

DESIGN ASPECTS RELATED TO THE RELIABILITY OF THE CONTROL ARCHITECTURE OF THE LHC BEAM DUMP KICKER SYSTEMS

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Abstract

The LHC beam dump extraction kicker system consists per ring of 15 magnets and their pulse generators. Their task is to extract the beams on request, over the whole operational beam energy range and synchronously with the beam abort gap. This operation must be fail-safe to avoid damage to accelerator equipment by undesired beam losses. The control system of the LHC beam dump kickers will be based on a modular architecture composed of different subsystems, each with a specific function like slow control, beam energy tracking, beam abort gap synchronisation, fast pulse signal monitoring and post-mortem data acquisition. Depending on the required functionality, the subsystems will be based either on passive fault-tolerant redundant hardware solutions or on active fail-safe hardware and software solutions. In addition, for the most critical subsystems like the beam energy tracking and the beam abort gap synchronisation, two redundant solutions based on different technologies will be implemented in order to prevent common mode failures. This paper presents the current status of the LHC beam dump kicker systems control architecture design and reviews the different subsystems in their functional aspects and their reliability requirements.

INTRODUCTION

The beam dumping system of the Large Hadron Collider (LHC), presently under construction at CERN, provides for loss-free fast extraction of the circulating beam from each of the two rings. It will be installed around the long straight section 6 and consists, per ring, of 15 extraction kickers, followed by 15 septum magnets, 10 dilution kickers, and finally an external dump, mounted in a separate cavern some hundred meters away [1].

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 collision energy of 7 TeV. Each of the two sets of extraction kickers must operate synchronously with the 3 μ s long beam abort gap foreseen for the rise of the kicker field, to deflect the beam safely away from the machine into the extraction channel, in one single turn of 89 μ s.

Incorrect operation of the extraction kickers can lead to full or partial beam loss and thus to severe damage (energy of normal beam at 7 TeV \sim 350 MJ) to the machine, to the experiments or to the beam dumping system itself. The extraction kickers are therefore one of the most critical components of the LHC beam dumping system (LBDS), in terms of potential impact but also in terms of complexity. Consequently great attention has

been paid to the design of the high voltage generators and their power switches, featuring a fully redundant approach based on dual-branch generators equipped with solid state switches [2].

CONTROL ARCHITECTURE

The performance of each extraction kicker system is determined by three operational parameters: its state, its kick time and its kick strength. To reflect this its control architecture comprises three independent sub-systems, each one 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). Figure 1 shows a functional layout of the control architecture for each set of 15 extraction kickers.

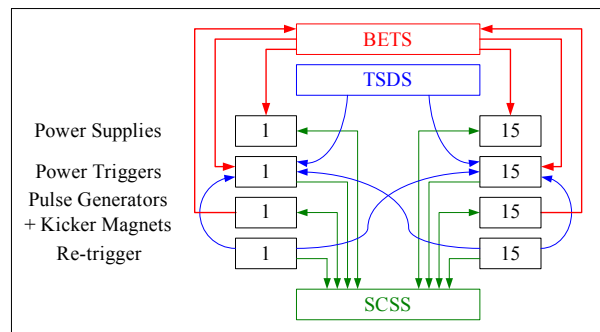


Figure 1: Functional layout of the LHC extraction kicker system per ring

The SCSS will be in charge of the control of the equipment state (ON, OFF, STANDBY...), the surveillance of the solid state switches, the generation of the kick strength reference voltages according to the beam energy, the monitoring of equipment low level status and the personnel safety aspects of the installation. It will continuously collect LBDS status information and generate a dump request when either a failure internal to the SCSS or an external fault has been detected.

The TSDS will distribute the dump requests arriving from the client interface to the power triggers, after synchronisation with the beam abort gap, and protect the machine against spontaneous firing in one of the pulse generators.

The BETS binds the deflection strength of the kicker magnets with the beam energy in order to ensure the correct extraction trajectory over the whole LHC operational range.

State control and surveillance system

The SCSS will be based on a fail-safe multi-master PLC architecture as shown in Figure 2. For each of the

two systems, a SIMATIC S7-400-F master will interface, through a single PROFIBUS-DP segment, 15 independent PROFIBUS-DP sub-segments. Each sub-segment, serving a single high voltage pulse generator, will be controlled by a SIEMENS S7-300-F master PLC. The interface between PROFIBUS-DP segments will be based on DP/DP couplers. Safe communication between the different PROFIBUS-DP segments will be based on the PROFIsafe protocol. Safety input and output function will be implemented using S7-300 fail-safe I/O modules. Redundant 4-20 mA current loop sensors will be used for analogue signal acquisition. Non-equivalent sensors will be used for digital inputs and redundant digital outputs will be used for actuators control.

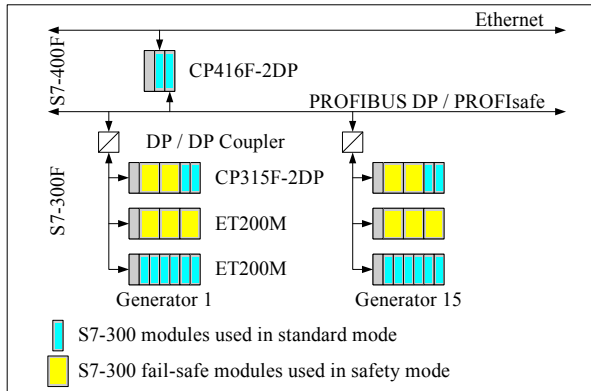


Figure 2: State control and surveillance

Due to the PROFIsafe protocol and the SIMATIC S7-F PLC family used in safety mode, any internal hardware faults or software failures occurring in the SCSS will safely issue a dump request by moving into a predefined safe state. With an architecture based on those two technologies, the SCSS will be in compliance with the IEC 61508 International Standard, achieving a Safety Integrity Level 3 (SIL3). Typical estimated reliability parameters for the complete SCSS are listed in Table 1.

Table 1: SCSS reliability parameters

Probability of the SCSS to perform its required functions under stated conditions during an assumed mission time of 12 hours	0.996
Probability of a undetected failure within the SCSS or a non correct response of the SCSS to its inputs per hour of operation	$6.1 \cdot 10^{-9}$

The SIMATIC S7-400-F master PLC will be connected to the Ethernet TCP/IP network for communication with the application layer.

Trigger synchronisation and distribution system

Dump requests will come from 3 different sources: the machine protection system for in emergency cases, the machine timing system for scheduled dumps or the LBDS itself in case of internal failures.

The spontaneously issued dump requests will be synchronised with the beam abort gap within the trigger synchronisation units (TSU). Once synchronized, dump

requests will be distributed through the trigger fan-out units (TFO) to the power trigger units (PTU) for firing of the pulse generators as shown in Figure 3 (only 2 out of 15 generators per ring shown). In addition, a redundant fault-tolerant re-trigger system (RTS) will be foreseen to re-distribute, as fast as possible, a trigger request issued from a spontaneous firing of one generator to the remaining 14 generators.

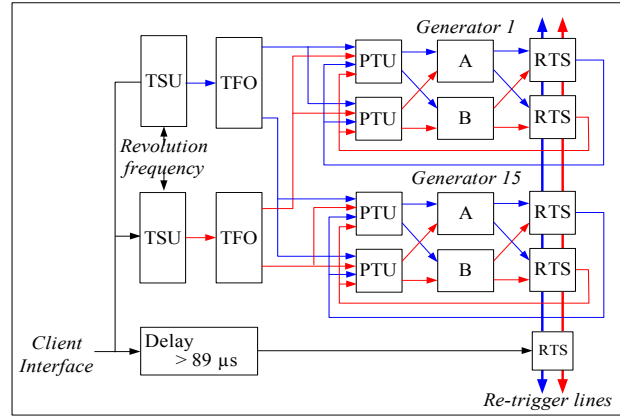


Figure 3: Trigger synchronisation and distribution

The dump request distribution from the client interface to the high voltage generators will be based on a redundant chain of stages using the “domino effect” strategy to trigger the next stage in the chain. The energy required to propagate the request will be pre-stored within each stage in order to guarantee the propagation to the next stage in case of power failures.

The TSUS will be based on a redundant fail-safe logic up to the TSU and thereafter on a redundant fault tolerant system up to the high voltage generator PTU in order to avoid asynchronous beam dumps in case of failure within the TSUS itself.

Locked to the LHC revolution frequency, two redundant TSUs produce continuously dump trigger pulse trains synchronised with the beam abort gap. The distribution of these pulse trains will be inhibited until a beam dump is requested. The pulses which pass the inhibit stage will then be sent via two redundant trigger fan-outs (TFO) to all power trigger modules. Time of flight of the circulating beam through the magnets as well as electronic and high voltage turn-on delays will be individually compensated for each kicker magnet through the trigger distribution cable length. In this way the first pulse after the reception of a dump request will synchronously trigger the system. The TSUs will be housed within two independent LynxOS VME front-end computers. Operating system and software capabilities available at the front-level will only be used for remote monitoring of the system and will not affect the operational aspects of the TSU.

In case the revolution frequency will be lost during more than one turn, an internally synchronised direct digital synthesiser based on a numerically controlled oscillator and a digital PLL, precisely locked on the revolution frequency, will issue a dump trigger which is

still synchronous with the beam abort gap. This mechanism reduces the probability of non synchronised dumps to almost zero. If the synchronisation of only one of the TSU fails, a synchronous dump trigger will be forced by the redundant system.

Furthermore, any dump request will also send a dump trigger, delayed by more than one turn, via the RTS to all power trigger modules. This additional trigger path guarantees that at least an asynchronous beam dump is initiated, even when both principal systems fail.

Beam energy tracking system

The main functions of the BETS are the generation of the kick strength reference signals for the extraction kicker high voltage generator power supplies (w.r.t. the beam energy), the continuous surveillance of the charging voltage of the different capacitors within the generators and the generation of a dump request if the measured values are not within predetermined tolerance windows relative to the beam energy, as shown in Figure 4.

Two independent sources of the beam energy, E_{beamA} and E_{beamB} , will be used to verify the correct tracking of the extraction kicker system. E_{beamA} will be used as reference signal and E_{beamB} as interlock signal.

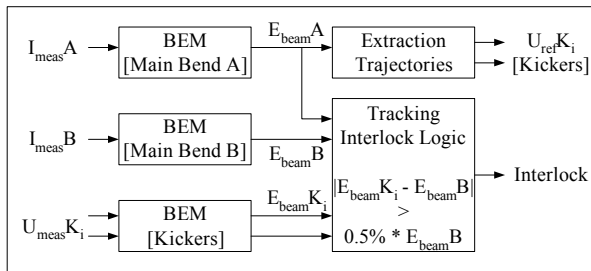


Figure 4: Beam energy tracking logic

The beam energy reference information will be obtained through two Beam Energy Meter (BEM) systems connected to two fully independent main bend power converters. The BEMs will convert, through the preloaded lookup table, the physical measurement of the main bend current into an absolute normalised value proportional to the beam energy. The same BEM device, but with a different lookup table, will be used to convert the charging voltage of the kicker capacitors $U_{meas}K_i$ into normalised beam energy $E_{beam}K_i$.

The coherence between the normalised values of E_{beamA} , E_{beamB} and $E_{beam}K_i$ will be continuously checked and a beam dump request will be issued if a discrepancy greater than 0.5 % will be detected.

The kicker power supply reference signals generation will be included within the SCSS as well as a first tracking interlock logic system. A second tracking interlock logic will be based on dedicated electronics built on the basis of the BEM system and housed in LynxOS VME front-end computers. A dump request will be issued if one of the two systems detects a tracking error.

POST MORTEM ANALYSIS

Verification of the correct execution of a dump request will require acquisition and analysis of many parameters during the dump action. Even if the previous beam has been correctly dumped, damage might have been caused on one or more components of the dump system itself, e.g. the solid state switches. To reveal this, a high precision data acquisition and analysis of the 50 magnet current pulse shapes will be performed. The acquisition system will be based on CompactPCI crates running LINUX and housing GAGE CompuScope 14100C digitisers with 14 bit resolution and 100 MS/s sampling rate for kick strength surveillance and Acqiris DC270 digitisers with 8 bit resolution and 1 GS/s sampling rate for kick synchronisation monitoring.

Additionally, a complete analysis of the SCSS, TSDS and BETS will be performed after each beam dump action. Detailed status information of each sub-system will be acquired, analysed and correlated in order to determine how well they carried out their task during the dump action. The beam dump system will be declared ready for the next dump if, and only if, it can be expected that all hardware, including all the redundant components, will be able to respond correctly to the next dump request.

CONCLUSION

The combination of fail-safe industrial components and the extensive use of redundant solutions, either in a fail-safe or in a fault-tolerant approach, result in a highly reliable control architecture for the critical LHC beam dumping system, to guarantee correct execution of dump requests.

The price to pay for this is a significant increase of the complexity of the system. This complexity will result in a higher dump request rate due to internal failures and in an increased LBDS downtime. It also complicates and lengthens the post-mortem analysis after each dump action, for monitoring of the redundant circuits and full validation of the operational parameters for the next dump request. Finally, it imposes a rigorous application of maintenance procedures throughout the entire LBDS life in order to maintain the high reliability level.

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