Alignment of low-b insertions with beam

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1. Introduction.

High energy experiments are simultanously aiming at high luminosity and low background rates from the accelerators and storage rings.

We will show that the alignment of the focusing quadrupoles in the experimental insertions has serious implications on the performance of the machines.

We will then describe the method developed at CERN for LEP to align the low-p insertions with the circulating beam itself.

We will finally present an attempt to use these techniques in the LEP experiment al insertions.

2 Effect of misaligned low-b quadrupoles.

The luminosity of colliding beams is given by:

$$\mathcal{L} = \frac{N^2 f_c}{4\pi\sigma_x\sigma_y} \tag{1}$$

where σ_x and σ_y are the r.m.s. beam sizes in the horizontal and vertical plane respectively, N the number of bunches and f_c the collision frequency.

A natural way to increase this luminosity is to reduce σ_x and σ_z in a low-β insertion. The beam size at the collision point is given by:

$$\sigma_z = \sqrt{\beta_z^\star E_z} \tag{2}$$

where E_z is the beam emittance in the plane labelled *z* and should be kept as small as possible.

In a space without focusing elements as an experimental area, the envelope function has a quadratic variation with distance, given by :

$$\beta(s) = \beta^\star + \frac{s^2}{\beta^\star} \tag{3}$$

where $\beta^\star$ is the value of the envelope function at the crossing point and s the distance from this crossing point. As the experiments need a large free space, the value of the envelope function at the first focusing quadrupole is the larger the smaller we want $\beta^\star$ to be.

At a location where the beam envelope function β is large, a misaligned focusing quadrupole will strongly perturb the closed orbit and produce a vertical dispersion in the machine. These perturbations scale with the square root of the β value in the quadrupole. They must be corrected since additional dispersion provoke an enlargement of the beam size at the collision point that will in turn affect the luminosity according to (1).

Strong orbit corrections will be applied to counteract the kick resulting from the misalignment of the quadrupoles, and this additional bending field will induce synchrotron radiation, thus increasing the background in the experiments.

To make life more difficult, the alignment of the quadrupoles with “standard” survey techniques is most problematic in these experimental area:

- The place is very crowded and the final focusing quadrupoles slide into the experimental set-up when in place. This makes it impossible to apply any direct visual alignment across the collision point and one must envisage complicated transfer of reference systems.
- The low-b quadrupoles also need to be very strong and are super-conducting magnets. The position of the coil axis is only known from fiducial marks outside of the cryostat and this adds an uncertainty on their alignment.

Combining all these errors, plus slow ground motions resulting from the displacement of heavy masses such as high energy experiments, the relative misalignment of quadrupoles situated on both sides of the collision point can reach the millimetre level.

3 Beam based alignment.

The preceding arguments call for a new alignment technique, using the beam itself as a reference. The basic idea is to turn off the low-b quadrupoles so that their relative alignment can be measured by means of the beam position monitors (BPM). Since the phase advance between corresponding low-β focusing quadrupoles on each side of the collision point is close to π, it is only their relative misalignment that matters, a common misalignment producing a localised closed orbit distortion called π-bump. Such a determination of the relative quadrupole positions is based on two measurements:

- The position of the quadrupole axis with respect to BPM’s, done by wobbling the quadrupole gradient. This subject is not covered in this note and we invite the reader to consult reference [1] for an extensive description of the usage of the K-modulation at CERN. We simply remind that we can presently determine the position of the BPM relative to the quadrupole with an accuracy of 100 μ-meter r.m.s..

- The alignment of the BPM in a region free of quadrupole fields where the particle trajectories are straight lines, and the definition of a reliable reference by means of the beam itself.

Potential problems result from the fact that some electro-magnetic fields still remain in the experiment al area and from the uncertainty on the beam position taken as a reference. We will first describe the optics of the insertion tuned for beam based alignment. We will then review the effects of parasitic electro-magnetic fields and of misalignment in the rest of the machine.

3.1 Insertion optics for beam based alignment.

The low-b insertions in LEP are schematized on figure 1 and we will concentrate on the final focusing quadrupoles QS0 and QS1A/1B.

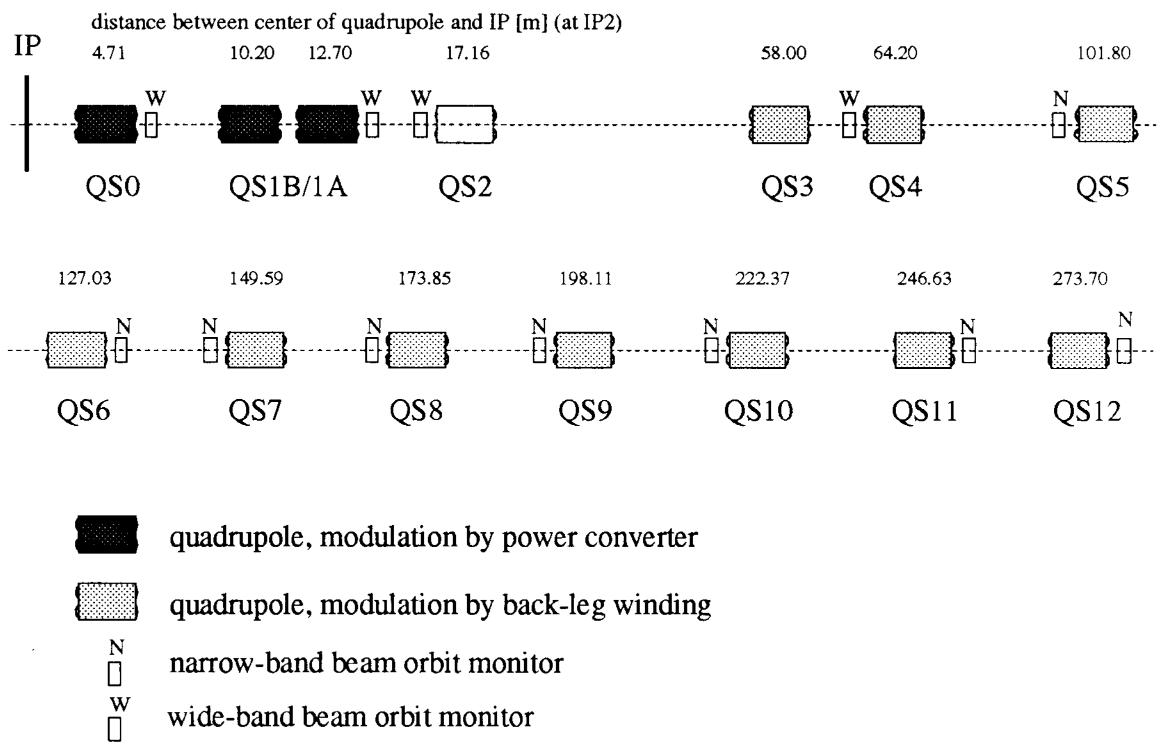

Figure 1: Location of quadrupole magnets and beam position monitors on the right side of a LEP experimental insertion. This arrangement is symmetrical around all even IP's.

QS2's are not used, and the optic rematched with QS0 and QS1A/1B switched off is shown on figure 2. The integer part of the horizontal and vertical tunes have been adjusted to odd values in order to be less sensitive to betatron mismatch.

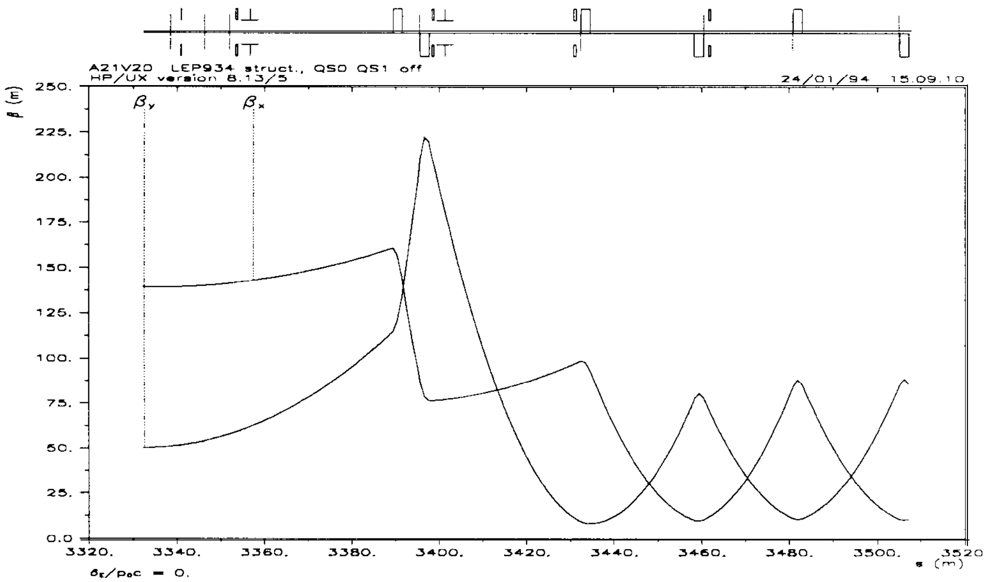

Figure 2: Horizontal and vertical b-functions in the physics insertions for the alignment optic with QS0 and QS1A/1B switched off. The crossing point is on the left, the derivative of the β-functions are made zero to make the functions symmetrical with respect to the IP. Note the parabolic variation of both β-functions in the field free region close to the IP.

3.2 Parasitic electro-magnetic fields.

The largest contribution comes from the earth magnetic field over a drift space of 120 meters between the QS3's. With a vertical component of $4.2 \cdot 10^{-5}$ Tesla, we get a sagitta and thus an horizontal displacement at the IP's of about 1.1mm at 20 GeV/c. In principle, the effect could be taken into account with reference trajectories being slightly curved instead of perfectly straight (note that the curvature will change with the beam energy). It is in fact an uncertainty since we do not know how much of this field is shielded by the various ring component and the experiment itself. It is then preferable to measure the relative alignment of the BPM's at the nominal energy of the machine where:

- The remanent field errors become less important in comparison to the main fields.
- The deviation from a straight line due to the earth field is the same as during operation.

The image current induced by the circulating charges in the vacuum chamber could also lead to trajectory distortions when the beam is not centred. It has been shown in reference [2] that this effect is negligible in the case of LEP.

3.3 Stability of the reference orbits.

The low-b quadrupoles QS0 and QS1A/1B will be aligned with respect to straight trajectories joining the QS3's on both side of the collision point. These references are closed orbits and their positions depend on the overall alignment and correction of the whole ring. The corresponding uncertainty can be estimated through simulation techniques using the optics program MAD [3] in the following way:

- The vertical positions of the quadrupoles, sextupoles and BPM's have been taken from the survey measurements and modified adding a random misalignment with an r.m.s. value of 0.15mm. This is slightly larger than the error on the positions expected in the arcs (see reference [4]) in order to be pessimistic.

- The closed orbit has then been corrected such that its r.m.s. value is 0.6mm or just below, as usually done in operation. The orbit correctors in the low-β insertions are not used in order to keep the trajectories straight in these areas.

- The calculation is repeated with 21 different distributions of random errors and the orbit positions at QS0 and QS1A/1B are recorded.

This calculation finds a standard deviation of the difference between the positions of the orbits at the QS0's of 0.044mm. This gives the magnitude of the uncertainty on the relative position of the QS0's due to the stability of the reference orbit.

We conclude that this uncertainty, rounded to 50 μ-meter, is still below the error on the relative alignment of the BPM with the quadrupoles, which is actually about 100 μ-meter. Furthermore, correcting the orbit with an r.m.s. of 0.6mm provides a good reference.

4 Machine experiments.

The first attempt to measure the relative alignment of the BPM's with the beam itself was performed during a LEP machine development (MD) session in August 93. Little time was available since for beam based alignment, the few MD periods being devoted to increase either the luminosity or the energy of LEP. It is only lately, in September 95, that we had an opportunity to resume the study.

4.1 Beam based alignment in 93.

A circulating beam was easily obtained after all low-b quadrupoles, QS0 and QS1's, where turned off, the closed orbit correctors having being taken from a standard run at injection. In order to make the beam go straight in the IP's, the correctors close to the experimental area were turned off progressively, making simultaneous closed orbit distortions. When this was done, an horizontal "bare orbit correction"[1] with 48 horizontal correctors and 10 vertical ones was done, the correctors close to the IP's being disabled. This gave a good closed orbit with an r.m.s. value below 0.6mm in both planes.

We then measured the BPM's response in all experimental insertions, and figure 3 shows such results for the experimental area 6 where the OPAL detector is installed

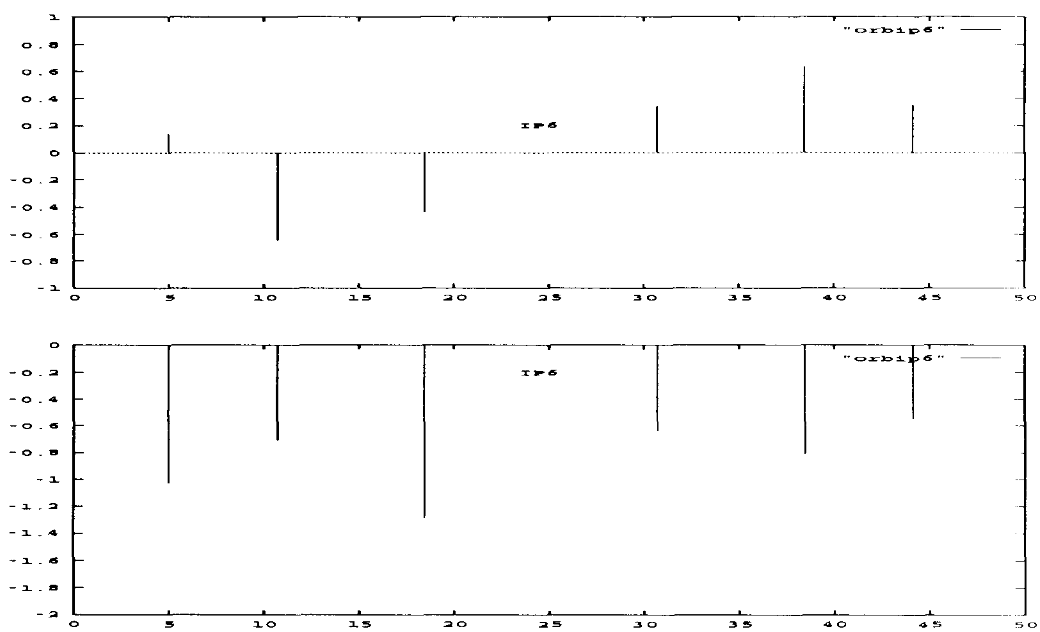

Figure 3: Orbit measurement for BPM's PU.QS2A.L6 to PU.QS2A.R6. The vertical scale is in millimetre, the horizontal one in meter. Upper curve : horizontal plane, r.m.s. deviation from straight line 0.35mm. Lower curve : vertical plane, r.m.s. deviation from straight line 0.23mm.

In absence of a reference for alignment, we used straight lines to fit these measurements. The r.m.s. residuals of the three BPM's on each side of the IP's, obtained for the 4 experimental insertions, ranged from 0.17mm to 0.60mm in the horizontal plane and from 0.13mm to 0.32mm in the vertical one.

The K-modulation technique to align the BPM with the coil axis was not routinely available at that time and we could not deduce the relative positions of the quadrupoles. However, their misalignment is of the same order as the BPM's and this illustrate that "standard" technique can lead to an off centring on the millimetre scale, as discussed previously.

[1] in the jargon used at LEP, the bare orbit corresponds to the orbit that, when corrected with the actual corrector strengths, gives the observed position in the BPM's. It can be determined at any time and corrected in a controlled way with a given number of correctors.

4.2 Beam based alignment in 95.

The alignment optic with QS0 and QS1A/1B switched off was applied in the experimental insertion at point 2 (L3) and 6 (OPAL). The beam was correctly injected, but at the contrary of what happened in the previous test, it was quite difficult to achieve the first turn and it was not possible to obtain circulating particles.

As the closed orbit was not available, it was not possible to use it as a reference for the alignment of the low-p quadrupoles. However, single pass measurement could still provide interesting alignment information. The K-modulation procedure to align the BPM's with respect to the coil axis has been applied in the vertical plane only and has been used to correct the measurements. We concentrated our analysis in this plane where we successively studied the error on the relative trajectory positions and estimated the vertical relative alignment of the QS0's.

4.2.1 Error on the trajectory positions.

A typical trajectory recorded during this MD session is shown on figure 4. It presents the beam position with respect to the quadrupoles, since their relative alignment with the BPM's are taken into account by the LEP monitoring system.

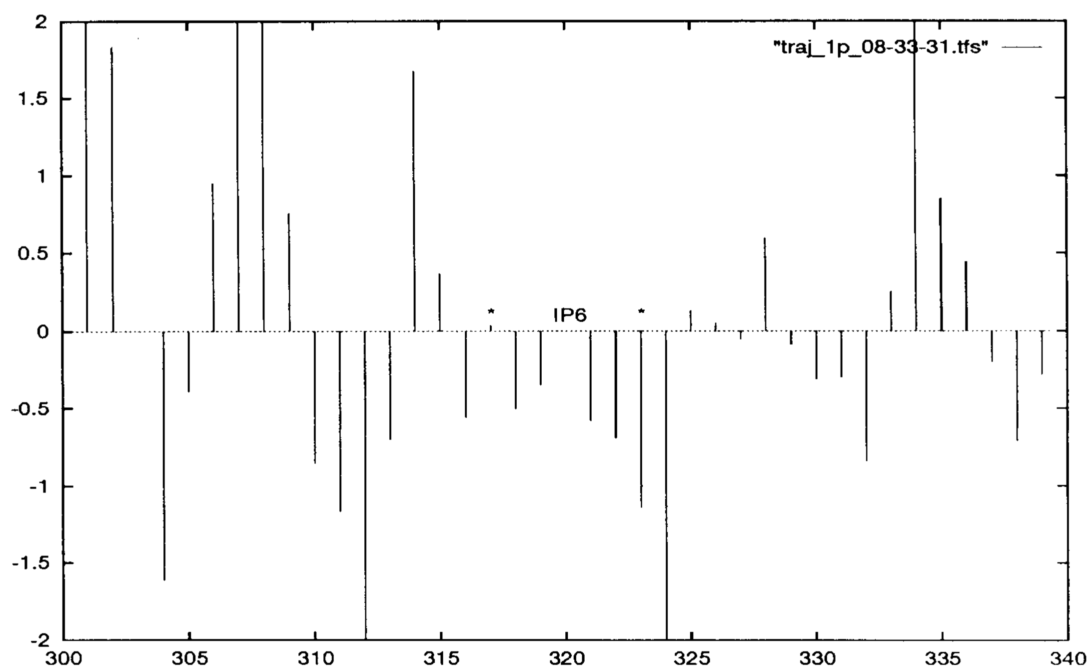

Figure 4: Typical vertical trajectories in IP6. The measurements with stars are those of QS3. The straight line between these measurements do not appear clearly on the plots because of the BPM misalignment and the horizontal coordinate which is the BPM number and not the longitudinal coordinate.

We have several measurements of such trajectories and their differences must be straight between the QS3's. A statistical analysis allows to disentangle the fluctuation due to injection instabilities from the accuracy of the BPM's in the following way:

- Take the first measurement as a reference, fit it with a straight line.
- Fit a series of subsequent measurements with a straight line.
- Compute from the difference between the reference fit and these fits the coordinate change at the measured points and add it to the first measurement.
- Make the difference between the measured positions and the latter.
- Do the statistics on this difference.

This statistics is shown for IP6 in table 1.

Table 1: Estimation of the reproducibility of the single pass measurement from 6 measurements in IP6.

BPM	QS2.L6	QS1A.L6	QS0.L6	QS0.R6	QS1A.R6	QS2.R6
average difference	0.03	0.20	-0.03	0.04	-0.01	0.24
r.m.s. difference	0.06	0.14	0.21	0.22	0.20	0.32

If the non reproducibility of the single pass measurements came from a pure noise, the average difference between measured values and values estimated from the change of the straight line around IP6 would be well below the r.m.s. difference:

- This is the case for four of the BPM's. For them the reproducibility is about 0.2mm r.m.s..
- For two of the BPM's there is apparently a drift or a discontinuity in the measurements as the average difference is of the same order as the r.m.s. difference.

We can thus estimate the accuracy of a single pass measurement to 0.2mm r.m.s., which is in good agreement with the reproducibility of the closed orbit measurement during normal operation.

4.2.2 Estimation of the vertical relative alignment of the QS0's.

We could go further and estimate the relative alignment of the QS0's on both sides of the collision points. We consider a line parallel to the straight line fitting the measurements and passing through QS0 on the left side of IP2 or IP6, and look at its position inside QS0 on the right side of the IP's. The results are shown on table 2, based on the analysis of 4 trajectories in each of the 2 insertions.

Table 2: Realignment estimation for QS0 on the right of IP2 and IP6 with respect to QS0 on the left. The uncertainty concerning the realignment is the standard deviation of the estimates done on four trajectories.

Insertion	r.m.s. fit residue	realignment of QS0.Rx
IP2	0.50	-0.14±0.12
IP6	0.13	-0.15±0.10

There is unfortunately another uncertainty concerning the average slope of the trajectories with respect to a reference given by a corrected closed orbit. We observed a vertical oscillation of ±2.5mm r.m.s. upstream of the insertions, measured at the BPM's where the envelope P-function has a value of 150m. This corresponds to a maximum vertical angle of the trajectory of $\pm\frac{2.5mm}{150m}$ at these positions, which in turn translates into a maximum vertical slope variation of $\pm\frac{2.5mm}{150m}\cdot\sqrt{\frac{150m}{\beta_{QS0}}}$ between the QS0's. The value of β_{QS0} can be read on figure 2 and is about 50m for the alignment optic, again in the vertical plane of motion. The QS0's being spaced by approximately 10m, we see that this uncertainty could affect the results of table 2 by ±0.3mm.

Although this analysis does not allow to realign the low-b quadrupoles in insertions 2 and 6, it still gives us some confidence that there is no important misalignment in these areas.

5 Conclusions.

The alignment of the low-β quadrupoles in the intersection regions is of paramount importance for the performances of the machine, both in terms of luminosity and of background affecting the experiments.

We have seen that “traditional” survey techniques are limited in these areas. A beam based alignment procedure has great potential, whenever associated with the positioning of the beam monitors with respect to the quadrupole coils now available through K-modulation. We could in principle achieve a relative alignment of the low-b quadrupoles with a precision of 0.12mm, where 0.10mm is due to the error on the alignment of the BPM's with respect to the coil axis and 0.05mm comes from the fluctuation of the orbit taken as a reference.

Preliminary results obtained on LEP are very encouraging and we will of course continue to develop such techniques.

References

[1] I. Reichel,"Beam position measurement by modulation of quadrupole strengths," Diplomarbeit at the RWTH, Aachen, Germany.

See also F. Tecker,"Dynamic beam based calibration of orbit monitor at LEP,"these proceedings.

[2] F. Bordry, P. Collier, A. Verdier,"Check of the BPM alignment with the LEP beam," SL-MD Note 99 (September 6, 1993).

[3] H. Grote and F.C. Iselin,"The MAD program (Methodical Accelerator Design) version 8.10, User's reference manual," CERN/SL/90-13(AP), (rev. 3)) (January 19, 1993).

[4] A. Verdier,"Analysis of the vertical LEP alignment measured in 1995," SL Note/95-69(AP) (June 26, 1995).