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INSTRUMENTATION AND DIAGNOSTICS USED IN LEP COMMISSIONING, WITH ACCENT ON THE LEP BEAM ORBIT MEASUREMENT SYSTEM

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ABSTRACT

The LEP machine is equipped with a very complete instrumentation [1,2] for beam position, intensity and profile, tune and optic parameters, interaction rate, from which a summary is first presented. Second, the largest instrument for beam orbit measurement is described in more depth.

The BOM System with its 504 Beam Position Monitors and 40 Processing Electronics Racks distributed along the 27 km of the LEP tunnel and linked by the Control System's Token Ring has been installed and pre-tested with simulated beam signals. The signal processing equipment must guarantee high reliability and precision despite of high γ -irradiation and of long cable transmission. In addition most of the electronics will not be accessible during operation. The analog signal processing is based on normalizers using phase modulation and on Flash ADC's. Local memories allow the recording of data at each bunch passage for more than 1000 revolutions. It is followed by digital signal processing in local VME crates equipped with 68000 μ P. The BOM system will be able to acquire data of up to 8 bunches from which injection trajectories, average orbits, integer and fractional part of Q, β function and post event analysis will be processed.

A first test with beam was successfully performed on a single station equipped for 12 monitors during the injection test of July 1988. It did validate the hardware and processing design. But complete results could only be reached in July 1989 when the proper triggering of all electronic stations could be adjusted on the circulating beam, via the Beam Synchronous Timing System. Most of the data analysis is done simultaneously in 40-microprocessors which communicate with a data Collector. Operational results are presented. The BOM System has been a key instrument for the success of LEP performance.

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3. ACKNOWLEDGEMENT

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1. SUMMARY OF LEP-BI MONITORS

1.1 INJECTION SPLIT FOILS

Four Split Foil monitors [3] are installed: one horizontal(BPFH)-vertical(BPFV) pair on each injection channel close to Interaction Point 1. They are made of two Ti strips of 7 μm thickness and with a gap of 40 μm . These position monitor present little interference with the injected beam and allow for many beam revolutions. Their sensitivity is about 30 pC per foil for a bunch of $8 \cdot 10^9$ particles. They have been used for injection tuning, mainly at LEP start-up while the BOM System was run-in and beam synchronised.

1.2 INJECTION SCREENS (with TV transmission)

The Luminescent Screens [3] are strongly perturbing position monitors, but they belong to the basic equipment of accelerators mainly for their start-up. They present the advantage to "see" the beam with its position, size and intensity. They are the most practical instrument to thread the beam for the first time along 28 km. They are made of Cr doped Al_2O_3 plates with a 2 mm thick Cu shield for synchrotron radiation protection. The screen picture is transmitted by a 45° stainless steel mirror and a CCD TV camera to video monitors in the control room. The 24 LS installed in LEP are:

- three successive LS after injection points
- two at each side of beam stoppers near QS10s
- two at each side of the safety stopper near Interaction Point 1

1.3. CURRENT TRANSFORMERS

Four assemblies (BCTR), on the same vacuum chamber with ceramic gap, comprising average current (DC), individual bunches (BB) and single turn (ST) current transformers [4,5], are installed in LEP: two at injection points and two at 163m from IP1.

The DC transformer is a parametric magnetic amplifier which present less noise than former Zero Flux CTs from which more than 500 are used for precision monitoring of magnets and klystrons current. The toroidal cores are made of wound amorphous Vitrovac 6025 tape with combined longitudinal and cross-field (perpendicular to the tape axis) annealing yielding an optimized BH curve with best dynamic properties and smaller magnetic domains for minimum Barkhausen noise. The Parametric CT covers a large dynamic range and the noise level is $< 0.2\mu\text{A}$ rms (1 s integration time). The DC transformer specification is a range of ± 10 mA with a resolution of $\pm 1\mu\text{A}$.

The BB and ST transformers are of the Integrating Current Transformer type. They are made with two toroidal cores also from Vitrovac 6025 tape. They are housed in a toroidal copper box with a gap forming a single turn winding. The integrating capacitor is formed of 36 capacitor chips of 100 pF forming a total capacity of 3800 pF. The charge induced I_b by each bunch is temporarily stored in this capacitor. The equivalent circuit is presented on Fig.1 and its transfer function correspond to a band-pass filter stretching I_b by a factor of about 1000. This analog signal is applied

- I_B : beam current (current source)
 C_1 : storage capacitor of secondary loop
 C_L : storage capacitor of tertiary loop
 L_1 : inductance associated with core 1
 L_2 : inductance associated with core 2
 L_3 : leakage inductance in secondary loop
 L_4 : leakage inductance in tertiary loop
 R_1 : core losses of core 1
 R_2 : core losses of core 2
 R_L : load resistor (coaxial cable, 50 ohms)
 n : number of turns, winding of core 2 (10 ... 20)

Fig.1 : Simplified equivalent circuit of ICT

Fig.2 : Block diagram of the BB Monitor

Fig.3 : Detailed diagram of the acquisition system

Fig.4 : Display of bunch currents with a beam loss

Fig.5 : LEP Current monitors layout

to 8 parallel analog processing channels (Fig.2) for bunch selection and Integrate-Hold function with DC level compensation and very low noise. The output signal is proportional to the charge, expressed as current, of the selected bunch and averaged for a given number of revolutions. Fig.3 present the acquisition system and Fig.4 an example of bunch currents display on a console. The BB and ST transformer specification is a range of ± 2.5 mA with a resolution of 10 nA. The BB and ST transformers use the Beam Synchronous Timing control for bunches and turns definition.

The transformers disposition in LEP is presented on Fig.5. The DC and BB channels are essential for the machine operation to the point that the picture of digital Ameters directly connected to the analog preprocessors is transmitted by TV in the control room ! All the filling process is followed with the BB transformers. The ST channel was intensively used for the injection test of july 1988 and at start up of LEP for the measurement of the number of particles injected. It is not as usefull once the beam can be accumulated with RF trapping.

1.4. COLLIMATORS

The collimators [6] have 3 different functions and their diposition around LEP is given on Fig.6 : Aperture Definition collimators, Total Aperture collimators for experiments protection and Total Aperture collimators for separator protection. The arcs H-aperture defining collimators could

not sustain (overheating) direct impact of full beam if they were made of high z material. Hence they are made low z block (18 cm Al) with high z thin plating (10 μ m Au). The other collimators are made of 13 cm W. They are well matched to the vacuum chamber with Cu transition blocks for RF losses or beam loading reasons. Their positioning is driven by stepping motors with a 5 μ m resolution and 100 μ m setting accuracy.

1.5. STOPPERS with SCREENS

Two beam stoppers (BCSC or BCSE) made of copper blocks [3] are installed near QS10s on both side of experimental Interaction Points. In addition another one has been placed near QL7 close of IP1 for safty reasons. Operationnaly they are either used for safety and personnal protection or for single turn injection necessary to verify and optimise injection and Beam Synchronous Timing fonctionning.

1.6. BEAM SCRAPERS

Two scrapers (BBCS) have been installed [3] and they are incorporated in the split-foil injection monitors (BPMO). They are foreseen for bunch charges equalisation but are practically not used.

1.7. PROFILE MONITORS:

Many instruments have been installed for the analysis of transverse and longitudinal profiles and emittances. The most used one is the synchrotron radiation UV telescope since it does not interfere with the beams and allows for life monitoring of the beam stability or cross-section on a TV screen in the control room. It gives a "feeling" about beam health to the operators while stacking and ramping.

1.7.1 U.V. TELESCOPES (BEUV)

Abundant synchrotron radiation, in the UV range, is available in LEP and is compatible with usual UV components and some air path, whilst minimising the broadening of the beam profile through diffraction [7]. The extraction mirror is a delicate piece of equipment since the ultimate optical quality (± 25 nm flatness) must be maintained under heavy power deposition. It is made of

Fig.6 : Total aperture collimator (BIMO)

Fig.7a : Telescope BEUV setup

Fig. 7b: Example of BEUV display

Fig. 8a : Motorized support in vacuum
or BEXE

Fig. 8b : Vertical detector layout

beryllium and is situated at 21m from the source and 75mm from the beam as can be seen from Fig.7a . Best performance is reached with a system at QD giving ϵ_z with high resolution and a system at Q12 for ϵ_x . $\Delta p/p$ can also be estimated from σ_x measured at QD and Q12. Hence 4 telescopes are installed on either sides of IP8. The beam image is captured by a pulsed intensifier and a CCD camera with 288x384 pixels. The precision on the profiles varies from 2 to 4 %. Digital processing allow for 3 modes of operations: i) The normal TV mode for observation in the control room, ii) Acquisition of a single shot with computation of the sigmas and data compaction for display on a console, iii) Acquisition of a series (10) of two dimensional profiles stored on the CCD before processing and spaced in time as close as to one revolution period apart. Operational results are shown on Fig.7b .

1.7.2 X-RAY vertical BEXE and longitudinal BEXE

Another profile instrument (Fig.8a) [8], for the X-ray range, is placed very close to the beam. A special vacuum enclosure allow direct exposure of solid state detectors to the main dipole synchrotron radiation, through a window of 400 μm beryllium. The CdTe photoconductors have been chosen for their very short carrier lifetime (10 ps). A vertical line array of photoconductors (Fig.8b) is measuring the vertical profile with a pitch of 100 μm , at each bunch passage. The detector and its movable support for alignment and in-out motions are inside a tank with a vacuum of 10^{-6} Torr for high voltage and corrosion reasons. The processing scheme is shown on Fig.9 .The multiplexed analog signal presenting the vertical profile is then acquired for each bunch and revolution by BOM NB-ADC modules and parallel buffer memory for further digital processing and display. One detector has been installed in LEP and has survived months of irradiation. This is a crucial and encouraging result because the power deposited by X Rays in the 4 μm of CdTe can be estimated to 40 mW/mm², for a beam of 1 mA, corresponding to a dose of 10^{11} Grays. No damages could be noticed, which is quite exceptional for a semiconductor device.

On the same support a longitudinal profile or bunch length detector is mounted. Its layout is presented on Fig.10 . The folded delay lines with different length are connecting a row of CdTe photoconductors. Once all photoconductors are illuminated by the intense X-ray pulse the P_0 ones polarized with a large DC bias send through the delay lines a pulse proportional to the light pulse to reach the other photoconductors P_i with staggered delays. At P_i the out-going pulses charge become points of an autocorrelation profile of the light pulse. The readout electronics is the same as for the the vertical profile. The detector prototype has been a long venture in collaboration with the D.LETI Institute C.E.A. Grenoble,F. The detector has not yet been fully tested with beam but a test with a subpicosecond laser has given an autocorrelation pulse of 19 ps.(FWHH). The acquisition hardware and software is also not yet completed.

Such instruments have very interesting features: non intercepting, real time single shot measurements, measuring at rate of 44 kHz, the vertical resolution is not diffraction limited and there is no critical timing needed. Two detectors are installed for e+ and e-.

1.7.3 WIRE SCANNER

Two sets of wire scanners [9], each for measuring the horizontal and vertical profiles, are installed in LEP in a straight section close to IP1 where the horizontal and vertical dispersion is zero. A carbon fibre with a diameter of 36 μm moves through the beam with a speed of about 0.5 m/s. When the bunch is traversing the fibre, the electrons or positrons produce bremsstrahlung photons with an energy spectrum of up to the beam energy. The bremsstrahlung photons are detected with a scintillator placed some ten meter downwards at the start of the bending section. The detector is shielded against low energy synchrotron radiation. This allows a measurement of the beam profiles which is practically background free.

Fig. 9 : Detector synoptic diagram

Fig. 10 : Autocor. circuit for longitudinal profile

LEP WS - Rui - Vertical IN - 45.50 GeV - 25/07/90 10.24.37 - sm25

Fig. 11 : Wire scanner display

Fig. 12 : Streak camera principle

Fig. 13 : Display of synchrotron oscillation

Fig. 14a : Principle diagram of a single pulse storage and stochastic sampling

By a precise measurement of the position of the fibre and of the pulse height induced by the bremsstrahlung photons whenever a bunch hits the fibre the profile is measured with a resolution of less than 10 micron. During the LEP run some thousand scans were done, during machine development periods as well as for optimization of the luminosity by minimizing the beam size. Very small changes of the beam height could be detected by the instrument and the calibration of other (nondestructive) monitors measuring the profiles could be done.

Some problems were encountered when the scanner was used to measure the vertical beam size at injection energy of 20 GeV. In this case the beam was substantially blown-up during the scan because of multiple coulomb scattering. This leads to a asymmetric profile, since the blow-up increases during the time the fibre traverses the beam. A reduction of it was achieved by increasing the speed of the scanner. In addition the emittance calculating software corrects for the asymmetry, which further reduces the error.

During the first month of LEP operation fibres broke occasionally. This is probably due to heating of the fibre by the coupling of the fibre with the electromagnetic fields of the beam. A second mechanism to heat the fibre is due to the energy loss from the beam particles traversing the fibre. A beryllium fibre which was tried out was even more fragile. In order to increase the lifetime of the fibres different measures were taken : the speed of the fibre passing the beam was increased, the control of the motion was improved. After that no fibres were destroyed anymore. Nevertheless the problem of the fibre heating by the beam remains a topic to be studied in more details.

The detector signal processing and display programs are runed-in and operational. Fig.11 presents an Appolo display in the control room.

1.7.4 STREAK CAMERA

An industrially developed Streak Camera [10], with two orthogonal deflections allowing for the stacking of up to 50 streaks on the screen of a CCD readout, is installed in the IP1 optical laboratory where it receives the visible light deviated by Be mirrors. The slow sweep can be varied for all bunches recording or interspacing for up to 20 synchrotron periods. Selected bunches are gated with a pulsed bias of the photocathode. The camera set-up is presented on Fig.12 . The time resolution has been measured with a picosecond laser pulse and is better than 6 ps FWHH. Fig.13 presents a beam longitudinal profile and synchrotron oscillation as recorded from the light produced by the low field bending magnets. The light source is being intensified with mini-wigglers. Synchronizing the Streak Camera and BEUV detector should allow for synchro-betatron oscillation observation. This instrument and its computer control and CCD camera image processing is also in the running-in phase.

1.7.6 PHOTON STORAGE RING

Another new technique for longitudinal profile from synchrotron radiation is in development but has not yet reached the operational level: the photon storage ring [11] with random sampling. Fig.14a explains the principle and Fig.14b describes the setup.

1.8. TUNE CONTROLLER or Q-METER

One Q-meter instrument [12] is installed in LEP near IP1. Its beam hardware is one standard button BPM and two single turn ferrite kickers installed around a ceramic vacuum chamber. It measures the coherent non-integer part of the betatron frequencies with a resolution $< 10^{-3}$ and this for e^+ and e^- beams. Fig.15 presents the principle of the instrument. The beam position acquisition uses the modules of the WB processing of the BOM system.

Fig. 14b : Measuring setup and random sampling of a bunch signal

Fig. 15 : Q-Meter block diagram

Fig. 16 : Signal flow diagram for PLL mode

Fig. 17 : Tune history record in PLL mode

Fig. 18 : Tune measurement display

The digital signal processing is done with two VME processors MOTOROLA 68020. Due to the flexibility offered by digital signal processing the Q-meter offers three modes of operation:

- FFT Mode: The beam is excited with random noise (constant spectrum) and the resulting motion (0.05 to 0.5 mm) is acquired for 256 to 4096 revolutions which are processed by FFT in a time of 170 to 860 ms. The resolution $\Delta q = 1 / n_s$, which is related to the number of samples, has been further improved by an interpolation algorithm. For continuous q monitoring the q_H and q_V data are stored in a circular buffer.
- Swept Frequency Mode: as in usual frequency analysers the beam excitation frequency is swept according a staircase function. The beam response is processed by Harmonic Analysis with an average of 1000 samples per point. The obtained accuracy is 2.10^{-4} which is smaller than the stability of LEP over 10 min.
- PLL Mode: the Phase Locked Loop mode block diagram is given in Fig.16 . With a correctly chosen phase shift between the PCO output and the beam shaker, the PLL will track and even capture the q resonance. An amplitude regulation is necessary to avoid over excitation and beam loss. This mode is a delicate one since it depends on machine state but it is faster than possible tune changes due to variation of current in the magnets. Fig.17 represents a tune record where tune changes were introduced and where the small peaks are due to parasitic influence of SPS cycles.

The use of LEP Q-meter has proved to be a precious tool for both operation and precise accelerator studies. One example is the observation of the σ and π mode of oscillation during collision which gives information related to luminosity, effective emittance and aspect ratio at I.P.. A closed loop tune regulation during ramping process was difficult to optimise but is now operational. Fig.18 is a tune display on APPOLO console.

1.9. INTERACTION RATE BHABHA MONITORS

Each H collimator-block of the IP collimators has been equipped with a compact silicon tungsten calorimeter [13] in order to be at very small angle for Bhabha monitoring. Four monitors per experimental IP, 15 m away, are forming the Lep luminosity monitoring system. Silicon detectors as active material and tungsten as absorber and shower generator form a compact design presented on fig.19a .The calorimeter is separated from the vacuum by a 1 mm stainless steel window and the back side is protected from synchrotron radiation by 30 rad. length of tungsten and a 2 mm lead shield and protective sandwich all around. During commissioning, the silicon detectors suffered from an alarming increase of their diode reverse current. Since these currents recovered during machine stop suggest phenomena of positive charge accumulation by SR and e^+e^- background in the silicon oxide. This was mostly overcome by the shielding and by biasing the detectors only during measurements. The calorimeter assembly with its front end electronics is shown on Fig.19b and luminosity measurement at IP4 with beam steering on Fig.20 . The monitors have shown their capability of measuring the relative luminosities but the potentialities are still not fully exploited (software).

1.10. TRANSVERSE POLARIMETER

A laser polarimeter [14] based on spin-dependent Compton scattering of circularly polarized photons from polarized electrons has been installed in the LEP straight section LSS1. The principle is shown on Fig.21 . The vertical angular distribution of the recoil high energy γ rays, as measured at a detector 247m downstream the laser interaction region (LIR) , shows an up-down asymmetry depending on the right - left helicity of the incident laser photons and proportional to the e^+e^- transverse polarisation level. The installation of the laser polarimeter has been completed in 1989 (Fig.22) with its Nd-YAG laser ($\lambda_\phi = 532$ nm) placed in the optical lab 125 m away from the LIR. Evidence of polarized beams has been recorded during the last run of 1990 , on Aug. 30 th. as can be seen from Fig.23 .

Fig. 19a : Construction of the calorimeter in the block

Fig. 19b : Calorimeter with front-end electronics

Fig. 20 : Relative luminosity rates versus vertical steering in the 4 IPs

Fig. 21 : Principle of the laser polarimeter

Fig. 22 : General layout of the LEP polarimeter

Fig. 23 : First natural polarisation measurement as function of time

2. BEAM ORBIT MEASUREMENT SYSTEM

2.1. INTRODUCTION

The BOM system has been designed to measure with a fast response the beam positions from 504 Beam Position Monitors (BPM) located near QD's along the 28 km of the LEP machine [15]. Since the radiation level in the LEP tunnel will be high, the processing electronics has been grouped in 24 shielded underground areas, resulting in long cable connections between monitors and electronic stations (up to 800 m) and restricted access during machine operation. The latter implies the need for very good remote diagnostic means and high reliability as well as easy maintainability.

The BOM system (Fig.24) has to be able to measure first turn trajectories (single passage) for local problem detection or closed orbits (average over many bunches and turns). This implies a synchronising mean for unambiguous capture of the same bunch signal all around the 24 stations. A special Beam Synchronous Timing (BST) system has been implemented [4] which is also used as a synchronous serial link for the control of the BOM system and other instruments. This requirement being satisfied, the data can be stored in the local processor's memories. Since the average time between bunches is 11 ns all signals are recorded and the memory has been tailored to contain up to 1000 revolutions.

Thanks to their development for TV applications, cheap 8-bits-FADCs could be chosen for the fast acquisition circuitry. These raw data will then be further processed by a local microprocessor to derive closed orbits or lattice parameters, or to make a post event analysis (transient recorder mode).

The resulting volume of data to be transmitted is very much reduced and does not create a heavy load to the control network. The overall BOM software organisation is presented in Fig.35 . It shows that, many users can make request to the BOM Server who will organize the BOM activity, set priorities and collect the results from the various points. The response time for a closed orbit request should be within seconds.

The radiation level in the LEP tunnel implies special design of critical parts of the BOM system. Careful attention has been devoted to the BPM button electrodes, signal cables and front-end electronics.

2.2. BEAM POSITION MONITORS

The design criteria for the LEP monitors were the following [15,34]:

- short length, about 10 cm,
- to be welded to the vacuum chamber,
- skewed sensor positions in order to avoid direct impact of synchrotron radiation,
- minimum RF loading and higher modes coupling to the beam,
- high precision for interchangeability,
- no further tests after welding,
- flanges for sensor exchange,
- resistance to corrosion and to baking up to 300°C,
- no difficult administration of test parameters, i.e. full interchangeability.

The best solution is a capacitive monitor with button-like electrode, as also used in most other electron machines [16,17,18,20]. The button electrode (Fig.25) is held by its 50 Ω central conductor and positioned by a ceramic Al_2O_3 washer. Both the electrode capacity and its distance to

BOM SYSTEM

Fig. 24 : BOM system

Fig. 25 : Button electrode

Fig. 26 : Feedthrough structure with its TDR response

the beam are critical elements for the sensitivity and for the zero offset of each monitor. This requires tight mechanical tolerances for both the buttons and the monitor block, in order to insure an overall transverse position tolerance of 0.15 mm.

The structure of the feedthrough (Fig.26) with its mixed vacuum(air)-ceramic dielectric and shifted inner and outer brazing has been inspired from the KEK design [19,20]. This design, as compared to the simple disc design, gives to the central rod a larger diameter and a better mechanical strength. The LEP design has been further improved for extending its frequency bandwidth in shifting the diameter transitions to achieve a local capacity compensation. The impedance matching is maintained well up to 12 GHz. The feedthrough TDR shows a performance comparable to the one of an SMA connection.

The central rod is made of titanium and the outer conductor as well as the flange with its plug are made of stainless steel 304L. Gold-nickel braze has been chosen for its corrosion resistance to nitric acid vapors [26] produced by the ionized moist air. Most of the LEP vacuum chamber is made of an extruded aluminium pipe which would not have provided an accurate nor stable enough support for the four buttons of a BPM. Aluminium blocks (Fig.27) have been designed to be welded onto normal vacuum chambers. But the button electrode flange (70 mm diameter) being made of stainless steel (304L) an important differential expansion will be present during baking at 150°C. Thorough testing has shown that the metallic seal (LEP type or Helicoflex) can take the expansion difference by its deformation and the seal leak tightness is very reliable. Some BPM blocks in experimental straight sections have different cross-sections (Figs. 28,29) to match the chamber geometry and are made of stainless steel to allow for bakings up to 300°C.

The BPM sensitivity has been carefully measured on a high precision test bench (Fig.30). The beam is simulated by a thin wire antenna held under tension by a frame which position is controlled by stepping motors with a resolution of 5 microns. The overall position reproducibility is within 30 microns. The HP 8505A network analyser is both used to feed the antenna (70 MHz) through an amplifier and to process the four reference button signals which are multiplexed by relays. The overall bench is fully computer controlled.

On reception from series production the button electrodes are first mechanically tested with a jig and then tested on the same bench for their coupling factors. Their capacity (about 8.7 pF) is finally measured with a capacimeter of 0.01 pF resolution. In order to insure the BPM electrical center precision both parameters are stored for each button and **quads are formed of buttons with very close values, in steps of 0.01 dB and 0.1 pF.**

Once the transverse electrical characteristics of each type of block have been established and recorded, **the series blocks are only tested mechanically to be within the given tolerances.** The blocks are produced with computer controlled milling machines. On installation the blocks are rigidly bound to machine quadrupoles **with an accuracy of 0,1 mm relative to their magnetic axes** constitute thereafter fixed points of the vacuum chamber.

Taking into account high mechanical precision for interchangeability, precision supports and alignment, the overall absolute position precision is 0.3 mm r.m.s.

The same BPMs are also installed for other applications: Experiments timing (8 BTPC), Instrumentation timing (2 BTPE), RF Phase control (20 BAPC), Q-meter (3 BQPE), Analog observation (2 BQPE) and Transverse Feedback (10 BAPE).

Fig. 27 : Aluminium block
(456 BPPE 131 x 70 mm)

Fig. 28 : Stainless steel block
(24 BPPC $\varnothing$ 100 mm,
8 BPPS $\varnothing$ 120 mm)

Fig. 29 : Stainless steel large
aperture block
(16 BPPM $\varnothing$ 160 mm)

Fig. 30 : Electrical test bench

Fig. 31 : Narrow band processing scheme

2.3. RADIATION CONSIDERATIONS AND CABLE SELECTION

The material used for the blocks, the button electrodes and the brazes have very high radiation and corrosion resistance. The button coaxial line has been lengthened in order to set the end N-connector as far as possible from the chamber. The BPM is coated with lead in order to reduce the radiation leak through the button hole toward the connected cable. At LEP maximum energy it is expected that those coax cable jumpers may have to be replaced by mineral coax cables.

The choice of coaxial cables, (of total length about 300 km) for signal transmission was of great concern since they have to run inside the LEP tunnel.

The cables were first selected according to their best possible immunity to EMC effects and minimum transmission attenuation. The influence of pulsed ionizing radiation was then tested at DESY in the PETRA machine. Different cables were laid against the unshielded vacuum chamber inside the magnet gap. The radiation peak rate was about 7×10^5 Rad/s. The result was that ionization effects could be observed in cables with air dielectric but none in the ones with foam or solid polyethylene. Cable samples were finally irradiated with a cobalt source up to a dose of 10^8 Rad. Different foam densities, 0.4 and 0.25, were tested as well as different foaming methods like using freon, nitrogen, or a chemical reaction. The result of the test was that **the main factor for radiation resistance is the foam density.**

Finally the selected cables are 75 Ω and 50 Ω CATV cables **with solid aluminium extruded outer conductors and 0.4 density polyethylene foam** produced with pure nitrogen (for inner corrosion reason). Their price is low and their electrical performance is quite close to the one of high quality air coax cables.

2.4. ANALOG SIGNAL PROCESSING

The bunch induced pulse on the button electrode has a range of 1 to 2500 V (8.7-pF capacity, 25 mm excursion) and a short duration of about 100 ps at mid-height. Since the signal power collected by the button electrodes is not large [15,24] and has to be transmitted over long distances of up to 800 m, the analog preprocessing is not obvious. A solution inspired by previous designs [15,21] has been adopted in LEP for 448 BPM's connected to the so-called narrow band (NB) processing circuit for monitors wherever the time of passage between e^+ and e^- is < 600 ns. Since the average time between bunches is 11 μ sec. all signals can be recorded and stored in a local memory for up to 1000 revolutions.

2.4.1 Narrow Band processing scheme

This circuit is presented on Fig.31. It is characterized by a FADC of 8 bits resolution and 15 MHz maximum rate (Thomson EF 8308). Eight bits resolution is coarse for a BOM measurement and would not cope with the beam intensity variation of 200. An intensity analogue normalizing circuit has been added, which is based on a differential phase modulator with a $\pi/2$ hybrid followed by a linear phase demodulator made of an exclusive or gate. The resulting transfer function is :

$$\delta = \arctg \Delta / \Sigma$$

But such a circuit has to be driven by a burst of sinusoidal signal. It is produced by ringing filters directly connected to the button electrodes (Fig.32). Their central frequency is 70 MHz and the burst last for about 150 to 400 ns. These filters must have very close and stable response to avoid phase errors very critical for the absolute precision of the BOM. The filters are double tuned circuits printed on Al_2O_3 substrate to withstand radiation. A capacitive test input allows for a complete test and

Fig. 32 : Beam induced signal at the output of the ringing filter

Fig. 33 : Wide band processing scheme

Fig. 34 : BOM system organisation

calibration of the processing chain since its overall gain is directly proportionnal to the BOM scaling factor.

The four signals are processed in diagonal pairs and transmitted to the electronic stations by only two cables. The transmitted pulses present a duty cycle modulation of 140 MHz carrier. The mean value is the position information and the carrier is used as auto-trigger for the FADC acquisition. Two acquisitions are programmed, one before the pulse to monitor the base-line and a second one 150 ns later to record the magnitude of the low-pass filtered pulse. The NB system needs then about 450 ns for the filter signal to decay before being ready for the next measurement. Therefore, it cannot be used for monitors near to the intersections, where e^+ and e^- bunches are closer together.

The eight bits of the FADC limit the readout resolution to:

$$\delta X = \pm 85 \mu\text{m} \quad \text{and} \quad \delta Y = \pm 130 \mu\text{m} \quad \text{for } \pm 1/2 \text{ LSB.}$$

But it can be improved by the use of either following two verniers:

- i) Statistical interpolation : if a random noise is added to the signal, the measurements are distributed around the steps defined by the LSB and the result of the average of these measurements is a smoothed transfer function. The optimum result is when the sigma of the input noise distribution equals 1/2 LSB. This noise signal is to be produced by noise generators which are not yet installed.
- ii) Zoom: if the FADC references can be reduced for a smaller input voltage excursion, then the resolution can be improved by the same factor (not yet implemented).

Both vernier methods are limited by the FADC non-linearities. These are due to some coupling between input and output registers (not Grey code) inside the chip. A good part of these non-linearities are systematic and are compensated during the digital processing, thus improving the resolution by a factor four. When the amplitude of a coherent oscillation is measured over many revolutions the resulting BOM resolution should reach:

$$\delta X_{\text{rms}} = 7 \mu\text{m}$$

$$\delta Y_{\text{rms}} = 11 \mu\text{m}$$

Since any calibration procedure of an electronic processing chain presents also some error, the estimated r.m.s. absolute position error is 0.1 mm, which has to be added to the mechanical ones.

2.4.2 Wide Band processing scheme

As mentioned before, the BPMs close to intersections (56 units) require a faster acquisition electronics [22] which is called the Wide Band system (WB). It is represented in Fig.33. Its characteristic is linear and therefore simpler to process. But its circuitry is more complex and requires gain changes according to intensity and a 12 bits ADC for larger signal magnitude dynamics. It is also beam self-triggered, can distinguish e^+ from e^- by their polarity, but can only treat one kind of particles at a time.

The button electrodes are directly connected to 50 Ω cables and low pass filters. This pre-integrated pulse is still asymmetric and the surface of the first part is sampled by an Integrate & Hold circuit. Its output value is then converted by the ADC in 3 μs . The WB system treats the four button signals separately. Two double directional couplers are used to inject the test and calibration signal before the low pass filters.

Fig. 35 : BOM software organisation

Fig. 36 : First order electrical transform

Fig. 37 : Orbit display with a closed horizontal local kick in arc 1-2

2.5. BOM SOFTWARE DESCRIPTION

The software for the control of the BOM system and data processing (Fig.35) did also represent a large effort (30%) relative to the hardware realisation. Its concept is strongly influenced by the system distribution (Fig.24) and by the BOM control scheme [28], which depends fully on the LEP Control System [29]. Its development took place while the Control system features were progressively frozen. This was quite a burden for the instrument specialists. The local software (ECA-VME bus) is written in pascal within RMS68K system.

The request from the user (Fig.34) on an APOLLO console is processed by the BOM Server (not yet fully implemented) which asks the BST Master to initiate a measurement sequence. It will define the BOM operating parameters like choice of particle type, gain setting, zoom condition, number of acquisitions etc. . These informations are forwarded to the Master of the Beam Synchronous Timing [27]. The task commands and the parameters are then transmitted to all stations through a command field of the BST message. All stations are synchronized by an acquisition command in the same command field and a turn number to be used as label for the self-triggered acquisition of up to 8 bunches position within a turn. The BST is synchronized to the RF clock. The turn period of 88,9 μ s is further subdivided in fine time periods for **bunch numbering purpose and rejection of parasitic signals** outside the normal bunch sequence.

The BOM hardware is set accordingly to the request parameters and raw beam position data are acquired and stored in the local ECA memory under beam synchronous commands. At each acquisition the base line data (NB Syst.) and position data are transmitted to a double multi-input acquisition memory situated in VME ECA crates (Equipment Controller Assembly). This acquisition memory has a depth of about 1000 revolutions. At the end of an acquisition sequence the Master sends a task command which starts the digital processing.

The BOM system has also the possibility to work in post trigger mode for transient capture. In this case the BOM system acquires permanently until it receives a stop command related to a defined event. The purpose of the double acquisition memory with its inputs in parallel is to allow for monitoring without perturbing the course of the running measurements.

When the processing task is started, the local CPU retrieves off line the data from the acquisition memory. The position calculation out of the raw data is done in two steps: first, the compensation and corrections of the analog acquisition errors and second the correction of the monitor non-linearities. It processes the data with the use of calibration and linearisation tables in order to correct for errors and non linearity of electronics, i.e. for the NB system: the Normalisers inverse transfer function (distorted arctan) as established by laboratory measurements and that of the FADCs. The first order electrical transform of a BPM of elliptical cross-section calculated from the diagonal differences [23,24] is shown in Fig.36 .

$$\begin{aligned}x &= K_H (\Delta_1 - \Delta_2) \\y &= K_V (\Delta_1 + \Delta_2)\end{aligned}$$

These measured positions x and y show strong non-linearities influenced by the particular geometry of the vacuum chamber equipotential. Polynomials $P(x,y)$, with only six coefficients have been fitted to the four types of BPM geometries and will serve to reconstruct real positions X and Y to the utmost accuracy:

Fig. 37 : Feedthrough ceramic crack due to braze ring

Fig. 38 : NB Processor input signal as seen by the FADC at acquisition for different signal ratios from a pair of electrodes

$$P(x,y) = ax+bx^3+cx^5+dxy^2+exy^4+fx^3y^2$$

$$X = P_j(x,y)$$

$$Y = P_j(y,x)$$

The positions will be further processed (Fig.35) for first turn trajectories (up to 16 turns), closed orbits, and FFT analysis. This last process means that magnitude and phase of the transverse oscillations of a permanently excited beam will be calculated for each monitor.

The resulting X and Y position file for 4 to 16 BPM is sent to the local PCA where a "Listener" routine sends it to the BOM "Collector" PCA via the Control System. The BOM Collector receives 40 files, checks for consistency, creates the BOM measurement output file and warns the user. The orbit output file is transmitted to an APOLLO display program (Fig.37) for visual analysis and further use [32].

The BOM software is also designed for hardware diagnostic, calibration and closed orbit simulation in the absence of beam.

Due to time shortage, only a stripped-down development version of the software could be supplied for the start-up, called version 0, which has been successfully used until 1990 for LEP beam control and the evaluation of BOM performance. It does not yet offer the beam and bunch selection and parasitic rejection according to the data time label. This version allows for two first revolutions trajectories measurement (e+/e- and first bunch) and closed orbit measurement averaged over 10 or 50 revolutions and all bunches (no separation of e+/e- beams or single beam measurement).

2.6. BOM FABRICATION AND INSTALLATION

The injection test of July 1988 validated the BOM hardware design and series production was launched.

The subsequent last year of LEP construction and installation was very loaded. All BPMs were ready and installed as part of the quadrupole vacuum chambers [25] by the Vacuum Group. About 15 leaks on button electrode feedthroughs (total 2200) appeared after transport and tunnel installation, but no more since then. The origin of the leaks (tot. about 40) appearing at the central titanium conductor (Fig.37) has been investigated with the manufacturer and found to be due to combination of gold-nickel braze (imposed by corrosion resistance) with titanium forming a very hard alloy and too large a chamfer filled with braze and hence reinforcing the thin central conductor tube. A new model is studied. About 10 electrodes presented short-circuits. They were due to very thin Al fibers produced by scraping the machining grooves at electrode introduction in the BPM block. The shorts could be removed by electrical discharge and current.

The BOM system did require an almost industrial production, testing and calibrating of its 3000 electronic modules and 150 crates. The series production and wiring was executed by industry, but the testing and calibration was done at CERN on especially developed and computer controlled test benches, which are also needed for BOM maintenance. Just after chamber installation and once the cables were pulled, a first team connected all the front-end electronics next to the BPMs. Two to three other teams assembled and tested the WB and NB stations hardware. The two months foreseen for overall BOM system check-out, with BST and Control system interface, were reduced to nothing due to late delivery of the tunnel under the Jura. It resulted in a tremendous debugging effort in the first weeks of LEP start-up.

Fig. 40 : Dispersion measurement

IP3: wide band ---- narrow band PU

Fig. 41 : Scale measurement WB/NB, measured beam positions relative to calculated ones

2.7. BOM PERFORMANCE AND PERSPECTIVES

The first overall BOM system test [31] was only possible with a beam passing all around LEP and hence at LEP start-up (July 1989). The first two weeks were mainly dedicated to communication software debugging and to BST synchronisation relative to beam signals in all stations. **This made it difficult to use BOM trajectory measurement to guide the beam all around.** The BOM performance and reliability improved quickly, closed orbits could be corrected and the first events from colliding beams could be recorded after a week. Thanks to hardware stability and its few failures or bugs during the first weeks the effort could be concentrated on the software. After two months "An r.m.s. orbit distortion of about 1 mm was achieved routinely" [30].

During the January to March 1990 shut-down the BOM HW has been further tested and it was found that high voltage command cards created disturbances and that the test generators were desynchronised resulting in noisy calibration. These problems were cured and the BOM calibration precision was improved by a factor of 4 as verified by simulated orbit test. The BOM system was recalibrated for the 1990 running period which resulted in a better vertical orbit distortion of sigma 0.7-mm and reduced emittance [32] using 100 correctors.

Different methodes have been used for BOM precision and resolution estimation. Since the average of position measurements either vertically from all BPMs or horizontally from those (112 BPMs) of straight sections presenting no dispersion should be zero, any discrepancy is an instrumental offset. The NB part of the system presents an horizontal offset of -0.8 for e- to -1.6 mm for e+ relative to its calibration and to other position measuring instruments. This offset is due to the sensitivity of the NB analog processing chain to the difference of length between the simulated beam signal (6 ns FWHH) used for calibration and the beam signal (100 ps, two polarities). In addition the double tuned circuit, chosen for faster decay reason, presents frequency variation during the burst (Fig. 3). Since the beam or simulation pulse width has an influence on the autotriggering of the measurement point, values may fluctuate by a few bits as it can be inferred from Fig.39. For the time being the NB Horizontal offset is corrected by a program (BOMCOROFFSET) which substract the offset. This NB circuit problem influences also the scale of the measurements. The scale has been checked by the dispersion method (Fig.40) : changing the RF by ± 100 Hz and comparing the horizontal position in the arcs with its calculated value or by the bump method: beam position is recorded with induced open or closed bumps both in straight section or arcs and a scattergraph [33] is plotted of the measured values relative to the MAD calculated ones. Fig.41 shows the comparaisou of NB and WB monitors for closed bump across an intersection point. All methodes have shown that the NB scale is too small and with variation from BPM to BPM: factor $0.8 \pm 10\%$. It is not the case for the WB system.

This NB problem is beeing cured during the 1990-91 shut-down: the test generators are modified, the ringing filters are replaced by a single tuned cicuit which does not present frequency variation and an improved normaliser generation is under developpment.

The WB part presents instabilities due to the degradation of gain relay contact. Laboratory investigation showed that these instabilities are due to the aging of a contact lubricant used in this type of coaxial relays. The replacement is progressing and should be ready for next start-up.

Except for these two points the BOM HW performance present good reliability and also has the advantage of its redundance. Calibration rate is of the order of two months. Special attention has been given to the cables for their EMC noise rejection and insensitivity to large bursts of synchrotron light. There has been no problems with cross-talk or picked-up noise.

Finally the orbit resolution is better than 65 μm and its absolute precision is 0.4 mm rms, as estimated from orbits analysis, even so the noise generators for interpolation are not yet operational.

The overall BOM system software reliability is insufficient and directly related to that of the LEP control system and to the present minimum diagnostic means. The version 0 software execution speed is too slow to allow for orbit averaging over a large number of revolutions. A version 1 has been installed and tested in the local processors (ECA). It not only offers additional BOM measurement facilities, like separate orbits for e^+/e^- in presence of the two beams, but also four times faster processing speed, i.e. 27 s for processing of the average orbit over 30 turns and 8 bunches. Further improvement is in progress in order to reach the original design aims like acquiring an orbit in a few seconds for which the hardware and BST have been designed. A version 2 software based on OS9 system and C language and also on the use of direct ETHERNET-TOKENRING bridge connection to the APPOLO console, is in preparation first for the WB monitors. Its purpose is to improve the response speed and performance.

2.8. CONCLUSION about BOM System

The main goal of the BOM system has been achieved, i.e. to allow for an orbit correction to less than 1 mm r.m.s. The absolute accuracy of the overwhole system was recently demonstrated when the vertical r.m.s. value was reduced to 0.5 mm (Polarisation run) with both results of increased luminosity of 20% and evidence of polarisation. Shortcoming in the normaliser NB system and gain switching of the WB system are being eliminated for the next running period by redesign of the involved modules.

Once version 2 of the software will be fully implemented more sophistications will be introduced to take advantage of the large acquisition capabilities of the BOM system like 1000 turns memory and second memory allowing to run surveillance and background tasks.

3. ACKNOWLEDGEMENT

The LEP Instrumentation has been quite an accomplishment requiring not only clever design but also tedious work and a lot of motivation for the 28 km of LEP and this from the scientific to the execution staff. This report should be a tribute to their merit.

I would like to thank my colleagues for their contribution to the preparation of this document. Their names are all quoted in the references.

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