Beam Loss Measurements at the LHC

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ON THE MEASUREMENT OF THE BEAM LOSSES IN THE LHC RINGS

Abstract

This functional specification is dedicated to the beam loss monitoring system (BLM) of the LHC main rings. Its use, both for machine protection and for machine operations and studies is considered. Taking into account the uses and the available information on quench and damage limits, the functional requirements are deduced.
3. Beam loss scenarios
5. Use of the blm’s for machine protection
6. Use of the blm’s for machine operation and studies
6.3 Setting of collimators and other movable targets
6.8 Beam and machine studies
6.9 Post-mortem analysis
7. Beam losses: dynamic range and time constants
7.3 Steady losses
7.3.3 Loss rates
7.4 Transient losses
8. Assumed quench and damage thresholds
8.1 Quench limit
8.1.1 Limit to the local heat deposition
8.2 Damage limit
9. Functional requirements for the BLM system
9.2 Layout & number of locations to be monitored
9.4 Dynamic range, resolution and response time
9.5.1 Absolute precision or calibration of the loss scale
9.5.2 Resolution and relative precision of the monitors
9.6.1 Beam 1/beam 2 discrimination
9.6.2 Collimator to collimator discrimination
9.7 Data and data handling
9.7.1 Data processing for quench prevention
9.8 Post-mortem analysis
9.9 Reliability and radiation resistance

- Specification (location of monitors, time response, dynamic range, safety and reliability requirements)
- System overview
- Detector
- Acquisition chain
  - Radiation tolerant electronics
  - Parallel and voting for safety and reliability Requirements
- Reliability software
- Failsafe system, human errors
- Firmware updates
- Functional tests
- Data path
- Preventive actions
- Management of settings
- **Aperture reduction** is concentration location for particle impact.
- **Particle tracking** shows location of losses at high beta values and reduced aperture.
- **Shower simulation** show dominant secondary particle intensity at beginning of the MQ and at the downstream transition.

**Injection optics, 450 GeV, Horizontal Halo coll @ 5sig (error scenario)**

![Aperture sketch](image)

- **MB**
- **MQ**
- **Beam screen**
- **BPM**
- **2 mm**

**Particle tracking**

![Particle tracking graph](image)

**Shower simulation**

![Shower simulation graph](image)
Location of Beam Loss Monitors

BLMs at quadrupole magnet

BLM at bending – bending magnet transition

BLMs at final focusing magnet

BLM at collimator

BLM at collimator
Magnet Quench Levels and Loss Measurement Ranges

4 order range

1 turn

loss rate (p/m/s)

450 GeV

time (ms)
Magnet Quench Levels and Loss Measurement Ranges

![Graph showing loss rate vs. time for different energies (450 GeV and 7 TeV) and indicating a 6 order range.](image)

- Loss rate (p/m/s) vs. time (ms)
- 6 order range
- 1 turn

B.Dehning: 10.11.2014

Joint International Accelerator School on Beam Loss and Accelerator Protection
Magnet Quench Levels and Loss Measurement Ranges

![Graph showing the loss rate (p/m/s) over time (ms) for 450 GeV and 7 TeV with a 7.5 order range and 1 turn indicated.](image-url)
Magnet Quench Levels and Loss Measurement Ranges

B.Dehning: 10.11.2014

Joint International Accelerator School on Beam Loss and Accelerator Protection
Magnet Quench Levels and Loss Measurement Ranges

![Graph showing loss rate vs time for 450 GeV and 7 TeV.](#)

- **450 GeV**
- **7 TeV**

**7 order range**

**1 turn**
To allow higher loss levels for short loss durations the concept of running sums is used.

- The acquisition chain needs to have a **dynamic range of 7 orders of magnitude**
- **12 running sums** are online calculated in range from 40 μs to 83 seconds
Dependability: Safety System Design Approach

Risk
Scaling:
frequency of events \times consequence

Safety
Mean time between failures
1 \times 10^{-8} to 1 \times 10^{-7} 1/h

Protection
Methods:
Stop of next injection
Extraction of beam

Systems:
Beam loss Monitors
Quench protection system
Interlock system
Dump system

Reduction of Availability
Reduction of operational efficiency

Solutions:
Reliable components
Redundancy voting
Monitoring of drifts

Damage
(system integrity)

Fail-safe
Redundancy Survey
Functional Check

Quench
(operational Efficiency)
**F (t) Probability that a failure occurs in the time 0 to t**

The exponential failure probability leads to a constant failure rate

\[ F(t) = 1 - e^{-\lambda t} \]
failure rate: Probability that a failure occurs at the time $t$, given that the system was operating before

No time dependence $\iff$ no memory effect
Redundancy - Survey - Functional Check II

failure rate: Probability that a failure occurs at the time t, given that the system was operating before

Single system

Two Systems parallel

No time dependence
$<=$
no memory effect
time dependent
failure rate
Redundancy - Survey - Functional Check II

failure rate: Probability that a failure occurs at the time $t$, given that the system was operating before.

- **Single system**
  - No time dependence
  - no memory effect
  - time dependent

- **Two Systems**
  - parallel
- **Surveyed System**
  - Reduction of failure rate by excluding failure modes

![Graph showing failure rates for single and parallel systems over time](image)
failure rate: Probability that a failure occurs at the time $t$, given that the system was operating before.

- **Single system**
  - No time dependence
  - No memory effect
  - Time dependent failure rate

- **Two Systems parallel**
  - Reduction of failure rate by excluding failure modes

- **Surveyed System**
  - After functional test
  - $\Rightarrow$ System new
BLM System Information Flow

- Safety relevant: thresholds, ...
- Data: 1Hz acquisition, post mortem, ...

Loss Detector
- Ionisation chamber
- Secondary Emission Monitor

Front-End Acquisition

Back-End Acquisition & Control

MPS
- Beam Permit

Setting DB
- ORACLE

Definition & Generation
- DB
- ORACLE

History

Display Logging

2 signatures
- GUI
- Monitor factor
- Change familie
- Group channels
- Enable/disable

1 signature
- GUI
- Model of:
- Magnets, collimators, ...
- Loss detectors
- Energy - loss parametrisation

Offline System Survey

Preventive Actions

Documentation
- Engineering Change Request
- Agreement by Pannel

Version: 04.06.2012 BD
Ionisation Chamber

- **Sensitivity** 54 uC/Gy
- **Time response**
  - Electron collection 150 ns
  - Ion collection time 80 % at 89 us (1 turn)
- **Absolute calibration** +/− 30%
- **Dynamic (linear range)**
  - minimum current < 1 pA
  - maximum current 10 mA
- **Radiation tolerance (gain variation):**
  - 30 kGy $\Delta\sigma/\sigma < 0.01$
  - 100 MGy $\Delta\sigma/\sigma < 0.05$
- **30 year of operation**

**Chamber response**

- $\sigma_{\text{length proton}} = 50 \text{ ns}$
- $\text{FWHM}_{e^-} = 150 \text{ ns}$
- 80 % of signal in one turn

**Gain variation**

- SPS BLMs

**Calibration**

- Horizontal cables downstream

<table>
<thead>
<tr>
<th>Positions</th>
<th>+10% Outer layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.32</td>
</tr>
<tr>
<td>2</td>
<td>1.14</td>
</tr>
<tr>
<td>3</td>
<td>1.31</td>
</tr>
<tr>
<td>4</td>
<td>1.08</td>
</tr>
<tr>
<td>5</td>
<td>1.29</td>
</tr>
</tbody>
</table>

**Frequency distribution**

- Extr., inj. BLMs
- Ring BLMs

Current [pA]
Beam Loss Measurement System Layouts

<table>
<thead>
<tr>
<th></th>
<th>Comment</th>
<th>Safety gain</th>
<th>Available gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failsafe</td>
<td>active state = beam permit</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Voting</td>
<td></td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Redundancy</td>
<td></td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic redundancy check</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>
The BLM Acquisition System

Real-Time Processing BEE
- FPGA Altera’s Stratix EP1S40 (medium size, SRAM based)
- Mezzanine card for the optical links
- 3 x 2 MB SRAMs for temporary data storage
- NV-RAM for system settings and threshold table storage

Analog front-end FEE
- Current to Frequency Converters (CFCs)
- Analogue to Digital Converters (ADCs)
- Tunnel FPGAs: Actel’s 54SX/A radiation tolerant.
- Communication links: Gigabit Optical Links.
Efficiency and limits of LHC collimation system

Proton impact on primary collimator and observation of downstream losses
(loss duration some seconds)

![Graph showing proton impact and collimation]

- **8 order range**
- **Collimation**
- **Beam**

**Lostes Fill_3569 B1_B2 4000GeV 2013-02-15 03:15:03**

**BLM signal [Gy/s]**

- **Atlas**
- **ALICE**
- **CMS**
- **LHCb**
Reliability: Fault Tree Analysis

- Definitions of failure modes (LHC 160)
- Three end effects:
  - **Damage risk**: probability not to be ready in case of dangerous loss
  - **False alarm**: probability to generate a false alarm
  - **Warning**: probability generating a maintenance request due to a failure of a redundant component
- Probability of a failure mode is calculated given the failure rate, repair rate and the inspection rate

**Used program: Isograph, includes component catalogue**
Example Approach of a Dependability Study

Creating the reliability methodology

- Learned the Isograph layout and the Prediction module tutorial
- Studied the reliability textbooks and technical notes
- Created the Prediction report template in Isograph
- Started the Predictions

- Did the tutorials for the FMECA modules
- Studied the MIL-HDBK-217F for MTTF-calculations
- Studied the reliability textbooks and technical notes
- Substituted the Criticality for a Risk Priority Number system
- Created the FMECA report template in Isograph
- Started the FMECA

- Looked at the tutorials for the Fault Tree Analysis
- Studied the MIL-HDBK-338B for failure modes and apportionments
- Learned how to do a quant.& qualit FTA from textbooks
- Used the FMECA and Prediction results to create a full FTA
- Simulated and verified results

Vegard Joa Moseng, CERN
The steps taken to ensure a reliable communication link:

- **Double (redundant) optical link**

- **CRC-32 error check algorithm**
  - All single-bit errors.
  - All double-bit errors.
  - Any odd number of errors.
  - Any burst error with a length less than the length of CRC.
  - For longer bursts $Pr = 1.16415 \times 10^{-10}$ probability of undetected error.
    - 224 bits of data plus 32 bits of CRC remainder = 256 bits

- **8b/10b encoding**
  - Clock data recovery (CDR) - guarantees transition density.
  - DC-balanced serial stream - ones and zeros are equal/DC is zero.
  - Error detection – four times more characters.
  - Special characters used for control – sync, frame.
    - 256 bits of data are encoded in 320 bits = 64 extra bits
To avoid misplacement of electronic cards or threshold and masking tables

- **Tunnel Card ID**
  - Unique number embedded in the FPGA (16 bit)
  - Included in every transmitted frame
  - Compared with the one stored in settings DB

- **Surface Card Serial number**
  - Unique number embedded in a IC (64 bit)
  - Compared with the one stored in setting DB
Steps taken for a Failsafe System: System Failures

To avoid loss of data

- **Frame ID**
  - Surface FPGA checks for missing frames
  - Incrementing number included at every transmission

- **Optical link is always active**
  - 8b/10b encoding sends “commas” when no data
  - Disconnection is detected in max 25ns

To ensure recognition of system failures and beam dump requests

- **FPGA Outputs (Beam Dump signals) generate frequency**
  - At a dump request, reset, or failure the transmitted frequency will be altered

- **Beam Permit lines are daisy-chained between cards**
  - Custom VME backplane
  - Dummy cards on empty slots to close circuit
Verification using Emulator Module

- In situ test of the TC in VME crate by emulation of output signals of CFC
  - Arbitrary Tx data
    - Comparison of different firmware versions
    - Playback of measured data for analysis
  - Tx errors
    - CRC, CID, FID
  - Wrong configuration
  - Errors in physical layer
- Manual testing procedure
- Results read out in Expert application
Verification of FPGA Functionality

- **Exhaustive verification** of the behavior of the Threshold Comparator block in FPGA
  - Check all permutations and their ability to trigger a beam dump request
  - Flash modified threshold table to FPGA targeting one table field at each iteration.
    - 16 cards/crate
    - 16 detectors/TC card
    - 12 integration windows/detector
    - 32 beam energy levels
    - 98'304 test cases/crate

- **VME readout check**
  - The same test case repeated 500’000 times

- **Automatic procedure** should ensure that beam permit inhibit could be issued by every channel and for every threshold
Check the beam permit lines inside and between crates
Check results are saved in the database
Exhaustive test yearly for every threshold (beam energy and integration time dependent)
Phase and amplitude are compared with thresholds
Beam permit not given if not done every 24 h
Local FPGA on VME card decides for all checks if beam permit is given
Connectivity check measurements (100x) on BLMQI monitors (Ionization chambers in the arcs)

- AMPLITUDE average
- AMPLITUDE StdDev
- PHASE average
- PHASE StdDev
BLM System Information Flow

- Safety relevant: thresholds, ...
- data: 1Hz acquisition, post mortem, ...

Loss Detector
- Ionisation chamber
- Secondary Emmission Monitor

Front-End Acquisition

Back-End Acquisition & Control

MPS
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History

Setting Database ORACLE
- 2 signatures
  - GUI
  - Monitor factor
  - Change family
  - Group channels
  - Enable/disable

Definition & Generation Database ORACLE
- 1 signatures
  - GUI
  - Model of:
    - Magnets, collimators, ...
    - Loss detectors
    - Energy - loss parametrisation

Display Logging

Offline System Survey

Preventive Actions

Documentation
- Engineering Change Request
- Agreement by Panel

Version: 04.06.2012 BD
Reliability: Comparison of Back-End Settings with Database

Corruption in frontend are more likely as in reference database, therefore =>

- Setting storage in Oracle database
- Settings:
  - Threshold values
  - Voltages, currents, phase limits
  - Serial numbers
  - Software version numbers
- If comparison negative and after retry, manual intervention (no beam permit)

Request for comparison issued by Back-End Acquisition (counter), most reliable (no software layers in between)
BLM System Information Flow

Safety relevant: thresholds, ...

data: 1Hz acquisition, post mortem, ...

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Documentation
Engineering Change Request Agreement by Pannel

Version: 04.06.2012 BD
BLM System – Online Display

- Extensively used for operation verification and machine tuning
- 1 Hz update and logging (12 integration times, 40 us to 83 s)
Extensively used for operation verification and machine tuning

- 1 Hz update and logging (12 integration times, 40 ms to 83 s)
- Integration times < 1s: maximum during the last second => loss duration can be reconstructed (20% accuracy)

Fit to data in the plan signal versus integration time => interception straight line parameterization => loss duration
Post Mortem Data

- Loss in a bending magnet
- Loss exceeds threshold = > abort of beam
- Rolling buffer stopped

PM application: BLM data of 0.082 sec online available

Longer PM buffer: BLM data of 1.72 sec offline available

Beam dump on 07/07/2010 @ 20:22
Measurements and settings (thresholds, monitor names, ...) are combined in VME crate (Back-End Acquisition & Control)
- Measurements and setting a joint in the FPGA memory (16 channels)
- Large decentralized structure
- Data flow path identical for both
- Display and logged data are coherently treated
- Reduction of number failure modes due to flow over same path
- Important for availability (false dumps) and dynamic range
- Main source of noise: long cables (up to 800 m in straight section)
- Aim: factor 10 between noise and threshold
- Thresholds decrease with increasing energy
- Noise reduction before 7 TeV operation
  - Single pair shielded cables, noise reduction: > factor 5
  - Development of kGy radiation hard readout to avoid long cables

Noise estimate in design phase with test installations at comparable locations
BLM System Information Flow

version: 04.06.2012 BD

Loss Detector
- Ionisation chamber
- Secondary Emmission Monitor

Front-End Acquisition

Back-End Acquisition & Control

MPS
Beam Permit

History

Setting DB
ORACLE

Definition & Generation
DB
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  - magnets, collimators, ...
  - loss detectors
  - energy - loss parametrisation

Offline System Survey

Preventive Actions

Documentation
Engineering Change Request
Agreement by Pannel
Daily Checks

If $\geq 10$ errors/link within 24h, send warning and start monitoring this link in more detail.

**Cases:**

a) constantly low error rate
b) increasing error rate: critical, take action!

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**Temperature and failure rate**

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**Card-Serial numbers**

<table>
<thead>
<tr>
<th>Card</th>
<th>BLECF Serial</th>
<th>BLET C Serial</th>
<th>BLECS Serial</th>
<th>CRC COMP A</th>
<th>LK1 ERRORS A</th>
<th>LK2 ERRORS A</th>
<th>LK1 LOST A</th>
<th>LK2 LOST A</th>
<th>FID COMP A</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR1-L 12</td>
<td>0282 0241</td>
<td>9511602473975246337</td>
<td>12177733450726613761</td>
<td>71</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SX4-R 14</td>
<td>0040 0230</td>
<td>8577453751483037953</td>
<td>11096869540207459585</td>
<td>224</td>
<td>0</td>
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<tr>
<td>SR7-L 14</td>
<td>0580 0426</td>
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<td>18</td>
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</tr>
<tr>
<td>SR8-C 12</td>
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<td>489991645551403009</td>
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<td>571</td>
<td>0</td>
<td>27762</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

---

**Graphical representation**

- LK1 CRC ERRORS B
- Temperature

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B.Dehning: 10.11.2014

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Survey of BLM thresholds

**Purpose:**
- Detect unwanted/unknown changes
- Detect changes done by EICs

**Example of weekly report:**

**Overview of changes between 2011-11-28 05:24:47 and 2011-12-05 13:14:36, all**

**Family THRI.DS.B11_MQ:**
BLMQI.09R7.B1E10_MQ, crate CFV-SR7-BLMR, dcum 20335:
Change between 2011-11-28 05:24:47 and 2011-12-05 13:14:36:
Energy level 14:
- Running sums [7] changed with ratio 3.75
- Running sums [8] changed with ratio 11.3527
- Running sums [9] changed with ratio 12.0038
- Running sums [10, 11, 12] changed with ratio 34.6335

**Running sum vs Integration duration**
Detailed Analysis of Modulation Result – Preventive Action

**Example: Connectivity Check – Results from Shape Analysis**

<table>
<thead>
<tr>
<th>Expert Name</th>
<th>Hardware Channel</th>
<th>Cable conn.</th>
<th>BIS conn.</th>
<th>$\chi^2 / NDF$</th>
<th>Gain min</th>
<th>Gain meas.</th>
<th>Gain max</th>
<th>Phase min</th>
<th>Phase meas.</th>
<th>Phase max</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLMQI.04R6.B1E10.MQY</td>
<td>6.R.01.02</td>
<td>True</td>
<td>True</td>
<td>73</td>
<td>2628</td>
<td>3772</td>
<td>4880</td>
<td>46</td>
<td>66</td>
<td>84</td>
</tr>
<tr>
<td>BLMQI.18R6.B2I30.MQ</td>
<td>6.R.07.01</td>
<td>True</td>
<td>True</td>
<td>87</td>
<td>2823</td>
<td>3973</td>
<td>5241</td>
<td>45</td>
<td>63</td>
<td>81</td>
</tr>
<tr>
<td>BLMQI.18R6.B1E10.MQ</td>
<td>6.R.07.02</td>
<td>True</td>
<td>True</td>
<td>92</td>
<td>2881</td>
<td>4052</td>
<td>5351</td>
<td>45</td>
<td>63</td>
<td>81</td>
</tr>
</tbody>
</table>

Connectivity check on 2010-10-21 19:00:27

**Example: Summary on Connectivity Check Measurement Results**

<table>
<thead>
<tr>
<th>Expert Name</th>
<th>Gain min</th>
<th>Gain max</th>
<th>Phase min</th>
<th>Phase max</th>
<th>spare channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLMQI.10R1.B2I10.MQML</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BLMEL.06R7.B2I20.TCSC.G.A6R7.B2</td>
<td>0 1</td>
<td>0 1</td>
<td>0 1</td>
<td>0 1</td>
<td></td>
</tr>
<tr>
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</tr>
<tr>
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<td>0 1</td>
<td>0 1</td>
<td>0 1</td>
<td></td>
</tr>
<tr>
<td>BLMCC.08R3.A8R3.BATT</td>
<td>0 1</td>
<td>0 1</td>
<td>0 1</td>
<td>0 1</td>
<td></td>
</tr>
<tr>
<td>BLMCC.06R3.A6R3.BATT</td>
<td>0 1</td>
<td>0 1</td>
<td>0 1</td>
<td>0 1</td>
<td></td>
</tr>
<tr>
<td>BLMCC.06R3.A6R3.HV</td>
<td>0 1</td>
<td>0 1</td>
<td>0 1</td>
<td>0 1</td>
<td></td>
</tr>
<tr>
<td>BLMCC.06R3.B2E10.TCAPA.BR3.B2</td>
<td>0 1</td>
<td>0 1</td>
<td>0 1</td>
<td>0 1</td>
<td></td>
</tr>
</tbody>
</table>
BLM System Information Flow

Now: C++ program and SVN storage

Future: all values and functional dependence in ORACLE
<table>
<thead>
<tr>
<th>Stage</th>
<th>Final</th>
<th>Master</th>
<th>Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>working level</td>
<td>becoming operational</td>
<td>operational</td>
<td>applied &lt; master</td>
</tr>
</tbody>
</table>

- Two layers
  - entry layer (stage tables)
  - validated layer (final tables)
- Concept of Master and Applied table – Comparison of Threshold values (Applied < Master)
  - Master: less frequent changes
  - Applied: change of thresholds possible with user interface

- 200 Families
- 4000 Channels
BLM System Information Flow

Safety relevant: thresholds, ...

data: 1Hz acquisition, post mortem, ...

Version: 04.06.2012 BD

Loss Detector
Ionisation chamber
Secondary Emmission
Monitor

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Key issue to high reliability and availability, survey, parallel system and functional tests =>
Test need to be regularly executed and automatically leading to beam permit inhibit if needed

Reliability and availability needs to be considered from the beginning of a design
- LHC: PhD thesis on reliability (path has been followed during project)

System reliability and availability is strongly depending on management of settings, creation of settings and preventive action

Issue of LHC design: protection and measurement functionality are implemented in same FPGA
- Critical, because of upgrades are more often needed for the measurement functionality compared to protection functionality
- New: modular FPGA design and locking of critical parts
Literature

- http://cern.ch/blm
- LHC
  - Reliability issues, thesis, G. Guaglio
  - Reliability issues, R. Filippini et al., PAC 05
  - Front end electronics, analog, thesis, W. Friesenbichler
  - Front end electronics, analog-digital, E. Effinger et al.
  - Balancing Safety and Availability for an Electronic Protection System, S. Wagner et al., to be published, ESREL 2008
Reserve Slides
## BLM Published Data – Event triggered Data Buffers

<table>
<thead>
<tr>
<th>BLM Buffer (IC &amp; SEM)</th>
<th>Integraton Time</th>
<th>Buffer Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post Mortem</td>
<td>40μs</td>
<td>80ms online 1.72s offline</td>
</tr>
<tr>
<td>Collimation Buffer</td>
<td>2.6ms</td>
<td>80ms</td>
</tr>
<tr>
<td>Extraction Validation Buffer</td>
<td>40μs</td>
<td>80ms</td>
</tr>
<tr>
<td>Capture Data (2 modes)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection Quality Check (IQC) – 8 crates only</td>
<td>40μs</td>
<td>20ms</td>
</tr>
<tr>
<td>Study (event triggered: for example UFO study)</td>
<td>80μs</td>
<td>Dynamical, currently up to 350ms</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event triggered</th>
<th>Sampling Rate</th>
<th>Integraton Time</th>
<th>Buffer Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post Mortem</td>
<td>0.2 ns</td>
<td>≈ 2ns</td>
<td>1ms</td>
</tr>
</tbody>
</table>
Hardware Failures (since Feb. 2010)

- Mostly, onset of system degradation detected by regular offline checks before malfunction
- Number of failures regarded manageable (no availability issue)

12 IC with bad soldering (out of 3600)
9 GOH with low power
1 damaged connector out of 1500
3 failed CPU RIO3 out of 25
2 with failed SRAM out of 350
7 CFC with ‘noisy’ components
2 cards with bad soldering out of 750
12 with ‘weak’ receivers out of 1500
1 VME Power Supply, out of 25
## Fault Statistic

<table>
<thead>
<tr>
<th>Element</th>
<th>Details</th>
<th>Number</th>
<th>Out of total installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC</td>
<td>bad soldering</td>
<td>12</td>
<td>3600</td>
</tr>
<tr>
<td>tunnel electronics</td>
<td>noisy analogue component (CFC)</td>
<td>7</td>
<td>359</td>
</tr>
<tr>
<td>tunnel electronics</td>
<td>bad soldering</td>
<td>2</td>
<td>720</td>
</tr>
<tr>
<td>tunnel electronics</td>
<td>low power optical transmitter (GOH)</td>
<td>9</td>
<td>1500</td>
</tr>
<tr>
<td>tunnel electronics</td>
<td>damaged connector</td>
<td>1</td>
<td>1500</td>
</tr>
<tr>
<td>surface electronics</td>
<td>weak optical receiver</td>
<td>12</td>
<td>1500</td>
</tr>
<tr>
<td>surface electronics</td>
<td>failed SRAM</td>
<td>2</td>
<td>350</td>
</tr>
<tr>
<td>VME64x Crate</td>
<td>failed CPU RIO3</td>
<td>3</td>
<td>25</td>
</tr>
<tr>
<td>VME64x Crate</td>
<td>failed power supply</td>
<td>1</td>
<td>25</td>
</tr>
</tbody>
</table>
Quench and Damage Levels

Specifications

- Time resolution ½ turn, 40 us
- Average calculation loss:
  - 12 values, 40 us to 83 s
- Max amplitude 23 Gy/s
- Min amplitude
  - 1E-4 Gy/s @ 40 us
  - 3E-7 Gy/s @ 1.3 s
- Dynamic
  - 2E5 @ 40 us
  - ~ 1E8 @ 1.3 s
- Damage level
  - 2000 Gy/s @ 1 ms
- All channels could be connected to the interlock system
- Thresholds
  - Loss duration dependent, 12 values
  - Energy dependent, 32 values
  - About 1.5 E6 thresholds
Functional Tests Overview

Functional tests before installation
- Barcode check
- Current source test
- Radioactive source test
- HV modulation test
- Beam inhibit lines tests
- Threshold table data base comparison
- Offset to check connectivity (10 pA test)
- Double optical line comparison
- System component identity check

**Inspection frequency:**
- Reception
- Installation and yearly maintenance
- Before (each) fill
- Parallel with beam
Classification loss signals to be used for functional and technical specification

Since not active protection possible for ultra-fast losses => passive system

Loss Durations and Protection Systems

**Loss Duration**
- Ultra-fast loss: 4 turns (356 μs)
- Fast losses: 10 ms
- Intermediate losses: 10 s
- Slow losses: 100 s
- Steady state losses

**Protection System**
- Passive Components
  - + BLM (damage and quench prevention)
  - + Quench Protection System, QPS (damage protection only)
  - + Cryogenic System
Combiner card inside the LHC BLM system

Beam Loss Monitors (4000)

Beam Energy Receivers (8)
[CISV]
Hardware:
BE-CO-HT (P. Alvarez)
Responsible:
TE-MPE-MI (B. Puccio)
Energy measurements:

Tunnel Cards (700)

Interlock Interfaces (16)
[CIBUS] TE-MPE-MI
(B. Puccio, B. Todd)

Tunnel Card test benches (5)

HV
HV
BLM HV supplies

Operational applications (2)

Expert applications (2)

Diagnostics application, phase and amplitude for the connectivity check

Settings applications (2)

around the LHC ring

B. Dehning: 10.11.2014
Software Overview, Management of Settings

Safety given by:
- Comparison of settings at DB and front-end
- Safe transmission of settings

Mediation properties:
- 256 monitors (16 units)
- Combiner surveyor
- 1 Hz (1 kHz re-sending)
- Beam interlock system
  - Maskable, un-maskable
  - Beam permit

1 second data: loss, thresholds, configuration, status
- Configuration data: integration times, conversion factors
- Triggered data: post mortem, XPOC, Study data, Collimation

SMDB oracle
description
history

Expert
threshold value
Generation

MTF DB
oracle
description
history

Layout DB
oracle
description

BLM expert

Layout GUI
DB expert

LSA DB
orache

Stage tables

Final tables
Master Applied

TRIM

Trim GUI
client mode
expert mode

VME crate

timestamp data
packaging
reception of
timing events

Threshold
comparator
beam permits
data treatment

Combiner
surveyor
beam permit
tests manager

Comparison
applied <> threshold (FPGA)
Result => BLECS
false = beam permit disabled

Safety relevant
Safety relevant: thresholds, channels
Availability relevant, scaling applied table

DB and front-end

[Comparison]

[TRIM]

[LSA DB oracle]

[Stage tables]

[Final tables Master Applied]

[Trim GUI client mode expert mode]

[Threshold comparator beam permits data treatment]

[Combiner surveyor beam permit tests manager]

[Comparison applied <> threshold (FPGA)]

Result => BLECS
false = beam permit disabled

[LSA DB oracle]

[MTF DB oracle description history]

[Layout DB oracle description]

[Expert threshold value Generation]

[Study Data 40 us, 6 ms 2k values event trigger]

[Post Mortem 40 us 2k values event trigger]

[Dump & Inj. 200 values event trigger]

[Collimation 2.6 ms 32 values collimator trigger]

[Display-Logging Concentrator function: unit conversion duration of integration LSA DB access after restart 1Hz update rate]

[Logging DB permanent]

[Displays Measurement DB 1 week every minute & on change [Gy/s]]
Software Overview, Management of Settings

1. Modular design of data base very useful (if changes are needed limited impact)
   1. MTF: history of equipment e.g. ionisation chamber, electronic cards, ...
   2. Layout: description of links between equipment
   3. LSA: reference for all data needed in the front-end (some imported from MTF and Layout)
2. Storage of data in frontend in FPGA memory (even here corruptions observed)
3. Master for comparison is the front-end (this allows immediate beam inhibit)
4. Design very early defined in PhD thesis on reliability (root was followed during project)
5. Issue of design: protection and measurement functionality are implemented in same front-end (review remark).
   1. Critical, because of upgrades are more often needed on measurement functionality compared to protection functionality
   2. New design: locking of FPGA firmware, which has protection functionality (partial solution)
   3. Occupation of FPGA by firmware too large, first estimate of occupation will be about 30% for new BLM systems
LSA Data Base Structure

Two layers
- entry layer (stage tables)
- validated layer (final tables)

Concept of Master and Applied table – Comparison of Threshold values (Applied < Master)
- Master: less frequent changes
- Applied: change of thresholds possible with user interface

LSA Settings Table
- $C_m$ = monitor factor

BLM Expert App
- Monitor Table
  - $F_m$ = function attributing monitors to families
  - Expert name, docum, maskable, connected electronic channel
  - 6400 records
- Family Table
  - Conversion factors (eg Gys to bits)
  - ~300 records
- Threshold Table
  - $T_f$
  - ~300 records

Master Table
- $T_{m}^{M} = F_{m} \times T_f$

Applied Thresholds
- $T_{m}^{A} = F_{m} \times C_{m} \times T_f$
- $C_m$ is trimmable

Implicit database rule
- $T_{m}(Applied) \leq T_{m}(Master)$

300 families → 4000 channels
Results and conclusions

- Beam based quench tests and model comparisons made for different loss durations and beam energies
  - For short and steady state loss durations sufficient prediction accuracy is reached
  - For intermediate loss durations model improvements are required and in preparation
  - Measurement errors could be reduced by increased sampling and time stamping of magnet coil voltage measurements, usage of higher upper limit loss monitors, ...

- The operation of LHC at the beam loss limits will require accurate setting of beam aborts thresholds == more quench tests envisaged
Impact position varied along the MQ

Black impact position corresponds to peak proton impact location

Position of detectors optimized

- Transition between MB – MQ
- Middle of MQ
- Transition between MQ – MB

- to minimize uncertainty of ratio of energy deposition in coil and detector
- Beam I – II discrimination

Good probability that losses are seen by two BLM detectors
LHC Ionisation Chamber Signal by Particle Composition

![Graph showing integrated detector signal (aC/p) vs. energy (MeV) for different particles: proton, neutron, gamma, e-, e+, muon+/-, pion+/- at LHC MQY 7TeV.](image)
Comparison of Reliability Tools

<table>
<thead>
<tr>
<th>Tool</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spreadsheet</td>
<td>Previously used by SNS, good source of data</td>
<td>Interface difficult to use, lack of visualization, error prone</td>
</tr>
<tr>
<td>AvailSim (free)</td>
<td>Previously used for ILC, many accelerator specific concepts</td>
<td>No GUI</td>
</tr>
<tr>
<td>Sapphire (semi-commercial)</td>
<td>Widely used by NASA and nuclear industries, developed by Idaho National Lab</td>
<td>Newest version (8) only US government organizations</td>
</tr>
<tr>
<td>ReliaSoft (commercial)</td>
<td>Good GUI, widely used, SNS uses it</td>
<td>File format is proprietary</td>
</tr>
<tr>
<td>Isograph (commercial)</td>
<td>Good GUI, open file format</td>
<td>Lacks some GUI features</td>
</tr>
</tbody>
</table>

Lit: S. Bhattacharyya, IPAC12
Why CVD Diamond?

- BLM ionisation chambers too big to be installed inside CMS
  - 9cm diameter, 60cm long
- CVD Diamond is now standard choice at other experiments
  - installed in CDF, BaBar, Belle, ZEUS
- Relative flux monitors
  - Radiation hard, tolerant beyond LHC nominal luminosity close to IP
  - Low maintenance, constant operating conditions, relatively insensitive to environmental conditions, compact size
  - Linear response to particle flux

1. Nano second response time
2. Large dynamic range
3. Operation at 1.8 Kelvin

CDF pCVD diamonds at r=3cm and r=10.7cm
Ionisation Characteristics in 500 um sCVD

Generated charge

- Particle bunches
- Single particles

Absorption

- Initial energy, MeV
- Charge, fC

Proton

10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}

10^4
10^5
10^6

Courtesy to E. Griesmayer
LHC: 152 bunches, 150ns bunch spacing (3/10/2010 12h48)
LHC: 152 bunches, 150ns bunch spacing (3/10/2010 12h48)
LHC: 152 bunches, 150ns bunch spacing (3/10/2010 12h48)

About 20 particle per pulse
- Not very complicated design “simple”
- Large Dynamic Range (8 orders)
  - Current-to-Frequency Converter (CFC)
  - Analogue-to-Digital Converter
- Radiation tolerant (500 Gy, 1 \(10^7\) p/s/cm\(^2\))
  - ADC custom ASIC
  - Triple module redundancy

![Diagram of LHC tunnel card](image)
Current to Frequency Converter

circuit limited by:

1. leakage currents at the input of the integrator (< 2 pA)

2. fast discharge with current source (<500 ns)
Advanced Current to Frequency Converter Principle

LHC current to frequency converter:
1. only positive signals (limitation in case of signal under shoots)
2. 500 Gy radiation tolerance

\[ f = \frac{I_{\text{input}}}{(I_{\text{ref}} \times T_{\text{ref}})} \]
Advanced Current to Frequency Converter Principle

LHC current to frequency converter:

1. only positive signals (limitation in case of signal under shoots)
2. 500 Gy radiation tolerance

$$f = \frac{I_{\text{input}}}{(I_{\text{ref}} \times T_{\text{ref}})}$$

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<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic range</td>
<td>six decades</td>
<td></td>
<td>positive and negative currents</td>
</tr>
<tr>
<td></td>
<td>nine decades</td>
<td></td>
<td>(indirect measurement)</td>
</tr>
<tr>
<td>Minimum detected current</td>
<td>1</td>
<td>nA</td>
<td>(user selectable, minimum value)</td>
</tr>
<tr>
<td>Linearity error</td>
<td>&lt; ±10</td>
<td>%</td>
<td>relative error $\Delta I/I$</td>
</tr>
<tr>
<td>Integration window</td>
<td>40</td>
<td>µs</td>
<td></td>
</tr>
<tr>
<td>Total integrated dose</td>
<td>$1 \times 10^8$</td>
<td>Gy</td>
<td>in 20 years</td>
</tr>
</tbody>
</table>

Target technology: CMOS 0.25 µm

Six decades to be covered with a direct measurement → 20 bit
Advanced Current to Frequency Converter Principle

LHC current to frequency converter:
1. only positive signals (limitation in case of signal under shoots)
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<td>relative error (\Delta I / I)</td>
</tr>
<tr>
<td>Integration window</td>
<td>40</td>
<td>(\mu)s</td>
<td></td>
</tr>
<tr>
<td>Total integrated dose</td>
<td>(1 \times 10^4)</td>
<td>Gy</td>
<td>in 20 years</td>
</tr>
<tr>
<td>Target technology</td>
<td>CMOS 0.25 (\mu)m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Six decades to be covered with a direct measurement → 20 bit
Advanced Current to Frequency Converter Principle

LHC current to frequency converter:
1. only positive signals (limitation in case of signal under shoots)
2. 500 Gy radiation tolerance

\[ f = \frac{I_{\text{input}}}{(I_{\text{ref}} \times T_{\text{ref}})} \]
Fully Differential Current to Frequency Converter Principle

1. Specifications:
   1. **Dynamic range 7 orders** integration window 2 μs
      1 nA to 200 mA
   2. **Dynamic range 9 orders**
      integration window 1 s
      10 pA to 200 mA

2. A status signal selects in which branch of a fully differential stage the input current is integrated.

3. Two comparators check the differential output voltage against a threshold, whenever is exceeded, the status signal changes to the complementary value (0 ! 1 or 1 ! 0) and the input current is integrated in the other branch.

**Bidirectional digitalisation; optical and Ethernet link**