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Final 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 and the transfer lines between the SPS and LHC will start whilst LEP and the SPS are running. This will be during 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. The predicted movements are of sufficient amplitude to prevent machine operation if no precautions are taken. This report contains the conclusions of the working group which has been studying these problems.

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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. An important feature of the LEP physics programme is the calibration of the beam energy and this relies on the polarimeter installed in point 1 – an area that will be strongly affected by excavations for the ATLAS caverns.

Since the publication of the preliminary report on this subject [1], more precise estimates of the likely movements have been made, technological solutions to the problems have been developed and the detailed layout of TI8 near the SPS has been fixed. In this report the more recent results are presented and the implementation plans are described. The changes planned include:

- Installation of monitoring equipment to measure the displacements (horizontal, vertical and tilts) in the SPS, TI12 and LEP.
- Modification of magnets, vacuum chamber and beam instrumentation supports so that they can be realigned following displacements.
- Utilisation of a de-tuned optics in the odd points in LEP.

The current planning for the work indicates that the first effects on the machines could be observed late in 1998 and tunnel movements will continue during the following three years as the work progresses. The majority of the modifications to the equipment will be made during the 1997/98 shutdown.

2 Civil Engineering

2.1 Transfer Tunnels to LHC

The two tunnels, TI2 and TI8, are about 2km long and initially they will be excavated up to a limit determined by radiation safety. In the region close to the SPS, the extension of the tunnels beyond this limit will be done during shutdown periods. At the LEP/LHC end, the break through will be after LEP has stopped running. The schedule for these works depends on the approval of the Gran Sasso project; in the case that it is approved, the works for TI 8 will start about 12 months earlier. These options are indicated in the summary tables (Tabs. 1 and 2) which give details of the separate works and the predicted effects.

It is very difficult to predict movements of the existing tunnels resulting from the TI2 and TI8 excavations for a number of reasons. The first problem is the lack of knowledge of the geological properties of the rock in the areas concerned - unlike ATLAS and CMS, no extensive surveys were made. The model used to predict the movements also introduces uncertainties because it assumes an elastic or elasto-perfectly-plastic material behaviour (molasse and concrete) whereas the actual behaviour is more complicated than this and varies for each type of rock encountered. With these uncertainties it is not possible to give numbers with better than 2mm resolution for the movements. A new feature associated with the transfer tunnels is the prediction of vibration when the tunnelling machine is very close to the existing tunnels.

2.2 Civil Works for ATLAS and CMS

The dates and displacements shown in the tables below (Tabs. 1 and 2) represent the latest values according to the construction programmes of possible civil engineering contractors. The figures given for the effects on SPS and LEP sum up the results of all analyses carried out so far for Point 1 and Point 5. The figures represent the predicted maximum total displacements resulting from the excavation of the associated structures.

2.3 Fringe Effects

Detailed studies of the profile of the tunnel movements indicate that the maximum displacement will only occur at the centre of the excavations. Fig. 1 shows the effect on the LEP tunnel on one side of point1 (ATLAS).

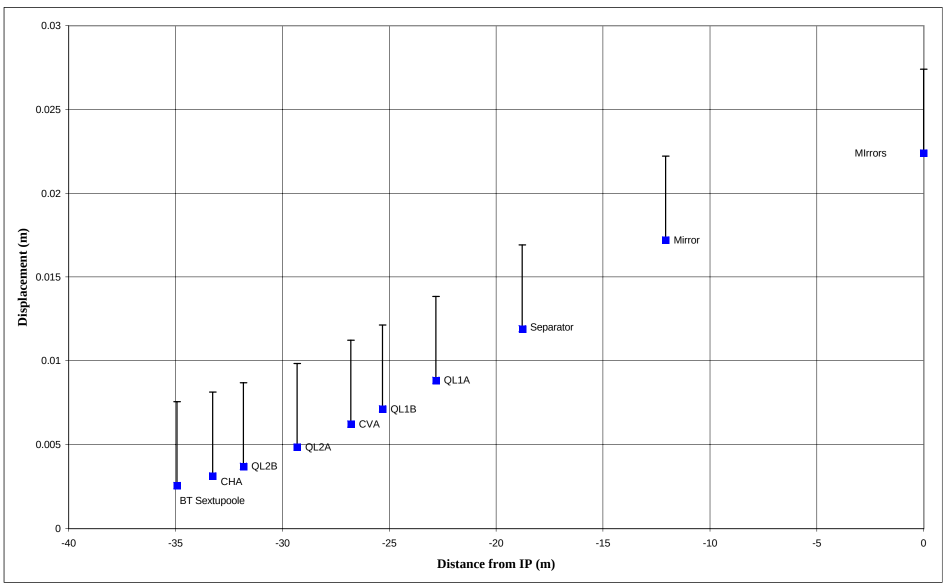

Figure 1: Tunnel movements resulting from the excavation of the top heading of the ATLAS cavern on the left side of point 1. The movements in the other half are symmetric.

The LEP tunnel will be affected from the excavation works over the length of the new caverns plus approximately half the length on either side (e.g. at point 1: tunnel between the outer end walls of UJ14 and UJ16). That means that outside of these areas no movements should occur. The amplitude of the displacements at the longitudinal limits of the new caverns should be in the order of 40% of the maximum values.

Results of some numerical analyses indicate minor tunnel movements further away from the above mentioned area. It is considered that this is rather a result of numerical effects than a true representation of the real situation. The application of engineering judgement leads to the interpretation summarised above.

Civil Engineering Structure		**Area Affected**	**Period**	**dx** (mm)	**dy** (mm)	**Vibration** (mm)
TI2	up to radiation limit near SPS	start TT60	6/00 to 10/00	0	0	0
TI2	Break through to TT60	start TT60	10/00 to 5/01	< 3	< 2	3
TJ8 & **PGC8**		200m downstream of ECA4	7/98 to 12/98	< 3	< 5	0
TI8	up to radiation limit near SPS	downstream of ECA4	12/98	< 2	0	0
PX14/ PX16		40m around QF614 and IQD1204	10/98 to 6/99	< 3	< 3	
USA15	Under SPS & TI12	40m around QF614 and IQD1204	1/99 to 10/99	0	< 5 (down)	
UX15		40m around QF614 and IQD1204	12/99	0	5 (down)	
UX15 (cavern)		40m around QF614 and IQD1204	7/01	0	10 (down)	

Table 1: Effects on SPS and TI12

Civil Engineering Structure		**Area Affected**	**Period**	**dx** (mm)	**dy** (mm)	**Vibration** (mm)
TI 2	up to radiation limit near LEP	QS11 to QS12.L2	6/00 to 10/00	< 2	< 2	1
TI8	Cross over LEP	QF21 to QF27.R8	Autumn 00 or 99	< 2	< 4(up)	0
TI8	up to radiation limit near LEP	QS11 to QS12.R8	End 00 or Autumn 99	< 2	< 2	1
PX14/ PX16		QL1A, QL1B, Separator PX14 - left,PX16 - right	10/98 to 6/99	0	< 5 (up)	
USA15		10m around the IP	1/99 to 10/99	< 5	0	
UX15 (vault)		QL1B left to QL1B right fringe effects to QL2 area	9/99 to 12/99	0	< 30 (up)	
PX56		QL1A, QL1B, Separator on right	4/99 to 2/00	0	< 3 (up)	
CMS Pillar		QL1B left to QL1B right fringe effects to QL2 area	7/99 to 2/00	< 10	0	
UXC55 (vault)		QL1B left to QL1B right fringe effects to QL2 area	8/00 to 10/00	0	< 20 (up)	

Table 2: Effects in LEP

3 Effects of Tunnel Movements

3.1 Effects on the Particle Beams

3.1.1 Beams in SPS and TI12

A displacement of quadrupoles in the SPS causes a degradation of the orbit which can not be corrected at high energy (450 GeV). A vertical displacement of QF614 larger than 2 mm will cause unacceptable orbit distortions. Displacements of quadrupoles in the SPS will arise from the excavation of USA15, PX14, TI8, TJ8, PGC8 and UX15 (see Tab. 1).

It has been shown for the SPS-LEP electron transfer line (TI12) that using all available vertical correctors plus two large strings of vertical bending magnets which are powered in series (IMAV), it is possible to correct the trajectory errors induced by a vertical displacement of IQDF1204 by 5 mm. The effects on the beam for the predicted displacements can therefore be accomodated during continued operation and the transfer line can be realigned during the shutdown following the USA15 excavation in 1999. However, any vibration affecting the transfer line magnets can not be corrected and will directly translate into injection jitter into LEP and a reduced injection efficiency.

3.1.2 Beams in LEP

Displacement of the quadrupoles in LEP introduces orbit distortions and vertical dispersion. Displacing both QL1 doublets by 1mm introduces a vertical dispersion which is an order of magnitude too large. The effect on the beam depends on the displacement of each of the magnetic elements and to some extent the effects can be compensated by orbit correction.

19% of the displacements shown in Fig. 1 (QL1A=8.84, QL1B=7.14, QL2A=4.85, QL2B=3.70) can be compensated at top energy using CVA.QL1B with the standard optics. If one uses a special detuned optics, up to 40% of the displacement can be compensated using the single corrector, CVA.QL1B on either side of the IP. A side effect of the detuned optics is a small increase in the parasitic beam-beam tune shift.

By using more correctors one gains in strength but introduces vertical dispersion because of vertical bumps. The studies found an almost exact compensation using CVAQL1B and CVAQL6 and the additional vertical dispersion was negligible. This use of multiple correctors depends strongly on the actual displacements at the quadrupoles and therefore it would be necessary to know the displacements to be able to find a solution.

The vibration from the excavation of TI2 and TI8 makes an oscillation of the position of QS12.R8 at a frequency of some Hz. A displacement of 1mm of QS12.R8 introduces an orbit distortion of 0.8 in the horizontal plane and 1.4 for a similar displacement of of QS11.R8, and vice versa for the vertical plane. Other consequences for the 90/60 optics at 94GeV:

- for a horizontal displacement of +1mm of QS12.R8
  Tune shifts: horizontal +0.0008, and vertical -0.0007
  Chromaticity shifts: horizontal -0.02 and vertical -0.17
  Horizontal emittance increased by 6%
- for a vertical displacement of +1mm of QS12.R8
  Tune shifts: horizontal -0.011 and vertical +0.016
  vertical emittance of 2.66nm

The orbit distortions are at or above the acceptable limits for background (collimation) and the tune shifts caused by vertical displacement of QS12 are clearly unacceptable. Displacement of magnets in the region of the cross over of TI8 (QF21-QF27.L8) are likely to cause effects of similar magnitude.

3.2 Effects on SPS Hardware

In the SPS and TI12, the vacuum chambers are supported in the magnets and the limiting factor is the acceptable distortion across a bellows. The limiting amplitude of 4mm is not expected to occur, since this would mean a differential movement of 4mm over a short length of the machine or transfer line.

The equipment installed in the SPS is capable of being realigned to accommodate the predicted displacements.

3.3 Effects on LEP Hardware

In LEP it is also the vacuum bellows that is the critical element and in this case the displacement limit is 2mm. The magnets and vacuum chamber supports have to be modified to accommodate the large amplitudes of displacement.

Because the movements predicted of the LEP tunnel are upwards, it will be necessary to lower the machine elements during realignment. To allow the high voltage conditioning of the separators at the largest gap of 160 mm (with the electrodes retracted), it will be necessary to make two small circular excavations per separator in the tunnel floor. These will accommodate the nitrogen cooling tubes during conditioning after the separators have been lowered. The existing supports permit adjustments over a sufficiently large range for the predicted movements.

There is some concern that vibration of radiation damaged cables in the LEP tunnel is likely to destroy them (in the SPS, the equipment is likely to be less sensitive because of lower radiation levels).

3.4 Effects on LEP Instrumentation

The beam instrumentation affected by the tunnel movements in point 1 will be the two polarimeter mirror boxes situated at 12m around interaction point (IP) and the BEMI mirror box at the IP which feeds the streak camera in the optical laboratory by means of two beryllium mirrors. In point 5 it will be the collimator installed at the IP. The BEMI box is connected via two telescopes (achromats) to light pipes which pass through 15m of rock to the optical laboratory. The bellows at the bottom ends of the telescopes will have to compensate for the full extent of the floor movement since it has been predicted that the optical laboratory, which is installed in the US15 area, will not move during the excavations for LHC.

The present configuration of the achromat does not allow for the required compensation and will be rebuilt acordingly. At the same time the light pipes will move at the tunnel end only; at present they are fixed to the tunnel ceiling and are constrained by a supporting frame in the rock, so some modifications are required.

The optical paths for the laser beam (polarimeter) and the synchrotron light (streak camera) can be realigned to accommodate movements of up to 5mm before physical realignment is necessary.

The mirror boxes and collimator are supported on normal supports, like the vacuum chambers, and these will be modified to accommodate the required realignment.

4 Modifications Required

4.1 LEP Optics

Studies of the side effects of bunch train bumps have demonstrated that the use of the detuned optics in LEP requires that the optics is installed in all four odd points. Under these conditions the optics checks are satisfied (bunch train bumps, collimator parameters etc.) and the luminosity performance of the machine should be unaffected. It has also been demonstrated that with this optics it may be possible to magnetically compensate the full displacement and achieve acceptable orbits and dispersion under physics conditions. However, the physical constraints remain i.e. the hardware limits from bellows and the beam instrumentation.

Use of the detuned optics should allow larger tunnel displacements before realignment is necessary, yielding a factor of two improvement in downtime for realignment.

As the -functions at IP1 are larger with this optics it will be advisable to check that the transverse dimensions of the backscattered gamma photons to the polarimeter detector do not suffer from the limited transverse aperture in the windows.

4.2 New Survey Equipment

The requirement for a remotely readable survey system was stated in the preliminary report [1]. A radiation-hard system has been developed during 1997 and will be installed during the 1997/98 shutdown. The system uses capacitative sensors, of the type developed for CLIC, placed around a stretched wire[2]. The wire will be anchored in stable regions of the tunnel at either side of points 1 and 5 and the sensors will be placed on or near each of the important elements in the affected regions. There will be about eleven sensors per IP and the data will be gathered and stored in the control system database.

In the SPS and TI12 the radiation environment is less severe and it should be possible to utilise technologies which are less expensive. A system which is under development for LHC has been proposed and a prototype will be installed during the 1997/98 shutdown. This system is based on optical captors which measure the position with respect to a stretched wire.

Movements of the SPS which should be monitored are in the regions affected by the ATLAS and TI8 excavations. Some improvements are required in the TI12 region so that a realignment can be carried out more efficiently. A study will be made during the 1997/98 shutdown with a view to improving visibility and installing additional reference points.

A special device will be installed by the BI Group in the optical laboratory to monitor the relative movements between the laboratory and the tunnel.

In order to monitor possible vibration of the tunnels, it has been proposed to install accelerometers in the regions likely to be affected. This proposal will be reviewed when the planning for TI2 and TI8 has been finalised.

4.3 Hardware Modifications

In the SPS, the quadrupoles around QF614 are at the limit of their horizontal adjustment at the moment. Some new parts will be fitted during the 1997/98 shutdown.

The LEP magnets (QL1 and QL2 doublets) in points 1 and 5 will be modified to accommodate up to 40mm of vertical movement. This will be achieved by installing new jacks in newly sunken holes below the girders. Modifications will also be made to allow the required horizontal movement (up to 15mm).

To accommodate the separator cooling pipes, two circular excavations per separator (400 mm diameter and 60 mm deep) will be made in the tunnel floor. These holes have the same dimensions as those mentioned above for the magnets and they will be made at the same time.

All vacuum chamber supports will be modified to accommodate the same amplitude of adjustment (40mm vertically and 15mm horizontally).

The collimator at point 5 and the mirror boxes in point 1 will be fitted with supports of the same type as the vacuum chambers. More complex modifications are required to the light pipes, which are located at the position of maximum displacement.

5 Realignment Strategy

It is planned that the realignment will be performed by teams composed of the various hardware experts and the surveyors. The adjustments to the equipment will be performed manually under the supervision of the survey team. In order to avoid the introduction of tilts on the separator tanks (resulting in twists on the bellows) the drive axes of the two screw jacks located either side of the beam axis will be linked by a rigid transmission bar. This will be installed after realignment and reconnection of the adjacent vacuum chambers during the 1997/98 shutdown. This will also simplify the realignment and save time because a single action will move both screw jacks.

The realignment will cause downtime of the machines and the figures given below in Tab. 3 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. In the SPS, the limiting factor for realignment will be the 2mm displacement of a quadrupole whilst in LEP it will be 5mm at the instrumentation (mirrors and bellows compression). The latter is also likely to correspond to the limit across a bellows. 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 if no changes are made.

The downtime for the SPS is dependent on civil engineering scheduling: the lower limit quoted in the table corresponds to the present schedule and the upper limit is if all movements would occur during operation. The lower limit in LEP corresponds to the use of the detuned optics in the odd points and the current schedule; the effect of scheduling is minor ($<$ 24 hours in the 200).

SPS downtime	36 to 72 hours
LEP downtime in 1999	100 to 200 hours

Table 3: Predicted loss of physics time for realignment interventions in the machines

Although the uncertainty on the predicted movements for the SPS as a result of the TJ8 chamber are large, the amplitude is great enough to warrant some precautions. In the region affected it would be very difficult to install a monitoring system since it is in the curved part of the machine. It has been decided to make reference survey measurements in the region during the 97/98 shutdown and to check the alignment from time-to-time when this can be done in the shadow of other interventions (magnet replacement, PS MD etc). Given the provisional planning, one would expect, in the worst case, only one realignment to be necessary during the operational period.

6 Budget

The cost of the various components of the project are as follows:

Beam Instrumentation	55kCHF
Magnets/Jacks	20kCHF
Survey (LEP)	200kCHF
Survey (SPS/TI12)	65kCHF
Vacuum equipment	100kCHF
Manpower (design, installation etc.)	160kCHF
Total	600kCHF

7 Conclusions

The programme of improvements and modifications outlined above should ensure the continued smooth running of the SPS and LEP machines during this critical period. Some elements of the plan remain to be verified:

An coordinated programme for realignment has to be established so that loss of physics time is minimised.

The correct functioning of the polarimeter with the detuned optics in the odd points should be demonstrated.

The detuned optics should be proven to deliver the same luminosity as the 'normal' optics.

The scheduling of the TI2 and TI8 excavation is far from being finalised and therefore the possible impact and precautionary measures which may be required will be reviewed towards the end of 1998. Possible precautionary measures would include the installation of a survey system in the region of the TI8 cross over and vibration monitoring in the affected areas.

Proof of the detuned optics is important because it will gain at least 4 days physics for LEP.

References

[1] B. Goddard et al., *Preliminary Report on the Consequences of LHC Civil Engineering for the SPS and LEP*, CERN SL 96-73 DI and ST 96-02, December 1996.

[2] W. Coosemans and H. Mainaud, *Métrologie linéaire: Ecartométrie biaxiale et fil tendu*, CERN CLIC Note 316, Sept. 1996.