ALIGNMENT METHODS APPLIED TO THE LEP MAGNET MEASUREMENTS

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Introduction

Electromagnets used as beam guiding elements in particle accelerators require very tight tolerances on their magnetic fields and therefore also on their geometric positioning in the accelerator. Construction techniques, measurement equipment and alignment methods must match these requirements. The length of the magnet is usually small compared to the wavelength of the betatron oscillations. This means that only the measurements of integrals of the magnetic field and its derivatives along the beam axis are of importance. The need for the very large number of electromagnets for LEP [l] called for a high degree of automation of the magnetic measurement and alignment procedures. Small computers were used for the control and data handling at the various measurement stations, and the relevant parameters for each magnet were transferred to the central database through standard communication lines for use during magnet installation [2].

Magnetic Measurements

Magnetic measurements are important at various stages of an accelerator project: design, construction, installation and operation. The magnetic properties can be characterized as magnet field strength, magnet field quality and magnet field geometry.

The measurement of the magnet field strength (or excitation curve) includes that of the hysteresis curve of the magnet, which is of particular importance in low-field magnets like the LEP dipoles. The results of these measurements were used to decide upon where to locate or how to combine individual magnets. They also serve for the definition of operational procedures, such as the cycling of the magnetic field or the determination of the energy of the particle beam.

The measurement of field quality is of interest during the magnet design phase and at a later stage for beam optics studies. The dispersion of the measured parameters is also of interest both in the case of field strength and field quality measurements.

The measurement of field geometry is of vital importance for the installation and alignment of the magnets. Two values are critical: the location of the beam axis and the angle of the median plane of the accelerator; In the following we shall describe how the magnetic references were defined and transferred to the mechanical references used during magnet installation and alignment in the LEP tunnel.

Median Plane References

The median plane of a magnet is usually expressed in relation to the direction of gravity. Commercially available electronic level gauges were used for the measurements of the LEP magnets. The measuring principle is based on a pendulum suspended between two electrodes forming a differential capacitor circuit. The measured values of capacitance are processed and made available on analog or digital display panels and are interfaced to the control system when required. Different types of level gauges were employed for the measurements and alignments of the LEP magnets: independent battery powered level gauges with a digital display having a range of ±20 mrad and a sensitivity of 0.01 mrad as well as a low cost transducer with a range of ±200 mrad and a sensitivity of 0.1 mrad. A settling time of a few seconds was measured. Two transducers can be connected for differential measurements. A calibration on a reference plane was performed before each measurement sequence in order to compensate for time and temperature drift.

Beam Axis References

The classical method for defining the position of the beam axis was the use of telescopes and optical targets. In view of the very large number of electromagnets to be handled, it was decided to develop an alignment system based on a stable light beam emitted from a HeNe-laser and captured by a position sensing photodiode as illustrated in figure 1.

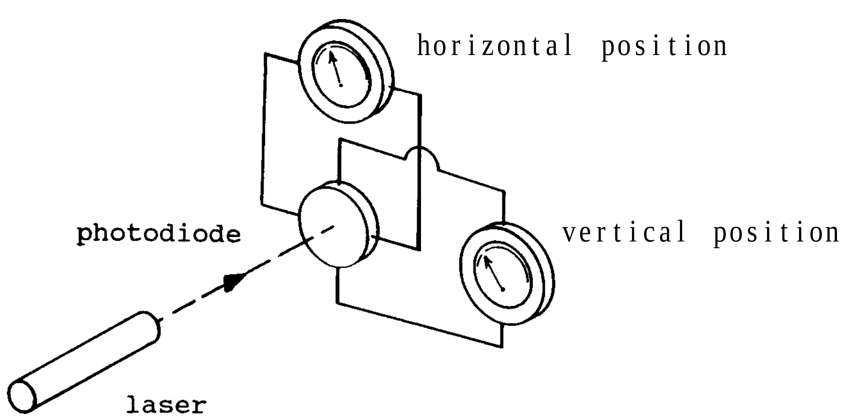

Fig. 1. Photoelectric alignment

HeNe-lasers have a very bright light compared to conventional sources. Its coherence properties allow easy positioning even in daylight and photoelectric detection is easily feasible. No additional optics were needed for distances up to about 8 m. A beam expander was mounted on the laser for applications at larger distances in order to reduce the relative beam divergence by a factor of ten.

A test programme was carried out to select a HeNe-laser with satisfactory properties such as a good beam position stability, low beam divergence and a low power output for safety reasons. The selected laser has the following characteristics:

wavelength	632.8 nm
output power	≅ 2 mW
beam diameter	0.75 mm
beam divergence	< 1.2 mrad
temperature drift at steady state conditions	< 0.01 mrad/°C

In order to reduce heat sources to a minimum, care was taken to mount the laser power supply away from the laser tube when used in fixed installations like on measurement benches. Figure 2 shows two of the laser tubes employed, of which one is fitted with a beam expander.

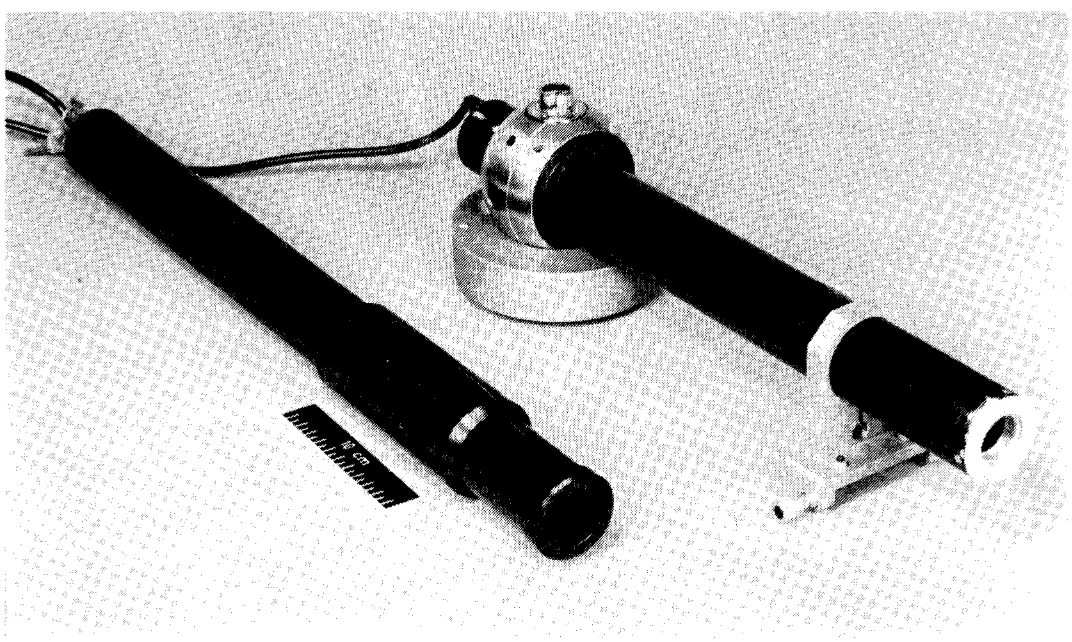

Fig. 2. Laser tubes

Three different laser units were constructed in order to meet the particular requirements for the LEP magnet measurements and alignments. A fixed laser unit with high accuracy and optimum temperature stability was used with the various semi automatic magnet measurement benches. A second type was the mobile laser unit used for short time alignment purposes such as the assembly and alignment of magnet sub-assemblies. The third type was the long distance (40 m) mobile unit used for the installation of the dipole pairs in the LEP tunnel. This laser was fitted with a beam expander, producing a beam diameter of 11 mm. The other lasers had a 400 mm long protection tube fitted at the end of the laser tube in order to avoid the refraction effect caused by local heating of the air around the laser tube. The supporting points of the laser tube itself were modified in collaboration with the manufacturer in order to minimize the heat drift. The lasers were mounted on special supports designed for minimum heat transfer and provided with the necessary possibilities for adjustment. The long distance units were fitted with a differential micrometer adjustment for precise and easy beam alignment. The mobile units were mounted into adjustable spherical housings for use with the CERN standard reference sockets.

The photodiodes used as detectors for the measurements were commercially available Schottky barrier sensors with different active areas. Two types of photodiodes were used. For the applications with the unexpanded beam below a distance of 8 m, a diode with an active area of 19 x 19 mm was employed, whereas for the long distance measurements with the expanded beam a diode with an active area of 45 mm diameter was chosen. A standard spherical housing with vertical, transverse and angular adjustments allowed measurements with an accuracy of ±0.02 mm. Short protection tubes were fitted in front of the photodiodes, as shown in figure 3, in order to reduce the influence of ambient light.

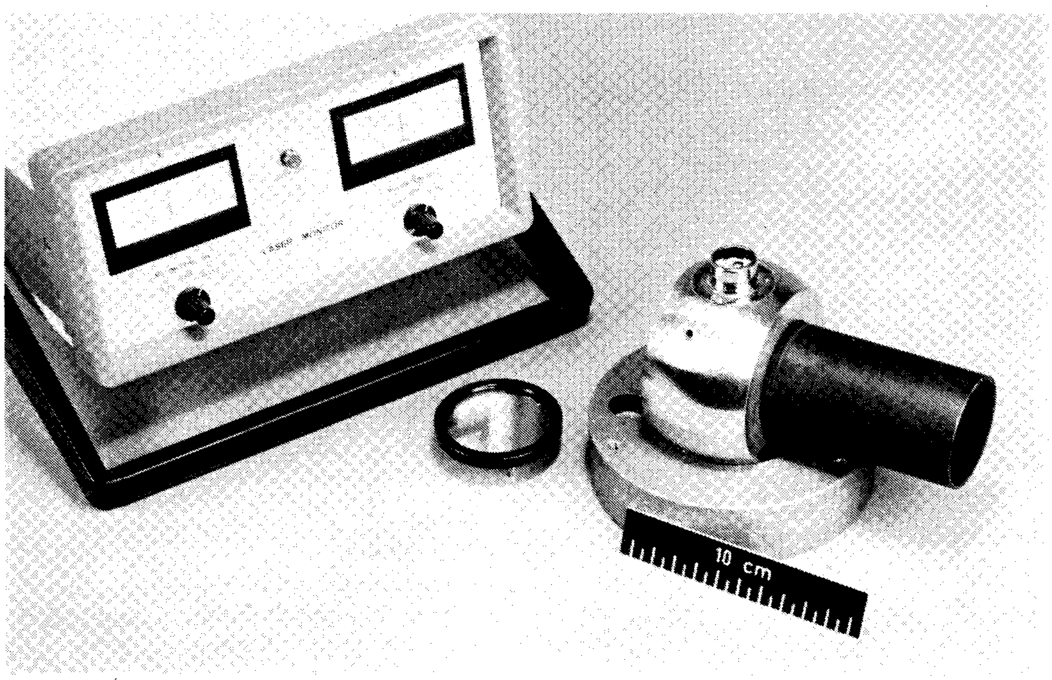

Fig. 3. Photodiode with analog displacement monitor

Two types of displacement monitors were developed: an analog and a digital instrument. Both were based on a simple electronic circuit which normalizes the signals from the photodiode, thus compensating for the change of light intensity with distance. A resolution corresponding to 0.02 mm was obtained. The analog monitor was a simple stand-alone unit which indicated the vertical and horizontal displacements on standard panel instruments. It is shown with its associated photodiode in figure 3. The digital monitor permitted the connection to a control system via a standard digital interface (GPIB or RS-232). This feature was useful for the recording and the subsequent application of positional corrections.

Dipole Geometry Measurements

The magnetic performance of the 3304 dipole magnets for LEP was deduced from systematic measurements of the magnetic geometry of their air-gap [3]. Included in this measurement was the determination of the angle of the median plane for each of the dipole cores. This value was of importance both for the pre-alignment of the dipole pairs and, in particular for the final alignment in the LEP tunnel.

The magnetic geometry was measured by a carriage rolling directly on the lower pole face of the dipole. A view of the measurement system is shown in figure 4.

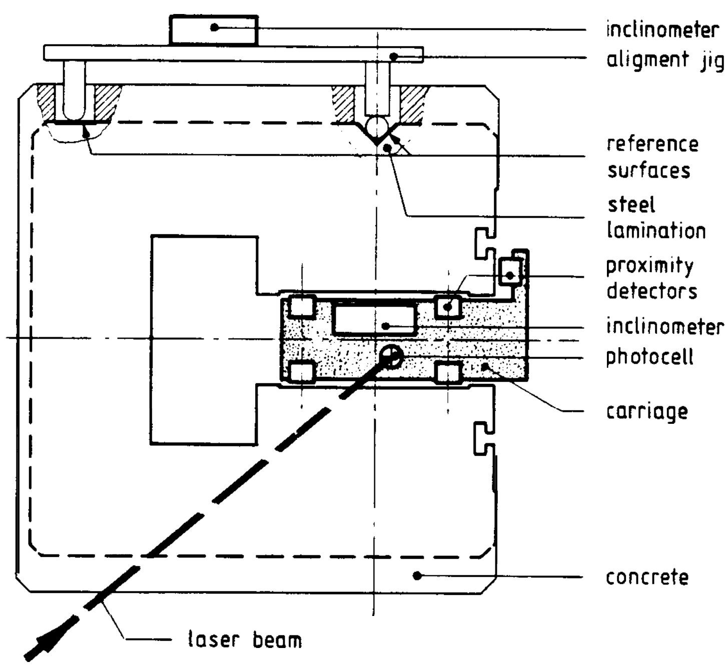

Fig. 4. Dipole geometry measurement

The beam emitted by a laser tube placed at one end of the dipole core and pointing at a fixed photodiode at the other end, defined a straight line. Five proximity detectors, based on a.c. magnetic circuits, measured the position of the carriage inside the air gap and thus the height of the gap in two points. A photodiode measured the position of the carriage with respect to the laser beam in a range of ±5 mm to an accuracy of ±0.05 mm and an electronic level gauge measured the tilt of the carriage. This tilt was compared to the tilt of the magnet core which was measured by a second electronic level gauge placed on the alignment jig. The level gauge measured with an accuracy of ±0.04 mrad in a range of ±20 mrad. Daily calibration improved the accuracy to ±0.02 mrad within a range of ±5 mrad. The measurement was made in successive steps over the whole length of the core. The overall accuracy of the measurement of the median plane angle was ±0.04 mrad. A small computer controlled the measurement, read the measurement results and deduced all relevant parameters.

Harmonic Coil Measurements

The LEP magnet system contains about 1300 quadrupole and sextupole magnets. Their magnetic properties, including the field geometry, were measured using the harmonic coil method. In view of the large number of magnets, these measurement benches were highly automated [4]. A laser beam was used as the reference axis both for the automatic pre-alignment of the magnet on the measurement bench and for the final positioning of the reference targets. Figure 5 shows the alignment equipment mounted on one of the LEP superconducting quadrupoles during its measurement. The magnetic axis of the quadrupole magnets was determined to an accuracy of ±0.02 mm and the median plane to ±0.05 mrad.

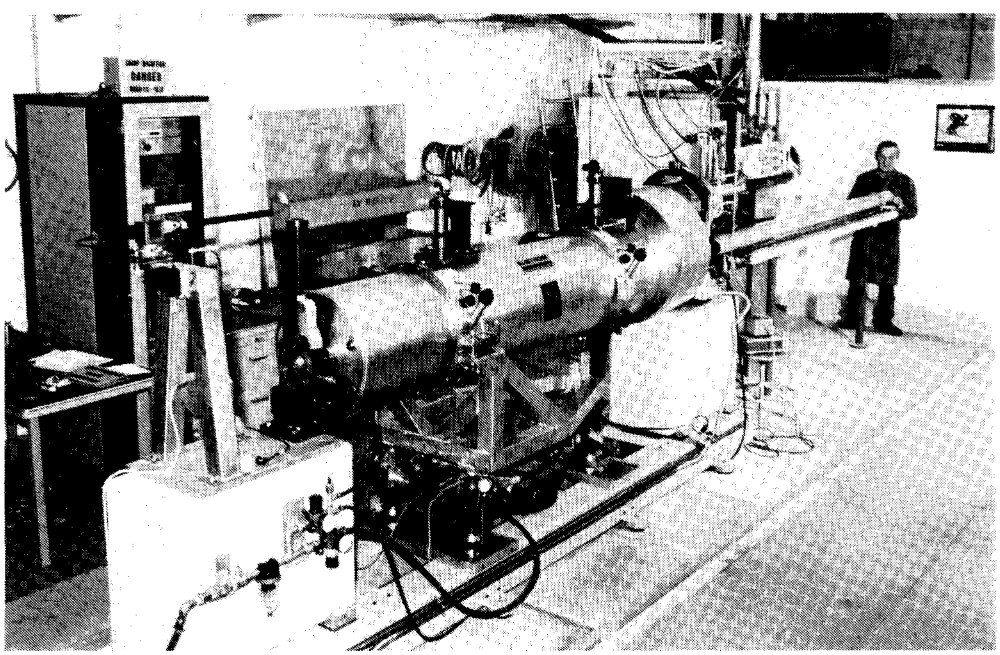

Fig. 5. Measurement of a superconducting quadrupole

Alignment of Straight Section Components

Quadrupoles, sextupoles and dipole magnets for orbit corrections were mounted and aligned, then equipped with their vacuum chamber and beam observation monitors on common girders, so as to form complete machine elements to be transported and installed in the LEP tunnel. A total of 744 units of 28 different types was assembled. The different components were aligned with respect to the quadrupole magnet, which was the only element carrying reference sockets for the final alignment in the tunnel.

The precision required for the alignment was ±0.05 mm in the horizontal and vertical planes for the beam position monitor and ±0.l mm for the other components. The tolerance on the transverse tilt was ±0.l mrad.

Alignment devices carrying photodiode targets for the determination of the transverse and vertical coordinates as well as electronic level gauges were built. The quadrupole reference axis was defined by a laser beam to an accuracy of ±0.01 mm during assembly. The laser was mounted on one of the reference sockets of the quadrupole as shown in figure 6.

Fig. 6. Laser reference beam and level gauge.

The median plane was defined by a master level placed on the quadrupole reference points and connected to the corresponding level gauge on the alignment jig for a differential measurement. Both instruments were calibrated on a reference plane before the measurement and verified afterwards. The time required for the alignment operation was typically 30 minutes, so the drift of the mobile laser units was acceptable. A typical alignment device, in this case mounted on a sextupole magnet, is shown in figure 7.

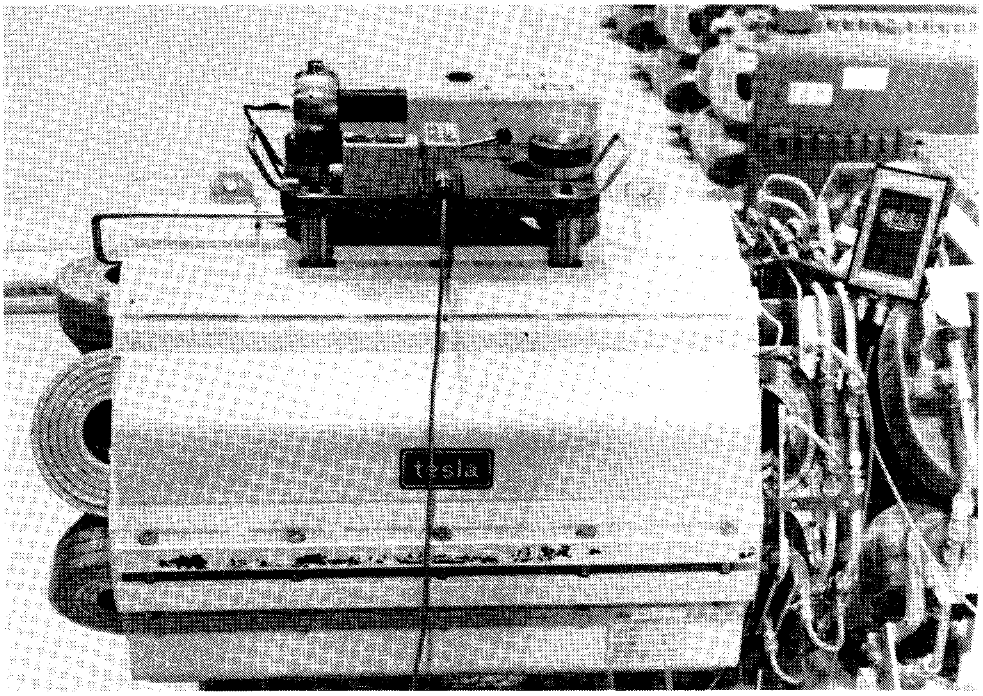

Fig. 7. Sextupole alignment device

Pre-alignment of Dipole Pairs

The 12 m long dipole pairs were aligned and fitted with excitation bars and vacuum chamber before the transport to the LEP tunnel. The alignment method is illustrated in figure 8.

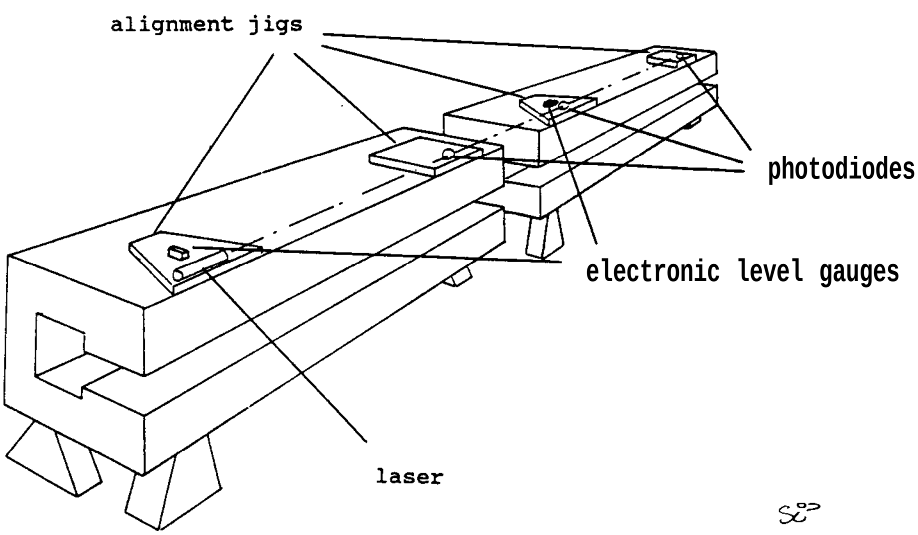

Fig. 8. Pre-alignment of dipole pairs

The two dipole cores were placed in the horizontal plane according to the results of the geometry measurements of the individual magnet cores. The reference axis was defined by an expanded laser beam and a mobile photodiode assembly, which in turn was placed in the relevant reference sockets. In order to improve the measurement accuracy, both laser and photodiode were shielded by two 6 meter long tubes covering the total measurement length. The reference plane was defined by electronic level gauges. The total length of the pair was adjusted at the same time. The measurement equipment was connected to a small computer which displayed the necessary instructions for the whole alignment operation. The six alignment jacks were operated manually. An accuracy of ±0.1 mm was obtained for the vertical and transverse alignment within a range of ±3 mm. The obtained angular precision was ±0.03 mrad. After assembly, the dipole pairs were clamped in special frames and transported into the LEP tunnel.

Dipole Installation in the LEP Tunnel

The dipole pairs were installed and aligned in the LEP tunnel using the already installed and aligned quadrupole magnets as reference monuments. Two expanded laser beams defined the alignment reference over a distance of about 40 m as shown in figure 9. Two simple analog monitors were used for the initial positioning of the dipole pairs which were installed in turn. Figure 10 illustrates the positioning of the central dipole pair.

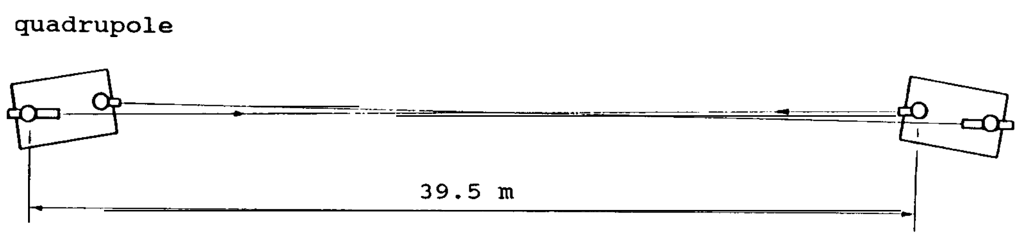

Fig. 9. Alignment reference in the LEP tunnel

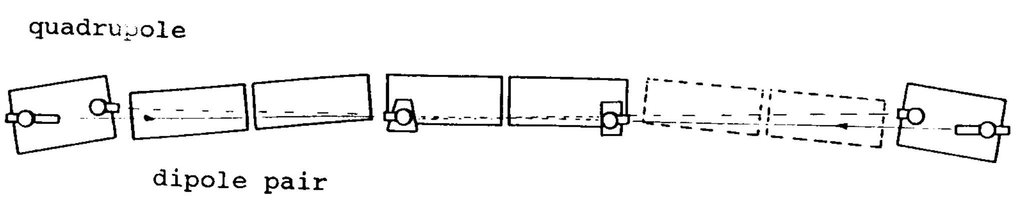

Fig. 10. Dipole alignment

During the final alignment of the dipole cores, two digital displacement monitors were connected to the mobile computer used by the LEP Survey Group. The original data from the dipole geometry measurements was combined with the machine geometry data for this alignment. An accuracy of ±0.15 mm with respect to the reference was achieved for the vertical and transverse alignment within a range of ±4 mm. The obtained angular precision was ±0.03 mrad.

Conclusion

In addition to considerable savings of manpower, the advantages of the applied methods can be summarized in two specific points: Firstly, the automation of measurement and alignment procedures significantly improved their quality compared to that of traditional methods. An important factor was the possibility of including filtering and averaging of observed signals, either at the level of analog signal treatment or in the data acquisition process. Secondly, the automatic transmission and handling of measurement and alignment parameters entirely excluded the usual risks of operational errors during routine work.

Acknowledgements

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References

[1] L. Resegotti, Journal de Physique, Cl-1984, 233
[2] M. Hublin, paper presented at this workshop
[3] J. Billan, J. P. Gourber, K. N. Henrichsen, Journal de Physique, C1-1984, 953
[4] O. Pagano, P. Rohmig, L. Walckiers, C. Wyss, Journal de Physique, C1-1984, 949