Comparative Precision Emittance Measurements in LEP

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Abstract

Beam profiles can be measured with high precision in LEP with three types of instruments: wire scanners, synchrotron light telescopes and X-ray detectors. The knowledge of the optical functions is crucial for the calculation of the beam emittances and for the comparison of the instruments. The cross-calibration of the instruments has been carried out in dedicated Machine Development sessions in order to have clean beam conditions necessary for high precision measurements and a dedicated evaluation of the optics functions. From these sessions, limits for the precision of the emittance given by the instruments are deduced.

1. INTRODUCTION

Whereas a knowledge of the relative beam sizes is necessary for the tuning of LEP, the precise value of the emittance of the stored beams is needed for the analysis of the performance of LEP. The relative value of the beam sizes has been provided since the LEP start-up by the Synchrotron light telescopes BEUV [1]. The precision measurement of beam sizes is provided by the wire scanners BEWH and BEWV [2]. The wire scanners are however limited to total stored currents below 1.8mA by the heating of the wires. More recently, X-Ray vertical profile monitors [3], BEXE, have become available. The four wire scanners and the two X-Ray detectors are located close to IP1, whereas the four synchrotron light telescopes are positioned around IP8.

The emittance is deduced from the measured profiles through the formula:

$$E=\sigma^2_{beam}/\beta$$

in which the two quantities σ_{beam} and β have to be known with precision. First tests have shown that β cannot be taken from the optics files but has to be measured. The beam sizes have to be deduced from the measured data after correction for various effects specific to each detector. They also measure the beam sizes under different conditions.

The wire scanners measure successive slices of the individual bunches over roughly 50 revolutions. They are potentially the most precise instruments, the wire position being read by a high precision optical ruler. Passing through the beam, they blow it up, which can create profile dissymetries.

The synchrotron light telescopes have two detectors: the first, a CCD chip, integrates the beam spots from all bunches during a controlled integration time, variable from 2 to 32ms, typically set at 20ms. They are hence sensitive to beam instabilities over that time and to beam size differences from bunch to bunch. A second detector, comprised of a gated intensifier and wavelength converter can select individual bunches but suffers from non-linearities. The precision of the monitors is degraded by diffraction and depth of field.

The X-Ray detector is a non imaging device which measures a vertical slice of each bunch at the revolution frequency. It is the fastest detector, suffering only from image broadening induced by the natural divergence of the synchrotron radiation, the diffraction being negligible.

2. OPTICS FUNCTIONS MEASUREMENTS

The values of the betatron functions at the beam profile detectors have been measured using the 1000 turns facility of the Beam Orbit Measurement system (BOM), which records the betatron oscillations at the Beam Position Monitors (BPM) when the beam is excited transversely [4]. The phase advance between BPMs is obtained from these oscillations. The values of the betatron functions can be computed from these phases, except for β_H at the QS18 BEUV telescopes where there is a lack of BPMs. Phase advance accuracies of better than half a degree have been obtained which yield vertical and horizontal beta values with a precision of 2 %. Deviations of the betatron functions from the theoretical values of up to 11% have been found. They further increase by up to 8% when the emittance Wigglers are switched on.

Table 1. Theoretical (MAD) and measured β's for electrons with Wigglers (W) OFF and ON

	β_H			β_V		
	MAD	W off	W on	MAD	W off	W on
BEWH/V	57.7	59	59	64.4	65	60
BEXE	73.7	79	77	38.7	38	42
BEUV 12	33.3	37	39	79.0	71	68
BEUV 18	29			137	135	126

3. WIRE SCANNERS

The details of the wire scanner monitors installed in LEP are described in [2]. Both the small angle (S.A.) and the large angle (L.A.) detectors have been upgraded to offer a better acceptance. The main features of the data collected during the tests are summarised hereafter.

Between the IN and OUT directions of the horizontal scans, the precision on the r.m.s. value resulting from a gaussian fit of the beam distribution is usually better than ±2% for a given monitor. The agreement is the same between data provided by the S.A. and L.A. detectors.

The beam aspect ratio in LEP is such that at the monitor locations, the vertical beam dimension is always smaller than half the horizontal one. Blow-up affects the beam during a scan [2], and the reconstruction of the non-perturbed distribution is more difficult, especially for very low emittances.

The agreement between vertical IN and OUT scans is as before whereas S.A. and L.A. detectors may provide r.m.s. values with discrepancies of up to ±5%. Usually the signal provided by the S.A. detectors is cleaner.

During the 1993/94 winter shutdown, the vertical monitor located on the positron side had its mechanics improved so as to suppress spurious mechanical effects affecting the absolute beam position for the IN and OUT directions [2] and the analysis of the beam blow-up. As a result, the average beam positions resulting from the fit between the two directions are now in agreement to within less than 10 μm (Fig. 1).

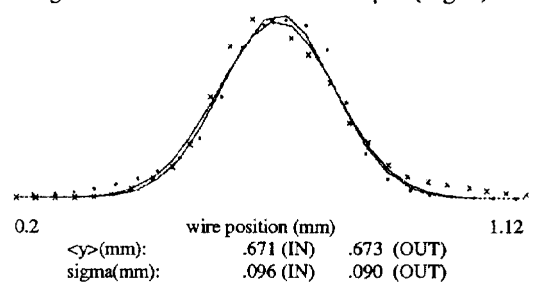

Fig. 1: IN(x) and OUT (o) vertical scans of an e^+ bunch taken with the new monitor and the S.A. detector

Depending on the beam conditions, the measured profiles may still present differences between the two directions. This can be seen in Fig. 2 which shows both distributions shifted with respect to each other by more than 50 μm.

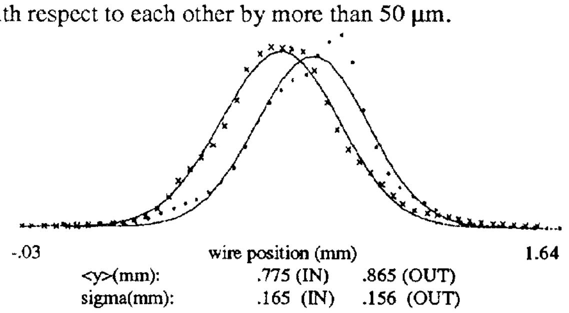

Fig. 2: IN (x) and OUT (o) vertical scans of an e^+ bunch taken with the S.A. detector in presence of a beam instability.

These observations can be explained by the presence of an instability on the beam resulting from coupling between the longitudinal and the transverse planes.

4. SYNCHROTRON LIGHT TELESCOPES

The telescopes have first to be aligned precisely with respect to the beam, which is achieved by monitoring the signal levels and beam sizes when moving a horizontal slit at the focal point of the focusing mirror. This alignment has not been stable over the past years while tunnelling activities were going on next to IP8, but has now been stable over the first part of 1994. The contribution of the depth of field is measured by varying the slit width and that of the diffraction by inserting wavelength filters and measuring the resulting beam sizes [1]. Finally the beam stability is measured by changing the integration time of the CCD and by measuring the changes in beam sizes. The resulting corrections to the measured emittances for normal beam optics and telescope operation are listed in Table 2. below. The precision of these contributions is critical for a precise determination of small beam emittances

Table 2: Diffraction and depth of field contributions to the emittances measured with the BEUV telescopes at 450nm.

	Diffraction	Depth of field	Total
δE_H	2.9±0.4 nm	0.2±0.02 nm	3.1±0.4 nm
δE_V	0.9±0.1 nm	0.1±0.01 nm	1.0±0.1 nm

Projections obtained from the two-dimensional profiles measured with the QS12 telescope are given in Fig. 3.

Fig. 3: Horizontal and vertical projections measured by the e^+ QS12 BEUV telescope.

5. X-RAY DETECTORS

These detectors measure a vertical slice of the hard synchrotron radiation emitted in a bending magnet [3]. They are placed after a beryllium window and an additional aluminium filter is introduced to absorb the lower energy radiation for better resolution. The detector has a pitch of 100μm and can be aligned horizontally and vertically for best precision. The acquisition software normalises the transfer function of the individual channels for equal sensitivity. The beam height is calculated from the measured size by subtracting from the calculated emittance a broadening contribution of 0.38nm

6. DATA PROCESSING

In order to compare the measured beam sizes given by the different instruments, the same method is used to extract this information from the recorded data. The chosen method is a three parameters (mean position, standard deviation and amplitude) iterative chi-squared minimisation algorithm for gaussian data. It requires a 'reasonable' initial estimate taken from an r.m.s calculation for the whole profile followed by a second iteration over a limited window. This method, applied on the data above a tenth of the maximum amplitude, is practically insensitive to noise and to non gaussian tails but assumes that the measured beam profiles are gaussian. To check the accuracy of the results, all the measured profiles and 2D images of the BEUV telescopes have been recorded together with the computed beam sizes to analyse off-line the quality of the results as well as an eventual tilt of the beam. No detrimental degradation of the results was noticed.

7. COMPARATIVE MEASUREMENTS

Two eight hour MD sessions were scheduled in late 1993 and in June 1994. In each session, one bunch of electrons and one bunch of positrons of approximately 300μA were stacked and accelerated to 45 GeV, without the Pretzel scheme.

During the first session, after the β function measurements and initial wire scanner and BEUV comparisons, the beams were collided and the Luminosity measured with the ALEPH detector. The resulting measured emittances are plotted as a function of time in Fig. 4.

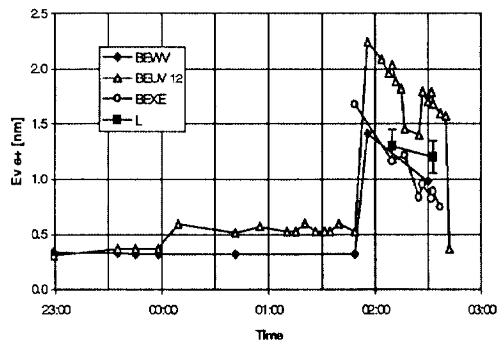

Fig 4: Positron beam emittance measurements from the three instruments: Wire scanner, BEUV and BEXE

The beams were kept separated until 1:45. Until 00:00, the emittances from wire scanners and BEUV were found equal within 0.1nm when using the measured β values. After 00:00, β* measurements took place, and the agreement between the two instruments decreased to 0.2nm. Once the beams were put in collision, the wire scanners and the X-ray monitors were in good agreement between themselves and with the emittance deduced from a vertical luminosity scan which gave a mean emittance of 1.3±0.15nm. The BEUV telescopes gave values which were offset from the other data except when the beams were again separated. It was concluded from these measurements, that the monitors were basically in agreement to better than 0.3nm, that the discrepancies were most probably coming from changes of β, and that new measurements should be done with separated beams and regular measurements of β. The β-beating due to collision can be as large as 100%, especially in the above experiment, when the beams were only colliding in one of the four interaction points, breaking the LEP symmetry conditions.

The results of the 1994 measurement are given in Fig. 5. After careful orbit corrections, very stable small emittance beams were obtained. After tuning of the monitors and β determination (Table 1), emittance measurements were performed with Wire scanners and BEUVs. Unfortunately only the e^+ BEXE was available for relative monitoring. The small emittance case gives an upper limit for the BEUV correction of 1.1nm, compatible with the calculated value of Table 2.

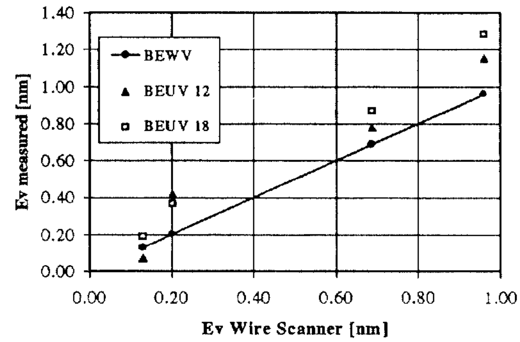

Fig. 5: Comparative emittance measurements with separated e^+ and e^- beams for Wire scanners and BEUV.

After these measurements, the bunches were blown-up by moving the beam close to a vertical synchro-betatron resonance. As the betatron tunes of the two bunches are different and as the resonance is narrow, the two resulting beam sizes are noticeably different. The bunches perform also vertical oscillations at a frequency around 700Hz, which were estimated by BEXE to have an amplitude around 100μm. These oscillations show up as profile irregularities on the Wire scans, see Fig. 2, and are integrated by the CCD detectors, resulting in apparent bigger beam sizes and emittance increases of approximately 0.13nm. Unfortunately, not enough time was left to investigate more precisely this phenomenon with the fast optoelectronic shutters of the BEUV. It can be seen in Fig. 5, that the measurements of the wire scanners and BEUV telescopes agree to better than 0.2nm.

8. CONCLUSION

Under these test conditions, the beam profile monitors are able to give the LEP vertical emittances to better than 0.2nm. For colliding beams, a precise knowledge of the β functions and further tests are needed to provide similar precisions.

Acknowledgements

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