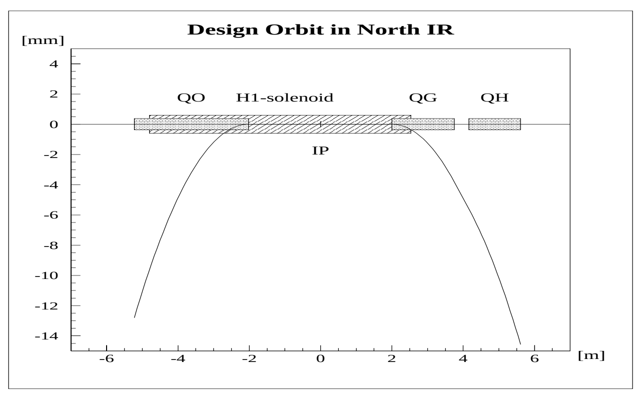

Figure 1: The curved design orbit inside H1 solenoid

With the beam entering and leaving the solenoid radially off centre it will experience radial kicks from the end fields; the vertical kicks are especially important. In addition, because of the curvature of the design orbit, the longitudinal field of the solenoid will contribute an effective radial field component with respect to the design orbit.

2 MODELLING THE SITUATION

None of the optics codes and codes for calculating and optimizing the polarization in common use at DESY contain mixed element types such as solenoid + dipole or solenoid + combined function magnet. In order to construct a useful model for the new situation, ways must be found to incorporate such special elements. The strategy has been the following: use the existing codes and, as a first step, build mixed elements out of existing magnet types. To improve the model, the next step has been to construct symplectic orbit maps and orthogonal spin maps by integration, using a hard edge model of the solenoid field. The spin motion is expected to be very sensitive to the details of the solenoid fields, especially the end fields, and ultimately the calculations should be based on fields from measured field maps.

2.1 Sandwich model

To get a first estimate for the polarization that can be expected with the upgraded machine the program SLIM [6] (and thick lens version SLICK) has been used. The regions with overlapping solenoid - combined function magnet fields have been implemented as series of interleaved thin slices of these magnet types. The fact that the design orbit inside of the solenoid is curved, causing the beam to be influenced by additional radial field components has to be taken into account in the model.

Two approaches have been tried out. In one the radial fields are represented by thin corrector coil slices at appropriate places [7]. In the other, an extended matrix [8, 9], for the solenoid that contains information on the curved design orbit with respect to the solenoid axis has been utilized. In this case no artificial elements have to be introduced. The magnet slices have been made thin enough to assure that non-commutation of spin rotations does not present problems. The results from the two approaches are in good agreement.

2.2 Correction schemes

Fig. 2 shows the deviation of the horizontal and vertical trajectories from the curved design orbit in and near the H1 solenoid assuming that the beams collide on the solenoid axis. The vertical motion is coupled to the horizontal motion in the solenoid so that a small horizontal orbit distortion results. The calculations have been made for the so called Rev. 2 version of the lattice [4] using the sandwich model. In an updated version of the lattice the QG combined function magnet has been replaced by a pure dipole magnet called BG.

The orbit distortion will be locally corrected using dipolar windings on the QO and BG magnets, whereas the solenoid induced betatron coupling will be compensated by skew quadrupoles. For more details on the planned correction schemes, see [4].

2.3 Polarization

In the absence of anti–solenoids and if no special measures are taken, the periodic solution to the T–BMT equation $\hat{n}_0$, is strongly tilted from the nominal direction in the whole machine (about 60 mrad only from H1).

With three pairs of spin rotators in HERA $\hat{n}_0$ will be non-parallel to the field in larger areas of the ring and this will

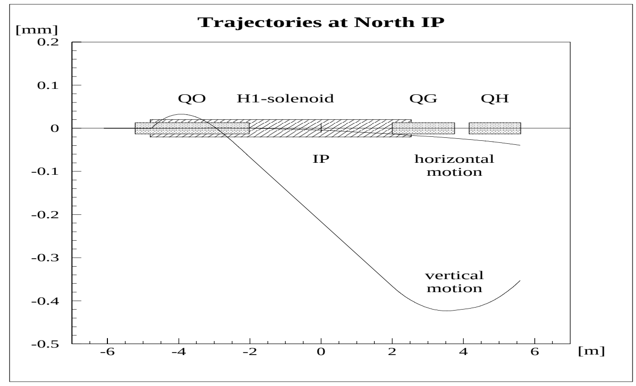

Figure 2: Uncorrected trajectories at North IP

result in a reduced polarization build up by the Sokolov-Ternov effect [1] (about 3% per rotator pair).

Note that $\hat{n}_0$ is not perfectly longitudinal when entering the experimental solenoids and that the solenoids are not centered with respect to the IPs. The resulting $\hat{n}_0$-tilt from the vertical in the arcs in this case can be compensated by using asymmetrical settings of the vertical bending magnets in the spin rotators [4].

Having arranged that $\hat{n}_0$ is vertical in the arcs one must consider the effects on the polarization from non-zero vertical dispersion and non-vertical $\hat{n}_0$ in large sections of the ring. It is therefore necessary to spin match [2, 11] the optics in order to minimize the spin diffusion. In spin matching the optics, the presence of the experimental solenoids has been ignored as a first step.

Linear calculations using SLIM/SLICK and the sandwich model show that the maximum polarization that can be achieved when the H1 solenoid is powered is reduced from 79% (ideal machine) to about 59%. The same calculations carried out after correction of orbit distortions, coupling and tilt of $\hat{n}_0$ axis give a maximum polarization of about 73%. (These calculations were made for the Rev. 2 version of the lattice.)

3 IMPROVED MODEL

The sandwich model is only a crude model and should not be used as a basis for the final spin matching. It has the obvious disadvantage that the mixing of the fields will not be complete because of the discrete nature of the slicing and, more seriously, it must contain non-physical hard-edge end fields for the solenoid slices to preserve symplecticity. These artificial end fields will not exactly cancel for consecutive solenoid slices due to the interleaved combined function (dipole) slices.

A completely different technique that avoids such intrinsic problems is the construction of the mixed field matrices from numerical integration of the orbital and spin equations of motion. We have followed this line and been able to produce a symplectic orbit map extended with two extra dimensions to describe spin as is required by SLIM/SLICK [6].

3.1 Orbit Calculation

The numerical integration of the orbital motion has been carried out in Mathematica 3.0 [12], using the full equations of motion with linearized fields. The solenoid has been implemented as a box-field (constant longitudinal field and hard-edge end fields), as a first attempt, for comparison with the sandwich model. A more accurate solenoid representation has also been tested, based on a parametrization of the measured field map [13], and using the first order Taylor coefficients for the field. The numerical integrator chosen is an Adams method. It gives similar accuracy to fourth order Runge-Kutta and is considerably faster in Mathematica. This integrator is not symplectic, but the deviation from symplecticity is so small that it can be taken care of after the integration of the mixed field region (instead of in every step with a symplectic integrator).

The reference coordinate system for the integration has been fixed on the solenoid axis and is not curvilinear. This was done in order to get simple expressions for the solenoid fields (the other elements look more complicated in this system). Before integrating various orbits, the curved design orbit, as defined by the dipoles, has to be determined. The canonical coordinates are reconstructed after the integration by means of a coordinate transformation. To improve numerical accuracy a switch to the common curved accelerator coordinate system will be made in the near future.

3.2 Symplectification

For a map to be useful as input to SLIM/SLICK (and other programs) it has to be symplectic. Since the chosen integrator is not symplectic, symplecticity must be restored after the integration. This will lead to slightly bigger numerical errors, but they stay at a level that we can tolerate. We symplectify the matrix using generating functions [14]: if, by integration, we can find a generating function that connects the initial and final coordinates and conjugate momenta, this generating function will by definition represent a symplectic transformation. It is found that for our particular case the generating function F_2 is most suitable. Applying the well-known relationship: $(\vec{q}_i, \vec{p}_f) = (\partial_{\vec{p}_i}, \partial_{\vec{q}_f})\, F_2(\vec{p}_i, \vec{q}_f)$ we can rederive the matrix that transforms the initial coordinates and momenta into the final ones. To fulfill symplecticity, the elements of the new matrix differ slightly from the original ones. Note that this transformation of the matrix is in no way unique.

3.3 Spin Calculation

The T–BMT spin equation has also been integrated with Mathematica. So far only the linearized form has been used. Three orthogonal spins have been tracked through the region of mixed fields. The three tracked spin vectors constitute the columns of a 3×3 spin rotation matrix. From this rotation matrix it is possible to construct the so called G-matrix [11], a 2×6 matrix that describes coupling of the spins to the orbit in linear approximation. Combining the 6×6 orbital matrix with the G-matrix we obtain an 8×8 matrix that can be used in SLIM/SLICK to describe the spin-orbit motion in the overlapping field regions. The agreement with the rough sandwich model is at the level we expect.

4 SUMMARY AND OUTLOOK

The effects of the H1 solenoid on the polarization for the Luminosity Upgrade design have been investigated using linear theory and correction schemes have been worked out. Several models have been developed and the results are in satisfactory agreement. More work will have to be invested in the model based on numerical integration of measured field data. So far the results look promising – we have been able to construct an 8×8 matrix (orbit motion and spin) that can be used by SLIM/SLICK and other programs. The integrated matrix is symplectic and looks reasonable when compared with the sandwich model. In a more refined model the tilts and shifts of the combined function magnets and dipoles in the IRs [3] will have to be included.

When a real machine with misalignment errors is considered the effects of the experimental solenoids becomes masked. In order to handle this situation mathematically we plan to use the SITROS code [15] in combination with the sandwich model/numerically integrated matrix. Nonlinear spin-orbit motion will also have to be investigated to give a better understanding of how dangerous higher order resonances will be in the new design.

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