LHC Beam Instrumentation Detectors and Acquisition Systems.

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Abstract

This paper will aim to give an overview of some of the detectors and acquisition systems being developed for measuring and controlling beam parameters in the LHC. The two largest systems concern the measurement of beam position, with over 1000 monitors, and beam loss, with over 3000 monitors. For the beam position system a novel wide band time normaliser has been developed to allow bunch-by-bunch 40MHz acquisitions with a dynamic range greater than 30dB and an overall linearity of better than 1%.

Also mentioned will be the acquisition system for the fast beam current transformers and the development of CdTe detectors for luminosity monitoring.

I. INTRODUCTION

The beam instrumentation for a particle accelerator encompasses all instruments and acquisition systems observing beam behaviour. In essence they are the "eyes" of the machine operators, and serve to control and optimise the accelerated beams.

The two largest systems in the LHC will be the beam position system with ~500 monitors per LHC ring and the beam loss system with over 1500 monitors per LHC ring. The majority of these detectors will be located at the quadrupole magnets distributed around the circumference of the LHC.

In addition, dedicated systems will be built to measure the beam intensity and lifetime, the beam size (both transverse and longitudinal), the collision rate and luminosity, and also some indirect parameters derived from beam oscillation measurements, such as the machine tune, chromaticity and coupling.

This paper will address the detectors and acquisition systems for the beam position and beam loss systems, the fast intensity measurement and the luminosity measurement.

II. THE LHC BEAM POSITION MEASUREMENT SYSTEM

The beam position measurement system is a key element of the instrumentation of any accelerator. In the case of the LHC, equal attention will be given to the system for the rings and the SPS to LHC transfer lines, of which the latter form an installation nearly as large as the present beam orbit system of the CERN-SPS. The specifications for both systems are very similar and hence a common approach for the readout electronics and for the calibration system is planned. The pick-ups themselves are different as the majority of the ring pick-ups are at cryogenic temperature, whereas all transfer line pick-ups are at room temperature.

A total of some 100 monitors are required for the SPS to LHC transfer lines, while ~1000 monitors measuring both the horizontal and vertical planes will be installed for the main LHC rings. A certain number of monitors around the experimental insertions have to be directional, as both beams pass in the same beam tube.
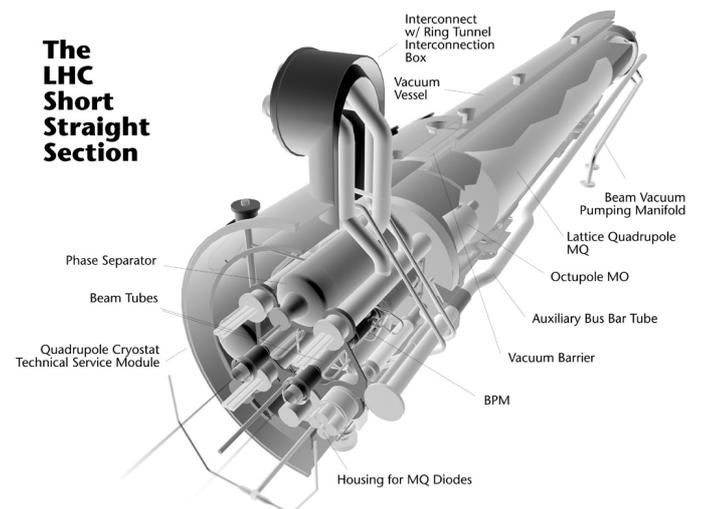
A. The LHC Arc Position Monitors

Figure 1: Location of the LHC beam position monitor (BPM) in an arc quadrupole.

Figure 1 shows the location of a standard LHC beam position monitor in a Short Straight Section (SSS) cryostat containing a main quadrupole magnet. A close-up of the monitor can be seen in Figure 2. It consists of four button electrodes that couple electrostatically to the beam to give signals whose amplitudes depend on the beam position. By comparing horizontal and vertical signal pairs, the resultant position can be determined.
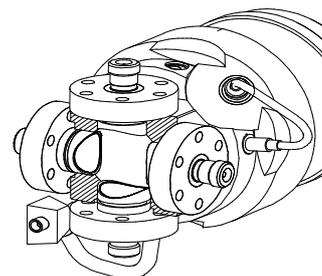

Figure 2: The standard LHC button electrode position monitor.

B. The LHC Interaction Region Position Monitors

In the regions close to the four experiments, where both beams occupy the same vacuum chamber, the button monitor is replaced by a stripline electrode (see Figure 3). This couples electromagnetically with the beam, allowing the signals from each beam to be distinguished. For an ideal so-called 'directional coupler' the signal from a given beam only appears at the upstream port.
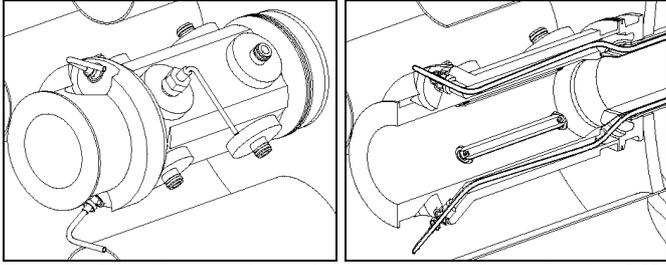

Figure 3: The directional stripline coupler pick-up for the LHC interaction region magnets. The cut shows the electrode and liquid helium capillary exits.

C. The Beam Position Acquisition System

Table 1 shows the three filling schemes of the LHC on which the choice of acquisition system had to be based. The first is the so-called 'pilot bunch', which is a low intensity bunch that will not quench a magnet, even if it is completely lost within a length of a few meters. This lowest possible beam intensity defines the required sensitivity limit for most beam instruments. The 'nominal' and 'ultimate' filling schemes are foreseen for luminosity production, and have 2808 bunches per ring with, for the most part, a bunch spacing of 25ns.

Table 1: LHC filling schemes and related bunch intensities.

Parameter	Pilot	Nominal	Ultimate
Particles/bunch	5×10^9	1.1×10^{11}	1.7×10^{11}
No. of bunches	1	2808	2808
Beam current (mA)	0.009	557	860
Bunch current ratio (dB)	0	27	31
Beam current ratio (dB)	0	96	100

The last two columns of Table 1 show the ratio of bunch and beam currents for these filling schemes respectively. If the analogue front-end electronics has a low bandwidth, such that it partially or completely integrates over all bunches, an amplitude range of over 90 dB would have to be covered. On the contrary, if the system is made with a bandwidth larger than the bunch spacing then only the variation in bunch intensity has to be taken into account, reducing the dynamic range to around 30dB.

A new technique known as 'Wide Band Time Normalisation' was therefore developed at CERN to fulfil this requirement [1]. Figure 4 shows the block diagram of the actual wide band time normaliser circuit. After passing through a 70MHz low-pass filter, the pickup signal from each electrode is split, and one half delayed by 1.5ns. The delayed signals are then recombined with the un-delayed signals from the opposite electrode. The position information is obtained from the difference in the zero crossings of both output signals.
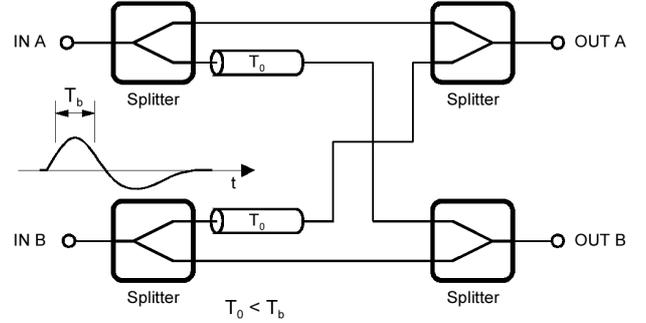

Figure 4: Block diagram of the time normaliser circuit

This working principle is illustrated in Figures 5 and 6. Figure 5 shows the normaliser input signals for three extreme cases:

a) beam in the centre (both signals equal)

b) beam close to pickup A

c) beam close to pickup B

while Figure 6 shows the corresponding normaliser output signals and their position dependent zero crossing.
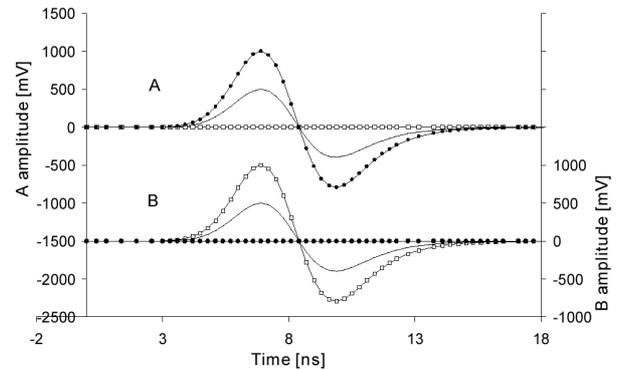

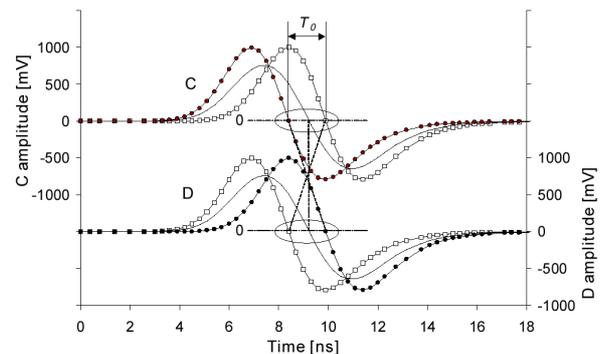Figure 5: Normaliser input signals.

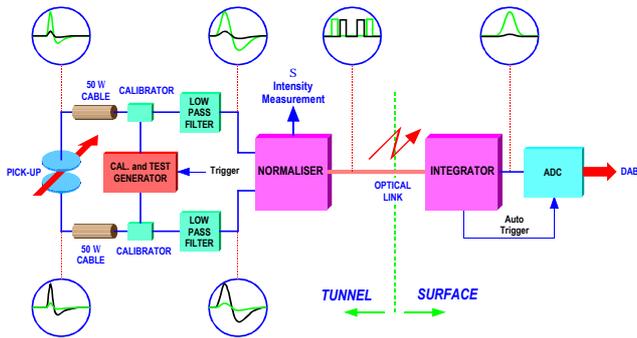Figure 6: Normaliser output signals showing position dependent zero crossing.

Figure 7: Layout schematic of the LHC beam position acquisition system.

The complete layout of the LHC beam position system can be seen in Figure 7. The very front-end electronics consisting of the normaliser and calibration circuits are located underneath the quadrupoles containing the beam position monitors. After the normaliser stage the position information is encoded in a pulse width modulation, which is transmitted via an optical fibre link from the tunnel to the surface. Here the signal is integrated to retrieve the position information from the pulse width, before being digitised using a 40MHz 10-bit ADC. Using this topology only the analogue electronics is exposed to tunnel radiation (~12Gy/year), avoiding the problems associated with the irradiation of sensitive digital electronics components. The analogue card has undergone testing in the CERN-TCC2 zone and did not show any significant deterioration in performance even after an integrated dose of 650Gy.
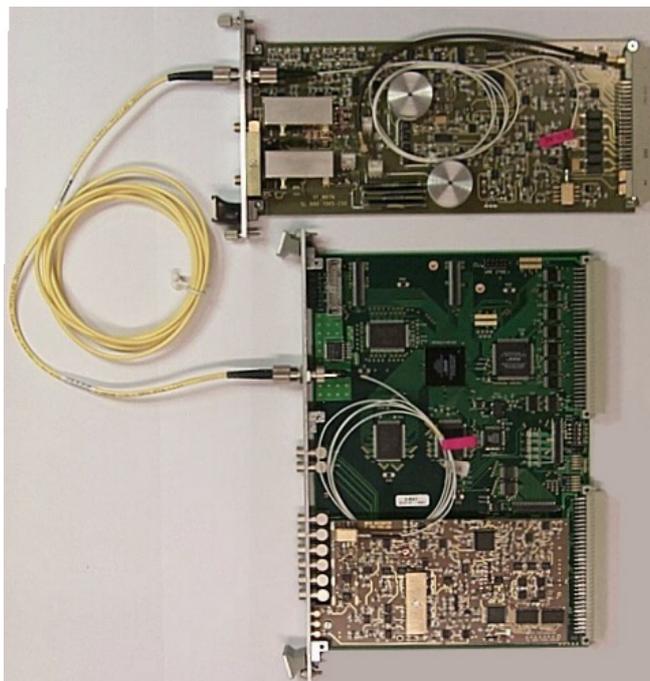

Figure 8: Wide band time normaliser front-end card (top), optical link, integrator/digitiser mezzanine card and VME digital acquisition board.

Figure 8 shows the electronics cards that will be used in the LHC and its transfer lines: the front-end card, the optical link, the mezzanine integrator/digitiser card and the VME digital acquisition board (developed by TRIUMF, Vancouver, Canada). The digitised data is treated on the VME card to give three types of data:

1. Global and batch orbit data – the global or batch average positions of all bunches measured over 20ms (to avoid 50Hz noise) and repeated every 100ms (giving 10Hz real-time data).

2. Capture data – single shot acquisition of the position of selected bunches for a given number of turns (maximum of 100,000 positions).

3. Post mortem data - a rolling buffer containing the last 1000 turns of average position data and the last 1000 orbit acquisitions.

In addition to lowering the overall dynamic range of the system, measuring the position of each bunch in the machine also has a great diagnostics potential. A prototype system in the CERN-SPS [2] is extensively used for electron cloud and instability studies where bunch-by-bunch resolution is imperative (see Figure 9).
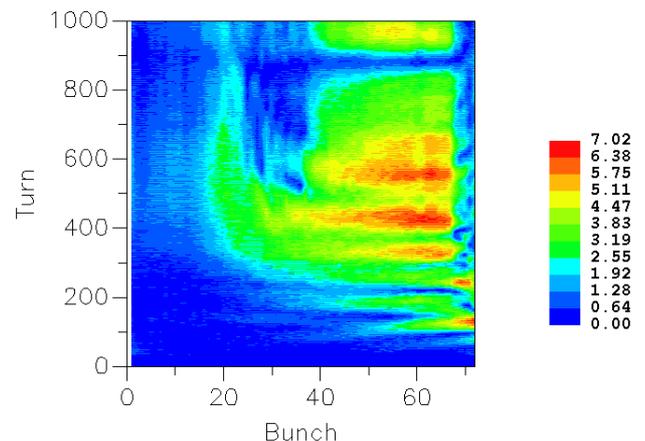

Figure 9: Beam oscillation amplitude in mm along one batch of 72 bunches in the CERN-SPS. An instability due to electron cloud build-up is seen to occur for bunches towards the tail of the batch.

III. THE LHC BEAM LOSS MONITORING SYSTEM

The beam loss monitoring system for the LHC has three main roles to play, which in order of importance are:

a) to protect the elements in the LHC from any damage.

b) to dump the beam in order to avoid time consuming magnet quenches.

c) as a diagnostics tool to improve the performance of the LHC by localising small losses.

These functions set the limits on the acquisition requirements for the ionisation chambers and subsequent electronics that will be used to measure the beam loss in the LHC. Some 3000 of these monitors will be located around the

LHC arcs, 3 per ring at each quadrupole, with additional fast systems located in the collimator regions (Points 3 and 7) to detect rapid beam loss [3].
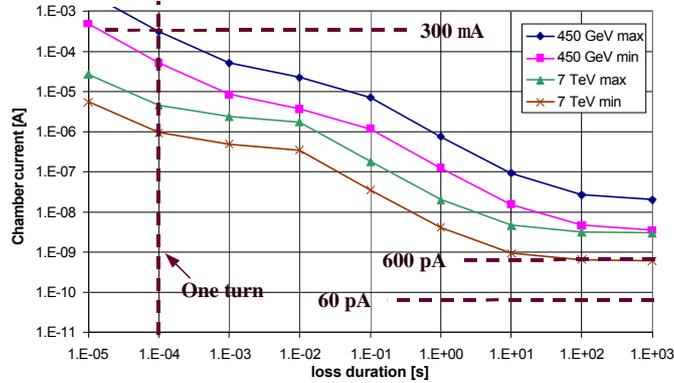

Figure 10: Calculations of quench level equivalent chamber currents for injection and collision energy as a function of the loss duration.

From the calculation of quench level equivalent chamber signals (Figure 10) the arc system will have to cope with currents from 600pA to 300μA. However, in order to obtain sufficient sensitivity for low losses the dynamic range has to be further extended by an order of magnitude to give a total operating range from ~60pA to ~300μA. As can be seen from Figure 10, the system also has to be capable of integrating small currents for long periods (up to between 10s-100s) while being able to detect large losses at the one turn level (89μs).

A. The Beam Loss Monitor Acquisition System

A schematic layout of the system can be seen in Figure 11. The ionisation chamber converts any particle losses into an electric current which is fed into an analogue front-end. This in turn is linked via a digital link to the surface where a so-called 'dump controller' processes the data and interfaces to the beam interlock system.
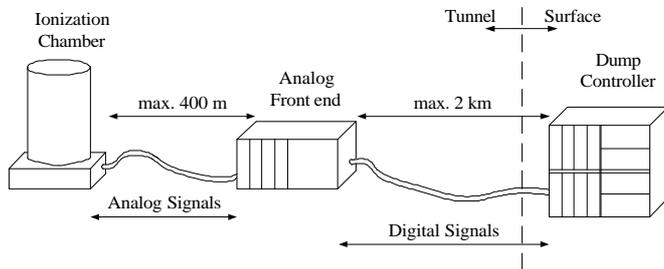

Figure 11: Schematic layout of the LHC beam loss monitoring system.

The analogue front-end processing will be based on charge-balanced conversion (see Figure 12) [4]. The signal from the ionisation chamber will be integrated and compared to a predefined upper threshold. Once this threshold is reached a one-shot is fired which switches on a constant current source to discharge the integrating capacitor until a

lower threshold is attained and the current source is switched off. In this way the frequency of the one-shot reset output is proportional to the input current from the ionisation chamber. As can be seen from Figure 13 the frequency ranges from a few Hertz to MHz for currents of 60pA to 300μA respectively with a linearity better than 1%.

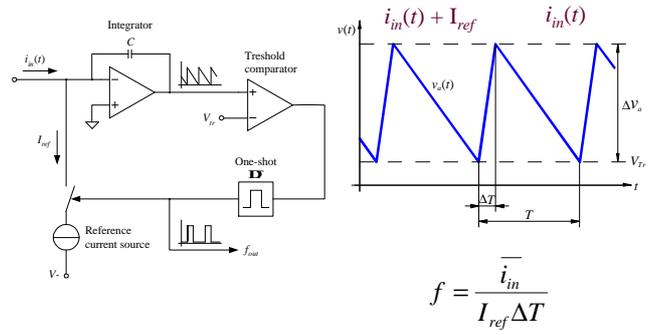$$f = \frac{\overline{i_{in}}}{I_{ref}\Delta T}$$

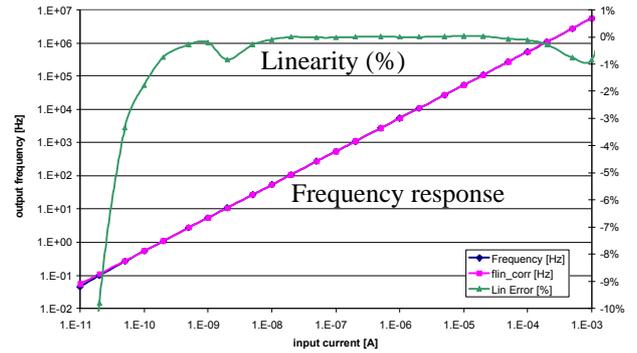Figure 12: Charge-balanced conversion.

Figure 13: Frequency range and linearity for the analogue front-end of the beam loss system.

The analogue front-end will count these reset pulses using an 8-bit asynchronous counter, with each count representing a fixed amount of charge. Every 40μs or so, the count from all six channels for a given quadrupole will be multiplexed into a Manchester encoded serial stream and transmitted to the surface. This transmission can either be done using differential cable transmission or via a fibre-optic link. The cable transmission has been tested for 2Mbit/s for distances up to 1.8km. However, for longer distances or higher transmission rates a fibre-optic link will be necessary. The decision on which transmission technique to implement will depend on the final layout and specifications of the beam loss system.

The surface dump controllers will be responsible for decoding the data from each channel and implementing an algorithm that compares the measured beam loss to the quench limits for the current energy. A 'master dump card' can then take these inputs from all the beam loss systems in a given octant to determine whether or not to dump one or both beams. The dump controller cards will also be required to save the input data for post mortem analysis and machine studies.

IV. FAST BEAM INTENSITY MEASUREMENT FOR THE LHC

The fast beam intensity measurements for the LHC will be capable of 40MHz bunch-by-bunch acquisition of intensities ranging from 5×10^9 to 1.7×10^{11} charges/bunch. A similar system has recently been installed and operated in the CERN-SPS. A picture and schematic of this transformer and its housing is shown in Figure 14.
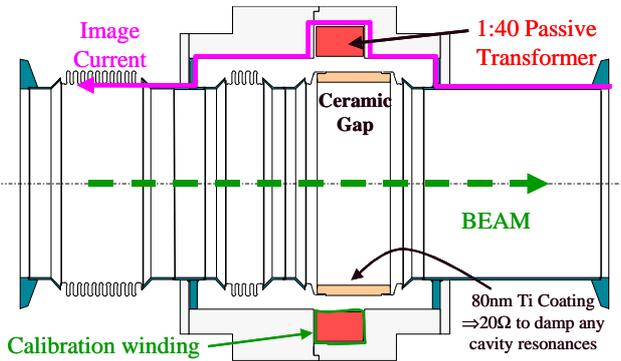

Figure 14: The CERN-SPS fast beam current transformer. The LHC transformer will be a scaled version of this design.

In order for the transformer to couple with the beam, a ceramic gap is placed in the vacuum chamber with an associated current by-pass to deviate the wall current around the outside of the transformer. An 80nm titanium coating is placed on the inner wall of the ceramic gap to damp any high frequency resonances caused by the by-pass cavity. The transformer itself has a bandwidth of 500MHz and a very low droop ($< 0.2\%$ /µs).

The analogue acquisition electronics uses an integrated circuit designed and developed by the Laboratoire de Physique Corpusculaire (Clermont-Ferrand, France) for use in the LHCb Preshower Detector [5]. The chip uses interleaved, 20MHz integrators and track and hold circuitry to give a 40MHz integration rate. This has been incorporated by CERN into a PMC style mezzanine card that also performs a 12-bit, 40MHz digitisation and sits on the same VME digital acquisition board (TRIUMF, Canada) developed for the LHC

beam position system (see section I). A schematic of the acquisition system is shown in Figure 15.
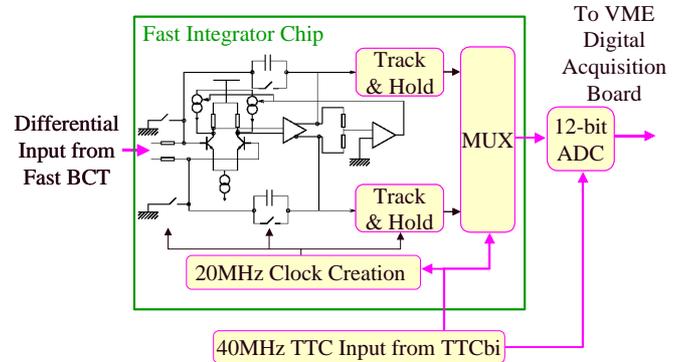

Figure 15: Schematic of the fast beam intensity measurement acquisition system.

The precise 40MHz timing is provided by the TTCbi card, part of the Timing, Trigger and Control (TTC) system developed for the LHC experiments [6].

An example of the integrator output measured with LHC type beam in the CERN-SPS is shown in Figure 16.
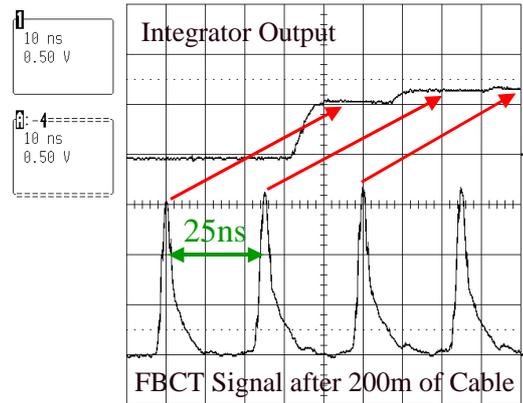

Figure 16: Example of the integrator input and output signals measured with an LHC type beam in the CERN-SPS.

V. LHC LUMINOSITY MEASUREMENT

The LHC luminosity monitors will sit in the TAN neutral absorber blocks either side of the experiments. Their purpose is to detect the particle showers created by the neutral particles hitting this absorber. The amplitude of this signal can then be used to optimise the collision rate and calculate the luminosity. They must be capable of 40MHz bunch-by-bunch acquisition and be able to withstand a very high radiation dose estimated at around 10^8 Gy/year. In total they will be subjected to around 10^{18} neutrons/cm^2 and 10^{16} protons/cm^2 over their lifetime (some 20 years of LHC operation). For this reason the installed system must be made maintenance free and hence as simple as possible.

The two candidates for such detectors are ionisation chambers and Cadmium Telluride (CdTe). Ionisation chambers are being developed by LBNL (Berkeley, USA) as

part of the CERN-US LHC collaboration and have the advantage of being radiation hard [7]. However, they are very difficult to get working at 40MHz [8]. In parallel CERN, in collaboration with LETI (Grenoble, France) are developing detectors based on polycrystalline CdTe [9]. These fulfil the 40MHz requirement, but are yet to be proven for the highest levels of radiation. In this section, only the CdTe detectors will be discussed.

CdTe detectors have been used at CERN for many years in the LEP accelerator as X-ray detectors for measuring the transverse profiles of electron and positron bunches. During this time they accumulated a total dose of some 10^{14}Gy (of which nearly all came from high energy X-rays) without significant deterioration.

Polycrystalline CdTe has several advantages as a luminosity detector over competing technologies. The response time is very fast (with typical signal rise times in the order of 2ns) it creates a large number of secondary electrons per incident MIP (typically 5 times more than diamond detectors) and allows for a very simple construction.
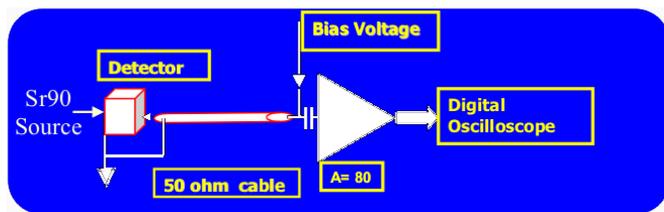

Figure 17: Experimental set-up

Figure 17 shows the set-up used for testing the response of the polycrystalline CdTe detectors to minimum ionising particles from an Sr90 source. The signal is amplified using a high gain GaAs broadband amplifier (DBA) developed by GSI (Darmstadt, Germany) [10], which also supplies the high voltage bias of between 100-600V required by the CdTe.
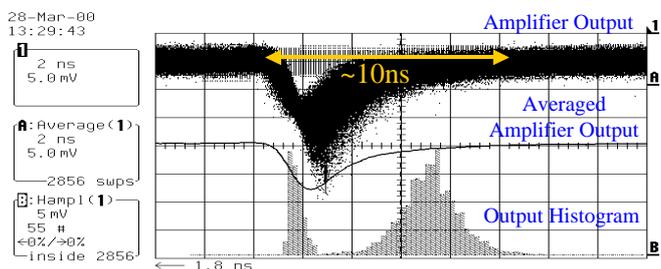

Figure 18: Typical response signals to single MIP events

Figure 18 shows some typical response curves from the CdTe after amplification. The averaged trace clearly shows the fast rise time of the signal and that the total signal duration is less than ~10ns. The signal amplitude, although small, is also seen to be distinguishable above the noise floor.

In order to test the immunity of the system to radiation, an initial experiment was performed during 2001in the CERN-SPS, accumulating around 10^{15} neutrons/cm^2. The results

from this test can be seen in Figure 19. It can be seen that although there is a slight increase in the pulse length after irradiation, there is no marked decrease in the signal level. First results from a subsequent test at a Triga type nuclear reactor in Ljubljana, Slovenia during 2002, with up to 10^{16} neutrons/cm^2 are also promising with no significant deterioration observed. The next step will be to reach the 10^{18} neutron/cm^2 level and qualify the detector for LHC operation.
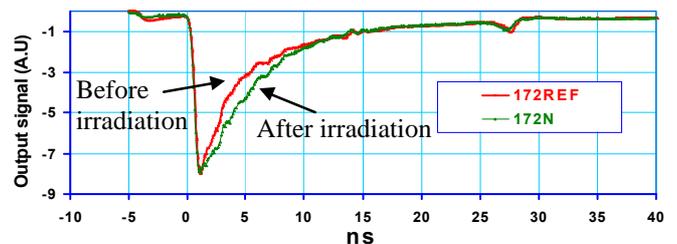

Figure 19: CdTe signal response before and after irradiation with up to 10^{15} neutrons/cm^2.

VI. REFERENCES

[1] D. Cocq, "The Wide Band Normaliser: a New Circuit to Measure Transverse Bunch Position in Accelerators and Colliders", Nucl. Instrum. Methods Phys. Res., A 416, 1998.

[2] D. Cocq et al, "First beam tests for the prototype LHC orbit and trajectory system in the CERN-SPS", CERN-SL-2001-030-BI, presented at DIPAC2001, Grenoble, France, May 2001.

[3] E. Gschwendtner et al, "The Beam Loss Detection System of the LHC Ring", CERN-SL-2002-021-BI, presented at EPAC2002, Paris, France, June 2002.

[4] W. Friesenbichler, "Development of the Readout Electronics for the Beam Loss Monitors of the LHC", CERN-THESIS-2002-028, June 2002.

[5] G. Bohner et al., "Very front-end electronics for the LHCb preshower", LHCb-2000-047, CERN, 2000.

[6] B.G. Taylor, "TTC Distribution for LHC Detectors", IEEE Trans. Nuclear Science, Vol. 45, No. 3, pp. 821-828, 1998.

[7] J. F. Beche et al., "An ionization chamber shower detector for the LHC luminosity monitor" presented at NSS-MIC 2000, Lyon, France, Oct 2000, 5/136-44 (v.1).

[8] P. Datte et al., "Electrical Design Considerations for a 40MHz Gas Ionization Chamber", presented at PAC2001, Chicago, IL, USA, 18, Jun 2001, New York, 2002. - pp.e-proc. 1327.

[9] E. Rossa et al., "CdTe Photoconductors for LHC Luminosity Monitoring", Nucl. Instrum. Methods Phys. Res., A : 480 (2002) no.2-3, pp.488-93.

[10]P. Moritz et al., "Broadband Electronics for CVD-Diamond Detectors" presented at ICNDST-7 2000, Hong Kong.