COMPENSATION OF LINEAR BETATRON COUPLING IN LEP

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1. Abstract

Beam observations brought into evidence the presence in the arcs of transverse coupling sources, with strong effects near the systematic resonance Q_x-Q_y = - 8. Analysis suggested to retune the machine away from this resonance, such that Q_x-Q_y = - 7 or - 6. Different configurations, obtained by varying the phase advance per cell or rematching the non-experimental insertions, were then tried. The best compromise for dispersion and orbit coupling was reached with the nominal phase of 60^o and Q_x-Q_y = - 6. Simulations showed that, with this tune separation, a second harmonic of skew-quadrupole had strong influence on the linear difference resonance. Compensation was based on this property and achieved by exciting the tilted quadrupoles installed in the four experimental interaction regions. Later, additional skew-quadrupoles in the arcs were used for ring-coupling compensation. Satisfactory coupling conditions were obtained for physics runs.

2. Observations

Early during LEP commissioning, direct observations of the beam on the screen of the synchrotron light monitors brought into evidence the presence of a large betatron coupling. With nominal parameters, one expects a vertical to horizontal emittance ratio of the order of 4%, the actual value depending on the imperfections in the machine. Looking at the two monitors placed in a dispersion suppressor, near the quadrupole QS12 where β_x = 28 m and β_y = 89 m and the quadrupole QS18 where $\beta_x \cong$ 50 m and $\beta_y \cong$ = 134 m, the beam was looking almost circular on the first one, where the nominal horizontal dispersion vanishes and only weakly elliptical on the second one. Furthermore, the main axes of the beam observed near QS18 were tilted, suggesting again the presence of linear coupling.

On the nominal optics, labelled A, the tunes are equal to 70.4 horizontally and 78.3 vertically. In these conditions, the actual emittance ratio was estimated to be of the order of 50%, i.e. much larger than expected. At this point, systematic measurements were carried on, using the principle of exciting an oscillation of the horizontal orbit in a limited section and measuring the resulting vertical perturbation [1]. The main conclusion was that the coupling source was not due to random imperfections, but rather originating from the arcs along which it is generally uniformly distributed. Simulations [1,2] based on these measurements predict correctly the strength of coupling, but give too small vertical dispersion and emittance ratio. The dominant contribution of the perturbation is the d.c. component, even so a significant first harmonic is present. This produces of course strong coupling for a tune split of Q_x-Q_y = 8q, q = 0, ± 1, ± 2, ...

This analysis suggested to retune the machine away from the strong linear resonance by decreasing the tune split from 8 to 7 and 6. This was first achieved by slightly changing the phase advance per cell in the arcs and adjusting accordingly the betatron functions, then by rematching the non-experimental insertions to modified phase advances. Coupling measurements were repeated in these different conditions and results are briefly summarized in Table 1. Optics B corresponds to Q_x = 71.4 and Q_y = 78.3, and optics C to Q_x = 71.4 and Q_y = 77.3.

Another interesting result from orbit transfer measurements is that the effect scales approximately with inverse energy. This indicates that the source is a constant (i.e. energy independent) skew component. Table 1 shows that the perturbations are still strong with optics B because of the presence of the first harmonic mentioned above. The optics C, with a tune split of 6, minimizes the orbit transfer and reduces betatron coupling in relation with the modulation introduced by the straight sections which do not contain strong skew

Measurement	Optics A	Optics B	Optics C
At 20 GeV			
Orbit transfer $\hat{y}/\hat{x}$	0.7 to 0.8	~ 0.5	~ 0.3
Width of Qx-Qy=p	0.2 to 0.4	0.04 to 0.05	~ 0.06
Emittance ratio	~ 0.5	~ 0.5	~ 0.3
At 47.5 GeV			
Emittance ratio	-	0.1 to 0.15	~ 0.10

Table 1

components. According to the measurements of the residual vertical dispersion [1], D_y is reduced by successive kick-cancellation in the arcs when the phase advance per cell is maintained precisely equal to 60^o. Hence, the best compromise for dispersion and orbit coupling was reached with the nominal phase and Q_x-Q_y = - 6.

3. Principles of the compensation

Once the best optics for minimizing coupling effects was defined, the next step consisted in minimizing the linear difference resonance. It is known from previous work [3] that the strength of this resonance is characterized by a complex coefficient C^- defined as:

$$C^- = \frac{1}{4\pi}\int_0^{C_L} \frac{\sqrt{\beta_x\beta_y}}{B\rho}\left(\frac{\partial B_x}{\partial x} - \frac{\partial B_y}{\partial y}\right) \exp\left[i\left(\mu_x - \mu_y - \theta\Delta\right)\right] ds$$

if the coupling sources are only skew-quadrupole components. C_L is the ring circumference and $\Delta = Q_x - Q_y - p$. For vanishing C^-, the bandwidth tends to zero and the associated emittance ratio is minimized, since [4]

$$\frac{\varepsilon_y}{\varepsilon_x} = \frac{|C^-|^2}{|C^-|^2 + 2\Delta^2}$$

Considering the origin of s at the centre of an experimental insertion, machine coupling imperfections generate a real component of C^-. For compensating this, one must create another component equal and opposite, and this is possible by using some of the the eight tilted quadrupoles installed in each experimental region in view of cancelling both the effects of the solenoids [5] and the machine residual coupling. From design studies [6], it came out that this could be achieved by two pairs of tilted quadrupoles QT2 and QT3 antisymmetrically powered and generating an imaginary component of C^-, with in addition two pairs QT1 and QT4 powered independently. Members of each pair are symmetrically located with respect to crossing point. When the members of a pair QT1 or QT4 have same strength with same sign, they generate a real component C^- that is aligned with the vector generated by arc imperfections. Both pairs can therefore be used for the ring compensation.

Numerical simulations [7] corroborated the expectation that a second harmonic of skew quadrupole component has a strong effect on the coupling resonance and vertical beam size. Indeed, such a second harmonic mixes with the strong eighth harmonic to create a sixth harmonic, that is very efficient since the tune split of the retained optics is equal to 6.

4. Compensation using QT1 tilted quadrupoles

Following the arguments developed in the previous section, either the QT1 or the QT4 magnets had to be used. QT1's were initially chosen. In order to generate the requisite second harmonic, the following excitation pattern of QT1 tilted quadrupoles was applied around the ring:

Position	L2	R2	L4	R4	L6	R6	L8	R8
QT1 polarity	-	-	+	+	-	-	+	+

Absolute normalized strengths for all QT1's: 0.006 m^{-2}

Absolute excitation currents for all QT1's: 20.07 A

The effect of this scheme was tested with back-up insertions by measuring the residual tune separation while crossing the resonance $Q_x - Q_y = 6$, that is proportional to the driving term of this resonance. For comparison, results are presented in the absence of compensation as well as in the presence of the QT1 scheme. Table 2 gives the fractional parts of the tunes measured as functions of the theoretical distance from the resonance and Fig. 1 shows the corresponding curves.

The results show the efficiency of the compensation scheme applied. After application, the tune separation is of the order of 0.001 (and the tune variation is almost linear), while it was 0.058 before. As a point of comparison, the strong solenoidal field of the ALEPH magnet separates again the tunes (fractional parts) by 0.067 approximately (measured value), and the value expected from the alignment imperfections is of the order of 0.015.

Tentative of energy ramping and betas-squeezing (in the presence of the four solenoids) indicated that the QT1-scheme with constant excitation currents was performing well during the ramp, but loosing its efficiency during the squeeze (high beam aspect-ratio). This can be explained from the fact that QT1's are near the strong focusing doublets and the optics functions change significantly at these positions when the betas are reduced at the crossing point. The measured relative variations of the vertical beam size clearly showed the efficiency loss of the compensation (relative increase of more than 60% when β_y was decreased from 80 to 32 cm).

5. Compensation using QT4 tilted quadrupoles

Since QT1 and QT4 are equivalent for the coupling coefficient C^- and QT4 magnets are placed near QS6 quadrupoles, i.e. at the extremities of the beta-bump of the experimental insertions, the use of QT4's should cure the effects observed during squeezing with QT1's. Calculations of the components of C^- show that the excitation current of QT4 has to be in the ratio 1 to 2 with respect to the current of QT1 for getting the same effect. This was tried with back-up insertions again and the following excitation pattern applied around the ring:

Position	L2	R2	L4	R4	L6	R6	L8	R8
QT4 polarity	+	+	-	-	+	+	-	-

Absolute excitation currents for all QT4's: 10 A

This improved scheme was quickly tested by measuring the residual tune separation that was found to be approximately 0.007 (no systematic search for the minimum). Without powering the experimental magnets, energy ramping and beta-squeezing were tried. The nominal vertical-beta of 20 cm (back-up insertion) was reached at 45.5 GeV in these conditions. No increase of the vertical beam size as deduced from the synchrotron light monitor signal has been observed during the whole process from injection to final configuration. No significant tilt of the normal modes could be deduced from the direct image of the beam. Since the machine appeared to be well compensated, this QT4 scheme was retained for the subsequent runs. Note that the strength applied in the QT4 corresponds to a C^- modulus of 0.057, in very good agreement with the measurement of tune separation before correction (0.058).

	No compensation		QT1 compensation	
DQth=(Qx-Qy)th	Qx	Qy	Qx	Qy
0.10	0.386	0.274	0.384	0.293
0.08	0.379	0.283	0.379	0.304
0.06	0.374	0.290	0.370	0.316
0.04	0.367	0.299	0.360	0.326
0.02	0.367	0.303	0.354	0.338
0.0	0.366	0.308	0.346	0.347
-0.02	0.369	0.307	0.340	0.357
-0.04	0.376	0.306	0.333	0.369
-0.06	0.382	0.303	0.326	0.382
-0.08	-	-	0.318	0.392

Table 2

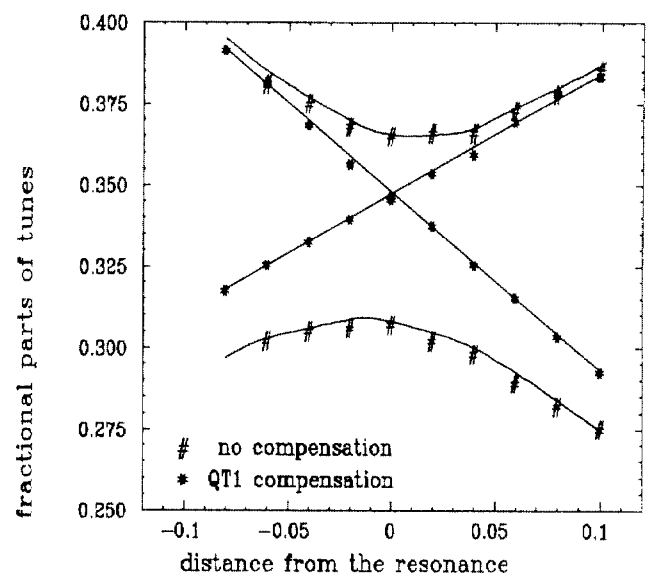

Fig. 1: Fractional parts of tunes as functions of the distance from the resonance, with and without QT1 compensation

In the latter compensation, one considers the back-up insertions, characterized by a distance from the crossing points to the first excited quadrupoles of ± 9.0 m and a vertical beta-value of 80 cm (injection value). The machine coupling is compensated in this case (20 GeV/c, optics C, Qx-Qy = -6) by powering the tilted quadrupoles QT4 to ± 10 A. Let us now turn to the so-called nominal insertions, associated with a distance from the crossing points to the first excited quadrupoles of ± 3.5 m (actual free space) and a vertical beta-value at injection of 21 cm. Since the QT4 magnets are placed near the QS6 quadrupoles, i.e. at the extremities of the beta-bump of the experimental insertions, the QT4 excitation should not change, switching from the back-up to the nominal insertions, assuming the coupling sources are located in the arcs (at least outside the beta-bump region). However, currents of ± 12 A were required for the nominal conditions in order to get a closest tune approach corresponding to $|C^-| = 0.002$. This 20% difference can be explained from the fact that the residual C^- was not accurately adjusted in the back-up conditions and from possible non-negligible tilts of the low-β quadrupoles where the betatron functions are different. Note that a careful compensation at 45.5 GeV required an adjustment of the QT4 scheme before and after squeezing to $\beta_y^* = 7$ cm, in relation with the second effect just described. Table 3 summarizes the setting values obtained for nominal (n) and back-up (b) insertions, β_y^* equal to 80, 21 or 7 cm and optics C, at two different energies.

Optics	Energy GeV	QT4.P2 Amps	QT4.P4 Amps	QT4.P6 Amps	QT4.P8 Amps
n21C20	20	12	-12	12	-12
n21C46	45.5	15	-15	15	-15
n07C46	45.5	14	-14	14	-14
b80C20	20	10	-10	10	-10

Table 3

6. Compensation with QTA tilted quadrupoles in the arcs

In order to distribute the correction in the arcs where the coupling sources are and to have additional control of related effects, 16 tilted quadrupoles, i.e. 2 QTA magnets per arc, placed near QF quadrupoles in the space left between the SF-coil end and the following flange have been installed. In each arc, the two tilted quadrupoles are separated by 9 cells; the one on the side of an even crossing point is at 4 cells from the arc centre and the one on the side of an odd crossing point is at 5 cells from the arc centre.

The integrated strength per magnet is approximately 1600 Gauss. The magnet length is 400 mm. The magnets are designed to be easily mounted around the vacuum chambers near the SF sextupoles or at the place of an orbit corrector. They are powered by the standard converters (5 A, +135 V) used for MCHA and MCVA correctors.

Considering the lattice with 60° phase advance per cell, the scheme proposed have pairs of magnets whose elements are separated by 3 π for the transverse phase advance, in phase for the difference resonance (μ_x-μ_y remains the same) and in phase for the sum resonance (μ_x+μ_y changes by 6 π). Hence, it allows independent control of coupling and vertical dispersion:

- Members of a pair have the same strengths: their contribution add for the coupling resonances and they create a minimum perturbation of the vertical dispersion (bump limited inside the 9 cells).
- Members of a pair have opposite strengths: their contribution to resonance excitation vanish near the stopband and they create an oscillation of the vertical dispersion around the whole circumference.

For linear resonance effects, the contributions of the 8 arcs (or 8 pairs) add and the design strength per magnet allows for compensating the coupling integral of the ring deduced from measurements. A modulation of the compensation per arc and a combination of the scheme with the QT4's are of course possible.

A pair of magnets powered to maximum current generates an almost purely real C^- component of 0.06 (origin at the nearest even crossing point, optics with tunes separated by 6) and corresponds to a normalized strength of $0.0018\ m^{-1}$ at 20 GeV (the integral of the perturbation over one arc should not exceed ~ $0.005\ m^{-1}$, according to measurements).

Since the elements of each pair are approximately at 1/3 and 2/3 of an arc, they tend to decrease the transfer of orbit deviations, when they have the same strengths.

For vertical dispersion adjustments, the vertical phase separation between the arcs (or pairs) makes it possible to combine pairs (whose elements have opposite strengths) in order to create two dispersion oscillations separated in phase by 90°. The peak of these oscillations is approximately 0.5 m in the arcs, i.e. of the order of the peak actually measured.

Using the formula for the coupling coefficient C^-, it is easy to compute the requisite strength of the QTA's that is equivalent to the QT4 excitation needed for a good compensation. Measurements of closest tune approach with the QTA scheme confirmed the efficiency of the correction. In this way, the compensation of the machine linear coupling is independent of the compensation of the experimental solenoids, since one uses different tilted quadrupoles placed close to the source of imperfections they are dealing with. This makes the operation a little easier, in particular during beam-size squeezing and the residual vertical dispersion was found to be ~ 30% smaller than with the QT4 scheme. The QTA's were also used to generate oscillations of the vertical dispersion since they stand in the arcs where D_x is maximum. The idea was to minimize possibly the residual D_y in the RF-cavity sections. At the time of the tentative, the resolution of the measurement made with an RF frequency sweep of ± 100 Hz only and the D_y amplitude were such that the minimization was actually not possible.

7. Complement to the QTA scheme

As briefly mentioned, it appeared that it would also be interesting to have means of controlling locally the vertical dispersion of the RF sections, as synchro-betatron resonances might be a source of limitation. This was achieved by complementing the QTA scheme with 8 additional tilted quadrupoles of same kind located on either side of points 2 and 6. There are 4 pairs of magnets installed at the extremity of the arcs 1, 2, 5 and 6 looking towards the experimental crossing. The elements of each pair are placed near the quadrupoles QS17 and QF21 where D_x is large. These 8 extra magnets allow to generate vertical dispersion bumps from one side of the crossing point 2 or 6 to the other, keeping D_y unchanged in the rest of the machine. Since the two elements of a pair are separated by 105° in vertical phase, it is possible to have such bumps across the RF-cavity regions either with a local maximum of D_y at crossing point or shifted by ± 90° around this position. Depending on the phase considered, the amplitude of the D_y-bump can reach approximately 25 cm at β_y = 84 m for injection energy. The linear coupling generated by these additional magnets is conveniently compensated by using the two pairs of QTA's sitting in the arcs adjacent to points 2 and 6. Promising results have already been obtained with beams.

8. Conclusions

Concerning linear coupling, the measured resonance width appeared to be much larger than the value expected from alignment imperfections and orbit distortions in sextupoles. On the nominal optics, the effects were so strong that the beam was almost fully coupled at injection energy. A new optics with a tune separation of 6 instead of 8 was therefore introduced, improving the operation of the machine. In these conditions, the measured bandwidth is equal to 0.057 with the back-up insertions and ranges from 0.068 to 0.045 with the nominal insertions. Compensation of linear coupling was possible with the tilted quadrupoles installed from the beginning near the experimental insertions for solenoid and ring correction. Other tilted quadrupoles have been added to have a better control on the coupling itself and related effects such as residual vertical dispersion. After compensation, the linear bandwidth was measured to be about 0.002. This good compensation does not solve all the problems since the anomalous field responsible for coupling does not seem to be a simple skew quadrupole.

References

[1] D. Brandt et al., Measurement of the LEP coupling source with a beam, this Conference
[2] J.P. Koutchouk, private communication (LEP Performance Note 29)
[3] G. Guignard, The general theory of all sum and difference resonances in 3D magnetic field, CERN 76-06 (1976)
[4] G. Guignard, Linear coupling in storage rings with radiating particles, CERN ISR-BOM/79-30 (1979)
[5] G. Guignard et al., Measurement and compensation of the solenoid effects in LEP, this Conference
[6] J.P. Koutchouk, private communication (LEP Note 480)
[7] G. Guignard, private communication (LEP Commissioning Note 5)