POLARIZED BEAMS IN THE EUROPEAN HADRON FACILITY

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Abstract: In the design of the European Hadron Facility great emphasis has been put not only on the production of a high intensity beam (100 μA) but also on the capability to accelerate polarized proton beams up to final energy (30 GeV). We will describe in this report both the expected depolarizing effects and the planned correction methods. While we propose to use in the case of the EHF Booster conventional correction methods like harmonic spin matching and fast tune jumps, we suggest in the case of the Main Ring a pair of Siberian Snakes as cure for resonant depolarization. For the selection and the design of different types of Siberian Snakes we analysed both the spin and orbit behaviour in the magnetic fields of various snakes.

Introduction

The ability to accelerate polarized protons up to the final energy is one of the main objectives of EHF /1/. It strongly influences, together with the requirements of beam stability and minimum beam losses, the design of the accelerator complex. In particular the transfer energy between Booster and Main Ring has been selected to enable the use of Siberian Snakes /2/ as a global cure of resonant depolarization in the Main Ring. The lattice design provides the space needed to accomodate Siberian Snakes, which are a sequence of transverse magnetic fields rotating the spin by an angle of π around an axis $\vec{m}$ in the plane of the orbit but not affecting the beam orbit outside the snake. Thus the spin tune becomes 1/2 and independent of energy. Therefore no depolarizing resonance will be crossed as long as the width of a resonance ε is not exceedingly large /3/.

Depolarizing resonances occur, whenever the spin precession frequency $\nu = G\cdot\gamma$ coincides with the occurence of a perturbing magnetic field. G is the gyromagnetic anomaly of the particle. The width of the resonance ε_0 is given by the correspondent Fourier component of the perturbing field. It turned out that the strongest resonances are excited by the vertical closed orbit distortion and the vertical betatron motion respectively.

imperfection resonances	$\nu = k$
intrinsic resonances	$\nu = kP \pm Q_y$

P is the periodicity of the lattice. The amount of depolarization due to the crossing of an isolated resonance is obtained applying the Froissart Stora formula /4/

$$P_f = P_i\,[2\,e^{-\frac{\pi|\varepsilon|^2}{2\alpha}} - 1] \quad with \quad \alpha = \frac{G\Delta\gamma \pm \Delta Q}{2\pi}$$

P_f and P_i are the final and initial polarization values, and α is the crossing speed of the resonance. Δγ and ΔQ are the change in energy and tune in one revolution. However, one has to be aware that the Froissart-Stora formula assumes an infinitely wide jump over a resonance with a constant crossing speed. Taking a finite width δ for the Q-jump into account a formula derived by Courant and Ruth /5/ has to be used.

$$\frac{P_f}{P_i} \approx \frac{\delta^2 - |\varepsilon|^2}{\delta^2 + |\varepsilon|^2} - \frac{2|\varepsilon|^2\delta^2}{3\alpha^2}\,\frac{\delta^2}{\delta^2 + |\varepsilon|^2}$$

Depolarization in the EHF BOOSTER

The Booster lattice consists of six superperiods, each of which includes nine cells with a doublet focussing structure. Thus low amplitude betafunctions are guaranteed. Each superperiod shows a missing magnet arrangement, which due to the selected phase advance forms two 2π achromates. Therefore a long dispersion-free straight section needed for the installation of the accelerating RF-cavities can be added.

We plan to preserve the polarization in the Booster by standard techniques: correction of the correspondent harmonic of the perturbing field to cure imperfection resonances and fast tune jumps to cure intrinsic resonances. Both methods are presently used at the AGS in Brookhaven /6/, Saturn /7/, and at KEK /8/.

While the horizontal phase advance per cell is about 90° to push the transition energy well above the maximum energy of the accelerator, the vertical tune is selected to give an odd multiple of π/2 phase advance between successive fast pulsed quadrupoles installed in the straights of the missing bending magnets.

During the acceleration from 1.2 to 9 GeV, 14 imperfection and due to the periodicity and tune four intrinsic resonances will be encountered. The strengths of these resonances have been evaluated with the help of the programme DEPOL written by E. Courant. For the imperfection resonances we assume that all magnets are misaligned according to a Gaussian distribution with σ=0.1 mm. Figure 1 shows the relative polarization after crossing

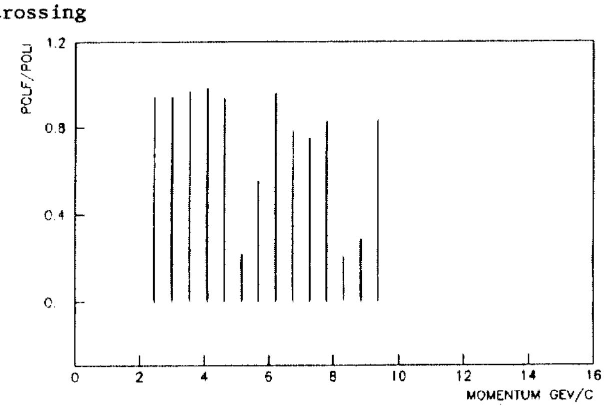

Figure 1. Depolarization due to imperfection resonances in the Booster

a single resonance. Apparently a harmonic correction is needed in order to preserve polarization in the Booster. In order to cancel the driving harmonics both in phase and amplitude, we plan to install in the center of each doublet a correction element, which will be pulsed with an appropriate amplitude and phase to minimize depolarization.

The effects of the intrinsic resonances have been calculated assuming a normalized emittance of 10 π mm

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mrad. Table 1 summarizes the strengths of the resonances, and the expected depolarizing effects assuming no fast Q-jump. Column 5 indicates the corrected situation calculated with the formula of Courant and Ruth assuming a fast Q-jump of 0.2, which has been established within one turn (1.7 µsec). We think that the overall depolarization effect in the Booster can be estimated to be of the order $P_f \approx 0.9\ P_i$.

TABLE 1: Depolarizing intrinsic resonances in the EHF Booster

$kP \pm Q_y$	γ	strength ε	P_f/P_i (F-S) $\Delta Q=0$	P_f/P_i (C-R) $\Delta Q=0.2$
18-	4.334	0.0028	0.885	0.9994
0+	5.706	0.0207	-0.890	0.9678
24-	7.681	0.0084	0.221	0.9947
6+	9.053	0.0152	-0.731	0.9820

Depolarization in the EHF MAIN RING

The Main Ring uses a FODO lattice with four arcs joined by dispersion suppressors and straight sections. The arc consists of seven regular cells with a phase advance per cell of 60° in both planes in order to push the transition energy below the injection energy. The dispersion suppressors consist of two cells, which have the same focussing structure as the regular cells of the arc but half the bending strength. In accordance with the phase advance of 60° all the bending power is concentrated in one cell and the second cell is free of any bending magnet. The dispersion-free straight section has an equivalent length of two regular cells, and is designed according to the requirements for the installation of snakes. A length of 16.2 m free of any element and with zero dispersion is provided. Thus a Siberian Snake even constructed with conventional magnets can be implemented.

Due to the low periodicity and large acceleration range (9-30 GeV) this lattice shows a copious occurence of depolarizing resonances: 20 intrinsic and 40 imperfection. Evaluatin the strengths of these resonances using similar assumptions as in the Booster, it turned out, that crossing all these resonances would be a laborious if not impossible enterprise. We therefore plan to adopt the Siberian Snake scheme to avoid the passage through a depolarizing resonance. As none of the EHF Main Ring resonances is stronger than 0.05, one snake should be sufficient to preserve the polarization in the whole energy range. However, in an one snake approach the longitudinal spin projection is preserved, and its orientation is independent of energy only opposite to the snake position. Thus one would have to inject and eject a longitudinally polarized beam at the azimuth π with respect to the snake position. This operation modus would suffer on flexibility and is not very attractive. We therefore prefer to preserve the vertical spin orientation in the ring for which one has to insert at least a pair of snakes with orthogonal rotation axes.

Siberian Snakes

There are many configurations of magnets discussed in the literature (e. g. /9/), which meet the snake criteria: rotating the spin by π and not distoring the orbit outside the snake. Comparing these different field distributions one comes to following conclusions:

- Configurations, which have a defined symmetry in the sequence of the field show clear advantages. Writing the spin transfer matrix through our device as a rotation:

$$M = e^{(i/2)\,\vec{m}\cdot\vec{\sigma}}$$

one component of the rotation axes m is zero, if the field distribution is symmetric on one plane and antisymmetric on the other (S-A) or if it is symmetric in both planes (S-S). This helps to meet the snake condition:

$$M = -i\sigma\cdot\vec{m} \qquad \text{with} \qquad \vec{m}\in(x,y)$$

- The use of a continuous wiggler field:

$$B = B_0(\sin ks, 0, \cos ks)$$

as proposed by E. Courant optimizes all snakes with a S-A symmetry. All such snakes can be built either with lumped dipole magnets (discretized snake) /11/ or as a continuous wiggler magnet (Helix). In both case a pair of corrector magnets are needed to restore the orbit.

- In many of these snakes one may reduce the required magnet apertures by adding further twists to the orbits within the snake (multi-twist snake) /10/. The gain in aperture, however, has to be traded off in length of the snake as can be seen from the equations of the trajectory.

$$x(s) = \frac{A}{2}(-\sin ks + d_1\theta + c_1)$$

$$z(s) = \frac{A}{2}(\cos ks + d_2\theta + c_2)$$

with a minimum aperture radius:

$$A = \frac{\mu^2}{B_0}\left[\frac{2mc}{eG^2}\right]$$

and a length:

$$L = 2\frac{\theta_0}{k} = \mu\frac{\theta_0}{B_0}\left[\frac{2mc}{eG^2}\right]$$

μ is a dimensionless constant that characterizes the snake. In case of a "well done" snake, i.e. if $d_1=d_2=0$

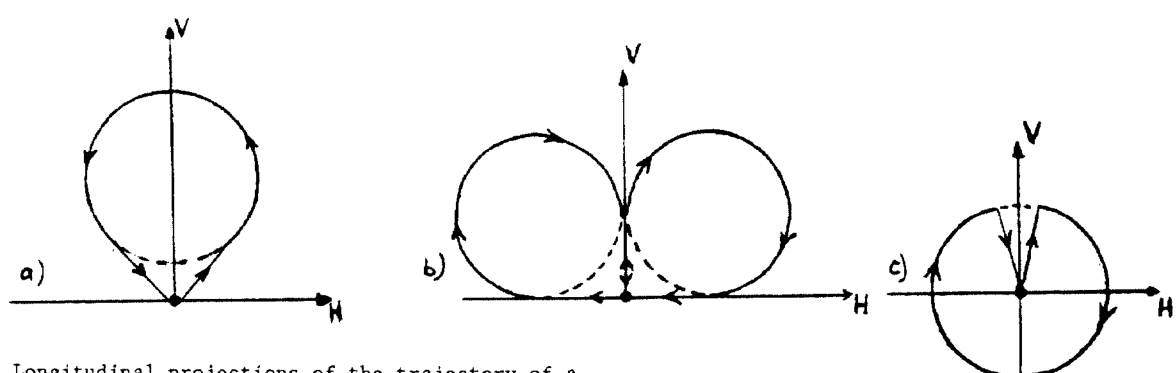

Figure 2. Longitudinal projections of the trajectory of a
a) Courant snake b) helical Steffen snake c) corrected Courant snake

by means of suitable correcting dipoles, the maximum orbit displacement is given by A. μ can then be evaluated as a function of Θ_0. It is found to have a negative slope /12/, which proves the advantage of increasing Θ_0, at least as long as $d\mu/d\Theta_0$ is large.

We would like to point at, that in principle both c_1 and c_2 have to be added to the displacement. But fortunately the first one is equal to zero due to the symmetry, and the latter can be adjusted to be zero by means of a second couple of corrector magnets.

Figure 2 shows the the longitudinal projection of the orbit for three typical snakes, and illustrates how the condition of a "well done" snake requires a tangentially injection into the wiggler magnet. The dashed part of the orbit indicates the case of a multi-twist snake.

There exists various possibilities to construct a snake with reasonable small magnet apertures even at lower energies, as can be seen from Table 2, where properties of a selection of Siberian Snakes are summarized. The snakes are labeled according to the names of their inventors. The set-up mode is indicated in brackets. The final choice between a continuous or a discretized snake is finally a problem of magnet engineering. Unfortunately all snakes with small aperture magnets are of S-A type for which the rotation axis always points into the direction of the beam propagation. Thus we have to look for a second kind snake, which rotates the spin around the horizontal x-axis.

TABLE 2: Properties of Siberian Snakes for a field of B = 3 T at 9 GeV

Snake type	Θ_0 deg	μ	A cm	ν
Steffen (discrete)	270	$\pi/4$	8.1	.500
(helix)	270	.8818	4.76	.500
(multi-twist)	450	.6633	2.70	.500
Courant (helix)	510	.591	2.13	.500
incl. correctors	468	.6388	2.50	.500
Steffen (left-pointed)	nwd	$\pi/2$	16.2	.500
Turrin (discrete)	90	$\pi/2$	16.2	.500
(helix)	90	1.86	21.2	.496
(multi-twist)	450	1.79	19.4	.452

(nwd = not "well done")

Such a snake, was proposed by Turrin /13/, which has a S-S symmetry, and can be regarded as a discretized version of a "well done" Helix: with two $\pi/2$ arcs of opposite helicity plus a central corrector bending. Figure 3 shows the orbit excursions in one half of the snake. In order to meet the snake conditions with this symmetry both tr M, and m_3 have to be zero in order to get $\nu=1/2$ and a horizontal rotation axis. For one twist ($\Theta_0=90°$) the solution is almost exact, but leads to pretty large orbit excursions at lower energy. Unfortunately a "multi-twist" optimization does not look possible in this case; in fact the introduction of a further twist ($\Theta_0=450°$) makes μ bigger, and ν more different from 1/2.

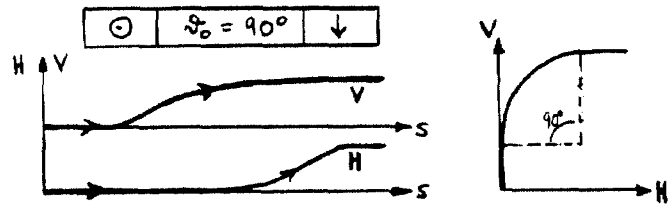

Figure 3. Helical version of Turrin Snake (half snake)

As a way out we studied a couple of left- and right-pointed snakes proposed by K. Steffen /14/, which both have orthogonal rotation axes at 45° with respect to the propagation direction of the beam. Unfortunately the orbit displacement in these snakes is still very large in the vertical plane. Again the introduction of a further twist does not improve anything. On the contrary due to the uncorrected lateral displacement the orbit excursion gets twice as large. Figure 4 displays the orbit excursion of a left-pointed snake, and demonstrates why a "multi-twist" optimization will not improve the situation.

We conclude that there doesn't exist a pair of snakes with both orthogonal rotation axes, and small magnet aperture requirements. As a way out one has to foresee a high injection energy in order to keep the orbit excursions small at injection. Otherwise one may use a one snake scheme with a "well done" snake, but then one has to inject a longitudinally polarized beam.

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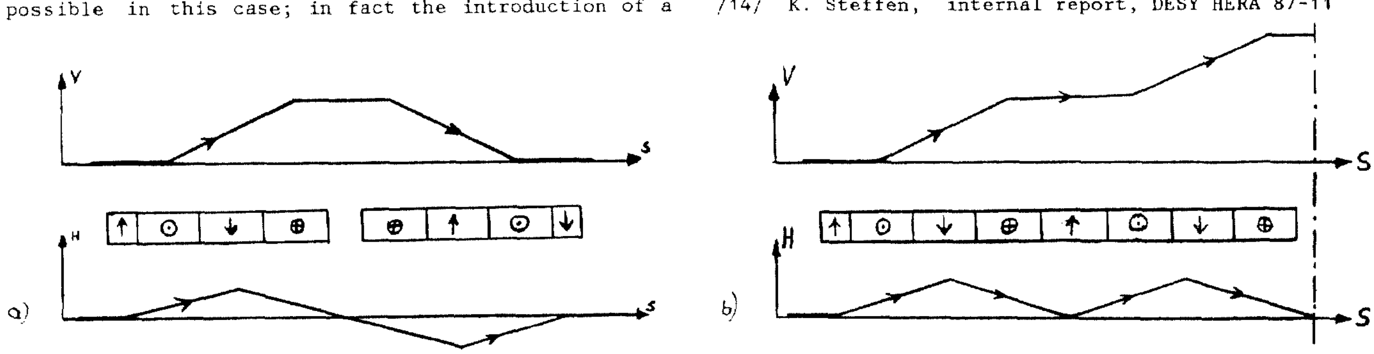

Figure 4. a) Steffen left-pointed snake
b) Steffen left-pointed snake with a further twist added (half snake)