The LEP Spectrometer

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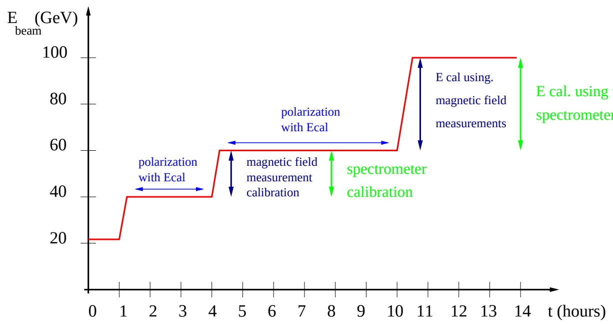
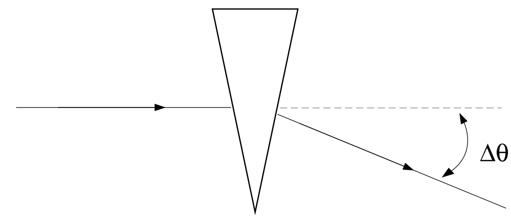


Figure 1: The beam energy calibration procedure.



$$\Delta\vartheta \propto \frac{\oint Bdl}{E_{beam}} \qquad (1)$$

Figure 2: The spectrometer concept.

1 INTRODUCTION

The beam energy of LEP is determined with high accuracy at energies (41 - 60 GeV) where polarization is observed. The extrapolation to the LEP operational energies is done by using different magnetic measurement methods. The beam energy error of LEP is dominated by the error on the extrapolation.

The energy calibration procedure is illustrated in figure 1. The resonant depolarization calibration technique is applied at 41 and 60 GeV. This energy step is used for the calibration of the magnetic energy determination methods. The magnetic methods are only used to determine the relative increase of the energy from 60 GeV to the operational energies above 90 GeV.

A spectrometer (see Fig. 1) was suggested in order to have an independent energy extrapolation method and to reduce the extrapolation error. The method is based on the determination of the deflection angle of a LEP lattice bending magnet. The spectrometer could also be calibrated using the accurate energies of 41 and 60 GeV (see Fig. 1). The high accuracy is only needed for the determination of the energy step between 60 GeV and the operational energy of LEP. It is in this case enough to measure the change of the deflection angle and the change of the integral magnetic field.

To reach the required extrapolation accuracy of $1 \cdot 10^{-4}$ (relative error) the integral magnetic field of the lattice magnet has to be determined with an accuracy of $3 \cdot 10^{-5}$ and the orbit on both sides of the magnet has to be measured with an accuracy of $1 \cdot 10^{-6}$ m.

The required use of a LEP lattice magnet imposes two strong conditions for the design of the setup. The radiation dose per year near the bending magnets is of the order of $1 \cdot 10^6$ Gray and the power deposition on the inside of the vacuum chamber changes from almost zero to 700 W/m (I_{beam} = 10 mA) during the ramp of the magnets.

2 THE SPECTROMETER SETUP

The spectrometer is located to the left of LEP interaction point 3 in a region with enough drift space on both sides of a magnet. This location was chosen because the rail way train currents which flow over the vacuum chamber and disturb the magnetic field are small [1]. Another reason for this choice is the short distance from the setup to the electronics racks (150 m).

The spectrometer magnet is located between quadrupole magnets 17 and 18. A free drift space of 10 m on each side (see Fig. 3) allows the placement of three beam orbit

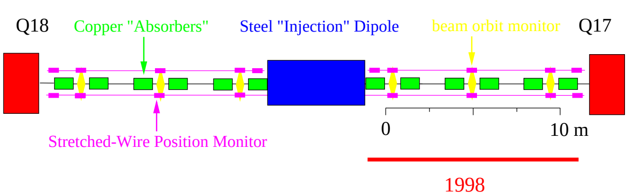


Figure 3: The spectrometer setup. The well measured and temperature controlled magnet in the centre is flanked on each side by a orbit determination measurement system.

monitors to determine the deflection angle change. With a redundancy of one monitor on each side it is possible to check the accuracy of the orbit monitors on each sides separately.

Each beam orbit monitor is located in the shadow of a copper block absorber to avoid the direct impact of photons on the orbit monitor electrodes and to avoid power deposition from synchrotron light in the whole orbit monitor support. The copper absorbers reduce the elliptical vacuum chamber aperture by 5 mm (see Fig. 4).

To reach a stability of the setup of 1 μm during the calibration each monitor support has to be temperature regulated, because a temperature variation of 1 degree will cause a dimensional change of 2.3 μm on a 10 cm Al support structure.

To be able to observe relative support structure position changes, a wire sensor monitoring system is installed. One wire extends over the whole length of the spectrometer (see Fig. 3) and the two others cover the sides of the spectrometer separately. Each wire is equipped with two rigidly mounted reference sensors and sensors which are mounted on the orbit monitor support (see Fig. 4). The

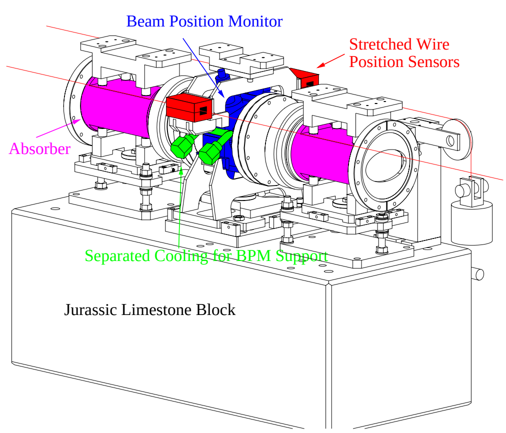


Figure 4: The orbit measurement station. The orbit monitor in the centre is surrounded by two protecting synchrotron light absorbers. The position changes of the setup are monitored by the wire position sensors.

whole setup consisting of two absorbers and the orbit monitor is mounted on a limestone block. The orbit monitor support block is joined to the absorbers with thin, highly flexible welded bellows to reduce vibration transmission and to reduce the railway train leakage currents by increasing the electrical resistance.

3 TEST MEASUREMENT RESULTS

Before the startup of the 1998 operational period of LEP the left side of the spectrometer was installed (see Fig. 3). With this setup it was possible to determine the orbit position measurement accuracy. During 1998 a new mild iron magnet was build and magnetic field measurements were begun.

3.1 The temperature regulation system

The temperature of the orbit monitor support is regulated by controlling the water temperature which flows through the support. The expansion and contraction caused by temperature variations of the support should be small compared to the required measurement accuracy of 1 μm.

In Fig. 5 the temperature variations of the LEP cooling

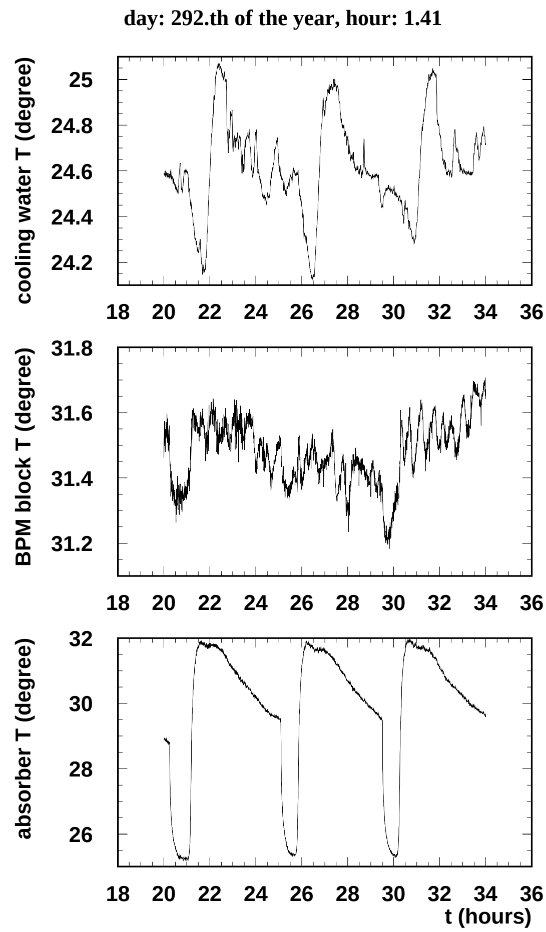


Figure 5: Comparison of the temperature variations of the cooling water. Top: LEP cooling water supply. Middle: Beam orbit monitor block temperature. Bottom: Absorber temperature.

water supply, an orbit monitor support and an adjacent absorber are shown. The orbit monitor support is varying by ± 0.2 degree, whereas the supply water is changing by 1 degree and the nearby absorber is varying by 7 degree. The variation of ± 0.2 degree translates into a ± 0.46 μm change of the monitor dimensions. This is small (0.1 μm) compared to the 1 μm requirement if added in quadrature.

3.2 The wire position sensors

The sensors from the company FOGALE determine the relative position between the electrodes of an air capacitor and a wire by measuring the capacity between the wire

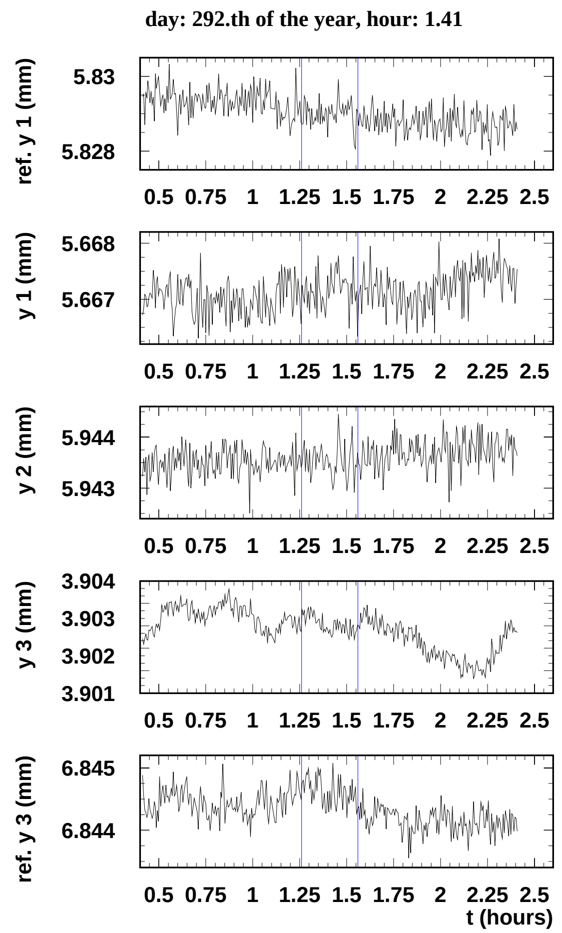


Figure 6: The (vertical) variations of the wire position sensor signals with time. From top to bottom are the five sensors on one wire (the first and last sensor are used as reference sensors).

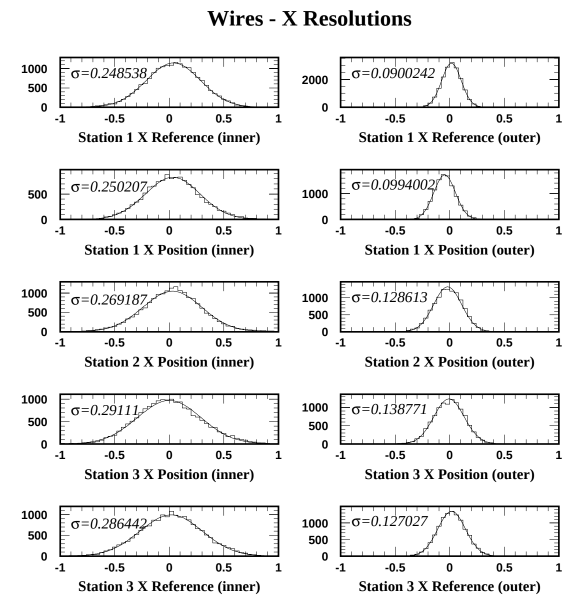


Figure 7: Resolution of the wire position sensors for the inner and outer wire (units in μm)

and both electrodes. The difference of the capacitance is proportional to the relative position of the wire. The sensors determine the relative horizontal and vertical position simultaneously. The measured variation for a period of 2 hours during a 60 GeV LEP fill is within a band of 1 μm (see Fig. 6) for all sensors on one wire. The resolution of the position sensors is calculated by subtracting adjacent measurements from each other. The results indicate (see Fig. 7) that the resolution is below 200 nm. This means no averaging is needed to determine the orbit monitor changes.

If the wire position signal is plotted for a period lasting over the length of several fills, fill to fill variations are visible (see Fig. 8, top). Every second sharp transition between signal levels coincides with the beam current step to zero (beam dump) (see Fig. 8, bottom). The other transitions coincide with the increase of the beam energy from 22 GeV to 92.0 GeV. The middle plot is shows the variation of the current in an air capacitor supplied with a DC voltage of 6 Volt. This current variation is in coincidence with the wire position signal changes for the positive and negative slopes of the transitions. The current variation indicates that the number of free charges is varying. Taking additional (not shown) measurements into account, the following conclusion could be drawn: the wire sensor or the wire itself is not moving when the current or the energy of LEP is changed. The effect itself is proportional to the relative wire position with respect to the sensor electrodes. It can be largely suppressed by shielding the sensor from synchrotron light.

3.3 The beam position monitors

The beam position monitors consist of the standard LEP monitor electrode for an elliptical vacuum chamber and specially optimised readout electronics from the company BERGOZ. The electronic is connected successively to all 4 electrodes of one monitor to avoid response changes with time.

The fluctuations from one orbit monitor setup were measured by calculating the difference between successive readings. The plot (top, left) of Fig. 9 shows the horizontal position signal (red) and the difference of the positions (black) measured by the monitor. The position of the beam is changing by 0.2 mm during the measuring period. These position changes are visible in the difference as large fluctuations. The distribution of the difference signal has a width of 9.61 10^{-3} mm. The next row of plots show the vertical position measurements. The width of the distribution of the differences is 1.49 10^{-3} mm. The difference between the widths of the horizontal and vertical distributions is not been unambiguously identified. The observed fluctuations in the difference signal include the beam orbit fluctuations and the fluctuations caused by the orbit mon-

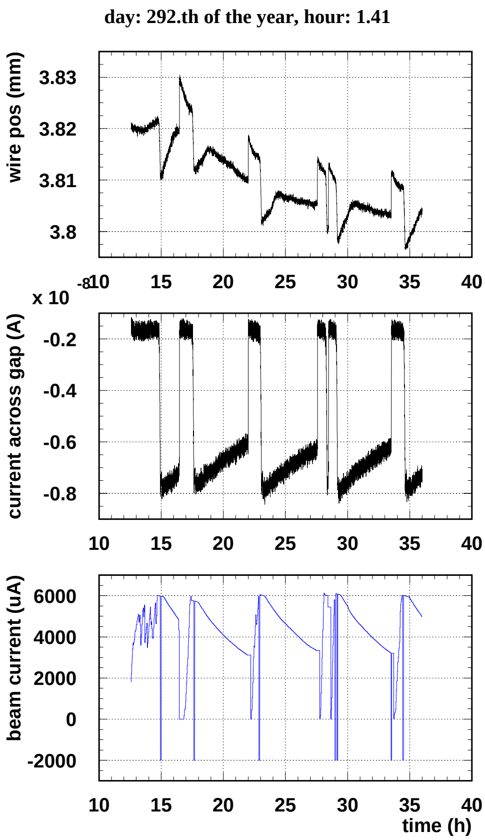


Figure 8: The wire position signal variation lasting for several LEP filling periods. Systematic signal changes (top) coincide with the LEP high energy fill time (bottom, beam current) and with the current variation of a air capacitor.

itor itself. Orbit fluctuations with a frequency smaller as the measurement frequency (1 Hz) could be suppressed by calculating the triple orbit monitor residual:

$$residual = \frac{x_{bpm1} + x_{bpm3}}{2} - x_{bpm2} \qquad (2)$$

The residual signal of the horizontal plane (see Fig. 10, top) shows a slight systemic drift, but the signal range is still dominated by the fluctuations. The residual signal range of the vertical plane is fully dominated by fluctuations. The frequency distribution indicates a width of σ = 7.3 10^{-4} mm for the horizontal plane (see Fig. 11, top) and σ = 2.6 10^{-3} mm for vertical plane (see Fig. 11, bottom). These data allow the conclusion that the beam orbit monitor system (electrode and orbit monitor electronic) is able to determine the orbit position with the required accuracy of 1 μm during a time period of 2 hours.

3.4 The bending magnet measurements

To determine the change in beam energy at the location of the spectrometer the ratio of the magnetic field integrated along the gap of the magnet has to be known with the required accuracy of $3 \cdot 10^{-5}$.

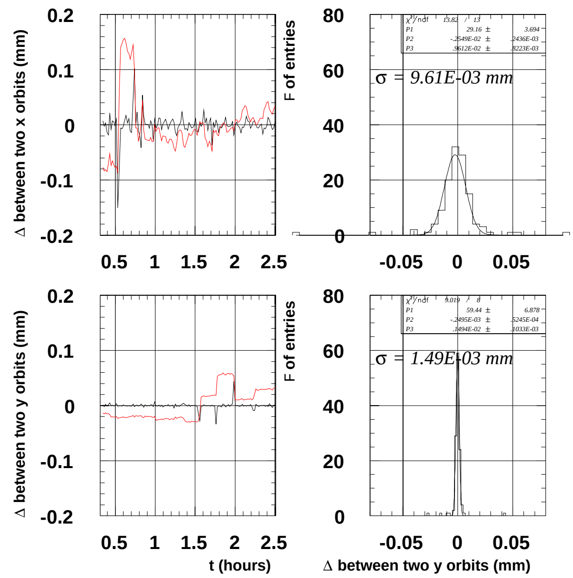


Figure 9: The resolution of the beam orbit monitors. Top left: Horizontal position signal of one monitor as function of the time (red). The black graph shows the difference of successive readings. Top right: Frequency distribution of the left difference signal. Bottom: Vertical position signal (treatment the same as for the horizontal signal)

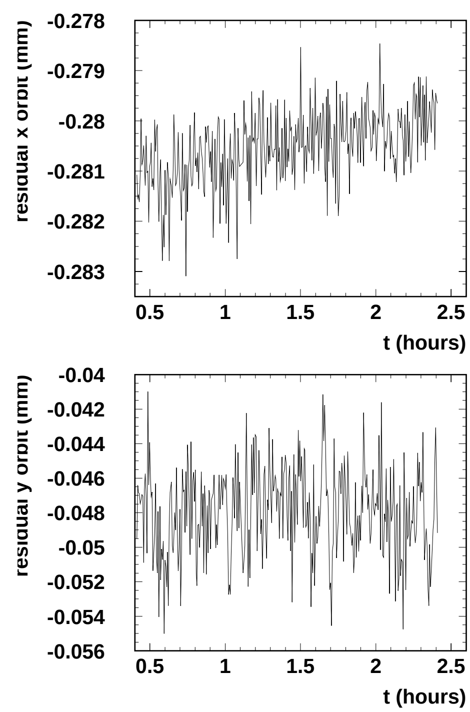


Figure 10: The residual positions of the three orbit monitors as function of time.

The field of the magnet can only be continuously moni-

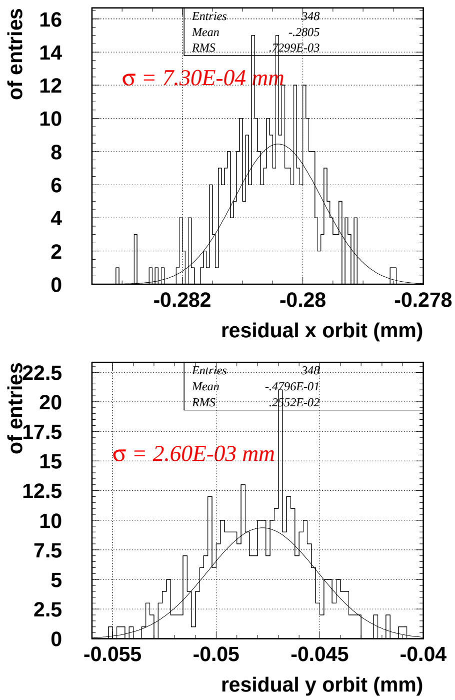
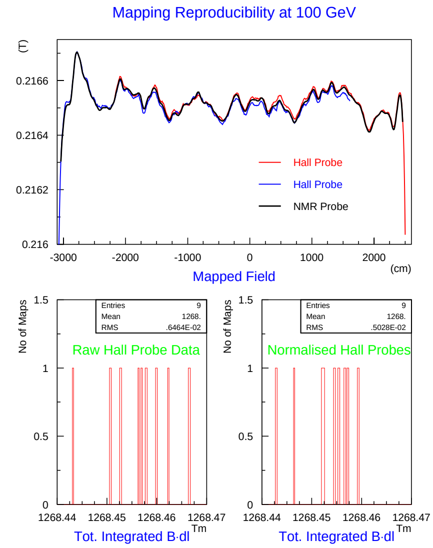


Figure 11: The frequency distribution of the orbit monitor residuals.



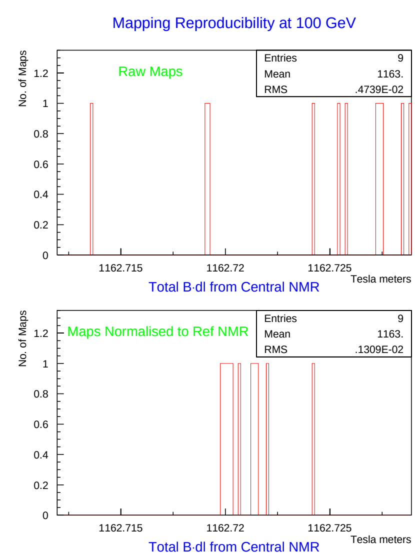
$$\frac{\Delta(\oint Bdl)}{\oint Bdl} = 4.0 \cdot 10^{-6} \quad (3)$$

Figure 12: The bending magnet field along the gap (top). Bottom, left: The frequency distribution of the total integrated magnetic field (not normalised). Bottom, right: The normalised frequency distribution of the total integrated magnetic field.

tored at few locations inside the magnet gap. Therefore the relations between local field measurements and integrated field has to be determined in advance. Moreover, possible variations of the relations depending on environmental conditions have to be stimulated and investigated.

A measurement bench carrying a precisely locate able NMR probe and to Hall probes were assembled. The new mild iron magnet were equipped with 4 NMR reference probes to determine the local fields. This measurements are not carried out inside the vacuum chamber. To cope with possible field variations introduced by the lead shielded aluminium vacuum chamber and to verify the field distribution after transporting the magnet to the LEP tunnel a wagon was developed which carries two NMR probes and one sense coil. The Hall probe and the sense coil are used to determine high gradient end field regions of the magnet.

The longitudinal field profile show variations of 0.2 % (see Fig. 12, top) but the integrated field varies only by $4 \cdot 10^{-6}$ (see Fig. 12, bottom, right). The central field of the magnet shows further decreased variations (see Fig. 13, bottom), because it is measured with the NMR probe. This result indicates that the largest contribution to the field fluctuation is introduced by the Hall probe instruments. This relative variations are almost 10 times smaller as the required accuracy for the variation of the ratio of the integrated and normalised fields. But several more test will be done to observe the influence of environmental condition changes on the field reproducibility.



$$\frac{\Delta(\oint Bdl)}{\oint Bdl} = 1.0 \cdot 10^{-6} \quad (4)$$

Figure 13: The frequency distribution of the central integrated magnetic field. Top: Distribution of different raw data maps. Bottom: Normalising each integrated map to the reference NMR probe readings.

Figure 14 shows the drawing of the wagon which is pulled trough the LEP vacuum chamber and which carries the two NMR probes and one sense coil. The wagon is pulled by a stepping motor and the accurate position of the probes is determined by a interferometer. Using this wagon

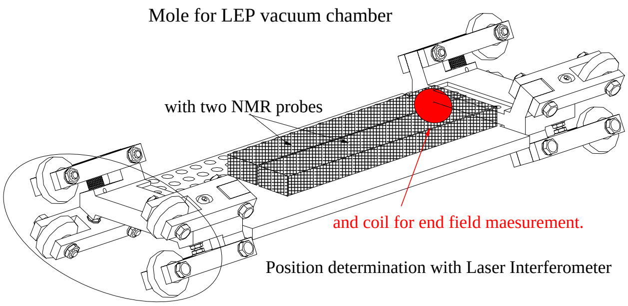


Figure 14: The movable NMR probe and sense coil support for the LEP vacuum chamber.

measurements with the vacuum chamber will be carried out before and after the transportation of the magnet into the LEP tunnel.

4 CONCLUSION

The test setup of the spectrometer is providing several valuable results.

The temperature control of the position sensors is sufficient, because the variations are smaller as $\pm$ 0.2 K which cause dimension changes well below 1 μm.

The beam position monitors show a residual position accuracy over 2.5 hours of 1 μm. The used BPM electronic is stable enough, but only in the one beam mode. With two beams the variations are 10 times larger. A different electronic solution for the two beam mode has to be chosen to overcome this problem.

The wire position sensors have a resolution of 0.2 μm, but systematic effects at 94 GeV are much larger as the required accuracy. Investigations have shown that this effect could largely be reduced if the synchrotron light can not reach the wire sensors. Shielding for the synchrotron light radiation has to be provided and a systematic study of the effect is needed.

5 REFERENCES

[1] "The Influence of Train Leakage Currents on the LEP Dipole Field", E. Bravin et al., CERN-SL-97-047-BI and Nucl. Instr. Meth. in Phys. Res. A 417 (1998) 9-17.