THE LHC ORBIT AND TRAJECTORY SYSTEM

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Abstract

This paper describes the definitive acquisition system selected for the measurement of the closed orbit and trajectory in the CERN-LHC and its transfer lines. The system is based on a Wide Band Time Normaliser (WBTN) followed by a 10-bit ADC and a Digital Acquisition Board (DAB), the latter developed by TRIUMF, Canada. The complete chain works at 40MHz, so allowing the position of each bunch to be measured individually. In order to avoid radiation problems with the electronics in the LHC tunnel, all the digital systems will be kept on the surface and linked to the analogue front-ends via a single mode fibre-optic connection. Slow control via a WorldFIP field bus will be used in the tunnel for setting the various operational modes of the system and will also be used to check power supply statuses. As well as describing the hardware involved, some results will be shown from a complete prototype system installed on four pick-ups in the CERN-SPS using the full LHC topology.

INTRODUCTION

The installation of the cabling structure and magnets in the LHC tunnel and its transfer lines started a few months ago in order to be ready for the commissioning in 2007. The complete Orbit and Trajectory system design is already definitive. The BPM sensors and electronics have been tested on the SPS, and the series production has started or will start by the end of the year for most equipment. This paper will review the chain of equipment involved in this system: from the beam sensors to the acquisition and processing units. The results of the tests in the SPS during 2002 will be also presented.

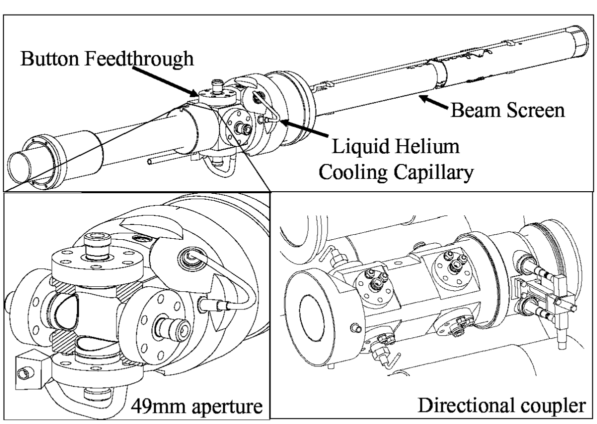

Figure 1. a) BPM body used in the LHC arcs. b) Zoom of the electrodes. c) Directional coupler used near the interaction points.

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COMPLETE SYSTEM LAYOUT

In the short straight sections of the LHC ring there is one BPM monitors per ring, per quadrupole. They are connected through a cryogenic coaxial cable to the outside of the cryostat and then to an electronic chassis, placed on the floor under the quadrupole. Each chassis contains a power supply card, 4 Wide Band Time Normaliser (WBTN) cards, an intensity measurement card and a control-communication card. The different working modes of the chassis are set and monitored through the control card, which receives and sends information via a WorldFip field bus. The measured position (or the intensity) of the beam is sent to the surface through a single mode optical fibre at 1310 nm. At each of the 8 access points, there are two racks, one per half octant. Inside each, there are 4 VME chassis, with a CPU, a TTC timing receiver card, and up to 18 Digital Acquisition Boards (DAB). Each DAB is able to handle the data from two measured planes. The calculated orbits are sent at 10 Hz through an Ethernet link up to a central processor, which calculates and sends any corrections to the orbit correctors and to the control room. Figure 2 shows the explained scheme.

BEAM SENSORS

The sensors used to measure the position of the beam in the LHC are going to consist mainly of a BPM body with 4 button electrodes (about 1008) placed at one end of each quadrupole, as shown in Fig.1a) and b). However, near the interaction points the two beams are going to share the same vacuum pipe, making it necessary to use directional couplers (about 24 in total) in order to discriminate with the desired resolution the position of each beam. The length of the strip-line coupler has been designed in order to provide the same shape of signal as that from the button electrodes. This is a critical requirement given the “timing working mode” of the front-end electronics. The induced signals will be transmitted to the outside of the cryostat through eight semi-rigid cryogenic 50Ω coaxial cables. All this equipment will be installed inside the cryostat (in a secondary vacuum environment) at 5-25 K, with very high radiation dose levels (up to about 1000Gy/y). Moreover, through out the lifetime of the LHC, they have to withstand being cooled down and warmed up from 5K to 300K (and vice versa) tens of times without damage or deterioration to the seals or the electrical connections, since they will be extremely difficult to access after installation. As a consequence, hard requirements on the thermal conductivity, vacuum, impedance, electrical length and radiation tolerance are imposed which make their manufacturing and testing a challenge.

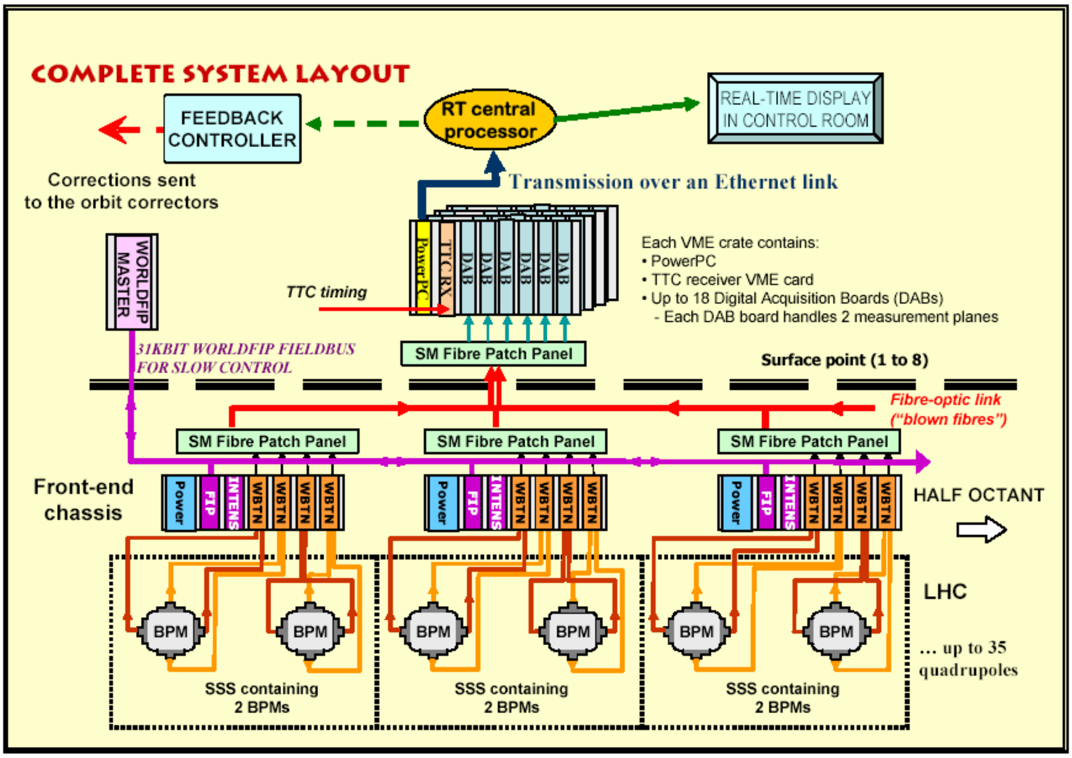

Figure 2. Layout of the LHC orbit and trajectory system.

TUNNEL ELECTRONICS

One of the main issues to take into account from the design stage of the electronics that will be placed in the LHC tunnel is the radiation tolerance they have to withstand. Doses up to 10G/y in the arc areas and up to 20Gy/y near the dispersion suppressor are expected [1]. Conventional electronics do not resist these levels. Because of that, the decision was taken to place all digital systems in surface buildings. Only the front-end electronics (called Wide Band Time Normaliser - WBTN) will remain under the quadrupoles, using specially designed rad-hard power supplies, a control-communication card and a fibre optic link to the surface. A beam intensity measurement card based on the same technology is also foreseen.

Front-end electronics

The WBTN uses an original method of normalizing the beam position with respect to the beam intensity. The method consists of measuring the time interval between the zero crossings of two signals which are the result of recombining the direct and delayed signals coming from opposite electrodes [2]. This method results in a system with a wide bandwidth up to about 70 MHz (able to measure the position of individual bunches) and a wide dynamic range of about 50 dB (from $1\cdot10^9$ to $2\cdot10^{11}$p per bunch). In order to be radiation tolerant, it has been based on ECL high-frequency components which tolerate up to $5\cdot10^4$ Gy. Figure 3 shows the measured linearity as a function of the bunch charge.

This card also provides a sum signal which is foreseen to be used in an intensity measurement.

The power supplies are simple linear power supplies with specially designed rad-hard voltage regulators. These can be remotely monitored, and switched on/off.

Control electronics

The remote control of the chassis status is performed with a dedicated digital module. This monitors and sets the configuration of the chassis thorough a rad-hard anti-fuse FPGA (used extensively in space applications) and reads and sends the information through a WorldFip field-bus at 31.25kbps. The WorldFip components have been successfully tested in radiation environments [3].

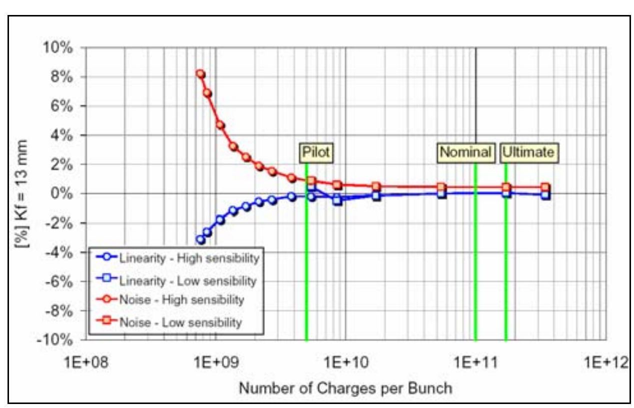

Figure 3. Linearity of the WBTN (LHC beam position front-end electronics card). Measured with a centered bunch of variable intensity.

Transmission systems

The position or intensity measurement (depending on the user request) is sent to the digital acquisition system on surface through a 1310 nm single mode optical fibre that will be blown through about 2 km of optical ducts. In both cases, the analogue data is coded in the time interval between the rising edges of two consecutive pulses (between 8.3 ns and 11.7 ns). This coding method has several advantages. The calibration of each segment in order to compensate for different lengths is not needed. Additionally the system will be less sensitive to the pulse degradation (in amplitude or rise time) due to ageing or radiation damage. A Fabry-Perot laser diode of 2 mW power and 1 GHz bandwidth will be used as the transmitter. This is the power required in order to have a jitter on reception smaller than 8 ps (~0.2% of resolution), considering that the ageing and radiation will increase the fibre attenuation and decrease the power efficiency of the laser diode. The expected attenuation (based on tests) of this fibre with the radiation is smaller than 3 dB/km after 500 Gy The decrease in power efficiency of the lasers after being irradiated has been considered negligible, smaller than a 5%.

ACQUISITION ELECTRONICS

The acquisition electronics is split in two parts:

i) First a mezzanine card that receives the optical signal and makes the AD conversion of the position of each bunch (40MHz) at 10bits.

ii) Secondly a Digital Board Acquisition (DAB) which takes care of the selection, sorting, pre-processing and validation of the data. The DAB has been developed by TRIUMF, in Canada. Each DAB is able to process the data from two planes of measurement (i.e. it has two mezzanines cards). It is capable of functioning in three parallel modes [4]:

- The *Orbit Mode*: calculates the accumulated position of all bunches, of each batch (up to 12), and of 16 selectable bunches over 224 turns (~20ms).
- The *Capture Mode*: In this mode, the user can obtain the turn by turn position information of selected bunches, or the sum of the positions in a given batch or the average position of all bunches over a large number of turns.
- The *Post Mortem Mode*: Records the last movements of the beam prior to total beam loss or a beam dump. It includes two cyclic buffers which contain the average of all bunches for the last 1000 turns and the last 1000 global orbit acquisitions.

There is also an extra working mode, called *Calibration Mode*, where the DAB is not synchronised to the 40 MHz bunch clock or to the 11 kHz revolution frequency. Instead, it uses the ADC strobe signal to trigger the acquisitions, allowing it to work independently of any machine timing. It is this mode which is used to calibrate the system using the pulses generated by a local 40 MHz oscillator on the low-level digital control card.

FUNCTIONAL TEST ON THE SPS

The LHC orbit system will be used as part of a real-time control system to stabilise both the global orbit and the local orbit at various positions in the rings. In order to explore the challenges of real-time control, it was decided to test a local orbit feedback system on the CERN-SPS. During 2002 this set-up involved equipping 4 horizontal pick-ups with the full chain of LHC acquisition electronics. Orbit measurements were performed every 100 ms, with the results transmitted to the control room, where they were displayed in real-time. The aim in 2003 will be to close the loop using a second real-time link connection to the existing orbit correctors. Figure 4 shows the display of the 4 pick-up positions throughout a complete SPS cycle, which is comprised of a 10 second injection plateau followed by acceleration from 26GeV to 450GeV. The resolution of the system was measured to be around 5µm with a reproducibility including shot to shot beam jitter of better than 20 µm. The linearity of the system was also tested using local orbit bumps and found to be within the estimated 5% accuracy of the position as calculated from the orbit corrector settings.

Figure 4. Control room display of the trajectory and orbit system during the 2002 tests on the SPS.

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