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Quadrupole Alignment and Closed Orbits at LEP : a Test Ground for LHC

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Summary

A statistical analysis of the corrector strengths used at LEP for closed orbit correction between 1994 and 1996 was performed to obtain information on the machine alignment. The typical quadrupole alignment error was found to be 400 ± 50 μm in the horizontal and 190 ± 20 μm in the vertical plane. The last value confirms results of vertical survey measurements.

A simple analysis of the closed orbit readings at the beam position monitors shows that during physics, readings reaching 4 mm are rare but not uncommon. These excursions can be reduced below 3 mm with a very strict closed orbit correction. Unless the configuration and number of monitors and orbit correction dipoles is significantly improved with respect to LEP, similar orbit excursions have to be expected at the LHC.

1 Introduction

To specify the required closed orbit corrector strengths and the mechanical aperture for the LHC, standard simulation and statistical techniques can be used [1]. The main difficulty of this task is to obtain good and reliable estimates for the most important alignment and field errors which affect the closed orbit.

Having obviously the same size and being housed in the same tunnel than the LHC, LEP is a good test ground for alignment and closed orbit issues. To check the reliability of survey data, the corrector strengths were analysed for the LEP runs from 1994 to 1996. The resulting distributions are used to extract estimates for the alignment errors of the LEP quadrupoles.

The large orbit samples can also used to evaluate the size of orbit excursions that must be tolerated at LHC for similar monitor/corrector configurations.

2 Closed Orbit Distortions

A dipole kick $\Delta\theta_j$ at position j produces a closed orbit displacement u_i at position i given by

$$u_i = \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi Q} \cos(|\mu_i - \mu_j| - \pi Q)\, \Delta\theta_j \tag{1}$$

where $\beta_{i(j)}$ and $\mu_{i(j)}$ are the betatron function and phase at the observation point and at the location of the kick. Q is the machine tune. u stands for the horizontal or vertical coordinate of the beam.

The dominant sources of dipole kicks on the closed orbit are :

- **Quadrupole misalignments** : A quadrupole of strength K and length L produces a kick

  $$\Delta\theta = K L \Delta q \tag{2}$$

  when it is displaced transversely by an amount Δq.

- **Dipole field errors** : A main dipoles with a relative field error $\Delta f = \Delta B/B$ will generate a horizontal kick

  $$\Delta\theta = \Theta\, \Delta f \tag{3}$$

  where Θ is the nominal bending angle of the dipole.

- **Dipole roll** : A main dipole which is rolled by an angle Δf around its longitudinal axis produces a vertical kick given by

  $$\Delta\theta = \Theta\, \Delta f \tag{4}$$

The closed orbit distortions generated by these perturbations will be compensated, at least partially, by orbit correction dipoles. The quality of the final closed orbit is a function of the ring design (number of correctors and monitors, strength of the correctors) and of the quality of the beam position monitor (BPM) readings. The resulting closed orbit measured at the i'th BPM can be described by

$$u_i = \Delta u_{0i} + \sum_{j}^{N_{COD}} C_{ij} \delta_j + \sum_{k}^{N_{QUAD}} Q_{ik} \Delta q_k + \sum_{l}^{N_{BEND}} D_{il} \Delta f_l \tag{5}$$

Δu_{0i} represents the i'th BPM alignment error (and/or electronic offset), δ_j is the strength of the j'th orbit corrector, Δq_k is the misalignment of the k'th quadrupole. Δf_l is either the roll angle (vertical plane) or the relative field error (horizontal plane) of the l'th dipole. The matrices C, Q and D describe the closed orbit response at the BPM due to the perturbations considered here. The elements of C, Q and D are given by

$$C_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi Q} \cos(|\mu_i - \mu_j| - \pi Q) \tag{6}$$

$$Q_{ik} = \frac{\sqrt{\beta_i \beta_k}}{2 \sin \pi Q} \cos(|\mu_i - \mu_k| - \pi Q)\, K_k L_k \tag{7}$$

$$D_{il} = \frac{\sqrt{\beta_i \beta_l}}{2 \sin \pi Q} \cos(|\mu_i - \mu_l| - \pi Q)\, \Theta_l \tag{8}$$

K_k and L_k are the strength and length of the k'th quadrupole. Θ_l is the bending angle of the l'th dipole.

Closed orbit correction algorithms like MICADO [2] try to minimise the left-hand side (LHS) of Equation 5 using and appropriate choice of corrector kicks. For a statistical analysis the precise algorithm is not important and Equation 5 can be solved for the corrector strengths using the matrix pseudo-inverse. Problems related to BPM failures are not considered here. Setting the LHS of Equation 5 to zero we obtain

$$\delta_j = \sum_{j=1}^{N_{BPM}} F_{ji}\,\Delta u_{0i} + \sum_{k=1}^{N_{QUAD}} G_{jk}\,\Delta q_k + \sum_{l=1}^{N_{BEND}} H_{jl}\,\Delta f_l \tag{9}$$

The matrices F, G and H are easily obtained from C, Q and D [1]. A statistical analysis of Equation 9 can give an estimate of the strengths required to correct the closed orbit for given distributions of Δu_0, Δq and Δf.

If the field and alignment errors are Normally distributed with zero mean, variances σ_M^2, σ_Q^2 and σ_B^2 and if they are uncorrelated, the corrector strengths are Normally distributed with variance

$$\sigma_\delta^2 = \frac{\sigma_M^2}{\kappa_M^2} + \frac{\sigma_Q^2}{\kappa_Q^2} + \frac{\sigma_B^2}{\kappa_B^2} \tag{10}$$

where

$$\begin{aligned}
\sigma_M^2 &= \text{Variance}(\Delta u_0) && (11)\\
\sigma_Q^2 &= \text{Variance}(\Delta q) && (12)\\
\sigma_B^2 &= \text{Variance}(\Delta f) && (13)
\end{aligned}$$

The coefficients κ_M, κ_Q and κ_B are the *correctabilities* [1] for the BPM's, quadrupoles and dipoles. They are given by

$$\begin{aligned}
\frac{1}{\kappa_M^2} &= \frac{1}{N_{COD}} \sum_{j=1}^{N_{COD}} \sum_{i=1}^{N_{BPM}} F_{ji}^2 && (14)\\
\frac{1}{\kappa_Q^2} &= \frac{1}{N_{COD}} \sum_{j=1}^{N_{COD}} \sum_{k=1}^{N_{QUAD}} G_{jk}^2 && (15)\\
\frac{1}{\kappa_B^2} &= \frac{1}{N_{COD}} \sum_{j=1}^{N_{COD}} \sum_{l=1}^{N_{BEND}} H_{jl}^2 && (16)
\end{aligned}$$

The correctabilities indicate how much strength is required from the correctors to compensate a given error. Large values imply small strengths.

3 Analysis of Corrector Strengths at LEP

The corrector strengths used for the closed orbit correction have been studied for the LEP runs of 1994 to 1996. A total of 2389 orbits have been analysed. These orbits were measured during normal physics runs or during transverse polarization experiments, the later requiring

Table 1: The full orbit sample used for the analysis is split into 5 sub-samples corresponding to the running conditions shown below.

Run	Optics	Beam Energy (GeV)	Conditions	Operation Mode
1994	90°/60°	45	Physics	Pretzel
1995	90°/60°	45	Physics	Bunch Trains
1996	90°/60°	45, 80.5, 86	Physics	Bunch Trains
1996	108°/90°	86	Physics	Bunch Trains
1996	90°/60°	45, 50	Polarization	Single beam, solenoids OFF

particularly well corrected orbits. Table 1 gives some details on the 5 orbit sub-samples that have been analysed. The majority of the orbits were measured on the LEP optics with arc phase advances of 90°/60° in the horizontal/vertical planes. About 100 orbits concern the low-emittance 108°/90° optics tested at the end of the 1996 run. For the whole orbit sample, the first correction steps were always made with the MICADO algorithm. At a second stage local short length corrections are used to improve the orbit RMS and the machine performance (backgrounds, luminosity).

The correctabilities defined by Equations 14 to 16 are given for the various optics in Table 2. At LEP beam position monitors (BPMs) are able to measure both coordinates of the beam. In the arcs BPMs are only installed on D-quadrupoles, while in the insertions almost every quadrupole is equipped with a BPM. The correctabilities were evaluated separately for the arcs and the insertions assuming that the correctors compensate errors locally. For the insertions, the superconducting low-beta quadrupoles (QS0's) installed just next to the IP and the corresponding monitors and correctors have been removed from the analysis. This cut was applied because the QS0's are moving vertically by up to 100 μm due to their special support. This movement is most likely driven by thermal effects [4]. When LEP is operated in bunch train mode with more than one bunch per train, a significant number of the insertion BPMs are not able to measure the beam position because of timing problems. For this reason, all orbit acquired in 1995 and a large fraction of the orbits acquired in 1996 have not been analysed in the insertions because of the poor(er) sampling.

Table 2: The correctabilities are shown below for the arcs and the insertions. The correctabilities for the arcs are identical for all versions of the 90°/60° optics used between 1994 and 1996.

Section	Plane	Optics	Run	κ_M (m)	κ_Q (m)	κ_B
Arc	Horizontal	90°/60°	All	41.8	20.5	117
		108°/90°	1996	35.7	18.2	130
	Vertical	90°/60°	All	93.8	22.9	109
		108°/90°	1996	98.4	19.6	120
Insertion	Horizontal	90°/60°	1994	67.5	14.0	251
		90°/60°	1996	69.9	13.9	236
	Vertical	90°/60°	1994	44.4	14.5	297
		90°/60°	1996	14.9	13.9	302

Table 3: Measured kick RMS σ_δ for all orbit sub-samples. The errors assigned to σ_δ corresponds to the RMS spread of σ_δ between different orbits. The last column gives the typical range for the ratio between the absolute value of the largest kick, $\delta_{\max} = \max|\delta_j|$, and σ_δ. N_{orb} is the number of orbits in the sample.

Section	Plane	Optics	Run	N_{orb}	σ_δ (μrad)	$\delta_{\max}/\sigma_\delta$
Arc	Horizontal	90°/60°	1994	903	19.4 ± 1.5	2-3
			1995	805	20.0 ± 2.4	2-3
			1996	571	18.3 ± 1.9	2-3
			All	2279	19.3 ± 2.1	2-3
		90°/60° (Pol)	1996	2	20.1 ± 2.2	2-2.5
		108°/90°	1996	108	20.8 ± 1.6	2-3
Arc	Vertical	90°/60°	1994	903	8.5 ± 1.2	3-4
			1995	805	10.4 ± 1.8	2-4
			1996	571	9.3 ± 0.9	2-4
			All	2279	9.4 ± 1.6	2-4
		90°/60° (Pol)	1996	2	7.0 ± 1.0	3.5
		108°/90°	1996	108	10.3 ± 0.7	2-3
Insertion	Horizontal	90°/60°	1994	903	31.9 ± 3.4	3-4.5
			1996	141	26.4 ± 2.0	3
		90°/60° (Pol)	1996	2	24.4 ± 1.6	2.5
Insertion	Vertical	90°/60°	1994	903	12.4 ± 2.7	2.5-4
			1996	141	17.2 ± 2.3	4-5
		90°/60° (Pol)	1996	2	13.8 ± 0.8	3.5-4

Table 3 shows the results for the corrector kick RMS σ_δ. The values of σ_δ are consistent for each plane and section of the ring (arc or insertion) within about 2 μrad. Table 3 also gives the typical ratio between the absolute values of the largest kick, $\delta_{\max} = \max|\delta_j|$, and σ_δ. In the arcs this ratio is usually in the range 2 to 3 for the horizontal plane and it can reach about 4 in the vertical plane, but the orbit can also be corrected with smaller values. The ratio $\delta_{\max}/\sigma_\delta$ increases in the insertions were values of about 4 where required in the vertical plane in 1996. Some distributions and time structures of σ_δ and $\delta_{\max}$ are shown in Figures 1 to 6.

The quadrupole alignments can be extracted from σ_δ once σ_M and σ_B are known. The vertical offsets of the BPMs are measured at LEP using the K-modulation technique with an accuracy of about 50 μm. The offsets for all monitors in two half octants around IP8 have been determined in 1995 and 1996. The vertical offset RMS was measured to be $\sigma_M = 180 \pm 30$ μm [3]. Roughly 20% of the insertion quadrupoles were also measured. The horizontal offsets were not determined, but it is likely that the values are similar. For the analysis we assume that σ_M is identical for both planes and that the measured BPM sample is representative of the whole ring. The relative dipole field spread has been determined at the time of installation in the tunnel to be $\sigma_B = 0.7 \cdot 10^{-4}$ [5]. The average dipole roll angle for LEP is 240 μrad. The errors on these two parameters are unknown and for this analysis I arbitrarily use an error of 20% for both numbers. The quadrupole misalignments

Table 4: The results for the quadrupole misalignment σ_Q extracted from σ_δ is shown below for the various orbit samples. The BPM misalignments σ_M have been obtained from K-modulation. For 1996 σ_M has been corrected to take into account the fraction of monitors whose offsets were already known. σ_B is the relative RMS field error, respectively the RMS roll angle of the main dipoles.

Plane	Section	Optics	Run	σ_M (μm)	σ_B (10^{-4})	σ_Q (μm)
Horizontal	Arc	90°/60°	All	180 ± 30	0.70 ± 0.14	370 ± 50
		108°/90°	1996			350 ± 30
	Insertion	90°/60°	1994	180 ± 30	0.70 ± 0.14	440 ± 50
		90°/60°	1996			370 ± 30
Vertical	Arc	90°/60°	All	180 ± 30	0.24 ± 0.05	205 ± 40
		108°/90°	1996	160 ± 30		195 ± 15
	Insertion	90°/60°	1994	180 ± 30	0.24 ± 0.05	170 ± 50
		90°/60°	1996	150 ± 30		190 ± 40

σ_Q extracted from the various data samples are shown in Table 4. For the arcs all the data from the 90°/60° optics has been combined into a single value. The results are very consistent and agree with survey data. In the vertical plane σ_Q is found to be in the range of 170 to 210 μm, in good agreement with the value of 150 to 180 μm obtained from survey data for the alignment of quadrupole with respect to a smooth polynomial (after each year's realignment campaign) [6]. In the horizontal plane the observed misalignment lies consistently between 350 and 440 μm.

4 LEP Closed Orbits

The LEP orbits can also be used to estimate the orbit excursions that must be tolerated at the LHC, unless of course the corrector and monitor density is increased with respect to LEP. Figures 7 to 13 show the correlation between the horizontal and vertical beam positions for all orbits of a given sample. The positions correspond in fact to the average position of the two beams to remove the biases due to energy sawtooth and electrostatic separators. The data is shown separately for arcs and insertions. No attempt was made to reject monitors that have "suspicious" readings (although their hardware status is good) in order to avoid biases. Usually about 2 to 10% of the monitors are faulty at LEP. The closed orbit RMS is typically in the range 0.5 to 0.8 mm for physics orbits. In practice it is possible to reduce the RMS further, but this usually results in lower luminosity performances. It is clear from the figures that on physics orbits, some positions reach and sometimes exceed 4 mm in either plane. Simultaneous large excursions in both planes are rare.

At injection energy, the typical closed orbit RMS is usually worse than during physics because the orbit quality is not very critical as long as its RMS remains below about 1 mm in both planes. Little time and effort would be required to make significant improvements on the orbit excursions at injection (and in the ramp) since the correction procedure is very fast and the machine is quite reproducible, the exception being the low-beta quadrupole movements. No data is shown for injection orbits since it is not possible to draw any useful conclusion from it.

Figures 12 and 13 show the position correlation for a well corrected “polarization” orbit. The closed orbit RMS was in that case 0.3 (0.5) mm in the vertical (horizontal) plane. Not a single monitor reading exceeds 3 mm for that orbit, which is quite typical for the best corrections that can be achieved. It is of course not possible to exclude that the orbit excursions exceed 3 mm in the regions between monitors. It is interesting to observe that the orbits used for polarization do not require larger correctors strengths. Only the number of excited correctors is increased.

5 Conclusion

The quadrupole alignment errors σ_Q have been extracted from the corrector strength distributions for the LEP ring. The results obtained from this study are :

- $\sigma_Q = 350$ to 440 μm in the horizontal plane
- $\sigma_Q = 170$ to 210 μm in the vertical plane

The estimates for the vertical plane are in good agreement with survey measurements.

Orbit excursion at LEP commonly reach about $\pm$ 4 mm in either plane during normal physics operation, with little correlation between the two planes. The excursions at the monitors can however be reduced to below 3 mm on very well corrected orbits.

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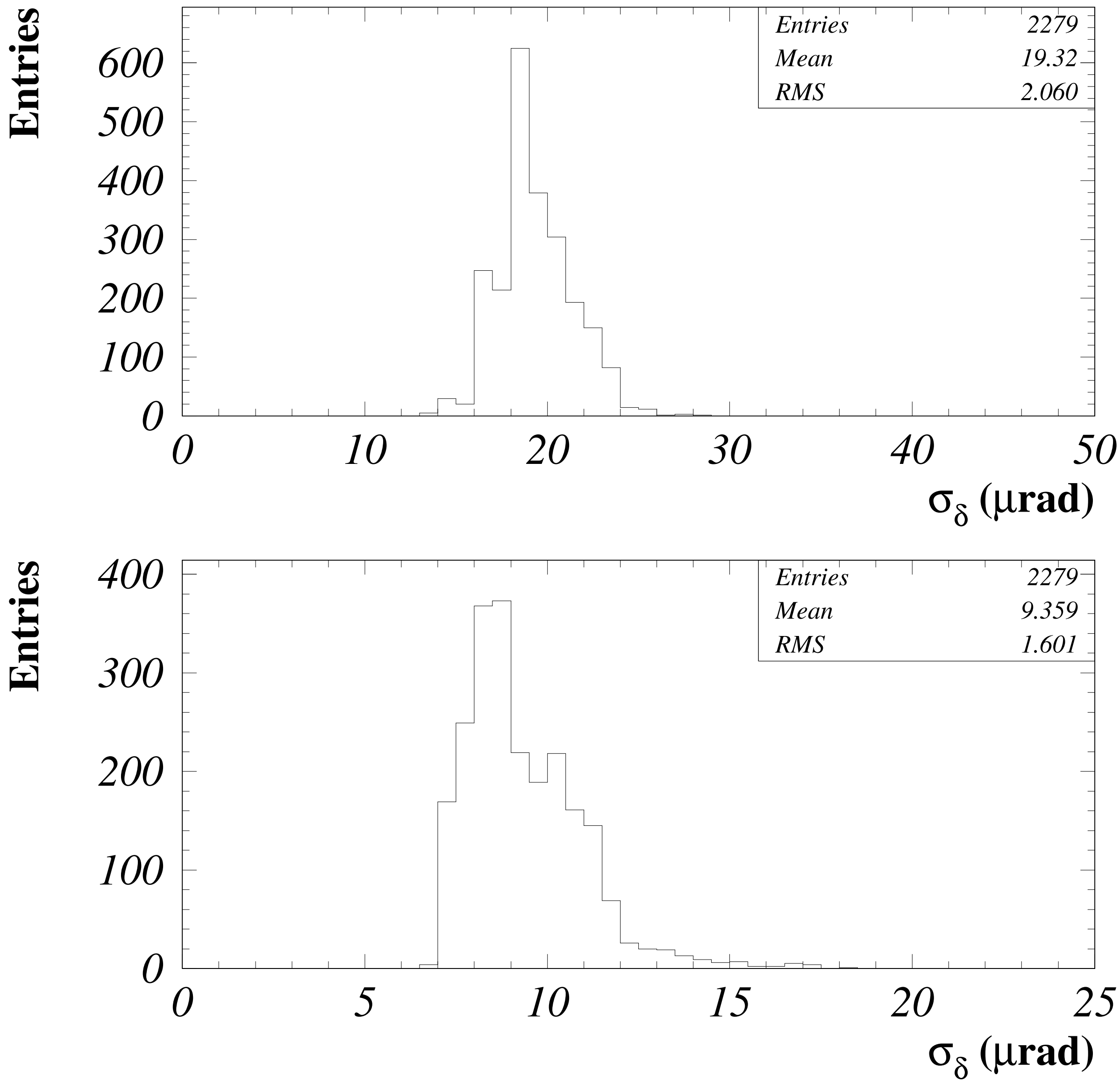

Figure 1: Distribution of the arc corrector strength RMS σ_δ for the horizontal (top) and vertical (bottom) plane. Each entry corresponds to the RMS for one orbit. The data sample corresponds to orbits measured between 1994 and 1996 with the $90°/60°$ optics. Note the difference of the horizontal scales for the two graphs.

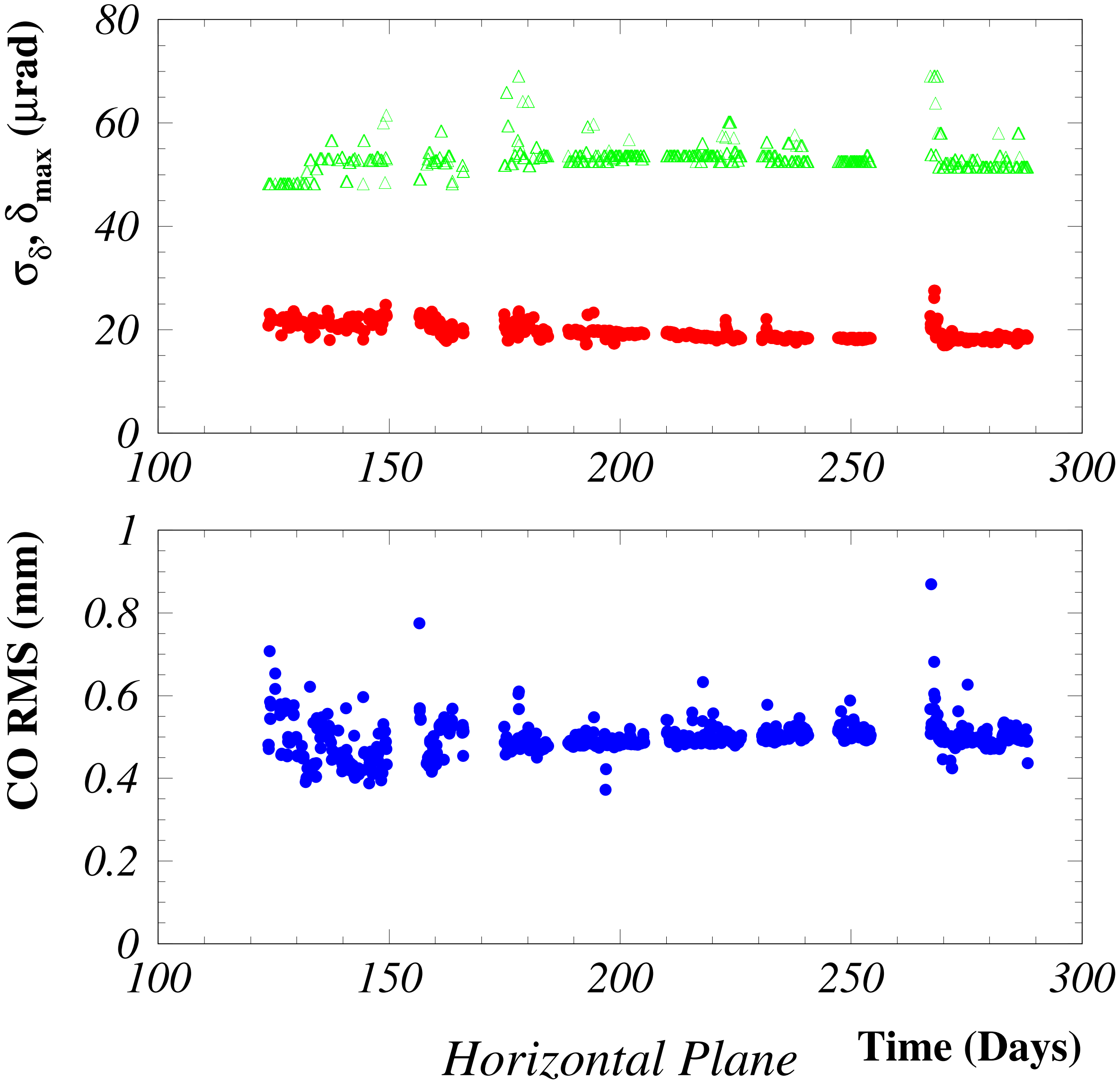

Figure 2: Top : Evolution of the horizontal RMS kick strength σ_δ (circles) and the absolute value of the largest kick δ_{max} (triangles) for the arcs as a function in time for 1994. Bottom : Evolution of the horizontal closed orbit RMS in the LEP arcs for the 1994 run.

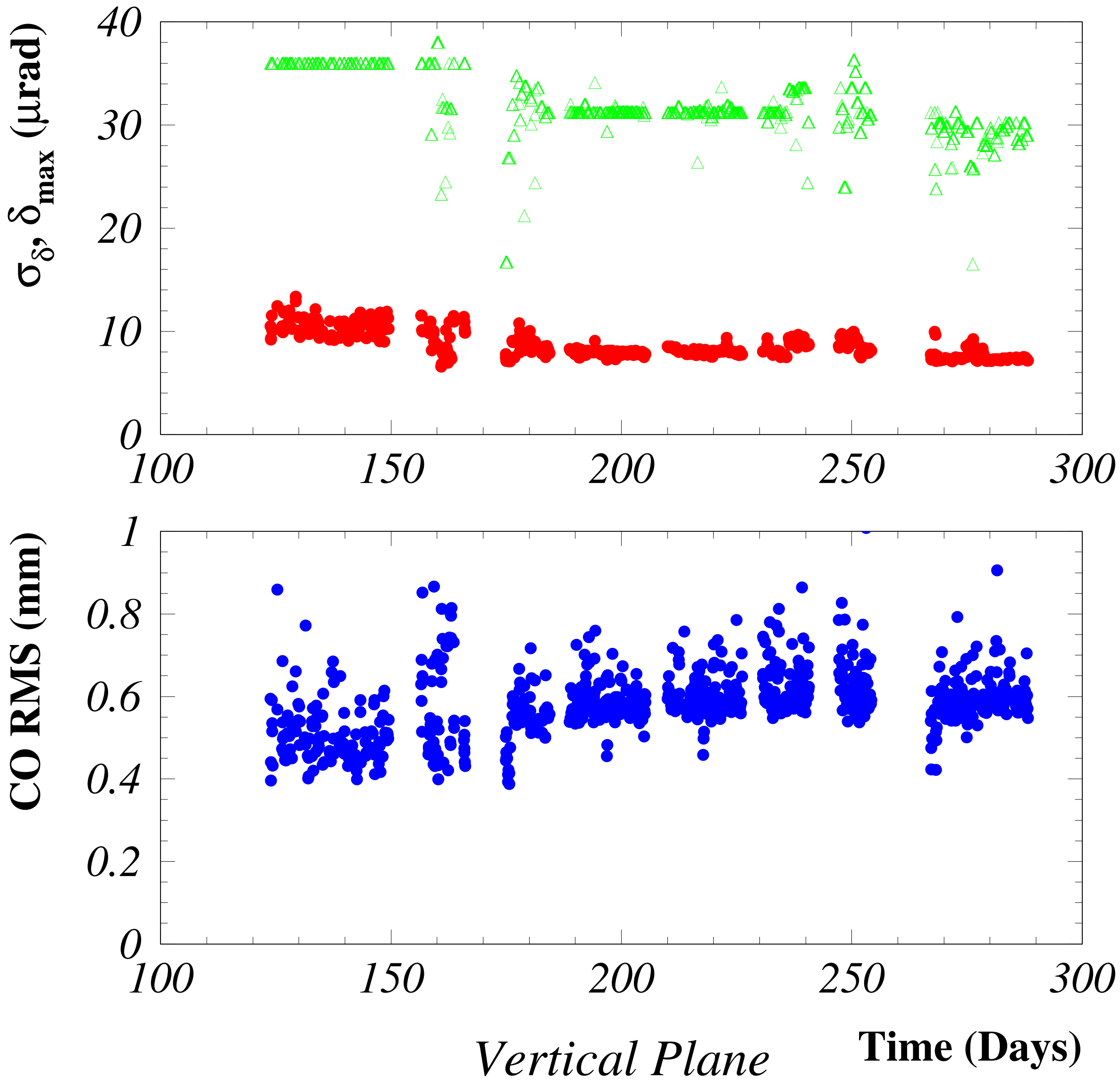

Figure 3: Top : Evolution of the vertical RMS kick strength σ_δ (circles) and the absolute value of the largest kick δ_{max} (triangles) for the arcs as a function in time for 1994. Bottom : Evolution of the vertical closed orbit RMS in the LEP arcs for the 1994 run.

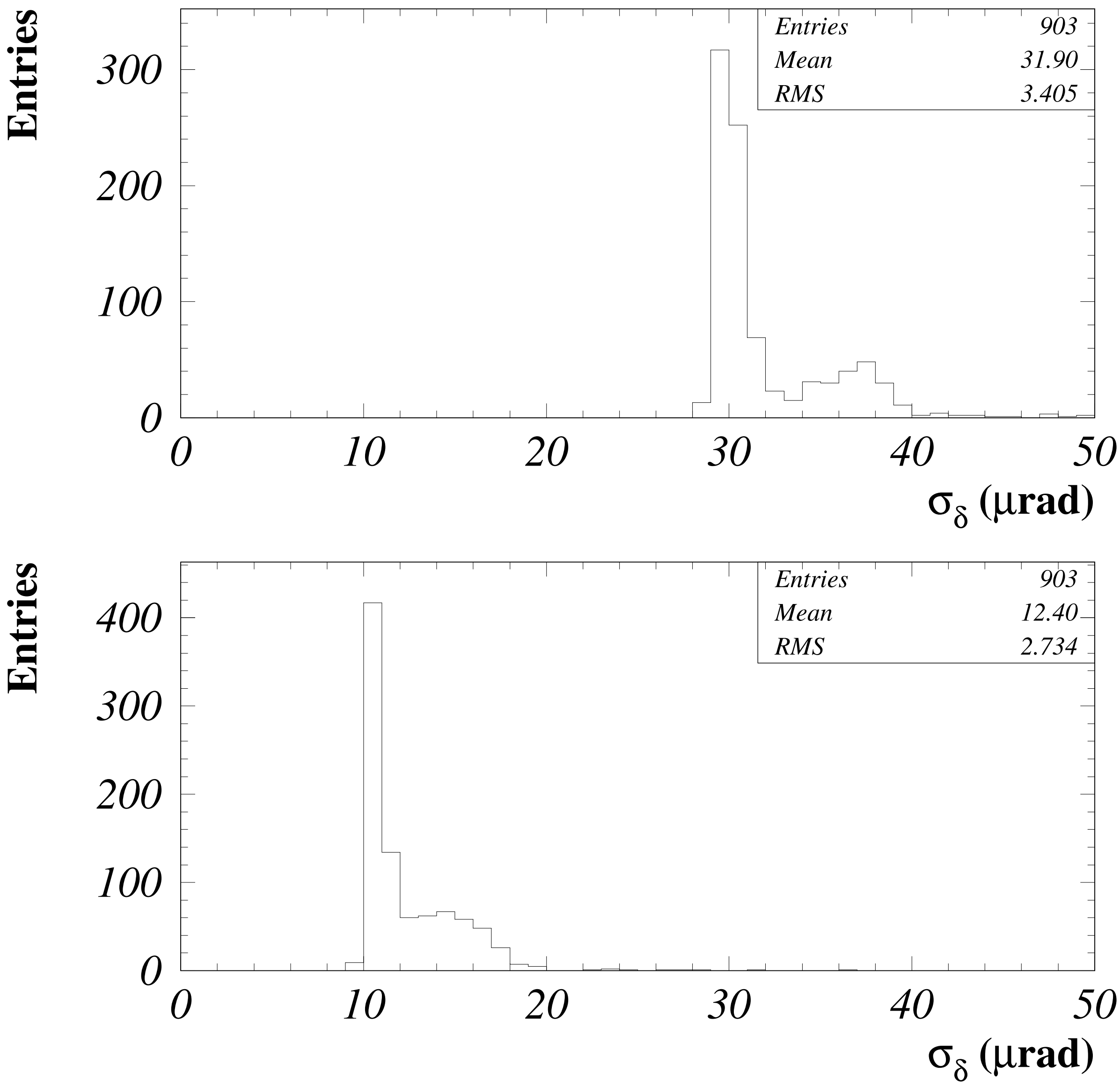

Figure 4: Distribution of the insertion corrector strength RMS σ_δ for the horizontal (top) and vertical (bottom) plane. Each entry corresponds to the RMS for one orbit. The data sample corresponds to orbits measured in 1994 with the $90°/60°$ optics.

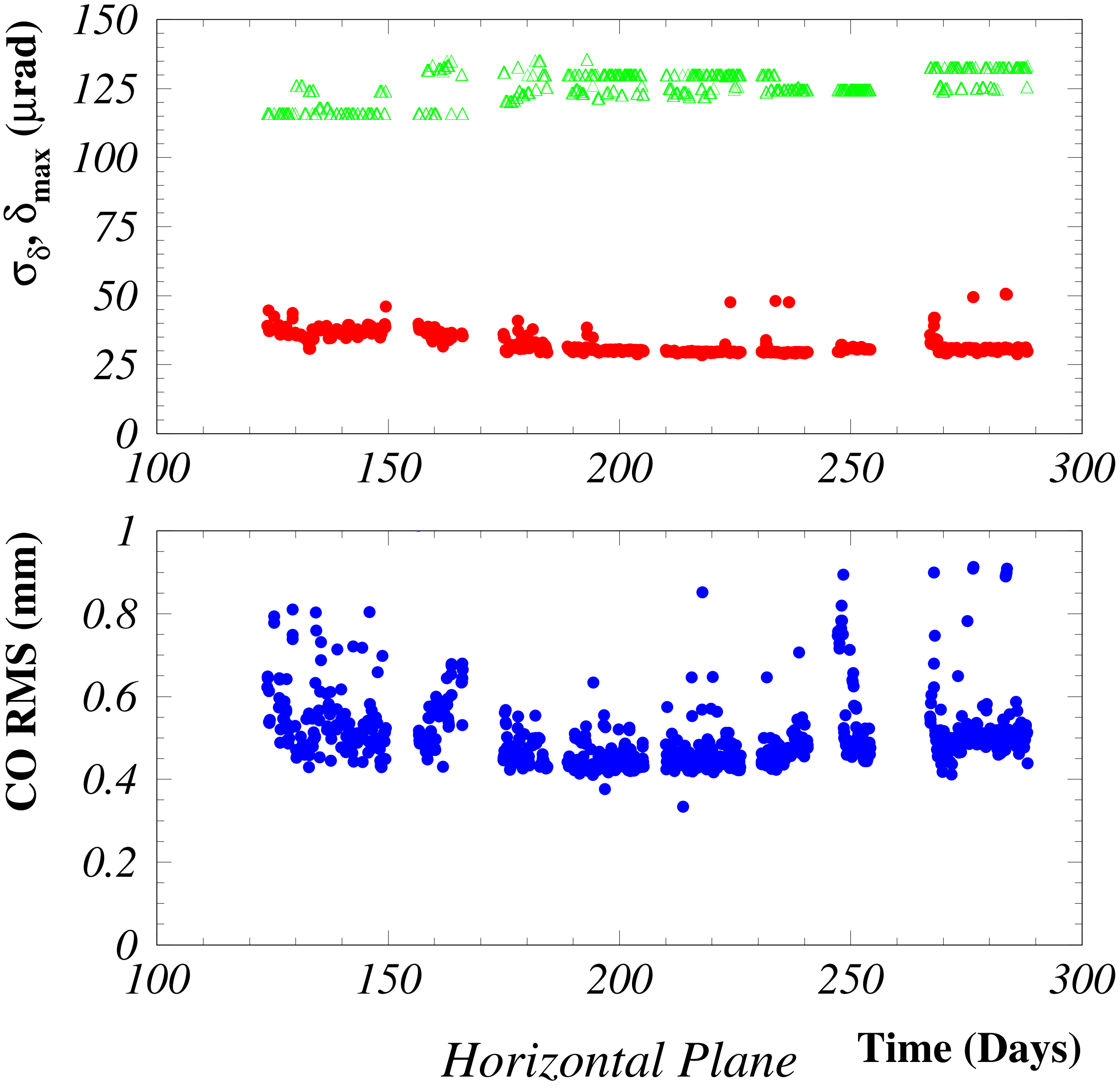

Figure 5: Top : Evolution of the horizontal RMS kick strength σ_δ (circles) and the absolute value of the largest kick δ_{max} (triangles) for the insertions as a function of time for 1994. Bottom : Evolution of the horizontal closed orbit RMS in the LEP insertions for the 1994 run.

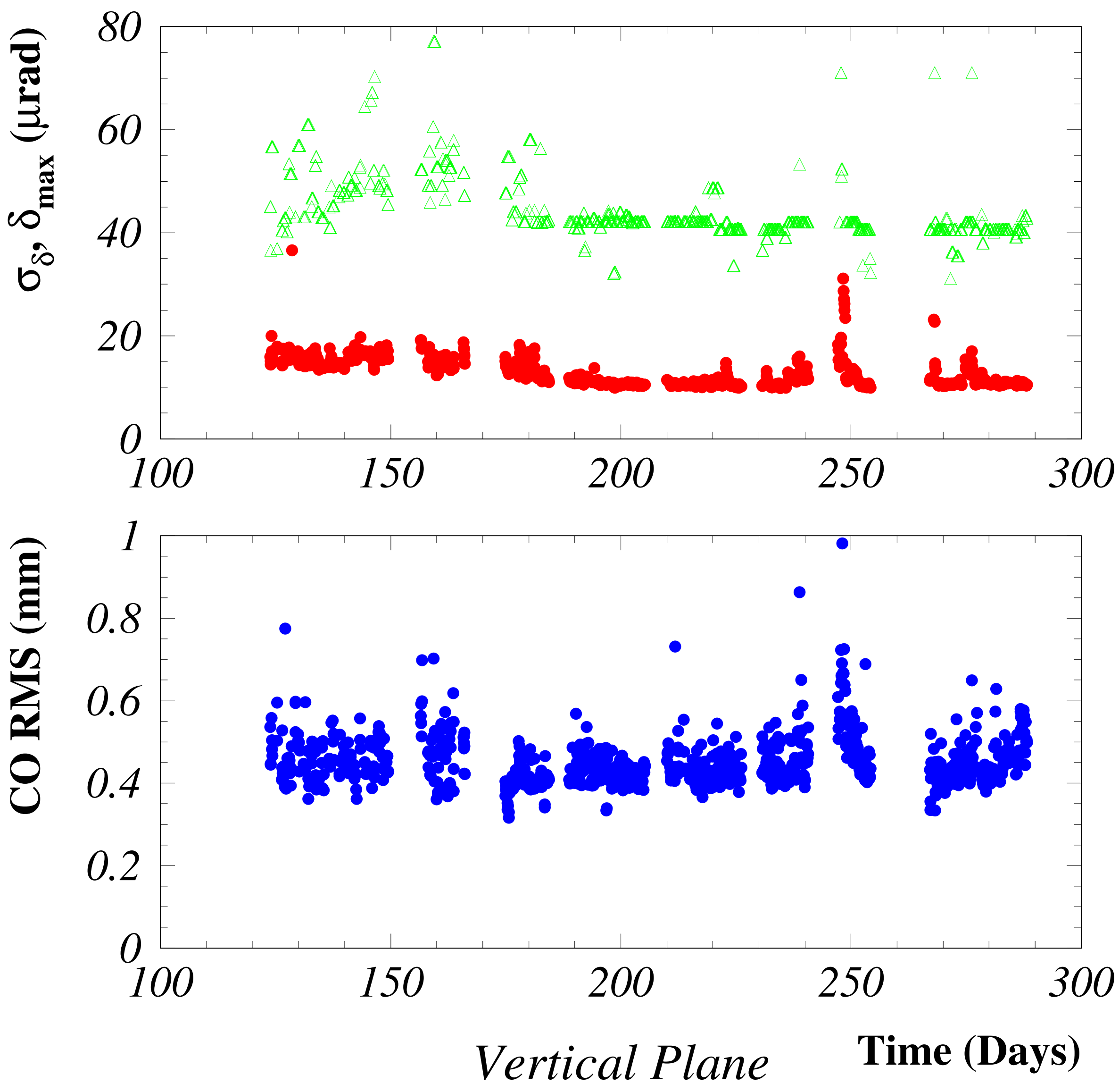

Figure 6: Top : Evolution of the vertical RMS kick strength σ_δ (circles) and the absolute value of the largest kick δ_{max} (triangles) for the insertions as a function of time for 1994. Bottom : Evolution of the vertical closed orbit RMS in the LEP insertions for the 1994 run.

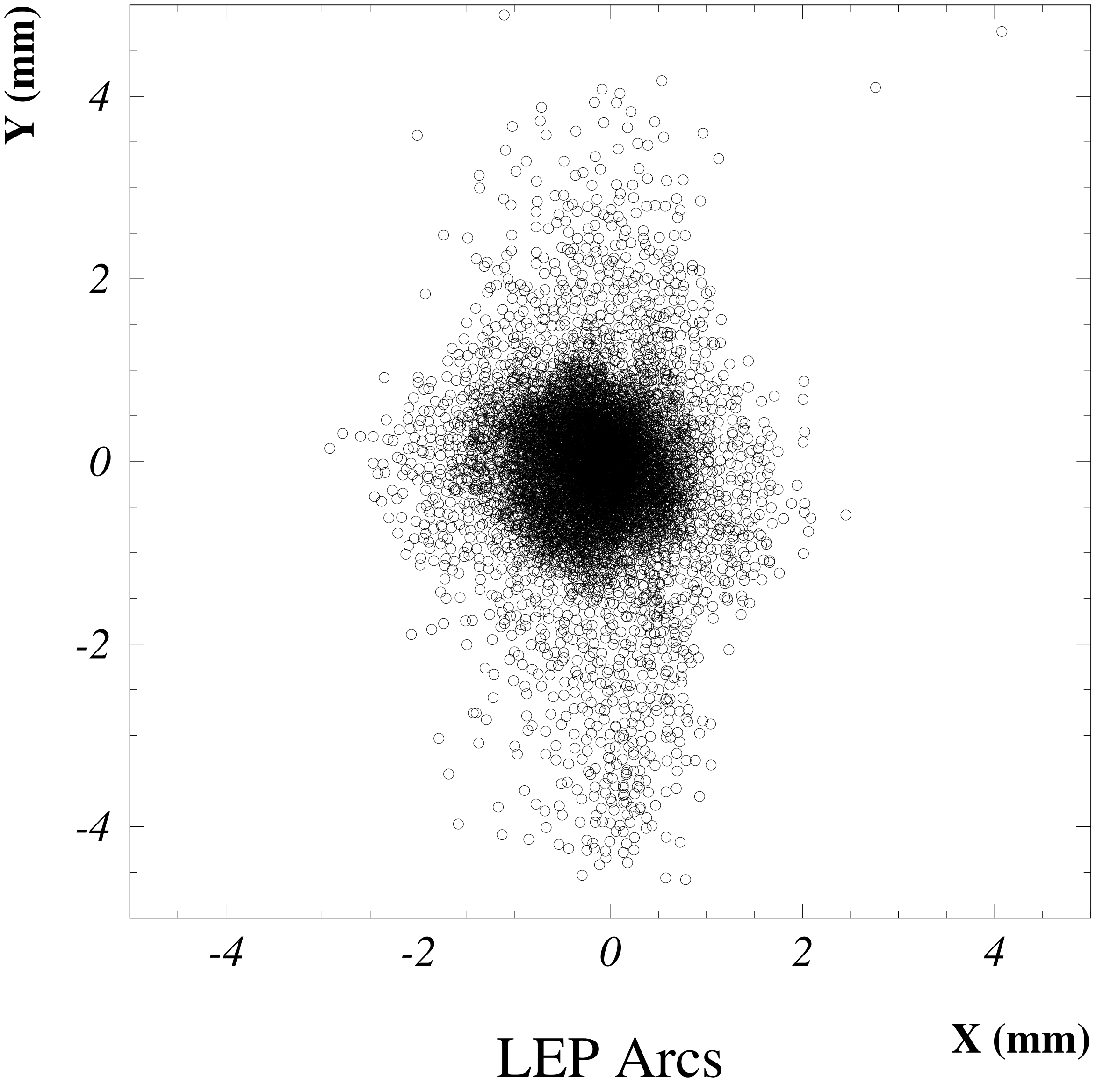

Figure 7: Correlation of the arc BPM readings of the two planes for orbits of 1994. X and Y correspond to the average position of the two beams.

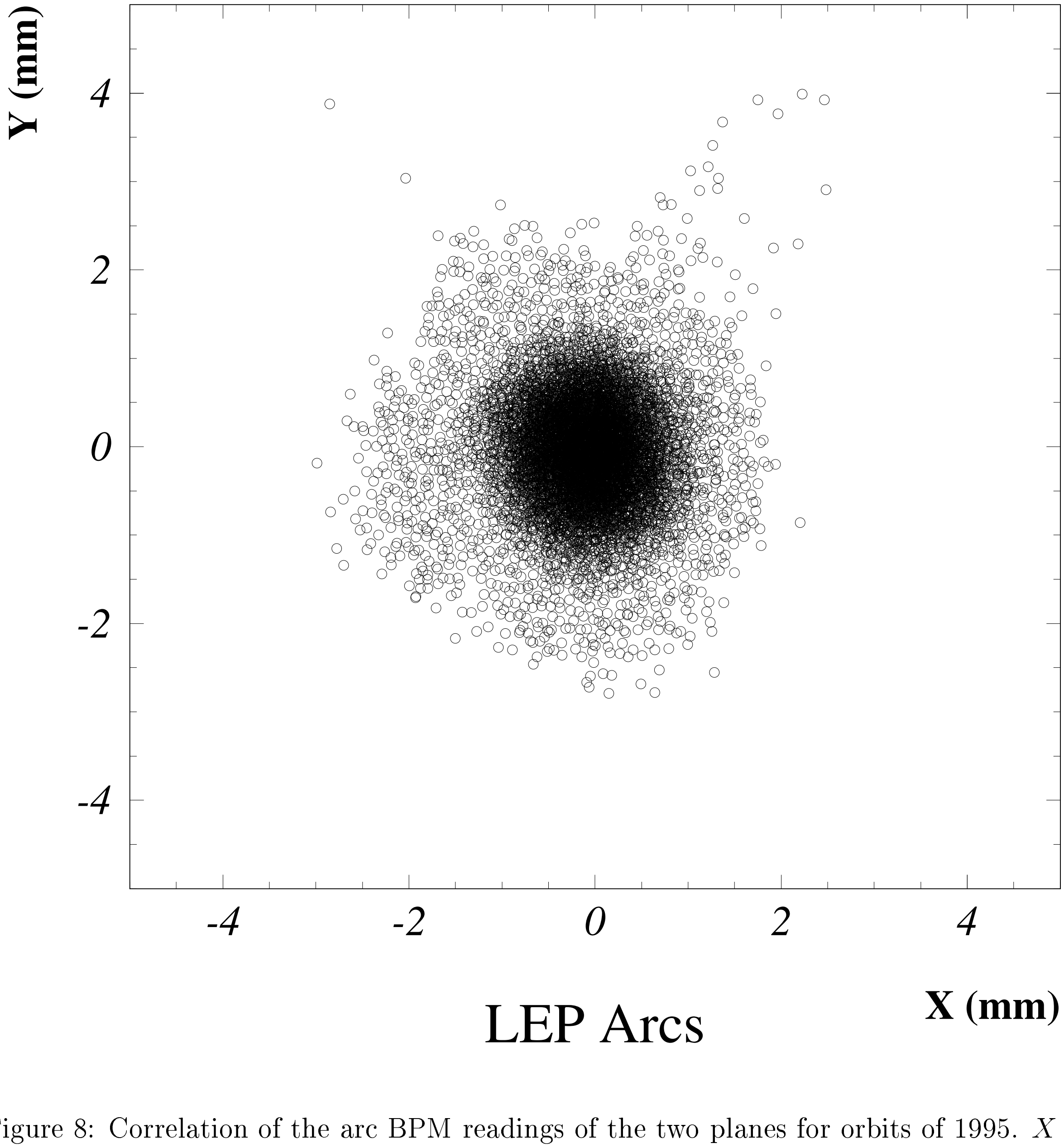

Figure 8: Correlation of the arc BPM readings of the two planes for orbits of 1995. X and Y correspond to the average position of the two beams.

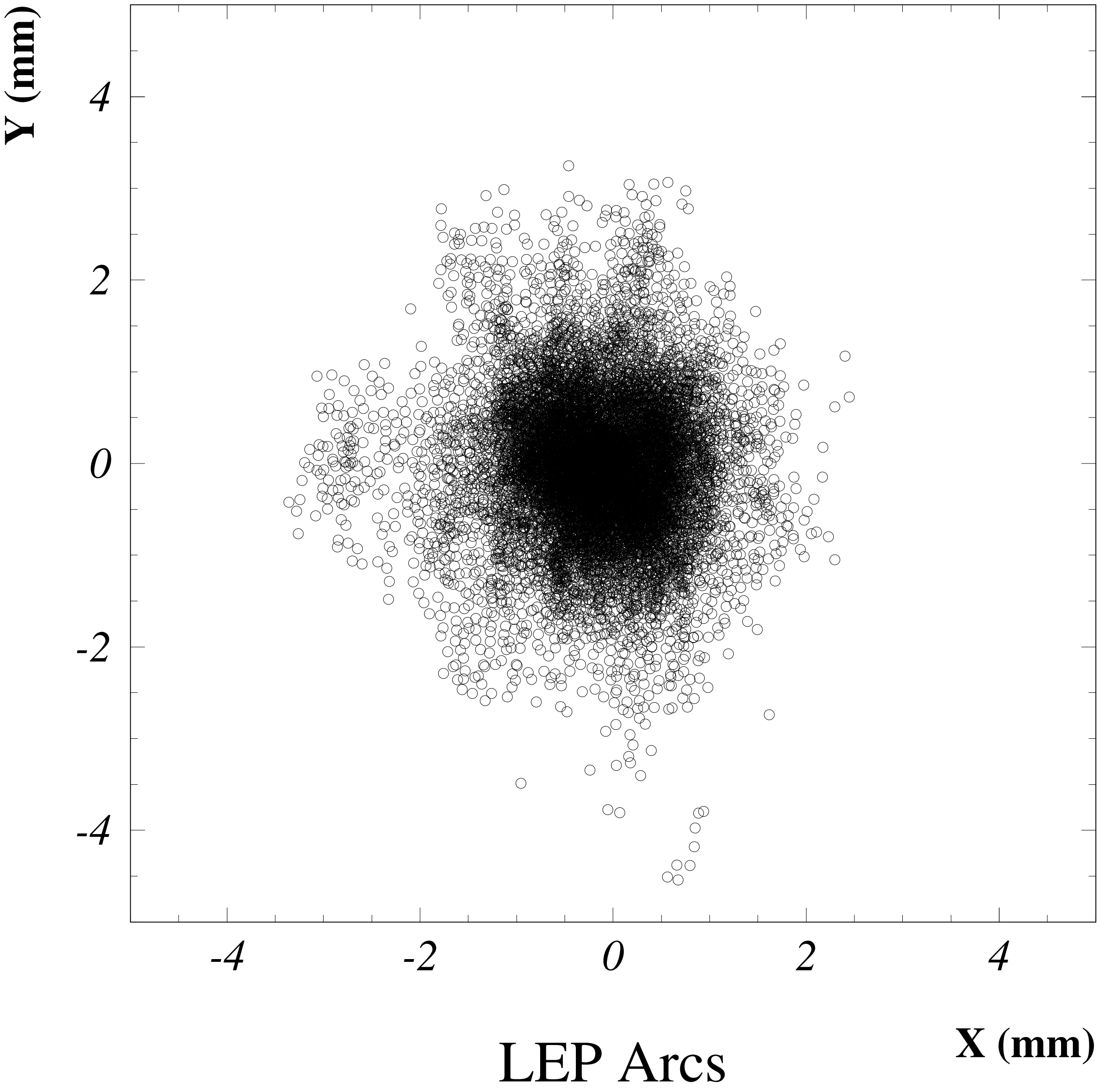

Figure 9: Correlation of the arc BPM readings of the two planes for orbits of 1996. X and Y correspond to the average position of the two beams.

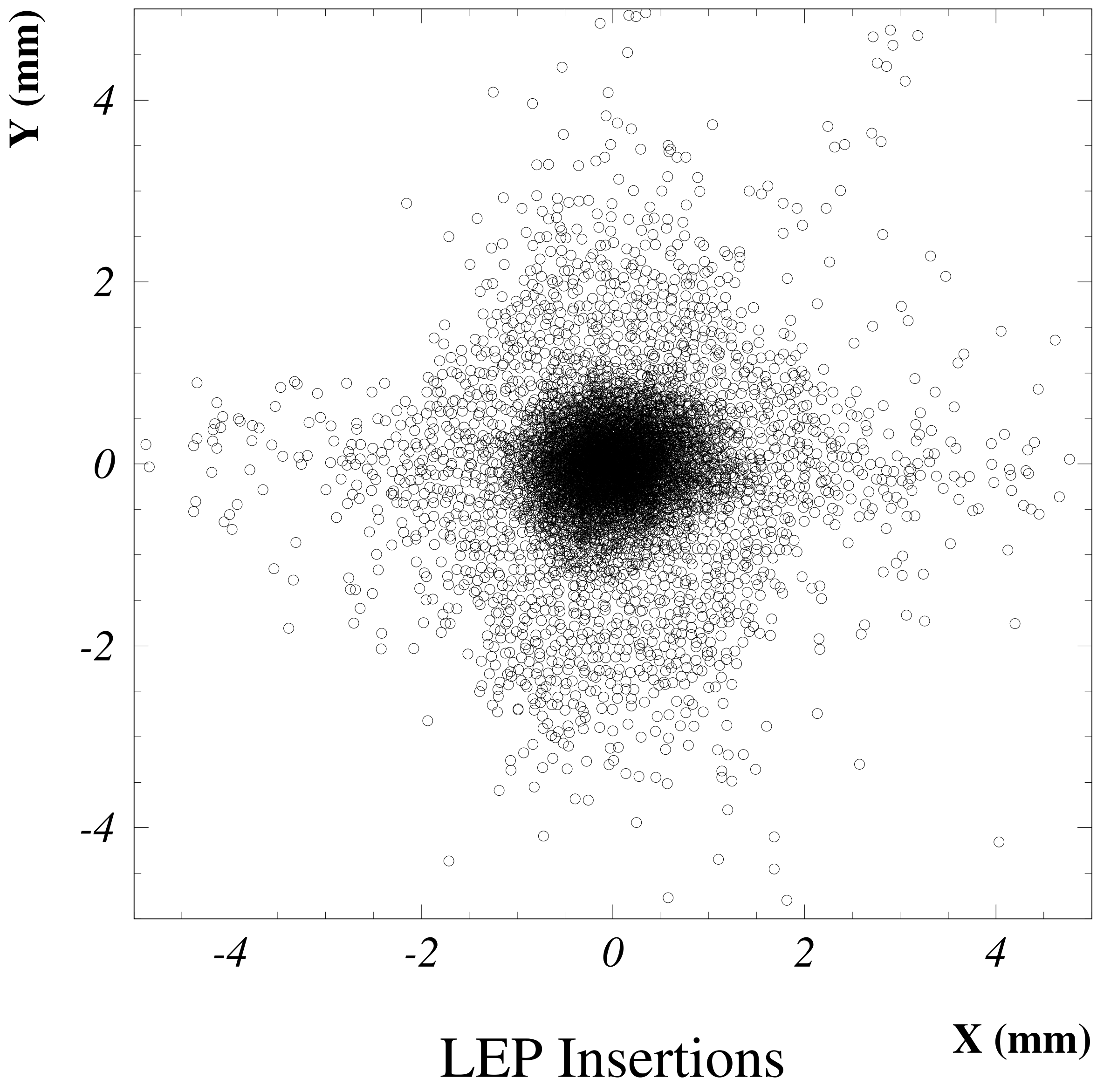

Figure 10: Correlation of the insertion BPM readings of the two planes for orbits of 1994. X and Y correspond to the average position of the two beams.

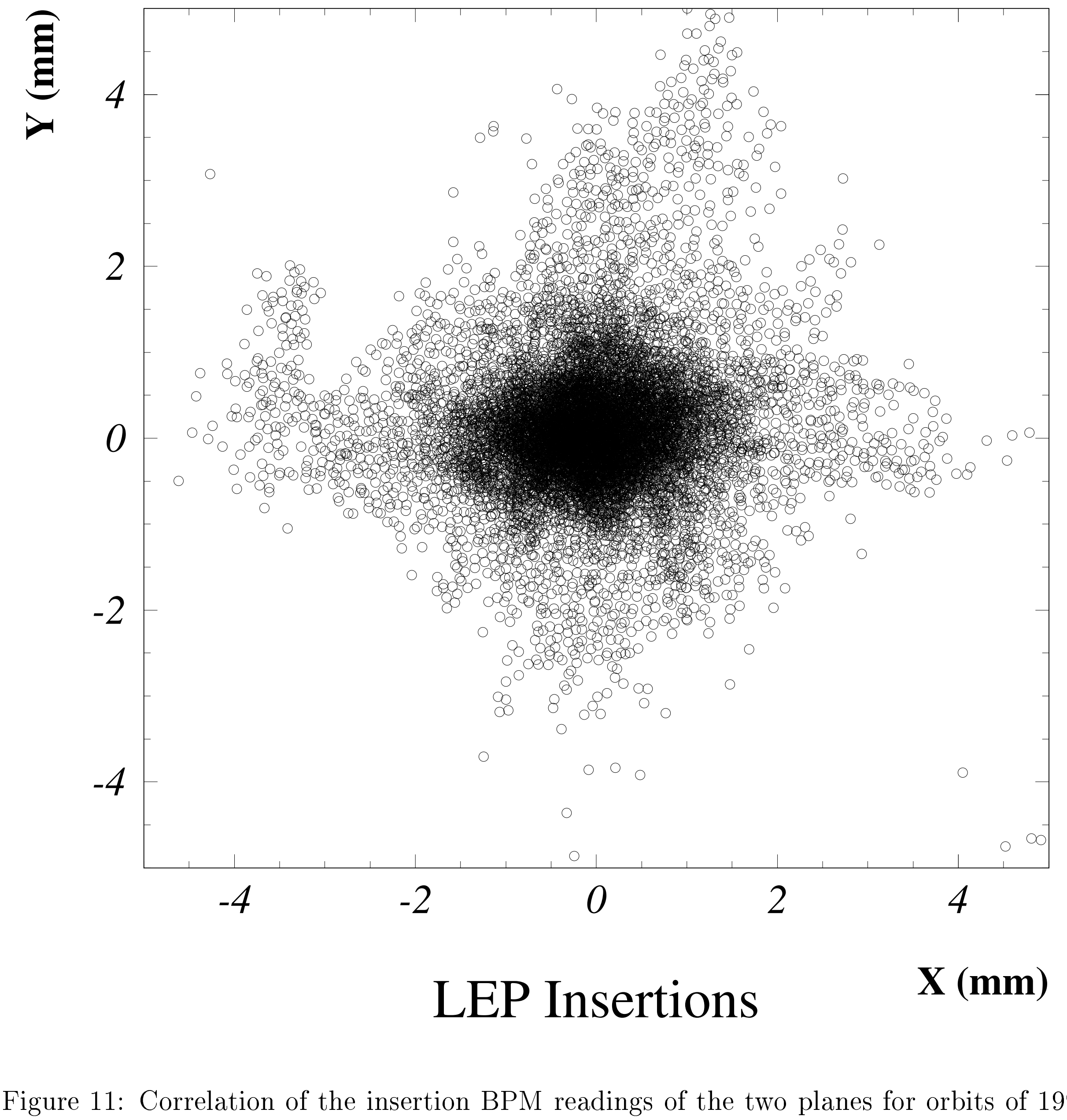

Figure 11: Correlation of the insertion BPM readings of the two planes for orbits of 1996. X and Y correspond to the average position of the two beams.

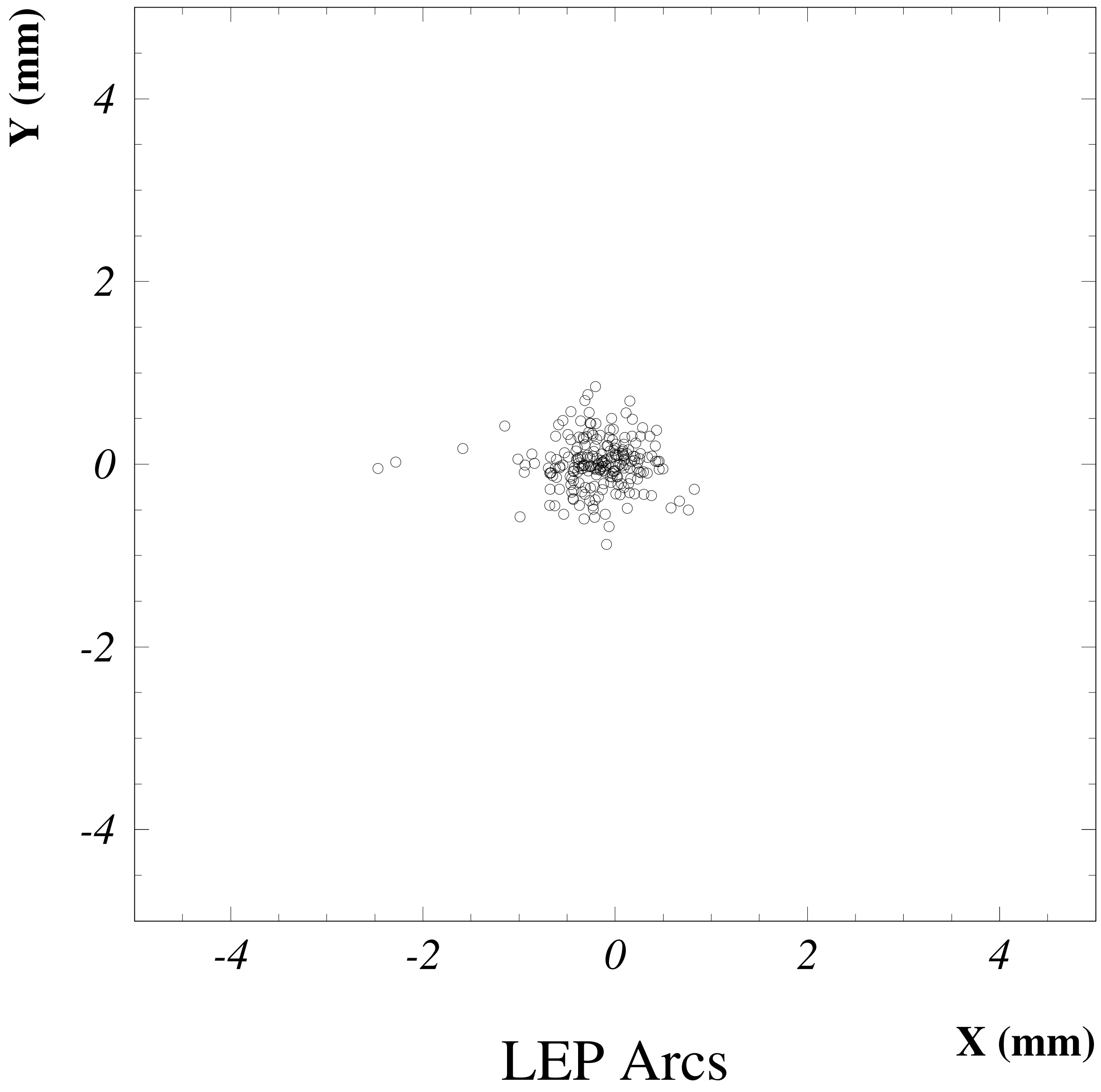

Figure 12: Correlation of the arc BPM readings of the two planes for a good polarization orbit of 1996.

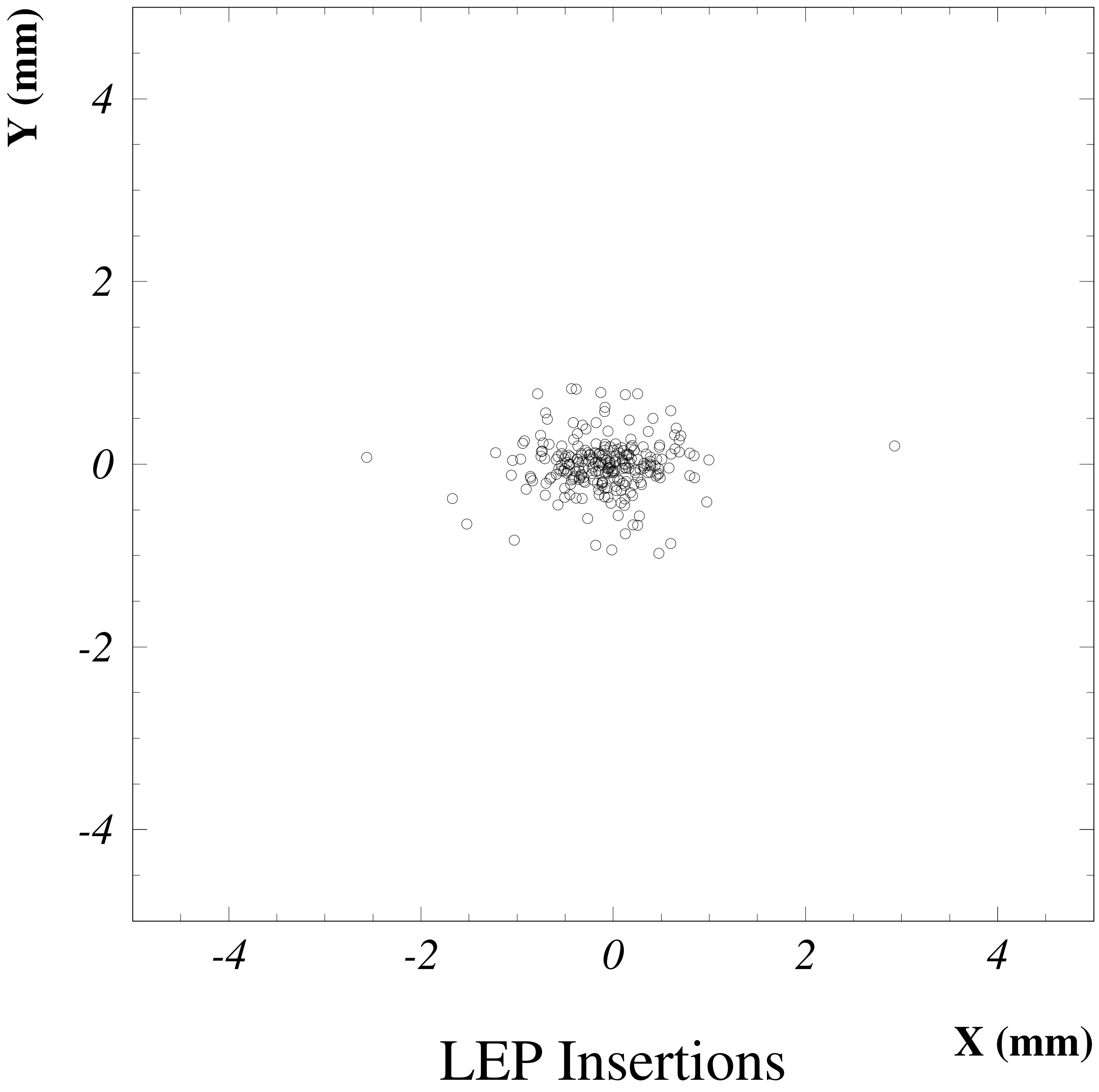

Figure 13: Correlation of the insertion BPM readings of the two planes for a good polarization orbit of 1996.