THE DCCT FOR THE LHC BEAM INTENSITY MEASUREMENT

P. Odier*, M. Ludwig, S. Thoulet, CERN, Geneva, Switzerland

Abstract

The LHC circulating beam current measurement is provided by eight current transformers, i.e. two DC current transformers (DCCT) and two fast beam current transformers (FBCT) per ring. This paper presents the DCCT, designed and built at CERN, including the sensor, the electronics and the front-end instrumentation software. The more challenging requirements are the needed resolution of 1μA rms for a 1s average, and the wide dynamic range of the circulating beam intensity from a single pilot bunch (8μA) to the total ultimate beam current of 860mA. Another demanding condition is the high level of reliability and availability requested for the operation and for the machine protection of this highly complex accelerator. The measurement of the first RF captured beam in ring 2 will be shown to demonstrate that the system is close to meeting these specifications both in terms of resolution and stability.

INTRODUCTION

The DCCTs, based on the fluxgate magnetometer principle [1], measure the mean current of the circulating beam. The DCCTs for LHC were designed according to tight engineering specifications [2] and built at CERN.

HARDWARE

General Layout

The DCCTs are installed in the long straight section in Point 4 of the LHC on a long girder which also supports the FBCT [3].

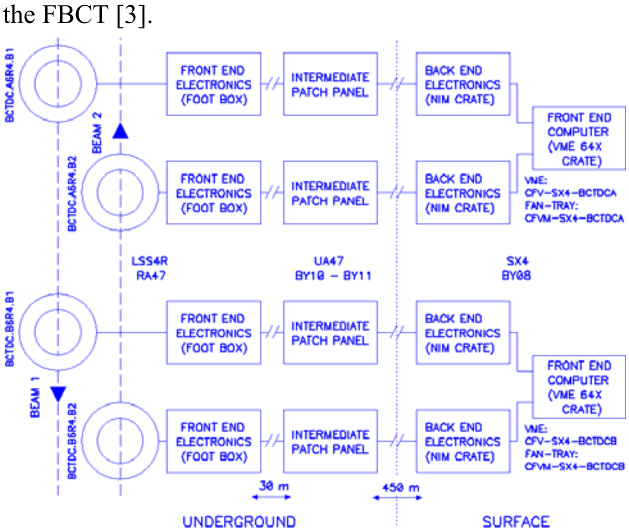

Figure 1: General Layout.

At this location the vacuum chamber is at room temperature and can be baked out to improve the quality of the vacuum. The front end electronics (FEE) is located in a shielded shelter under the girder and thus protected to some degree from beam induced radiation. An intermediate patch panel located in a parallel gallery housing the FBCT electronics provides an underground monitoring facility. The back end electronics (BEE), as well as the Front End Computer (FEC), are located in a surface building in Point 4 (Fig.1). The two systems named A, normally in operation, and B, normally kept as a spare, each contain one 1 DCCT per ring and 1 FEC.

Sensor

Different elements are installed between the external diameter of the vacuum chamber (64mm) and the internal diameter of the DCCT (114mm) [3]. This includes an electrical heater for baking out the vacuum pipe at 200ºC, combined with a thermal insulator and a water cooling circuit to ensure a temperature below 60ºC at the level of the magnetic cores.

The magnetic shielding is made of three layers of Mu-metal plus one external layer of pure iron. The external diameter (265mm) is limited by the second ring vacuum chamber (at this location the 2 beam pipe axes are separated by 192mm).

Figure 2: The DCCT with the connexions for the beam image current.

The "heart" of the DCCT consists of three ring cores of nanocrystalline alloy (inner diameter 146mm, cross-section 190mm^2, μ_i >100000) installed in a copper shielding. To avoid mechanical stresses and vibrations inducing noise, the cores are fixed loosely by flexible clips. Two cores, carefully matched to have an identical magnetization curve, are wound to form the fluxgate sensor. The third core is wound to form the AC part providing the bandwidth extension [4]. A magnetic shielding is placed between AC and DC cores to reduce the modulation ripple crosstalk. Two windings of 4 turns

*patrick.odier@cern.ch

embracing the three cores are used for the feedback and calibration. Two temperature probes (PT100) are fixed on the cores to monitor the DCCT output signal temperature dependence and to provide an alarm in case of overheating during the bake-out phase. The external layer of the shielding, electrically connected to the vacuum chamber via four copper braids on each side, offers a path for the LF components of the beam image current (Fig.2). The HF components pass through the DCCT via a series of capacitors placed around the ceramic gap cancelling the magnetic field induced by the beam current at these frequencies.

Back End Electronics

The BEE consists of separate modules placed in one NIM crate per DCCT (Fig.3). This modular approach allows for future improvement on particular elements and for retrofitting on existing DCCTs.

The SYNCHRO CLOCK generates both the modulation and demodulation clock (at twice the modulation frequency) with an accurate phase shift setting between them. A modulation frequency of 212Hz was chosen to avoid a very low frequency beat between the second harmonic of the modulation and any harmonics of the mains frequency.

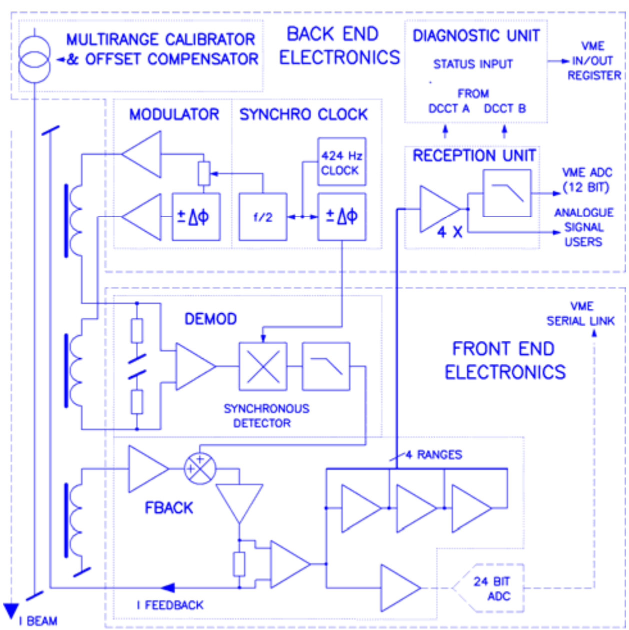

Figure 3: DCCT simplified schematics.

The MODULATOR generates the sinus wave used to modulate the two DC cores far into saturation. Small differences in the two cores are compensated by the amplitude balance and phase shift settings. A demagnetization process is automatically launched at power on.

The MULTIRANGE CALIBRATOR & OFFSET COMPENSATOR (CalPG) can generate a quick calibration sequence which consists of four successive calibrated current pulses sent into the sensor. This is performed on request and synchronously with the acquisition. The module also serves to remotely cancel the static offset.

The RECEPTION UNIT receives the analogue signal of four ranges, provided simultaneously, that cover the entire beam dynamic range from a few 10^9 to $5x10^{14}$ circulating charges (~3µA to ~900mA). After common mode rejection the 4 ranges are low-pass filtered before distribution to the various users. The cut off frequency ranges between 20Hz for the 12 bit ADC and 1.5 kHz for the analogue signal users.

The Acquisition and Control System consists of 4 VME boards served by a Central Processor Unit (CPU): the Timing Generator, the ADC, the Input/Output Registers and the Interface with the Safe Machine Parameter (SMP) System. The 12 bit ADC scans 16 channels (4 ranges and 4 auxiliary signals per DCCT) every 20ms.

The DIAGNOSTIC UNIT, which can be connected to the Input/Output Registers, will perform a crosscheck between systems A and B based on the comparison of the signals and statuses delivered by the DCCTs. The result of this check will help the instrument specialist to select the appropriate operational system.

Front End Electronics

The FEE consists of separate boards placed in one dedicated box per DCCT.

The modulation current of the two DC cores contains a second harmonic proportional to the DC beam current. The DEMOD board performs a synchronous detection of the second harmonic by multiplying the difference of the two modulation currents by the demodulation clock. The resulting signal has its frequency response limited to 10 Hz by a low pass filter.

The FBACK board adds the signals from the DEMOD board and from the AC winding and then generates the feedback current which, when passing through the sensor, cancels the magnetic field induced by the beam current. Measurement of the feedback current over a shunt resistor, taking into account the ratio of the number of turns, is a direct measurement of the beam current. The voltage drop across the shunt resistor is amplified by four different amplifiers providing in parallel the signals to the four ranges (spaced in sensitivity by a factor of 10) and to a fifth range dedicated to a 24 bit ADC. This ADC, soon to be added to the system, will have the highest resolution over the whole dynamic range and will transmit the data to the BEE via a serial link.

FRONT END SOFTWARE

The instrument front-end software runs on the CPU and reads out the ADC, selects an acquisition channel among the four ranges with optimum gain, averages data and controls the calibration. A common front-end software architecture is used to implement a set of real-time actions synchronized by events (acquire, publish). A structured shared memory (device) holds the data and provides the decoupling between the synchronized real-time activity and the nearly asynchronous user communication. A communication process provides standard but nevertheless client specific communication interface. The real-time Unified Modeling Language (UML) diagram (Fig.4) shows the synchronized communication between the ADC and calibrator (hardware objects boxed), acquisition and machine protection link, device buffers and result publication and user control (software objects circled). During normal acquisition the ADC is triggered at 50Hz, read out and linked to machine protection at 10Hz with the results published at 1Hz. In order to check the instrument precision before first injection into the LHC a quick calibration sequence (grey area) can be triggered. This acquires the noise and calibration signal of all four ranges and lasts some 4 seconds, during which time the machine protection link is disabled.

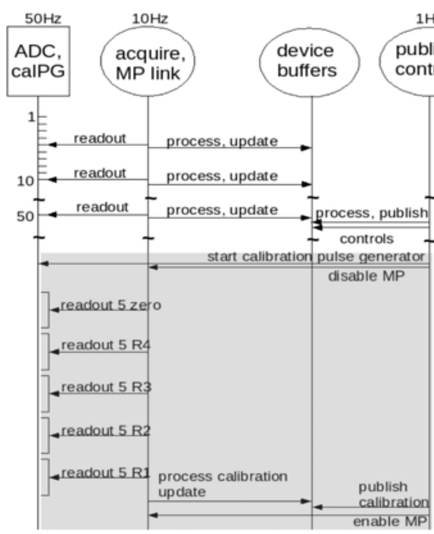

Figure 4: Real-time UML diagram showing hardware and software object invocation with time.

Interfaces and Usage

A standard software interface for general purpose provides the total beam intensity of each ring with a time resolution of 50Hz for the last 30s at an update rate of 1Hz. Further specialist interfaces provide the functionality for calibration and access to special functions such as simulation and client programs within the technical network of the control system. A dedicated optical link provides intensity acquisitions and status information to the LHC machine protection system at a rate of 10Hz.

FIRST RESULTS

During the first days of LHC running a fixed display, refreshed once per second was used to view the DCCT acquisition. It allowed the observation of total beam current as soon as the beam was circulating for more than 1 second (~11000 turns). This was the case for beam 2 on September 12th 2008. The two DCCTs on ring 1 were not commissioned with beam since beam 1 did not circulate for a sufficient duration before the LHC incident on September 19th 2009.

In Figure 5, one can see four successive injections of a single pilot bunch containing from 3.5×10^9 to 6×10^9 protons and circulating for between 100 seconds and 40 minutes. The DCCT used for this measurement was the operational system (A).

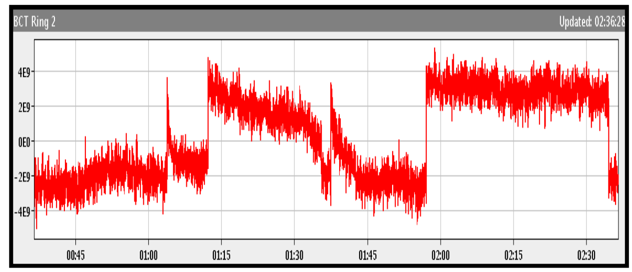

Figure 5: First circulating beam in ring 2 seen by BCTDC A (12/9/2008).

The noise and the slow fluctuation in the signal corresponds to 7×10^8 protons (rms value for a 1s integration time) which is equivalent to 1.3µA. There is a small negative offset of 2.5×10^9 (4.5µA) which should be automatically corrected for in the future.

CONCLUSION AND OUTLOOK

Although the beam time was not sufficient to commission the whole system, the short time with beam did allow confirmation that the DCCTs work as expected and meet the specifications in terms of noise and stability.

There are still numerous things to be commissioned with beam (DCCTs on beam 1, automatic range selection, transmission to the machine protection system and automatic offset correction). Also still to be implemented is the DIAGNOSTIC UNIT and the 24 bit ADC covering the entire dynamic range.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to J.Longo for his invaluable involvement in the project. Thanks are also due to many colleagues in the CERN mechanical workshops for their very high quality work.

REFERENCES

[1] P.Odier, "DCCT TECHNOLOGY REVIEW", CARE-Conf-2004-023-HHH, Lyon, December 2004.

[2] C.Fischer, R.Schmidt, "On the Measurements of the Beam Current, Lifetime and Decay Rate in the LHC Rings", LHC-BCT-ES-0001, EDMS 359172.

[3] D.Belohrad, S.Longo; P.Odier; S.Thoulet, "Mechanical Design of the Intensity Measurement Devices for the LHC", DIPAC'07, Venice, May 2007, WEPB09, p. 253 (2007).

[4] G.Gelato, "Beam current and charge measurement", Beam instrumentation, ed.J.Bosser, CERN-PE-ED 001-92.