Wire Scanners at LEP

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Abstract Two sets of wire scanners, each for measuring the horizontal and vertical profile, are installed in LEP in a straight section where the dispersion in both planes is zero. A carbon fibre with a diameter of 36 μm moves through the beam with a speed of about 0.5 m/s. The Bremsstrahlung photons generated by the passage of the wire through the beam are detected in scintillators located 80 m downstream. These detectors are shielded against synchrotron radiation and allow a measurement of the beam profiles which is practically background free and has a resolution of better than 10 μm. We present the design, the results and discuss some limitations of the instrument. During the first months of LEP operation, the fibres were destructed occasionally. The various causes, tests and remedies are discussed. At injection energy a significant blow-up of the beam results from the wire scan and has to be taken into account for the estimation of the genuine emittance. A modellisation of this blow-up is proposed, wherein the effect is renormalized on the actual measured data. This provides an effective data treatment to obtain the unperturbed beam size.

1 Mechanics and Motor Control

The LEP wirescanner is based on a linear movement of a 36 μm carbon fibre through the beam at a speed of up to 1 m/s [2]. The mechanics of the wire scanner is shown in fig. 1 [1].

The carbon fibre is mounted on a fork with a gap of 55 mm. The fork holding the fibre is firstly accelerated, then kept at constant speed during the traversal of the fibre through the beam, and finally decelerated to the end of the 128 mm long stroke. The speed as a function of the position is programmable. An amplifier (with a maximum power of 1000 W) generates the signal for the motor. A feedback ensures that the scanner moves as requested (fig. 2).

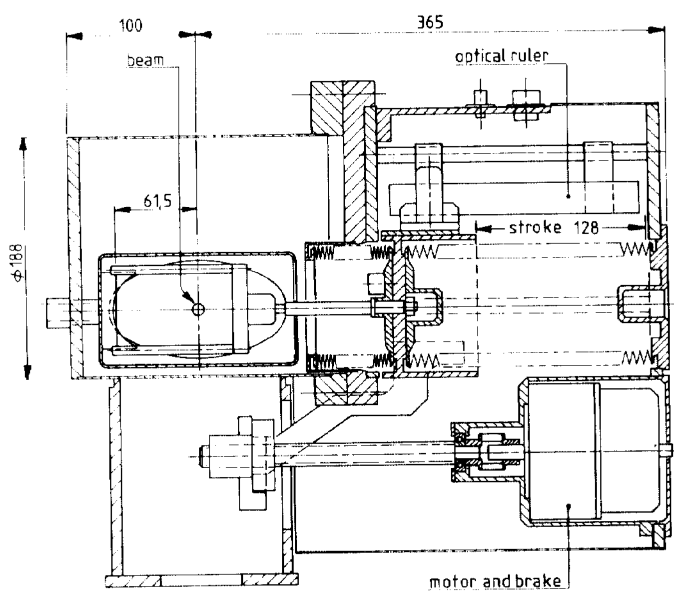

Figure 1: Wire Scanner Mechanics

The position of the fibre is measured with a high precision transducer [3]. A metal rod with reflecting rulings every 20 μm is scanned with the help of a light emitting diode and a light detector. As the rod moves the detector counts light pulses giving a measurement of the instantaneous position with a resolution of 4 μm. A reference mark is deposited onto the metal rod which allows the absolute spatial position to be determined. The ruler allows a maximum speed of 1 m/s. The wire mechanism is fixed to a vacuum tank designed for minimum beam induced wakefield losses.

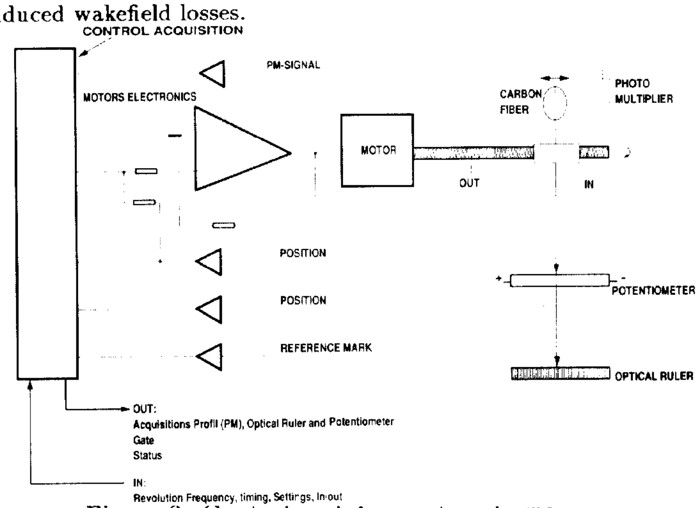

Figure 2: Control and Acquisition Logic

2 Detector and Acquisition System

The local density of the electrons traversing the fibre is detected by measuring the secondary particles produced by the interaction of the beam particles with the carbon fibre. For leptons the dominant interaction process is the emission of bremsstrahlung photons into a cone with an opening angle of about $1/\gamma$ with an energy spectrum up to the beam energy. The number of photons generated by one passage of the bunch through the fibre above an energy threshhold of 10 % of the beam energy is in the order of 10^5 to 10^6 [4] [5].

The scanners are installed in a straight section [6] (see fig. 3). For the detection of the photons the vacuum chamber and some of the magnets were modified: in the vacuum chamber a 50×20 mm^2, 2 mm thick aluminium window was foreseen and the magnets in that region have a gap to allow for the passage of the photons. The photon burst travels 80 m, traverses the window and is detected by a scintillator and a photomultiplier which measures the total energy of the photon burst. A lead shielding of 25 mm prohibits synchrotron radiation to enter the scintillator. The signals from the photomultiplier are practically noiseless (the noise is less than 10^{-3} of the signal). With this detector only bremsstrahlung photons generated by either electrons or positrons can be measured.

To measure with a single scan the emittances of both beams a second scintillator is installed close to the vacuum chamber

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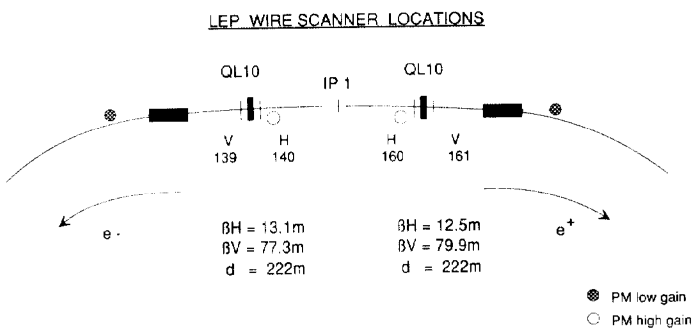

Figure 3: Wire Scanners Locations

towards the inside of the ring about 3 m downstream. The scintillator detects secondary particles with a much smaller signal and therefore high gain photomultipliers are used. The scintillator is sensitive to synchrotron radiation. The intensity of synchrotron radiation is independent of the fibre position and generates an offset in the profiles which becomes visible with LEP operating at high energy, e.g. 46 GeV.

The signals from the individual bunches are transmitted over a 300 m long cable and digitized in the electronics (fig. 2). After a scan the memory in the VME crate housing the electronics contains the digitized profiles from 4 electron and 4 positron bunches (LEP operates with 4 bunches per beam separated by 22 μs). In the local data preprocessing the software searches and finds the profiles within the memory, fits a Gaussian distribution and sends the results from the fit as well as the raw data to the operator consoles. The result of all scans are saved in a catalog and can be retrieved later.

3 Operation and Results

Since the start of LEP operation some thousand scans were done. The main use of the wire scanners is for the measurement and optimization of the vertical beam size, mainly at an energy of around 46 GeV (LEP was operating most of its time around this energy which corresponds to the enery of the Z_0).

Whereas the horizontal beam size is relatively independent on the fine tuning of the machine, the vertical emittance changes with parameters like betatron tune, closed orbit deviation etc. During luminosity operation the vertical emittance varies between about 2 and 20 nm, mainly due to the blow up of the beams caused by beam-beam effects. The blow-up depends on the tuning of the machine. In fig. 4 the vertical beam profile is shown. The beam energy was 46 GeV, the emittance 3 nm, and the rms beam size is 0.49 mm.

Always one IN scan is followed by one OUT scan. If the measured beam sizes from both scans do not agree within certain limits, it can be assumed that either the beam is not stable or the scanner is not working correctly. The results of a scan are displayed to the operator as shown in Table I.

The smallest emittance observed at 46 GeV beam energy was 0.7 nm after an orbit correction in the vertical plane down to an rms value of 0.65 mm and a careful coupling compensation. This corresponds to a betatron coupling between the horizontal and the vertical plane of about 2 %. The current per bunch was about 0.2 mA. Discrepancies with results from other emittance measurements were observed [7]. The cause of these discrepancies is still unknown. A similar scanner installed in the SPS using the same data acquisition system and the same software measures within the errors the same emittance as other instruments.

TABLE I: Bunch currents, beam sizes and emittances.

LEP WS-Rul-Vertical OUT-45.50 GeV - 28/08/90 10.33.16
Energy:45.50 GeV   Beta:79.92 m   Velocity:-386mm/s

##	Len	mA	Amp	Mean /mm	Sigma /mm	Em /nm	err%
p1	133	0.21	1179	0.026+-0.005	0.602+-0.004	4.532	1.4
p2	133	0.21	1204	0.024+-0.004	0.610+-0.004	4.657	1.2
p3	136	0.20	1158	0.025+-0.004	0.596+-0.004	4.440	1.1
p4	132	0.20	1209	0.019+-0.004	0.610+-0.004	4.650	1.2
e1	150	0.20	885	0.095+-0.000	0.618+-0.000	4.775	2.1
e2	153	0.18	906	0.132+-0.000	0.631+-0.000	4.986	2.6
e3	135	0.17	933	0.124+-0.000	0.561+-0.000	3.943	2.6
e4	148	0.18	900	0.103+-0.000	0.613+-0.000	4.701	2.0

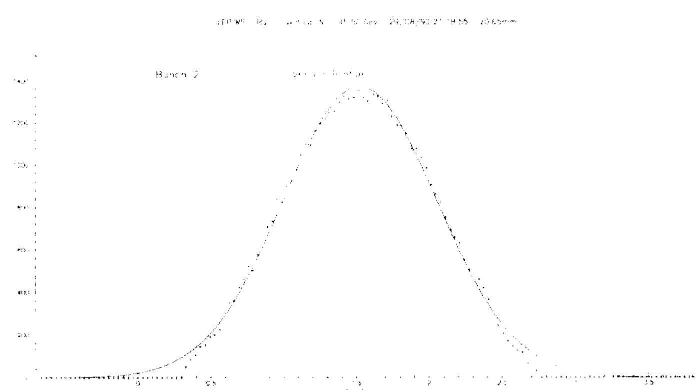

Figure 4: Scan in the vertical plane at 46 GeV beam energy

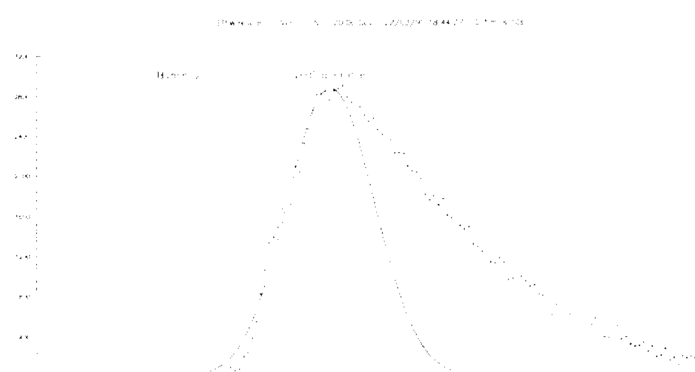

Figure 5: Scan in the vertical plane at 20 GeV beam energy

At high energy (46 GeV) most profiles have a regular shape and can be fitted by a Gaussian plus a constant offset. All the vertical scans done at a beam energy of 20 GeV show a large systematic asymmetry which can be explained by Coulomb scattering of the electrons at the Carbon atoms (see fig. 5). Due to scattering the emittance increases more and more as the fibre moves through the beam.

In the following we roughly estimate the emittance growth expected from a scan : the rms scatter angle is given by $\Theta = p_0/p \times \sqrt{(\frac{L}{L_r})}$ with p_0 = 14 MeV/c, p the beam momentum, L the effective thickness of the fibre and L_r the radiation length of the material, 0.275 m for carbon. The emittance increase for the Coulomb scattering becomes: $\Delta E = \beta \Theta^2/2$.

In Table II the estimated emittance increase for a scan at 20 GeV is compared with the design emittance and the measured emittance. Values of 2.5 % for the coupling and of 0.2 m/s for the speed of the fibre are assumed.

TABLE II: Blow-up by a scan at a beam energy of 20 GeV

Plane	β [m]	ΔE [nm]	E_m	E_t
H	12.4	0.31	15	6.7
V	78.4	2.0	1.5	0.27

β is the beta-function, E_m the measured emittance and E_t the theoretical emittance. At this fibre speed the emittance growth in the vertical plane is much larger than the emittance to be measured. As a consequence the speed of the fibre has been increased from initially 0.2 m/s to about 0.4 m/s which reduces the blow-up by a factor of two. To obtain a better estimation of the true emittance the measured profile is matched with a Gaussian fit at the less perturbed side in the data treatment. In general this method gives a too optimistic result and an improved data treatment is foreseen : It can be shown that only one parameter k is sufficient to fit the profiles in the case of blown up beams. This can be determined by the skewness $t = \mu_3/\mu_2^{3/2}$, where μ_i are the moments of the distribution. In Table 3 the different methods of fitting the profiles are compared.

TABLE III: Emittance estimation from three algorithms

Algorithm used in the analysis of vertical profile at 20 GeV	σ (μm	ϵ (nm)
$\sqrt{\mu_2}$	0.304	1.16
From Gaussian fit at one side	0.120	0.18
From skewness t	0.133	0.22

At 46 GeV beam energy no blow-up has been observed as expected : The emittance blow-up decreases with $1/\gamma^2$ and the emittance increases with γ (with γ the relativistic factor of the particles).

Some of the carbon fibres were destroyed during the 1990 LEP run. From previous experience with protons [2] it appeared unlikely that this was due to the beam energy deposition. Two of the four fibres were replaced by 50 μm beryllium fibres. After they were destroyed, the inspection showed clearly that the fibre was melted and not broken (see fig. 6). All fibres were not broken at the beam location. This indicated that electromagnetic heating of the whole fibre is probably the cause of the problem.

A resistance measurement for monitoring the temperature confirmed this hypothesis. A typical temperature evolution over a scan is shown in fig. 7. A the "OUT" position left, the temperature is about 400 degrees per mA circulating beam. As the fibre approaches to the beam, but before touching it, the temperature increases rapidly hinting to a coupling with the electromagnetic field of the bunch. The temperature increase is about 300 degrees for one mA beam current. After the beam traversal in the "IN" position, a new temperature level of 780 degrees is measured. The fibre is then brought back to its "OUT" position and the same phenomenon is observed. The two temperature peaks decrease with increasing fibre speed, whereas the steady levels stay unchanged. At a speed of 0.4 m/s no further fibre were broken.

One measure to reduce the temperature rise is to decrease the electromagnetic coupling. The parasitic loop enabling the current flow is suspected to be closed through ceramic pieces isolating the wire holders from the aluminium fork. These pieces were redone on two wire scanners to decrease the parasitic capacity. On the other two scanners the arms of the fork were entirely made of ceramics. Quantative measurements could only be made on the scanner with the modified isolation piece. They indicate a reduction of approximately 30 % of the temperature increase. The scanners with the complete ceramics arms seem to present a larger improvement. This has still to be confirmed.

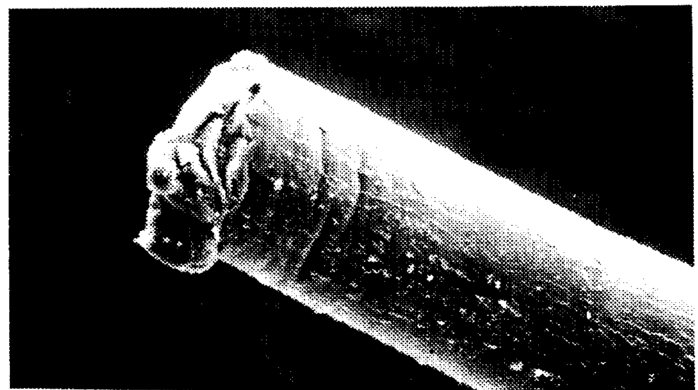

Figure 6: Destroyed Beryllium Fibre

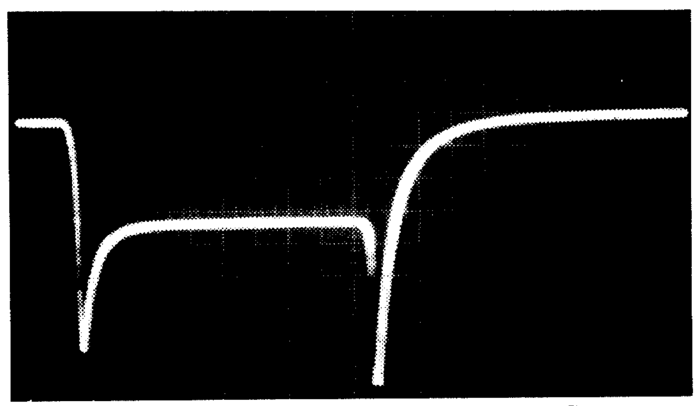

Figure 7: Fibre Temperature for IN-OUT Scan

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