Realignment of LEP in 1993-1994

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Abstract

The vertical position of the whole LEP quadrupoles was measured in one month at the beginning of the 92/93 and 93/94 shutdowns. Large displacements were found in the 92/93 session, and were corrected. The simulation of closed orbit corrections including computation of vertical dispersion were used to specify realistic realignment tolerances. The errors found in 1993 were smaller and needed only local realignments.

1. MEASUREMENT OF THE VERTICAL ALIGNMENT

Since the start-up of LEP in 1989, only partial measurements and corrections were made for controlling the vertical alignment along the eight straight sections and in that part of the machine under the Jura mountain, since these areas were likely to be unstable. No special attention was paid to the regular arcs for three years, but increasing problems led us finally to undertake a complete measurement

The vertical position of the LEP quadrupoles was measured with a fully automatic high precision level of a new type [1]. Its optical axis is constrained to remain horizontal through a suspended prism, i.e. referring to the local gravity vector, like in previous models. The improvement dwells on the readout on an encoded invar staff, which is done via a CCD array, with image processing and automatic determination of the height of the sight within a few hundreds of a millimetre. This new facility exempts completely from the tedious optical reading through the eyepiece and the micrometer. It increases thus the efficiency and the reliability of the process. Along the forward-backward traverses, about 1600 points were measured twice at each complete loop around the machine.

The expected r.m.s. accuracy of the levelling process is 0.5 mm/km$^{1/2}$. However small systematic errors may increase this value. In the first complete measurement of the LEP ring with this device, larger discrepancies appeared in the closure of the loop and were corrected. Such misclosure errors are resorbed by the adjustment of the data and they have no significant consequence. This was coming from slight defects of the instruments, which were fixed later on. An angle of 1.3 µrad appeared also in the least squares fit of the median plane. Such an uncertainty has obviously no effect on the optics, as it is a mere change of reference frame.

The vertical positions of the quadrupoles obtained after subtraction of the position of the median plane from the original measurements is shown on figure 1.

The long range discrepancies between new measurements and initial data come partly from systematic errors at installation time, when the levelling loop was not constrained by fixed points and closure condition. Such variations are smooth and do not affect the beam orbits.

The dented deformations result from the geo-mechanical forces and strains which apply to the concrete structures of the tunnel : decompression effects, thermal constraints, hydro-static changes, micro-tectonic moves (subsidence of faults), cracks and moves of the floor, etc., as in other CERN tunnels [2].

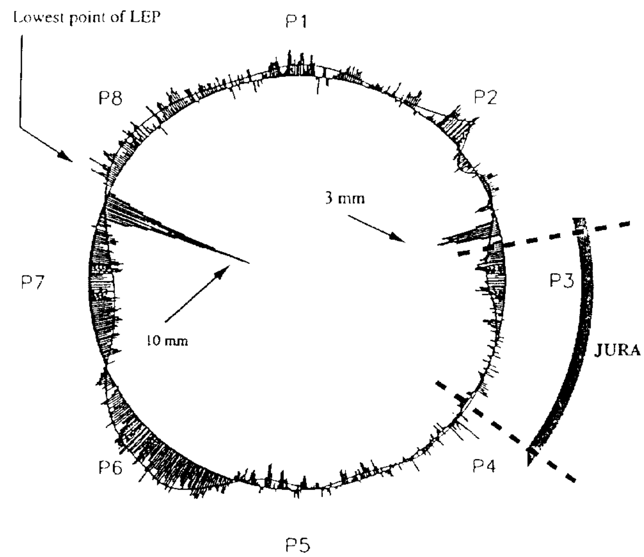

Figure 1.
Vertical position of the LEP quadrupoles at the end of 92 measured with respect to the best reference plane.

The large peak between P7 and P8 has an amplitude of -10 mm. The misalignment of the set of quadrupoles between P2 and P3 is about -3 mm. The r.m.s. value is σ = 0.65 mm w.r.t. the smooth polynomial curve (see below).

2. REALIGNMENT STRATEGY

The first step was to determine goal positions for the realignment. To this end, the above described measurements were fitted with a smooth curve consisting of overlapping polynomials. This curve is shown as a full line on figure 1. Piece wise functions were chosen because they are much easier to handle in our case.

Spline functions or a restricted break up into Fourier series could be used instead, but with some drawbacks. When trying to do an overall fit of a curve around the ring, many constraints and strong correlations are induced by the big bumps and holes of the deformation pattern - leaving large discrepancies or creating new ones. When using Fourier series, the limitation of the smooth fit to a given harmonic may leave a cyclic pattern of non-adjusted positions and generate resonant effects.

The use of successive "local" polynomials is more flexible and their span can be interactively adapted to the deformation pattern. The degree of the polynomials is always kept as low as possible, in order not to create undesirable oscillations. Singularities with a large amplitude, like subsidences near point 7 or point 3, are removed from the data when determining the local polynomials, and the overlap is chosen and weighted in such a way that the residual discontinuities of the link are negligible. This global procedure, based on common sense and a wide experience with other machines, is fully justified by the following analysis.

3. EFFECT OF THE VERTICAL MISALIGNMENT ON THE VERTICAL CLOSED ORBIT AND DISPERSION

The assessment of the quality of a realignment has been done by computing its effect on the vertical closed orbit and vertical dispersion by means of the MAD optics program [3]. To this end, the originally measured vertical positions of the quadrupoles, sextupoles and beam position monitors have been used to make a MAD input file which specifies their vertical misalignment.

As the measurements have been done after the experiments were dismounted, the positions of the low-ß doublets QS0 and QS1, which lay very close to the experiment, were not measured. This has to be kept in mind when considering the results below. As these quadrupoles had to be given a position, they were put at the average position of the last quadrupoles QS3 measured on both sides. Apart of the QS0's alignment, other important missing contributions to the vertical closed orbit distortion are :

- transverse tilts of the dipoles, which contribute to the vertical closed orbit,
- transverse tilts of the quadrupoles, which contribute to the vertical dispersion and coupling.

These associated realignments were treated separately. They are completely decoupled from the quadrupole realignment.

The vertical closed orbit distortion as well as the vertical dispersion (derivative of the vertical position w.r.t. momentum) computed both for the original positions and for several realigned machines are shown on table 1.

It is important to note that :

- vertical positions as in 1992 make the machine difficult to operate since ten correctors are not enough to obtain an r.m.s. vertical closed orbit distortion ensuring a circulating beam (from operational experience, the r.m.s. must be below 2.5 mm);
- the smooth curve defined by the survey algorithm is not the best one as it leads to an r.m.s. closed orbit of 2.14 mm;
- although the smooth curve is not the best one, it is a good realignment goal as the orbit correction is extremely easy once the quadrupoles are positioned on it;
- after the orbit correction for all cases shown on table 1, the tunes are changed by less than 0.0005 w.r.t. the tunes without any error. The damping partition numbers are changed by less than 0.02 and the vertical emittance is smaller than 0.1 mm. The computation is done with a 6-D algorithm implemented in MAD[3].

Table 1. r.m.s. vertical closed orbit distortion and dispersion due to vertical misalignment as a function of the alignment tolerance.

Alignment Tolerances (mm)	No C.O. correction		C.O. corr. 10 correctors	
	$\langle y \rangle$ (mm)	$\langle D_y \rangle$ (m)	$\langle y \rangle$ (mm)	$\langle D_y \rangle$ (m)
92/12 ∞	9.82	0.238	3.18	0.258
0.6	6.88	0.499	1.49	0.148
0.5	3.17	0.162	1.24	0.100
0.4	7.91	0.639	1.07	0.092
0.3	5.33	0.481	0.82	0.072
0.0	2.14	0.105	0.16	0.008
93/4 realign.	2.33	0.18	0.79	0.11
93/12 ∞	11.63	0.36	2.43	0.076
0.3	9.91	0.28	1.51	0.16
0.0	0.65	0.0097	0.104	0.0090
94/4 realign.	7.6	0.17	1.2	0.13
0	0.16	0.006	0.032	0.001

The alignment tolerance is the value of the magnet misalignment, measured w.r.t. a smooth polynomial of order less than 5, below which the quadrupoles are not realigned. If it is infinite, this means no realignment, i.e. measured misalignment. The LEP optics used for the MAD calculation has arc cells with 90° phase advance in the horizontal plane and 60° in the vertical plane, and the low-ß insertions are detuned (G21P20v2 in LEP nomenclature).

The estimation of the realignment effect with an optics program was a key point in the realignment strategy. Indeed speculating on the effect of a given realignment tolerance is meaningless, as a perfect alignment plane can never be defined by a levelling process over the 27 km circumference of the machine.

An important outcome of the computations was that the realignment tolerance does not have to be strict : as can be seen on table 1, there is a smooth degradation of the orbit quality when the tolerance is relaxed but nothing dramatic appears. This result in itself gave a good confidence in the realignment procedure.

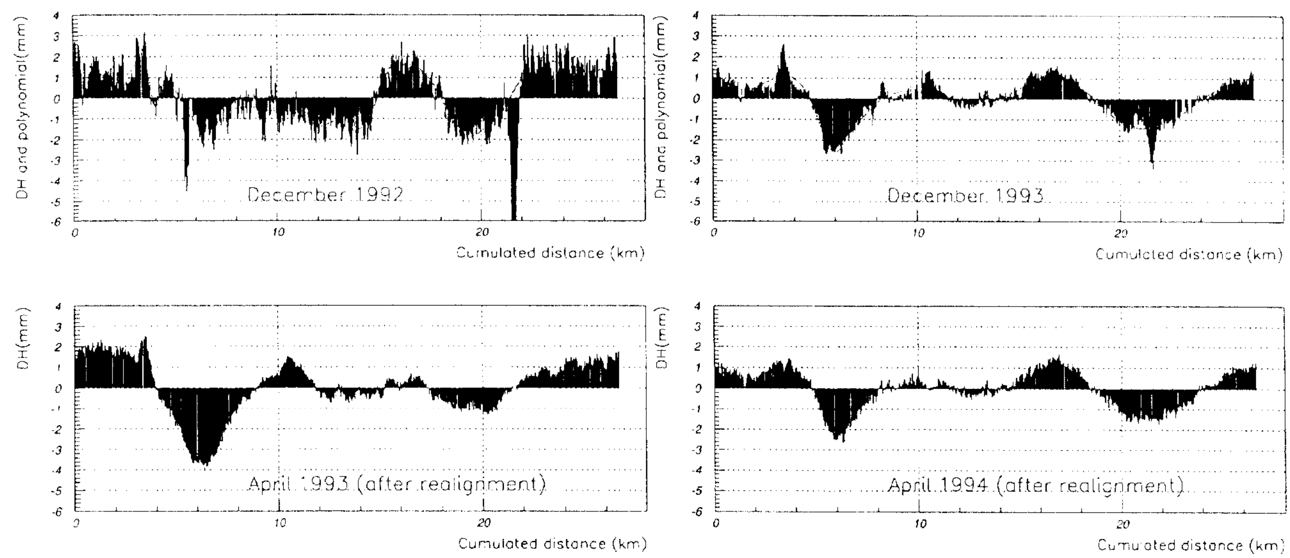

Figure 2. Vertical Alignment of LEP Quadrupoles

4. RESULTS FROM THE MEASUREMENTS AFTER THE 1993 START-UP

The main problems came from the QS0 alignment, which is in any case difficult, due to various restrictive factors. Subtracting the effect of these misalignments, the remaining r.m.s. vertical closed orbit distortion estimated after subtraction of the corrector contribution was 9.8 mm, i.e. substantially larger than the expected 2.33 mm. This is not surprising as the random survey errors were not included. These are about 0.06 mm r.m.s. between two neighbouring quadrupoles and the r.m.s. value of the realignment really done was 0.15 mm w.r.t. the polynomial. Such errors contribute on average to about 4 mm r.m.s. to the closed orbit distortion (MAD simulation), and therefore dominate. If the r.m.s. error is larger than 0.06 mm, or if the distribution of errors is unfavourable, a value of 9.8 mm as above can easily be explained.

5. RESULTS FROM THE MEASUREMENTS AFTER THE 1994 START-UP

The measurements done during the 93/94 shutdown showed that the motion which occurred during the first three years of the LEP life were still continuing (Figure 2). The subsidence between P7 and P8 was 3 mm. However, the alignment with such a degradation is still better than that found in 1992 as can be seen in table 1. Another improvement was included : the large misalignment around P2 was cancelled by a global elevation of the quadrupoles surrounding this pit. Thanks to the correct 92/93 realignment, a fit of the vertical offsets with five polynomials, against nine in 92/93, was possible for the whole ring. The better quality of the alignment curve appears in the much smaller r.m.s. distortion of 0.16 mm without any correction. However, the quality of the optics with the measured realignment seems rather worse than that obtained in 1993 (compare lines for 93/4 realigned and 94/4 realigned, in table 1).

This shows clearly that the realignments done in 1994 are at the limit of what is reasonable to be asked, although they seem definitely better than those of 1993. Furthermore, the polynomial reference of 1994 can be considered as a perfect goal. It is interesting to note that the maximum excursion associated with this reference is about 2.5 mm.

6. CONCLUSION

Surveying the whole LEP at the end of 1992 was extremely useful. It revealed large local misalignments which were detrimental to the machine optics.

A new procedure implemented in 1992, involving optics computations with various estimated realignments made it possible to assess reasonable realignment goals. It shows to what extend the measured misalignment was detrimental.

7. ACKNOWLEDGEMENTS

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