MEASUREMENT OF THE LEP COUPLING SOURCE

J. Billan, D. Brandt, A.M. Fauchet*, T. Fieguth†, J.P. Gourber, G. Guignard, L. Hand‡, A. Hofmann, K. Hübner, J. Jowett, E. Keil, J.P. Koutchouk, A. Millich, H. Moshammer, T. Risselada, L. Rivkin§, F. Ruggiero, R. Schmidt, E. Weihreter¶
CERN
CH-1211 Geneva 23

Abstract Early during the LEP commissioning it was discovered that there was an abnormally large horizontal to vertical optical coupling in the vicinity of the resonance $Q_x - Q_y = -8$. Precision beam measurements were undertaken to hunt for the source. Measurements of the closest tune approach, of the coupling of horizontal to vertical orbits and of the coupling of dispersion were performed. These measurements pointed to a weak source within the dipoles, which was independent of energy, not constant around the ring, and which showed the symmetries of skew quadrupole and skew sextupole. Comparison with magnetic measurements showed that the source could be identified as being a magnetized thin layer of nickel used to clad the lead shielding onto the aluminium chamber. Retuning the optics away from this resonance (to $Q_x - Q_y \approx -6$), allowed near normal operation of the machine. The linear coupling which remained could be compensated as described in a companion paper. The LEP optical model modified according to the measurements, could predict well the coupling resonance. Demagnetization of a short machine section gave some improvement.

Introduction

When beam was first injected into LEP only a few orbit corrections were required for the beam to circulate one turn and soon thereafter a recirculating beam was obtained while injecting on the central reference orbit. However, when using the nominal off-axis injection, the accumulation of a significant beam current became unexpectedly difficult.

The first striking observations had been made even before the beams circulated. Kicking the beam horizontally or vertically created large vertical or horizontal displacements as observed on the luminescent screens. As soon as the measurements of the first-turn trajectory became available, a clear coupling of the trajectories could be observed (50 % on the PU's, i.e. 15 % in normalized amplitudes, figure 1). This coupling manifested itself in other ways also. The beams appeared tilted and blown-up on the synchrotron light monitors. The measurement and control of the betatron tunes were particularly confusing: increments of the horizontal tune caused comparable changes in both tunes; the ambiguity as to whether the tunes were below or above a half integer was very difficult to resolve in presence of coupling. Analysis of the 'cusp' and spectrum of the closed orbit were in fact the most reliable tools. The measured chromaticities could not be trusted ($\approx$ -50). From the data collected at the time, the strength of the coupling resonance $|C|$ can be estimated to lie between 0.2 and 0.5.

Finding a solution to this challenging difficulty became a high priority for the LEP accelerator physicists and their visitors. Once an unexpectedly strong linear coupling resonance $Q_x - Q_y = 70.34 - 78.47 \approx -8$ was identified as the cause of the beam behaviour, a series of optics measurements was carried out to identify the offending parasitic fields.

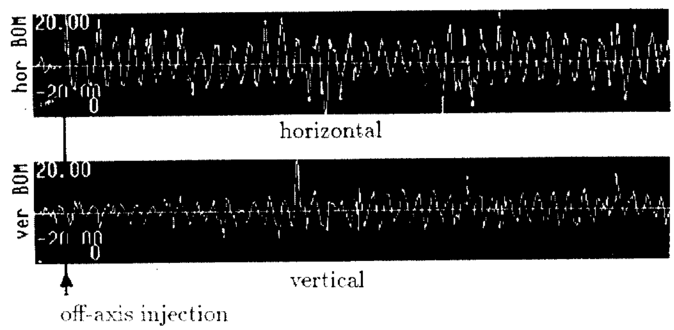

Figure 1: Vertical oscillations due to coupling with the horizontal injection oscillations.

*on leave of absence from BNL, USA
†on leave of absence from SLAC, USA
‡Cornell U., USA
§PSI, Switzerland
¶BESSY, Germany

Study of the parasitic coupling

Orbit coupling

Trajectory coupling The first systematic study was based on the observation of the vertical injection trajectory induced by horizontal kicks at various machine azimuths. This technique revealed that:

- the coupling sources were not localized,
- coupling occurred in the LEP arcs,
- coupling did not occur in the straight-sections proper.

We concluded that a parasitic skew gradient existed and was distributed along the arcs. This was further confirmed by the fact that no localized source could be isolated by the orbit correction algorithm MICADO.

Closed orbit coupling The first hypothesis was a perturbation of the dipole field by the earth magnetic field. To test it, horizontal closed orbit bumps extending over a single complete arc were produced. The induced vertical orbit perturbation is not closed and extends over the whole machine. Figure 2 shows the rms vertical orbit versus the arc number for measurements at two energies. We concluded that the parasitic skew gradient is neither significantly related to the earth magnetic field nor is it constant. It also does not scale with beam energy, thus excluding usual magnetic or alignment defects.

Further work improved both the azimuthal resolution and the analysis of our measurements. The horizontal orbit bumps were made shorter, closing after only one full oscillation (there are five oscillations per arc) and it was shown that the measured rms perturbation to the closed orbit directly yielded the strength of

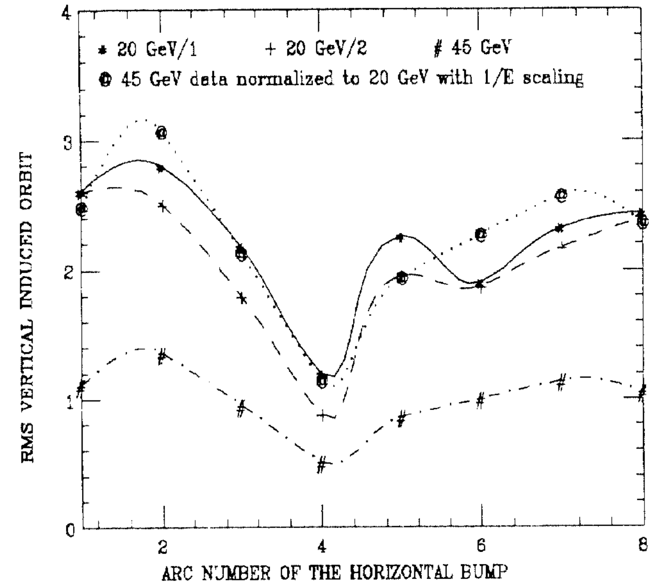

Figure 2: Relative strength of the parasitic gradient in the LEP arcs.

the skew gradient:

$$|K_s| = \frac{\sqrt{2}}{6L_{cell}} \frac{|\sin \pi Q_y|}{\sqrt{\beta_y \beta_F \beta_D \beta_{xcor}}} \frac{< y_{co} >}{x'}$$

using usual symbols. The skew gradient was found to be $\approx 2\,10^{-4}$ T/m (fig. 3). By studying the difference and sum responses to positive and negative bumps, it was possible to study the multipole content: while arc 2 is dominated by a skew quadrupole, arc 4 shows an almost pure skew sextupole. Arc 3 is intermediate.

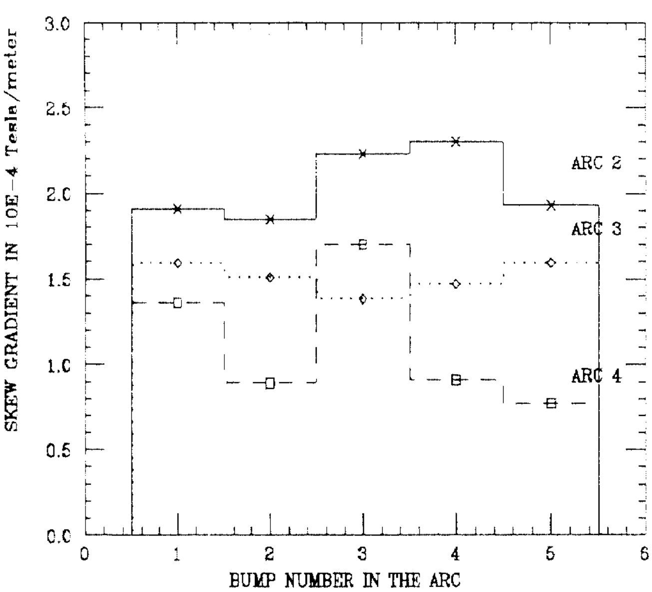

Figure 3: Variations of the parasitic gradient within 3 LEP arcs.

Harmonic content of the coupling source

The harmonic analysis of the data collected in the study of the orbit coupling shows the following azimuthal spectrum:

harmonic number	amplitude
8k	1.00000
8k ± 1	0.28
8k ± 2	0.14
8k ± 3	0.14
8k ± 4	0.12

In the nominal optics, the linear coupling resonance is excited by the harmonics $8k$. This result was a clear incentive to change the tune difference to 6.

Closest tune approach

The closest tune approach $|Q_x - Q_y|_{min}$ when varying the focusing gradients is a measure of the strength of the linear coupling resonance $|C|$. On the design optics, it was very difficult to perform and gave around 0.2. After increasing Q_x by 1.0, we obtained the results shown on figure 4. These results are consistent with orbit coupling results and confirm that the coupling field is independent of the guide field level.

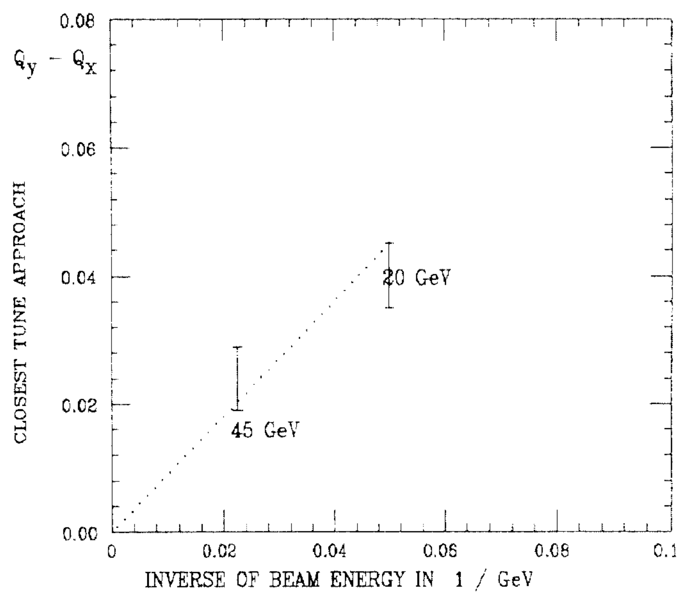

Figure 4: Closest tune approach at two energies.

Dispersion coupling

Due to the small damping aperture, the dispersion is difficult to measure in LEP. Still the only technique presently possible is to measure the displacement of the beam while changing the RF frequency. It was initially feared that the parasitic coupling would produce a large vertical dispersion. Indeed, a large vertical dispersion (20 to 40 cm) is measured in LEP as compared to that expected (8 cm). Since there was no provision to correct it, the operational optics was chosen with a phase advance of exactly 60°; indeed the dispersion coupling then cancels in the arcs and just leaves the contributions of the dispersion suppressors. In addition, some small skew quadrupoles were added in the arcs.

With the refinement of the optical models, it was found out that the apparently consistent picture of parasitic coupling, high vertical dispersion and large vertical emittance was in fact inconsistent. The parasitic coupling does not explain the high vertical dispersion, which is still being investigated. The high dispersion in turn cannot explain the emittance by the extra radiation.

Studies of the coherent synchro-betatron resonances show a possible explanation.

Comparison of optics

A systematic search of the best tune split was carried out over a few shifts. The tune changes were either obtained by a straightforward excitation of the QF and QD chains (unmatched optics), or by rematching the non-experimental insertions, thus keeping the cell phase advance at exactly 60°. Orbit coupling, closest tune approach, vertical dispersion and vertical emittance were measured in the following cases:

- the nominal optics (70/78, i.e. $Q_x = 70.38$ $Q_y = 78.28$),
- the unmatched optics (71/78),
- the unmatched optics (71/77),
- the matched optics (71/77),
- the unmatched optics (71/76).

The unmatched optics showed a lower betatron coupling due to their cell phase advance of 58.5° causing a partial cancellation. The matched 71/77 optics gave a definite reduction of the dispersion coupling and orbit coupling (-30 %). Since in all cases, except for the 70/78 optics, the betatron coupling $|C|$ would not exceed 0.055, the matched 71/77 optics was selected for operation.

Simulations

The optics program MAD does not allow superimposed dipoles and skew quadrupoles. The parasitic gradient was simulated by a thin skew quadrupole between each dipole block, i.e. 2 by half cell. One can show that it is strictly equivalent to a uniform skew gradient. The values of the skew gradient computed from the orbit coupling were specified and the closest tune approach experiment simulated (fig. 5). If one takes into account the other

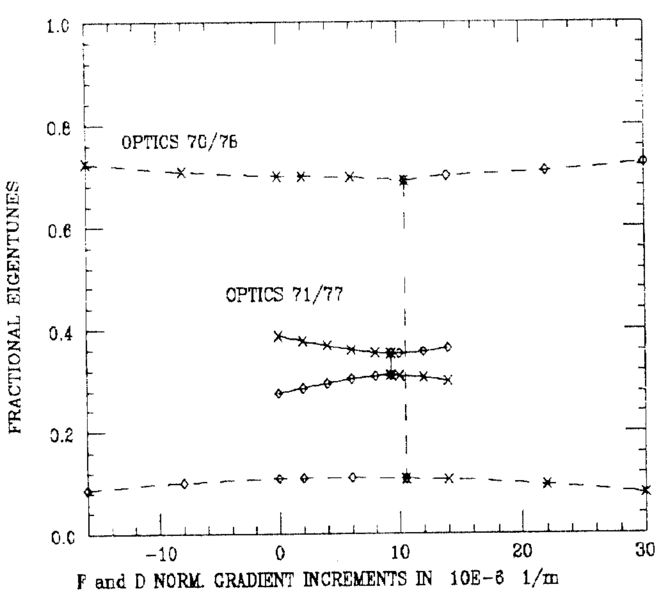

Figure 5: Simulation of the closest tune approach.

imperfections, the predictions for the 71/77 optics fit very well the measured data. The model predicts a small parasitic vertical dispersion of only 3 cm rms and an emittance ratio of only 1.3 % at 45 GeV. For the 70/78 optics, it predicts a striking strength of the coupling resonance of 0.6.

Magnetic measurements

Three possible sources of horizontal parasitic field have been investigated:

- The earth magnetic field makes a residual horizontal field gradient of 15.10^{-6} T/m in the center of the gap, insufficient to explain the coupling.
- The asymmetry of the dipole excitation bars with respect to the median plane, measured statistically, is small(less than 40.10^{-6} T/m) and proportional to the energy, in contradiction with the observations.
- On reception at CERN, the 7 micron thick nickel layer used to clad the lead shield on the aluminium vacuum chamber was seen to have a remanent magnetization in the x-direction. Measured with a special permeameter, this layer exhibits a rather square hysteresis cycle associated with a high coercive force (4500 A/m) . Thus, in a dipole, the magnetization of the horizontal nickel layers cannot be changed by the dipole field while all the others (not horizontal) are influenced. The strength of the remanent skew gradient is found comparable to the figure from the beam measurement (200.10^{-6} T/m), with a large spread.

A 50 Hz, 50.10^3 A/m axial field demagnetization of the chamber has shown a reduction of the parasitic skew gradient by a factor 2 to 3 (figure 6).

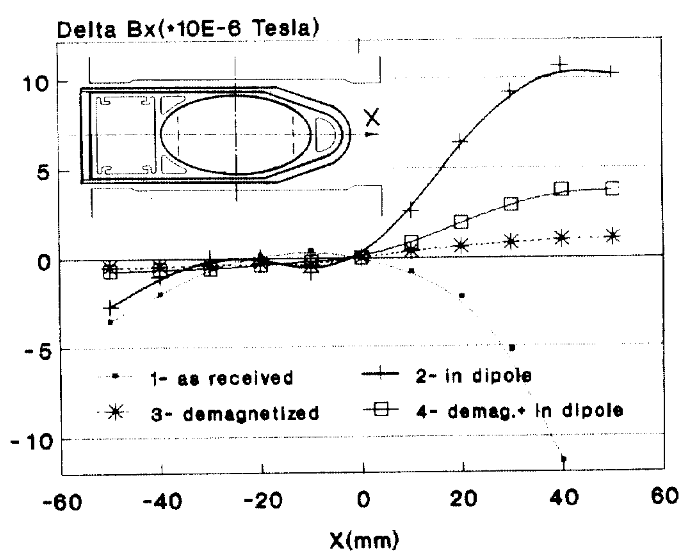

Figure 6: Typical field map measured inside the dipole vacuum chamber.

Conclusion

The parasitic coupling in LEP has been sufficiently understood to eliminate its consequences for normal operation. However, it is suspected to have detrimental effects on the dynamic aperture and the beam polarization. An important experimental program is on the way to better understand the source and its consequences, and to find ways to eliminate or compensate it.