Advanced Beam Observation Methods for LEP

C. Bovet
CERN, SL Division, CH-1211 Geneva 23 (Switzerland)

Abstract

Some new tools used for LEP diagnostics are reviewed : fast analyses of coherent bunch oscillations provide detailed information on machine optics; synchrotron radiation is received on solid state detectors, on CCD's and on a streak camera; direct signal processors are now implemented in several instruments; transverse polarization has been measured and used for determination of LEP energy.

1. ANALYSIS OF COHERENT OSCILLATIONS OF PARTICLE BUNCHES[1]

The LEP beam position measuring system [2,3] has been conceived with large local memories capable of storing positions of all bunches for more than 1000 turns. This has recently permitted very useful studies of coherent oscillations. Once positions have been recorded at the 504 beam position monitors (BPM), together with a turn number distributed by a beam synchronous timing system [4], they can be processed locally by 40 microprocessors giving, for example, in one minute a harmonic analysis [5] of the trajectory of a bunch. This tool turns out to be particularly powerful to measure with great precision some machine optics properties like the phase advance between collision points, beta beating, dispersion, etc.

1.1. Study of coherent betatron oscillations [6]

For this measurement coherent betatron oscillations have been maintained with a constant amplitude of several millimeters at a frequency close to the natural tune, with the help of the tune-measurement shaker. The phases obtained from a harmonic analysis of 1024 turns have a resolution of 1^o and there is no systematic error in them because the BPM calibration does not matter, and because the precise timing of the measurement is given by the bunch itself.

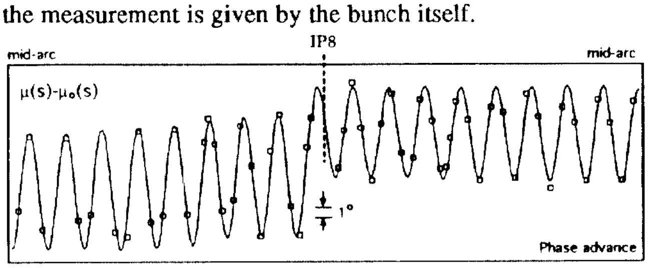


Figure 1. Difference between measured and computed horizontal betatron phases around IP8.

These phases, $\mu(s)$, compared with MAD, show a large modulation at a second harmonic of the betatron frequency, which can be fitted [7] with Eq. (1) as shown in figure 1 :

$$\mu(s) = \mu_o(s) + B(s) \sin[2\,\mu_o(s) + \theta(s)] + D(s). \quad (1)$$

By differentiating Eq. (1) $\beta_o(s)$ can be corrected as :

$$\beta(s) = \beta_o(s) \,/\, \{1 + 2B(s) \cos[2\,\mu_o(s) + \theta(s)]\}, \quad (2)$$

which provides the most accurate (1 %) measurement of beta ever achieved in a large machine.

Once the effect of beta beating has been subtracted, phase differences (measured minus MAD) can be plotted for the whole machine , see figure 2.

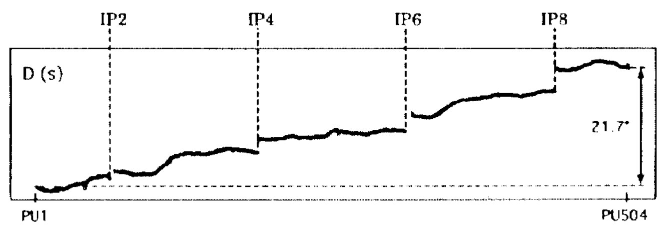


Figure 2. Betatron Phase differences, D(s) in Eq. (1), after elimination of the beta beating effect, for the whole LEP.

The step of 21.7^o comes from a difference of tune between the MAD file and the actual machine and is therefore not significant. The jumps at the four IP's are real discrepancies of about 5 % in the low beta insertions, and the ondulations in the rest of the machine could be explained by quadrupole gradient error of a few 10^{-4} at most.

1.2. Renormalization of the BPM scaling factors

BPM scaling factors are obtained with a calibration procedure using electronic test pulses to simulate beam signals. Although this calibration works well and is reproducible it is not correct, mainly because the circuits do not have the same response to test pulses (1 ns) and to beam signals (100 ps). Once we have determined the precise beta values at all BPM's through Eq. (2), the amplitudes, obtained with the harmonic analysis mentioned above, can be used to renormalize all BPM scaling factors.

In reality, things are a bit more complicated because the signals of the four electrostatic buttons are processed by two different electronic chains for the two diagonal differences (at 45^o of the x,y axes). If the beam is excited in x there is also a visible oscillation in y due to the calibration errors and to linear coupling in the machine. The latter effect has to be identified and subtracted for a renormalization to be applied to individual scaling factors of both electronic channels [8]. The accuracy of the scaling factors is not vital for closed orbit corrections where it only affects the convergence of the process and, probably, not much the final result ... but it enters to first order in any measurement of dispersion.

1.3. Analysis of coherent synchrotron oscillations

A very elegant method to perform dispersion measurement is by exciting coherent synchrotron oscillations with a phase modulation of the accelerating RF voltage. A harmonic analysis made of these oscillations at each BPM reveals a horizontal pattern which corresponds to the expected dispersion function (figure 3).

Figure 3. Horizontal dispersion obtained from harmonic analysis of coherent synchrotron oscillations.

The spurious vertical dispersion also detected can be scaled to the known horizontal dispersion measured simultaneously and has been determined for LEP with the best accuracy so far reached. But these measurements will only have their full power once the scaling factors of the BPM system have been properly renormalized during 1992.

2. USE OF SYNCHROTRON RADIATION

In LEP the electron energy is always higher than 20 GeV producing an abundant synchrotron radiation, even in the low field (0.025 to 0.060 T) of the main dipoles. Three different methods are used to exploite this light for beam monitoring:

i) synchrotron light (180 nm to 1100 nm) is extracted by means of beryllium mirrors and focussed onto CCD matrices without and with the help of a light intensifier-shutter (see para. 2.1);

ii) at two other places in the arc special recesses of the machine vacuum chamber have been made, equipped with thin beryllium windows, to allow the exposure of solid state detectors to hard X-rays produced in normal dipoles (see para. 2.2);

iii) in the middle of LSS1 where there are no dipolar fields available, two small wigglers have been installed to yield synchrotron light which can be extracted from the machine by means of beryllium mirrors located at IP1. The light is focussed with achromats made of SiO2 and CaF2 lenses and brought to an accessible underground laboratory through 17 meters of evacuated pipes; there the beam light is distributed simultaneously to different instruments by means of dichromatic mirrors : UV light to an image intensifier and visible light to a streak camera (see para. 2.3).

2.1. LEP tunnel telescopes [9]

Four telescopes are installed in LEP, two per particle type, of which two are at dispersion free locations. The light has its origin in the main dipole field. The source is imaged onto the detectors by means of catadioptric optics. For each telescope two detectors are used alternatively, one is a CCD matrix which is operated as a conventional TV camera with an integration time of 20 ms thus providing a continuous observation of beam cross-section.

The other detector is made up of a fast optoelectronic shutter, amplifier and wavelength shifter coupled to a CCD matrix. This detector enables to take an image at a unique bunch passage. But the TV repetition frequency of 50 Hz is by far not adequate to observe the bunch dynamic behaviour. A novel idea has been pioneered by R. Jung, which allows to reduce by a factor of 1000 the time interval between two successive image acquisitions. It works as follows.

The CCD chip consists of 110'000 light sensitive pixels, each 23 μm square, arranged in 288 rows of 384 columns. The CCD is of the frame transfer type meaning that there are two active areas on the chip, one area, *the image zone*, is used to acquire the new data whilst the second area, *the memory zone*, is used to read out the previously acquired data.

In normal TV mode the transfer between the two zones takes 0.16 ms and is operated every 20 ms. Now, if the beam image only occupies a fraction of the rows (see figure 4) it can be saved in the memory zone by a partial transfer and a second image can be acquired soon after (the transfer of 36 rows takes 25 μs). Figure 5 shows a typical example of data taken with these technics.

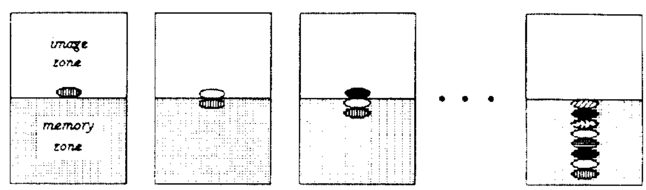


Figure 4. Illustration of the acquisition of 8 bunch images made at short time intervals on a CCD matrix.

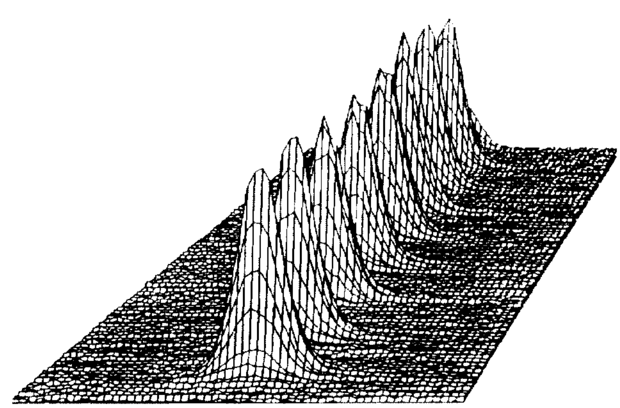


Figure 5. Plot of a bunch seen at eight successive turns.

2.2. Use of CdTe photoconductors

Small detectors can be placed in LEP to receive the direct synchrotron radiation produced in a normal machine dipole. The radiation passes through a beryllium window, 0.4 mm thick, and illuminates a surface of 1 mm x 20 mm.

CdTe obtained by metalorganic chemical vapour deposition, often used to detect infrared light, is normally produced in large crystals in order to raise their detection sensitivity. For fast response, on the contrary, polycrystalline layers have been produced and measured (σ = 6ps) [10], or by the other authors (σ = 480fs) [11].

Due to low dark current CdTe is capable to stand high polarization voltages (few kV) and can generate important electric pulses. It can also withstands nearly any amount of irradiation. As reported in [12] CdTe layers of 4 µm have been exposed to a dose of more than 10^{14} Sv in LEP during 1990 and their drop of sensitivity of 30 % is attributed only to the deposition on the circuit surface of a thin layer of sputtered aluminium. This anomaly will be avoided in a future production by means of an additional insulating coating.

2.2.1. Vertical beam emittance detector [13,12]

The direct observation of hard X-rays constitutes the simplest application of this material. Emittance is computed from the observed vertical profile of impinging X-rays. Although what is measured is the beam divergence augmented by the angular distribution of the photon emission, emittance can be safely determined [12] down to $\varepsilon \geq$ 0.5nm. If lower emittances occur with LEP in the future, a detector with a pitch of 50 µm will replace the present 100 µm one. Figure 6 illustrates the chip with 64 channels realised by D. LETI [14].

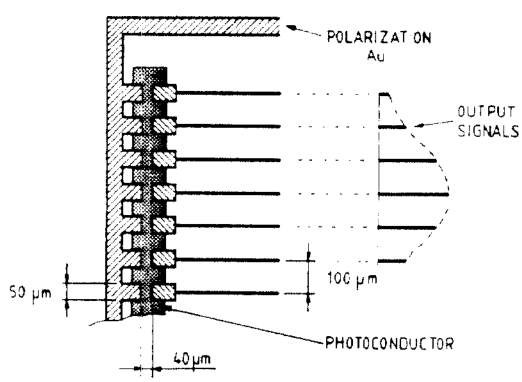


Figure 6. Circuit for vertical profile.

2.2.2. Bunch length measurement by aucorrelation [15]

Another more sophisticated device has been the outcome of a long industrial development venture between CERN and CEA in Grenoble [14].

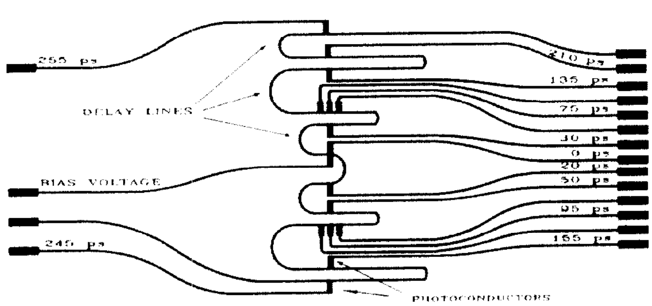


Figure 7. Autocorrelator circuit for longitudinal profile.

The aim of this detector is to monitor the autocorrelation of the longitudinal profile of LEP bunches by means of a micro-electronic circuit realized with embedded matched lines and using CdTe photoconductors. The circuit layout is shown in figure 7 and works as follows.

Photoconductors, P_i, are illuminated directly by the hard X-ray pulse. P_0, the only photoconductor polarized with a d.c. bias voltage, emits on the line an electric pulse which, in turn, polarizes the other photoconductors at delayed times. The charges collected on the output channels represent auto-correlation points corresponding to the known staggered delays.

For both circuits in figures 6 and 7, the analogue signals of all bunches up to 8 per beam are multiplexed for transmission to a common electronic crate near IP1. They are acquired sequentially by an ADC module made for reading the BPM system and stored in a parallel buffer memory for further digital processing.

2.3. Viewing bunches in three orthogonal directions

An industrially developed streak camera [16], equipped with two orthogonal deflections (fast and slow sweeps) has been installed in the IP1 optical laboratory. The slow sweep can be varied in order to spread 10 to 50 streaks on the same picture. Selected bunches are gated by pulsing the bias voltage of the photocathode.

Fast sweeps are triggered from RF signals transmitted through 3 km of optical fibres. The jitter in this triggering system is now less than 10 ps. When the fast sweep is set to 500 ps a best time resolution of 6 ps FWHM has been measured [17]. Since the readout is made with a CCD chip where the length of the streak is recorded by 288 pixels, there is enough resolution for stacking two images.

For instance the light from two counter rotating bunches e+ and e- crossing at IP1 can be brought together onto the streak camera, with an appropriate time lag to avoid image superposition. In this way the behaviour of both LEP beams can be recorded on the same picture.

The fast sweep being vertical, streaks represent projections of bunch density on a horizontal plane (top view). During 1991 a novel idea for bunch observation has been implemented by E. Rossa [18]. In front of the streak camera a beam splitter divides the photon bunch in two ways. On one of the paths the bunch traverses a Dove prism and is rotated by 90^{o} around the longitudinal axis. On the other path the bunch is delayed in order to be staggered in time at the entrance slit. Thus both top view (x,t) and side view (y,t) of the same bunch can be seen on each streak, as shown in figure 8.

As mentioned above, front view of the bunches (x,y) is also available in UV light in the optical laboratory and can be detected with a CCD chip programmed for multi-bunch acquisition as described in para. 2.1. Both streak and UV cameras are capable of storing independently a series of bunch images on phosphor screen (up to 16) taken at any time interval larger or equal to a revolution period. A MaxVideo20 system of Datacube will be used to acquire the data from both cameras at a speed of 25 Hz [19]. Data will be treated on line for background cleaning, CCD noise subtraction, persistent light correction, etc. ... and some parameters characteristic of bunch sizes, like σ_x, σ_y, σ_s will be computed on line, prior to the creation of comprehensive images with a resolution of 800x600 pixels produced in RGB standard. These images showing three views of each bunch (x,y), (x,t) and (y,t) will be transmitted to LEP control center.

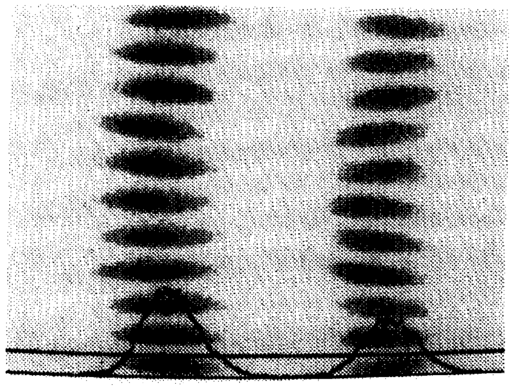


Figure 8. Double sweep streak camera picture showing top and side view of the same bunch observed for eleven turns: left : side view, right : top view, total sweep : 500 ps.

3. USE OF DIGITAL SIGNAL PROCESSORS

With the advent of yet faster processors more real time tasks, which used to be tackled with analogue electronics, can now be treated digitally. One of the most evident use of DSP's is for performing FFT's. Already in 1989 a fast acquisition system used at the SPS (BOSC [20]) was fitted with an AT&T DSP32C chip capable of executing a 1024 point FFT in 4 ms.

3.1. Luminometers

Sophisticated DSP's are implemented in the data acquisition system [21] for the eight LEP luminosity monitors. In this system a Motorola DSP 56001 chip is integrated in a VME module (DSP8150 [22]) which also contains a sequencer and a FIFO memory. The module is built to control ADC boards for which the sequencer organizes the I/O multiplexing. DSP and sequencer work in parallel and, at the lower trigger level, they can analyse two signals from a tungsten-silicon calorimeter, decide which type of event has been seen and increment the related counters in less than 11 us. A more detailed analysis can be started upon the type of recorded event. The data are then written in a buffer memory (dual port RAM) which can be accessed by a Motorola 68030 CPU controlling the VME crate. With 10 MIPS, this DSP can be operated very fast but must be programmed in assembler language and it only works with integers.

3.2. Tune-meter

Due to LEP long revolution time (89μs) the tune-meter has been conceived with a totally digital processing of the beam data on line [23]. Three different modes of operating the instrument are offered and the switch between different modes is enabled by the software :

i) FFT : single shot or continuous, ii) swept frequency : most accurate measurement, iii) Phase Locked Loop : used for tune history and tune loop.

At every revolution the following sequence has to be executed in real time : acquisition of beam position raw data (typically 5 to 10 words of 16-bit), computation of either tune and oscillation amplitudes or spectra and finally computation of the beam excitation and write operations to the beam shaker DAC's (typically one, maximum 4 data output cycles).

For the second generation of this instrument, presently under realization, DSP's of the type TMS320C30 capable of 30 Mflops have been chosen. They will be programmed in C-language and implemented as shown in figure 9, connected to a PC-AT which will handle the software development tools and in particular a "TRACE" facility, offered by the manufacturer, allowing to monitor and display any variable of the programmed algorithm while it is executed in real time. The on-line data acquisition and control uses the PHS-bus, a fast parallel bus of the DSP hardware manufacturer. This more powerful system will be able, for instance, to excite four bunches with correct phases in order to avoid the unwanted beam-beam π-mode which has been jumbling the PLL during 1991 run.

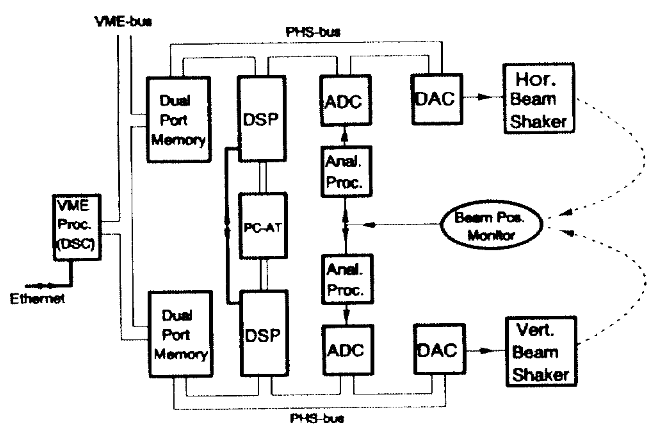


Figure 9. Block diagram of the new LEP tune-meter.

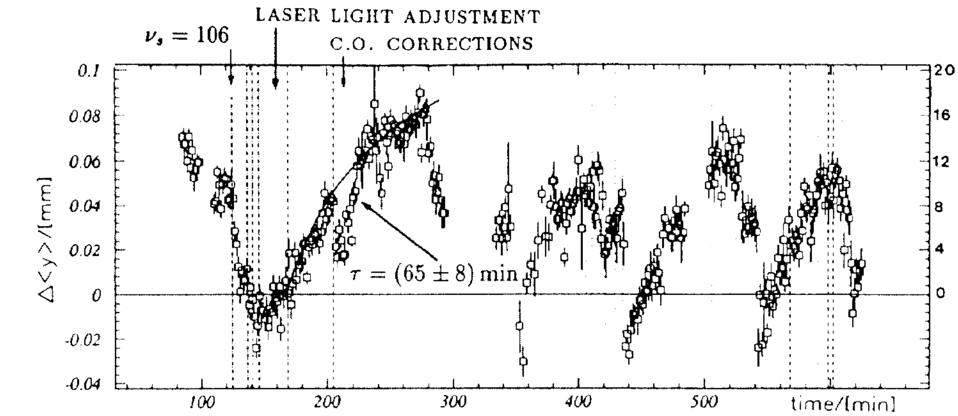
4. POLARIMETRY

Transverse beam polarization was observed in LEP in 1990 [24] with a Compton laser polarimeter [25]. Its commissioning and operation are described in Ref. [26] and the basic features are briefly recalled here.

Like the two other polarimeters presently in operation at TRISTAN [27] and HERA [28] the LEP polarimeter detects the asymmetry in the spin-dependent Compton scattering of circularly polarized laser light on a polarized electron beam. The 532 nm, 90 mJ light pulses generated at 30 Hz repetition rate from a frequency doubled Nd-YAG laser located in an optical laboratory about 15 m off the tunnel intercept the electron beam and produce about 1000 backscattered photons in an energy range 5 to 28 GeV. A tungsten calorimeter with silicon strip readout installed 247 m downstream the scattering point records the ~4 mm rms vertical profile of the recoil photons.

Figure 10. Polarization signal showing four consecutive phases:

1) initial polarization P≈10%;
2) depolarization by resonance;
3) polarization rise;
4) resonant depolarization with partial "spin flip".



The shift $\Delta\langle Y\rangle$ of the centre of gravity of the distribution under reversal of the photon helicity from $-\xi$ to $+\xi$ is proportional to the level of transverse polarization $P_\perp$ of the electron beam : $\Delta\langle Y\rangle = \kappa\, \xi\, P_\perp$, where κ = 500 ±30 µm is the analysing power of the polarimeter estimated by Monte-Carlo simulations.

After the first experimental observation of transverse polari-ation an intensive development programme has been scheduled for the 1991 LEP run. The polarimeter has undergone various modifications leading to a substantial improvement of the data acquisition system, hence to a higher event rate. Dedicated polarization studies have confirmed the 1990 results and levels up to about 16% have been measured as shown in Table 1.

Experiment	date 1991	y_{rms} mm	Polarization %
1	29.5	0.69	11
2	24.6	0.76	9
3	8.8	0.69	-
4	2.9	0.94	5
5	16.9	0.81	8
6	2.10	0.61	16
7	26.10	0.75	10
8	11.11	0.61	8

Table 1. Results from polarization runs in 1991 at nominal beam energy of 46.5 GeV (ν_S=105.5). The quality of the vertical closed orbit is mentioned in column 3.

The validity of the polarization signal was confirmed at each experiment using a depolarizing resonance at ν_S=106.

The polarimeter analysing power has also been obtained in a completely independent way through the effective polarization time τ obtained from a three-parameter fit (figure 10). Indeed the asymptotic polarization $P_\perp(t\rightarrow\infty) = 0.92\ \tau/\tau_p$, where τ_p is LEP natural polarization time at 46.5 GeV (τ_p = 304 min).

It is worth noting that the maximum *asymptotic* value P_∞ = (19.6±2.4)%, corresponding to the best *observed* polarization figure (16% in Table 1), was obtained without any correction of the depolarizing resonances.

During 1991 five experiments were carried out for the determination of LEP absolute energy by the resonant depolarization technique, reaching an accuracy of 1 MeV [29].

5. ACKNOWLEDGEMENTS

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