Critical Systems Labs

Strategic Insight for Safety

Proposal for an External Review of the CERN LHC Beam Loss Monitoring System

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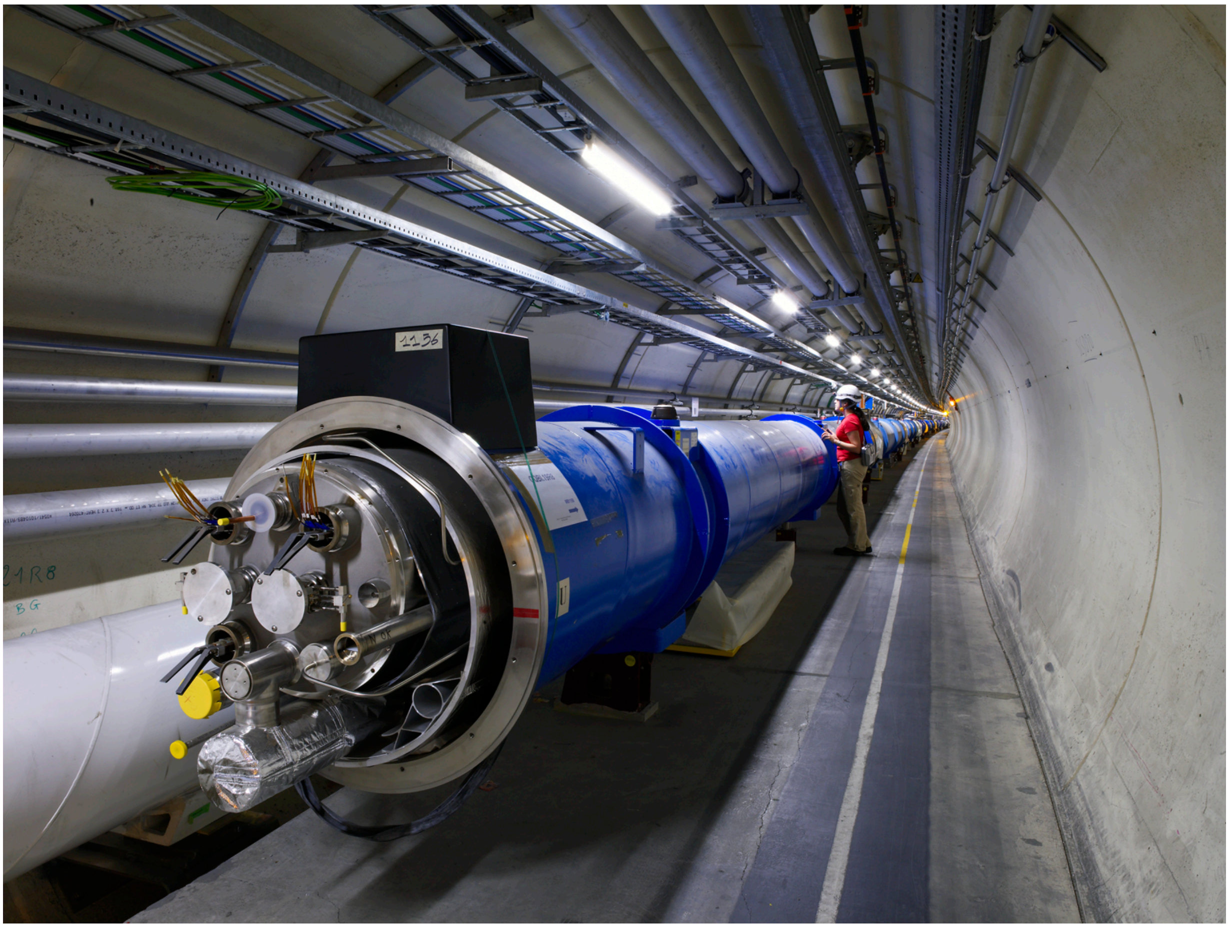

Submitted by:

Critical Systems Labs, Inc.
#618 - 475 Howe Street
Vancouver, B.C.
Canada V6C 2B3

Submitted to:

CERN
European Organization for Nuclear Research
CH-1211
Genève 23 Switzerland

1 Overview

[1], [2], [3], [4], [5]

The **L**arge **H**adron **C**ollider (**LHC**) at **CERN** (The European Organisation for Nuclear Research) is one of the world's largest and most complicated machines. The LHC has been designed and implemented to create collisions of sub-atomic particles with extremely high energies and intensities for the purpose of observing the inner workings of the quantum world.

Inside the LHC accelerator two beams of particles travel in opposite directions, they are accelerated from injection energy of 450 GeV to collision energy of 7 TeV, being held in a circular orbit by magnetic fields. A 7 TeV circulating beam within the 27km circumference of the LHC requires a dipole magnetic field of 8.33 Tesla. Superconducting dipole magnets generate this field, operating with a forward current of almost 12kA at temperatures just above absolute zero (1.9 K or -271°C).

The energy stored in each of the two circulating beams in the LHC reaches a maximum of 360 MJ at collision energy and design intensity (3.2 x 10^{14} protons per beam). Beam impact into the material of the accelerator produces a cascade of particles due to nuclear and electromagnetic interactions, which deposit energy into the accelerator equipment. For *fast beam losses*, over a millisecond to second timescale, losing as little as $\mathbf{10^{-8}}$ of the beam into one of the superconducting magnets will lead to a quench, where the magnet becomes normal conducting and has to be switched off before it destroys itself. A fast beam loss of $\mathbf{10^{-4}}$ of the beam into any part of the machine will cause damage, such as rupturing the machine vacuum, which in the best case results in costly repairs and weeks of downtime, in a worse case the destruction of one or more dipole magnets would mean many weeks of repairs to return the machine to operation.

In order to prevent damage to the accelerator due to beam losses, a **M**achine **P**rotection **S**ystem (**MPS**) has been implemented, which detects emerging dangerous situations, and ultimately extracts the circulating beam onto a purpose built graphite target, safely depositing its energy. Several subsystems make up the MPS, at the heart of which lies the **B**eam **I**nterlock **S**ystem (**BIS**) and the **B**eam **L**oss **M**onitoring (**BLM**) system.

The BLM system detects particle losses and performs advanced computation to decide if a beam dump should be requested to ensure proper operation of the magnets and a safe system behavior. This beam dump trigger is then relayed to the BIS as a USER SYSTEM input. Although other kinds of USER SYSTEM inputs might also trigger a beam dump request, the BLM is regarded as the primary inputs to the system.

LHC Safety requirement: The BLM should generate a beam dump trigger for amount of particle losses that are deemed unsafe for magnet operation.

LHC Availability requirement: The BLM should not adversely affect the availability of the LHC by erroneously requesting beam dumps.

The BLM has been designed to achieve reliability for the damage risk equivalent to SIL 3, i.e. $\geq 10^{-8}$ to $< 10^{-7}$failure/h.

2 Purpose

CERN internal reviews have been performed in the past and it is CSL's understanding that these reviews focused primarily on the analogue parts of the system design. Therefore CSL review will focus more on the digital parts and more particularly on the programmable parts of this system. The essential and foremost question that will drive CSL technical review is "Are the digital and programmable parts of the BLM system going to perform as they are intended to in the context of the BLM system?"

This review will seek to:

- assess the **adequacy of the overall** BLM system design with a focus on the programmable parts
- **identify possible weaknesses** in the programmable parts of the mission-critical BLM
- **suggest activities that could increase the level of confidence** that the programmable parts of BLM system performs as intended
- **suggest potential improvements** of the BLM
- provide a **general comparison of the BLM with approaches in industrial systems**.

The programmable parts of the BLM system are likely to implement some complex mathematics based algorithms. The review of the correctness of the implementation of these algorithms will be limited by the time CSL is allocated for this project. For these situations, CSL will focus on engineering activities that can provide assurance that these algorithms have been correctly implemented.

3 Scope

The main elements of the BLM system in the LHC tunnel are the ionization chambers and the tunnel cards (BLECF). This card receives the analog signal, i.e. current, from the detector and digitizes it. This information in the form of a frequency is then sent to surface electronics for further processing.

Electronics in the tunnel is connected to surface electronics via gigabit optical links.

The main element of the BLM system at the surface is a VME64x crate that includes the processing cards (BLETCs), the combiner and survey card (BLECS) and the front-end computer (FEC). The FPGA on each of the BLETC cards computes a dump information that is transmitted to the BLECS. In turn the BLECS card performs some basic logic processing and relays the consolidated dump information to the BIS system.

For the purpose of this project, components of the BLM system can be itemized as follows:

1. Beam loss detectors – The passage of particles through the detector result in charge. This part is purely analogue.
2. Acquisition card (BLECF) – Performs some analogue processing and then produces a digital output.
3. Processing card (BLETC) – This is entirely digital and likely the most complex component in this list. The real-time data processing is performed by an FPGA that makes uses of preset thresholds and masking information.
4. Combiner and Survey card (BLECS) – This combines outputs from multiple instances of threshold comparators to produce one signal.
5. Settings Management – This is an oracle database of threshold settings which are accessed, distributed and then read-back to verify that the settings in use are valid. This involves software implementation (in C and Java).
6. Display of beam losses monitoring data for post mortem analysis.

The scope of this review is limited to component #2 (digital part only) and components #3 to #5. Component #6 is in this proposal outside the scope of this project.

The task of reviewing the "Settings Management" component does not include review of the framework code, which is understood by CSL to be previously developed code used by a variety of projects in CERN. However, the review will consider how well the application code conforms to rules of use for the framework, as given in documents provided in advance to CSL in preparation for the site visit.

The scope of this review is also limited to a consideration of:

1. Potential sources of **unsafety** within the BLM, where the detection of an amount of particle losses that has the potential to quench the magnet is not relayed to the Beam Interlock System, resulting in a 'missed generation of beam dump trigger' and potentially machine damage.

2. Potential sources of **unavailability**, where failure of the BLM leads to a request to the Beam Interlock System to dump the beam, resulting in a 'false dump trigger' and some machine downtime.

While motivated by CERN's interest in the protection of the LHC from damage, **this review is not a safety analysis of the BLM**. In particular, **the scope of this review does not include the task of identifying additional hazards**. For the purpose of this review, the only hazard of interest is a 'missed generation of beam dump trigger', where the BLM fails to generate a dump trigger for some amount of particle losses that should result in a dump trigger.

A quantitative assessment of residual risk or reliability is also outside the scope of this review.

4 Method

CSL will consider documentation concerning the LHC BLM during a pre-visit study. The key areas which are required are as follows:

1. Single Gain Radiation Tolerant LHC Beam Loss Acquisition Card
http://www.cern.ch/blm/Talks_and_papers/DIPAC07/ab-2007-028.pdf

2. The LHC Beam Loss Monitoring System's Surface Building Installation
http://www.cern.ch/blm/Talks_and_papers/BLMTC/papers/BLM_Surface_Installation_LECC06.pdf

3. An FPGA Based Implementation for Real-Time Processing of the LHC Beam Loss Monitoring System's Data
http://www.cern.ch/blm/Talks_and_papers/BLMTC/papers/SRS_NSS06.pdf

4. Configuration and Validation of the LHC Beam Loss Monitoring System
http://www.cern.ch/blm/Talks_and_papers/DIPAC09/tupb31.pdf

5. LHC BLM Single Channel Connectivity Test using the Standard Installation
http://www.cern.ch/blm/Talks_and_papers/DIPAC09/tupd26.pdf

The above documentation includes descriptions of the BLM architecture and information specific to some components of the BLM. Additional documents are expected to be received by CSL with further information such as existing functional requirements, specifications of interfaces between the BLM and other systems, more detailed descriptions of the BLM, informal and formal representations (e.g., VHDL) of the design and implementation of the FPGA, verification procedures and corresponding results, results of any reliability, availability, maintainability and safety analysis that have been performed, descriptions of the tools used to design and implement the BLM, etc.

To facilitate searching, the majority of the documentation will be in PDF format (.pdf) or Microsoft Word (.doc). A convenient format will also be provided for the VHDL code.

Following this pre-visit study period, two CSL consultants will visit CERN for four (4) days to attend briefings and participate in informal discussions with CERN personnel. A tentative agenda for this week at CERN will be mutually agreed between CSL and CERN.

Following the site visit, CSL will prepare a written report that documents the results of this review. **This report will be delivered to CERN within four weeks of the completion of the site visit.**

5 Budget

For this project only, the CSL rate for one day of consulting services is $1280 CAD per consultant. To facilitate the visit of two consultants for 4 days at CERN, CSL will invoice CERN for 5 days of per diem costs (hotel and living expenses) at a rate of $200 CAD per consultant. Finally, CSL will invoice CERN $1500 CAD per consultant for economy airfare between Vancouver and Geneva and ground transportation.

ID	Task	Effort days	Cost CAD$	Comment
A1	Pre-visit study of CERN documentation	5	$6,400	
A2	4-day site visit by two CSL consultants	8	$10,240	
A3	Post-visit analysis and report preparation*	14	$17,920	
T1	2 CSL consultants × 5 days of per diem**	10	$2,100	Arrive Monday - depart Saturday
T2	Airfare and ground transportation	2	$3,000	Economy airfare
	Total		**$39,660**	

* Task A3 includes 7 to 8 days dedicated to code review either VHDL or C / Java.
** T1 amount would be reduced by an amount of $1500 CAD if CERN arranges pre-paid single occupancy accommodation for both consultants in one of the CERN hostels.

6 Schedule

The following table shows a tentative schedule for this project.

Date	Responsible	Deliverable
16th August 2010	CERN	Delivery of project documentation
6th September 2010	CSL/CERN	Finalization of site-visit agenda
13th to 16th September 2010	CSL/CERN	On-Site visit - 4 full days
18th October 2010	CSL	Delivery of written report

7 References

[1] Beam loss scenarios and strategies for machine protection at the LHC
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[2] How can we lose the Beam? Beam Loss Scenarios and Strategies for the Design of the Protection Systems.
R. Schmidt, CERN, January 2003
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[3] A Beam Interlock System for CERN High Energy Accelerators,
B. Todd, CERN/Brunel University, 2006.
http://cdsweb.cern.ch/record/1019495/files/thesis-2007-019.pdf

[4] CERN FAQ LHC The Guide
CERN Communications Group, CERN, February 2009
http://cdsweb.cern.ch/record/1165534/files/CERN-Brochure-2009-003-Eng.pdf

[5] M. Brice and C. Marcelloni. CERN-EX-0606036 - View of the LHC tunnel with worker.
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