# Situation Analysis and Stability Evaluation of Large Electron Positron Collider in CERN*

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## Abstract

LEP (Large Electron Positron Collider) is the largest particle accelerator in the world. It was installed in tunnel underground and on service from 1989. The physicists and surveyors in CERN are very concerned with the stability of the tunnel and the accelerator. Several monitoring methods have been used for supervising. Especially, an annual global leveling is carried out from 1992 to 1999.

The paper presents the methods used for the situation analysis and stability evaluation of LEP, and shows some interesting results. The dynamic features of the accelerator and the tunnel were discussed. Some statistical parameters are proposed to be as the indexes of degradation and stability, which can truly reflects on the situation of LEP. Also some researches are also done about possibility of using in the stability and deformation analysis of the large linear or curvilinear objects, such as large accelerators, tunnels, bridges, highways and railways.

# 1. Introduction

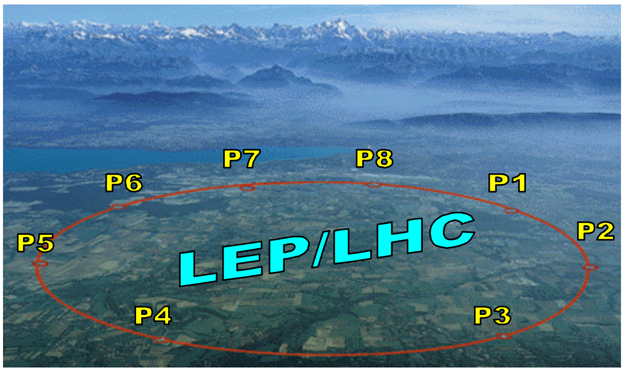


Fig.1 LEP/LHC

LEP is totally located in an underground tunnel, almost circular with a circumference of 27 km and a depth from 40 to 160 meters (Fig.1). It is the largest particle accelerator in the world (about 5000 elements, quadrupoles or dipoles). It is in the region of GEX (France) and partly in Geneva (Switzerland), and on service from 1989. The electrons and positrons strike each other in four different points after being accelerated around the circle. The collisions are observed with four detectors (ALEPH, DELPHI, L3 and OPAL) in large experience halls underground.

The physicists and surveyors working with it pay much attention to the stability of tunnel and accelerator after the installation of its elements. Several monitoring methods have been used for supervising. In certain particular zones an automatic system or some transverse profiles, serving as deformation observation line, have been installed. An annual whole deformation metrology is carried out on leveling. Some times measurements are done on tilts of dipoles and profiles. Here its stability was investigated based on the accumulated data. In this procedure there are three bigger problems: the first is to do pre-processing of the observed data, data-filtering and data-restoring. The second is how to create a technique, which could be used to find its situation and stability without any influence from the surveying adjustment datum and the other uncertainty parameters or factors. The third is how distinguish the stability of the tunnel and that of the accelerator from their mixed signal.

## 1.1 Monitoring Surveying

After the installation of elements, monitoring surveying includes annual leveling, tilt and profile. Some zones are under automatic surveillance with certain sensors (on the pressure, temperature and humidity) located into the rock external of the tunnel. Transverse profiles have been laid out in some zones in order to find the transverse variation of the tunnel. Among the various monitoring surveying data, the most interesting is annual leveling from 1992. It offers us continuous information about the situation of LEP.

Actually, monitoring measurements realized as 1. Annual leveling from Dec.1992 to Dec.1999, 2. Tilt measurement of dipoles in 1992 and 1998, 3. Complex polygon in 1993, 4. Transverse profiles in 1990, 1991, 1992,1998 and 1999.

### 1.1.1 Annual Leveling

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The level circuit of LEP is characterized as follows:

- **A quasi circle of 27 km on circumference, whole circuit in the tunnel**
- **With NA3000 in general , with level NA2 in the jam zones of 8 shaft areas**
- **Maximum height difference of 120 m between the highest point and the lowest point**
- **Measured points being the alignment brackets of the quadrupoles**
- **800 quadrupoles, 1600 points to measure with fore and back measurements**
- **Fig.2 illustrates the method of leveling between two success**
- **Free network adjustment for data processing**

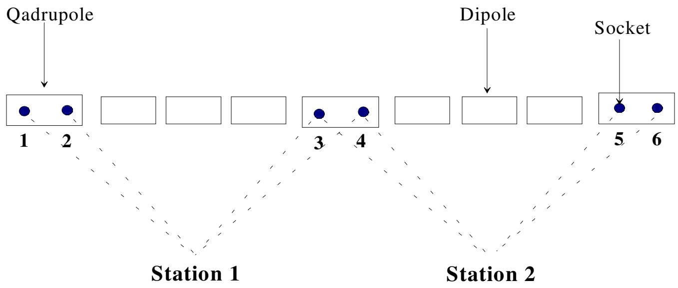


**Fig. 2 Method for Leveling of LEP**

#### 1.1.2 Tilts of Dipoles

There are about 2400 dipoles in LEP. In 1992 and 1998 their tilts were measured with a precision of $\sigma = \pm 0.07$ mrad. The dipoles with the tilt offset bigger than 1.0 mrad were brought to their theoretical positions. Those measurements would help to know the transverse stability of the elements and the tunnel. They could be also used as supplementary information for vertical deformation analysis.

#### 1.1.3 Transverse Profiles

In three zones (around the shaft 1, the highest zone and the lowest zone), more than 40 profiles were installed onto the floor of the tunnel in 1990 and 11 profiles were added in 1998. Monitoring surveys were executed in 1990~1992,1998 and 1999. So the transverse stability of the tunnel were directly checked by these profiles. Initially the profiles in the zone around the shaft 1 were served to monitor the stability of the zone where there are many intersections of the tunnels. Those in the highest zone served to monitor the stability of the zone within the Mountain Jura and those in the lowest zone were mainly in the purpose of the monitoring of the subsidence of the section underground the village of Ferney-Voltaire.

## 1.2 Stability Analysis

After the installation of LEP in 1986, a very interesting question for all people working in CERN is the situation of the LEP accelerator and the tunnel, especially after some natural accidents (mud going into tunnel) occurred within the tunnel. Therefore not only the desire of the LEP, but also the demand of the LHC (7+7 TeV Large Hadron Collider, Operational in 2005), as well as the enormous datum obtained during the past ten years encourage us to considerate this research project. Analysis will be in many interesting fields, such as stability of the tunnel and stability of the accelerator.

#### 1.2.1 Datum for Study

In order to keep the accelerator in its configuration, leveling has been annually done from 1992. Compared the others, the leveling data is more interesting. The calculation and adjustment were realized with the software of the group. Because there are volunteer displacement on certain quadrupoles, the points leveled are not exactly the same for every year. In addition, one thing very special is that the points leveled are located on the quadrupoles, not installed into tunnel's floor directly. That brings some difficulties to find the zones where there are the vertical movement and deformation of the tunnel. Some research works have been done for this problem.

Due to the features of the vertical offsets, its stability, deformation and movement analysis needs a special technique for the following purposes:

- The result obtained should be able to reflect the deformation information of the tunnel.
- The analysis procedure should not be interrupted by the choice of a basic point used to calculate the heights and the adjustment.
- The analysis results should introduce the necessary deformation description for the whole LEP, the special interesting zone or points, and the special aspects. The descriptions would be mathematically presented if necessary.
- The analysis results should be modeled with physical parameters (such as inclination, linear tensor and movement subsidence speed and acceleration) for people concerned to easily understand and freely use the results.

- For the deformation analysis results a very reasonable explication for the causes should be given following the all information from the documents and site investigations.

#### 1.2.2 Key Problems in Stability and Deformation Analysis

There three key problems in the deformation analysis of LEP, they are

- It is absolutely necessary to restore the vertical offsets for getting a continuous movement information of LEP. It is because that some elements are realigned if they are considered far away from their smoothing positions after the leveling measurement and smoothing. And some elements moved voluntarily should be eliminated or considered specially. Those elements generally locate in the straight section around the shaft areas.
- Because of the particular problem of LEP, the traditional and usual method for deformation analysis is not available at all. A new technique and procedure should be reconstructed in order to find correctly the moving zones and points. And also it could be used to find the tunnel deformation and the element movement, and could be do the analysis of the deformation pattern for the deformed area.
- The evaluation of stability situation of whole LEP should be done, and also that for sections or zones. For some zones or points their deformation or movement should be correctly modeled in the purpose of the next steps.

## 2. General Investigation

In order to find a technique for the deformation and movement analysis, the dynamic features of both the accelerator and the tunnel must be known. Some research works have been done by the statistic method. Based on the F-Test theory, a general investigation on the vertical offsets, the inclination, deformation, the tilt of elements and the vertical offset differences have been done. The correlation analysis method and the linear regression method are also used to the whole configuration deformation analysis.

### 2.1 Restoration of Vertical Offsets

Due to realignment of the elements every year, the vertical offsets obtained on these elements realigned could not continuously reflect their vertical variation. The accumulated offsets could be restored based their measurements in Spring next year. This restoration procedure is also done for the smoothing offsets.

### 2.2 Statistic Analysis on Stability

In order to know the situation of LEP, a statistic analysis should be done based on some assumptions. The first one is that the offsets every year should be the same theoretically if there are not any movement of the elements. The leveling precision every year should be the same theoretically. The leveling precision of every section should be the same as that of the others and the same as that of itself every year. So some statistic analysis based on different measurements of LEP were carried out.

#### 2.2.1 Difference of Vertical Offsets

The RMS of vertical offset differences between every year and 1992 was estimated (Table 1: **Differences w.r.p to Dec-92**). The RMS of vertical smoothing offsets every year was also calculated (Table 1: **Accumulated Smoothing Offsets, Smoothing Offsets and Offsets after Smoothing Correction**). And then some F-tests were done between two successive years, and

**Root Mean Square of Vertical Offsets**

**Table 1**

| Year / RMS(mm) | Dec-93 | Dec-94 | Dec-95 | Dec-96 | Dec-97 | Dec-98 | Dec-99 |
|---|---|---|---|---|---|---|---|
| Differences w.r.p to Dec-92 | 1.25 | 0.81 | 1.04 | 1.56 | 1.68 | 1.73 | 2.54 |
| Accumulated Smoothing Offsets | 0.35 | 0.45 | 0.61 | 0.65 | 0.69 | 0.73 | 0.91 |
| Smoothing Offsets | 0.35 | 0.22 | 0.26 | 0.20 | 0.18 | 0.19 | 0.25 |
| Offsets after Smoothing Correction | 0.18 | 0.16 | 0.18 | 0.15 | 0.14 | 0.16 | 0.14 |

**Root Mean Square of Accumulated Smoothing Offsets**

**Table 2** **(mm)**

| Zone | section | Dec-93 | Dec-94 | Dec-95 | Dec-96 | Dec-97 | Dec-98 | Dec-99 |
|---|---|---|---|---|---|---|---|---|
| P1-p2 | 1 | 0.34 | 0.41 | 0.45 | 0.45 | 0.47 | 0.51 | 0.63 |
| P2-P3 | 2 | 0.41 | 0.46 | 0.56 | 0.60 | 0.63 | 0.69 | 0.87 |
| P3-P4 | 3 | 0.32 | 0.29 | 0.35 | 0.36 | 0.39 | 0.42 | 0.49 |
| P4-P5 | 4 | 0.38 | 0.46 | 0.49 | 0.49 | 0.52 | 0.54 | 0.61 |
| P5-P6 | 5 | 0.23 | 0.25 | 0.28 | 0.27 | 0.31 | 0.35 | 0.43 |
| P6-P7 | 6 | 0.18 | 0.17 | 0.21 | 0.21 | 0.26 | 0.31 | 0.34 |
| P7-p8 | 7 | 0.57 | 0.91 | 1.45 | 1.55 | 1.64 | 1.69 | 2.15 |
| P8-P1 | 8 | 0.18 | 0.24 | 0.32 | 0.36 | 0.41 | 0.50 | 0.66 |

between successive sections. The results of the statistical tests could be found in reference [1]. From the analysis some conclusions arrived as following:

- **The LEP machine has been moving since its beginning. The RMS is from ±0.81 mm in Dec. 1994 to ±2.54 mm in Dec.1999. It means the machine is running farther and farther from its vertical theoretical position.**
- **The movement of LEP is quite different from section to section. The biggest one is the section 7. Its RMS are ±1.85 mm in Dec.1999.**
- **From Dec.1993 to Dec.1999, the increase of the RMS of vertical smoothing offsets is 0.56 mm. That means the configuration of accelerator has been slightly varying.**
- **The RMS of the smoothing offset was about 0.20 mm on average. There are some elements moving away from their smoothing position every year.**
- **The configuration variation is quite different from section to section. The biggest section is the section 7 (RMS is 2.15 mm) and the second biggest one is the section 2 (RMS is 0.87 mm).**

#### 2.2.2 Vertical Smoothing Offset Difference between E and S

Statistic analysis on the different types of vertical smoothing offset difference, such as between the point E and the point S of the same quadrupole, and between the point S and the point E of the following quadrupole, have been carried out. Conclusion and experience are gotten as:

- **RMS of smoothing offset difference between E and S is ± 0.13 mm ~± 0.14 mm, and ± 0.16 mm ~ ± 0.18 mm between S and E.**
- **The variation of the variance for S-E is statistically significant from year to year. It means there probably are a ground motion or deformation in this area.**

#### 2.2.3 Tilt Deviation of Dipoles

The statistic analysis of tilt deviations of dipoles was executed with variance tests on the tilt deviation difference between two points (((N+1)-N)~((N+5)-N)) for 1992 (Fig.3). Some conclusions were got based on the analysis:

- **Based on the tests, until 1992 the tilt differences among the dipoles L, M and R were not significant.**
- **The tilt deviation of sections 3, 4, and 7 (-0.263 mrad, 0.554 mrad and -0.209 mrad) were outside the error envelope ($\pm 2 \times 0.07\, mrad = \pm 0.14\, mrad$ ). They have some unstable zones or elements.**
- **Until 1998 the sections 3~8 presented unstable. The tilt deviation in1998 was much bigger than that in 1992, it means that the transverse movements of the elements or the tunnel existed during this period.**
- **The transverse turning tendency existed in sections 3, 4 and 7 from its beginning to 1992, and in sections 3~8 from 1992 to 1998.**

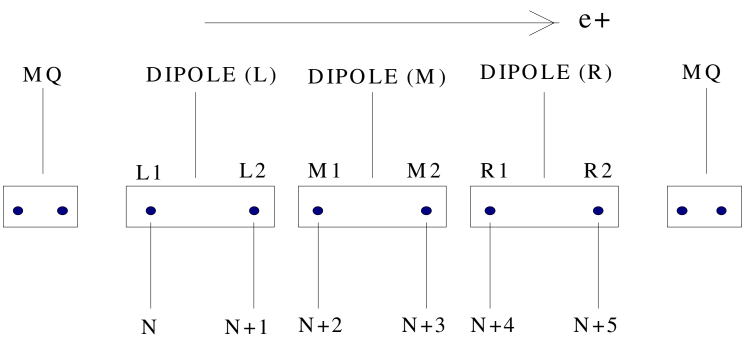


**Fig.3 Positions of Dipoles and Quadrupoles**

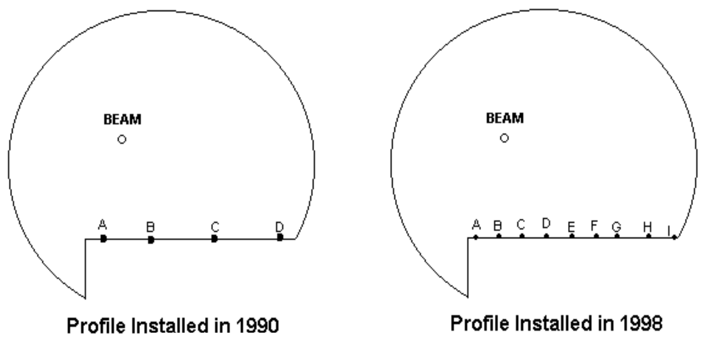


**Fig.4 Transverse Profiles**

#### 2.2.4 Profiles in Tunnel

The transverse profiles (Fig.4) installed in three zones, (around the point 1, around highest point and around the lowest point), had been measured in 1990, 1991, 1992 and 1999. During the first three years, the measurements presented the zones stable. After 7 years the measurements in 1999 show some zones unstable during the past years. The correlation analysis between the tilts and the profiles has been realized. A detailed analysis on stability is carried out for every zone. The conclusions may be roughly obtained from the comprehensive analysis as fellows:

- **The zone before Point 1 (14 profiles) is relatively stable in the transverse direction of the tunnel, except two profiles have some floor deformation.**
- **The zone after Point 1 (11 profiles) is unstable in the transverse direction of the tunnel. It has a turning tendency towards the center of the accelerator circle. At the same time it has also some deformation.**
- **The zone of highest point (12 profiles) is unstable in the transverse direction of the tunnel. It reflects mainly the deformation of the floor.**
- **The zone of lowest point (8 profiles) is just the same as the zone after Point 1. But its deformation is smaller.**

# 3. Inclination and Deformation Investigation

## 3.1 Inclination and Deformation

Because the reference datum for the leveling adjustment is different from year to year, and because the points measured are not installed onto the tunnel floor directly, we should find a technique, from which the analysis results would not be disturbed by the choice of the reference datum. This technique should also permit us to get the movement information of the elements themselves and the movement information of the tunnel floor.

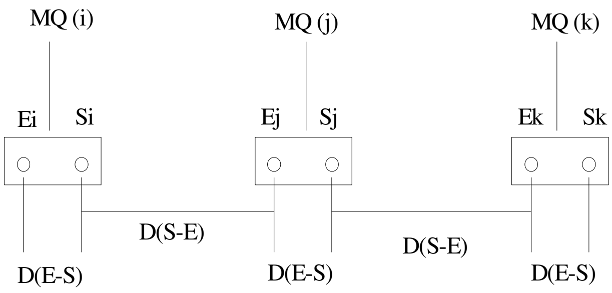


**Fig.5 Positions of Quadrupoles**

### 3.1.1 Definitions

After some experiments and studied, the **inclination** between two points and the **deformation** between two inclinations had been considered as the analysis statistics. Their definitions could be get from the Fig.5.

**INCLINATION1: The inclination on the MQ is written as** $In_{(E-S)} = \dfrac{\Delta H_{Ei} - \Delta H_{Si}}{D_{(E-S)}}$ **.**

**INCLINATION2: The inclination between the point** $S_i$ **and** $E_j$ **is written as** $In_{(S-E)} = \dfrac{\Delta H_{Si} - \Delta H_{Ej}}{D_{(S-E)}}$ **.**

**DEFORMATION1: The deformation from inclination of the MQ is** $De_{(E-S)} = \dfrac{In_{(E_j-S_j)} - In_{(E_i-S_i)}}{(D_{(E-S)} + D_{(S-E)})}$ **.**

**DEFORMATION2: The deformation from** $In_{(S-E)}$ **is** $De_{(S-E)} = \dfrac{In_{(S_j-E_i)} - In_{(S_k-E_j)}}{(D_{(E-S)} + D_{(S-E)})}$ **.**

**Where** $\Delta H$ **is the vertical offset,** $D$ **is the distance.**

### 3.1.2 Tolerance

For determining the precision of the calculated inclination and the calculated deformation, the precision of the levelling carried out on LEP should be found. There are two parameters maybe used to estimate the desired parameters: the first is the maximum tolerance 0.08mm for the difference between going and coming on the height difference of two consecutive points. The second is the precision of the instrument marked by the producer 0.4mm/km. For the calculation on the E-S the average distance interval is 1.2m and that on the S-E is 38.0m.

**Tolerance of Leveling Precision**

**Table 3**

| Tolerance | E-S | S-E |
|---|---|---|
| Inclination (rad) | $\pm 4.70\times10^{-5}$ | $\pm 2.10\times10^{-6}$ |
| Deformation (rad/m) | $\pm 1.69\times10^{-6}$ | $\pm 7.58\times10^{-8}$ |

The half of the maximum tolerance is taken as the r.m.s of the height difference and then the tolerances of inclination and deformation could be got in Table 3.

### 3.1.3 Analysis on Inclinations and Deformations

The inclinations and deformations of E-S and S-E were worked out and presented in Table 4, Table 5 and graphically in Fig.6, Fig.7. It was found that a systematic increase of the inclination and deformation exists on most of elements every year. Its sign was perfectly correspondent with the sign of its inclination and deformation. It can be seen from the extracted examples, such as Fig.8~9 (Inclination Distribution of LEP: Piut 7--Puit 8: E--S, Deformation Distribution of LEP: Puit7-- Puit 8: E—S). The means of absolutes and the means of the inclination and deformation on E-S and S-E from 1992 to 1999 are shown in Table 4, Table 5 and presented graphically in Fig.5~6. The same procedure as above is also done from the section 1 to the section 8. From the analysis, some interesting conclusions may be summarized as fellows:

- **The inclination of the quadrupoles (E-S) has been increasing from 1992 to 1999 with an average speed of 0.008 mrad/year. The inclination increase direction of each quadrupole is correspondent to its inclination. This also means that a systematic movement exists on qdadrupoles.**
- **The inclination between two quadrupoles (S-E) has been increasing from 1992 to 1999 with an average speed of 0.0014 mrad/year. This shows a systematic movement exists on the floor of the tunnel. If we convert it into a height difference between two successive quadrupoles, it would be 0.04 mm/year in the most favorable case.**
- **The deformation following the quadrupoles (E-S) has been varying from 1992 to 1999 with an average speed of 0.00018 (mrad/m)/year. The deformation increase direction is correspondent to its original deformation value.**
- **The deformations following the quadrupoles (S-E) has been varying from 1992 to 1999 with an average speed of 0.00006 (mrad/m)/year. The deformation increase direction is correspondent to its original deformation value.**
- **The analysis on actual situation of each section based on LEVELING PRECISION shows:**
    1. **The inclination variation and the deformation variation existed along the whole tunnel of LEP following studying on the inclinations of S-E.**

**Vertical Movement Description of LEP**
**(Inclination)**

**Table 4**

| Section 1- 8 | Mean of Absolute Value (rad) | | Mean (rad) | |
|---|---|---|---|---|
| Year | E-S | S-E | E-S | S-E |
| Dec-1992 | 1.11E-04 | 1.14E-05 | -2.08E-05 | 5.56E-07 |
| Dec-1993 | 1.21E-04 | 1.34E-05 | -1.22E-05 | 3.09E-07 |
| Dec-1994 | 1.30E-04 | 1.48E-05 | -9.33E-06 | 2.20E-07 |
| Dec-1995 | 1.42E-04 | 1.65E-05 | -1.02E-05 | -3.64E-08 |
| Dec-1996 | 1.48E-04 | 1.73E-05 | -8.28E-06 | -3.80E-08 |
| Dec-1997 | 1.55E-04 | 1.85E-05 | -1.21E-05 | 9.32E-08 |
| Dec-1998 | 1.60E-04 | 1.99E-05 | -8.10E-06 | -1.08E-07 |
| Dec-1999 | 1.65E-04 | 2.12E-05 | -6.42E-06 | -1.75E-10 |
| Tolerance | 3.75E-05 | 1.68E-06 | 4.70E-05 | 2.10E-06 |

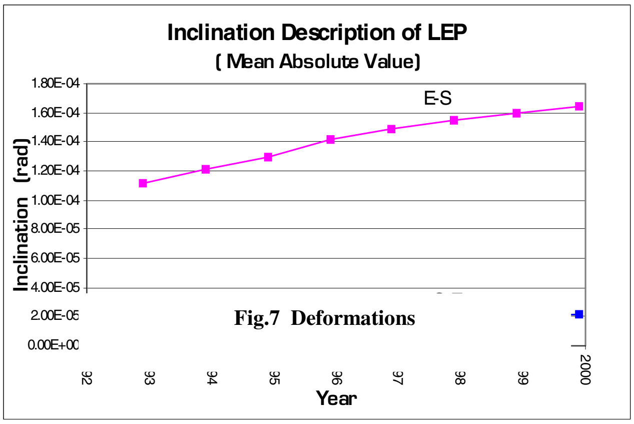


**Fig.6 Inclinations**

**(Deformation)**

**Table 5**

| Section 1- 8 | Mean Absolute Value (rad/m) | | Mean (rad/m) | |
|---|---|---|---|---|
| Year | E-S | S-E | E-S | S-E |
| Dec-1992 | 4.13E-06 | 4.74E-07 | -1.86E-08 | 2.53E-09 |
| Dec-1993 | 4.61E-06 | 5.83E-07 | -8.00E-08 | -5.93E-09 |
| Dec-1994 | 4.90E-06 | 6.41E-07 | -7.82E-08 | -7.64E-09 |
| Dec-1995 | 5.28E-06 | 7.23E-07 | -7.26E-08 | 2.00E-08 |
| Dec-1996 | 5.64E-06 | 7.42E-07 | -1.14E-07 | 2.27E-08 |
| Dec-1997 | 5.90E-06 | 7.97E-07 | -2.27E-08 | 2.83E-08 |
| Dec-1998 | 6.10E-06 | 8.54E-07 | -1.48E-07 | 2.42E-08 |
| Dec-1999 | 6.42E-06 | 9.00E-07 | -9.77E-08 | 1.86E-08 |
| Tolerance | 1.35E-06 | 6.05E-08 | 1.69E-06 | 7.58E-08 |

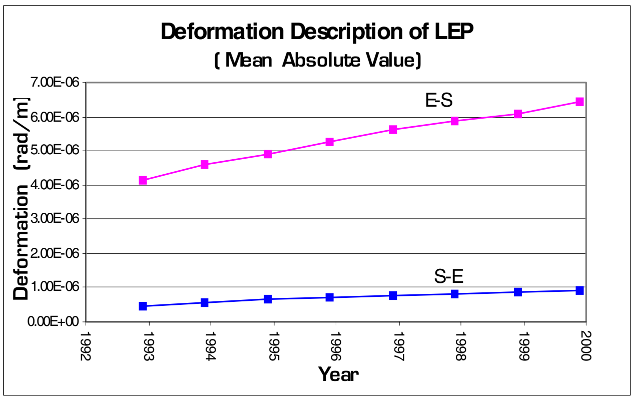


**Fig.7 Deformations**

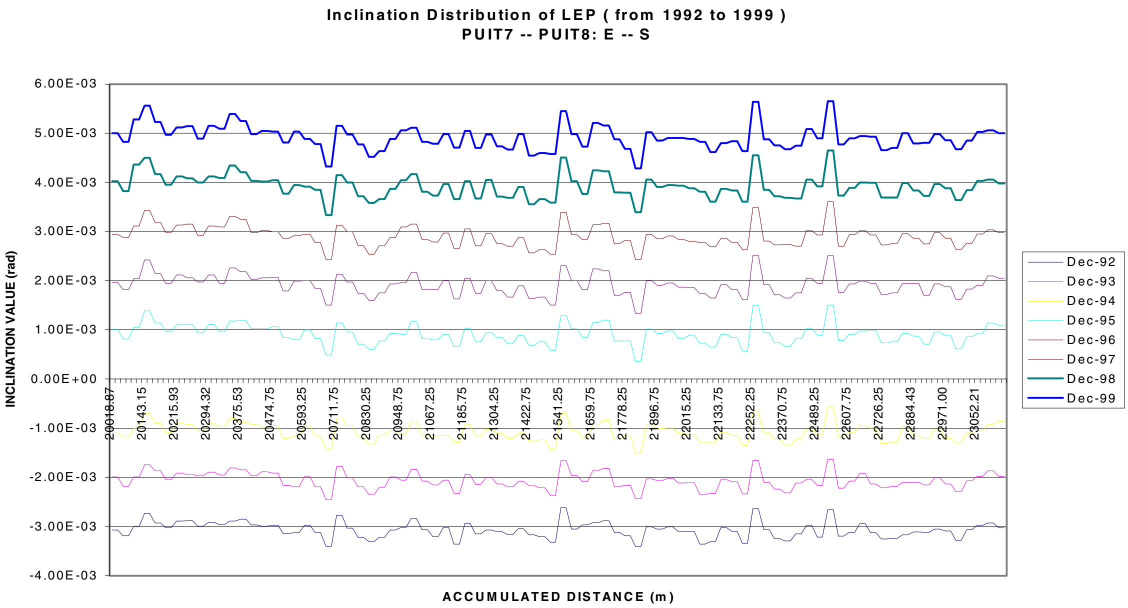


**Fig. 8**

2. **The sections 7 and 8 have an evident inclination variation of quadrupoles. The sections 2, 3 and 7 have evident deformation variation following studying on the inclinations of E-S.**
3. **The sections 2, 3, 7 and 8 are more active than others.**

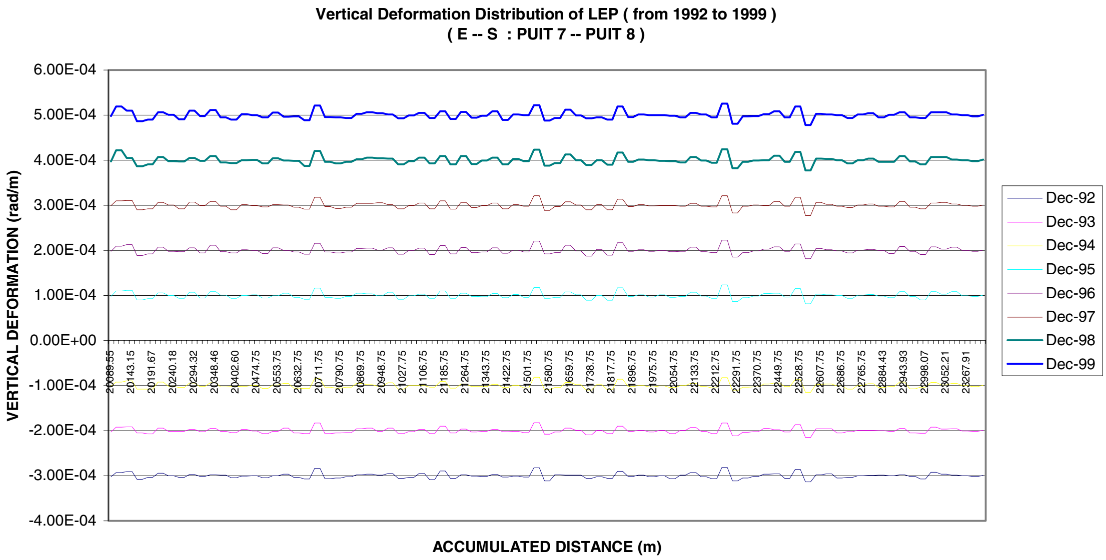


**Fig. 9**

## 4. Conclusions

From the results above and on the basis of the relevant information, a comprehensive analysis had been done on the stability and dynamic situation of LEP. The following important conclusions were obtained:

- **Both LEP's accelerator and tunnel have been moving since their beginning. That has been bringing some movements on the accelerator and some deformation on its configuration.**

- **The systematic movement of the elements comes partly from the elements themselves (probably their supporting and adjusting system) and partly from the movement and deformation of the tunnel. The former shows annul inclination increase in a speed of 0.008 mrad/year. It presents the systematic movement of the elements themselves rather than others. The latter shows annul inclination increase in a speed of 0.0014 mrad/year.**
- **Although the machine and tunnel are always moving or deforming, the smoothing and realignment was always keeping the accelerator in the desired situation.**
- **Locally, the tilts show us the sections 1, 3, 4, 5, 7 and 8 being longitudinally unstable. There are not any section being much more stable than others. Relatively speaking, the sections, 3, 5 and 7, are more active than others.**
- **The profile zones after the Point 1, lowest point and the highest point are transversely unstable and deformed and the first two zones are of a turning tendency towards to the center of the circle.**
- **The sections 2, 3, 7 and 8 have been more active than the others during past years.**

And also we got some experience from the work as fellows:

- **Statistic methods, such as F-test, tendency test, correlation test, are quite useful for the stability evaluation of whole structures and for studying dynamic features.**
- **The inclination and deformation defined in this paper are two very good parameters to describe the dynamic features of elements of long linear and curve line structures, such as accelerator, tunnel, railway, highway, tube system etc. They are very independent and local.**
- **The speed of the mean of absolute inclination can be used as the index of dynamic situation and stability of the object.**
- **The speed of the mean of absolute deformation can be used as the index of degradation of shape and stability of the object.**

## 5.Acknowledgements

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