MAGNETIC BEAM POSITION MONITORS FOR LEP PRE-INJECTOR

S. Battisti, M. Le Gras, J.M. Roux, B. Szeless and D.J. Williams
CERN, 1211, Geneva 23, Switzerland

Summary

Identical magnetic beam position monitors are used for the linacs, injection lines, accumulator ring and transfer lines of the LEP Pre-Injector (LPI). There were several reasons for developing a magnetic pick-up rather than a more conventional electro-static one, namely,
(1) the magnetic pick-up is less perturbed by the high losses experienced in linacs,
(2) the total length can be short (130 mm) for horizontal, vertical and sum measurements,
(3) the sum and difference signals can be generated directly into 50Ω loads using passive components, and
(4) a calibration wire allows testing with a simulated beam.

For the accumulator ring, the longitudinal impedance of the monitor had to be kept low and the pick-up was designed to behave like a wall current monitor at high frequency. A maximum value of Z/n of 70 mΩ has been measured up to 3 GHz. The pick-up is wide band, 60 kHz to 250 MHz for the sum signal and 500 kHz to 250 MHz for the difference. Single bunch trajectories are measured using integrators. A sensitivity of 470 mV/A and 15 mV/A.mm have allowed measurements to be made with a resolution of 10^7 particles per bunch and ± 1.6 mm for 2.10^8 particles.

General requirements

The purpose of the LPI complex is to accelerate and accumulate electrons and positrons which are destined for the CERN Large Electron Positron ring [1]. The LPI complex comprises 2 linacs, an Electron Positron Accumulator (EPA) and the Electron and Positron Transfer Lines leading to the CERN Proton Synchroton (PS).

During its passage through the LPI machines, the bunch shape, as well as its intensity evolves. Starting in the linacs, before the electron/positron converter, the bunch length is between 12 and 25 nS and the intensity between 3.10^{10} and 5.10^{11} electrons After the converter, the lengths remain in the range 12 to 25 ns and the intensity varies from 2.10^8 to 6.10^9 particles. The bunches are accelerated to 600 MeV before injection into EPA where each linac pulse coïncides with one of eight pre-synchronized buckets. In EPA, the bunch is quickly compressed to 3 nS length and during accumulation, the individual bunch intensities increase from 2.10^8 to $2.5.10^{10}$ particles. The range of peak bunch currents varies between 1 mA and 2.7 Ampères.

The precision required for the complete position measurement system (detector plus electronics) has two component parts [2] : 1) ± 0.5 mm zero offset for mechanical, alignement and electronic offset errors, and 2) ± 3% of output for linearity and gain errors.

To minimize costs and manpower, only one design of detector was considered for the whole LPI complex, and to allow trajectory and closed orbit measurements existing PS modules have been used. For compatibility, with these modules, the detector and transmission need to be wideband, also allowing analogue observation. The minimum bandwidth considered desirable was 400 kHz to 50 MHz [3]. Additional objectives for the pick-up design were set by the mechanical space available in the linacs and the longitudinal impedance seen by the beam. This parameter was important for EPA where 20 pick-ups are installed and the objective was to keep Z/n below 100 mΩ up to 3 GHz.

The total number of position detectors installed in the LPI complex is 42.

Choice of Magnetic Beam Position Detector

In most accelerators the beam position detectors are electro-static, so why have magnetic ones been chosen for the LPI ?

The anticipated beam losses and the injection efficiency of EPA indicated that significant numbers of secondary particles would be produced in the machines. Electro-static pick-ups are severely perturbed by accumulated charge and digital results would quickly lose all credibility. An additional reason was that, for a total length of 100 mm and a minimum internal diameter of 100 mm, it was inconceivable to make an electro-static pick-up to measure both horizontal and vertical positions with the sensitivity and precision required.

Incidental advantages obtained from the magnetic monitor are : 1) the possibility to have a calibration wire allowing simulation of the beam and 2) the derivation of the sum and the difference signals using passive components. Also, the beam position monitor, whilst not being a substitute for a dedicated beam transformer, allows the evolution of beam intensity to be monitored with a reasonable accuracy.

The principal disadvantages of a magnetic position monitor are : 1) the inherent longitudinal impedance, 2) the non-linearity, particularly of a dual plane detector, and 3) the low frequency response. This latter parameter is related to physical length and sensitivity and cannot be made as low as desired. Even given the possibility to increase the length,the Z/n impedance would increase.

Development of the LPI Beam Position Detectors

No simple way of precisely calculating all the parameters of a magnetic beam position detector could be found and the development followed an empirical evolution process with careful measurements and critical evaluation of results.

The schematic principle of a dual plane magnetic beam position detector is shown in Fig. 1. An accurately centred beam will produce an equal flux in the four coils, but if the beam is offset towards C, the flux in C will increase and decrease in A.

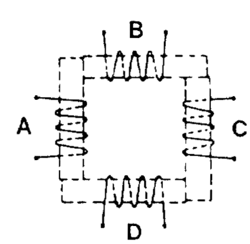

Fig. 1

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Adding a magnetic material has three effects :

1) it increases the low frequency time constant, an effect much more significant for the sum of the fluxes than for their difference. The difference being largely dependant on the free space, the reluctance of the magnetic path can, at most, be halved by the presence of a material with $\mu \gg 1$,
2) the shape of the magnetic material can modify the linearity of the detector. Initial tests with toroïdal ferrites gave less linear results than the square shape adopted for the final version. Probably better linearity could be obtained with a 'pin-cushion' magnetic frame but the cost would be prohibitive,
3) the ferrite also damps the high frequency resonances that occur in an otherwise empty box.

Initial tests were carried out with multiple turn windings, symmetrically spaced, on a permalloy toroïd. The beam was simulated by a current carrying conductor through the centre. The results were unsatisfactory with strong resonances within the required pass band. An improved mechanical structure, and ferrites replacing the permalloy was tested with grounded and floating windings feeding additional secondary transformers. Little improvement could be observed. A significant effect of electro-static pick-up was seen. Apparently the induced charge resonated with the self inductance and unsymmetrical ground capacitances. The number of turns on the ferrite frame was reduced and the optimum performance was obtained with a single wide turn kept as short as possible. Small secondary transformers were threaded onto the single turn windings and the number of secondary turns chosen for the sensitivity, longitudinal impedance and low frequency time constant.

The secondary transformers installed in the LPI monitors have 25 turns on a small 6 mm o.d. ferrite toroïd. Each of the 4 transformers sees 50Ω, therefore each primary impedance is 80 mΩ and the low frequency impedance seen by the beam is 20 mΩ. The sensitivity to be expected for the sum of the 4 outputs is 2 Volts/Amp.

Having reduced the primary windings to a single turn, their self inductance was reduced as was the L/R term. Increasing the number of secondary turns reduces R, but for a given sensitivity, the original value of L/R cannot be recovered. The values of low frequency time constant achieved are 330 ns for the difference signal and 2.5 µs for the sum.

During the development of the detector, comparison of beam impedances was made using a mechanically simple system and measuring the reflected wave with a network analyser. Later more precise measurements were made on a wide band test facility [4] [5]. The longitudinal impedance was greatly reduced when the single turn solution was adopted and improved even more when the single turns were brought in as close as possible to form a continuity of the vacuum chamber. Complete alignment was prevented by the ceramic ring for vacuum containment and the requirement to house the secondary transformers outside the vacuum.

Figure 2 shows a partial section through the pick-up and with figure 3, a partially assembled unit, it can be seen how much this detector resembles a wall current monitor.

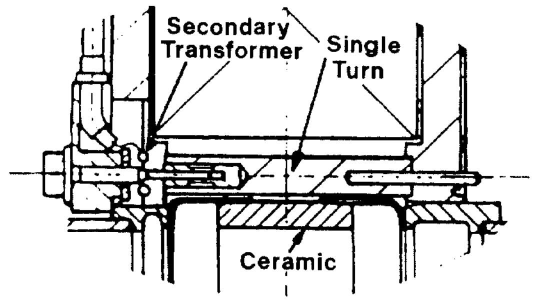

Fig. 2

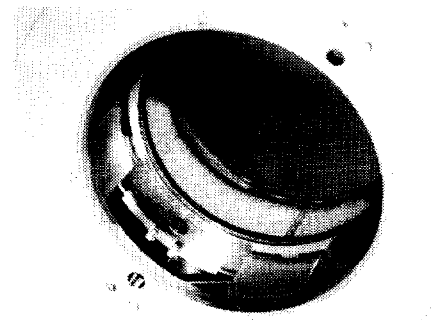

Fig. 3

Two calibration wires were built into every pick-up and situated at 45° to the horizontal and vertical planes. The wires are physically 50Ω semi-rigid cables with a short break in the insulation. They are situated outside the vacuum containment but inside the ferrites.

Investigations into the effects of small changes of µ and air gaps (up to 2 mm) between the blocks of ferrite showed little significant influence on the measurement of position but did alter the time constant of the sum signal. The sum signal was also slightly dependent on the beam position varying by roughly 1% over the complete excursion.

Hybrid Circuit

The hybrid circuit or magic Tee, converts the four signals from the position detector into two difference signals and a sum signal. The circuit has been designed for 50Ω input and output impedance. Commercial units could not be found to meet the common mode rejection requirements. Better than -56 dB up to 20 MHz was considered desirable, corresponding to 0.05 mm positional error. This result was consistently obtained with the circuit shown in Fig. 4.

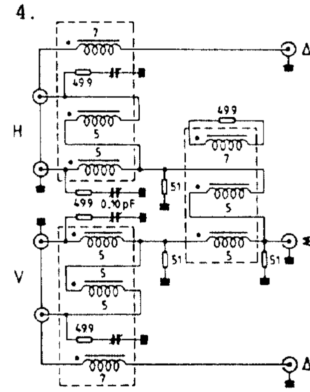

Fig. 4

The capacitors and input resistors compensate the normally inductive input and give better 50Ω matching. Low frequency time constant for the sum signal was improved by making a d.c. path and sacrificing 6 dB compared with a conventional hybrid. The finesse of the final adjustment lies in the lengths of wire between the p.c. board and the transformers and even the inclination of the transformers.

The theoretical sensitivity of the detector plus hybrid is 0.5 V/A but in practice approximately 0.5 dB is lost in winding resistance.

Hybrid performance measured with a current source :
Sum attenuation - 12 dB, bw d.c. to 250 MHz
Diff.attenuation - 4.3 dB, bw 160 kHz to 250 MHz

Mechanical Aspects of the Design

The magnetic position monitor consists of two sub-assemblies, the pick-up box and the vacuum tube, welded together. The rigid square box, made of stainless steel, houses 4 ferrite blocks of square section (40 X 40 X 160 mm) retained by springs and 4 Cu 'electrodes', the primary windings are brazed to one wall of the box with particular attention being paid to the accuracy of their angular and radial positions. The opposite wall provides openings for the small ferrite toroïdal transformers mounted on pins that engage in the primary windings. The box also contains two calibration lines going from wall to wall.

A ceramic ring (100mm i.d.), with a resistive metallization inside (~ 10 kΩ) to prevent charge accumulation, is welded to the stainless steel tubes and flanges which, in turn, are welded to the pick-up box. The top of each box has a support for the geometer's sphere and an arrangement for adjusting its position.

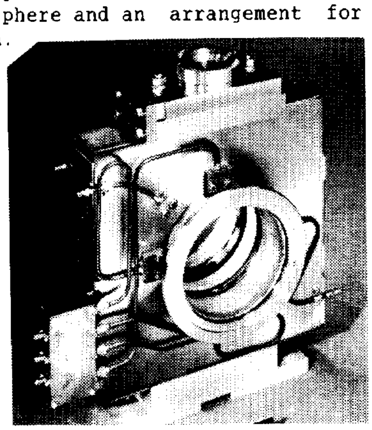

Fig. 5 Assembled Monitor

Measurement Table

The ultimate accuracy of a beam position monitor depends on the measurement table and the calibration procedures. The equipment used for the LPI pick-up consists of a very precisely machined pick-up holder mounted on a milling machine. This table allows the position of the geometer's sphere support to be adjusted with respect to the position of the primary turns of the detector to an accuracy of ± 0.1 mm.

A current to simulate the beam passes through a very thin Cu Be wire terminated in 50Ω. The wire is held taut by a weight touching a bath of mercury to provide electrical continuity. Measurements were made at 10 MHz but the system was unaffected by the mismatched calibration wire up to 50MHz.

Direct measurements of difference/sum have been made using a Network Analyzer with a computer to acquire and calculate the results. Every pick-up has been measured for electrical zero, sensitivity, non-linearity and horizontal to vertical interdependance.

Errors have been compensated by a third order equation :

$$\text{Position} = a_0 + a_1 (1 + b\,y)x + a_3\,x^3$$

x = difference/sum signal for horizontal plane
y = difference/sum signal for vertical plane

Typical values are :

$$\text{Position} = 0.24 + 31.9\,(1 + 0.06\,y)\,x - 1.61\,x^3 .$$

The residual errors are < ± 0.2 mm for up to ± 40 mm excursion.

System considerations and Performance of Detector

The very wide range of beam intensities seen by some of the detectors makes it necessary to amplify the signals locally. Low noise amplifiers having gains of 50 and equivalent noise input of 3 $nV.Hz^{-1/2}$ are commutable when required. The amplifier bandwidth is 150 MHz but a more important limitation is due to cable attenuation typically reducing the bandwidth received in the control room to 100 MHz. CK50 cable has been used for the signal transmission and distances vary between 50 and 230 metres. To economise on cable costs, it was decided not to have differential transmission unless interference levels proved it necessary. The practical results show this was a good economy for the signals received are all clean.

Calibration generators have been made using r.f. VMOS FETs, driven by step recovery diodes, to discharge delay lines. Reference zener diodes and the very low "on" voltages of the VMOS FET assure consistent pulses. Where amplifiers are installed, the pulses are reduced by parallel current transformers driven from a master pulse.

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