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LHC BEAM INSTRUMENTATION

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Abstract

The LHC will have very tight tolerances on nearly all beam parameters. Their precise measurement is therefore very important for controlling and understanding the machine. With over two orders of magnitude higher stored beam energy than previous colliders, machine protection is also an issue, with any beam losses having to be closely monitored. This presentation will aim to give an overview of the beam instrumentation foreseen for the LHC together with the requirements for initial and nominal operation. A summary of the main systems will be followed by a discussion of areas where there have been recent advances, such as in the measurement of tune, chromaticity and coupling.

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The LHC will have very tight tolerances on nearly all beam parameters. Their precise measurement is therefore very important for controlling and understanding the machine. With over two orders of magnitude higher stored beam energy than previous colliders, machine protection is also an issue, with any beam losses having to be closely monitored. This presentation will aim to give an overview of the beam instrumentation foreseen for the LHC together with the requirements for initial and nominal operation. A summary of the main systems will be followed by a discussion of areas where there have been recent advances, such as in the measurement of tune, chromaticity and coupling.

INTRODUCTION

For each of the various stages of LHC commissioning the functionality requested from the beam instrumentation will evolve, leading ultimately, it is hoped to full functionality for nominal operation. A brief summary of when the various systems are required is presented below:

<u>Sector test and first turn</u>

- Optical transition radiation screens.
- Single pass beam position measurement.
- Fast beam current transformers.
- Beam loss monitors.

<u>Circulating beams at injection energy (450 GeV)</u>

- Multi-turn position measurement.
- DC beam current transformer.
- Beam lifetime measurement.
- Single shot tune, coupling and chromaticity measurement.
- Emittance measurement using wire scanners.

<u>Acceleration</u>

- Continuous orbit, tune, coupling and chromaticity measurement – with possible feedback on some or all of these parameters.
- Continuous emittance monitoring via the synchrotron light monitor and/or the ionization profile monitor.

<u>First Collisions</u>

- Collision rate monitors.
- Schottky monitors for non-perturbative tune, chromaticity and emittance measurement.

BEAM POSITION MEASUREMENT SYSTEM

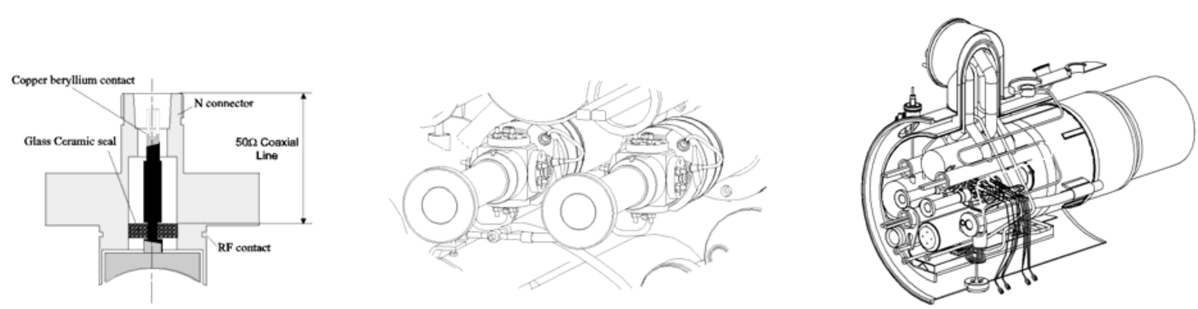
The LHC orbit and trajectory measurement system has been developed to fulfil the functional specifications described in [1]. The system consists of 516 monitors per LHC ring, all measuring in both horizontal and vertical planes.

Beam Position Pick-ups

The majority of the LHC beam position monitors (860 of the 1032) are of the arc type (Fig. 1). These consist of four 24mm diameter button electrode feedthroughs mounted orthogonally in a 48mm diameter beam pipe. The electrodes are curved to follow the beam pipe aperture and are retracted by 0.5mm to protect the buttons from direct synchrotron radiation from the main bending magnets. Each electrode has a capacitance of 7.6 ± 0.6 pF, giving a transfer impedance of 1.4Ω, and is connected to a 50Ω coaxial, glass-ceramic, UHV feedthrough.

The button feedthroughs are connected to the cryostat feedthoughs via semi-rigid, 50Ω coaxial cables capable of coping with a high radiation environment and the temperature gradient from cryogenic to ambient temperature. These semi-rigid cables are constructed from copper clad stainless steel inner and outer conductors to give good electrical conductivity and poor thermal conductivity, and use a silicon dioxide foam dielectric. The N-type connectors on either end use a glass-ceramic dielectric seal. The cables work in a frequency range up to 2GHz, with the electrical length difference in each quadruplet (i.e. the four cables associated with a single BPM) being less than 10ps.

The inner triplet BPMs in all interaction regions are equipped with 120mm, 50Ω directional stripline couplers



(a) (b) (c)

Figure 1: Arc Beam Position Monitor Pick-ups. (a) 24mm button electrode, (b) Mounted BPM bodies, (c) Location in the main quadrupole cryostat including semi-rigid coaxial cables.

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capable of distinguishing between counter propagating beams in the same beam pipe. The location of these BPMs has been optimised by placing them away from parasitic beam crossings to further enhance the directivity. A 120mm stripline length was chosen as it gives a similar signal to that of the button electrode, so allowing the use of the same acquisition electronics for all monitors.

Beam Position Acquisition System

The LHC orbit and trajectory acquisition system is based on a Wide Band Time Normaliser (WBTN) capable of processing the analogue signals from the pick-up at 40MHz. This wide band time normalisation principle developed at CERN [2] encodes the position information for each passing bunch into a pulse width. The analogue normalisation process is performed in the tunnel, with the pulse width encoded signals transmitted to the surface via a single mode fibre-optic link using a 2mW, 1310nm laser transmitter (Fig. 2). In this way the radiation sensitive digital electronics can be separated from the more robust analogue electronics which will be subjected to a dose of 12Gy per year or more during nominal LHC running. On the surface the position information is decoded, digitised using a 10-bit ADC, and processed by a custom made VME64x Digital Acquisition Board (DAB64x) developed by TRIUMF, Canada [3].

The DAB64x is capable of working in parallel in two different modes: orbit and turn-by-turn. In orbit mode the incoming position data is validated, calibrated and averaged over 20ms to eliminate 50Hz noise. This is repeated at a frequency of 10Hz, so allowing the possibility of a 1Hz closed loop bandwidth for orbit feedback. In turn-by-turn mode the user is free to choose when, for which bunch(es) and for how many turns the DAB64x stores the position data. This mode has been extensively used on a prototype system in the CERN-SPS to study multi-bunch instabilities.

The LHC beam position system has a linearity of better than 1% of the half radius, corresponding to ~130μm for arc BPMs, and has a single shot, single bunch resolution of ~50μm for a nominal bunch. During orbit measurements the resolution is at the micron level, which is what is required by the collimator system for maintaining efficient cleaning.

BEAM LOSS MEASUREMENT SYSTEM

The LHC will operate with an unprecedented amount of stored beam energy, approximately 200 times greater than at previous hadron accelerators. In addition, the operation of the superconducting magnets at very high fields (8-9T) leaves very little heat margin. This has the effect of reducing the quench levels by an order of magnitude compared to other superconducting accelerators (Fig. 3). The combination of these two factors means that a single pilot bunch of 5×10^9 protons is close to the damage level at 7TeV, while a loss of only 3×10^{-7} of a nominal beam over 10ms can create a quench at 7TeV. In order to monitor and react to these losses the LHC will be equipped with a comprehensive beam loss monitoring system [4] capable of fulfilling the following criteria:

- Protecting the LHC from damage.
- Dumping the beam before a magnet quench is allowed to occur.
- Diagnosing and improving the performance of the accelerator.

The system consists of over 3500 beam loss monitors, the majority of which are 50cm long, 1.5 litre, nitrogen filled ionisation chambers. These have been optimised to give an ion collection time of 85μs, i.e. less than one LHC turn. They will be located around each quadrupole magnet (six per quadrupole), in the collimator regions, and at other aperture restrictions around the machine. In order to fulfil the three criteria mentioned above the system has to

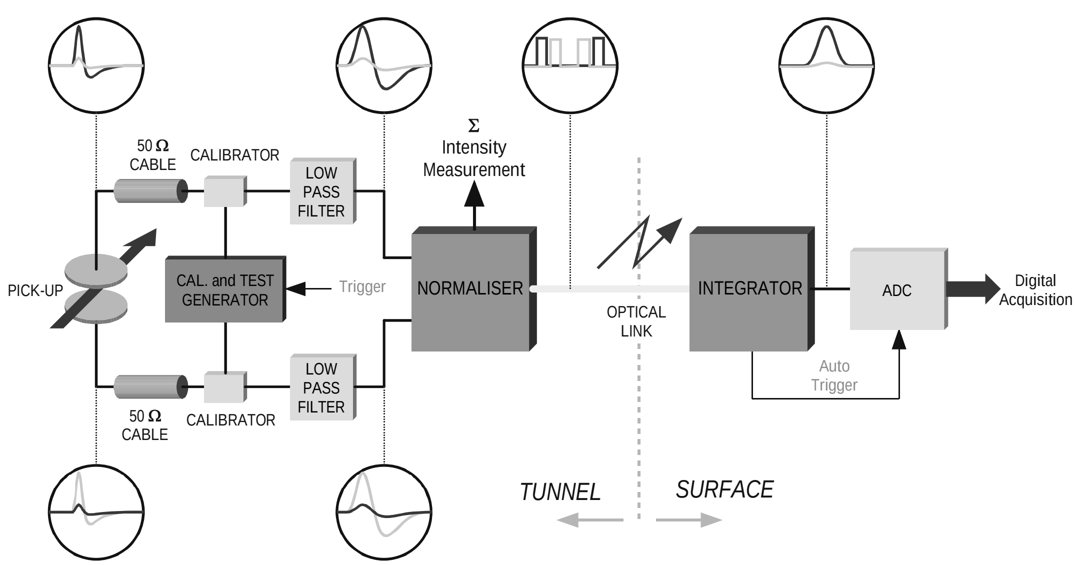


Figure 2: Implementation of the Wide Band Time Normalisation electronics for the LHC BPM System.

be able to cope with a total dynamic range of some 10^{13}. This is achieved by combining the ionisation chambers with secondary emission monitors (SEMs) having ~30000 times smaller gain.

Beam Loss Monitor Acquisition System

The same acquisition system will be used for both the ionisation chambers and SEMs, and will be based on current to frequency conversion. The frequency ranges from 0.01Hz to a MHz for currents of 3pA to 300μA respectively with a linearity better than 5%. The analogue front-end will count the reset pulses of the converter using an 8-bit asynchronous counter, with each count representing a fixed amount of charge. Every 40μs, the count from all six channels for a given quadrupole will be multiplexed into a Manchester Encoded serial stream and transmitted to the surface using a Gigabit Optical Link with cyclic redundancy. The surface electronics calculates the integrated loss values for time periods of between 80μs and 100s and compares them to a table of threshold values which depend on loss duration and beam energy.

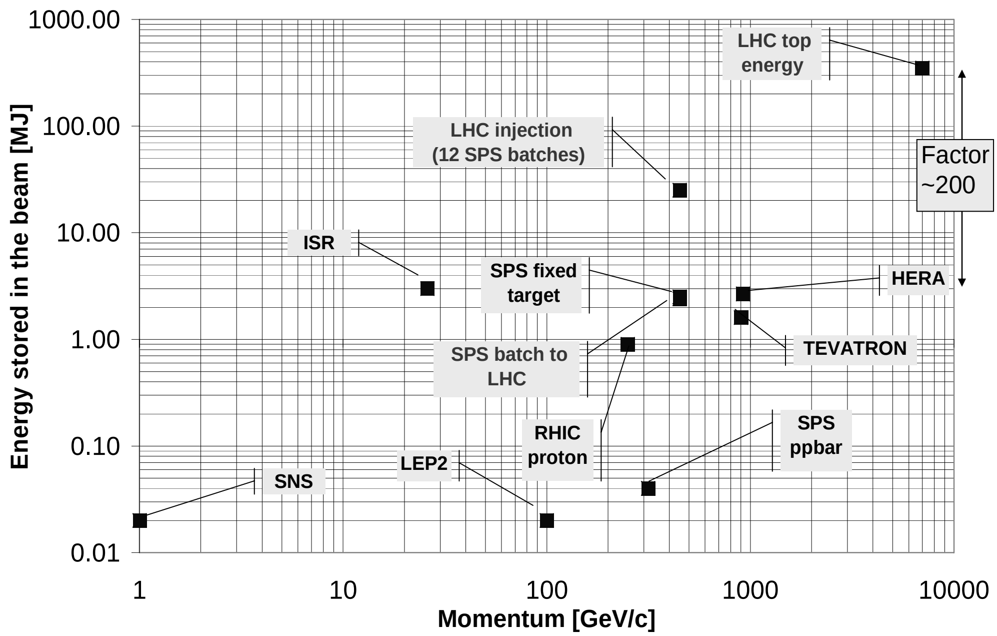
Beam loss monitor acquisition is an integral part of the machine protection system, and for losses occurring on a time scale of less than 10ms is the only loss detection system available for the LHC. For this reason the failure rate and availability requirements are very stringent and have been evaluated using the Safety Integrity Level (SIL) approach. The system has been calculated to reach SIL3 level, corresponding to a probability of not detecting a dangerous beam loss of 10^{-3} per year. This is achieved by duplicating the signal treatment chain for all elements after the current to frequency conversion, incorporating error correction and detection techniques and constantly monitoring the availability of all monitors.

MEASUREMENT OF TUNE, CHROMATICITY AND COUPLING

The implementation of tune, chromaticity and coupling measurements in the LHC will proceed in three clear steps. On Day 1 the measurements will be carried out with kicked beams, with the tune measured by Fourier analysis of the resulting beam oscillation, chromaticity measured either via the head-tail method [5] or by observing the tune change due to slow momentum variation, and coupling measured by combining information from horizontal and vertical beam oscillation data. The excitation will be performed either using a dedicated tune kicker or by chirp excitation using the transverse damper.

As soon as possible the single kick approach will be replaced with phase locked loop (PLL) tune tracking, allowing continuous tune, chromaticity and coupling measurements to be performed with minimal emittance growth. Once the PLL measurement has been confirmed to be robust then the final step of feedback on tune, chromaticity and coupling can be attempted.

The time scale for moving through these three stages will depend on the quality of the tune measurement and on the robustness of the PLL operation.



Quench Levels	Units	*Tevatron*	*RHIC*	*HERA*	*LHC*
***Instant loss* (0.01 - 10 ms)**	[J/cm^3]	4.5 10^{-03}	1.8 10^{-02}	2.1 10^{-03} - 6.6 10^{-03}	8.7 10^{-04}
***Steady loss* (> 100 s)**	[W/cm^3]	7.5 10^{-02}	7.5 10^{-02}		5.3 10^{-03}

Figure 3: Comparison of stored energy and quench levels at various accelerators

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Measuring Oscillations at Very Low Amplitudes

Considerable progress has been made over the past few years in detecting oscillations at very low amplitudes. This has been made possible by the development of the Base Band Tune (BBQ) measurement system [6], which has now been installed and tested in the CERN-PS Booster, PS, SPS, and at BNL-RHIC and FNAL-Tevatron. Based on AM detection techniques the advantages of this system are the following:

- Sensitivity - the noise floor of the BNL-RHIC system has been calculated to be in the 10nm range.
- Robustness against saturation.
- Simplicity and low cost.
- Base band operation allowing the use of excellent 24 bit audio ADCs and powerful signal processing.

Tracking the Tune using a Phase Locked Loop

The LHC PLL tune tracker is being developed in collaboration with BNL and FNAL as part of US-LARP. The advantage of this technique is that it provides a continuous tune measurement with a resolution in the 10^{-5} range for a bandwidth of 1-10Hz. The LHC PLL tune tracker acquisition system will use a BBQ front-end to detect the low amplitude oscillations, combined with a digital PLL algorithm implemented in an FPGA. In addition to tracking the tune it also allows the measurement of chromaticity via momentum variation and, if configured correctly, can provide a continuous measurement of coupling [7].

Tune, Chromaticity and Coupling Feedback

Experience from other machines has shown that it is not trivial to go from a PLL tune tracker to a complete tune feedback loop. Although feedback was available from an early stage at BNL-RHIC, for example, there has been considerable difficulty in making it reliable under varying machine conditions. The two main problems encountered were the fact that excessive coupling immediately breaks the feedback loop, and the saturation of the front-end electronics due to closed orbit variations.

These problems have been intensively studied by the CERN-BNL-FNAL collaboration through LARP, and with the advances in detection sensitivity and coupling measurement mentioned above it is hoped that they have to a large extent been solved. In fact, during 2006 BNL-RHIC managed a world first by being the first machine to successfully ramp with both tune and coupling feedbacks turned on, reaching full energy with good transmission at the first attempt.

BEAM SIZE MEASUREMENT

The preservation of transverse beam emittance is important for maximising the luminosity in all circular colliders. LHC is no exception, which is why it is equipped with several instruments for measuring the transverse beam size.

The injection and dump lines are equipped with 12μm, Ti foil OTR monitors which will be used to set up the lines as well as verifying the beam size at their locations. In addition, a further OTR monitor is fitted with a fast camera, capable of capturing turn by turn images for optimising the injection matching.

For the circulating LHC beam, the instrument of reference, used for calibrating the other monitors, is a linear wire scanner. Eight such systems are installed in the LHC, one operational and one spare system per plane and per beam. These are fitted with 30μm diameter carbon wires capable of moving at up to $2ms^{-1}$ across the beam aperture. The shower particles created by the beam/wire interaction will be detected by a photomultiplier placed downstream of the wire location, with the resulting signal integrated using a fast 40MHz integrator ASIC [8]. This gives the possibility of measuring the beam size on a bunch to bunch basis. However, the heat deposition in the wire and the possibility of quenching the downstream superconducting magnets with the shower particles produced limit the use of the wire scanners to a few nominal bunches at 7TeV.

The workhorse foreseen for on-line monitoring of the beam size in the LHC is the synchrotron light monitor. From injection energy (450GeV) to 2TeV this will use the light produced by a dedicated, compact, 2 period, 5T, superconducting undulator while from 2TeV to top energy (7TeV) the parasitic light produced by a neighbouring separation dipole is sufficient. A dielectric coated silicon mirror extracts the synchrotron light, which is then collimated, filtered and focussed onto a 10Hz CCD camera providing a direct video signal to the control room. The monitor is also fitted with a fast camera capable of being gated on a single bunch or groups of bunches for special studies.

LHC is also installed with a rest gas ionisation monitor, a prototype of which has been successfully tested in the CERN-SPS. This is mainly foreseen for ion operation, as the current synchrotron light monitor cannot be used due to insufficient synchrotron light emission, while the rest gas ionisation signal is enhanced as compared to protons, scaling as Z^2.

MEASUREMENT OF COLLISION RATES

The design and construction of the collision rate monitors for the high luminosity experiments of the LHC (ATLAS and CMS) is under the responsibility of LBNL (US). These monitors will be mounted inside the TAN absorber, a 5 tonne block of copper used to protect the downstream magnets from neutral collision debris.

The main challenges associated with building this instrument is the requirement to provide 40MHz, bunch by bunch data with a 1% relative accuracy and the fact that the detector has to withstand a very harsh radiation environment with an overall expected dose over its 20 year lifetime of over 3GGy and 10^{18} neutrons/cm^2.

The detector is based on a four quadrant ionisation chamber [9] which, in addition to giving a signal proportional to the collision rate, also provides information about the crossing angle. Only metal and ceramics are used in the construction of the monitor, making it very resistant to radiation damage.

The main problem with an ionisation chamber detector is the time required for the ionised gas to be collected at the electrodes. Even fully optimising the high voltage and gas pressure in the chamber still gives a final pulse of ~100ns in length, clearly well above the 25ns maximum pulse length required for 40MHz operation. A pre-amplifier sitting just outside the detector is therefore followed by a shaper, whose job it is to reduce this pulse length to less than 25ns. This shaped pulse is integrated using a fast integrator and the resulting signal is digitised and treated in an FPGA based VME64x acquisition card. In this way it has been shown that the instrument gets very close to the bunch to bunch measurement requested, although some deconvolution of the final signal may still be required for nominal operation.

OTHER BEAM INSTRUMENTATION

Beam Current Transformers

The LHC will be equipped with a dual set of both DC and fast beam current transformers for redundancy reasons. These have to be capable of monitoring currents ranging from 10μA for a single circulating pilot bunch to over 0.5mA for a full nominal machine. The resolution of the DC transformer is limited to ~2μA, requiring the fast transformer to be used when filling with a low number of bunches. The fast transformer will also be used for lifetime measurement and for measuring bunch to bunch intensities. The latter is again performed using the 40MHz integrator ASIC [8].

Abort Gap Monitors

Constant monitoring of the 3μs abort gap will be required from very early on in LHC operation to avoid systematic quenching when dumping the beams. The quench level at 7TeV is at the level of $7x10^7$ protons per 100ns in the abort gap, corresponding to 7ppm of the nominal beam. Detection of such low intensities is difficult with electromagnetic monitors, which is why the LHC system will be based on detecting the synchrotron light emitted during the abort gap using a gated photomultiplier. Since the available light is shared with the synchrotron light monitor and that the photomultiplier has only a 7% efficiency this equates to detecting 128 photons per 100ns per turn at $1/10^{th}$ of the quench level. This is a fairly comfortable detection level, considering that the signal can be integrated over several tens of milliseconds.

Schottky Monitors

The LHC Schottky system has been designed by FNAL and is based on travelling wave pick-ups [10]. The advantage of this type of pick-up is that it can provide bunch to bunch Schottky information. For the LHC, the centre frequency will be set to 4.8 GHz with a minimum bandwidth of 200MHz to allow bunch by bunch gating. A triple down-conversion scheme combined with heavy filtering will be used to move the Schottky sidebands into the baseband, keeping an instantaneous dynamic range of >100dB throughout. One in the baseband the system will use the same processing electronics as the LHC tune system to provide continuous FFT spectra [11].

SUMMARY

The LHC beam instrumentation systems have moved through the research and development and construction phases, and are now being installed and commissioned without beam. Significant progress has been made to address the remaining challenges, with much of this made possible through the US-LARP collaboration and the testing of new techniques on existing machines such as BNL-RHIC and FNAL-Tevatron. If all goes well the LHC will turn on with a comprehensive set of beam instrumentation built to very high specifications.

ACKNOWLEDGMENTS

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