MEASUREMENT AND COMPENSATION OF THE SOLENOID EFFECTS IN LEP

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1. Abstract

The four experimental solenoids excite linear coupling and may induce orbit distortions in case of misalignment. Control is required to prevent large background and emittance. Coupling compensation is based on the perturbation theory of the transverse motion and the cancellation of both resonance coefficients C^+ and C^-. It has been precalculated for each solenoid considering the 8 skew-quadrupoles, symmetrically placed with respect to crossing point, and taking into account possible overlap of solenoid stray-field with quadrupole. Coupling minimization was based on the closest tune approach and the reference was a machine configuration that included the scheme compensating the linear stopband of the ring. Trajectories were also measured, and showed some local perturbations which were reduced with near dipoles. Both corrections with beam resulted in a good compensation of the solenoid effects.

2. Linear coupling evaluation

An analytical formalism [1], based on a perturbation treatment of the Hamiltonian, describes the coupled motion introducing the so-called coupling coefficients. These coefficients represent the driving terms of the resonances and are complex quantities, that become purely imaginary for a longitudinal magnetic field at the centre of a straight section. If such a field overlaps the field of a quadrupole, the coupling coefficients can, however, be significantly modified.

The most important resonances excited by linear coupling are the sum and the difference resonance. The distance from the working point is denoted by the following parameter.

$$\Delta^{\pm}=Q_x \pm Q_y - n$$

The coupling coefficients are given as [1]:

$$C^{\pm}=\frac{1}{4\pi}\oint\sqrt{\beta_x\beta_y}\left[2K+M\left(\frac{\alpha_x}{\beta_x}-\frac{\alpha_y}{\beta_y}\right)-iM\left(\frac{1}{\beta_x}\mp\frac{1}{\beta_y}\right)\right]\times$$
$$\times\exp\left[i\left(\mu_x\pm\mu_y-\frac{s}{R}\Delta^{\pm}\right)\right]ds \qquad (1)$$

M contains the longitudinal field of the solenoid, K contains the field gradient of the skew-quadrupoles, s is the arclength and R is the radius of the storage ring. Let us denote the coupling coefficients arising from skew – quadrupoles and solenoids by $C^{\pm}_{SQ}$ and $C^{\pm}_{SOL}$. Now the requirement of full compensation may be formulated easily.

$$C^{\pm}_{SOL}+\sum C^{\pm}_{SQ}=0$$

The summation has to be done over all skew quadrupoles that are excited to compensate the solenoid effect. Hence, there are 4 linear equations since C^+ and C^- are complex. In a thin lens approximation for the skew-quadrupoles only, this system may be written as follows:

$$\sum_j\frac{1}{2\pi}\left[\sqrt{\beta_x\beta_y}K_s l\right]_j\cos(\mu_x-\mu_y-\frac{s}{R}\Delta^-)_j+C^-_{SOL,r}=0 \qquad (2)$$

$$\sum_j\frac{1}{2\pi}\left[\sqrt{\beta_x\beta_y}K_s l\right]_j\sin(\mu_x-\mu_y-\frac{s}{R}\Delta^-)_j+C^-_{SOL,i}=0 \qquad (3)$$

$$\sum_j\frac{1}{2\pi}\left[\sqrt{\beta_x\beta_y}K_s l\right]_j\cos(\mu_x+\mu_y-\frac{s}{R}\Delta^+)_j+C^+_{SOL,r}=0 \qquad (4)$$

$$\sum_j\frac{1}{2\pi}\left[\sqrt{\beta_x\beta_y}K_s l\right]_j\sin(\mu_x+\mu_y-\frac{s}{R}\Delta^+)_j+C^+_{SOL,i}=0 \qquad (5)$$

where l denotes the length of the skew-quadrupoles.

In the case of a solenoid with a pure longitudinal field and centred at the minimum of the betatron functions, the coupling coefficients can be derived analytically from Eq.(1), using the known variation of the Twiss parameters in a drift space [2],

$$C^{\pm}_{SOL}=-i\frac{ML}{4\pi}\left[\sqrt{\frac{\beta^*_y}{\beta^*_x}}\mp\sqrt{\frac{\beta^*_x}{\beta^*_y}}\right] \qquad (6)$$

where L is the solenoid length and the beta-functions are taken at the crossing point.

In LEP, the solenoid field of the experiment L3 extends beyond the superconducting quadrupoles (QSC) that focuses the beam vertically on either side of the interaction region (IP), as shown by field measurements (Fig. 1). In this particular case, the integral (1) is made of two parts, covering either the drift spaces or the quadrupoles, and the corresponding betatron-functions have to be used. For the L3 solenoid, the following coefficients have been calculated at 20 GeV,

$$C^+ = 0.7976 - 0.1973\, i$$
$$C^- = -0.8901 - 0.3780\, i \qquad (7)$$

and can be compared to the values 1.2471 i and - 1.3511 i evaluated in the absence of the field superposition. The effect is to rotate the coupling vectors by an angle as large as ~70°. The same vectors have been computed for the other three experiments OPAL, ALEPH and DELPHI, where Eq. (6) applies.

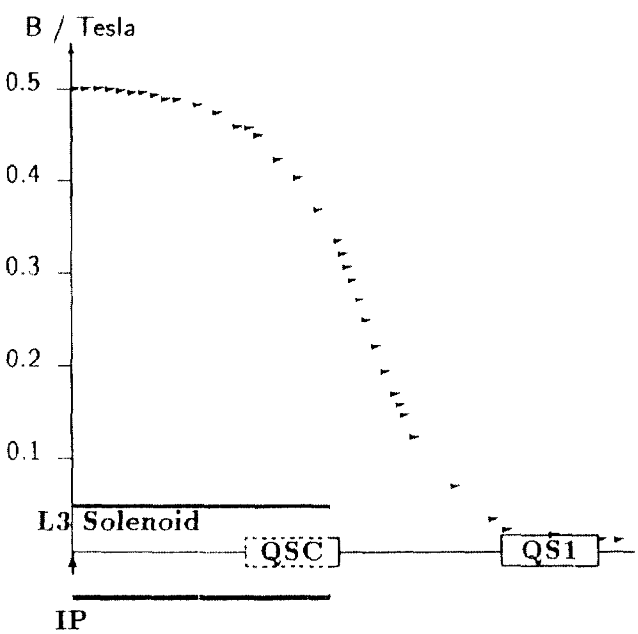

Fig. 1: Half the L3 solenoid field

With four skew-quadrupoles on each side of every solenoid, it is possible to decouple the transverse betatron motions outside the experimental straight sections as well as at the interaction point [3], to optimize the luminosity. The corresponding pairs of magnets are termed QT1 to QT4, the elements of a pair being symmetrically placed with respect to the solenoid center (Fig. 2). If these elements are antisymmetrically powered, they generate an imaginary component of C^- as for cancelling the contribution of Eq. (6), while they can also create a real component as required from Eq. (7) when they are powered with the same sign. The two magnets of pairs QT1 and QT4 are powered independently and therefore usable for the compensation of ring imperfections [4].

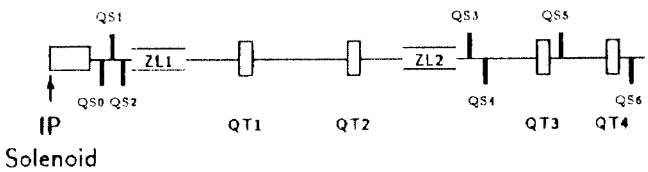

Fig. 2: Half insertion with solenoid and tilted quadrupoles

3. Compensation of solenoid coupling with back-up insertions

The reference used for this initial compensation is a machine configuration that includes the back-up insertions [5] and the QT1-scheme [4] for minimizing the linear stopband of the ring. In these conditions and the absence of solenoids, measuring the residual tune separation gave a value of 0.003. It has to be noted that this quantity is a direct measure of the modulus of C^- defined by Eq. (1).

With OPAL set at full current (i.e 2.6 Tm), the linear stopband is excited and the tune separation was found to be ~0.013 (calculated C^- is equal to 0.016). Precalculated compensation using the 8 tilted quadrupoles (6 independent power converters) symmetrically placed w.r.t. the solenoid was then set. The residual tune separation in the presence of this correction was back to the value of 0.003 (Fig. 3) quoted above.

When L3 magnet was ramped to nominal current of 30336 A (i.e 6 Tm), the tune separation measured was equal to 0.035. With the precalculated compensation of the same kind as for OPAL, the residual tune separation was between 0.01 and 0.014, depending on measurements. Adding a real component of C^- (origin at the solenoid centre) equal to + 0.015 reduced this separation to ~0.008 (Fig. 3) and this is the best result obtained at the time.

The superconducting magnet of ALEPH takes a very long time to be ramped and has the strongest field integral (i.e 10 Tm) corresponding to a tune separation of 0.062 (calculated, but not measured). The precalculated compensation using the 8 tilted quadrupoles sitting around point 4 gave a very good result, i.e. a residual tune separation of 0.006 (Fig. 3). An attempt of small adjustments of imaginary component of C^- around the precalculated value did not improve the result.

The superconducting solenoid of DELPHI also takes a long time to reach the nominal excitation current of 5000 A (i.e. 9 Tm). In this case, the compensation optimization had to be done in the presence of ALEPH-magnet, since the time needed for ramping it down is prohibitive. As for the other experimental magnets, the precalculated compensation was set. Fine adjustment of this correction indicated that the minimum effect was observed for a strength about 10% larger than expected. With this setting and two experimental magnets simultaneously powered, the residual tune separation was very good again, i.e. 0.003 (Fig. 3).

In general, precomputed coupling corrections were successful. Some adjustments were required in the interaction points 2 and 8. They may, however, correspond to a general minimization of the actual coupling around the ring, rather than to a local correction.

Trajectories have been measured also when the solenoids were switched on for the first time. In points 4 and 6, the experimental magnets of ALEPH and OPAL have no important effect on the trajectory. On the contrary, the magnets of L3 and DELPHI induce a significant perturbation of the vertical component of the trajectory. Measurements before correction clearly show that this component is flat with relatively small deviations up-stream from the solenoid considered, but makes large oscillations down-stream. Corrections were calculated by using a minimization algorithm and limiting the correctors to the CV's that stand between the QS6 quadrupoles on the left and right sides of points 2 and 8 [5]. In the case of L3, the

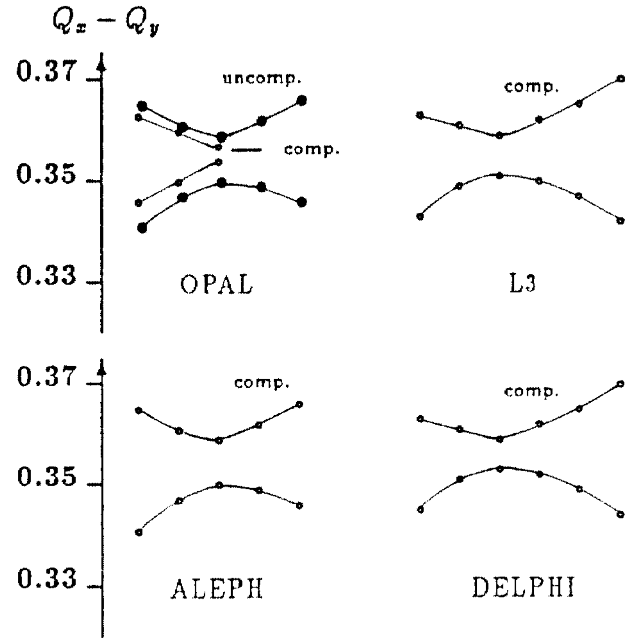

Fig. 3: Residual tune separations measured after compensation of each experimental magnet

algorithm selected at the first iteration already a corrector near QS1, i.e. close to the solenoid, and only in the next iterations correctors placed in the neighbourhood of QS4 and QS6 (Fig. 2). In the case of DELPHI, it is at second iteration that a corrector close to the solenoid (near QS0) was selected. Since the position of the imperfection sources was known, it was decided to apply only the corrections computed for the correctors close to the solenoids and to distribute it (antisymmetrically) on either side of each interaction point concerned (symmetric kicks create only a closed bump in the insertion, to first approximation). The total kick found by the program was 136 µrad for L3 and 124 µrad for DELPHI, vertically.

The next point concerns the coupling compensation when all the solenoids were powered simultaneously. Therefore, coupling adjustment was foreseen in the presence of the four experimental magnets, the QT4 ring-compensation scheme [4] and the back-up quadrupoles in the insertions. Starting with the setting found during individual compensations (see above), the real and imaginary components of C^- had to be incremented in order to minimize the measured tune separation. Both increments were generated by using the QT4 magnets and of the order of 10% of the requisite strength for the compensation of the ring only [4]. With this adjustment, the minimum tune separation measured was 0.007, at injection energy. Moreover, compensation of solenoids and experimental adjustments to minimize overall coupling gave successful results in the back-up insertion configuration, down to a vertical beta-value of 20 cm at even crossing points, after squeezing at 46 GeV/c.

4. Compensation of solenoid coupling with nominal insertions

For this compensation, the reference used is the nominal insertion at injection energy [5] and the QT4 scheme for minimizing the residual linear coupling coefficient of the ring [4]. The nominal insertions include on either side the two quadrupoles nearest to the interaction point, the first being superconducting and distant from the collision point by 3.7 m. By comparison, the back-up insertions use the second and third quadrupoles on either side of the interaction point, both running at room temperature. At 20 GeV, the insertions are detuned to larger β^*-values in order to reduce the machine sensitivity. In the nominal conditions described and the absence of solenoids, the residual tune separation was measured to be 0.002. This value is very close to the one obtained with back-up insertions.

For reasons explained in the previous section, L3 and OPAL experimental magnets could be ramped up, compensated individually and ramped down, since they have warm coils. The superconducting solenoid of DELPHI was then ramped up to a current of 2800 A, but not to the design top-current of 5000 A, for technical reasons. Once the compensation of DELPHI was achieved, its solenoid was kept on since the time needed for ramping it down is very long. The ALEPH magnet was ramped up then and compensated in the presence of the DELPHI magnetic field.

The precalculated compensation using 8 tilted quadrupoles symmetrically positioned with respect to the interaction point and 6 independent power converters, gave directly the minimum residual tune separation for the solenoids of L3, OPAL and ALEPH. For the DELPHI magnet, the excitation values of the tilted quadrupoles had to be increased slightly with respect to calculation in order to minimize the stopband, as it is shown in Table 1. With the four experimental solenoids powered simultaneously (and the nominal detuned insertions), the linear stopband measured of 0.004 confirms the validity of the individual compensations.

	Current (A)	Magnetic field (Tm)	Compensation/ calculation	Residual stopband
L3	30000	6	100%	0.003
ALEPH	5000	10	100%	0.003
OPAL	7000	2.6	100%	0.002
DELPHI	2800	5	100%	0.003
all four			103.5%	0.004

Table 1

As described previously, the stray field of the experimental solenoids may overlap the field of the first quadrupoles (on either side). The compensation of the DELPHI and ALEPH magnets is only slightly influenced by this effect, but the L3 solenoid (12 m long) compensation is dominated by the presence of the superconducting quadrupoles. Hence the coupling compensation of L3 depends upon the strengths of these quadrupoles and the betatron configuration used in the interaction region. For instance, during ramping from 20 to 46 GeV, the constant field of the solenoid is superimposed to increasing quadrupole fields. In a similar way, the conditions are changing during the squeeze (or reduction) of the β^*-values at 46 GeV. This implies that the coupling adjustment be redone at the end of energy ramping and beta-squeezing. Residual values of the order of those quoted above were also reached in these conditions.

One has seen that trajectories had to be corrected with the back-up insertions and the solenoids switched on. Major corrections were necessary near L3 and DELPHI, in the vertical plane. This remains true with the nominal insertions, but in addition the vertical orbit near ALEPH and the horizontal orbit near DELPHI had also to be corrected. Total vertical correcting kicks found are equal to 64, 48 and 19 μrad for L3, DELPHI and ALEPH respectively. The horizontal kick for DELPHI is 15 μrad. Differences can be observed for those corrections that are common to both insertion kinds, and they are likely to come from the local variations of the optics functions. Another difference comes from the fact that DELPHI was only powered up to 2800A in the nominal case, instead of 5000A for the other one, and the minimization program selects different correctors.

Experimental adjustment allowed to minimize successfully the linear coefficient and orbit distortions in the nominal configuration, at injection and top energy, before and after beta squeeze.

5. Other effects related to the solenoids

During the ramping process of the ALEPH solenoid, the tunes of the normal modes were actually shifted by 0.028 and -0.015, horizontally and vertically. The initial values of the non-integer parts of the tunes corresponded to a separation of 0.04. These measurements have been compared with numerical simulation results, that give tune shifts of 0.019 and -0.008 respectively for a separation of 0.07. Taking into account the difference in the tune separation, simulations are in good agreement with the observation. Tune corrections have been introduced.

Beam emittance ratio depends on coupling strength that is reduced by the compensation reported in this paper. It is nevertheless likely that the larger the initial coupling coefficient the more important the residual effect. Since one aims in LEP at an emittance ratio equal or lower to 4% after compensation, it is interesting to have an idea about it for different configurations of uncompensated solenoids, at nominal strength and all fields in the same direction. With betatron tunes separated by 6.07, the following results have been obtained.

Solenoid configuration:	$\varepsilon_y/\varepsilon_x$ at 20 GeV:
ALEPH on, others off	30%
L3, OPAL, DELPHI on, ALEPH off	16%
All magnets on	60%

The emittance ratio before any compensation is relatively small in the second configuration, in connection with the fact that μ_x-μ_y advances by 3π from one crossing point to the next with the optics considered. It follows that the initial effect of coupling on the vertical emittance depends on the choice of the tunes as well as the amplitudes and signs of the four solenoidal fields.

There is a particular effect in LEP associated with the fact that the tilted quadrupoles for solenoid compensation are interleaved with the electrostatic devices (ZL) that separate the beams vertically at the crossing points (Fig. 2). Since there remains some local coupling between the interaction point and the last skew-quadrupole on either side, the two normal betatron modes are not exactly horizontal and vertical in the separators, but tilted by about 5 degrees in the worst case. This generates a horizontal closed orbit deviation, that propagates over the whole circumference of LEP and cannot be compensated by magnetic orbit correctors. With the nominal optics and four solenoids with same polarity and the design fields, the r.m.s. horizontal orbit deviation is equal to 0.67 mm at 20 GeV and 0.15 mm at 46 GeV, assuming a vertical beam separation of ± 0.78 mm and ± 0.32 mm respectively. Any different polarity arrangement increases this orbit deviation. The peak value can reach 1.6 mm at injection and, if this has to be reduced, it is possible to minimize the solenoid coupling without using the quadrupoles QT1 and QT2 sitting between the two separators (Fig. 2). This decreases the r.m.s. orbit at 20 GeV to 0.16 mm at the expense of some small residual coupling that induces an emittance-ratio contribution of only 0.4%. During energy ramping and beta-squeezing, it is possible to use again QT1 and QT2 for an optimum compensation of the solenoids, since the effect on the orbit decreases with energy and the electrostatic separators are switched off when beams collide. This fine control of the orbit had not yet to be used.

6. Summary

In the absence of solenoids, the linear coupling was compensated in the ring by using either the QT1 scheme or the QT 4 scheme of tilted quadrupoles. Each experimental solenoid has then an independent correction, using four skew-quadrupoles on either side of each crossing point. These magnets QT1 to QT4 are installed near quadrupoles QS2, QS3, QS5 and QS6, in this order, and antisymmetrically powered to compensate solenoid effects. Precalculated compensations used the field integrals quoted in section 2 and cancel the driving terms of sum and difference resonances. Fine adjustment in the ring as well as a local correction of the vertical orbit were necessary for ALEPH, L3 and DELPHI magnets. Successful physics runs have been done including and superimposing coupling compensation and solenoid correction. A control procedure has now become operational for the compensation of the solenoid effects.

References

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