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An energy spectrometer has been installed in the LEP accelerator to determine the beam energy with a relative accuracy of 10^{-4}. A precisely calibrated bending magnet is flanked by 6 beam position monitors (BPM). The beam energy is determined by measuring the deflection angle of the LEP beams and the integrated bending field. An accuracy of less than 10^{-6} m on the beam position is necessary to reach the desired accuracy on the LEP beam energy. Capacitive wire positioning sensors are used to determine the relative mounting stability of each BPM and to calibrate the beam position monitors. Two-dimensional sensors are attached to each side of every BPM support and provide a position measurement with respect to two stretched wires mounted on either side of the LEP beam pipe. The fixing points of each wire are monitored by additional reference sensors.

The position information is digitised via a multiplexed high accuracy digital voltmeter and read out continuously during LEP operations. Wire position sensor accuracy was tested in the laboratory with a laser interferometer, while relative accuracy tests are performed in the LEP environment. Systematic effects of synchrotron radiation on the wire position sensor performance were studied.

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Determination of the Accuracy of Wire Position Sensors

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Abstract

An energy spectrometer has been installed in the LEP accelerator to determine the beam energy with a relative accuracy of 10^{-4}. A precisely calibrated bending magnet is flanked by 6 beam position monitors (BPM). The beam energy is determined by measuring the deflection angle of the LEP beams and the integrated bending field. An accuracy of less than 1μm on the beam position is necessary to reach the desired accuracy on the LEP beam energy. Capacitive wire positioning sensors are used to determine the relative mounting stability of each BPM and to calibrate the beam position monitors. Two-dimensional sensors are attached to each side of every BPM support and provide a position measurement with respect to two stretched wires mounted on either side of the LEP beam pipe. The fixing points of each wire are monitored by additional reference sensors.
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1 SETUP OF THE SPECTROMETER

In Fig. 1 the setup of the spectrometer is sketched as it was installed for the 1999 LEP run. The dipole magnet lies in the centre of the two arms and is equipped with six beam position monitors (BPM).
Fig. 2 shows the setup of one BPM station with the BPM

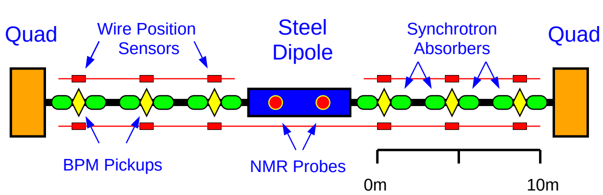

Figure 1: Layout of the Spectrometer

in the centre flanked by the two copper synchrotron light absorbers. The wire, its stretching weight and the position sensors attached to the BPM can be seen. The BPMs are mounted on individual limestone blocks to reduce vibrations. For avoiding unnoticed movements of the whole BPM blocks with respect to each other a system of wires with wire position sensors (WPS) attached to both sides of the BPMs was installed. The sensors detect movements of

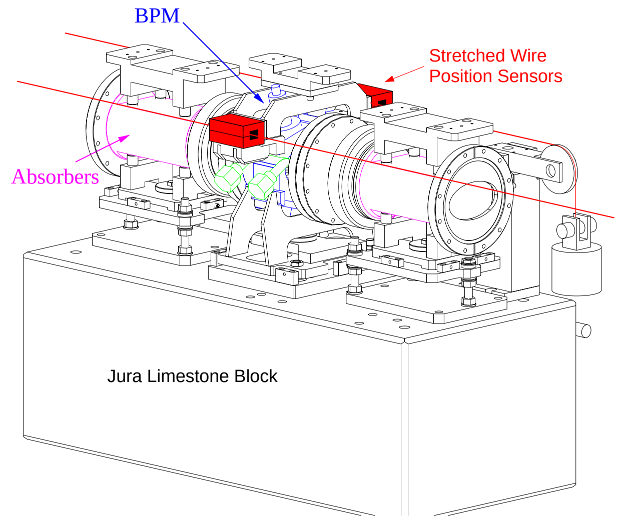

Figure 2: One of the BPM stations with its wire system.

the BPMs with respect to the wire and thus with respect to each other. The position of the wire mounting is measured by WPS which are attached to the supporting limestone block by a temperature regulated copper tube. The wire position system uses three wires, which consist of carbon surrounded by kevlar. The wires have a diameter of 0.4 mm. The first extends over the whole spectrometer and is intended to observe movements of the arms of the spectrometer with respect to each other. Two further wires are installed, one on each arm for redundancy and also to distinguish between shifts and expansions of the BPM supports.

2 PRINCIPLE OF OPERATION

The principle of the position measurement is based on sensing the capacitance between opposite planar electrodes of the sensor and the wire. This is achieved by measuring the current from the electrodes while an alternating voltage is applied to them. The voltage has an amplitude of 10 V peak to peak relative to the grounded conducting wire and a frequency of 4 kHz. The capacitance is, to the first order, inversely proportional to the distance in this arrangement. To obtain the wire position, the analogue signals from opposite plates are subtracted. To ensure that the electrodes measure only the capacitance with respect to the wire, they are surrounded by guard rings, which are supplied by an oscillator in phase with the potential on the electrodes. Since the potential difference between guard ring and electrode is zero, the field lines do not bend towards the grounded frame of the sensor head.

3 MEASUREMENTS

A basic test to check the behaviour of the sensors is to change the set point of the water temperature regulation system for the BPMs. A temperature increase ΔT leads to an expansion of the BPMs Δl, which is measured by the wire position system. This test was performed on several occasions for all BPMs. The expansion of the BPMs determined from the WPS signals can be compared with the expansion coefficient of aluminium α, from which the BPMs are made :

$$\Delta l = l\, \Delta T\, \alpha\, . \tag{1}$$

Fig. 3 shows the results of such an experiment; the top plot shows the introduced temperature change $\Delta T = 10^o$C, the lower the resulting expansion. Taking into account the distance between the wires $\Delta l = 30$ cm and the expansion coefficient $\alpha = 2.4 \times 10^{-5}$ 1/K this should result in an expansion of 69 μm, which agrees with the measurement.
Fig. 4 shows the movements of one BPM during an energy calibration measured by the WPS. The setup enables us to access four modes of motion: horizontal and vertical shifts, expansion and tilt of the BPMs.

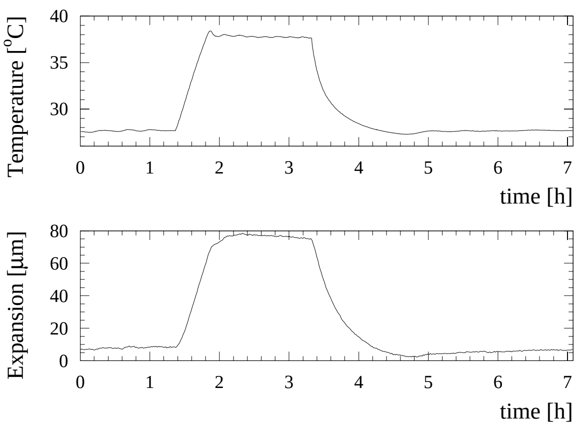

Figure 3: Top: Temperature of the BPMs against time, Bottom: Expansion of the BPM measured by the WPS against time.

4 RESOLUTION AND STABILITY OF THE WIRE POSITION SENSORS

An upper limit of the resolution of the wire position system can be determined by the differences between successive readings of the WPS. If the wire does not move in such a 12 s period, this difference provides the resolution. The distribution of the difference between successive readings was found to be Gaussian (see Fig. 5, left); such Gaussians were plotted for all 18 WPS and the mean value of their RMSs was found to be (153 ± 11) nm (see Fig. 5, right). The resolution of all sensors is better than the accuracy required. To determine the absolute accuracy of one WPS,

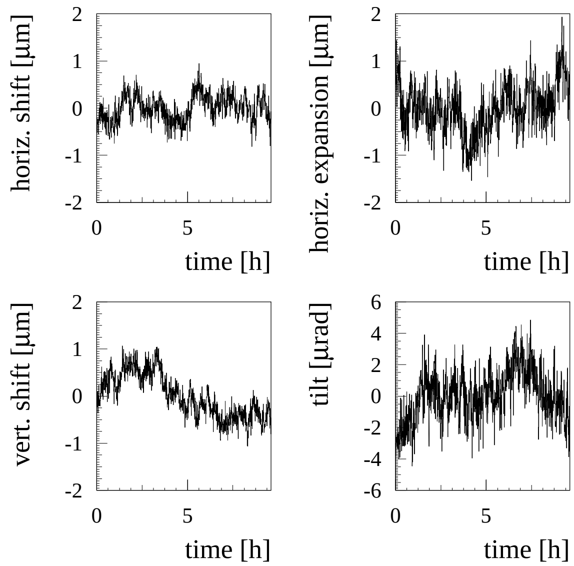

Figure 4: Horizontal shift (left top), horizontal expansion (right top), vertical shift (left bottom) and tilt (right bottom) of the BPM measured by the wire system.

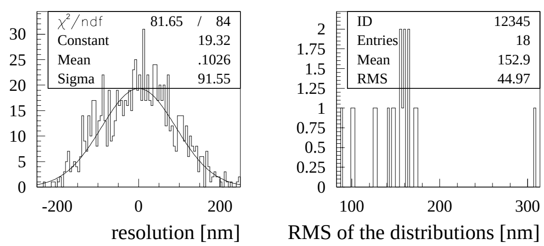

Figure 5: Left: Distribution of the difference between successive readings of one WPS over 17 h. Right: The standard deviation of these distributions for all 18 Sensors.

a test stand was constructed to move the sensor head with respect to a fixed wire employing stepping motors. The measurement of the WPS is compared with that of the displacement measuring interferometer [3], which determines displacements of the WPS.
The resolution of the laser interferometer was estimated by calculating the difference between successive readings and was found to be of the order of 20 nm.
The gain of the WPS was estimated as follows: The sensor was shifted such that the wire was moved in 100 steps within the centre ($\pm$ 0.5 mm) of the aperture of the sensor. The gain results from the slope of the linear fit to the correlation between the WPS reading and the position measurement of the interferometer. This procedure took approximately 20 min. To test the stability of the response characteristics this gain estimation was repeated 99 times. The results are plotted in Fig. 6. A relative stability of the

gains of 5×10^{-4} was found.

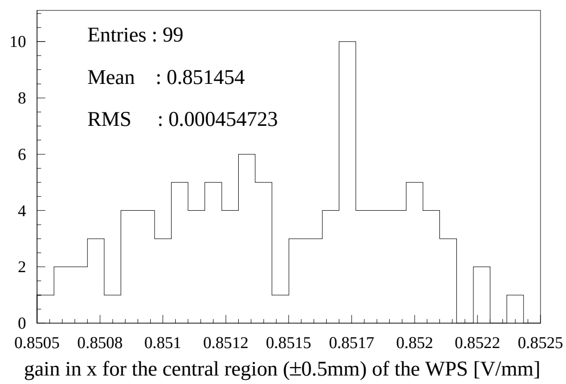

Figure 6: Stability of the WPS response.

5 SYNCHROTRON LIGHT AFFECTS THE MEASUREMENT

The LEP filling pattern is clearly seen in the raw signal of the WPS: During a beam dump and the particle acceleration, there are fast position changes in the signal (so-called "jumps") with a height of approximately $4\,\mu$m.
During particle acceleration the energy deposition from the beams due to synchrotron light increases from almost 0 to about 700 W/m for a beam current of 10 mA. The particle acceleration and the beam dump correspond to the appearance and disappearance of synchrotron light. The high radiation affects the sensors significantly as is shown in [2] and [1]. The effect was suppressed by shielding the sensor heads with about 2 cm of lead. The unpleasant effect disappeared, after the sensor heads were shielded with about 2 cm of lead.
To test the effect of the air in the sensor, another type of sensor was brought into the LEP tunnel. This sensor measures a capacitance, in a similar way as the wire sensors, but allows evacuation of the sensor head. With this sensor it is possible to measure the capacitance between two fixed plates, with and without air between them. The jumps occurring during the beam dump are reduced by a factor of 7 when the sensor is put under vacuum, as can be seen in Fig. 7, in which the signal of the sensor is plotted versus time. The bars in the top part of the plot indicate when LEP was operating and the arrows above the plot indicate when the sensor was evacuated.
The size of the signal while the sensor is under vacuum is similar to the situation where LEP is running and there is air between the electrodes. Changes in the signal can only be explained by variations of the dielectric properties of the medium between the plates. The synchrotron light coming from the beams ionises the air surrounding and within the sensor head. This leads to the creation of free charges. Furthermore the N_2 and O_2 molecules are split [4]. This results in a decrease of the dielectric constant ϵ_r ($= 1 + \delta, \delta = 5.94\,10^{-4}$ for dry air), as observed in Fig. 7. While the sensor is under vacuum or LEP is running, delta is zero or close to zero respectively.

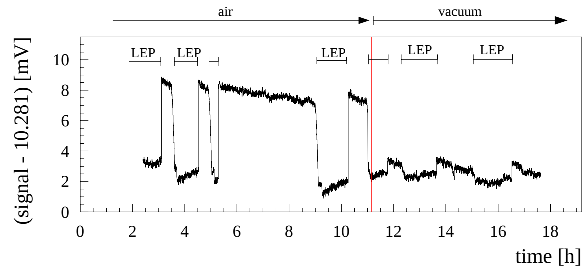

Figure 7: The signal from the sensor (inversely proportional to the distance), after offset subtraction, against time.

6 SUMMARY AND CONCLUSIONS

The performance of the wire position system was studied. A resolution of less than 300 μm and a relative stability of 5×10^{-5} was found. The disturbing effect of high radiation on the measurement was inhibited by shielding the sensor heads with lead.

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