

THE LEP BEAM ORBIT MEASUREMENT SYSTEM

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Summary

This paper describes the Beam Orbit Measurement (BOM) equipment and its current status. The 28 km circumference of LEP will be equipped with about 500 monitors adapted to the specific machine conditions. The signal processing equipment must guarantee high reliability and precision despite of high  $\gamma$ -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. It is followed by digital signal processing in local VME crates equipped with 68000  $\mu$ P. The BOM system will be able to acquire data of up to 8 bunches over 1000 revolutions from which injection trajectories, average orbits, integer and fractional part of Q,  $\beta$  function and post event analysis will be processed.

1. Introduction

The BOM system is being designed to measure with a fast response beam positions from 504 Beam Position Monitors (BPM) located near QD's along the 28 km of the LEP machine [1]. 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.

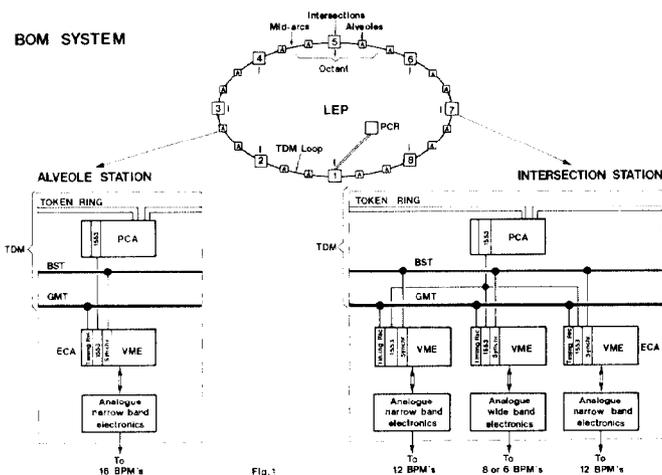


Fig. 1

The BOM system (Fig. 1) has to be able to measure first turn trajectories for local problem detection. This implies a synchronising procedure between electronics stations for unambiguous capture of the same bunch signal all around [12]. This requirement being satisfied, the data can be stored in the local processor's memories. Since the average time between bunches is 11  $\mu$ s all signals are recorded and the memory has been tailored to contain 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).

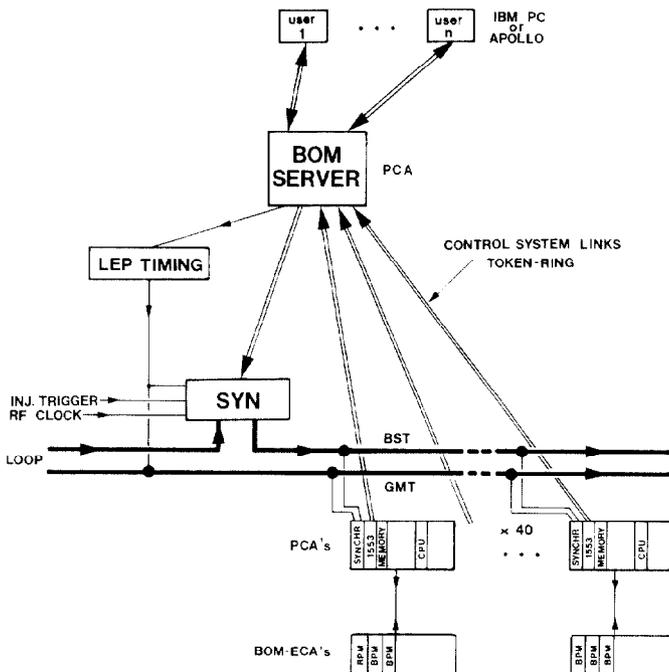


Fig. 2 : BOM System organisation

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 system organisation is presented in Fig. 2. 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.

For the BPM's both button-electrodes and vacuum chambers are in series fabrication. A complete prototype electronic station for an alveole is in preparation for a general test.

2. Beam Position Monitors

The design criteria for the LEP monitors were the following [1,2] :

- short length, about 10 cm,
- 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,
- flanges for sensor exchange,
- resistance to corrosion and to baking up to 300°C.

The best solution is a capacitive monitor with button-like electrode, as also used in most other electron machines [3,4,5,7]. The button electrode (Fig. 3) is held by its 50  $\Omega$  central conductor and positioned by a ceramic  $Al_2O_3$  washer. Both the electrode capacity and its distance to 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.

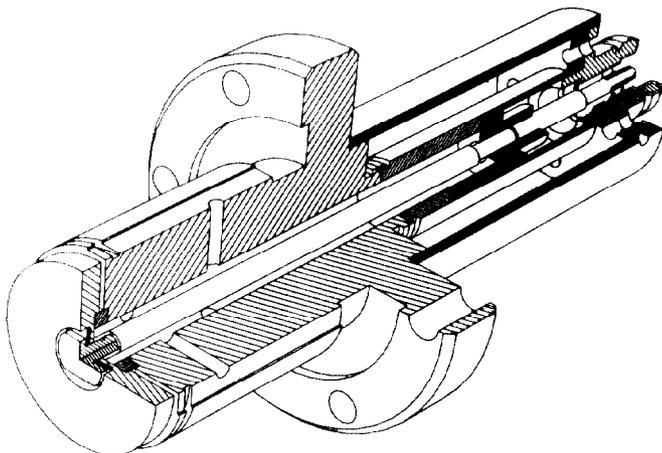


Fig. 3 : Button electrode

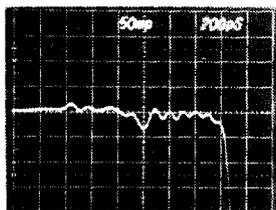
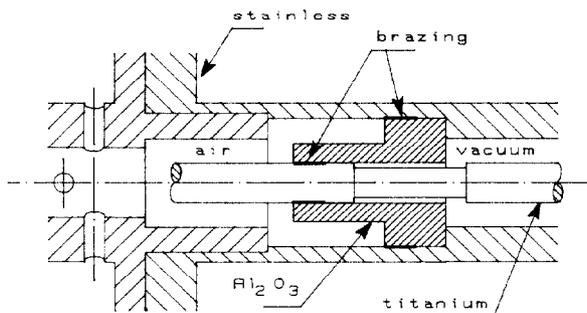


Fig. 4 : Feedthrough structure with its TDR response

The structure of the feedthrough (Fig. 4) with its mixed vacuum(air)-ceramic dielectric and shifted inner and outer brazing has been inspired from the KEK design [6,7]. This design, as compared to the simple washer 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

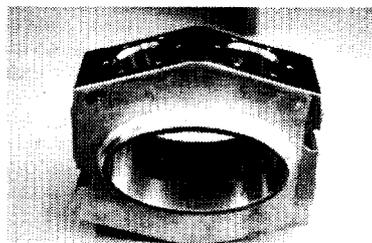


Fig. 5 : Aluminium block

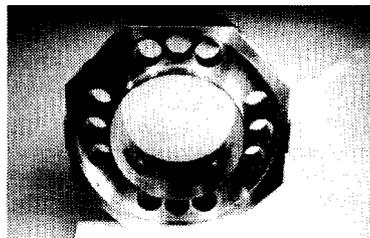


Fig. 6 : Stainless steel back



Fig. 7 : Stainless steel large aperture block

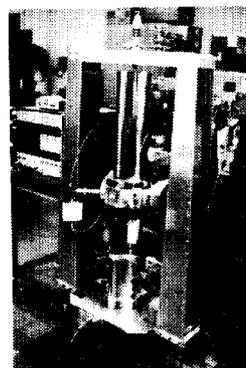


Fig. 8 : Electrical test bench

are made of stainless steel 304L. Gold-nickel braze has been chosen for its corrosion resistance to nitric acid vapors 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. 5) 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 6,7) to match the chamber geometry and are made of stainless steel to allow bakings up to 300°C.

The BPM sensitivity has been carefully measured on a high precision test bench (Fig. 8). 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 capacitometer of 0.01 pF resolution. 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 should be 0.3 mm r.m.s.

### 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 will 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  $7 \times 10^5$  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  $\Omega$  and 50  $\Omega$  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 per-

formance is quite close to the one of high quality air coax cables.

### 4. Analog signal processing

Since the signal power collected by the button electrodes is not large [2] 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 [1,7] 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  $\leq 600$  ns.

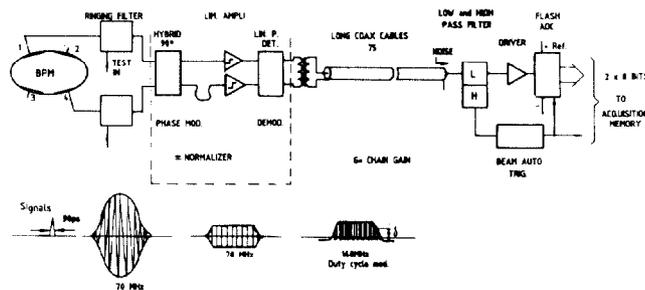


Fig. 9 : Narrow Band processing scheme

This circuit is presented on Fig. 9. 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  $\pi$  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 sinusoidal signals. They are produced by ringing filters directly connected to the button electrodes. 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 calibration of the processing chain.

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  $\delta X = \pm 85 \mu m$  and  $\delta Y = \pm 130 \mu m$ , for  $\pm 1/2$  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.

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.

Both vernier methods are limited by the FADC non-linearities. These are due to some coupling between input and output registers inside the chip. A good part of these non-linearities are systematic and will be 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 [11] should reach :

$$\begin{aligned} \delta X_{rms} &= 7 \mu\text{m} \\ \delta Y_{rms} &= 11 \mu\text{m} \end{aligned}$$

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.

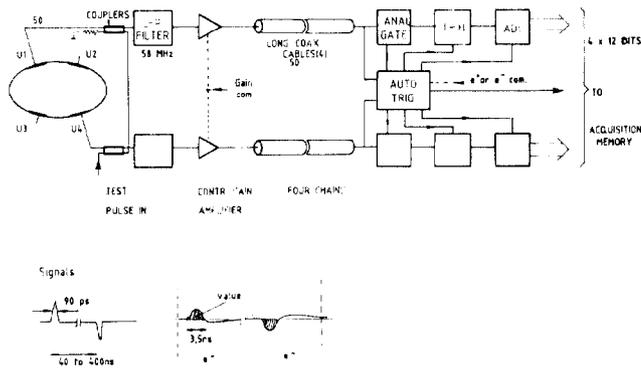


Fig. 10 : Wide Band processing scheme

As mentioned before, the BPMs close to inter-sections (56 units) require a faster acquisition electronics [9] which is called the Wide Band system (WB). It is represented in Fig. 10. 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  $\Omega$  cables and low pass filters. This pre-integrated pulse is still asymmetric and the surface of the first part is sampled by an Integrate and Hold circuit. Its output value is then converted by the ADC in 3  $\mu\text{s}$ . The WB system treats the four button signals separately. Two double directional couplers are used to inject a test signal before the low pass filters.

### 5. Digital Acquisition

The BOM server (Fig. 2) will receive requests from the users. It will define the BOM operating parameters like choice of particle type, gain setting, zoom condition, number of acquisitions etc. [11]. These informations will be transmitted to the synchronizer of the Beam Synchronous Timing [12]. The parameters will be transmitted to all stations through a command field of the BST message. Then all stations will be synchronized by a start 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 synchro-

nized to the RF clock. The turn period of 88,9  $\mu\text{s}$  is further subdivided in fine time periods for bunch numbering purpose and rejection of parasitic signals outside the normal bunch sequence. At each acquisition the base line data and position data are transmitted to a 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 synchronizer sends a stop command which also 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. A secondary acquisition memory is also foreseen with inputs in parallel with the main memory ones. Its purpose is to allow for instantaneous monitoring without perturbing the course of the running programme.

### 6. Digital processing

When the acquisition is stopped, the local CPU can retrieve asynchronously the data from the acquisition memory.

The position calculation out of the raw data [11] is done in two steps : first, the compensation and corrections of the analog acquisition errors and second the correction of the monitor non-linearities.

For the NB system the sequence is: correction of common FADC non-linearities, correction of offset and gain factors obtained from the calibration procedure and correction of the arctg characteristics. The first order electrical transform of a BPM of elliptical cross-section calculated from the diagonal differences [10,11] is shown in Fig. 11.

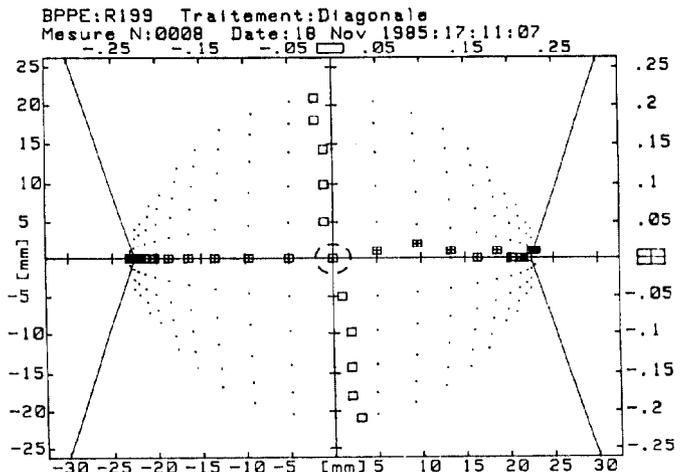


Fig. 11 : First order electrical transform

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

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 :

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

have been fitted to the four types of BPM geometries and will serve to reconstruct real positions  $X$  and  $Y$  to the utmost accuracy :

$$\begin{aligned} X &= P_j(x,y) \\ Y &= P_j(y,x) \end{aligned}$$

The positions will be further processed for first turn trajectories (up to 10 turns), closed orbits, and FFT analysis. This last process means that magnitude, frequency and phase of the transverse oscillations of a permanently excited beam will be calculated for each monitor.

Once the requested digital processing is finished, the data are sent to the BOM Server which collects them from the 24 stations, checks their validity and send them back to the user.

#### 7. Acknowledgement

We wish to thank the LEP Vacuum Group and the LEP-IM Group for a continuous collaboration, especially J.C. Brunet and C. Reymermier for the mechanical design of the BOM monitors and of the test bench and for the follow-up during the production of the BPM blocks and alignment supports.

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