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Vertical beam size, non-closure and LEP performance

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Abstract

The luminosity in LEP is critically dependent on the vertical beam size and thus on the effective control of contributing factors. Electrostatic separation bumps are used in LEP to avoid parasitic beam encounters and to allow the possibility of running with bunch trains. These vertical bumps are not closed at highest energies. The non-closure leads to different orbits for electrons and positrons and prevents effective minimisation of the residual vertical dispersion for both beams simultaneously.

The various sources of the non-closure and a correction scheme which globally minimises the effects of this non-closure using only a few degrees of freedom are presented. The contributions to the vertical beam size from dispersion, coupling, beam-beam and other effects are quantified and the means used to control them are discussed.

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1 VERTICAL BEAM SIZE IN LEP

The luminosity and therefore the performance of LEP depends crucially on the beam size at the collision point. While the horizontal beam size is mainly determined by the energy of the beam and the focussing properties, the vertical beam size is determined by imperfections or coupling between the two planes, either through magnetic elements or beam-beam effects.

1.1 Effect of coupling

The coupling between the horizontal and vertical plane is induced by skewed magnetic elements in the machine or the experimental solenoid magnets. Special tilted quadrupoles are used to compensate these effects and if this coupling is properly corrected, the resulting contribution to the vertical beam size is smaller than 0.01 nm.

1.2 Beam-beam blow up

The beam-beam effect couples the horizontal and vertical planes. As long as the intensity is smaller than the so-called beam-beam limit, the beam-beam tuneshift ξ increases linearly and the luminosity quadratically with the intensity. Above the beam-beam limit the vertical beam size is increased by the beam-beam forces to keep the tune shift constant, and the luminosity increases only linearly with the intensity and the life time of the beam usually becomes smaller. While LEP at Z^0 energy was clearly limited by beam-beam effects, it is not expected that LEP will be beam-beam limited at the highest energies. It is therefore important to minimize the other effects which dominate the vertical beam size.

1.3 Residual vertical dispersion

The residual vertical dispersion contributes to an increased beam size at the interaction point by an extra term

$$\sigma_y^* = \sqrt{\sigma_y^{0*} + (D_y^* \cdot \sigma_e)^2} \qquad (1)$$

where σ_y^{0*} is the unperturbed beam size, σ_e the momentum spread and D_y^* the vertical dispersion at the interaction point.

The contribution of the dispersion to the vertical emittance can be estimated as

$$\Delta\epsilon_y = C_q \cdot \gamma^2 \cdot \frac{I_5}{I_2 - I_4} \qquad (2)$$

where C_q is a constant, γ the relativistic factor and I_2, I_4 and I_5 are the synchrotron integrals as defined in [1]. This contribution can reach values up to 0.4 nm and eventually become the dominating factor to the vertical beam size, in particular when the beam-beam limit is not reached.

A further side effect of the vertical dispersion is a coupling between the vertical and longitudinal plane, possibly exciting synchro-betatron resonances. It is therefore important to keep the vertical dispersion small.

The dispersion function $D_y(s)$ around the ring can be calculated and is defined as a solution of

$$D_y(s)'' + k_y(s) \cdot D_y(s) = \frac{1}{\rho(s)} \qquad (3)$$

where $\rho(s)$ is the local bending radius. Vertical bending fields generate vertical dispersion and the main contribution are therefore large vertical orbit distortions. Local vertical bending generated by electrostatic fields further introduce a vertical dispersion of different sign for differently charged particles and therefore the creation of orbit distortions by electrostatic separators needs special attention.

2 NON-CLOSURE OF BUMPS

2.1 Bunch train bumps

The LEP vertical separation system was modified in 1995 for operation with bunch trains [2, 3, 4]. The purpose of these bumps is to separate the bunches in the vertical plane

at the unwanted encounters around the interaction regions. These separation bumps are provided by a system with four separators per odd point, powered in two left-right pairs (ES1 and ES8), and six separators per even point, powered in three left-right pairs (ES2, ES4 and ES7). The gaps of the separators are not variable in operation. The orbits of positrons around the even (experimental) and odd (unused) interaction points are shown in Fig.1. Electrons have the opposite orbit. At the even interaction points the separa-
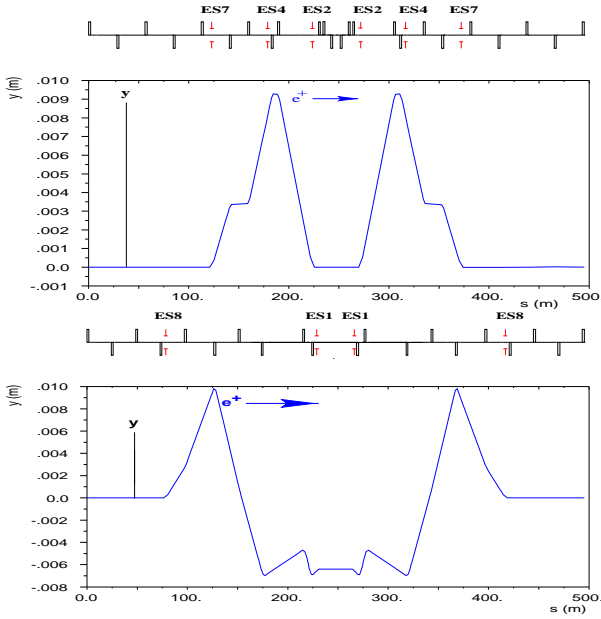

Figure 1: Positron orbit around an even (upper) and odd (lower) interaction point. Positions of separators indicated in the schematic layout above the figures.

tion at the centre must me adjustable to ensure head on collisions. Imperfections of the insertions optics or small errors on the equipment may lead to a non-closure which cannot be corrected, resulting in a different orbit of electrons and positrons outside the bumps and at the collision point. The latter is corrected by adjusting the local bump amplitude to ensure head on collisions, so-called "vernier adjustments". However this normally does not affect the global non-closure of the bumps. The typical adjustment necessary can be up to 20 m, i.e. several times the vertical beam size, and the possible range of these adjustment is limited. It is therefore desirable to minimize the global non-closure before this procedure is applied.

2.2 Origin and effect of non-closure

The non-closure of the separation bumps normally cannot be attributed to a single effect or imperfection. It is rather a mixture of different smaller effects which sum up to the observed non-closure. The obvious source for a electron positron difference is the precision of the separators themselves. The voltage on the plates is known to a precision of 100 V, i.e. about 0.04 to 0.1% of the used voltage. The

size of the gap is known to 0.1 mm for a nominal gap size of approximately 10 cm. Using this information in a simulation we found that only about 10% of the non-closure can be explained by these uncertainties. Rather important are errors on the focussing strength of quadrupoles inside the separation bumps, in particular where the orbit amplitude is large. Using the expected resolution and stability of the power supplies of maximum 35 ppm a significant non-closure is observed. At high energy a further contribution comes from the large energy mismatch caused by the significant energy loss (2.1 GeV/turn at 90 GeV) which, at the positions of the separators, is different for electrons and positrons. Not negligible is the contribution from the beam itself: the coherent orbit kick from the parasitic long range interaction are of the order a few rad at each encounter and can explain another part of the observed non-closure[2]. An appropriate choice of the separation scheme can largely compensate this effect but it cannot be suppressed completely. Combining these effects in a simulation, the largest part of the non-closure can be explained by these known imperfections. The remaining non-closure can be accounted for by other small imperfections such as e.g. closed orbit errors, beating etc.

2.3 Operational difficulties: $e^+ \, e^-$ split

A very important consequence of non-closed separation bumps are the resulting differences between electrons and positrons such as closed orbits, dispersion, tunes and chromaticities, which can make the optimization of the machine parameters impossible. The minimization of these differences is one of the main reasons to reduce the non-closure.

3 CORRECTON OF NON-CLOSURE

The purpose of a correction of the non-closure must be to minimize the vertical dispersion and the differences between electrons and positrons. It has been demonstrated that the origin of the non-closure cannot be localized or is an unavoidable feature (e.g. energy mismatch) which makes a local correction impossible. Global corrections have shown to be very successful for correcting closed orbits, even with a very limited number of correctors. We have chosen a similar strategy to correct the global non-closure of the separation bumps. This requires to control at least some of the separators independently.

3.1 Hardware modifications

In order to improve the potential for correcting the vertical non-closure, independent left-right high voltage supplies were added to the positive electrode of the ES8 separators in points 1 and 3 (see Fig.1). This modification was relatively straightforward, requiring some recabling of the high voltage zone, modification of interlocks and upgrade of the control and application software. A standard 160 kV high voltage generator was used so that the maximum dynamic range could be achieved. In operation the kicks of these

four separators can be adjusted by around 1 μrad at 22 GeV, corresponding to rad at 100 GeV. The separators in the odd points were used because these stay powered throughout the LEP fill, whereas the separators in the even points are switched off when LEP runs without bunch trains.

3.2 Corrections scheme

The correction strategy used is very similar to the correction of closed orbits in LEP and the identical software can be used[5]. For the correction, the independent separators are treated as orbit correctors and the difference orbit between electrons and positrons is corrected with a best kick algorithm[5]. The criteria for a good correction are a reduced global non-closure, quantified as the r.m.s. of the difference orbit, and the difference orbit at the four collision points, i.e. the collision offset. This is shown in
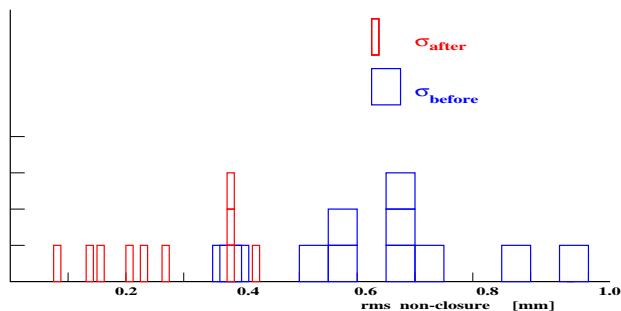
Figure 2: Orbit r.m.s. before and after correction

Figs.2 where the r.m.s. of the vertical orbit difference is shown before and after the correction is applied for simulated orbits with the above mentioned errors. The r.m.s. non-closure can be reduced by roughly a factor three and the resulting dispersion and splits are reduced accordingly. The electron-positron offsets at the collision point are reduced from an average of 10 μm to 3 μm during this process, which allows a much easier adjustment.

3.3 Experience in operation

The system was used to correct the non-closure of LEP in normal operation. The uncorrected non-closure of the e^+-e^- difference orbit has a r.m.s. of approximately 1.2 - 1.5 mm at injection. The difference was corrected using a best kick method with four independent correction kicks from the separators. Typical corrections found are in the order of a few μrad. The predicted improvement is between 30 and 50% on the r.m.s. The resulting orbit agrees extremely well with the expected and the attempt to correct further with the available four correctors does not find another improvement. A typical reduction of the non-closure from 1.3 mm to 0.7 mm is found, in agreement with the expectation. The effect on the collision offset is shown in Fig.3. where the required vernier adjustment and the measured vertical emittance for the four experiments are plotted as
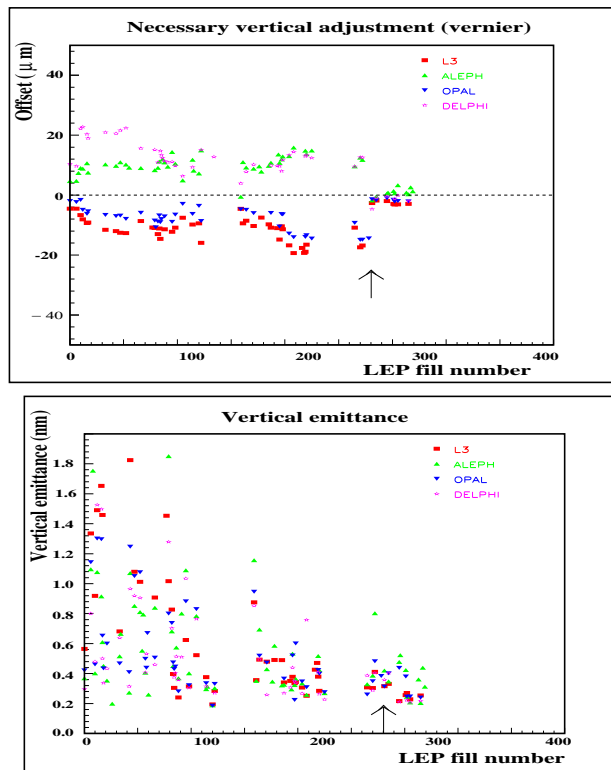
Figure 3: Required adjustment and vertical emittance before and after correction as a function of time (fill number)

a function of the fill number, i.e. the time[6]. The arrow indicates the time of a correction and the required adjustments become significantly smaller, as expected from the simulation. They are reduced from an average of 10.6 μm before the correction to 1.7 μm. An improvement on the measured vertical emittance is more difficult to observe, in agreement with the expectations for non-closures of the observed magnitude.

3.4 Possible improvements

Having some confidence in the procedure, we assumed additional four correctors, possibly available after a similar transformation at the points 5 and 7, and simulated a correction. This reduces the non-closure in all cases to values between 0.3 and 0.4 mm.

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