RESULTS WITH LHC BEAM INSTRUMENTATION PROTOTYPES

C. Fischer, CERN, Geneva, Switzerland

Abstract

The beam instrumentation foreseen to provide the necessary diagnostics in the transfer lines and in the main rings of the LHC was conceived in the past years. The requirements expected from the different systems are now being closely analyzed and specified. In a few cases, tests of prototypes have already been performed, profiting from the facilities offered by existing machines.

The beam position measurement system had to be tackled first, as the pick-ups had to be integrated into the cryogenic part of the machine. Over the last two years other topics started to be experimentally investigated in order to define the best way to meet the requirements for the LHC era. Amongst these different studies are luminosity monitoring devices, various instruments for the measurement of the transverse beam distributions, the use of head-tail sampling to measure the beam chromaticity and quadrupole gradient modulation to derive the local amplitude of the lattice function.

The paper discusses the results of these tests.

1 BEAM POSITON MEASUREMENT

Along the two LHC rings about 1000 position monitors will be distributed, one per ring and per quadrupole, each with four electrodes to provide the beam excursion in both the horizontal and the vertical planes. The signal treatment is based on a Wide Band Time Normalizer as sketched in Figure 1. More details are provided in [1]. After normalization, the signal is transmitted via optical link outside the machine tunnel, where it is digitised. The Digital Acquisition Board, (DAB), treats then the data. Three prototypes of the normalizer card have been tested in the laboratory and some results on linearity and reproducibility are presented in Figures 2 and 3.

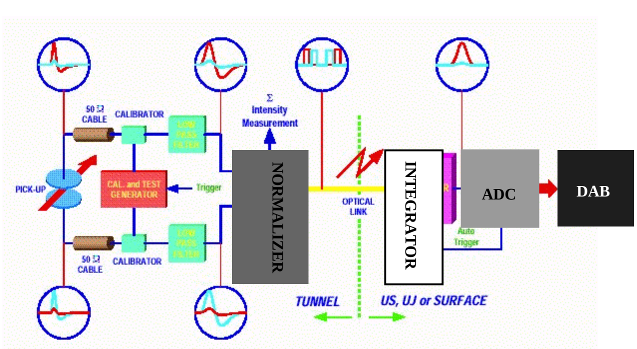

Figure 1: LHC BPM signal treatment block diagram.

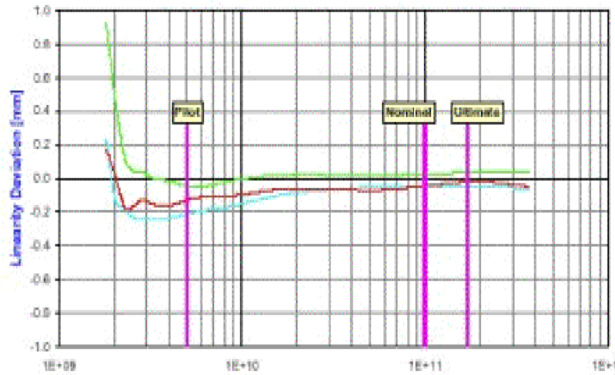

Figure 2: Normalizer card linearity vs bunch current at the LHC bunch frequency (40 MHz).

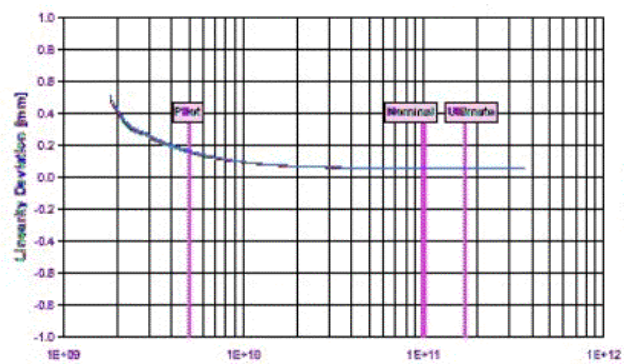

Figure 3: Signal rms deviation vs bunch current

Three bunch current levels are considered, first the pilot bunch intensity of 5. 10^9 protons which will be used during the machine setting-up, and then the nominal and an ultimate bunch current levels of respectively 1.1 10^{11} and 1.7 10^{11} protons. At the nominal bunch current and above, the linearity is good for the three samples, whereas for the pilot bunch current, deviations up to 200 µm are observed, (Figure 2). These results are quite satisfactory. The measurement rms noise is 50 µm at nominal current and remains below 200 µm for pilot bunches, (Figure 3).

A prototype position monitor equipped with the complete LHC control system was tested last year in the SPS. Comparison with the data from a standard SPS MOPOS) monitor is made in Figure 4. The agreement is quite good. The prototype monitor was also used during a test on “AC dipole “ excitation [2], and results are presented in Figure 5. It is possible to appreciate the difference between this type of maintained beam oscillations and the more classical excitation from a classical kick, which is very quickly damped.

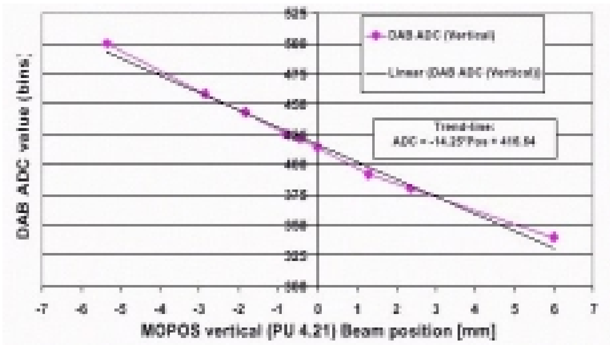

Figure 4: Comparison between LHC prototype BPM and standard MOPOS SPS monitor

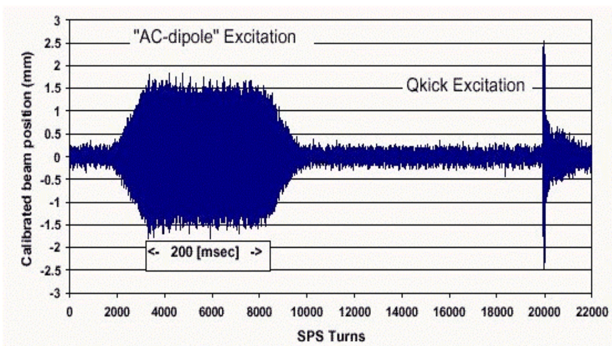

Figure 5: Detection of “AC Dipole” type excitation with the LHC prototype BPM in the SPS

2 Q’ MEASUREMENT BY HEAD-TAIL SAMPLING

The method, presented in [3], uses the fact that in presence of chromaticity, the head and the tail of a bunch respond with different phase to the same excitation. Recording the periodic phasing and de-phasing between the two signals allows to determine the chromaticity within the bunch. This is illustrated in Figure 6 with respectively in a) and b) the response of the bunch head and tail, in c) the phase difference and in d) the corresponding value of the measured chromaticity, (Q’=1.7). Figure 7 compares data from this method with the one from tune measurement at different radial positions got by changing the RF frequency. The factor of 2.2 found between the two methods is being investigated.

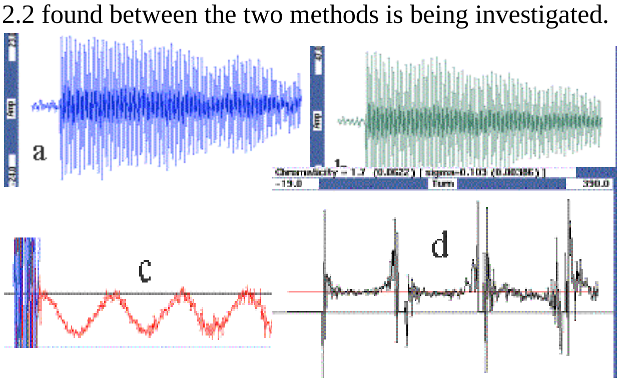

Figure 6: Q’ measurement by head-tail sampling.

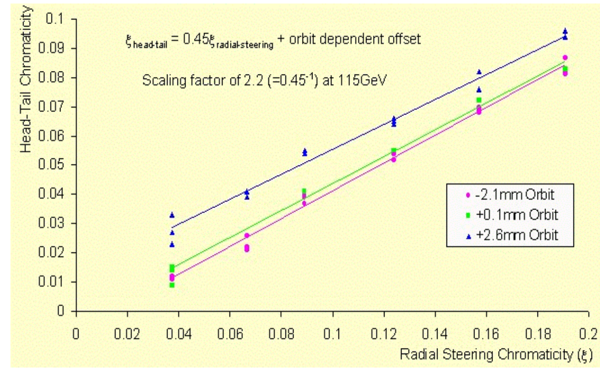

Figure7: Comparison of head-tail chromaticity measurements with radial displacement data.

The head-tail sampling method was also used to measure the chromaticity variation with radial beam position, Q”. This is illustrated in Figure 8.

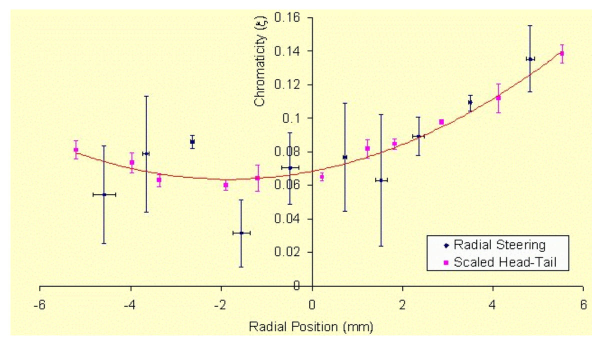

Figure 8: Chromaticity variation (Q”) across the SPS aperture measured by head-tail sampling ().

3 INDIVIDUAL BUNCH MEASUREMENT SYSTEM

This system measures the population of each individual bunch, at the nominal LHC bunch frequency of 40 MHz, by looking at the maxima, (peaks), and minima, (valleys), of the analog signal from a fast current transformer [4], as shown in Figure 9. When the timing is adjusted to properly trigger measurements within the right time slots, individual bunch currents are provided from the difference between consecutive top and valley values (Figure 10)

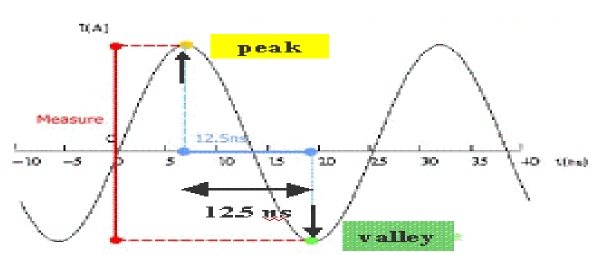

Figure 9: Principle of the Individual Bunch Measurement System sampling mode.

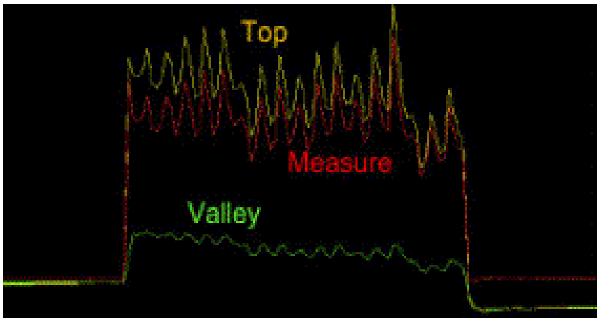

Figure 10: Current of a train of 72 bunches spaced by 25 ns, (LHC batch), on one turn, by difference between peak and valley signals.

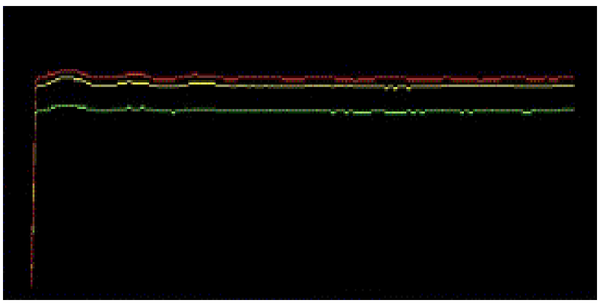

Figure 11: Turn by turn current evolution of 3 particular bunches over 20 ms, (850 turns).

Within a given bunch train, (batch), data relative to individual bunches are available for each passage and can be monitored, (Figure 11).

4 INTERACTION RATE DETECTORS

On each side of the LHC experimental insertions, the flux of secondary particles coming from the insertion point, directly related to the interaction rate, will be monitored with detectors installed within absorbers. Two types of detectors have been investigated for that purpose.

4.1 Ionization Chambers

Tests with ionization chambers were performed in the SPS experimental lines , using proton beams at 450 GeV, [5]. Some of the results are summarized in Figure 12.

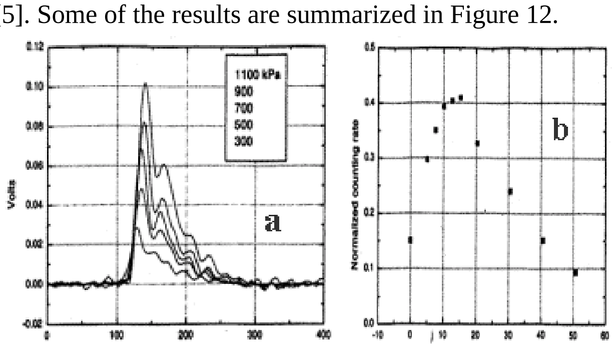

Figure 12: Ionization chamber data: a) signal response for different gas pressures; b) rate versus Fe absorber thickness.

Figure 12a exhibits the recorded pulse shape for various gas pressures. In all cases, the pulse length is of the order of 175 ns. This is significantly longer than the nominal bunch spacing of 25 ns, which, if confirmed, would not permit to sample at the bunch collision frequency of 40 MHz. The maximum shower rate is observed after an Fe absorber thickness of about 15 cm, (Figure 12b), which is in agreement with simulations.

4.2 CdTe Photoconductors

Polycrystalline CdTe photoconductors have also been tested [6]. First they were exposed to a picosecond laser source, with wavelength of 1060 nm, and their time response was studied. Figure 13.shows typical results.

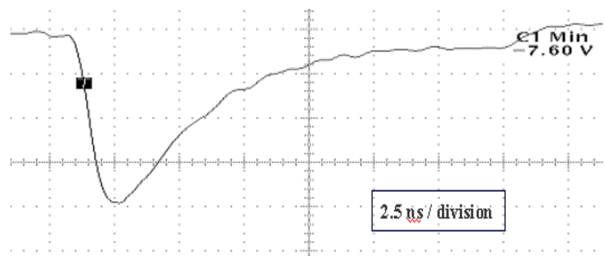

Figure 13: Time response of a CdTe photoconductor sample to a laser source at 1060 nm.

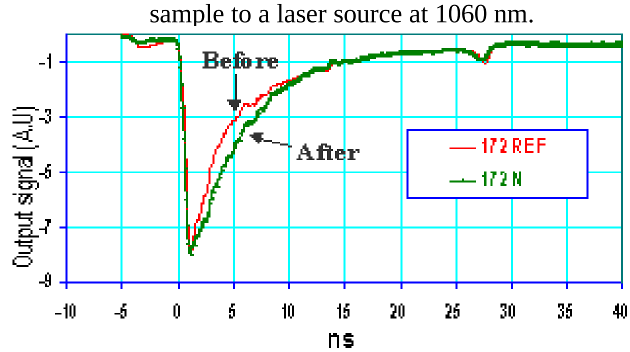

Figure 14: Time response before and after irradiation under 10^{15} n/cm^2.

The total pulse length of the photo-conductor response is about 10 ns, (Figure13), and fits very well the nominal 40 MHz LHC event rate. Samples have also be exposed in a reactor to a dose of 10^{15} neutrons /cm^2 without any significant change of sensitivity or speed, (Figure 14). The tests will be resumed up to about 10^{18} neutrons /cm^2, which is the dose the detectors will have to withstand during the LHC operation lifetime.

5 TRANSVERSE PROFILE MEASUREMENTS

5.1 Luminescence Profile Monitor

This monitor makes use of the light emitted by the gas molecules when they return to ground state after excitation by the beam. Promising data has been obtained in the SPS with Nitrogen, which has a good cross-section for this process and is easy to pump [7].

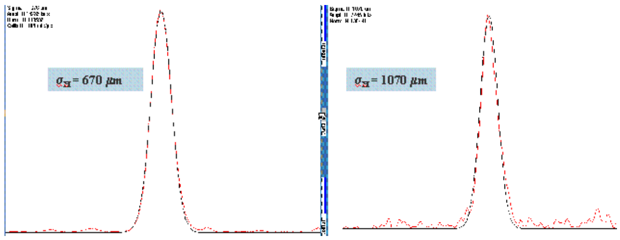

Figure 15: Profiles taken over 840 SPS turns under 6.10^{-7}hPa of N_2 pressure; left:2.10^{13} p; right:9.10^{8} Pb ions.

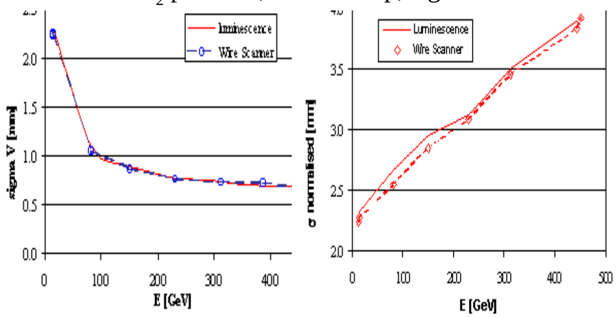

Figure 16: Vertical beam rms value variation recorded with the luminescence monitor and with the wire scanner.

In Figure 15, horizontal profiles acquired at 450 GeV on 840 SPS revolutions of, left, a proton beam and, right, a Pb ion beam, are represented. Data got with the luminescence monitor throughout an SPS acceleration cycle from 14 GeV to 450 GeV are compared in Figure 16 to corresponding ones made with the wire scanner, the usual reference. The agreement is good: both devices indicate an emittance blow-up when the rms beam dimension is normalised with the energy, (Figure 16, right).

5.2 *Optical Transition Radiation Screens*

Thin Titanium foils of a few micrometers can be left in beam, making it possible to record, with such monitors, beam profiles for several hundreds of consecutive turns. Hence injection matching studies can be performed, [8], as illustrated in Figure 17: oscillations of the beam size, resulting from imperfect tuning between the transfer line and the ring optics, occur in both H and V planes at injection. A constant blow-up is observed, (straight line slope), as the screen is left in the beam for the exercise.

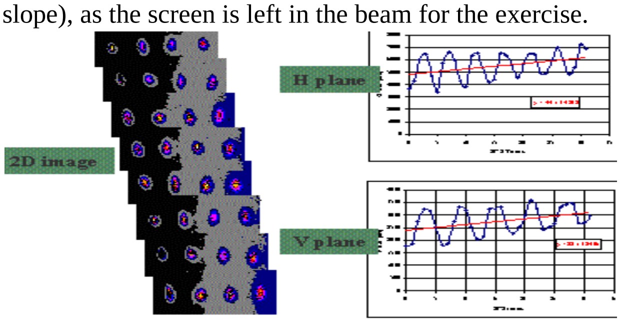

Figure 17: Oscillation of the horizontal and vertical rms beam size at injection into the SPS on the first 35 turns, and associated 2D image.

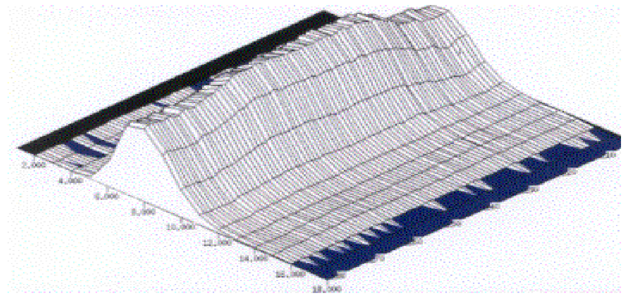

Figure 18: Train of 80 bunches, spaced by 25 ns, recorded on one passage in a SPS transfer line.

OTR screens are also used to sample at 40 MHz the individual bunch profiles belonging to a given LHC train, [9]. Such data is shown in Figure 18.

5.3 *Rest Gas Ionisation Profile Monitor*

A monitor analysing the signal from electrons produced due to the ionisation of the residual gas molecules by the beam is installed for tests in the SPS, [10]. Very good data has been recorded, as illustrated in Figure 19, following the evolution of a bunch of 6 10^{10} protons, (half the LHC nominal current), throughout an acceleration cycle. Horizontal profiles, integrated on 850 SPS revolutions, are well defined down to rms values of 700 µm. The residual pressure is around 10^{-8} hPa.

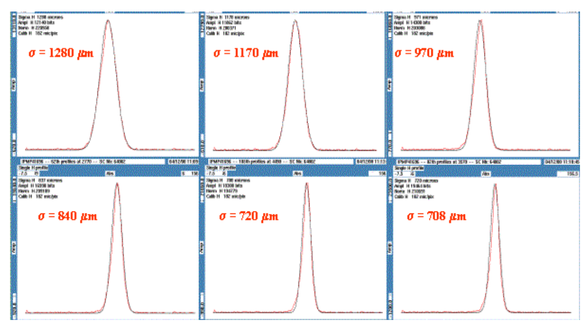

Figure 19: Horizontal dimension evolution of a bunch of 6 10^{10} protons during acceleration from 26 GeV to 120 GeV. The residual gas pressure is below 10^{-8} hPa

The residual gas monitor can also acquire turn by turn data, [10]. Such data are displayed in Figure 20 for a beam made of 40 bunches of 3.5 10^{10} protons each, monitored on 500 consecutive turns after injection into the SPS.

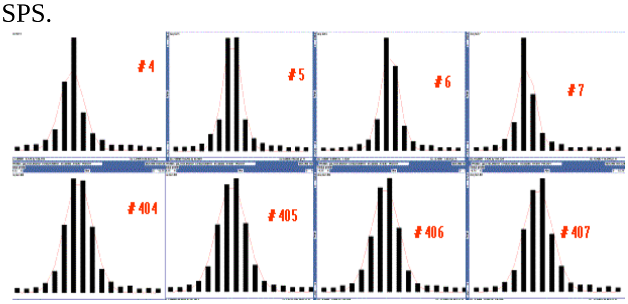

Figure 20: Turn by turn horizontal profiles of a beam of 1.4 10^{12} protons after injection into the SPS. The spatial resolution is 3mm /strip.

In this mode, the advantage, compared for example to an OTR screen, is that matching studies can be performed in a fully passive way for the beam, (no blow-up).

6 β FUNCTION MEASUREMENT BY K-MODULATION

The aim is to determine the average β function within a quadrupole by applying the smallest possible gradient variation, in order to not perturb the circulating beams, while getting a precision in the per cent range, [11]. This is achieved by modulating the magnet gradient, repeating numerous measurements to gain on statistics. The method was tested on a super-conducting quadrupole in LEP, using a square wave modulation, Figure 21.

Figure 21: Tune variation in LEP by square wave modulation of a SC quadrupole gradient at 0.25 Hz.

Results from this method are compared in Figure 22 to data got using the classical static method whereby gradient perturbations applied in several steps are left IN, and the associated tune variation recorded. <β> is given by the slope of the curve $\Delta q(\Delta k)$. The static method leads to $\langle\beta_V\rangle$ = 165 m, Figure 22 left, whereas the k-modulation result averaged over several measurements gives $\langle\beta_V\rangle$ = 162.9 m, Figure 22 right.

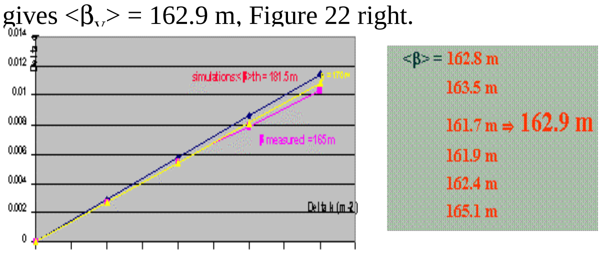

Figure 22: $\langle\beta_V\rangle$ measurement within a SC quadrupole: in LEP: left, static k – right, k-modulation results.

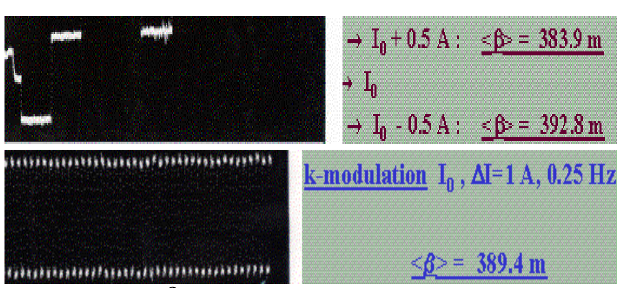

Figure 23: $\langle\beta_V\rangle$ measurement within a SC quadrupole in LEP: top, static k - bottom, k-modulation results.

Figure 23 gives another set of data acquired parasitically during a physics period, with two 103.4 GeV beams colliding in LEP. The value of $\langle\beta_V\rangle$ measured by k-modulation with a current I_0 in the SC quadrupole fits well between the values measured by the static method at currents of I_0+0.5 A and I_0-0.5 A. The method is very sensitive and does not perturb the beams.

7 CONCLUSION

Interesting results were recently obtained on prototype instruments developed for the LHC. However this is not an exhaustive review of all the beam instrumentation foreseen to operate the machine. Other fields are being investigated like synchrotron radiation monitors, beam loss detection, special pick-ups and shakers, and, in the CERN PS/BD group, DC beam current transformers.

ACKNOWLEDGMENTS

This paper reports on the work of many of my colleagues of the CERN-SL/BI group where most of the reported topics are handled, with the participation of external institutes. In particular, the collaboration with TRIUMF, LBNL, BNL, DESY, GSI, LYON1, the LETI is acknowledged as is the valuable help of colleagues from other groups at CERN to prepare and install the monitors, or to arrange their tests.

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