THE BEAM ENERGY TRACKING SYSTEM

OF THE LHC BEAM DUMPING SYSTEM

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ABSTRACT

The LHC Beam Dumping System (LBDS) of the Large Hadron Collider (LHC), presently under construction at CERN, will be installed around the straight section 6. It comprises per ring 15 horizontally deflecting extraction kickers, followed by 1 quadrupole, 15 vertically deflecting steel septum magnets, 10 dilution kickers and, in a separate cavern several hundred meters away, an external absorber assembly. A beam dump request can occur at any moment during the operation of the collider, from injection at 450 GeV up to top energy at 7 TeV. The Beam Energy Tracking System (BETS) monitors the deflection strength of each active element of the LBDS with respect to the beam energy in order to guarantee the correct extraction trajectory over the complete operational range and under all operational conditions. Its main functions are the acquisition of the beam energy, the generation of the kick strength reference signals for the extraction and dilution kickers, the continuous checking that the charging voltages for the kicker high voltage generator capacitors follow their references within tolerance windows defined by the extraction channel aperture, the continuous surveillance that the quadrupole and septum magnet currents are within predefined tolerance windows and the generation of a dump request after detection of an upcoming tracking fault. The beam energy reference is obtained through look-up tables from redundant real time measurements of the current in the LHC main dipoles. This paper describes the BETS and reviews in detail its different functionality aspects.

INTRODUCTION

The LHC Beam Dumping System (LBDS) [1] of the Large Hadron Collider (LHC) provides loss-free fast extraction of the circulating beam from each of the two rings to an external absorber. It consists, per ring, of 15 horizontally deflecting extraction kicker magnets (MKD) followed by a superconducting quadrupole (Q4) providing some kick enhancement, 15 vertically deflecting septum magnets (MSD) and together 10 horizontal and vertical dilution kickers (MKB) to distribute the beam energy on an external absorber mounted in a separate cavern some hundred meters away.

A beam dump request can occur at any moment during the operation of the collider, from the injection energy of 450 GeV up to the maximum energy of 7 TeV. Each of the two sets of extraction kickers must operate synchronously within the 3 μs long beam abort gap foreseen for the rise of the kicker field, to deflect the beam safely into the extraction channel, in one single turn of 89 μs.

Incorrect operation of the extraction kickers can lead to full or partial beam loss and thus to severe damage to the machine, to the experiments or to the beam dumping system itself. The extraction kickers and their control system are therefore one of the most critical components of the beam dumping system, in terms of potential impact but also in terms of complexity.

The performance of each of the two extraction kicker systems is determined by three operational parameters: its state, its kick time and its kick strength [2]. To reflect this, their control architecture comprises three independent sub-systems, each dedicated to the control of one specific parameter: the State Control and Surveillance System (SCSS), the Trigger Synchronisation and Distribution System (TSDS) and the Beam Energy Tracking System (BETS).

Within the LBDS, the Beam Energy Tracking System (BETS) links the deflection strength of each active kicker sub-system to the beam energy in order to achieve the correct extraction trajectory over the complete LHC operational range and under all operational conditions.

BETS FUNCTIONALITY

The main functions of the BETS are:

- the acquisition of the beam energy through 4 independent measurements of the LHC main dipole magnet current;
- the generation of the kick strength setting references for the high voltage pulse generators of the extraction and dilution kickers w.r.t. the beam energy and the required extraction trajectory;
- the continuous surveillance that the charging voltages of the different capacitors within the high voltage pulse generators follow their references within predefined tolerance windows w.r.t the beam energy, the extraction trajectory and the physical aperture of the extraction channel;
- the continuous surveillance that the currents in the extraction septa and the ring quadrupole Q4 are within predefined tolerance windows w.r.t. the beam energy, the extraction trajectory and the extraction channel aperture;
- the generation of a dump request if the measured values are outside predefined tolerance windows w.r.t. the beam energy (i.e. a developing tracking fault is detected);
- the distribution of the beam energy to external clients.

Figure 1 shows the relationship between the BETS, the different LBDS sub-systems and its interfaces to external systems.
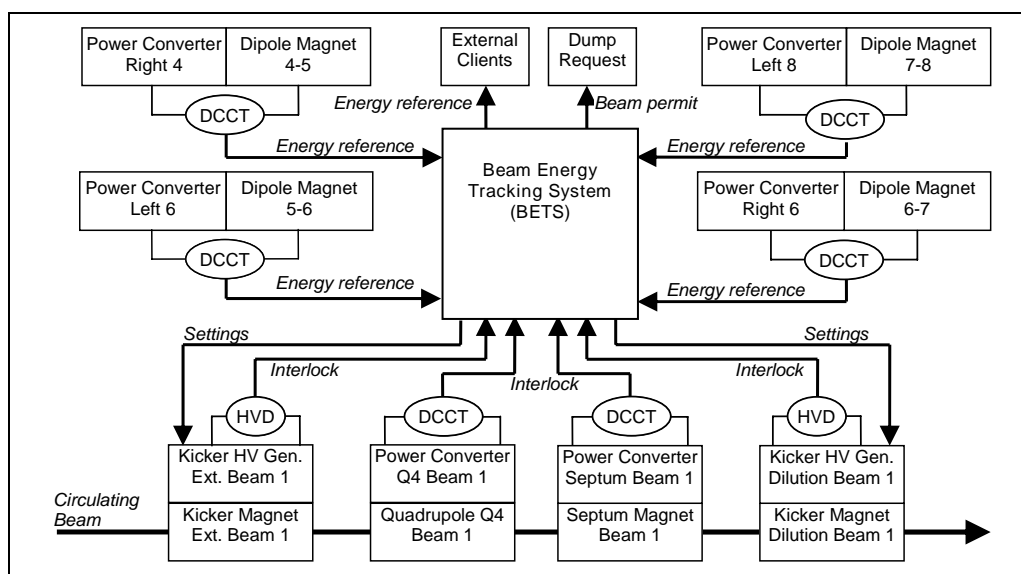

Figure 1: BETS context diagram

The BETS will be based on two redundant systems built using two different technologies. One system will be based on fail-safe SIEMENS SIMATIC S7-F Programmable Logic Controllers and will be implemented within the SSCS system. This system will be used for the generation of the DC Power Supply (DCPS) setting references for the extraction and dilution kickers and for the surveillance of the correct charging of the capacitors in the high voltage generators through redundant high precision High Voltage Dividers (HVD).

The other system will be based on dedicated hardware housed in a LynxOS VME front-end for the tracking surveillance of the extraction kickers, the ring quadrupole Q4, the extraction septa and the dilution kickers. Both systems have to be continuously in agreement. In order to reduce common mode failures independent and redundant sensors are used within each system. In case of discrepancy within a system or between the two systems a beam dump request will be issued.

BETS ARCHITECTURE

Two independent sources of information about the beam energy, $E_{beam}A$ and $E_{beam}B$, will be used within the BETS to control the correct tracking of the different LBDS sub-systems. $E_{beam}A$ will be used as beam energy reference signal for the generation of the kick strength settings and $E_{beam}B$ will be used as energy reference signal for the LBDS interlock logic.
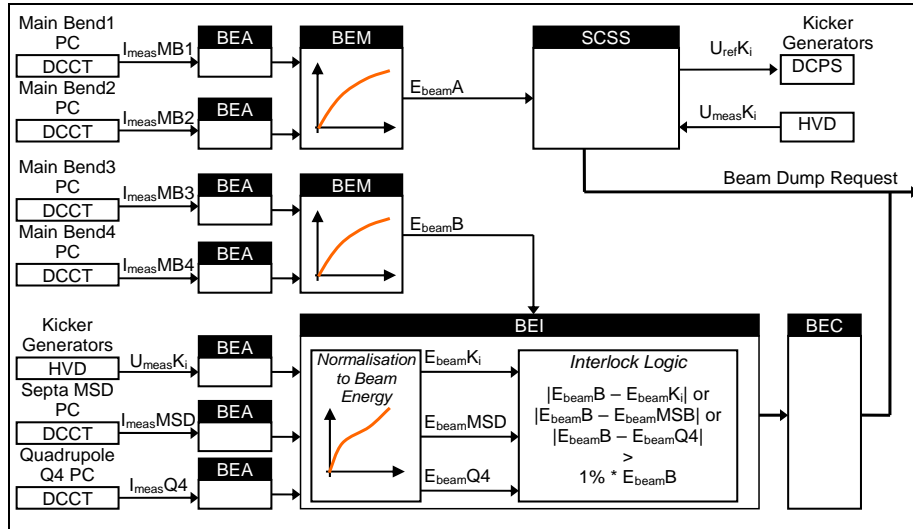

Figure 2: BETS architecture

The beam energy reference signals are obtained through two fully independent and redundant Beam Energy Meter (BEM) modules connected to 4 independent main dipole power converters. Within each power converter, a Beam Energy Acquisition (BEA) module acquires, with 16 bit resolution and 65 kHz sampling rate, the main dipole current through a high precision Direct-Current-Current-Transformer (DCCT). The acquired value is transmitted, after filtering, to the BEM modules through secure serial transmissions using fibre-optic links. The BEM converts, through a resident calibration look-up table, the physical measurement of the main dipole current into an absolute normalised value proportional to the beam energy. This value is used as energy reference within the BETS for the LBDS kicker reference settings generation or for the LBDS tracking interlock logic.

For the LBDS tracking interlock logic, a set of Beam Energy Interlock (BEI) modules will acquire, through individual BEA modules, all the measurements of each active LBDS sub-system. They will normalise the measured values to their corresponding beam energy values through pre-loaded calibration look-up tables. The coherence between the normalised values of the LBDS sub-systems beam energy $E_{beam}K_i$, $E_{beam}Q4$, $E_{beam}MSD$ and the beam energy reference $E_{beam}B$, will be continuously checked and a beam dump request will be issued via the Beam Energy Controller (BEC) module when a discrepancy greater than 1% is detected.

The BEC module interfaces the BEM and BEI modules to external systems through redundant fail-safe connections. It produces the dump request signal that will be fed to the machine protection system for any failures detected within the BETS.

HARDWARE

The different hardware modules used within the BETS are built around a XILINX SPARTAN-3 FPGA. The required functionalities have been modelled in VHDL.

Beam Energy Acquisition

The BEA module acquires and digitises 2 independent unipolar channels with 16 bit resolution. Signals are digitally filtered before secure transmission through the optical fibres. Two high precision reference signals are simultaneously digitised, modulated and transmitted in order to survey the linearity of the ADC and to probe the transmission. A block diagram of the BEA module is shown in Figure 3.
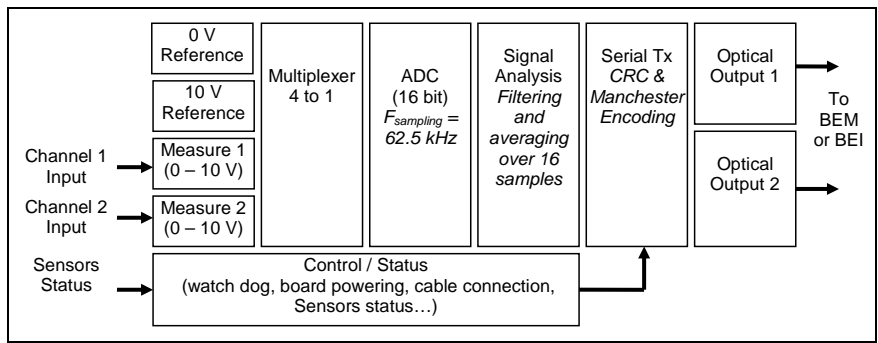
Figure 3: BEA block diagram

In order to automatically compensate the ADC offset and to adjust its gain, two high precision reference signals are used within the BEA. Via a 4-to-1 analogue multiplexer the BEA consecutively measures the two analogue input voltages as well as a high precision 10 V reference voltage and a ground reference in order to generate full scale and zero reference signals. The analogue input range of the ADC extends from slightly below 0 V to a little above 10 V. In this way any possible offset and gain error of the ADC and the amplifier driving its input can be eliminated after conversion and the precision of the measurement depends only on the precision of the voltage references. The ADC continuously samples the 4 input signals every 16 μs. To reduce the noise all four signals are averaged over 16 samples before transmission.

Beam Energy Meter

The BEM receives 4 digital measurements proportional to the beam energy from two different BEA boards as shown in Figure 4.
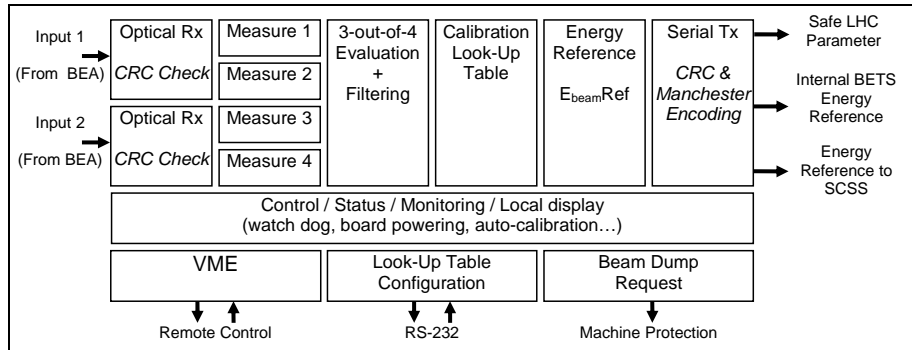

Figure 4: BEM block diagram

These measurements are compared within the BEM with a 3-out-of-4 logic and a relative error between measurements of ±0.5%. The mean value of the 4 measurements is then converted into an absolute beam energy reference through a calibration look-up table. Calculated energy is then internally distributed within the BETS to the interlock logic and externally distributed to the SCSS for settings generation and to the machine protection system for distribution around the LHC.

The main bend magnet calibration data will be stored within a serial flash ROM memory. The calibration look-up table will contain 32 points. A first order linear interpolation mechanism will be implemented when a measure falls between two calibration points in order to get the corresponding energy value. It will be locally possible to read the content of the flash ROM and to upload a new table via a RS-232 local link. Remotely, it will only be possible to read the look-up table content via the VME interface.

Beam Energy Interlock

The Beam Energy Interlock (BEI) receives the beam energy reference signal from a BEM module, lodged in the same crate, and two independent measurements from kicker generator HVDs, from septa or quadrupole Q4 DCCTs. It normalises these measures to values proportional to the energy through

independent calibration look-up tables. These normalised values are then compared with the beam energy reference signal and a beam dump request is issued if a discrepancy larger than a predefined tolerance is detected.
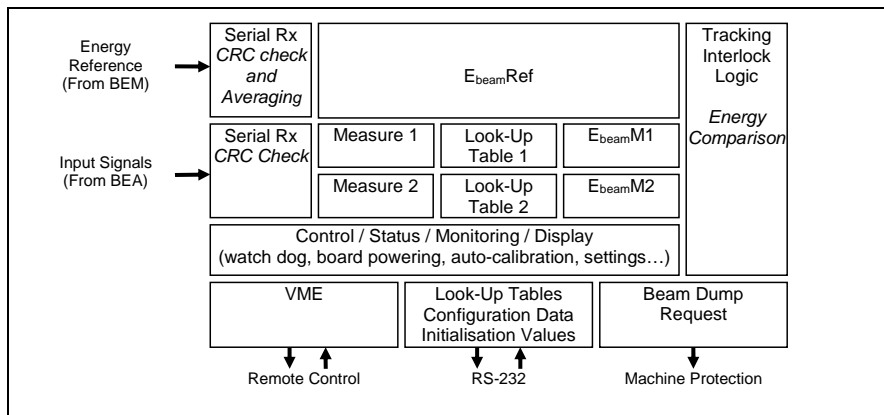

Figure 5: BEI block diagram

Within the BEI, the calibration look-up tables are stored in external flash ROM memories. In comparison to the BEM where a first order linear interpolation is processed to determine the energy the BEI look-up table contains all the points from below the pre-injection plateau up to the maximum energy. The flash ROM also contains initialisation values for the BEI (threshold, tolerance, version…). A configuration utility GUI made in MatLAB is provided with the BEI to generate the file to be placed in the external flash ROM through a local RS-232 link. As for the BEM, it will be locally possible to read the content of the flash ROM and to upload new calibration tables via the RS-232 link. Remotely, it will be only possible to read the look-up table content via the VME interface.

During operation, the BEIs are controlled through the VME interface. After a beam dump request, the different status values are stored and have to be acknowledged before the re-arming of each module will be enabled. Internal values like input signals, generated energies, thresholds and tolerances can be continuously read trough the VME interface. Finally, in case of a dump request, an inhibit signal is received from the BEC. This signal prevents a BEI module from requesting another beam dump if one request is already pending.

Beam Energy Controller

The BEC module interfaces the BEM and BEI modules to external systems through redundant fail-safe connections. It produces the dump request signal that is fed to other systems for any failures detected within the BETS.

The BEC has a redundant pair of on-board current loop generators that feeds all the BETS modules (BEMs and BEIs). The current loop is returned to the BEC where the signals are treated. When all the BETS modules operate correctly and are armed, the presence of a current in both current loops will be detected by the BEC and a 10 MHz frequency will be sent to the TSDS system. On the contrary, when one of the two current loops is broken, the 10 MHz signal disappears which produces a beam dump request (BDR) signal to the TSDS system. Simultaneously, a trigger signal is issued by the BEC to the LHC timing system in order to record the UTC time of the BDR action for post mortem analysis.

The BEC module also features an additional output in the form of a non ambivalent floating contact relay to the SCSS. This contact will negate the LHC machine protection beam permit loop until the BETS is fully operational and armed. The BEC also receives a signal from the TSDS that masks unwanted dump triggers to the BEI after a beam dump action has been executed.

PERFORMANCE

The typical performances of the BETS system are listed in Table1.

Table 1: Typical performance

Power converter DCCT precision	±0.1 %
Kicker HV divider precision	±0.2 %
BEA sampling frequency	65 kHz
BEA resolution	16 bit
BEA–BEM / BEI transmission rate	~100 kbit/s
Error during ramp (10 A/s)	< 0.01%
Dipole, septum and quadrupole magnets look-up table precision	±0.1 %
Kicker magnet look-up table precision	±0.5 %
Beam energy reference precision to SLP / BEI	±0.5 %
BEI tracking frequency	1 kHz
BEI tracking reaction time	1 ms
Bending magnet tolerance window	≥ ±0.3 %
Kicker magnet tolerance window	≥ ±1 %

CONCLUSIONS

The BETS system will be based on a fail-safe redundant approach relying on two different technologies. No voting between the two systems will be implemented and any failures detected within one of the system will automatically issue a dump without cross-check with the other system. This approach will result in a very reliable system [3] but the number of false dumps issued by the BETS needs to be maintained at an acceptable level to not become an operational issue.

The performance of the BETS relies on a good knowledge of the magnetic characteristics of its different sub-systems over the complete LHC operational range. High precision calibration measurements will be mandatory for all sub-systems included in the BETS in order to guarantee their correct operation over the complete LHC operational range.

ACKNOWLEDGEMENTS

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