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Preliminary Report on the Consequences of LHC Civil Engineering for the SPS and LEP

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Abstract

The excavation of the shafts and caverns for the ATLAS and CMS experiments of the LHC will start whilst LEP and the SPS are running. This will be at a period when LEP should be at its peak performance and the SPS will be providing beams for LEP, fixed target physics and LHC test beams. Simulations show that movements of the machine tunnels can be expected during the excavation and it is essential that this does not affect the performance of the SPS and LEP. These movements are of sufficient amplitude to prevent machine operation if no precautions are taken. This preliminary report outlines the problems and suggests what actions should be taken to ensure efficient operation of the SPS and LEP during the critical period.

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Contents

1 Introduction

The schedule for the construction of LHC requires that civil engineering work starts during the final period of LEP operation (when it should be at its highest performance) and whilst the SPS continues to run, providing beams for LEP, fixed target physics and test beams for LHC. It is therefore essential that the LHC civil engineering work does not affect the performance of the LEP and SPS machines.

The excavation of shafts and caverns for the Atlas and CMS experiments are predicted to cause movements of the LEP and SPS tunnels as well as the LEP electron injection line. A 3-D projection of the ATLAS experiment is shown in Fig. 1 and the position with respect to the SPS is shown in the section view Fig. 2. The CMS experiment (Fig. 3)is somewhat different in as much as there are 2 large vertical shafts and a vertical pillar at the base separating 2 caverns. The amplitude of the movements have been estimated using finite element modelling techniques which predict both vertical and horizontal movements of sufficiently large amplitudes to prevent the operation of the machines and ultimately break vacuum elements if no precautions are taken. The length of tunnels affected by the work is restricted to about 55m (with fringe areas extending a further 15m on either side) in LEP Points 1 and 5 and about 80m of the SPS and TI12.

In order to ensure the continued operation of the machines during these civil engineering works, several steps must be taken:

- Install monitoring equipment to measure the displacements (horizontal, vertical and tilts).
- Modify the equipment so that it can be realigned following displacements.
- Optimise scheduling to minimise the impact on operation

The current planning for the work indicates that the first effects on the machines could be observed during 1999. It has been stated that nothing should be done to prevent the operation of LEP during the year 2000 and therefore the measures implemented should be capable of compensating for the effects predicted for the year 2000. Since the monitoring systems and the realignment techniques will be new, the system should be installed during the 1997/98 shutdown so that it can be tested during 1998 and reference values established before the start of the work.

2 Civil Engineering Planning

The official LHC Project Planning requires the completion of civil engineering as soon as possible. To meet the milestone dates, as much excavation as possible has to be carried out before the LEP shutdown. A thoughtful planning of the excavation sequence is therefore required to complete the civil works within this tight schedule and with the minimum possible effects on the LEP.

The effects on the LEP machine are highly dependent on the construction programme adopted. Parts of the LHC excavations have to be carried out while the LEP is running, whilst the remaining parts can be excavated after the permanent shutdown of the LEP. Depending on how much or which portions of the underground structures will be excavated before the LEP shutdown, the effects on the LEP machine will vary. The construction programme cannot be modified in any useful way to minimise the effects on the SPS machine because much of the work must be carried out whilst LEP is still running and therefore it cannot be left until the extended shutdown of the SPS.

The current civil engineering programme is based on the following key dates of the official LHC Project Planning which is outlined in Table 1.

FC approval of civil works contracts	Dec. 1997
Start of civil works	Apr. 1998
Start of LEP dismantling	Oct. 2000
Completion of civil works at Point 1	Mar. 2002
Completion of civil works at Point 5	Oct. 2002

Table 1: Key dates in the LHC Project Planning.

2.1 Civil Works at Point 1

The underground works at Point 1 (Figs. 1 and 2) will start with the excavation of the new shaft PX14 in early 1999. The excavation will reach the crown level of cavern UX15 after approximately 6 months in mid 1999. The excavation of the PX16 shaft will follow and will last about 4 months. The work should be completed before the end of 1999. In early 2000, the excavation of the top heading of cavern UX15 will start. It will need about 5 months for completion and will be followed by the concreting of the vault. These works should be completed by October 2000 in order to continue with the cavern excavation immediately after the start of dismantling of the LEP machine.

The USA15 cavern will be excavated via the existing PX15 shaft. This shaft needs to be lined first, as it is protected only with a thin layer of shotcrete. The excavation works in the cavern will start with the top heading in mid 1999, followed by the excavation of two further layers to reach the cavern floor level in early 2000. This will allow completion of the installation of the concrete lining before the end of 2000.

2.2 Civil Works at Point 5

The underground works at Point 5 (Fig.3) will require the two new shafts PX56 and PM54 to be started immediately in order to excavate the fifty metres of water bearing moraine strata. It is anticipated that PM54 will be completed and lined with concrete by May 1999 and the larger shaft, PX56, by March 2000.

Prior to any excavation work on the two caverns, a concrete pillar will be constructed in order to ensure that the substantial vertical loading from the rock mass can be effectively transferred between the caverns. This concrete pillar will be constructed from the PM54 shaft and should be completed by the end of October 1999. Once this pillar is completed, the two large caverns can be excavated. The excavation of the US cavern is likely to be completed by October 2000 although the concrete lining will not take place until after all the smaller tunnels and galleries have been completed. The larger UX cavern will be completed around April 2001 including the concrete lining. The current planning assumes that only the UX cavern crown may be completed before the October 2000 shutdown of LEP.

3 Predicted Effects

Excavation of the LHC underground structures will cause ground movements around the new openings. The excavation for the large new underground complexes envisaged at Points 1 and 5 will affect the alignment of the existing LEP and SPS tunnels.

Comprehensive site investigations have been undertaken at Points 1 and 5 to permit the definition of the stratigraphy and to assess the parameters to be used for numerical modelling of the behaviour of the rock mass.

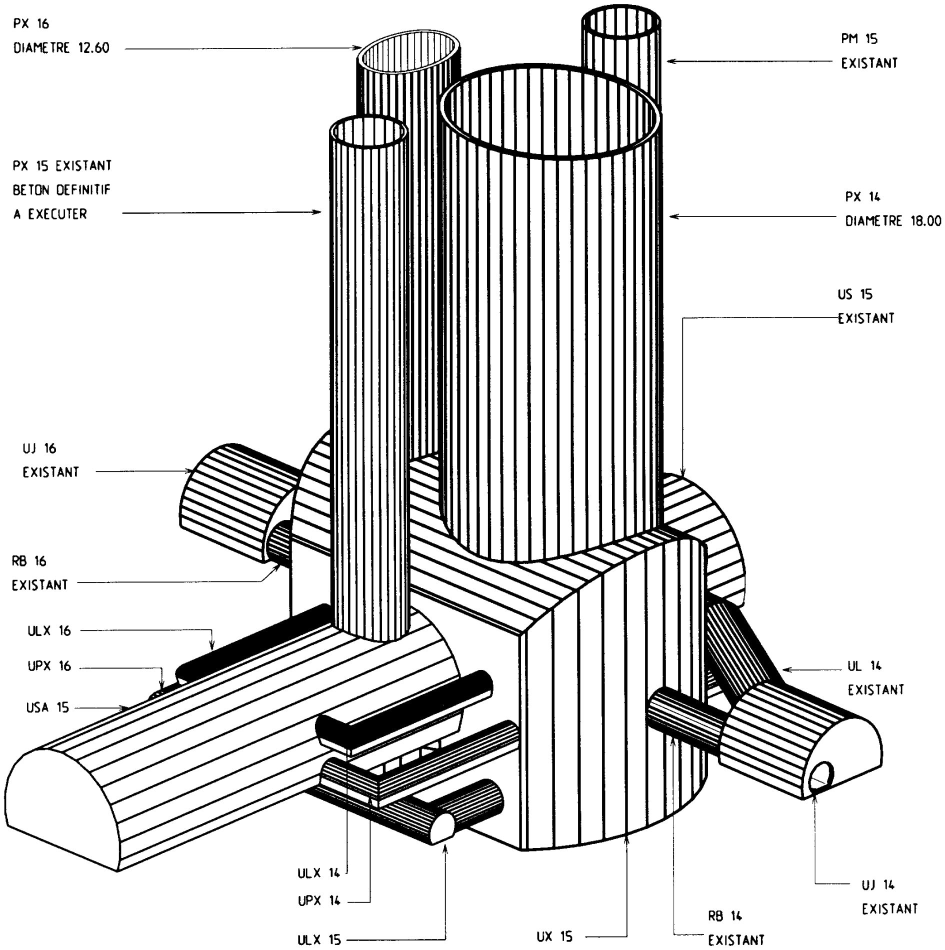

Figure 1: 3-D projection of the ATLAS installation at Point 1.

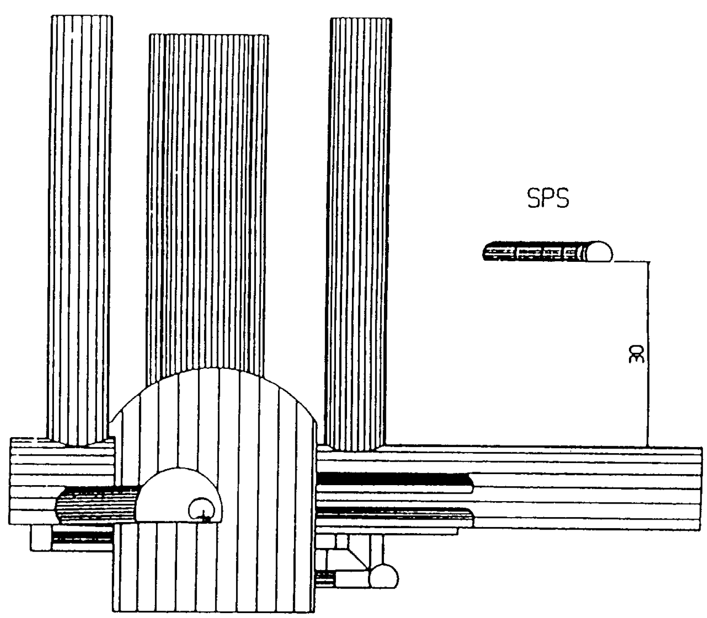

Figure 2: Vertical section of the ATLAS installation showing the position of the service cavern below the SPS and TI12 tunnels.

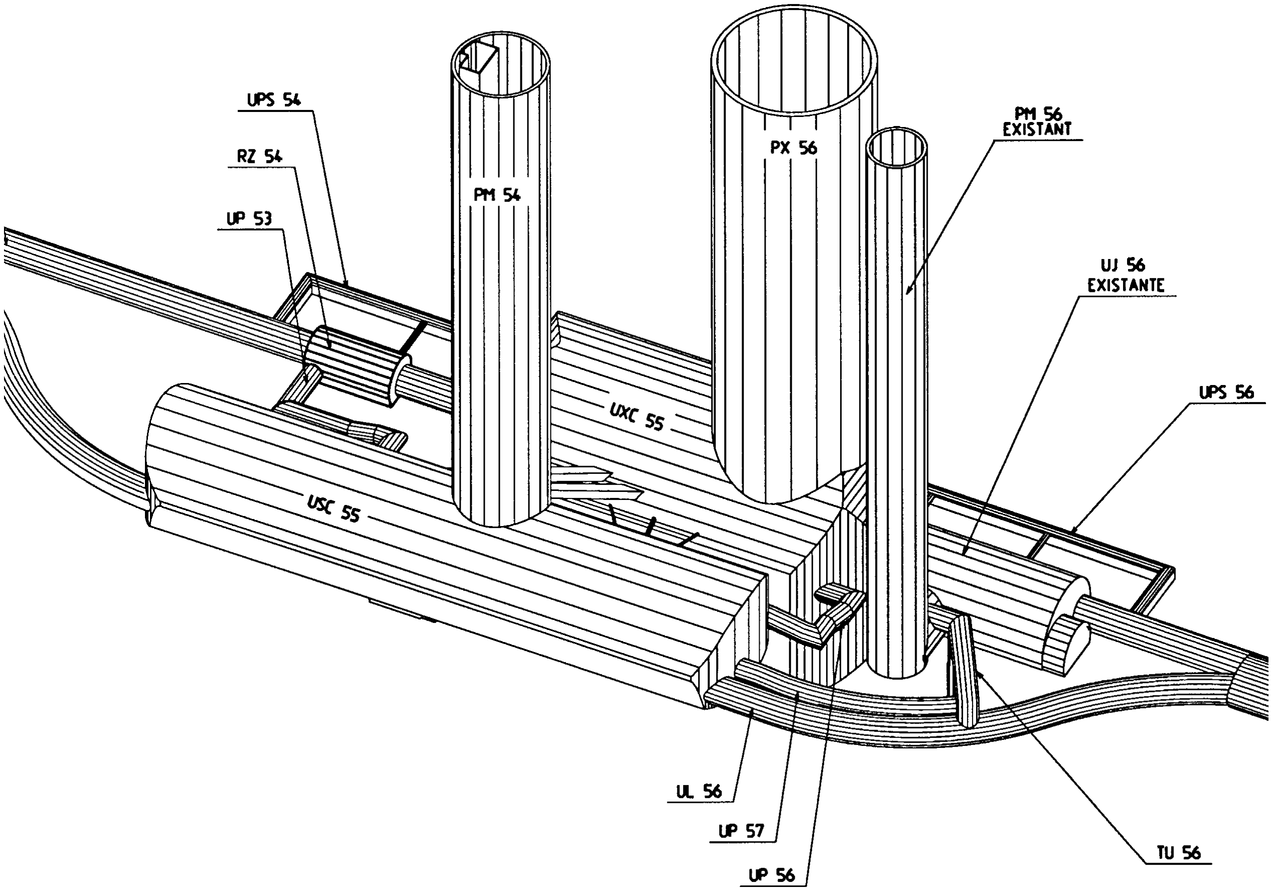

Figure 3: 3-D projection of CMS experiment to be installed at Point 5. Note the large service cavern running parallel to the cavern for the experiment.

2D and 3D analyses for the design of the new underground structures have been performed and are still ongoing. The primary objective of this kind of analysis is to assess the stress and strain redistribution in the ground due to the civil engineering. The output of the analyses can be used subsequently to assess the predicted movements of the existing structures.

The following studies are available for extracting information concerning movements of existing structures caused by the new LHC excavations:

GOLDER Feasibility Study Point 1, February 1996 2D and 3D analyses, based on site investigation of 1993

EDF/KP Civil Engineering Consultancy Services Point 1, ongoing 2D and 3D analyses, based on site investigation of March 1996

GIBB/SGI/GC Civil Engineering Consultancy Services Point 5 - ongoing 2D and 3D analyses, based on site investigation of March 1996

CERN/ST-CE 2D analyses, based on site investigation of March 1996

The CERN civil engineering group have, together with the authors of these studies, interpreted the results with respect to the predicted movements of the existing underground structures. GOLDER's feasibility study for Point 1 is based on limited geological data available at that time. Furthermore the structural layout of the underground complex at Point 1 has changed in the meantime. In GOLDER's study an oval shaft with dimensions of 29m $\times$ 25m was used, whereas in EDF/KP's analyses for Point 1 a circular shaft with the actual size of 18m diameter is used. Nevertheless GOLDER's study is a useful source of information and was therefore applied for interpreting the behaviour of the rock mass, with careful consideration of the different input parameters.

Generally speaking the accuracy of numerical models for underground structures is limited. Although the material behaviour and the failure criteria of individual rock samples can be determined in a reasonable manner and mathematically described, even extensive numerical models are always only simple representations of the very complex natural conditions. Many factors of influence can be taken into consideration, but in any case there remain even more unpredictable effects which may have an influence on the accuracy and certainty of the results of such analyses. This does not necessarily mean that the actual behaviour of a rock mass due to underground excavations will be worse than the theoretical results; the calculated results may even be on the safe side and the actual deformations may be less than predicted. Consequently the results of numerical calculations must be judged critically with respect to the degree of accuracy of the applied model and the input parameters used.

It is good engineering practice to use rather conservative parameters for the design of underground structures. Therefore the predicted movements will probably be in the upper range and the actual movements could be less.

3.1 Effects on SPS at Point 1

The layout of the LHC underground complex at Point 1 (see Fig. 1) requires the excavation of the new PX14 and PX16 shafts, the new UX15 cavern and the new USA15 cavern which extends below the SPS tunnel and is about 30m below it.

Results from different studies indicate no ground movements around the SPS tunnel during the construction of the shafts and the UX15 cavern. However, previous experience at CERN (described below in section 3.4), shows that one cannot exclude that some small movements (less than 3mm horizontally towards the shafts and vertically down) could occur.

The predicted effects on the SPS caused by the excavation of the USA15 cavern can be summarised as follows:

Effects of USA15 excavation on SPS	
Dimensions of excavation	20m diameter, length 62m
Position of centre with respect to the LEP IP	perpendicular to LEP (axis at IP1), 30m below SPS
Length of tunnel affected	approx. 80m
Currently planned dates for the work	Mid 99 - Early 2000
Predicted total displacement and direction	$<$10mm SPS (down)
Average rate of displacement	not applicable
Maximum rate of displacement	$<$ 3mm/week

3.2 Effects on LEP at Point 1

There will be two independent underground work sites at Point 1. One is the excavation of the USA15 cavern via the existing PX15 shaft and the other is the excavation of the PX14 / PX16 shafts and the UX15 cavern. However the tight time schedule for the civil works requires that the USA15 cavern must be completed before the LEP shutdown. Also, the shafts and parts of the UX15 cavern must be excavated before the LEP shutdown to allow the completion of the rest of the work in the short time remaining after shutdown. These two work sites represent two separate causes for movements of the LEP tunnel and should therefore be considered individually.

The excavation of the USA15 cavern will be carried out via the existing PX15 shaft and will take place in three steps. The first step is the excavation of the top heading of the cavern, followed by the excavation of the lower part of the cavern in two further steps. Consequently the movements of the LEP tunnel will be related to these three excavation stages. However, only the total displacements at the completion of the whole cavern can be extracted from the results of the numerical analyses.

The table below summarises the predicted effects on the LEP caused by the excavation of the USA15 cavern.

Effects of USA15 excavation on LEP	
Dimensions of excavation	20m diameter, length 62m
Position of centre with respect to the LEP IP	perpendicular to LEP (axis at IP1), 30m below the SPS
Length of tunnel affected	$<$ 20m
Currently planned dates for the work	Mid 99 - Early 2000
Predicted total displacement and direction	$\leq$ 5mm (horizontally towards USA15)
Average rate of displacement	not applicable
Maximum rate of displacement	$<$ 3mm/week

The excavation of the two shafts PX14 and PX16 is currently planned to be carried out in sequence, but it will be the contractor's decision whether to do it sequentially or in parallel. At the time when the excavation reaches the bottom of either shaft (crown level of UX15 cavern), the maximum movements at beam tunnel level will be in the order of 5 mm. The majority of the displacements will have occurred during the last month of the excavation.

Effects of PX14 excavation on LEP	
Dimensions of excavation	18m diameter
Position of centre with respect to the LEP IP	13.5m from IP towards Point 8
Length of tunnel affected	$<$ 20m
Currently planned dates for the work	early 1999 - mid 1999 (approx. 6 month)
Predicted total displacement and direction	$\leq$ 5mm (up)
Average rate of displacement	not applicable
Maximum rate of displacement	$<$ 1mm/week

Effects of PX16 excavation on LEP	
Dimensions of excavation	12.6m diameter
Position of centre with respect to the LEP IP	17.7m from IP towards Point 2
Length of tunnel affected	$<$ 20m
Currently planned dates for the work	end 1999 (approx. 4 month)
Predicted total displacement and direction	$\leq$ 5mm (up)
Average rate of displacement	not applicable
Maximum rate of displacement	$<$ 1mm/week

The excavation of the UX15 cavern will start after completion of the two shafts PX14 and PX16. In the current planning the excavation and concreting of the top heading of the vault will be carried out before the start of dismantling LEP, in October 2000. The predicted maximum total movements of the LEP tunnel after completion of the cavern vault will be up to 30mm.

The continuation of the UX15 cavern excavation further down is currently scheduled after the LEP dismantling. At the time when the excavation will reach a zone within 4m of the LEP tunnel, the maximum total displacements will be in the order of 80mm.

Effects of UX15 vault excavation on LEP	
Dimensions of excavation	width 30m, length 53m
Position of centre with respect to the LEP IP	cavern parallel to LEP
Length of tunnel affected	area between UJ14 and UJ16
Currently planned dates for the work	early 2000 - mid 2000
Predicted total displacement and direction	$\leq$ 30mm (up)
Average rate of displacement	1mm/week
Maximum rate of displacement	3mm/week

3.3 Effects on LEP at Point 5

The underground works at Point 5 (see Fig. 3) will start with the excavation of the two new shafts PM54 and PX56. As the PM54 is 26.5m away from the LEP tunnel, no movements are predicted from the excavation of this shaft. However at the time when the excavation reaches the bottom of the PX56 shaft, vertical movements of up to 5mm may have occurred at beam tunnel level.

Effects of PX56 excavation on LEP	
Dimensions of excavation	21m diameter
Position of centre with respect to the LEP IP	14m from IP towards Point 6
Length of tunnel affected	$<$ 20m
Currently planned dates for the work	End 98 - Mid 99
Predicted total displacement and direction	$\leq$ 5mm (up)
Average rate of displacement	not applicable
Maximum rate of displacement	$<$ 1mm/week

Prior to the excavation of the two new caverns, a central concrete pillar will be constructed between these two caverns. The excavation for this pillar will be performed from the PM54 shaft. The predicted movements of the LEP tunnel caused by this excavation are up to 10mm horizontally towards the pillar.

Effects of pillar excavation on LEP	
Dimensions of excavation	7.3m width, length 53m
Position of centre with respect to the LEP IP	parallel to LEP, 14.3m from LEP
Length of tunnel affected	cavern length plus half the length on either side
Currently planned dates for the work	May to September 1999
Predicted total displacement and direction	$\leq$ 10mm horizontally towards the pillar
Average rate of displacement	1mm/week
Maximum rate of displacement	3mm/week

After completion of the construction of the pillar, excavation of the two new caverns can start. The US cavern will be excavated behind the previously constructed concrete pillar and will cause no additional movements to the LEP tunnel. According to the current planning the excavation of the UXC55 cavern vault will be completed before the dismantling of the LEP. At this stage maximum total displacements of the LEP tunnel of the order of 20mm are predicted.

Effects of UXC55 vault excavation on LEP	
Dimensions of excavation	width 28.7m, length 53m
Position of centre with respect to the LEP IP	cavern parallel to LEP
Length of tunnel affected	cavern length plus half the length on either side
Currently planned dates for the work	July - December 2000
Predicted total displacement and direction	$\leq$ 20mm (up)
Average rate of displacement	1mm/week
Maximum rate of displacement	3mm/week

3.4 Comparison with Measurements

The most useful measurements come from the vertical survey of the SPS machine and the transfer lines, where the survey data is quite accurate.

The excavation of the LEP tunnel underneath the SPS tunnel caused movements of the SPS. The LEP tunnel crosses 30 below the SPS at two points, at a distance of 250m and 650m from Point 1, near the quadrupoles 60610 and 63510. A drop of 6mm was measured in one place (position 60610), whereas no displacements were recorded at the other location (position 63510).

Site records show that poor ground conditions were encountered in the region of the first crossing point, resulting in overbreaks, cracking of the rock and drainage of the natural ground water during the excavation of the LEP tunnel. No particular problems were recorded during the excavation of the tunnel in the area of the other crossing point. These different rock conditions at the two crossing points is therefore thought to have caused the different movements of the SPS tunnel.

A numerical analysis was performed to simulate the behaviour of the SPS tunnel when the excavation of the LEP tunnel is crossing underneath. Because of the lack of meaningful geological data for the particular crossing points, the geo-technical model developed for the new LHC excavations at Point 1 (based on the comprehensive site investigation performed at Point 1) has been applied for the analysis.

The geological conditions at Point 1 can be considered as being quite favourable. They might be comparable to those in the area of the second crossing point. However the calculations did not show any movements of the SPS tunnel due to the excavation of the LEP. This result could be interpreted as being applicable for the second crossing point, and that the poor ground conditions and any other unconsidered facts in the region of the first crossing point resulted in movements which were not predictable by the numerical model applied.

The only place where horizontal displacements might have been detected is around the LEP klystron galleries in Points 4 and 8. These galleries were excavated during 1992 and 1993, after the start of LEP operation. Radial survey of these areas is very difficult because there are no points which can be considered stable enough on the interaction point side, and the propagation of wire measurements from the tunnel direction makes the resulting error of the order of several mm. i.e. movements of a few mm would not show up in the results of survey measurements. Other data from beam orbit measurements and closed orbit corrections are not precise enough to allow any conclusions to be drawn.

4 Effects on Beam Optics

4.1 Effect of a vertical displacement of QL1 and QL2 in LEP

Transversely displacing a quadrupole is equivalent to making a change of coordinates at its entrance. Therefore a displaced quadrupole can be represented exactly by a dipole field superposed on a quadrupole field. The kick θ_d associated with the dipole field is equal to :

$$\theta_d = Kl\Delta z$$

where K is the normalised quadrupole gradient, l its length and Δz its transverse displacement.

For the case of QL1, K is –0.021m^{-2} (i.e. vertically focusing) and l is 2m. The kick associated with a displacement of 1mm of each QL1 doublet is then 0.084mrad. As the phase difference between both doublets, on the right and on the left of IP1, is about $0.1\times 2\pi$, the two doublet kicks effectively add.

The closed orbit distortion associated with the vertical displacement of both QL1 doublets by 1mm is 5.3mm and the RMS vertical dispersion is 0.2m. These values are large and have to be reduced by about one order of magnitude. The compensation of the same vertical displacement of both QL1 doublets can be done with the two CVA's close to them. As the closed orbit distortion due to a kick scales with the square root of the β-value at its location, the compensator strength must be multiplied with the square root of the β-ratio (β_y is 32.8m in the middle of the QL1 doublet, and 45m in the middle of the CVA). The CVA's kicks must then be –0.098mrad to compensate for a positive vertical displacement of both QL1 doublets of 1mm. The maximum kick of a CVA at 90GeV is 0.105mrad (field of 0.056T over a length of 0.56m). Consequently the maximum CVA strength can compensate a vertical displacement of QL1 doublets by about 1mm.

The exact calculation has been done with the MAD program. The QL2 doublets have also been displaced and the results are given in Table 2. For a zero displacement of QL2, MAD finds a corrector strength very close to that expected. We see that even in the most favourable case where both QL1 and QL2 are displaced by the same amount, a maximum displacement of about 3mm can be corrected by means of CVA's resulting in a closed orbit distortion of some hundredths of a mm.

Δy (All QL1's)	Δy (All QL2's)	CVA1B kick/mrad	<y>/mm	<Dy>/cm
1	0	-0.101	0.009	0.1
1	0.5	-0.068	0.018	0.26
1	1	-0.036	0.007	0.32

Table 2: Closed orbit distortion and vertical dispersion created by a displacement of the QL1 and QL2 doublets in a single odd IP.

If the QL1's and QL2's are displaced vertically only on one side of the IP, the corrector strength which is needed to compensate the effect is smaller. The limit is still due to the maximum strength of CVA.QL1B and the vertical displacement of both QL1 and QL2 by the same amount is then 4.7mm.

4.2 Changing the Optics in Points 1 and 5

With a proper rematching of the odd insertion[1] in IP1/IP5, it is possible to reduce the sensitivity to the vertical displacement of the QL1 and QL2 doublets on one side of the IP. For a displacement

[1]Studies by A. Verdier show that this is possible and gives a β^*_{y} of 36m and a β^*_{x} of 69m whilst keeping the original phase advance between the arc and the IP. Further studies to check the impact of this optics on machine performance have started

of 1mm, the maximum corrector strength needed becomes 0.0087mrad. Consequently, the corrector strength would be sufficient to compensate a displacement of 12mm at up to 90 GeV. This solution has the advantage that it does not require relocation of the active elements but it does not remove the mechanical constraints of the vacuum system.

4.3 SPS and SPS-LEP transfer lines

Because the existing magnetic corrector dipoles (COD) are inefficient for the proton beam at 450 GeV in the SPS, the beam sees essentially the bare magnetic machine and the closed orbit is almost entirely driven by the alignment and magnetic errors of the machine. Over the past few years an effort has been made to improve the SPS orbit by adding controlled misalignments (0.4 to 1.2mm) to the well aligned machine on some quadrupoles. The vertical orbit was improved from 2mm RMS to 1.4mm RMS and this has contributed to the increased performance of the SPS

The LHC civil engineering will affect the SPS in an area centred around quadrupole QF614 some 60m upstream of the septa used for the extraction of the proton beam to the neutrino experiments and the West Area. A downward movement of the tunnel floor by up to 10mm over a length of about ± 40m is expected.

A vertical movement of 1mm of a horizontally focusing quadrupole such as QF614 generates a vertical RMS orbit of 0.55mm with peaks of 1.3mm. A vertical movement of 10mm for the same quadrupole generates a vertical RMS orbit of 5.5mm. The tolerable limit is clearly in between and can be practically established by allowing the present RMS vertical orbit to double under the effect of this misalignment. This limit is 2.2mm of vertical displacement at QF614.

From the beam optics standpoint, a realignment of the SPS in this area will very likely be needed when we accumulate a drift of 2mm. It should be possible to monitor the quadrupole movements using the orbit data. One should keep in mind that this area of the SPS ring shows very high doses of remanent radiation and all efforts should be made to keep the dose received during realignment operations as low as possible.

The TI12 transfer line is used to bring the electron beam from SPS to LEP and is also in the area concerned by the LHC civil engineering work. The area of interest is centred around quadrupole IQD1204 and the surrounding bending magnets. The integrated strength of this quadrupole is at present $K_1 L = 0.05 \times 0.82 \text{ m}^{-1}$ which generates a vertical kick of $41\ \mu\text{rad}$ per mm of vertical displacement of this quadrupole. Less than one meter upstream of quadrupole IQD1204 are two strong vertical bending magnets (IMAV) with a bending angle of 44mrad each. It is not possible to use these strong bends alone since they are on a common supply with two other bends at the end of the line. It is however, possible to use the IMAV bends together with other vertical steering dipoles in the line to correct the effect of the displacementof IQD1204 on the beam trajectory. A 3mm displacement of IQD1204 requires corrector strengths below 90μrad, about 5% of their maximum strengths. Probably TI12, which presents no induced radioactivity, will not require realignment as frequently as the SPS because the limitation will be mechanical (see below).

5 Effects and Constraints

5.1 Vacuum

5.1.1 SPS

No problems are expected: the chamber is fixed in the magnets and will follow their movements. One vacuum team will follow the realignment operations as is done in normal practice. An upper limit for the vertical offset of bellows is 4mm (very unlikely as the magnets will not move step wise).

5.1.2 LEP

The vacuum equipment in the region affected in Point 1 consists of stainless steel chambers interrupted by several complicated pieces of BI equipment (BSMRN, BCMI). The main criterion for choosing a solution is the speed for the displacement rather than the total amplitude. A displacement of $\pm$2mm can be accommodated before it is necessary to realign. Realignment in Point 1 would require about 4 hours, working partly in the shadow of the survey work. All of the equipment (vacuum chamber and BI) could be installed on a girder mounted on jacks. Such a solution might lead to economies in manpower but this should be weighed against the cost. An upper limit on the number of jacks would be 50. The cost of modification of the existing feet of the vacuum chamber should not exceed 50 kCHF.

If the section of the tunnel concerned by the movement can be transformed to a bare pipe (no BI, no separator, no magnets), the cross section of the pipe could be made such as to accommodate large displacement of the beams. The cost for a 40m, 300mm diameter pipe would be about 85 kCHF including installation and bakeout. If however, the streak camera or polarimeter equipment had to be incorporated in such a pipe, the cost would be much higher.

In point 5 the vacuum system mainly consists of about 40m of aluminium chambers supported by aluminium beams standing on 20 feet. The cost of modification of these feet and of other supports should not exceed 30 kCHF. After modification, these feet would accommodate the required vertical excursion. The lateral movement ($\leq$10mm) will be more difficult to follow, but the time needed to move the chambers is approximately 4 hours again.

5.2 Magnets

5.2.1 LEP

The LEP ring is built with its plane tilted by 1.42% and the tilts are of opposite sign and have an absolute value of 1.23% in Points 1 and 5. The magnets are installed such that the jacks are perpendicular to the tunnel floor, which follows the slope of the machine in longitudinal direction and is horizontal in the transverse direction. There is no guarantee that the movements with be exclusively in the horizontal and/or vertical directions and over the length of 40m on each side of the IP it is likely that a gradient will be seen.

The magnets concerned by the movements are the first 2 doublets on both sides of IP1 and IP5 and the first bunch train sextupole. Each doublet is positioned on a girder and the sextupole is placed on a single foot. The doublet girders are supported by 3 mechanical jacks which can lower the girder by about 15mm at the moment. On the sextupoles, the foot can be adjusted by about 10mm using 3 screws.

For an automated, feedback type alignment the following would be needed:

1. A fully automatic and radiation hard position measurement system.
2. Automated jacks of a type which can supply movements in 3 dimensions on a 1.23% slope.
3. A control system for the measurements and the jack movements.
4. Software to control the realignment process.

The last point alone would require one man-year of effort. The commissioning of such a system with a running accelerator could take half a year.

The mechanical jacks are at present retracted by about 25mm. When fully extended, a total movement of about 40mm should be feasible. There are two possibilities which allow use of the jacks over their full range of adjustment.

1. Position the jacks in 25mm deep holes in the floor. This will still allow access to the bolt used to adjust the height.

   Advantages: no new hardware needs to be made.

   Disadvantages: the girder with its magnets have to be removed to drill the holes, during alignment one jack is still situated under the girder, as at present.

2. Position 4 jacks on the sides of the girder on the standard lifting points.

   Advantages: the jacks are more easily accessible during alignment and no holes have to be drilled in the tunnel floor.

   Disadvantages: the alignment has to be done on a girder supported by 4 jacks, new parts have to be made to attach the jacks, we need a fourth jack for each girder (from stock).

Both possibilities can be executed with existing personnel and with costs of around 500 CHF per jack. The feet of the bunch train sextupoles can be shortened and longer screws can be used. For this the sextupoles would have to be removed during a shutdown.

In order to render the machine less vulnerable to alignment problems it could be useful to add more corrector magnets. One could envisage to double 2 or 3 corrector magnets on each side of the IP in both planes so as to be able to survive longer without realignment. The magnets and manpower for this are available. It remains to be seen if suitable power converters can be found.

5.3 Effects on Beam Instrumentation in LEP Point 1

A brief description of the LEP beam instrumentation installed in Point 1 is given below, together with considerations about the sensitivity to ground motion and consequences for the measurement of beam parameters and related diagnostics. Requirements for the operation of the polarimeter in terms of beam sizes and divergences at IP1 as a consequence of possible layout changes in which the active elements are moved back from the IP are also given.

5.3.1 LEP instrumentation in Point 1

The instruments installed in Point 1 are listed below and those in the region of the tunnel movements are shown schematically in the layout of Fig.4.

BPM Beam position monitors for the BOM system and other applications

- PU.QLxx – 22 BOM beam position monitors associated to each of the eleven quadrupoles each side of IP1 (QL12 included);
- PUT.QL1A – Two BPMs for timing purposes;

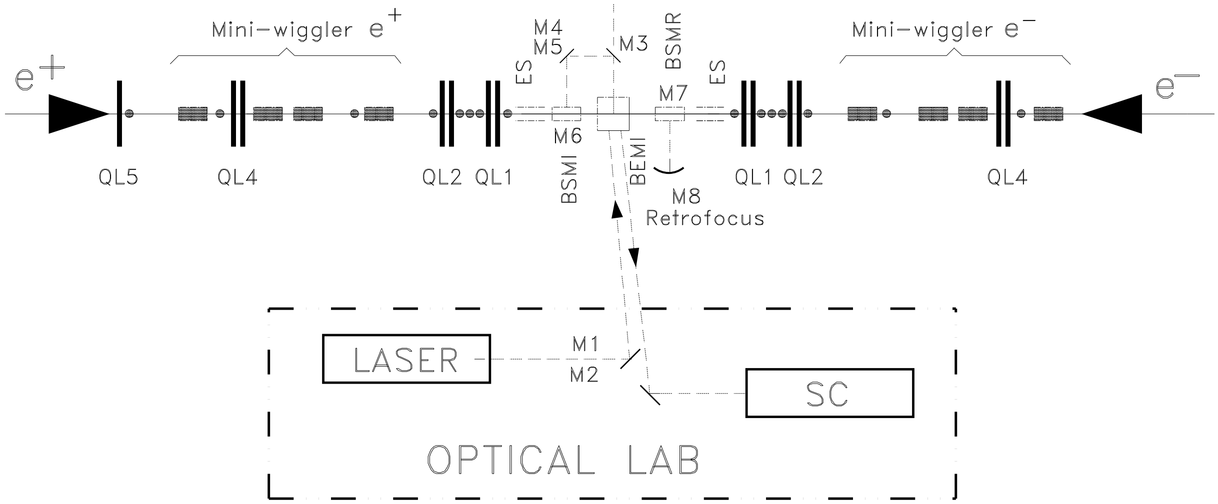

Figure 4: Layout of equipment in Point 1. The length of tunnel which will move includes the QL1 magnets, the QL2 magnets are in the fringes.

- PUG.QL2A – Two BPMs for analog observation;
- PUQ.QL2A, PUQ.QL4A – Four BPMs for tune measurements.

BEWV, BEWMV Horizontal and vertical Wire Scanners at ± 220m and ± 224m from IP1 both sides of QL10. Bremsstrahlung radiation is collected at detectors close to QL10 (wide angle) and downstream QL13 (small angle).

BEXE Two X-ray vertical beam profile monitors are located at ± 165m from IP1 (next to the beam current transformers between QL7 and QL8) and collect synchrotron radiation from the 10% bends BW1.

BCT Two beam current transformers at ± 164.5m between QL7 and QL8.

KIKQH, KIKQV Four kickers for betatron tune measurements, two each side of IP1, at ± 122.7m and ± 152m close to QL6 and QL7.

POLARIMETER The laser polarimeter involves several optical elements to focus and steer the laser light from the Optical Laboratory (OL) against the e^- and/or the e^+ beams. Backscattered radiation leaves the vacuum chamber through a 28×56mm^2, 2mm thick Aluminium window inside the first bending dipole and is analysed at two γ-detectors situated downstream QL13 either side of IP1. The external coils of both quadrupoles QL13 have been accurately machined to allow a 30mm vertical clearance for the backscattered γ's to match the vertical aperture of the upstream window. The components are listed below.

- BSMI, BSMR – Two insertions in the LEP beam pipe at ± 12m each side of IP1 housing the in-vacuum mirrors M6, M7;
- BSOP – Optical line connecting BSMI to the OL in four segments connected via three tanks containing the steering mirrors M3, M4, M5 and focusing elements;
- BSLME – Optional light extraction channel parallel to the beam pipe via an extraction mirror on top of BSMI for laser light diagnostics;
- Optical benches in the OL supporting the mirrors M1, M2, the laser(s) and the associated matching optics;
- BSG – Two γ-detectors at ± 313m downstream QL13 equipped with a variable-thickness lead absorber and mounted on remote controlled supports;
- BGCD – Two water cooled tungsten stoppers at each Al window to protect the BSG electronics when polarimeter is not used.

STREAK CAMERA for S.R. Diagnostics The visible part of the synchrotron radiation beam generated by two dedicated sources (mini-wigglers) is reflected and focused onto the image plane at the Streak Camera (SC) in the OL for $e^+ e^-$ 3D bunch size measurements. The components are described below.

- BEMI – Optical insertion at IP1 housing two Beryllium extraction mirrors;
- BEMR – Mirror M2 tank for light deflection into OL;
- BEOP – Twin telescopes connecting the BEMI to the BEMR housing two achromatic lenses to focus light from e^+ and e^- onto the SC;
- Vertical optical bench in the OL supporting dychroic mirrors for 3-fold light bandwidth selection;
- Three optical benches for light diagnostics on the selected lines. One of them supports the SC.

5.3.2 CONSEQUENCES OF A TUNNEL DEFORMATION

The predicted movements will affect the following beam instrumentation:

1. BOM BPMs PU.QL1B (at ± 26.485m)
2. The use of the Streak Camera (BEMI insertion and optical connections to the OL);
3. The Polarimeter (BSMI, BSMR insertions and the laser line).

The operation of the Polarimeter relies on the precise and reproducible alignment of both the $\sim$60m long laser optical line between the OL (which is located in the existing cavern US15) and the laser interaction region and that of the backscattered γ-lines towards the two γ-detectors at the end of the straight section.

The use of the Streak Camera also requires tight alignment of the synchrotron light beams from the mini-wigglers onto the extraction mirrors (BEMI) and, along the telescopes (BEOP), up to the image plane in the OL.

It is then clear that the performance of both instruments will be affected by misalignments induced by deformations of the LEP tunnel.

5.3.3 POSSIBLE SOLUTIONS

Different philosophies can be envisaged to alleviate the effects of floor deformation on the components of the machine. In the following considerations two possibilities are discussed:

1. Mechanical realignment of the components;
2. *Terrain-following* beam steering.

5.3.4 COMPENSATION OF THE FLOOR MOVEMENTS BY REALIGNMENT

According to the simulations for the ATLAS cavern, the tunnel vertical displacement will be contained within $\sim$ 5mm initially, but will reach $\sim$ 30mm during the excavation of the top heading of UX15.

Two hypotheses have been analysed:
A) The tunnel and the PM15 pit will move TOGETHER;
B) The tunnel will move RELATIVELY to PM15.

In the first case it can be assumed that the misalignments of the optical lines of the Streak Camera and the Polarimeter relative to the OL will be small enough to be compensated in the limits of tunability of the various elements.

The real problem is to maintain the position of the in-vacuum mirrors in the BSMI, BSMR and BEMI insertions in the design position relative to the beams. As these insertions are rigidly mounted on the tunnel floor **new supports for all of them must be built** in order to accommodate a vertical floor displacement of the order of $+50$mm (allowing some contingency). The vertical segment of the BSOP optical line from the BSMI to the mirror box housing M4 and M5 can be made to match the adjustments needed for the BSMI support.

This same problem exists for the BEOP/Achromat telescopes, but here the solution is far more complicated as they are not orthogonal to the BEMI and the connecting bellows have to undergo a 30mm skew elongation without breaking.

In hypothesis **B**, which at present seems the most likely, damage to the optical lines is likely to occur if the amplitude of the relative movements exceeds the play at the bellows ($\sim$10mm). In addition to the previously mentioned problems with the supports in the tunnel, further complications arise with the part of the BSOP optical line linking the Optical lab to the tunnel. This three-fold evacuated pipe travels in a 15m long 50mm diameter hole excavated in the rock between the two buildings and it is rigidly supported inside it.
Any relative movement of the tunnel w.r.t. the pit will cause unacceptable deformation to the channels and severe reduction to the optical acceptance for laser and Streak Camera.

5.3.5 BEAM STEERING

Given the difficulties associated with the realignment of the many machine components (vacuum chamber included), the solution of making the beam follow the floor movements, *terrain following steering* looks attractive. However, mechanical constraints impose realignment after displacements of about 2mm.

A three-corrector vertical closed bump around IP1 can be implemented using the existing CVAs at QL1B, QL4B and QL6 (or adding one for more flexibility in the orbit correction) to satisfy the constraints on the vertical kick at W4 (SR light towards the displaced mirrors in the BEMI) and amplitude and angle at IP1 (laser and backscattered γs steering for the polarimeter).

5.3.6 MOVING QL1 AND QL2

It has been suggested by A. Verdier (meeting held on 24.09.96) that one could either make use of an optics with the QL1 and QL2 quadrupoles moved back from the IP, away from the zone which will move, or re-match the insertion to render it less sensitive to ground motion.

The larger beta-functions at IP1 resulting from either of these changes will have consequences for the polarimeter because this will affect both the $\mathrm{e}^+\,\mathrm{e}^-$ beam sizes and divergences at the laser-beam interaction region. Larger beam sizes will reduce the luminosity of the laser-beam interaction while a reduced beam divergence, although quadratically combined with the Compton opening angle, would favour the transmission of the backscattered γ's to the detectors. It seems that a factor of three to four in the beta-values at IP1 can be accepted without serious problems for the performance of the polarimeter.

It has been suggested that the BSLMR and BSLMI and therefore the Laser Interaction Region (LIR), could be re-installed at their original position near QL4. In this case it would be possible to calibrate the energy in special runs in which the bunch train bumps were off. In their original location these elements should not be affected by the tunnel movements. (This proposal has yet to be studied by the BI and vacuum groups)

The use of a larger vacuum chamber at IP1 would unfortunately require **all the special vacuum insertions housing mirrors (BEMI, BSMI and BSMR)** (120mm present diameter) **to be rebuilt** in addition to the new supports already mentioned if the realignment solution is adopted.

This is a major drawback from the cost and manpower point of view. If the large chamber solution is adopted, it has to be kept in mind that use of the Streak Camera and of the Polarimeter might have to be abandoned.

5.4 Separators

The inner two vertical separators (ZL) installed in Point 1 and the inner two installed in Point 5 are part of the equipment affected by the anticipated movement of the LEP tunnel during the LHC civil engineering.

Without any modification of the existing system, the supports for the ZL separators allow some movement to correct the position of the separators:

a) in the vertical plane, from +15 to -25mm
b) in the horizontal plane, from +30 to -30mm
c) in the longitudinal plane, from +30 to -30mm

The anticipated movements in the LEP tunnel are mainly upward. It will therefore be necessary to lower the separators and without modification of the supports the mechanical movement of the separators cannot exceed -25mm downwards. This is limited by the travel of the support system, and also by the clearance required between the floor and the lowest part of the separator, which at present is 30mm for the Nitrogen connection for the feedthrough insulation circuit.

Another 10mm can also be gained by adjusting the positions of the separator high voltage electrodes in such a manner as to keep the beam centred in the nominal 100mm gap but introducing an offset between the beam axis and the axis of the separator tank. The extent of this type of movement is limited by the vacuum bellows between the separator and the adjacent vacuum chamber which have to be capable of absorbing this vertical offset.

All the movements mentioned above can only be done manually using dedicated tools need access in the LEP tunnel. However the system exists and no extra investment is necessary.

If the realignments have to be made remotely without tunnel access, all the reserves expressed in section 5.2.1 for the other equipment also apply to the separators. The use of a stepping motor system for vertical displacements of the separator tanks and the high voltage electrodes would be much easier than for the horizontal and longitudinal planes. The vertical displacement of the separator and electrode supports is by means of screw jacks, and stepping motors could be adapted to power these jacks. Since the direction of the movement is generally unidirectional, the question of mechanical play is not a problem, and as the movements will be made over a relatively long time scale, the power requirements would be small.

6 Alignment Monitoring Systems

The area affected by the civil engineering works in both Points 1 and 5 is about 55m long (with fringes extending a further 15m on either side) and two pairs of quadrupoles, a few beam position monitors and the polarimeter and streak camera equipment as well as the vacuum chambers are concerned.

Several techniques can be used for monitoring these elements both in the vertical and horizontal planes .

6.1 Control in the horizontal plane

The simplest technique for monitoring the critical elements in the horizontal plane is certainly to use a Wire Positioning System (WPS), i.e to stretch a wire about 150m long and to measure the movements of the elements with respect to this reference line. The wire is fixed in a presumed stable area each side of the unstable one. Very simple low cost optical sensors (0.1mm resolution and $\pm$3mm range) are under study for the LHC and these could be used to monitor the tunnel movements. Two sensors would have to be fixed on each element.

The transverse tilt could be monitored by using the same sensor with respect to a plumb line. Such a very basic “clinometer” is probably the cheapest option and there is no problem of drift of the electronics for the accuracy required.

However, since the detectors are being developed for the LHC no consideration has been given to radiation damage. Since the synchrotron radiation in LEP is so strong, some modification of the sensors would be necessary. This could be the use of fibre optics, or the capacitive sensors which are used at ESRF and for the CLIC study.

6.2 Control in the vertical plane

A first solution is to install hydrostatic levels on the critical elements, as well as on a reference point which is fixed deeper on the rock, far (20m) from the area. This solution has already been implemented on the low beta quadrupoles of the LEP ring and we could benefit from the experience gained with this equipment. This solution is rather expensive if all parameters of each component need to be monitored, this involving three levels per element. In addition, even if the hydrostatic levels are not sensitive to the radiation, the electronics have to be protected. Today the maximum distance between the sensors and the electronics is 20m.

Another solution is to use a motorised and automatic optical level, with encoded staves installed on each element to be monitored. Such an equipment exists and is presently used intensively for controlling the works of the “metro” construction in Berlin, in a fully remote process running from Zurich. It is also possible to install a reference point outside the area as in the previous solution. With this method only one instrument, the motorised level, has to be protected against the radiation.

The last proposition is to use a stretched wire technique. The wire is stretched over about 150m with a controlled tension, and it refers to supposed stable points. It is detected vertically by the same sensors described for the horizontal monitoring, and three hydrostatic levels (two at the ends and one in the middle) are added for controlling any change in the catenary. Combining sensors on the same attachments, such a solution would allow a bi-axial control of the position of all the elements at the same time.

6.3 Realignment of the components

In order to minimise the realignment work as well as the number of detectors, one could group existing elements on common girders, wherever possible. The vacuum chamber could also be mounted on long beams, supported by fewer jacks.

One could imagine a self alignment method, linked with the measurements, which could be made automatically on motorised jacks, but this would require the development of all the process - with rather complicated safety controls to avoid breaking the vacuum. Such a procedure would be also very expensive, compared to a manual realignment.

Manual realignment would probably need one day for three people per area and would be cheaper than developing an automatic process.

7 Conclusions

7.1 Cautionary Notes

It has been assumed that the simulations are providing an upper limit on the movements. If the movements extend beyond the range over which a correction can be envisaged, then LEP operation could be jeopardised by the excavation for the CMS pillar during the latter half of 1999. The works planned for the year 2000 affect both Point 1 and Point 5 to such an extent that similar problems at either location would prevent operation of LEP.

The tolerance on torsional stress on vacuum bellows is such that rotations of $>$1mrad cannot be accommodated. The simulations make no prediction concerning this kind of movement, although it is felt that it is unlikely to happen. It is therefore important that the monitoring system is capable of measuring rotational movements.

7.2 Summary of Effects

7.2.1 SPS and TI12

Period	**Movement**	**Region Affected**
Early 99 to end 99	$\leq$3mm horizontal and down	$\pm$40m around QF614 in SPS and IQD1204 in TI12
Mid 99 to early 2000	$\leq$10mm down	$\pm$40m around QF614 in SPS and IQD1204 in TI12

7.2.2 LEP Point 1

Period	**Movement**	**Region Affected**
Early 99 to mid 99	$\leq$5mm up	From the left QL1's to the left separator
Mid 99 to early 2000	$\leq$5mm horizontal	$\pm$10m around the IP
End 99 to Apr/May 2000	$\leq$5mm up	From the right QL1's to the right separator
Early 2000 to mid 2000	$\leq$30mm up	QL1B left of IP to QL1B right of IP with fringe movements out to 40m

7.2.3 LEP Point 5

Period	**Movement**	**Region Affected**
End 98 to mid 99	$\leq$5mm up	From the right QL1's to the right separator
May 99 to Sept 99	$\leq$5mm horizontal	QL1B left of IP to QL1B right of IP
July 2000 to Dec 2000	$\leq$30mm up	QL1B left of IP to QL1B right of IP with fringe movements out to 50m

7.3 Consequences

There seem to be a number of possible solutions to most of the problems and in any case, it is clear that a remote monitoring system has to be installed. The idea to modify the optics and/or the layout of the insertion so that active elements are less sensitive or even no longer affected, implies that the number of interventions for realignment of LEP would be reduced to one or two and these could possibly be made in the shadow of scheduled short stops. Moving everything between the separator and the bunch train sextupole away from the IP by 15m should remove all active elements from the area which is likely to move[2]. One outstanding area of concern is the light pipes to the optical lab, where there is not enough clearance through the rock to accommodate any movement.

If the layout is not modified it will be necessary to realign LEP machine after transverse movements of the order of 2mm. The necessary modifications to the equipment to allow for total vertical movements of up to 30mm (LEP Point 1) and horizontal movements of up to 10mm (LEP Point 5) have to be made. An early decision on the techniques and tools to be employed is required so that delivery can be made in time for installation next year.

Each realignment will require an intervention of about 6 to 8 hours, depending on the length of machine affected. It can be seen from section 7.2 that about 5 interventions each at Points 1 and 5 could be necessary during 1999.

If LEP is operating in the year 2000, the excavation of the top heading of the ATLAS cavern in Point 1 could require about 2 realignments per week during the early part of the run (May-June). Following this period, work on the CMS cavern could require as many as 10 realignments, reaching up to 2 per week at the end of the period.

In the SPS, constraints from the beam dynamics and vacuum equipment allow similar displacements to those in LEP before realignment is necessary (as long as an additional corrector can be installed in TI12). It is possible that about 7 interventions in the SPS and about 5 in TI12 will be required, TI12 being less sensitive to movements. These realignments will be mainly needed in the second half of 1999.

If the predictions are a factor of two or three too small, the movements in 1999 could still be accommodated. If the ground movements measured during the early phases of the construction indicate that the predicted displacement values are too low, then additional remedial steps may be necessary to safeguard the LEP and SPS machines.

7.4 Cost Estimate

The following numbers are based on very preliminary data and work is continuing in many areas. Several ideas which could reduce the cost of the alignment monitoring equipment are under investigation, however until better information regarding the extent of the movements into the fringe areas is known, these numbers should only be regarded as ballpark values.

[2] This assumes that movement in the fringe areas is of very limited amplitude

Modify Beam Instrumentation	100kCHF
Displace polarimeter	75kCHF
Modify Magnets/Jacks	25kCHF
Survey Instrumentation LEP	200kCHF
Survey Instrumentation SPS/TI12	50kCHF
Modify vacuum equipment	100kCHF
Sub-total	550kCHF
Modify insertion layout	
– move active elements	150kCHF
– vacuum pipe	170kCHF
– modify polarimeter	150kCHF
– modify streak camera	300kCHF
Total	1320kCHF

There will also be a cost in terms of downtime of the machines in order to perform the realignment. The figures given below are based on the assumption that the monitoring system has been installed and interventions will only be made when it is clear that realignment is required. The interventions in SPS could also have an effect on LEP operation because the door at the top of TI12 is interlocked with the LEP beam, therefore access to TI12 will kill the beam in LEP at the moment. In the worst case, the LEP downtime would be increased by the SPS downtime.

SPS downtime in 1999	60 hours
LEP downtime in 1999	80 hours
LEP downtime in 2000	120 hours

7.5 Recommendations

A project should be set up to continue the investigations and to ensure that the necessary equipment and resources are in place before the civil engineering work starts. In particular, the following points should be covered:

1. Initiate further studies to evaluate the proposal to displace the active elements away from the unstable regions in LEP[3]. Continue optics studies concerning rematched insertions which will be less sensitive to floor movements.
2. Critically examine the requirements for the streak camera and polarimeter for 1999 and 2000.
3. Carry out the necessary design work for modifications to magnets, vacuum chambers and instrumentation and order the necessary materials in time for installation in the 1997/98 shutdown.
4. Define a survey system for monitoring LEP Points 1 and 5 and the SPS and TI12 tunnels in the regions affected. Order and install this equipment.
5. Establish more detailed information concerning the displacements in the fringe areas.[4]

It seems clear that constructing a fully automated system is not feasible in the time available, even if the technical problems could be solved.

[3] Initial studies indicate that the machine can be re-matched but detailed studies of the side effects for instrumentation, bunch trains etc. are on-going.

[4] The civil engineering consultants have agreed to deliver more details early in 1997.