A Short Matched Spin Rotator for LEP

H. Grote, E. Keil and E. Söderström
CERN
CH-1211 Geneva 23

Abstract A Richter-Schwitters spin rotator for LEP is described which is some 100 m shorter than an earlier version. The spin rotator can be installed in the straight sections surrounding the LEP experiments. Since it includes quadrupoles, spin-matching is not automatic. All optical conditions and the most important spin-matching conditions can be formulated such that standard beam-optical matching programs can be used to find the solution. The solution obtained is presented. The behaviour of the polarization in LEP is discussed.

1 Introduction

Richter-Schwitters spin rotators [1] are attractive for LEP because they can be installed in the long straight sections surrounding the interaction points (IP). At the Z_0 energy of 45.6 GeV, the bending angle needed to turn the spin from the vertical to the direction along the orbit is 15.1768 mrad. To leave the LEP geometry undisturbed outside the long straight section, small vertical deflections are needed at the far ends. Since the LEP lattice contains quadrupoles inside the spin rotator where the spin is not oriented vertically, the quadrupole strengths must satisfy extra constraints, the spin-matching conditions. The first spin rotator designed and spin-matched by Blondel and Keil [2] occupies a total length of about 442 m. Hence, most of the equipment in the long straight sections, and in particular the present and future RF cavities would have to be installed above and below the median plane. This paper describes a shorter spin rotator of some 325 m total length which provides adequate space for the installation of RF systems in the median plane.

2 Layout of the Spin Rotator

The schematic layout of half of the Richter-Schwitters spin rotator is shown in Figure 1. The other half is antisymmetric with respect to the interaction point IP at $s = 0$. The string of bending magnets B1 between the quadrupoles QS1M and QS4M bends the beam vertically by 20.4825 mrad, and the bending magnet string B2 between the quadrupoles QS7M and QS8M bends the beam by $\psi = -5.3057$ mrad. Compared to the earlier version [2], the bending magnet string B2 is two half-cells closer to the IP, and two extra quadrupoles have been added.

The maximum vertical displacement of the design orbit with the spin rotator from the median plane in the standard LEP configuration occurs in the B1 dipoles. It amounts to ±556 mm and is caused by the distance of these dipoles from the IP, although they are inserted into the LEP lattice at the nearest place to the IP where a straight section of adequate length is available. A larger distance from the IP would make it easier to shield the experiments from the synchrotron radiation emitted in the B1 dipoles. The properties of the dipoles in the spin rotator are summarized in Table 1.

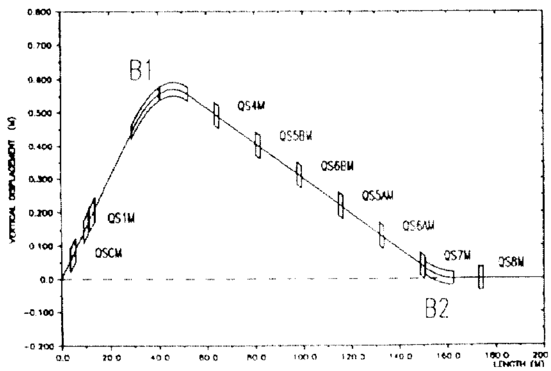

Figure 1: Layout of the Richter-Schwitters Spin Rotator

Table 1: Properties of Spin Rotator Dipoles at 45.6 GeV

Dipole	B1	B2	
Eff. length	23.1	11.55	m
Bending angle	20.4825	5.3057	mrad
Field	0.135	0.070	T
Radiation loss	1106	148	keV
Radiation power at 3 mA	3318	445	W
Critical energy	187	97	keV

3 Optical and Spin Matching

Since the spin rotator replaces a section of the standard LEP lattice, it has to be matched optically. The optical matching conditions are given below. In addition, the spin rotator has to satisfy spin-matching conditions which will be formulated below such that they can be solved by standard beam-optics programs.

Optical matching conditions

The spin rotator is inserted into the straight part of the LEP lattice occupied by the low-β and RF insertions, and must be matched to the neighbouring dispersion suppressor such that the values of α_x, α_y, β_x, and β_y at both ends remain unchanged when the spin rotator is installed. This yields four optical conditions. The new bending magnets bend the beam only in the vertical plane. Therefore, the vertical dispersion D_y and its derivative D'_y do not vanish any longer. Because of the antisymmetry of the spin rotator, D_y vanishes at the IP, but D'_y does not. Without matching, the vertical dispersion will propagate through all the arcs. This is undesirable because of the increase in the vertical beam size due to vertical quantum excitation, and because of the coupling for off-momentum particles. Looking from the arc towards the IP, one can start with $D_y = D'_y = 0$ at the end of the straight section, and impose the condition $D_y = 0$ at the IP. Hence there are five optical matching conditions.

Spin-matching conditions

The spin-matching conditions which are caused by the quadrupoles between the dipole strings of the LEP spin rotator and which have to be satisfied by a Richter-Schwitters spin rotator in LEP were given by Buon [3] and Blondel [4]. They are:

- The vertical phase advance μ_y from the IP to the centre of the B1 dipole string should be a multiple of π.
- The vertical phase advance μ_y between the centres of the B1 and B2 dipole strings should be a multiple of 2π.
- Spin matching of the horizontal betatron oscillations implies the following condition [4]:

$$\int_{IP}^{B1} K\sqrt{\beta_x}\cos\mu_x ds = \sin\xi \int_{B1}^{B2} K\sqrt{\beta_x}\cos\mu_x ds \qquad (1)$$

Here $\sin\xi = 0.521953$ is the projection of the spin vector onto the orbit between B1 and B2, and K is the quadrupole strength. As noted in [4], the integrals in Equation 1 are proportional to the change of the slopes of a particle starting at the IP with $X \neq 0$ and $X' = 0$. The two conditions on the vertical phase advance are familiar to standard beam-optics programs. The horizontal spin-matching condition can be expressed as a relation between the R_{21} elements of the 6×6 TRANSPORT [5] matrices R from the IP to the centres of the dipole strings B1 and B2 which are routinely calculated by standard beam-optics programs:

$$R_{21}(B2) = \frac{1+\sin\xi}{\sin\xi} R_{21}(B1) \qquad (2)$$

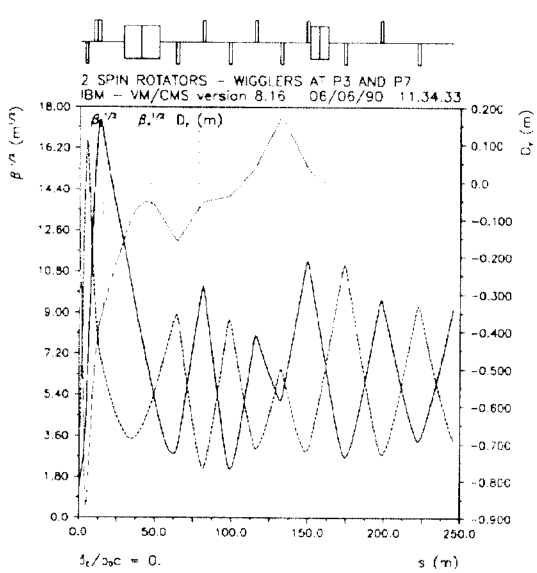

Figure 2: Orbit Functions in the Spin Rotator

Thus, eight conditions must be satisfied in total. One condition is on matrix elements, the other conditions are on orbit functions, e.g. α, β, μ, and D. The variables available to satisfy these matching conditions are the gradients of the eight independently powered quadrupoles QSCM to QS6AM shown in Fig. 1. Hence, there are enough variables to satisfy all conditions.

Matching Procedure

The earlier spin rotator for LEP [2] was matched with TRANSPORT [5]. Entering the constraints on the optical functions α and β, and on the dispersion D_y is straightforward [6]. The conditions that the vertical phase advances are multiples of π become conditions that the R_{43} elements vanish for a matrix which is initialized at the centre of the B2 dipole string. Eq. 2 is satisfied by performing arithmetic in and putting constraints on TRANSPORT registers [6].

The optical and spin-matching of the present rotator was done with the MAD program, using the new facilities for matching matrix elements and expressions. The MAD commands are shown in [7].

Table 2: Quadrupole Strengths for Spin Rotator

Quad.	Strength [m^{-1}]
KDSMN	-0.0354406089
KFSMN	0.0357073434
KQS6AN	-0.0471248813
KQS5AN	0.0421265550
KQS6BN	-0.0497624949
KQS5BN	0.0496453308
KQS4MN	-0.0419507362
KQS1MN	0.0382690728
KQS0MN	-0.1663265230

4 Spin Matched Solution

The optical properties of our solution are described first, followed by a discussion of the results of a spin simulation.

Optical properties of the solution

The solution satisfies all optical and spin-matching conditions. The quadrupole strengths after spin-matching are shown in Table 2. Each spin rotator increases the tunes by $\Delta Q_x = 0.6586$ and $\Delta Q_y = 1.2316$, since the matching does not impose a constraint on the phase advance in a superperiod with a spin rotator. Such constraints can be satisfied later by varying quadrupoles in the neighbouring dispersion suppressor.

The orbit functions through half the spin rotators are shown in Figure 2. Despite the extra conditions due to the spin-matching, the orbit functions do not differ much from those in the standard LEP configuration [8], apart from the vertical dispersion. The vertical dispersion is small in the vertical dipoles of the spin rotator because of the first two spin-matching conditions. Therefore the increase of the vertical emittance due to the emission of synchrotron radiation in these dipoles is also small. The ratio of the vertical and horizontal emittances was computed with the MAD program [7] for the case of spin rotators near two experimental pits. It was found to be 3×10^{-3}, about a factor of two smaller than that expected from the misalignments in LEP [8], and more than an order of magnitude smaller than that needed for optimum luminosity. With four spin rotators, the emittance ratio should be twice that value.

During injection and energy ramping, the values of β_x and β_y at the even IP's are about a factor of three higher than in the collision configuration. They are reduced to their nominal set-

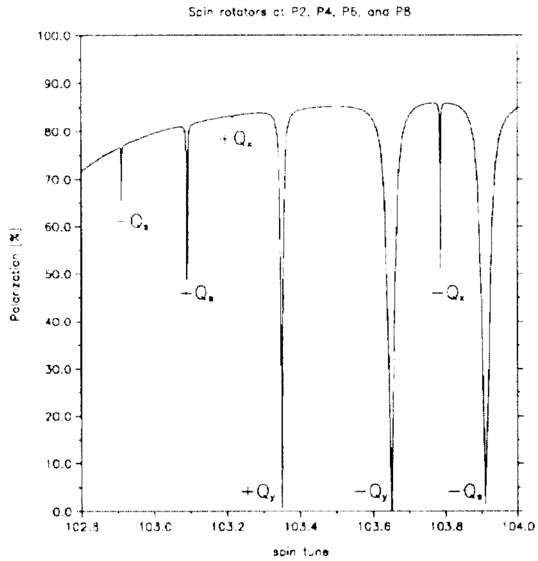

Figure 3: Polarization degree in LEP with four spin rotators. The tunes are: $Q_x = 74.21$, $Q_y = 82.35$, $Q_s = 0.088$. Machine equipped with polarization wigglers such that $\tau_p = 36$ minutes.

tings once the collision energy is reached. We have checked that there is a continuous tuning path between these configurations.

Spin simulation results

The program SMILE was used to calculate the depolarizing effect of the spin rotators in LEP. Since SMILE works with thin lenses, the matching was redone in TRANSPORT [5], each quadrupole being replaced by eight 1 mm lenses. A survey file with the new gradients was created with MAD and then translated into SMILE format.

SMILE is based on Mane's [9] extension of the Chao algorithm [10] that serves as the basis for SLIM. Both use a perturbative approach to calculate numerically the equilibrium polarization given by the formula of Derbenev and Kondratenko [11], under the assumption that the spin-orbit coupling is linear. However, whereas SLIM keeps only terms of first degree in the perturbation ω of the vector Ω in the spin equation of motion $ds/dt = \Omega \times s$, SMILE can take higher degrees of ω into account, in principle up to arbitrarily high degrees.

The convergence of the perturbative evaluation is governed by the term $\alpha = (a\gamma\sigma_e/Q)^2$, where $a = (g-2)/g$ and g is the gyromagnetic ratio of the particle, γ is the Lorentz factor, σ_e the energy spread, and Q the tune. In the case of LEP, $\alpha \simeq 10^{-6}$ for Q_x and Q_y, which leads to a rapid convergence of the depolarization terms caused by betatron motion. However, $\alpha \simeq 1$ for the synchrotron motion, meaning that these contributions converge very slowly, if at all. The net result of this is that when going to higher and higher degrees in the synchrotron terms, the polarization becomes smaller and smaller, to the point of practically vanishing. This, however, does not agree with other calculations, or with spin tracking calculations using the program SITF [12].

It was therefore decided to consider only the contributions to first order in the sidebands, up to which SLIM and SMILE agree. The result of this calculation is given in Figure 3 for energies around 45 GeV. The graph shows that no integer resonances are excited by the spin rotator, and that the overall depolarization effects are small. In particular, one notes that the effect of the Q_y sidebands remains limited, although the spin-matching was only done in the horizontal plane. The Q_s sidebands are even less pronounced at this order of the calculation.

The lattice includes the polarization wigglers suggested by Blondel and Jowett [13], but neither solenoids nor tilted quadrupoles.

5 Outlook

For the design of the spin rotator described here it was assumed that it would be installed within about two years from now in the present LEP configuration, which should therefore be modified as little as possible. It appears now that spin rotators will have to be installed much later – if at all – in a LEP configuration with a large number of superconducting RF cavities and possibly horizontal electrostatic separators for operation with more than four bunches in each beam [14]. A new layout is being studied which is even shorter and provides space for one or two cryostats with four RF cavities each between the magnets just outside the spin rotator. A total of 224 RF cavities can thus be installed in the median plane of LEP.

A spin rotator for a straight section surrounding an odd pit in LEP has also been designed and spin-matched. Since it does neither involve tilting the detectors of the LEP experiments, nor installing the existing or future RF systems above or below the median plane, it might perhaps be installed sooner in order to demonstrate the feasibility of spin rotation in LEP.

References

[1] R. Schwitters and B. Richter, PEP Note 87, 1974.

[2] A. Blondel and E. Keil, CERN 88-06, Vol. 2, 250 (1988).

[3] J. Buon, LAL-RT 88-02, 1988.

[4] A. Blondel, LEP Note 603, 1988.

[5] K.L. Brown, D.C. Carey, Ch. Iselin and F. Rothacker, CERN 80-04, 1980.

[6] D.C. Carey, Fermilab Report TM-1046, 1981.

[7] H. Grote and F.C. Iselin, CERN-SL/90-13 (1990).

[8] CERN-LEP/84-01, 1984.

[9] S.R. Mane, Phys. Rev. A36 (1987) 120.

[10] A.W. Chao, Nucl. Instr. Meth. **180** (1981) 29.

[11] Ya. S. Derbenev and A. M. Kondratenko, Sov. Phys. JETP **37** (1978) 968.

[12] A. Ackermann, J. Kewisch, and T. Limberg, to be published.

[13] A. Blondel and J.M. Jowett, CERN 88-06, Vol. 2, 216 (1988).

[14] J.M. Jowett, S. Myers, W. Kalbreier, Preparations for High-Luminosity LEP, this conference (TUP08L).