# INVESTIGATION ON COMPACT SPIN ROTATORS AT LEP

G. Guignard and J.P. Gourber
SL and AT Divisions, CERN
Geneva, Switzerland

## 1. Summary

In the following, compact spin rotators are referring to schemes made of two short rotator halves, each consisting of dipole arrangements in a drift space free of quadrupoles. Such schemes produce very localized orbit distortions and have the potentiality of being switched off on request as well as tuned at any momentum, within certain limits. Furthermore, most of the elements of the accelerator can be left in place and the beam optics is independent of the rotator setting, provided the orbit deviations be closed. These are the reasons for investigating the possibility of having in LEP compact, variable-energy spin rotators located in the straight sections at the end of the arcs. Symmetrical combinations of separate-field magnets and asymmetrical configurations with combined-field dipoles have been considered. From the point of view of geometry and optics, such schemes are possible. However, limitations arise from the requisite high fields and consequent synchrotron radiation. Hence, it was not possible to obtain solutions with small enough emittances and a high level of polarization simultaneously. We conclude from these studies that compact tunable rotators of the kind described are not applicable to LEP. The results might, however, be interesting in other possible applications. For instance, one of the special configurations discovered completes the list of such schemes that make it possible to generate the group of 24 rotation operators, associated with half-serpents, -snakes and -rotators.

## 2. Basic principles

The rotation of the spin of the $e^+$ and $e^-$ beams from the vertical to the longitudinal position requires an horizontal integrated field of 2.309 Tm [1], which also produces a vertical orbit distortion. The basic idea in the design of spin rotators consists in finding a set of magnets to be installed across the interaction region, which rotates the spin from the vertical to the longitudinal position at the crossing point and back to the vertical position while producing only a localized closed orbit bump.

Using the usual notation in which $H_i$ or $V_i$ stand for horizontal and vertical bending magnets (vertical and horizontal fields respectively) and the index i for the precession angle of the spin in degrees, the two rotator schemes which have been proposed so far for LEP can be written as follows:

- Richter-Schwitters type [2]:

$V_{-\varepsilon} V_{(90+\varepsilon)}$ Int. Point $V_{-(90+\varepsilon)} V_{\varepsilon}$

- Montague type [1,3]:

$V_{22.5}\ H_{180}\ V_{-45}\ H_{180}\ V_{22.5}$

Int. Point $V_{-22.5}\ H_{180}\ V_{45}\ H_{180}\ V_{-22.5}$

These schemes extend over long distances and produce beam displacements of the order of 0.5 m. They imply a permanent realignment of the machine along the deformed orbit with the following drawbacks:

- Many elements of the machine shall be displaced.
- The rotator rotates the spin by 90° only at the momentum for which it has been designed.
- The rotator cannot be switched off.

The various magnets of a rotator give rise to additional synchrotron radiation losses which must be compensated by the RF system. In that respect, the sum of the absolute values of the precession angles on one side of the interaction point can be retained as an indicator: the closer it is to 90°, the most "economical" is the rotator. Since the Montague rotator uses the main bending magnets to produce the rotations $H_{180}$, it is the most "economical" with a sum of 90°. The Richter-Schwitters design is also rather economical with a sum of $90° + 2\varepsilon = 153°$ in its last version [4].

Previous studies [5] succeeded in obtaining Siberian snakes and tunable spin rotators with mid-point longitudinal polarization and no net orbit deviations. Extending these results, we tried to investigate the practicability in LEP of such less "economical" but much more compact schemes located in the straight sections and made of two short rotator halves at the ends of the arcs (using eventually the weak-field dipole half cell). The first half would turn the spin by 90° into the longitudinal position and the second half would bring it back to vertical position, the spin remaining parallel to the propagation direction through the whole straight section in between. Such schemes produce very localized and small orbit distortions which can be accommodated by a large enough vacuum chamber or by displacing the magnets and vacuum chamber as a function of momentum (as for some HERA schemes). In this way, one gets a tunable spin rotator which rotates the spin by 90° at any momentum and which overcomes the inconvenience mentioned above for the presently proposed schemes.

## 3. Investigation of possible schemes

In reference 5, the author showed that basic rotations of the spin vector with specific rotation angles and axes can be associated with a group of 24 operators , isomorphic to the group of rotational symmetries of a cube. These 24 operators are noted A, C, D, E, I and S with variable indices, as described in the reference. The author also identified two magnet arrangements corresponding to operators $A_1$ and $E_2$ which satisfy our requirements. This does not exclude that other combinations of dipoles may achieve the same kind of transformations. Following another approach, a code was written to investigate any symmetrical combination of four horizontal-field magnets interleaved with four vertical-field magnets in half the rotator. The conditions imposed were a spin rotation from the vertical to the longitudinal direction as well as vertical and horizontal orbit distortions which could be of any kind (flat or sloping bumps made with three or four magnets) but should be localized in each half rotator only. Between the two rotator halves, the orbit and the machine geometry is unchanged, but the spin is longitudinal. Six possible solutions have been found after scanning the first two spin-rotation parameters and are given in Table 1, together with the sum of the precession angles.

| Solution number | Magnet type and precession angles for half a rotator | | | | | | | | Sum of angles |
|---|---|---|---|---|---|---|---|---|---|
| | V | H | V | H | V | H | V | H | |
| 1 | 90 | 90 | -180 | -180 | 90 | 90 | | | 720° |
| 2 | 90 | 90 | -90 | -180 | -90 | 180 | 90 | -90 | 900° |
| 3 | 90 | 90 | -180 | -90 | 180 | -90 | -90 | 90 | 900° |
| 4 | 90 | 90 | -180 | -180 | 180 | 180 | -90 | -90 | 1080° |
| 5 | 45 | 90 | -90 | -180 | 90 | 90 | -45 | | 630° |
| 6 | 45 | 90 | -45 | -180 | -45 | 90 | 45 | | 540° |

Table 1: Possible separated-bend schemes of short length spin rotators

Having, however, regard to the difficulty of getting a reasonable polarization degree with this kind of solutions, configurations with tilted dipole magnets and asymmetrical orbit bumps have also been considered. An existing code [6] was used for this purpose. The conditions imposed on the spin rotation and the localization of the orbit distortions were the same as above, but the fields were combined and the magnet arrangements not necessarily symmetrical within half a rotator. Some of these solutions are given in Table 2. The first number in brackets is the spin precession angle $\phi$, the second is the field inclination with respect to vertical and T stands for tilted bending magnets. These solutions do not seem really economical. However, some magnets may play the role of polarization wigglers, in particular in solution 10 that gives the highest polarization degree (Table 3).

| Solution number | Precession angles and field inclinations for half a rotator | Sum of angles |
|---|---|---|
| 7 | T(180.4, 49.4), T(163.9, -107.2), H(-180), T(99.6, -10.7), T(49.1, 66) | 673° |
| 8 | T(83.9, 60.3), T(117.6, -62.7), T(-101, -20.4), T(-121.8, -18), T(160.6, -53.6), T(90.2,77.4) | 585° |
| 9 | T(-58.3, 40.1), T(-2.7, 50), T(-105.3, 46.3), T(276, 54.2), T(128, -10.5), T(-188.3, 26.8) | 759° |
| 10 | T(-93.6, 26.8), T(19.9, 62.3), T(-111.3, 48.9), T(291.6, 42.5), T(90.4, -18.4), T(-57.2, 31.2), T(-108.8, 16.2) | 773° |

Table 2: Some combined-bend schemes of short length spin rotators

Solutions 1 and 5 correspond to the already quoted arrangements. Solutions 2 to 4 are new, but not very attractive since they require rather high integrated fields. Solution 6 is also new and interesting because it corresponds to a minimum radiation loss, though all solutions are less "economical" than the Richter-Schwitters or Montague schemes. Fig. 1 gives a sketch of orbit distortions and spin precessions for solution 6. This arrangement is associated with the operator E3 and its rolled version, obtained by inverting H and V, with the operator D3. It was also found that this configuration neatly provides the operations needed to complete the list of simple magnet configurations which rotate vertical spin into longitudinal spin [7]. Furthermore, two half-serpents of solution-6 type give a spin rotator if they have opposite polarities, and a snake of the second kind if they are identical.

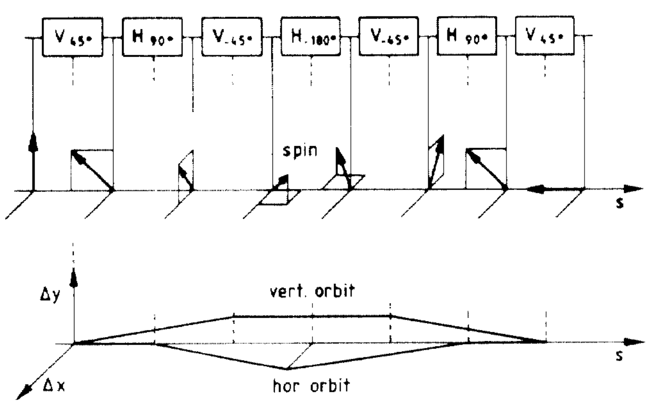


Fig. 1: Spin precession and orbit deviation in solution 6

## 4. Arrangement in the LEP straight section

The existing long straight sections on either side of the experimental interaction points are made of a low-beta insertion and by five regular half cells that contain or not RF cavities. They are followed by half a cell in which the low-field bending-magnets are installed.

In view of accommodating the space required for a tunable spin rotator, the straight sections have to be reorganized. The proposal described in this section is based on a series of layout modifications discussed hereafter. The weak-field bending-magnets are removed from the half cell enclosed by QS11 and QS12, and this half cell is suppressed. The first half cell in the straight sections, from QS11 to QS10, is also suppressed. The following four regular half cells (designed for RF cavities), from QS10 to QS6, are shifted towards the interaction point. As a consequence of this shift, the low-beta insertion becomes shorter, from 126.337 m to 114.665 m in our study. In order to achieve still small beta values at the crossing points, the relative positions of QS5 and the doublet QS3/4 with respect to QS6 and QS1 have to be modified. In the space created by the suppression of two half cells and the shift of another four, an insertion can be introduced with a long drift in which the dipoles of the tunable spin rotator can be installed. The length of the drift is equal to 55 m.

All these changes in the geometry imply modifications of the optics and rematching of the betatron functions. These modifications and additions are summarized below. Since the weak-field dipoles are removed, the preceding groups of four dipole cores must have a field 10% higher than usual and the dispersion suppressor that becomes shorter has to be rematched. The RF cell layout is kept identical and has not been modified in view of the superconducting cavity requirements. However, the phase advance per matched cell is now equal to 45° to make the adjustment of the shorter low-beta insertion easier. Once the dispersion suppressor is matched to the half cells of RF type, the spin rotator insertion is adjusted between these two sections of the machine so that one gets parallel beam with $\beta_x = 59.5$ m and $\beta_y = 60.6$ m at the centre of the long drift. This insertion includes two quadrupole doublets, one at each extremity, and a long drift in between of 55 m. The doublets are made of two quadrupoles, 2 m long and separated by 1 m. The total insertion length becomes 65 m. The shorter low-beta insertion was first rematched for the nominal values of $\beta^*_x = 1.75$ m and $\beta^*_y = 0.07$ m. Later, modifications of the machine parameters implied to study the possibility of adjusting the optics of this low-beta insertion for different beta-ratios, between 10 and 15.

With this arrangement, each half spin rotator comes immediately at the end of an arc. It is installed in a 55 m long drift totally free of quadrupoles and is followed by 4 standard RF half cells. Then, comes the low-beta insertion which begins with two half cells that have a length of 24.2 and 25.2 m and could also contain RF cavities or electrostatic separators if required. This layout combines the advantages that the RF cavities will all be installed in regions of the tunnel with normal slope and the absence of quadrupoles in the rotator halves is favourable for spin matching.

The betatron functions become rather different in the straight sections, compared with existing LEP and it is desirable to be able to modify the beta values at the experimental crossing points in an attempt to follow the emittance variations associated with the presence of the rotators. The studies made showed that it is possible to make the beta ratio equal to the emittance ratio and maintain the performance, for values ranging from the nominal 4% up to an extreme of 20%.

## 5. Spin matching and polarization level

The spin motion is perturbed by both betatron and synchrotron oscillations due to magnetic fields experienced by particles passing off-axis through quadrupoles. It is possible to reduce these effects by applying constraints to orbit functions in the whole rotator, i.e. in the straight section (s.s.) where it is installed. This reduction implies that the integral of the transverse fields over the straight section vanishes and imposes the following independent conditions [1], in the presence of non-zero dispersion functions across the rotator.

$$\int_{s.s.} K(\vartheta) D_x \, d\vartheta = 0 \qquad \int_{s.s.} K(\vartheta) D_y \, d\vartheta = 0$$

$$\int_{s.s.} K(\vartheta)\sqrt{\beta_x}\sin\mu_x \, d\vartheta = 0 \qquad \int_{s.s.} K(\vartheta)\sqrt{\beta_y}\sin\mu_y \, d\vartheta = 0$$

$$\int_{s.s.} K(\vartheta)\sqrt{\beta_x}\cos\mu_x \, d\vartheta = 0 \qquad \int_{s.s.} K(\vartheta)\sqrt{\beta_y}\cos\mu_y \, d\vartheta = 0$$

A nice property of the compact configurations studied is that these conditions are automatically satisfied. The first two are obviously satisfied since there are no quadrupoles where the dispersion is different from zero. The second two conditions are satisfied because the whole straight section is symmetrical with respect to the interaction point, i.e. the centre of the spin rotator. The last two conditions are equivalent to the cancellation of the coefficients $m_{12}$ and $m_{34}$ of the transfer matrix M from the entry to the centre of the spin rotator.

Since the chosen optics corresponds to a waist to waist (focus to focus) transformation between the middle of half-rotator dipoles and the crossing point, these last conditions are naturally fulfilled. Hence, spin matching is ensured across the straight sections equipped with the rotators discussed.

However, there are still conditions to make sure that the main arcs of the machine are spin-transparent for the vertical betatron oscillations induced by the photon emissions in the rotator magnets. There are four such constraints [1], which can be written as follows:

$$\int_{\text{arc}} K(\vartheta)\vec{x}.\vec{\ell}\sqrt{\beta_y}\sin\mu_y d\vartheta = 0 \qquad \int_{\text{arc}} K(\vartheta)\vec{x}.\vec{\ell}\sqrt{\beta_y}\cos\mu_y d\vartheta = 0$$

$$\int_{\text{arc}} K(\vartheta)\vec{x}.\vec{m}\sqrt{\beta_y}\sin\mu_y d\vartheta = 0 \qquad \int_{\text{arc}} K(\vartheta)\vec{x}.\vec{m}\sqrt{\beta_y}\cos\mu_y d\vartheta = 0$$

where $\vec{x}$ is the unit vector in the radial direction and $\vec{\ell}$, $\vec{m}$ are the unit vectors perpendicular to the precession axis $\vec{n}$. Nothing has been made specifically in the arcs, in an attempt to fulfil these constraints in the particular configurations considered. It is nevertheless interesting to mention that first order calculations of polarization indicate that, in perfect LEP structure with spin rotators, the spin matching across the arcs is rather good for a spin tune of 104 (Fig. 2).

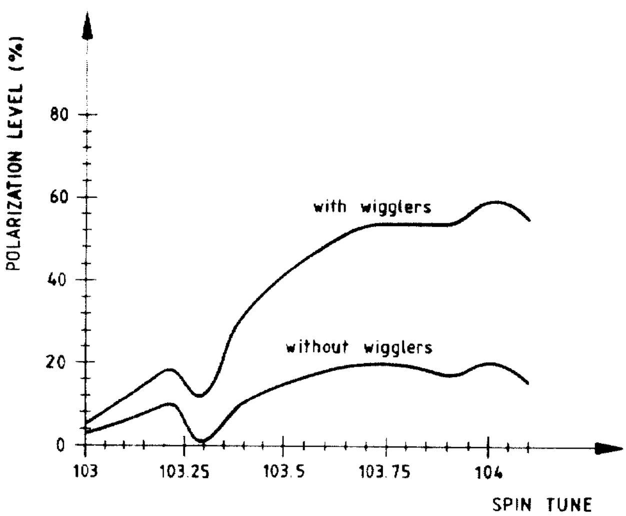


Fig. 2: First-order polarization of solution 6 with and without dedicated wigglers.

The asymptotic level of polarization is given by the following relation [1]:

$$P(t \to \infty) = -\frac{8}{5\sqrt{3}} \frac{\oint B^3 \cos\vartheta \, ds}{\oint B^3 ds}$$

where B is the amplitude of the magnetic field and $\cos\vartheta$ is the projection of the field unit-vector on the precession axis. This asymptotic polarization was computed for the spin-rotator solutions 6 to 10.

## 6. Particular schemes and obtained results

Among the possible separated-bend schemes, solution 6 was retained and then compared with the combined-field configurations of Table 2. Numerical simulations were carried out with the program PETROC in order to compute the beam parameters and the asymptotic polarization was deduced from the formula given in section 5. Some of the results are summarized in Table 3 and Fig. 2 gives the first-order polarization for solution 6 as function of spin tune.

| Solution | Max. $D_x$ (m) | Max. $D_y$ (m) | Emittance ratio (%) | Asymptotic polarization (%) |
|---|---|---|---|---|
| 6 | 0.194 | 0.116 | 7.3 | 18 |
| 7 | 0.293 | 0.185 | - | 7 |
| 8 | 0.218 | 0.124 | 20.3 | 35 |
| 9 | 0.278 | 0.255 | - | 54 |
| 10 | 0.358 | 0.211 | 40.0 | 61 |

Table 3: Characteristic parameters for particular schemes

The $D_x$ and $D_y$ values (or orbit amplitudes) are taken in the rotator halves. Going from solution 6 to 10, the dispersions and emittances have unfortunately the tendency to grow when the polarization level increases. For instance, at 46.5 GeV, the horizontal emittance rises from 35 to 100 nm.rad and the energy spread goes from 1.3 ‰ to 2.2‰. This encountered difficulty results from the total energy losses in the presence of 4 spin rotators, which range from 225 to 362 MV/turn. Solution 8 seems to be the best compromise we found, though the emittance ratio reaches the limit of feasibility for the optics of the insertion (Section 4). Solution 10, with an emittance ratio of 40%, is certainly not practical, even if it corresponds to the highest polarization level obtained.

As an exemple of tunability with beam momentum, one considers solution 6 that is the most favourable from the energy-loss point of view. Restricting the orbit displacement to ~ 20 cm, the lower limit in energy would be ~ 40 GeV. Assuming that the total energy loss with 4 rotators remain that foreseen without rotators, the highest momenta of 55 and 95 GeV/c attainable in phase 1 and 2 would be reduced to 49 and 91.5 GeV/c, respectively.

## 7. Conclusions

Present investigations show that, from the point of view of geometry and optics parameters, it is possible to design spin rotators made of two local insertions in the long straight sections of LEP. There is a good interval of momentum in which the schemes are tunable and the rotators can be switched off, keeping the geometry and the nominal conditions for collisions. Effects of synchrotron loss, also present in other designs, remain to be analysed. The major difficulty met results from the conflicting requirements of small vertical emittance and high degree of polarization. This made it impossible to find such compact rotators that give beam parameters required for the performance and a polarization degree close to the best possible value.

## References

[1] B.W. Montague, Polarized beams in high energy storage rings, Physics Reports 113 (1984)1.
[2] A. Blondel and E. Keil, A matched spin rotator for LEP, Proc. of Polarization at LEP, CERN 88-06, Vol. 2, (1988) 250.
[3] B.W. Montague, Spin rotation for LEP, CERN/ISR-TH/80-39 and LEP Note 256 (1980).
[4] E. Söderström, A matched short spin rotator for LEP, CERN/LEP-TH/89-58 (1989).
[5] T. Fieguth, Snakes, rotators, serpents and the octahedral group, Part. Accelerators, Vol. 22, No 3 (1987) 183.
[6] D. Plane, Spin program 3D, private communication.
[7] T. Fieguth and G. Guignard, to be published.