Beam Loss Measurements at the LHC

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Specification

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the
Large Hadron Collider
project

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328146

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Functional Specification

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.

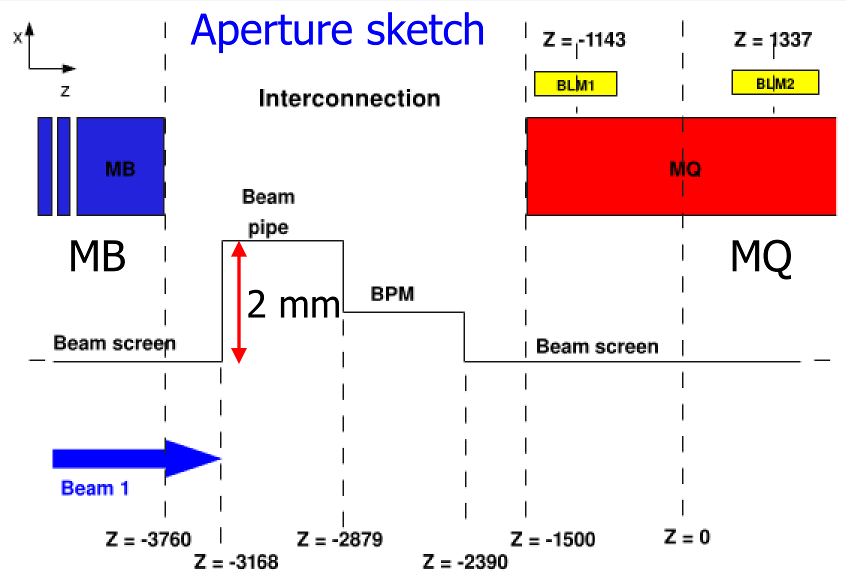
Content of Specification (selection)

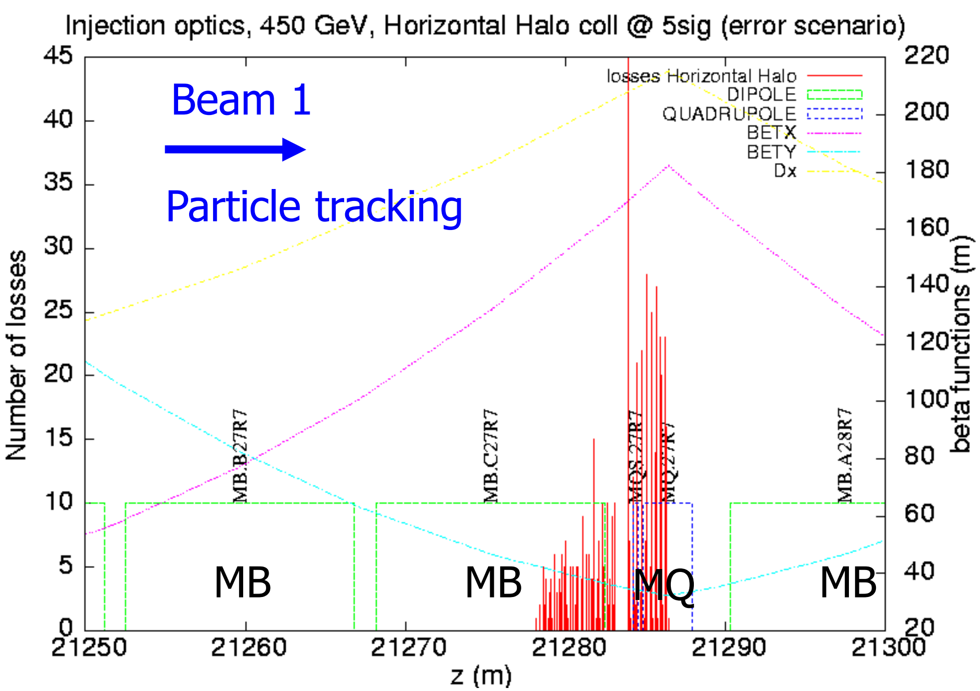
3. Beam loss scenarios
5. Use of the blm's for machine protection
6. Use of the blm's for machine operation and studies
6.3 Setting of collimators and other movable targets
6.8 Beam and machine studies
6.9 Post-mortem analysis
7. Beam losses: dynamic range and time constants
7.3 Steady losses
7.3.3 Loss 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

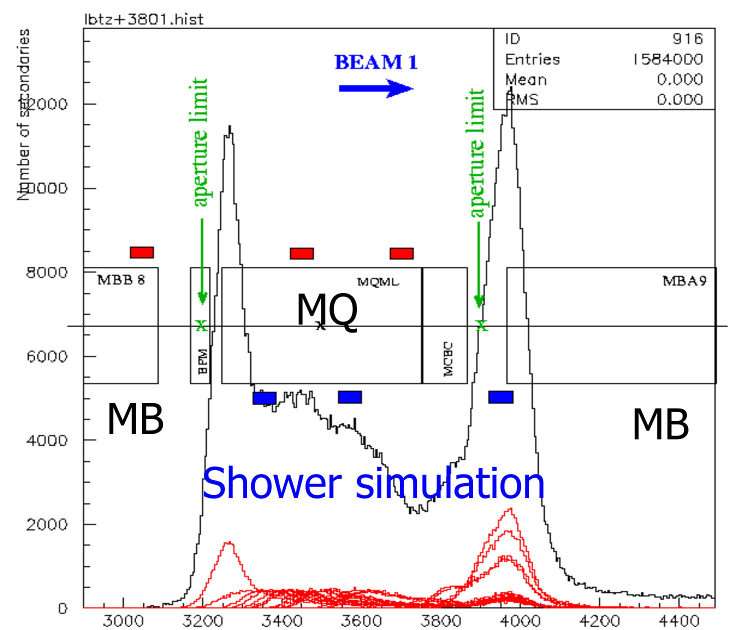
- Specification (location of monitors, time response, dynamic range, safety and reliability requirements)
- System overview
- Detector
- Acquisition chain
  - Radiation tolerant electronics
  - Parallel and voting for safety and reliability Requirements
- Reliability software
- Failsafe system, human errors
- Firmware updates
- Functional tests
- Data path
- Preventive actions
- Management of settings

Loss Location Determination

- 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

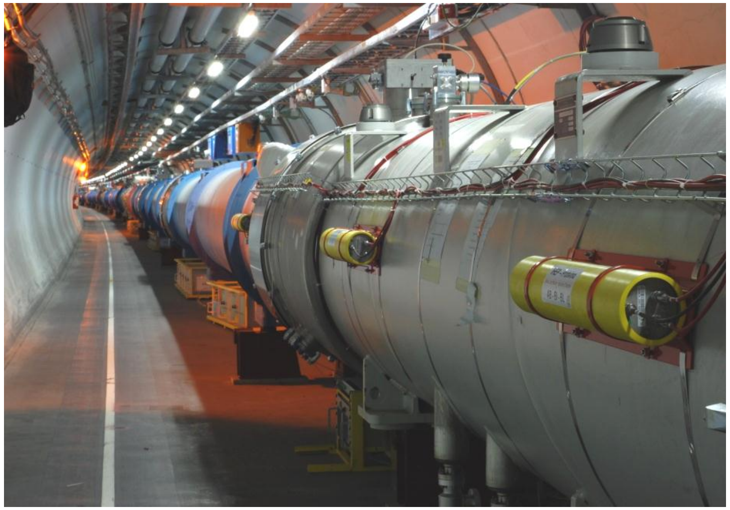




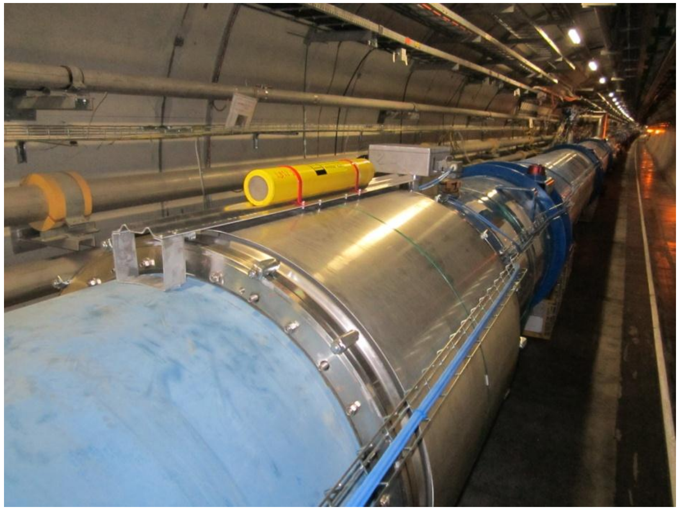


Location of Beam Loss Monitors

BLMs at quadrupole magnet

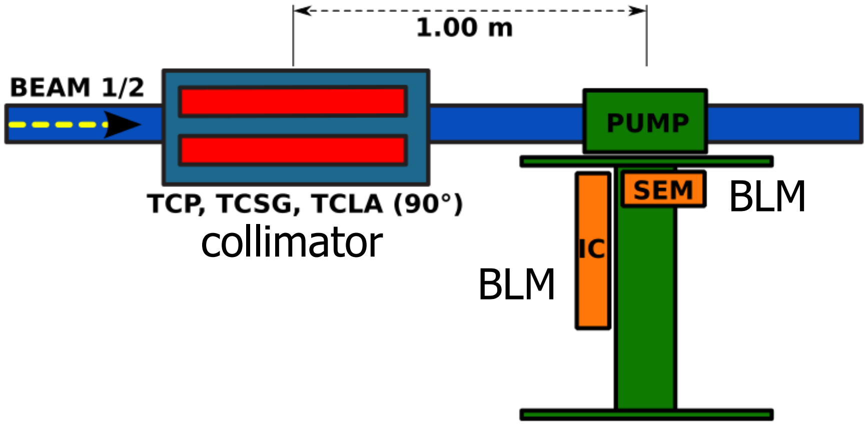


BLM at bending – bending magnet transition

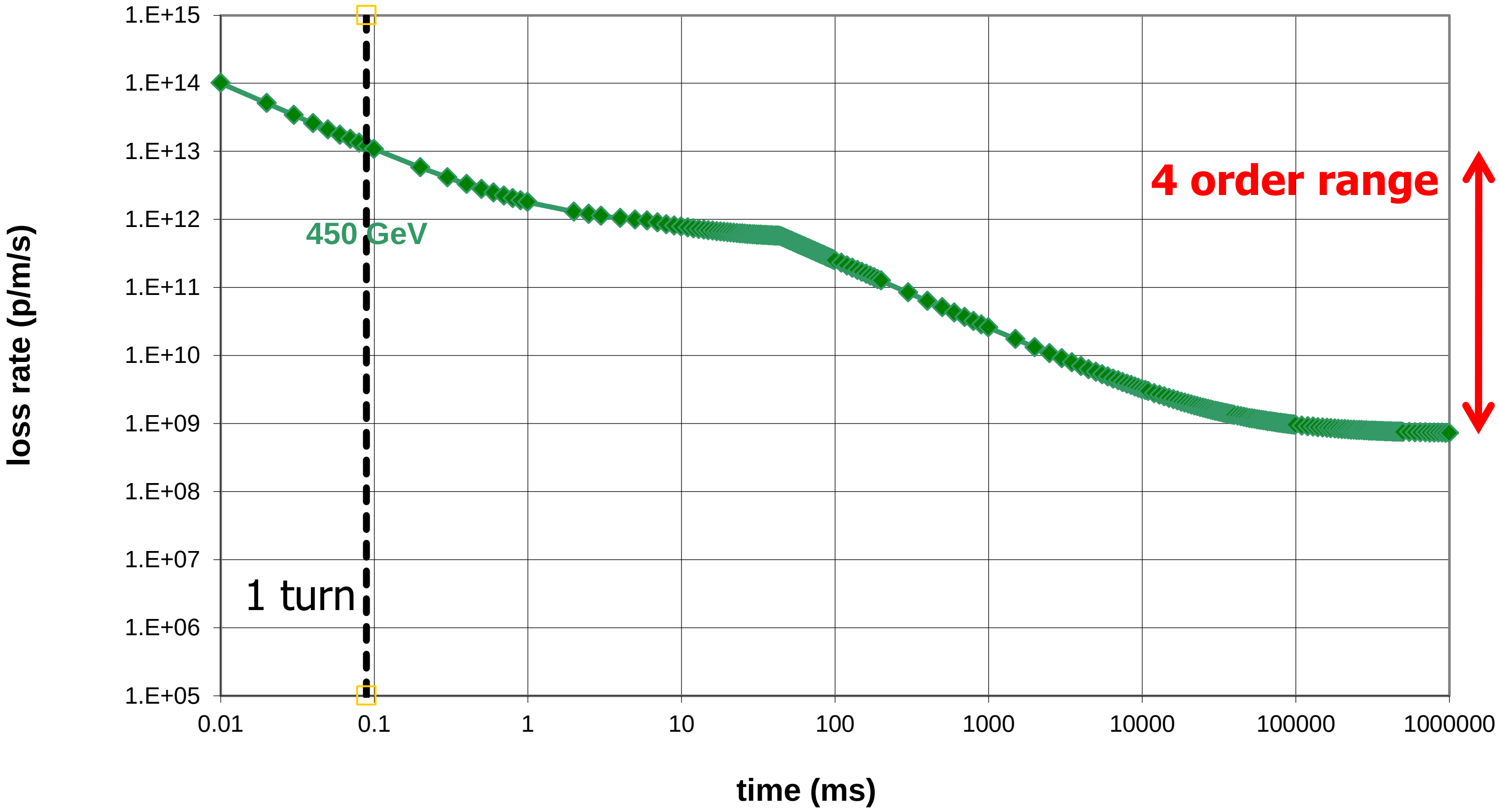


BLMs at final focussing magnet

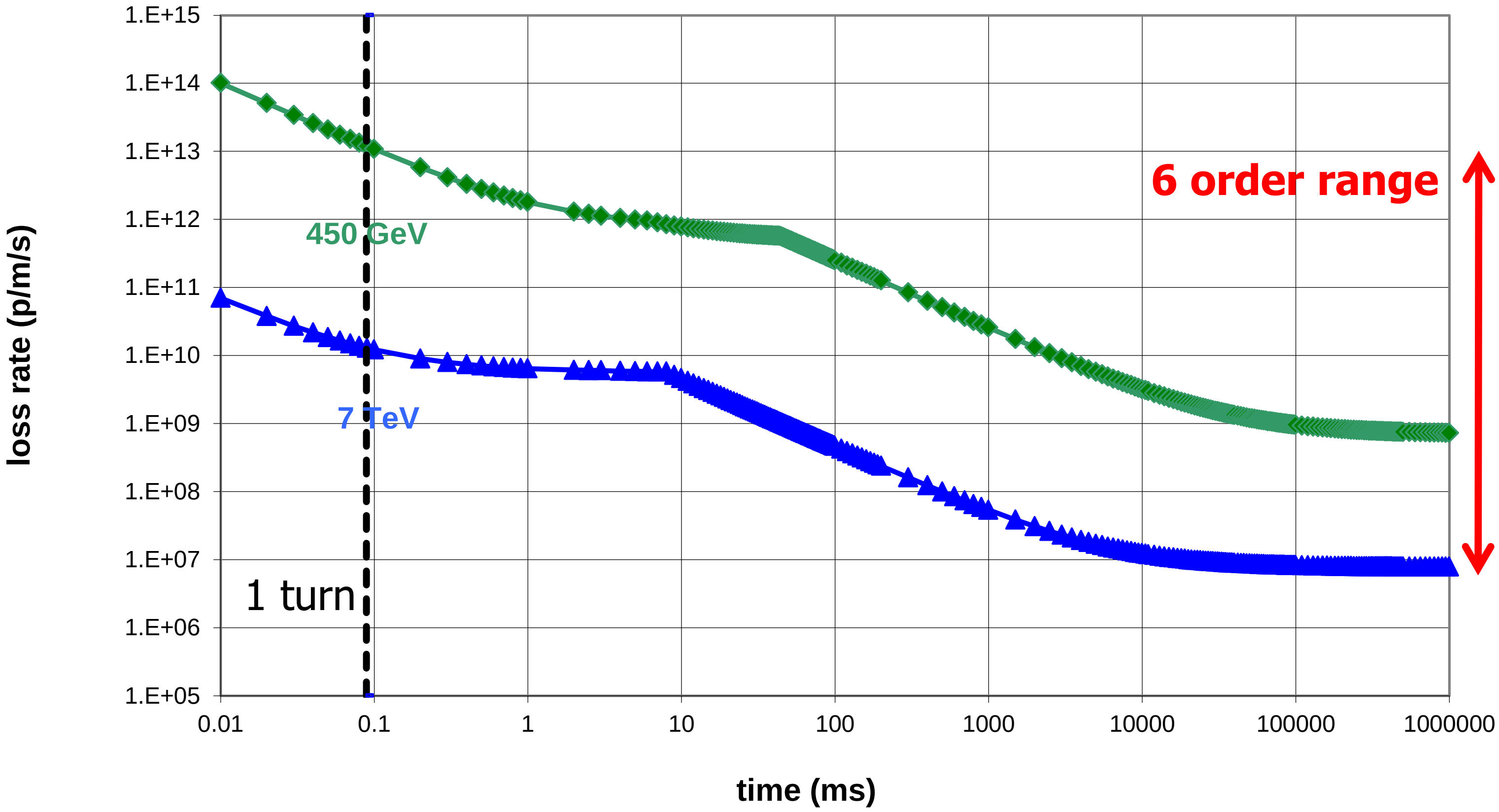
BLM at collimator



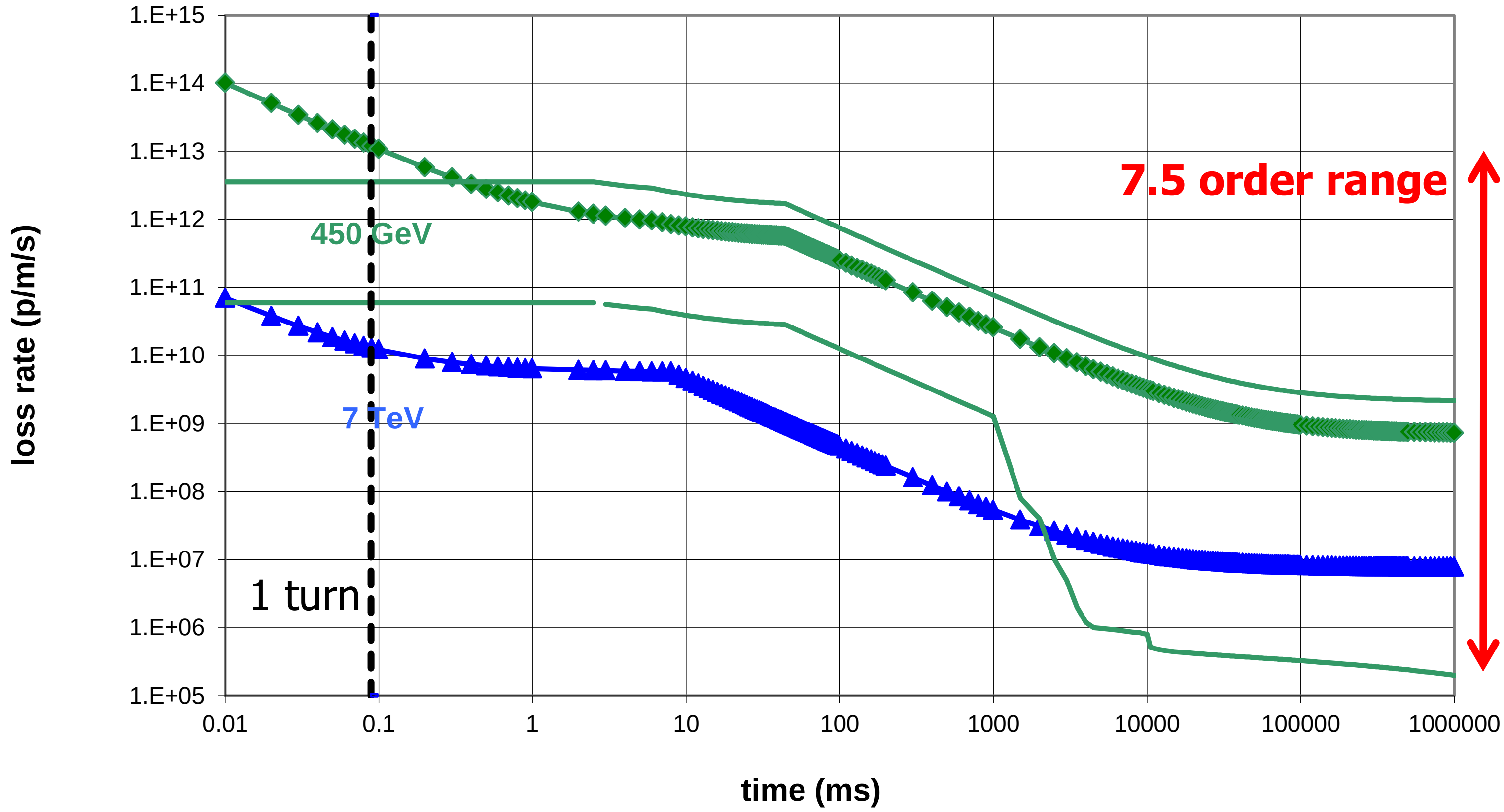
Magnet Quench Levels and Loss Measurement Ranges



Magnet Quench Levels and Loss Measurement Ranges



Magnet Quench Levels and Loss Measurement Ranges



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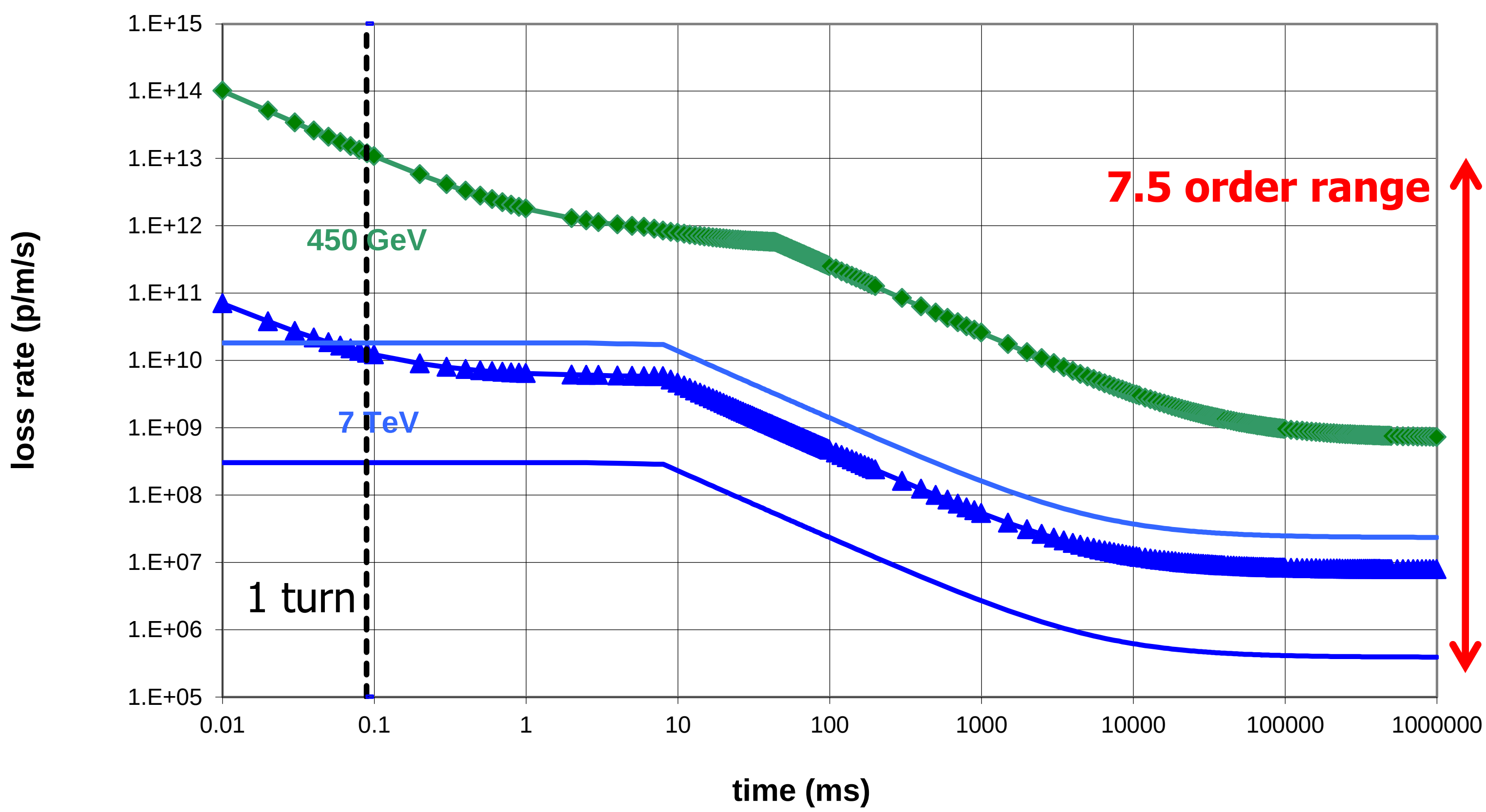

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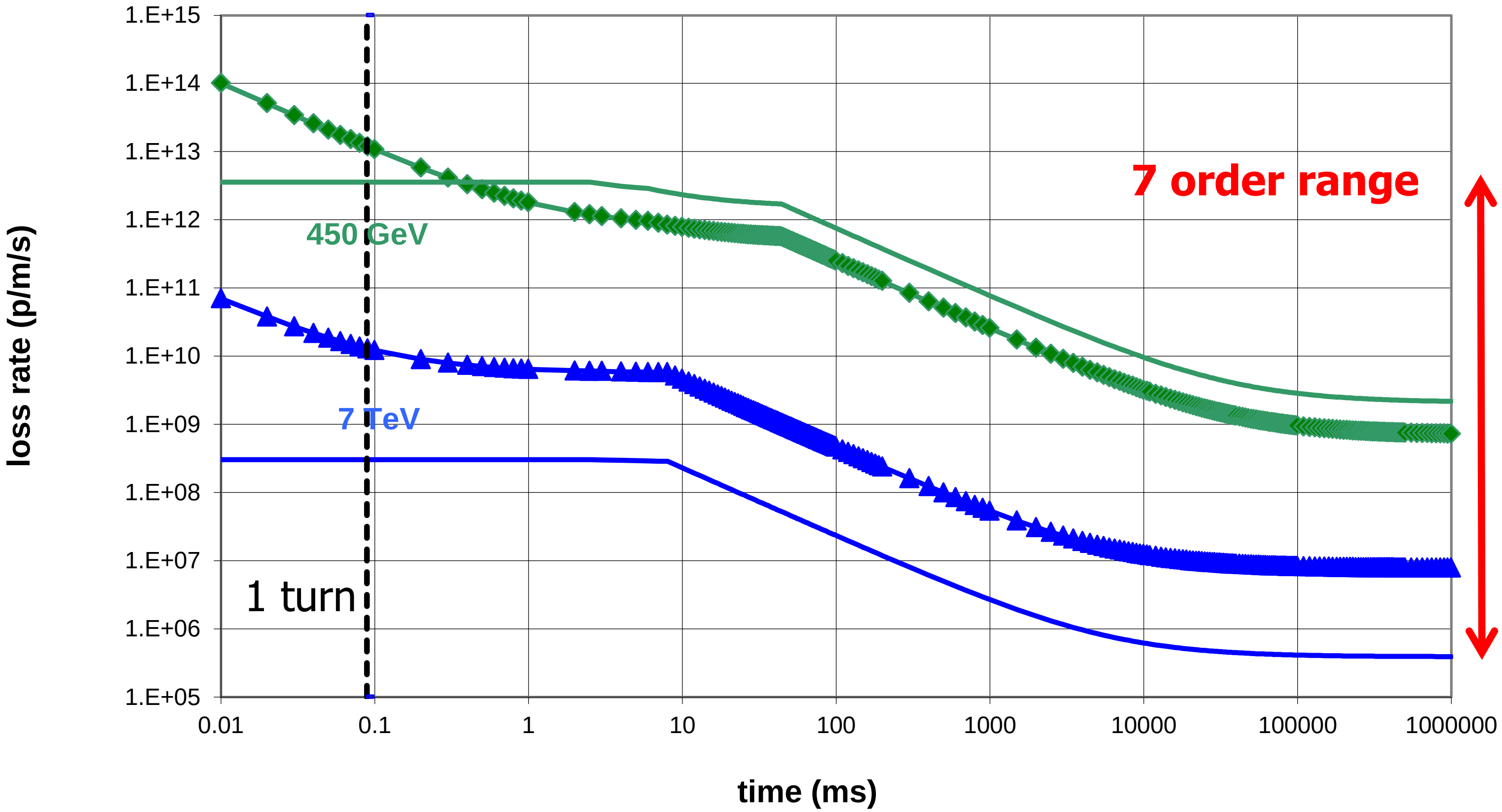
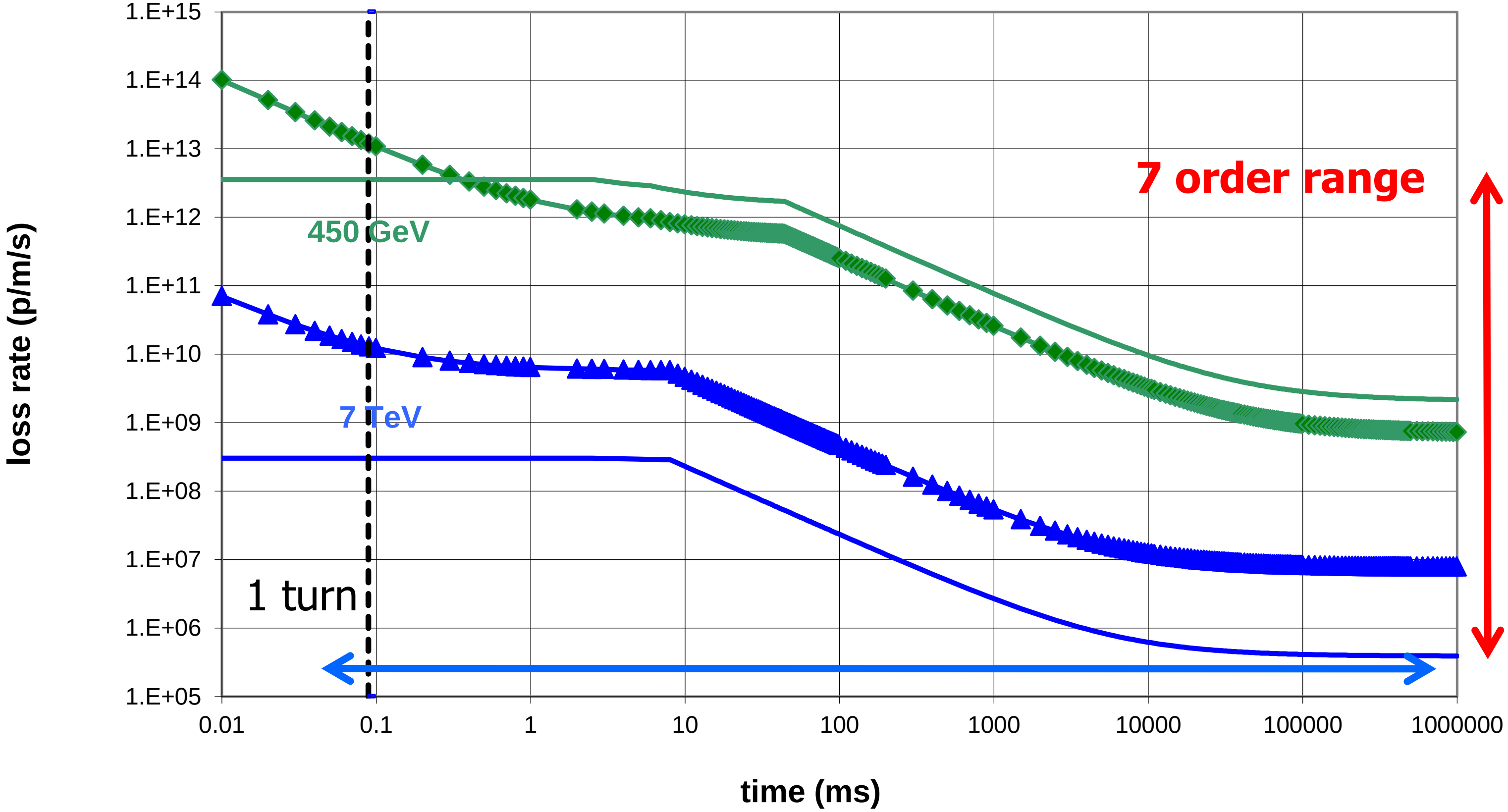


Magnet Quench Levels and Loss Measurement Ranges



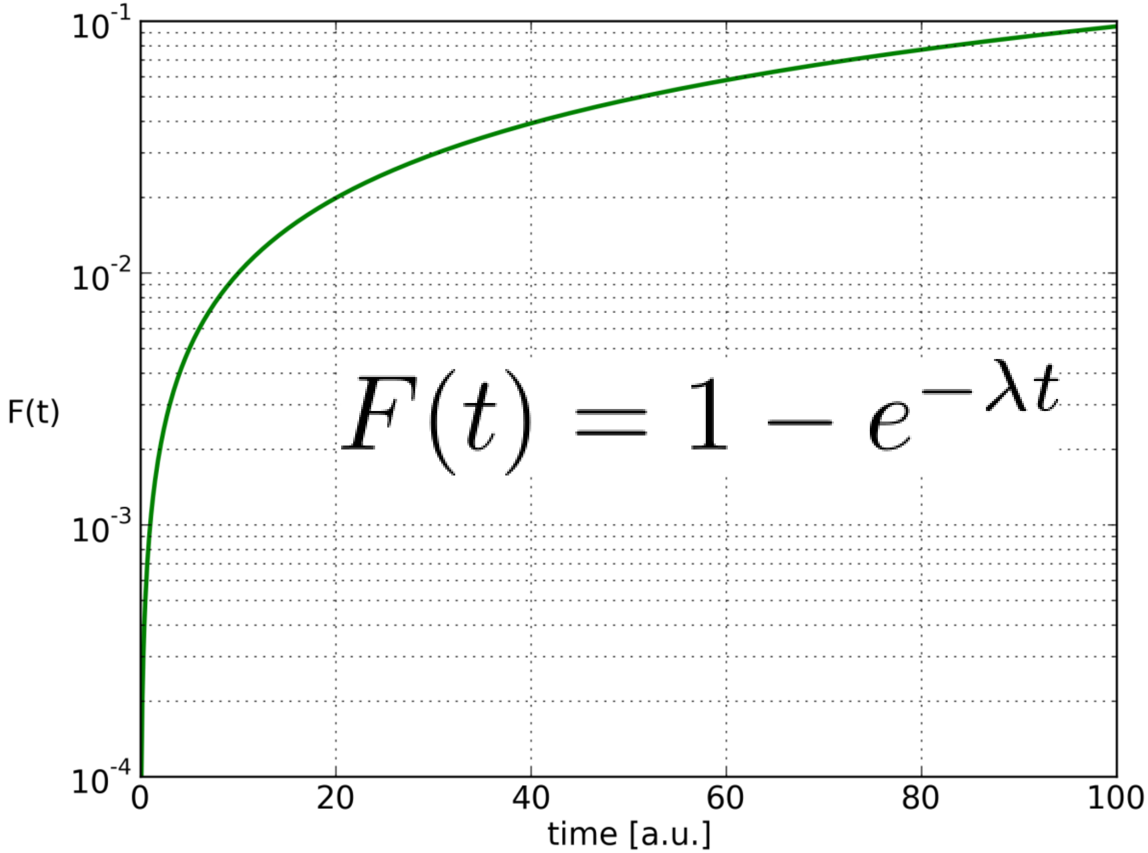
To allow higher loss levels for short loss durations the concept of running sums is used

- The acquisition chain needs to have a dynamic range of 7 orders of magnitude
- 12 running sums are online calculated in range from 40 us to 83 seconds

Dependability: Safety System Design Approach

Risk	Safety	Protection	Reduction of Availability
Scaling:		Methods:	
frequency of events x consequence	Mean time between failures	Stop of next injection Extraction of beam	Reduction of operational efficiency
SIL ALARP	$1\ 10^{-8}$ to $1\ 10^{-7}$ 1/h		
		Systems:	**Solutions:**
Damage (system integrity) **Quench (operational Efficiency)**	**Fail-safe** **Redundancy** **Survey** **Functional Check**	**Beam loss Monitors** **Quench protection system** **Interlock system** .. **Dump system**	**Reliable components** **Redundancy voting** **Monitoring of drifts**

F (t) Probability that a failure occurs in the time 0 to t



$$F(t) = 1 - e^{-\lambda t}$$

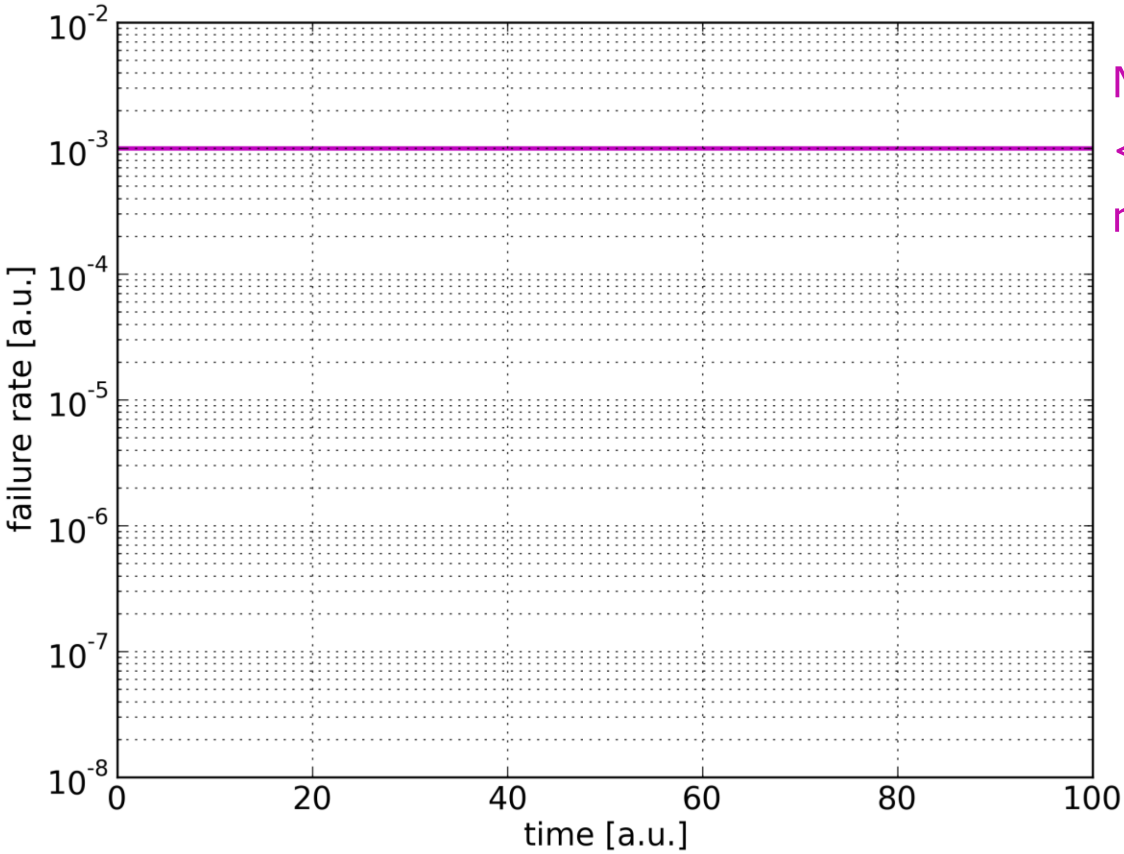
The exponential failure probability leads to a constant failure rate

$$Failurerate = \lambda$$

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

<=>

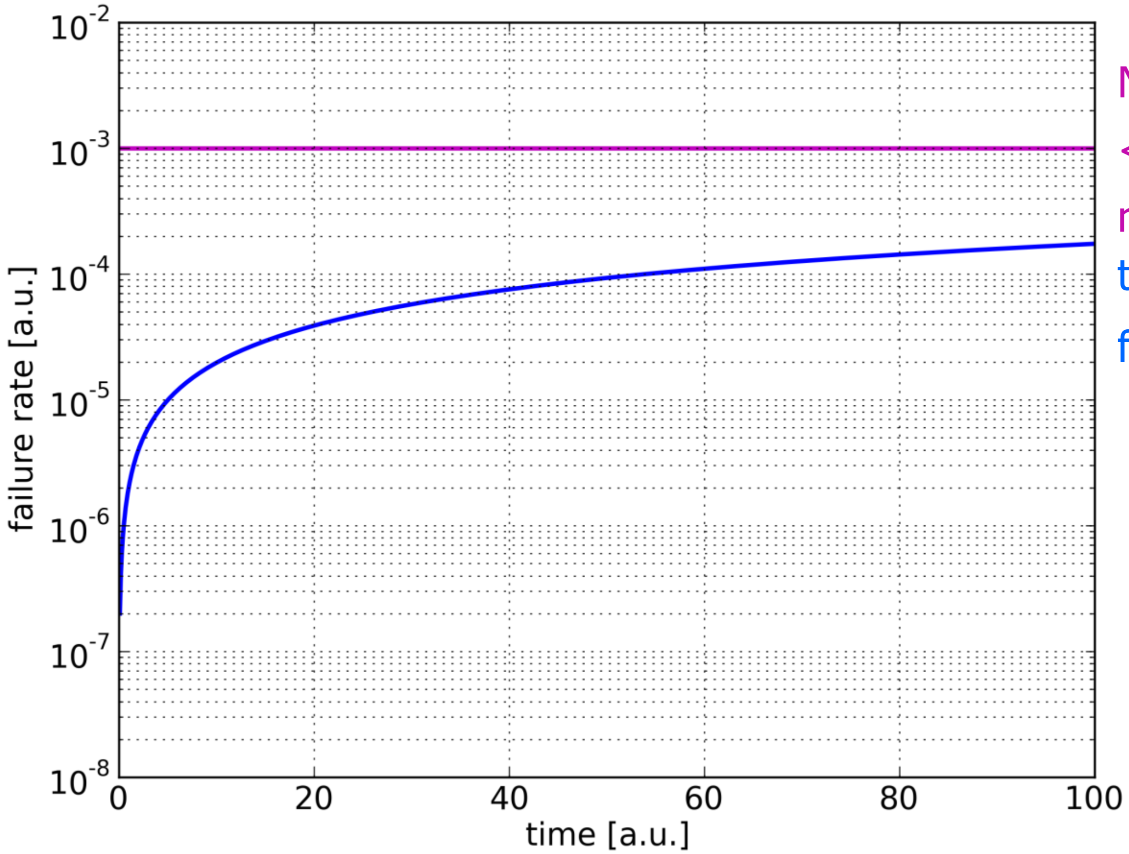
no memory effect

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

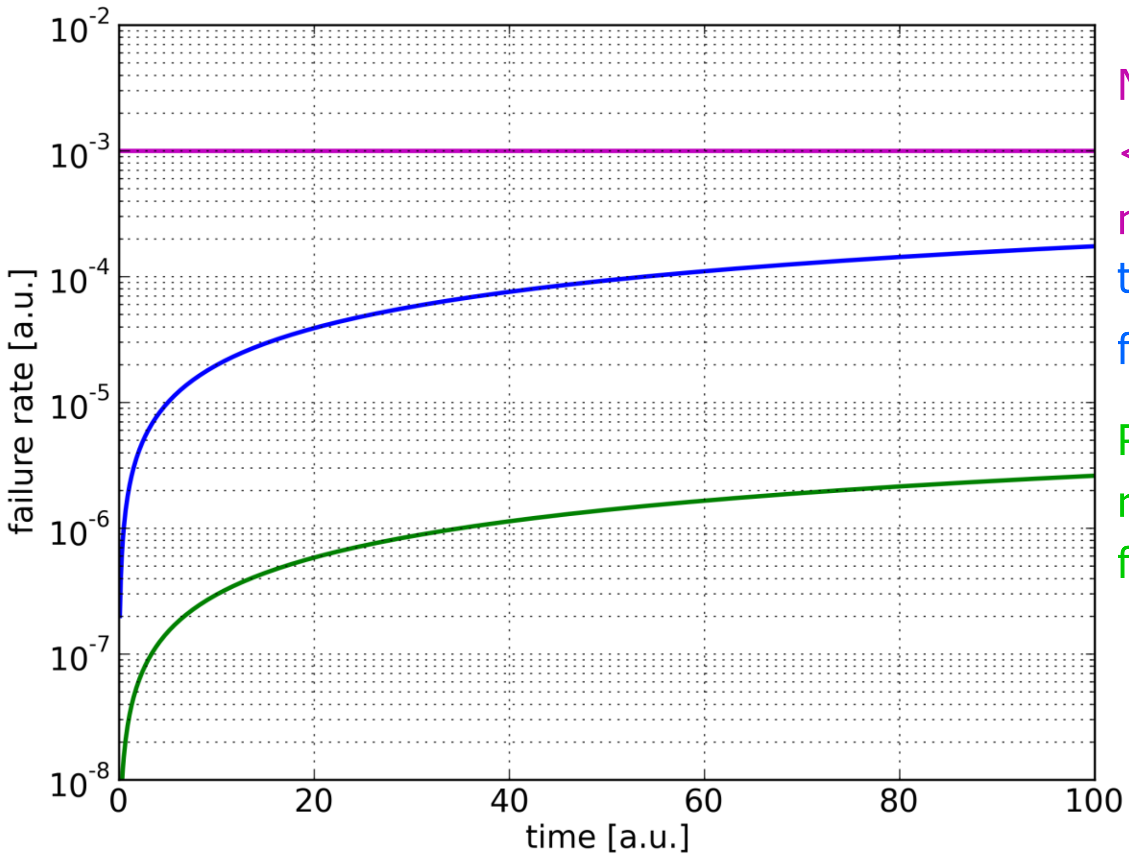
Redundancy - Survey - Functional Check II

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

Single system

Two Systems parallel

Surveyed System



No time dependence

<=>

no memory effect

time dependent

failure rate

Reduction of failure rate by excluding failure modes

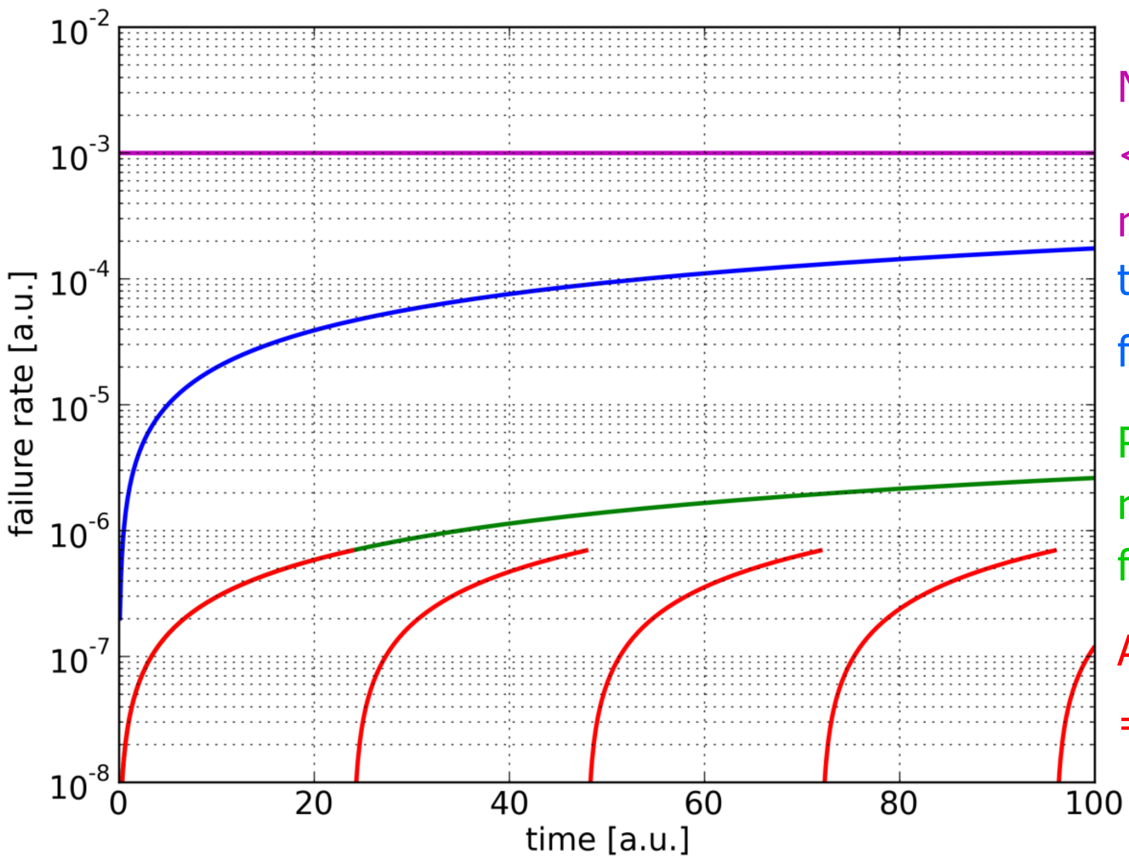
Redundancy - Survey - Functional Check II

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

Single system

Two Systems parallel

Surveyed System



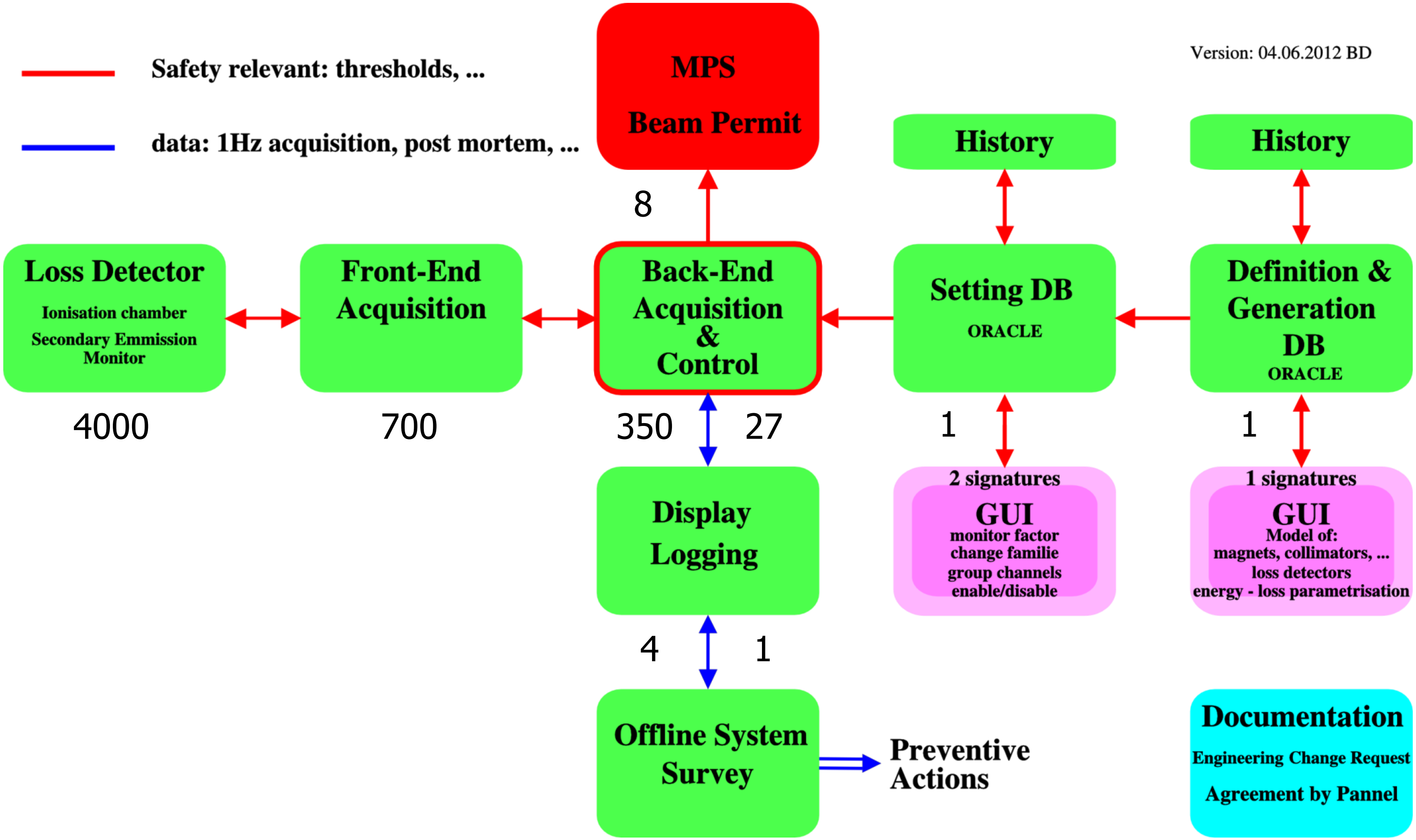
No time dependence
<=>
no memory effect

time dependent
failure rate

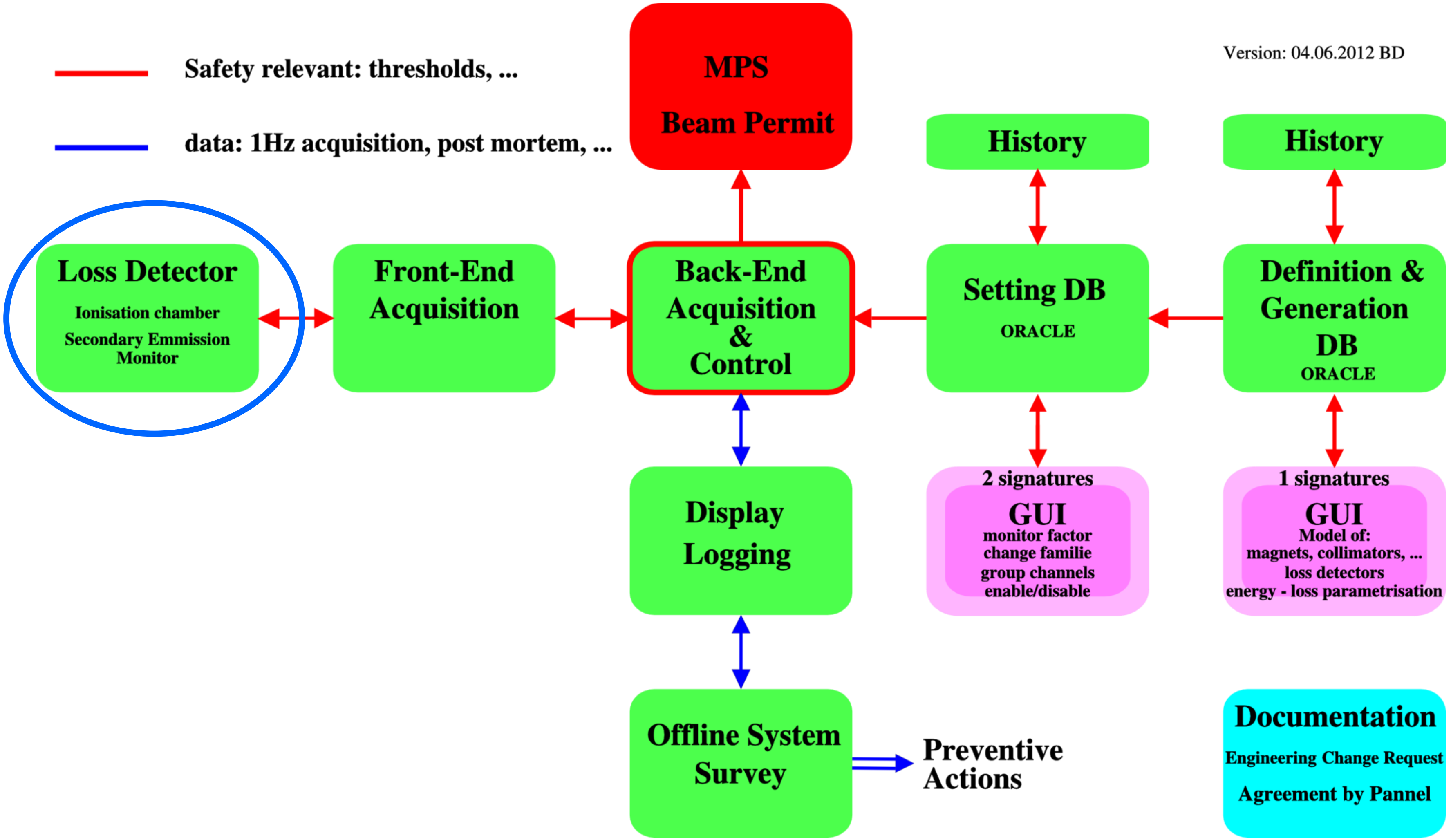
Reduction of failure rate by excluding failure modes

After **functional** test
=> **System new**

BLM System Information Flow



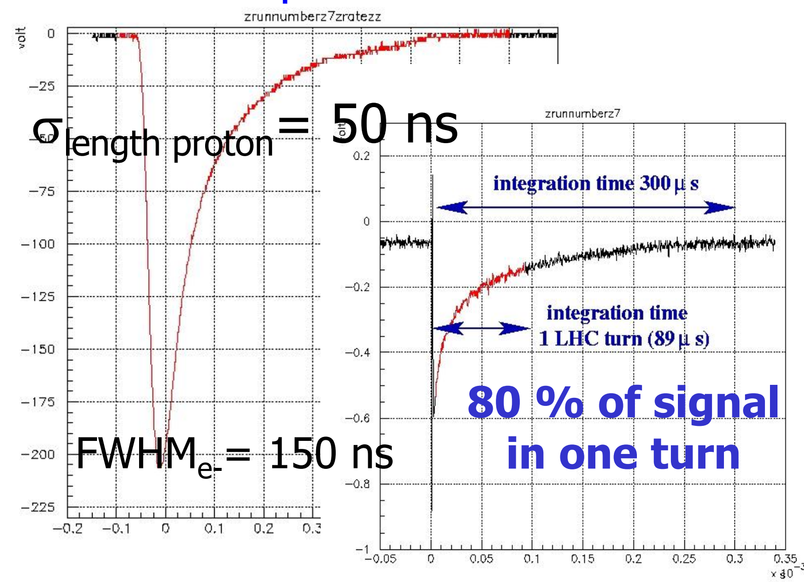
BLM System Information Flow

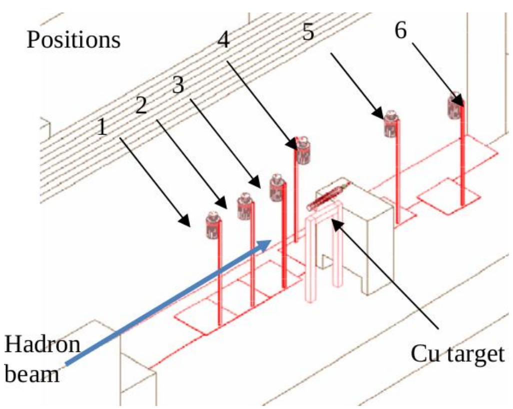


Ionisation Chamber

- 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

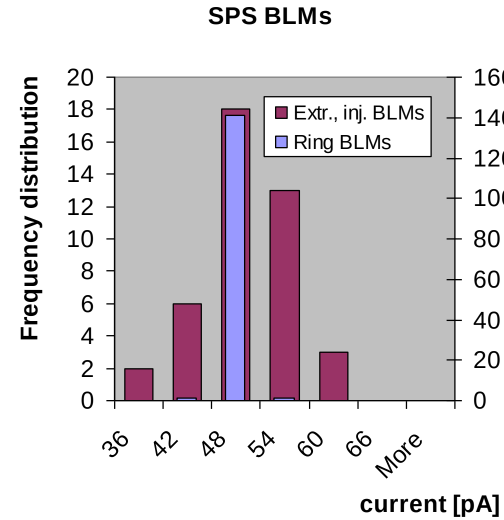




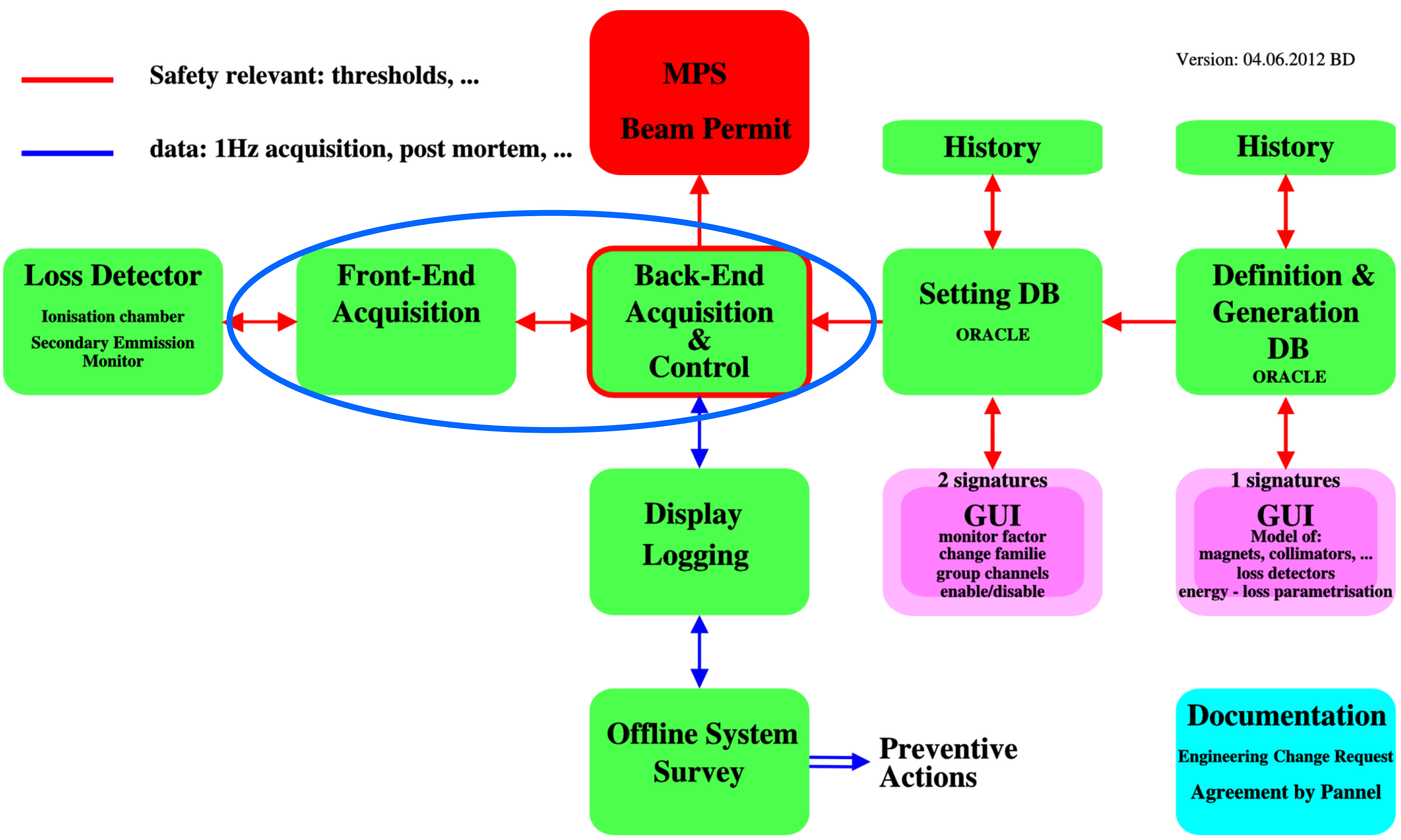
Calibration

		+ 10% Outer layer
Horizontal cables downstream	1	1.32
	2	1.14
	3	1.31
	4	1.08
	5	1.29

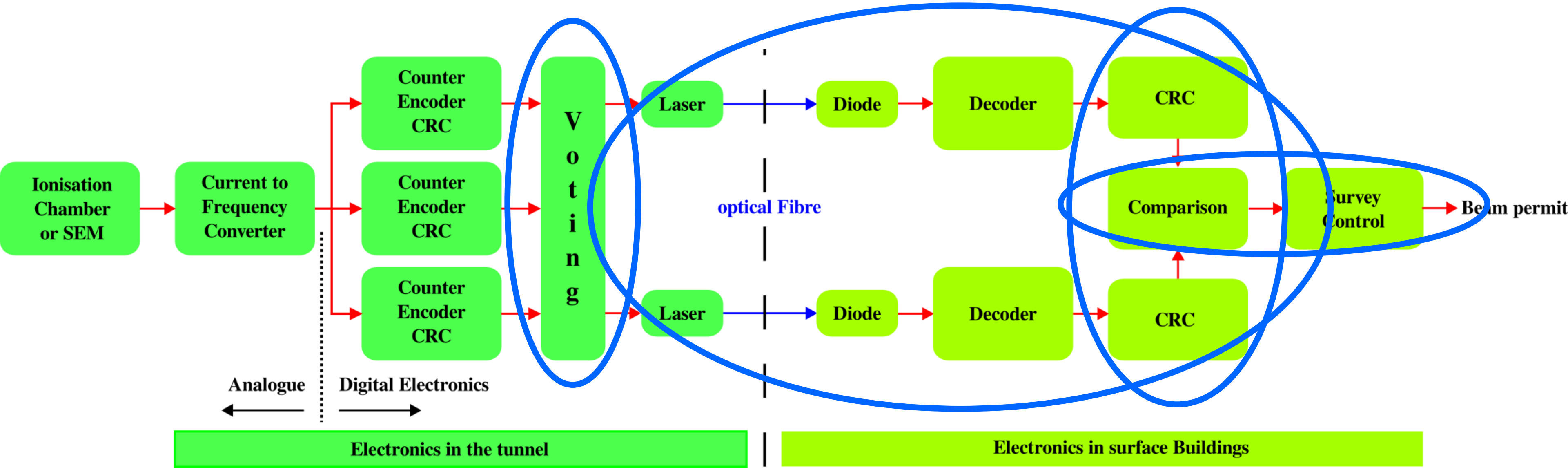
Gain variation



BLM System Information Flow

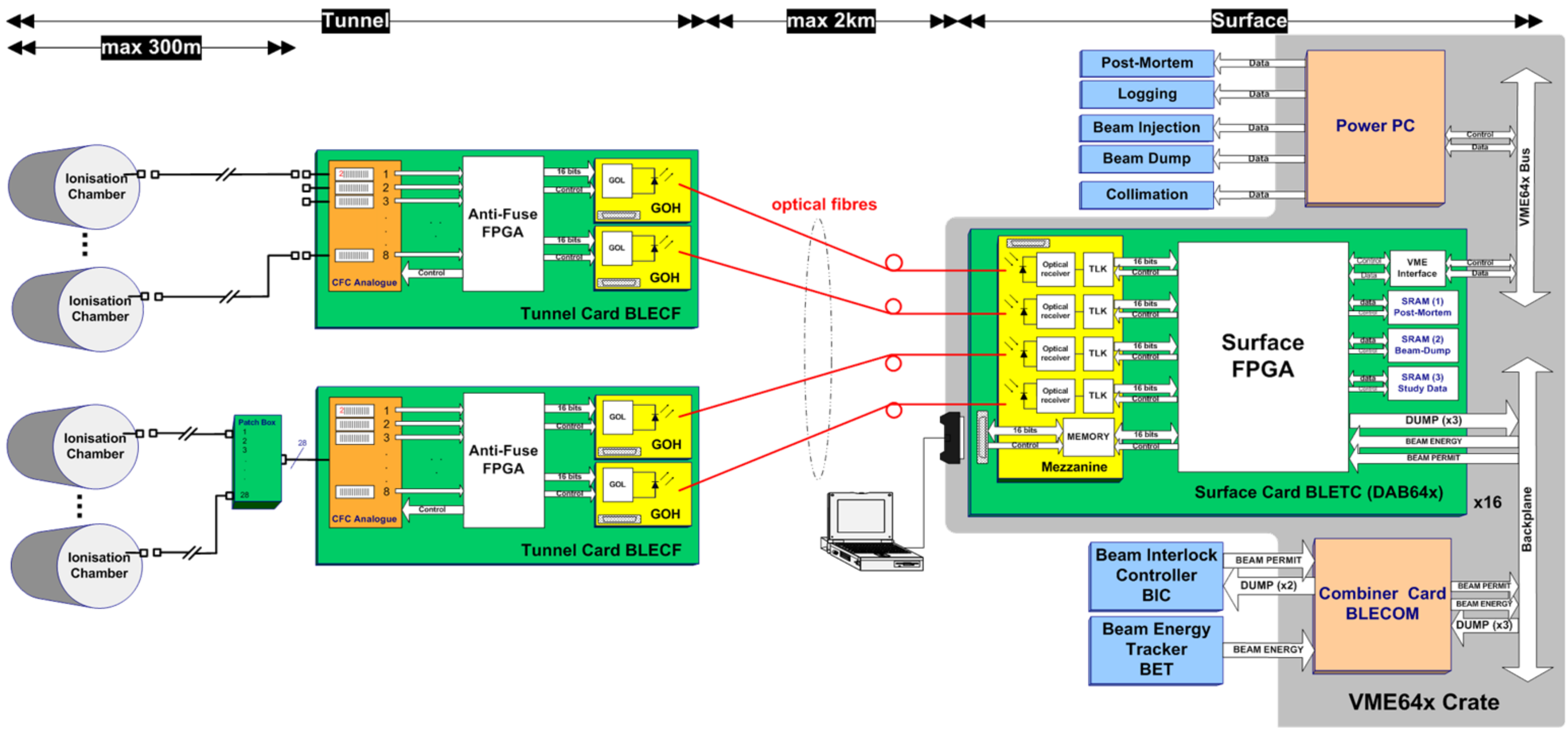


Beam Loss Measurement System Layouts



	Comment	Safety gain	Availably gain
Failsafe	active state = beam permit	yes	no
Voting		yes	yes
Redundancy		yes	yes
CRC	Cyclic redundancy check	yes	no

The BLM Acquisition System



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.

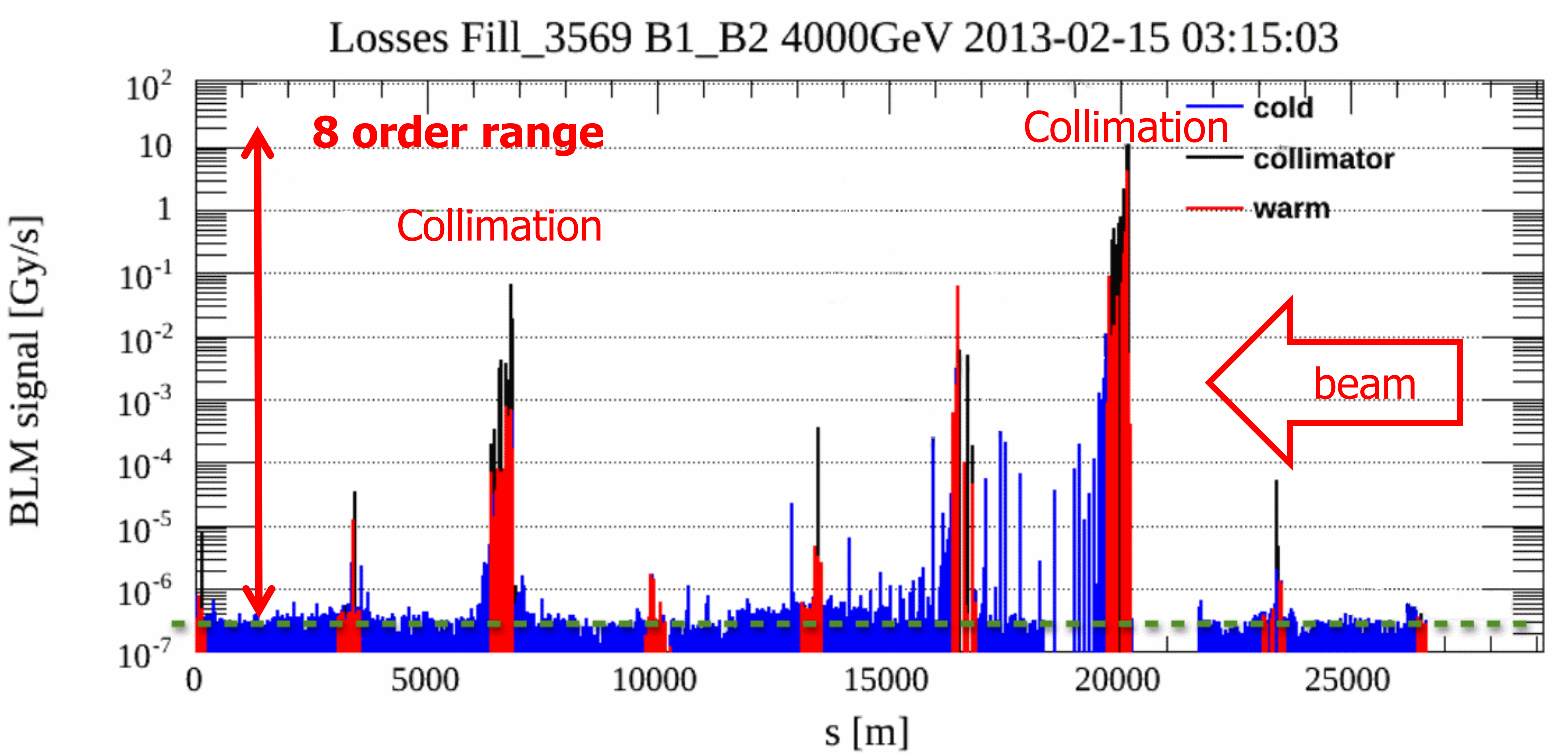
Real-Time Processing BEE

- **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**

Efficiency and limits of LHC collimation system

Proton impact on primary collimator and observation of downstream losses

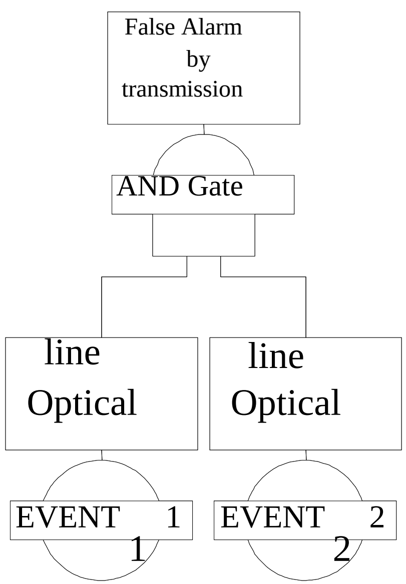
(loss duration some seconds)

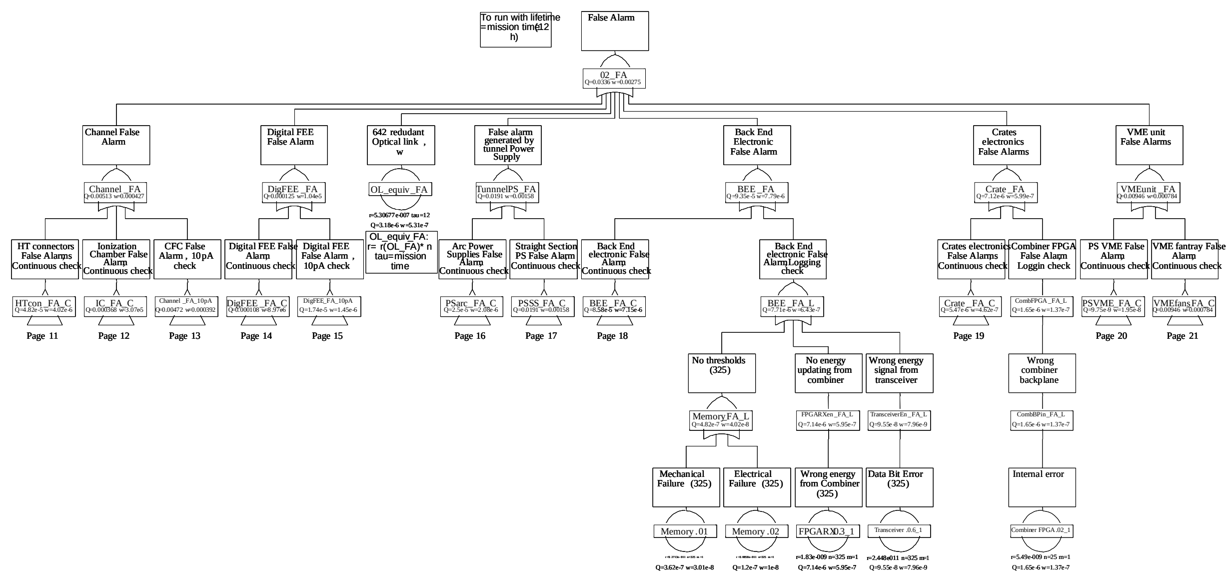


Atlas ALICE CMS LHCb

Reliability: Fault Tree Analysis

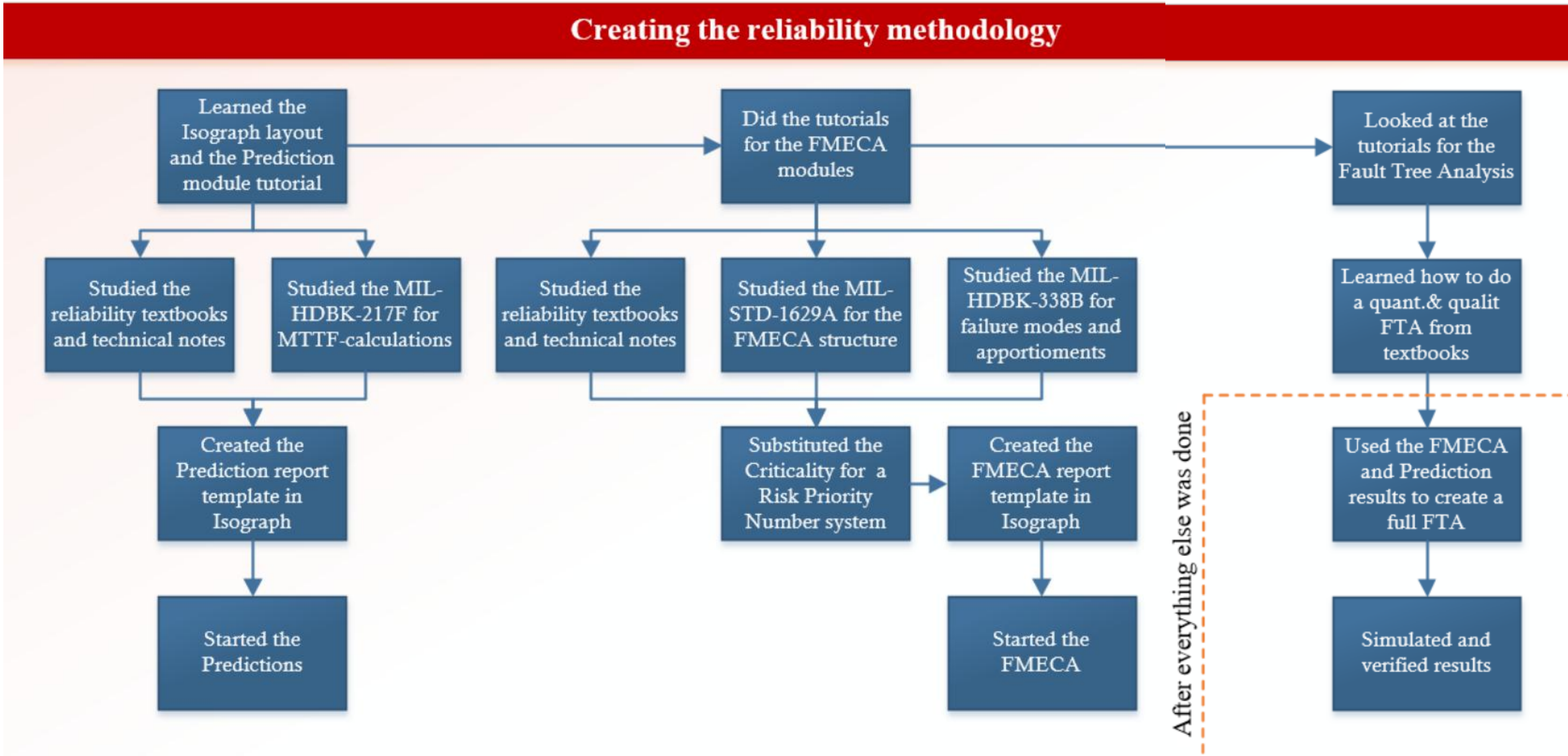
- Definitions of failure modes (LHC 160)
- Three end effects:
  - Damage risk: probability not to be ready in case of dangerous loss
  - False alarm: probability to generate a false alarm
  - Warning: probability generating a maintenance request due to a failure of a redundant component
- Probability 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



Vegard Joa Moseng , CERN

Steps taken for a Failsafe System: Error-free Communication

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 $Pr = 1.16415 * 10^{-10}$ 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

Steps taken for a Failsafe System: Avoiding Human Errors

To avoid misplacement of electronic cards or threshold and masking tables

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

- Surface Card Serial number
  - Unique number embedded in a IC (64bit)
  - Compared with the one stored in setting DB

Steps taken for a Failsafe System: System Failures

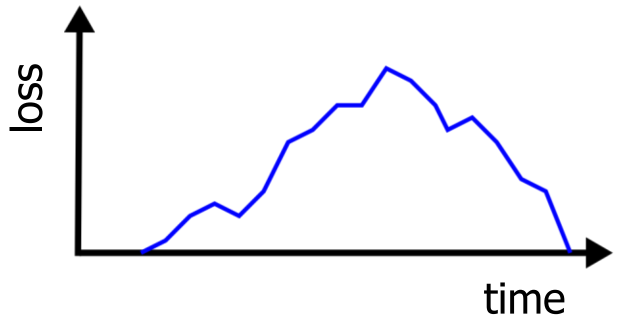
To avoid loss of data

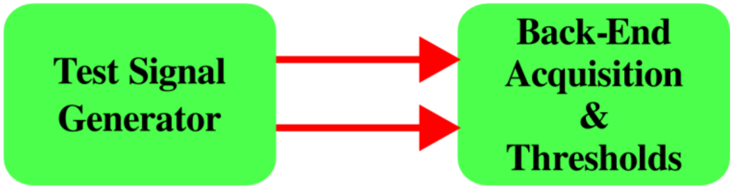
- Frame ID
  - Surface FPGA checks for missing frames
  - Incrementing number included at every transmission
- Optical link is always active
  - 8b/10b encoding sends "commas" when no data
  - Disconnection is detected in max 25ns

To ensure recognition of system failures and beam dump requests

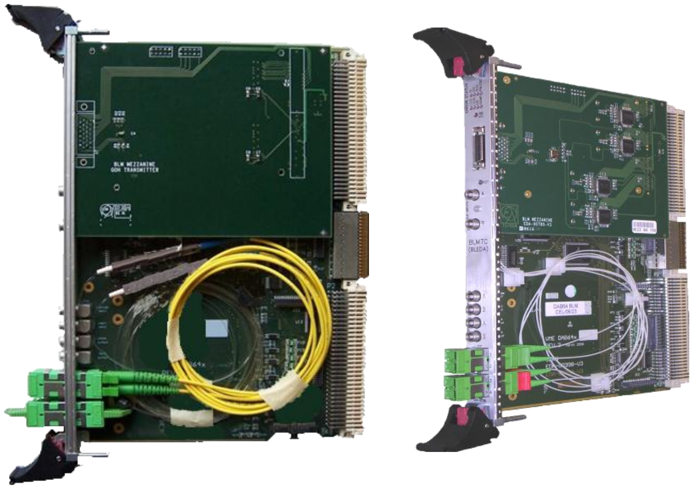
- FPGA Outputs (Beam Dump signals) generate frequency
  - At a dump request, reset, or failure the transmitted frequency will be altered
- Beam Permit lines are daisy-chained between cards
  - Custom VME backplane
  - Dummy cards on empty slots to close circuit

Verification using Emulator Module



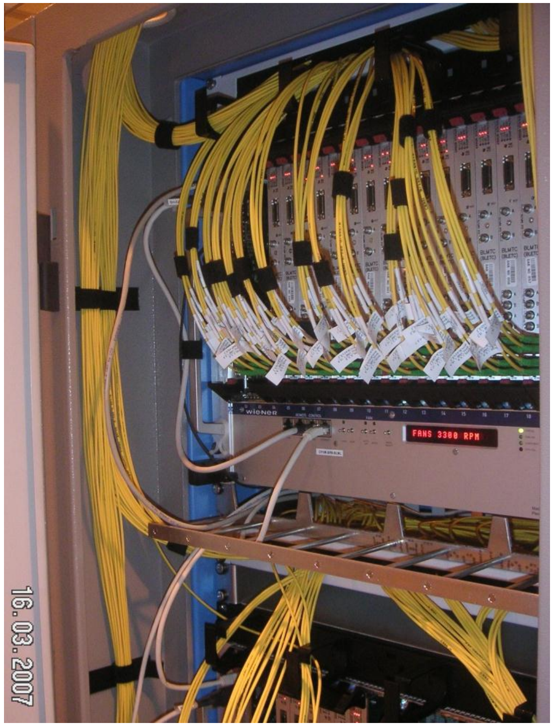


- In situ test of the TC in VME crate by emulation of output signals of CFC
  - Arbitrary Tx data
    - Comparison of different firmware versions
    - Playback of measured data for analysis
  - Tx errors
    - CRC, CID, FID
  - Wrong configuration
  - Errors in physical layer
  - Manual testing procedure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



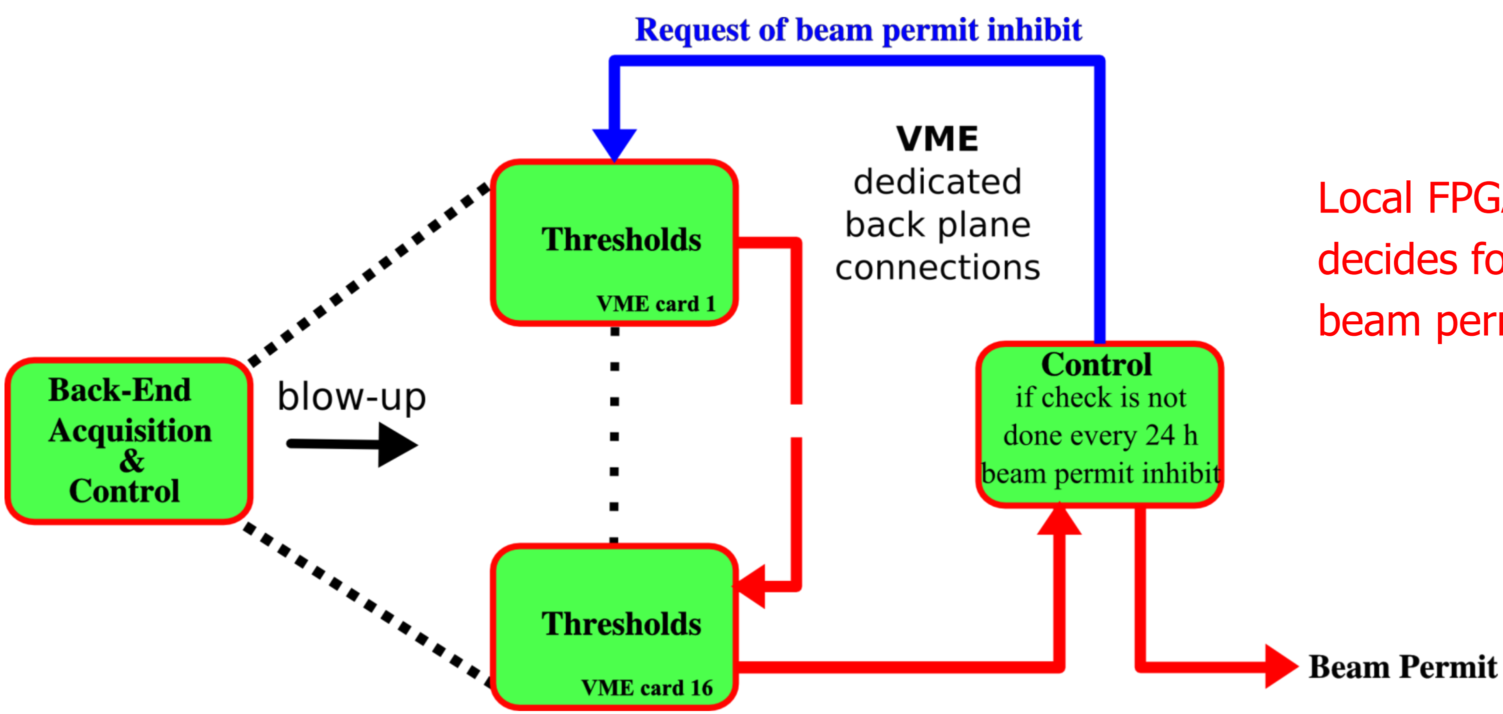
Verification of FPGA Functionality

- 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



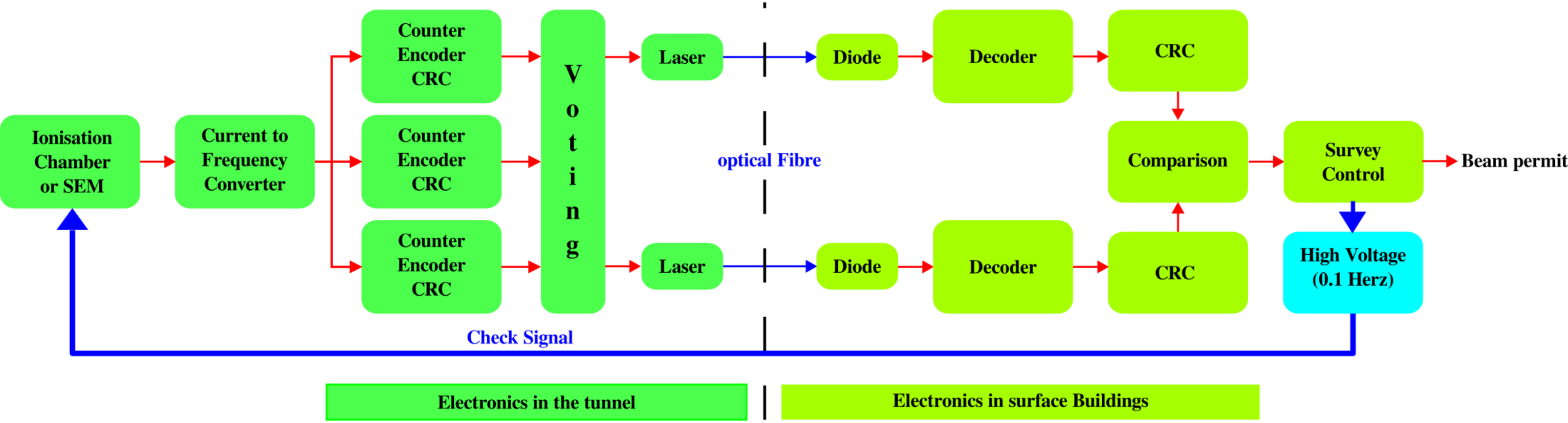
Beam Permit Line Checks

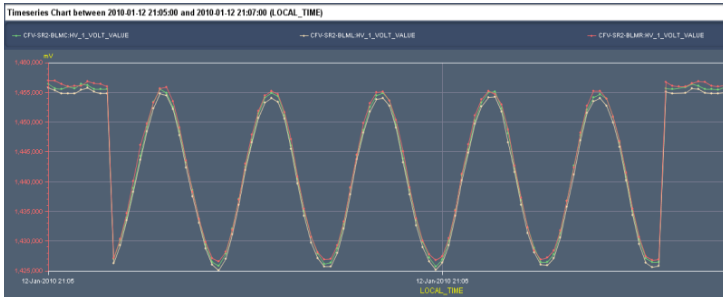
- Check the beam permit lines inside and between crates
- Check results are saved in the database
- Exhaustive test yearly for every threshold (beam energy and integration time dependent)

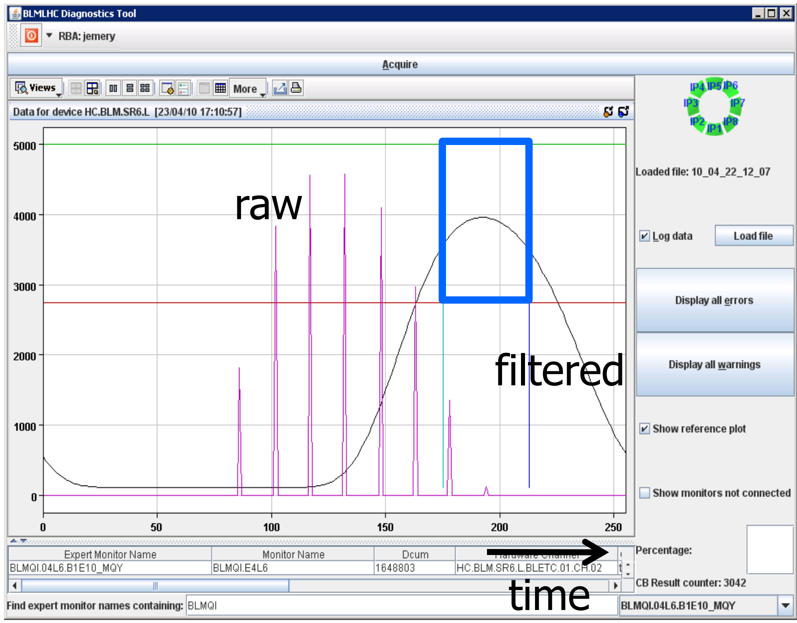


Local FPGA on VME card decides for all checks if beam permit is given

Check of Acquisition Chain (Modulation of HV)

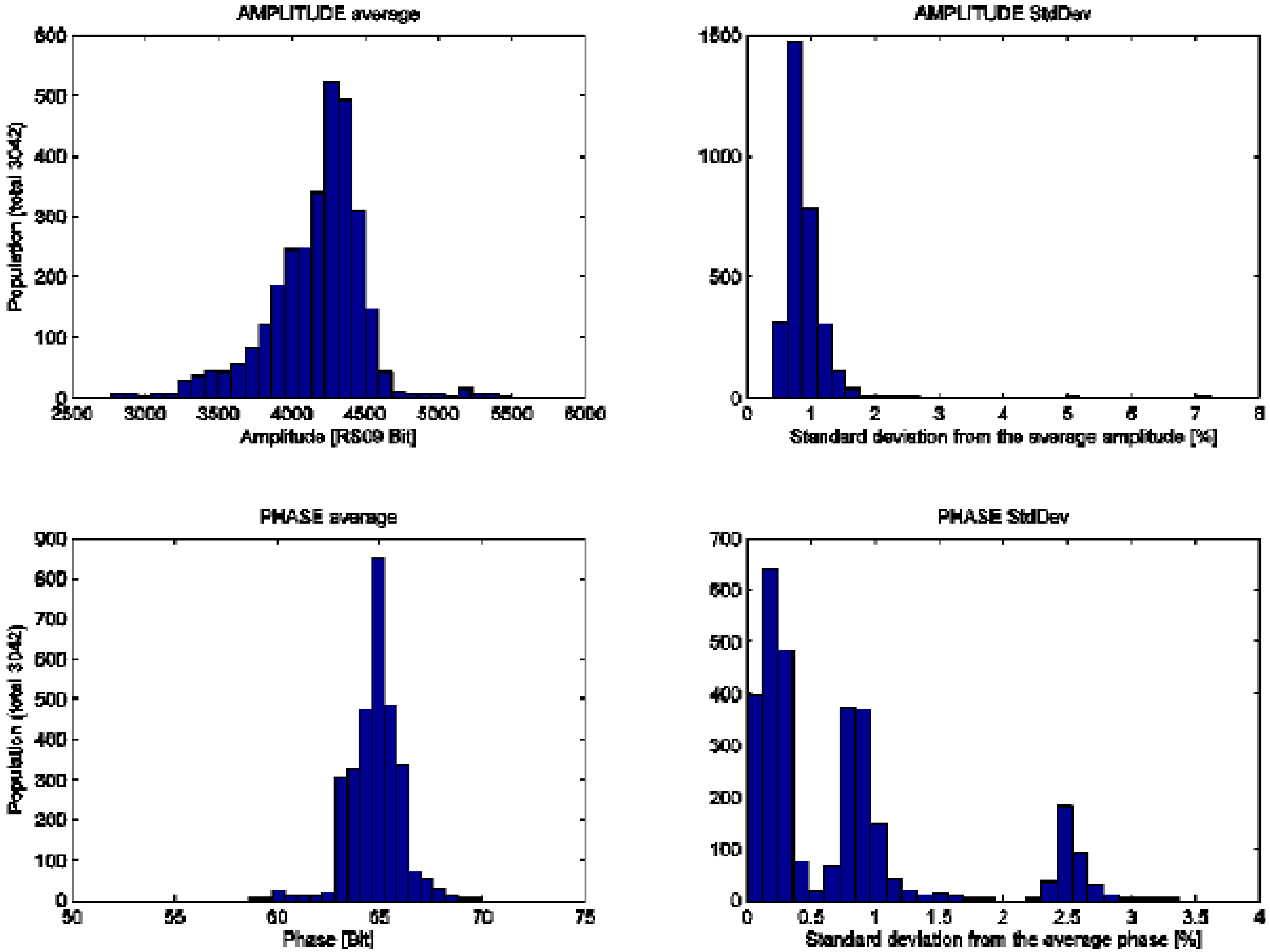




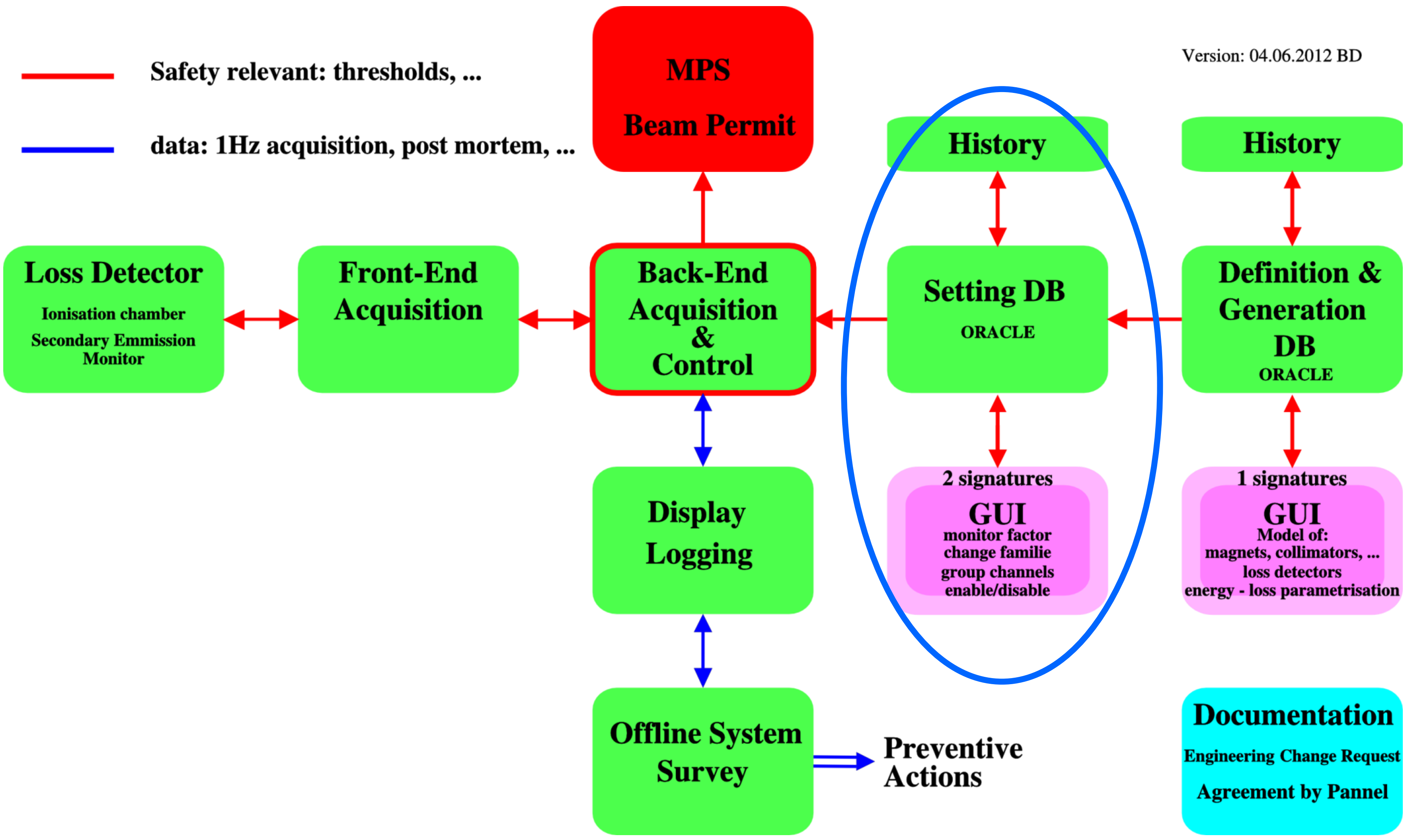


- Phase and amplitude are compared with thresholds
- Beam permit not given if not done every 24 h
- Local FPGA on VME card decides for all checks if beam permit is given

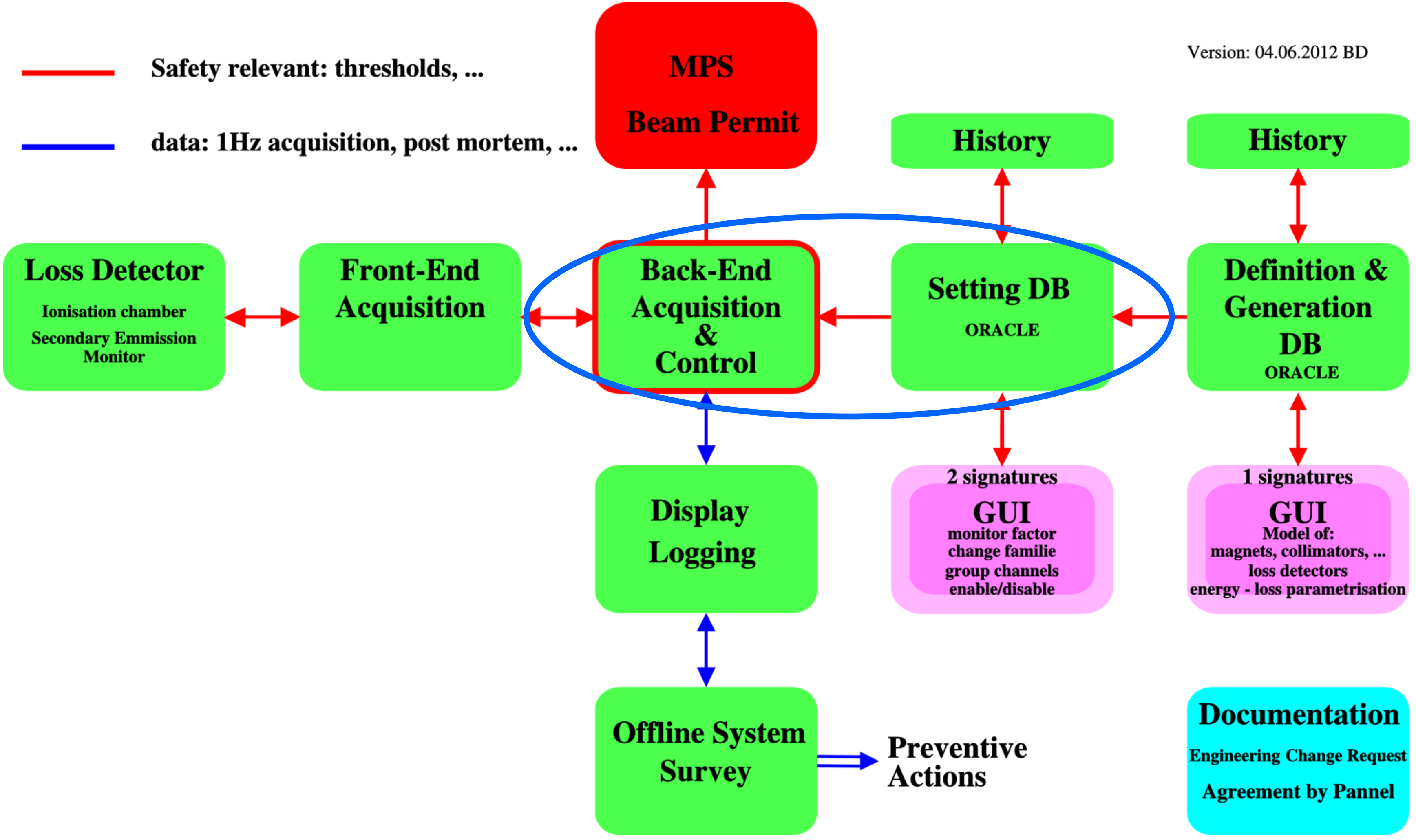
Connectivity check measurements (100x) on BLMQI monitors (Ionization chambers in the arcs)



BLM System Information Flow

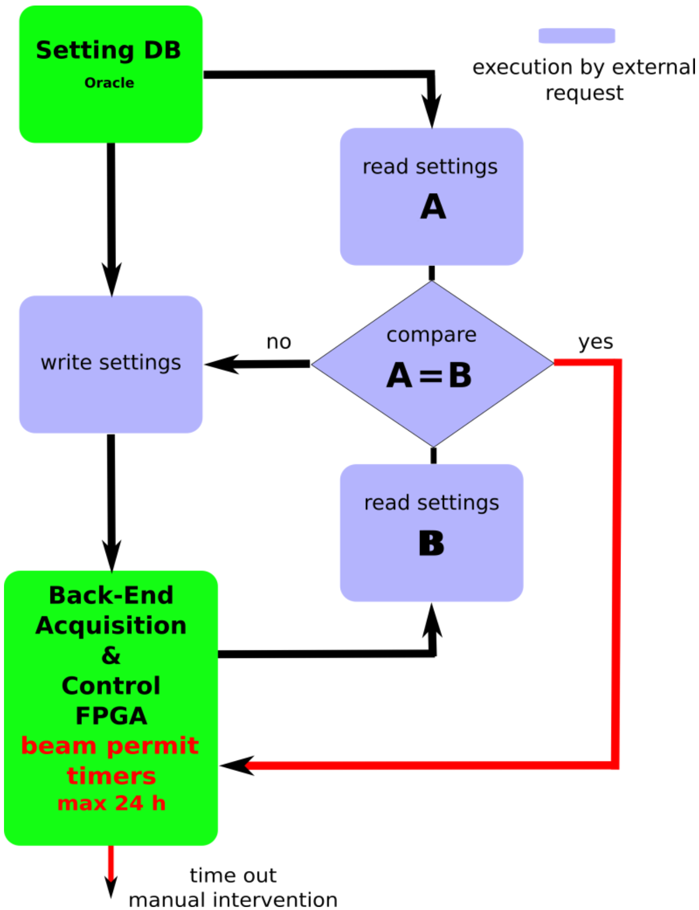


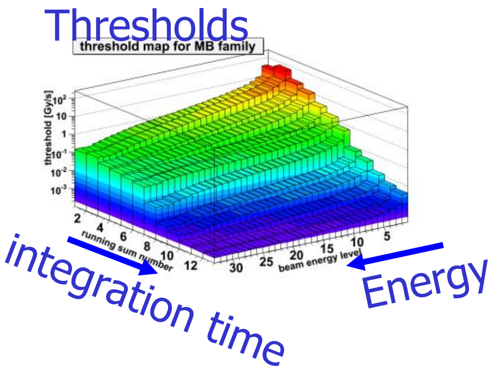
BLM System Information Flow



Reliability: Comparison of Back-End Settings with Database

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

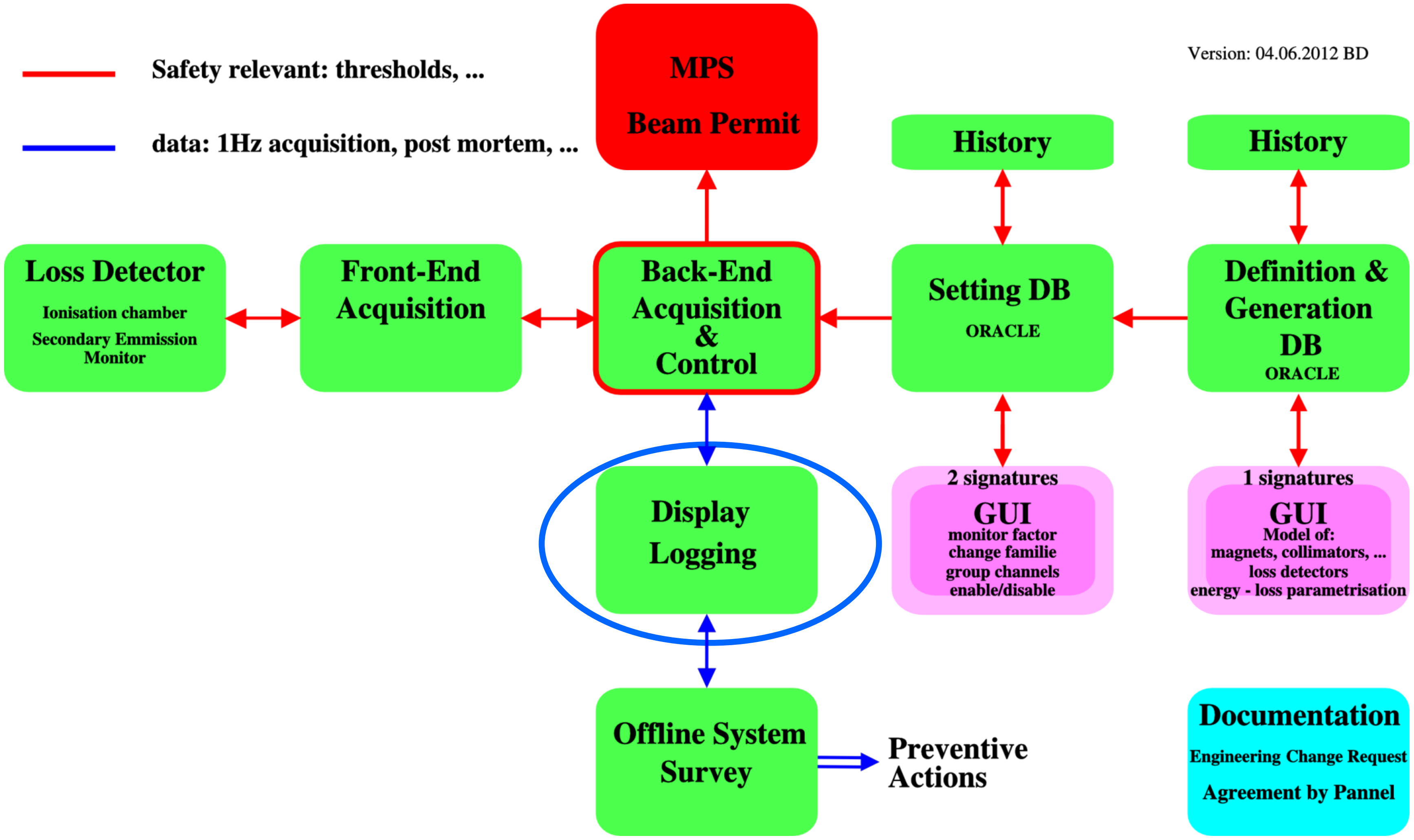




- Setting storage in Oracle database
- Settings:
  - Threshold values
  - Voltages, currents, phase limits
  - Serial numbers
  - Software version numbers
- If comparison negative and after retry, manual intervention (no beam permit)

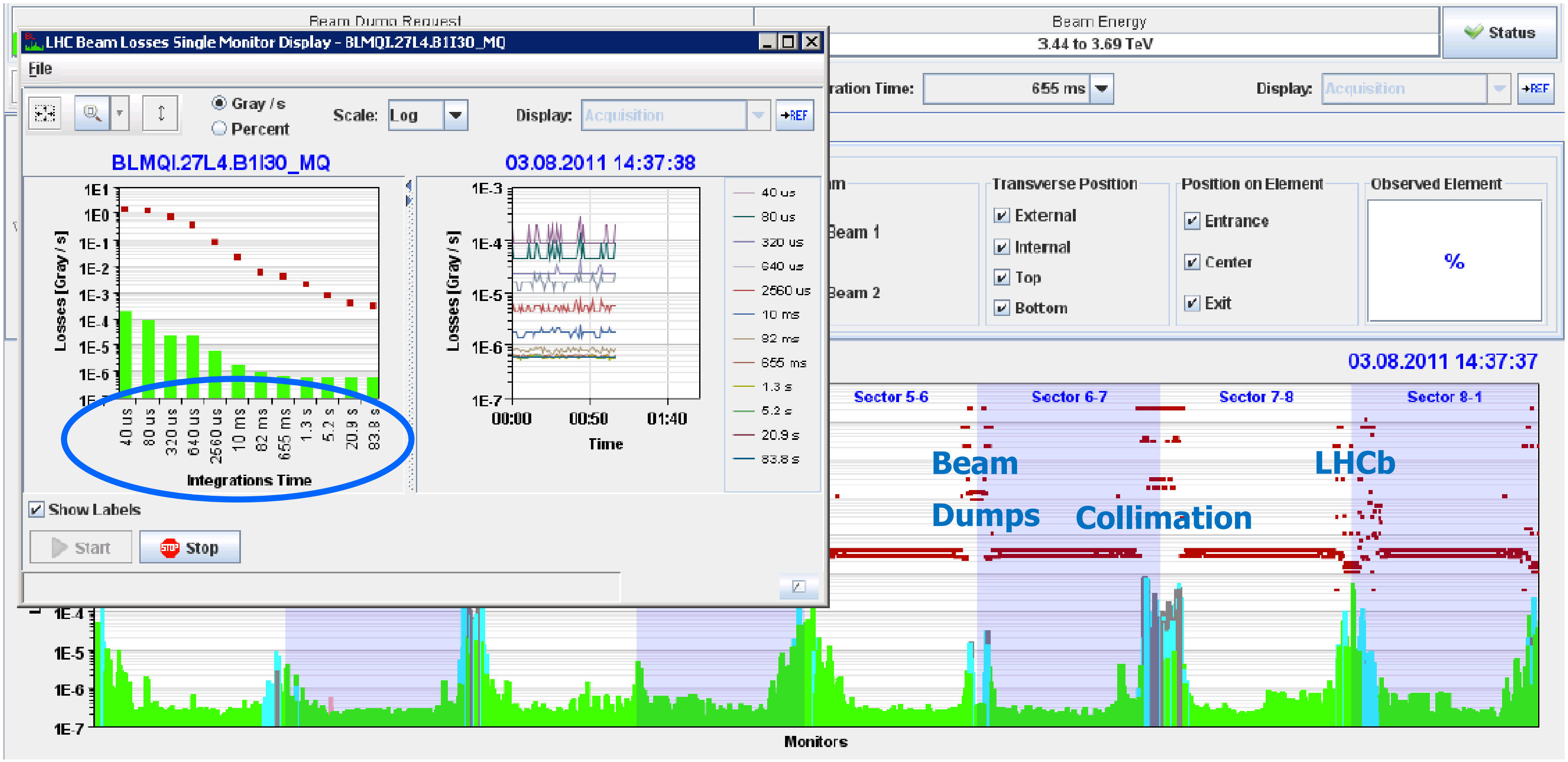
Request for comparison issued by Back-End Acquisition (counter), most reliable (no software layers in between)

BLM System Information Flow



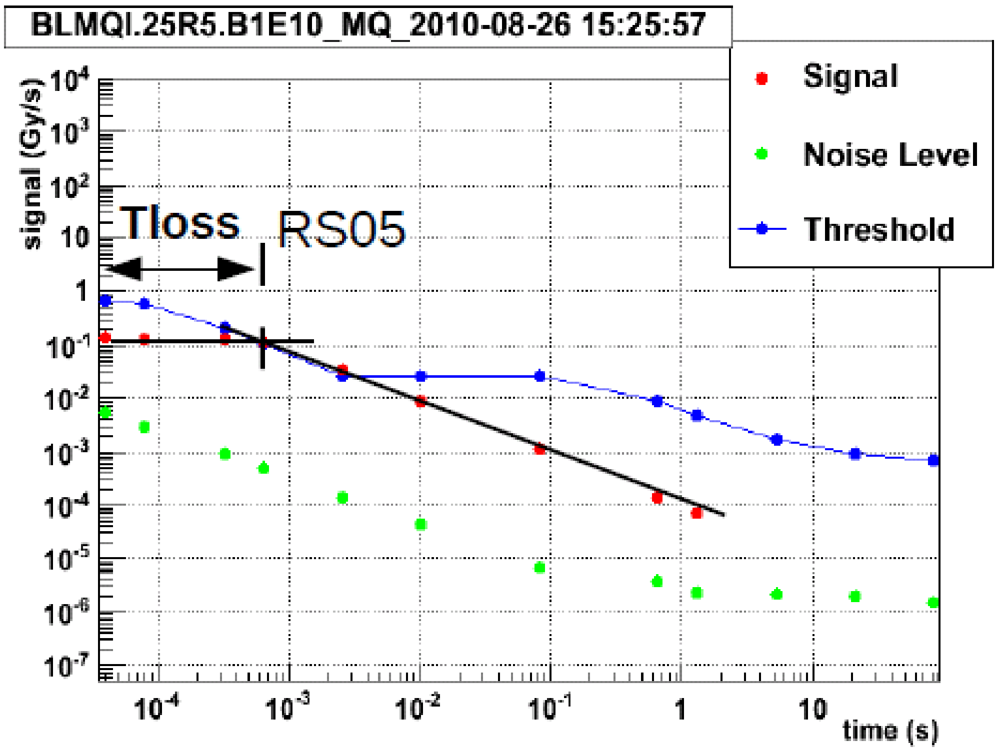
BLM System – Online Display

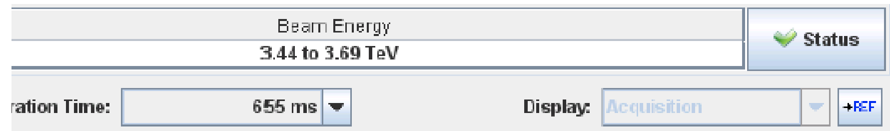
- Extensively used for operation verification and machine tuning
- 1 Hz update and logging (12 integration times, 40 us to 83 s)



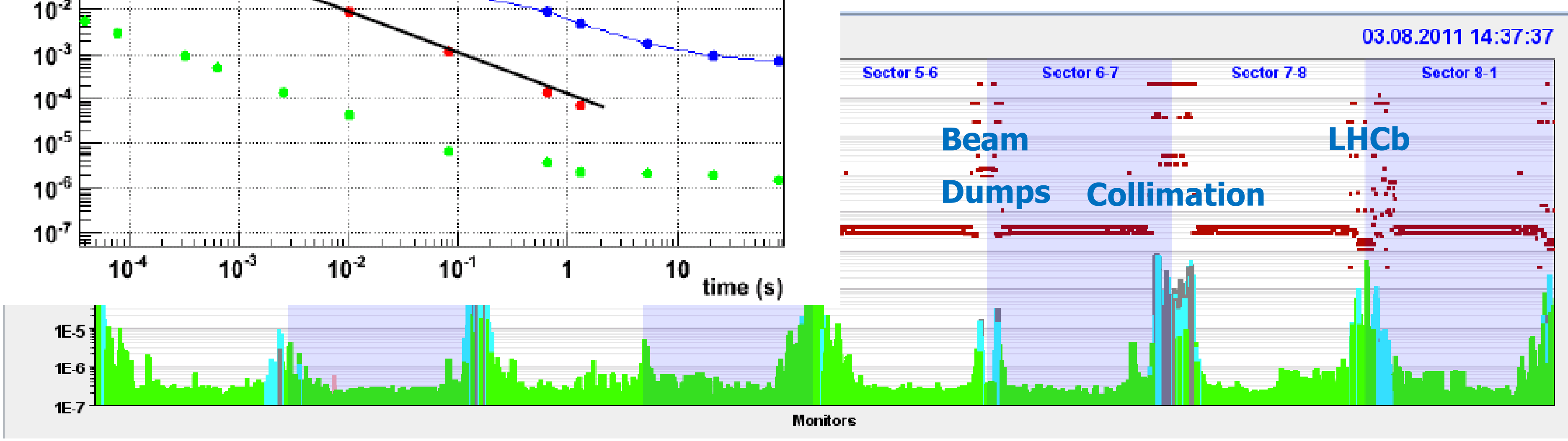
BLM System – Online Display

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

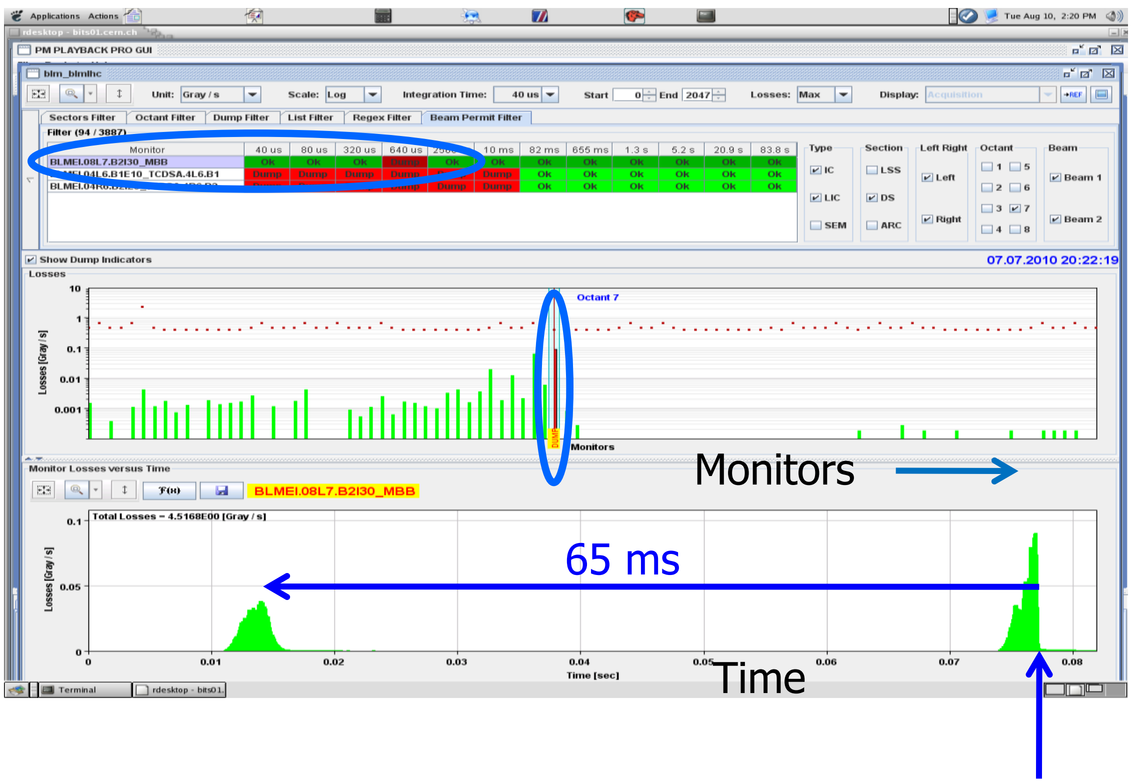


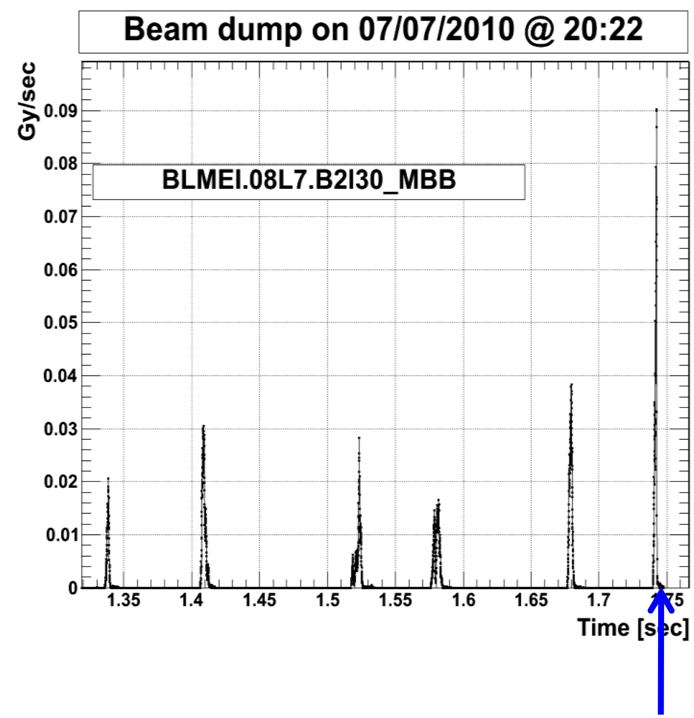
Post Mortem Data

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

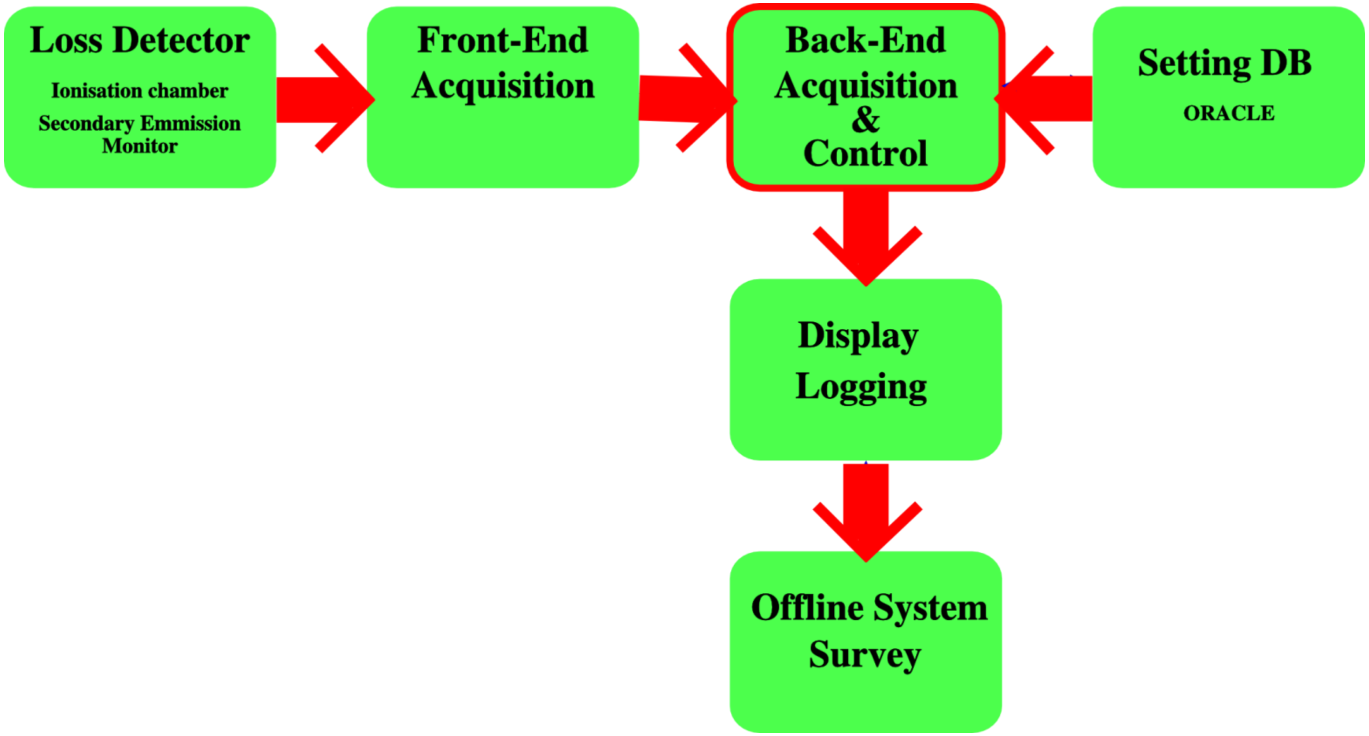
PM application: BLM data of 0.082 sec
online available

Longer PM buffer: BLM data of 1.72 sec
offine available





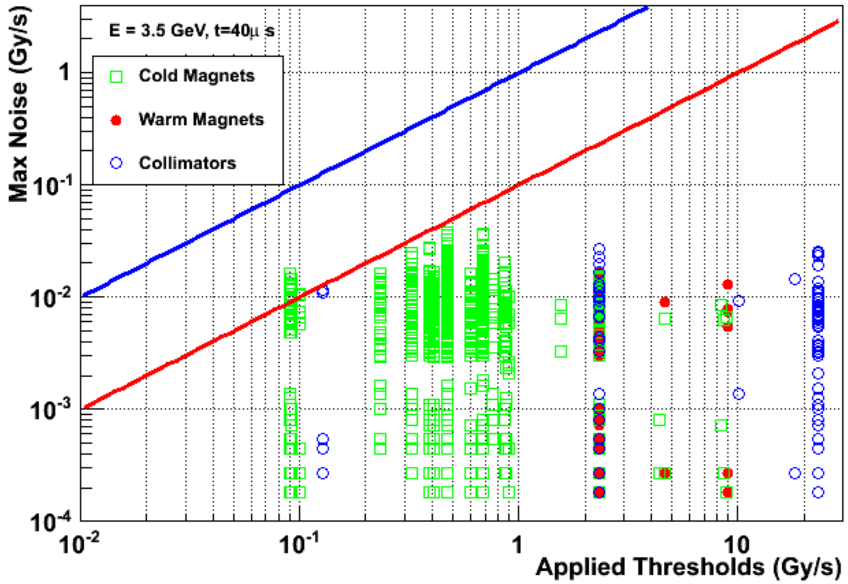
Combined Flow of Measurements and Settings

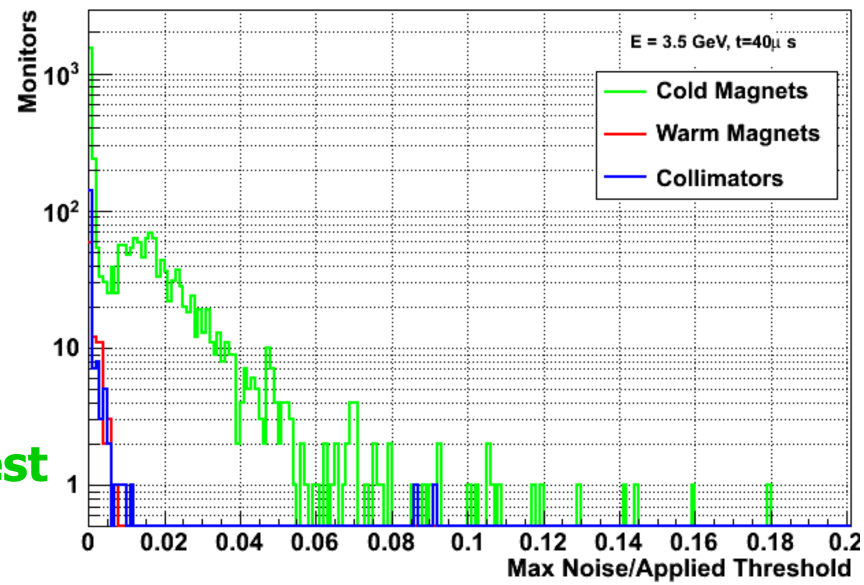


- Measurements and settings (thresholds, monitor names, …) are combined in VME crate (Back-End Acquisition & Control)
  - Measurements and setting a joint in the FPGA memory (16 channels)
  - Large decentralized structure
- Data flow path identical for both
- Display and logged data are coherently treated
  - Reduction of number failure modes due to flow over same path

Noise and Fast Database Access

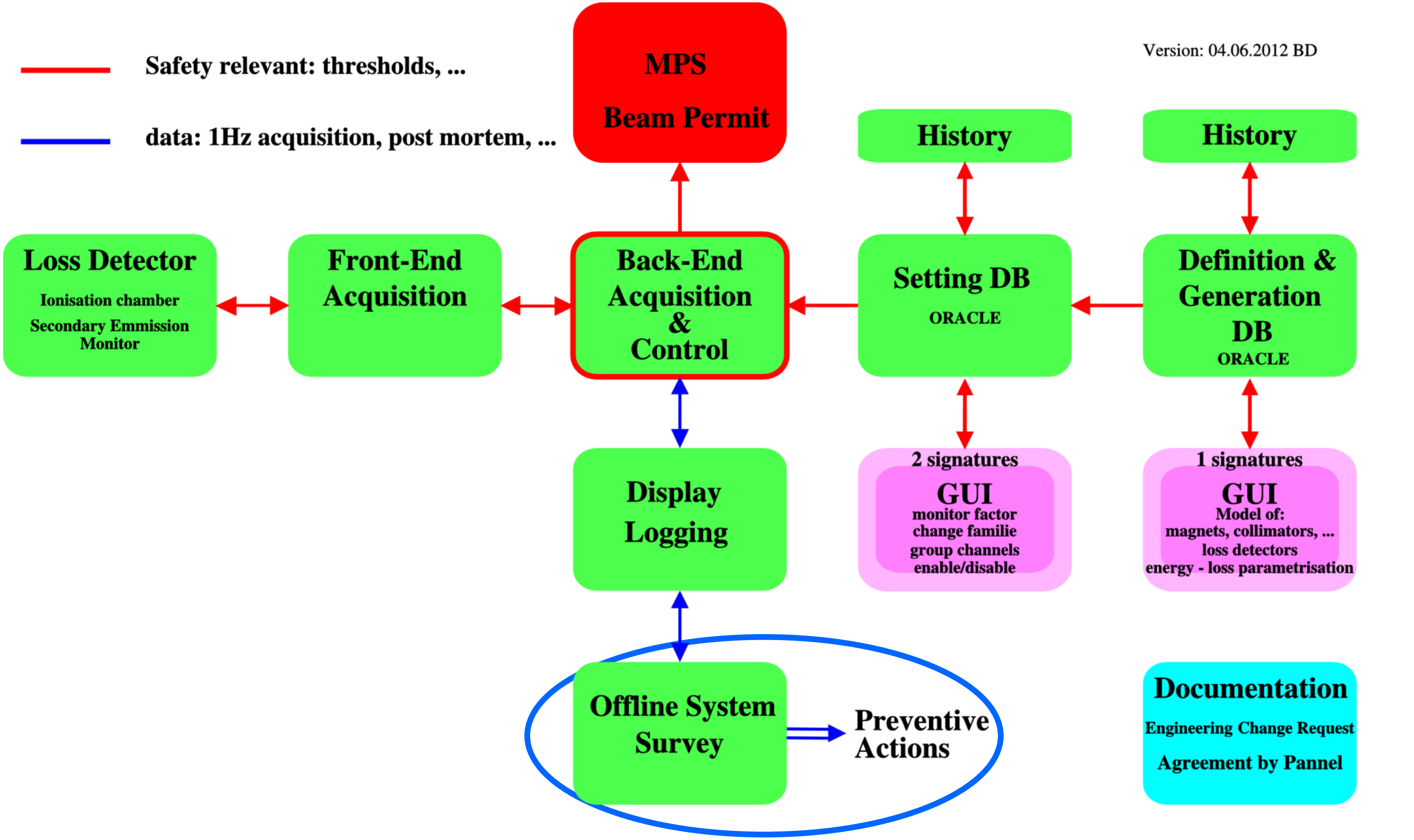
- Important for availability (false dumps) and dynamic range
- Main source of noise: long cables (up to 800 m in straight section)
- Aim: factor 10 between noise and threshold
- Thresholds decrease with increasing energy
- noise reduction before 7 TeV operation
  - Single pair shielded cables, noise 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



Daily Checks

If >=10 errors/link within 24h, send warning and start monitoring this link in more detail

Cases:

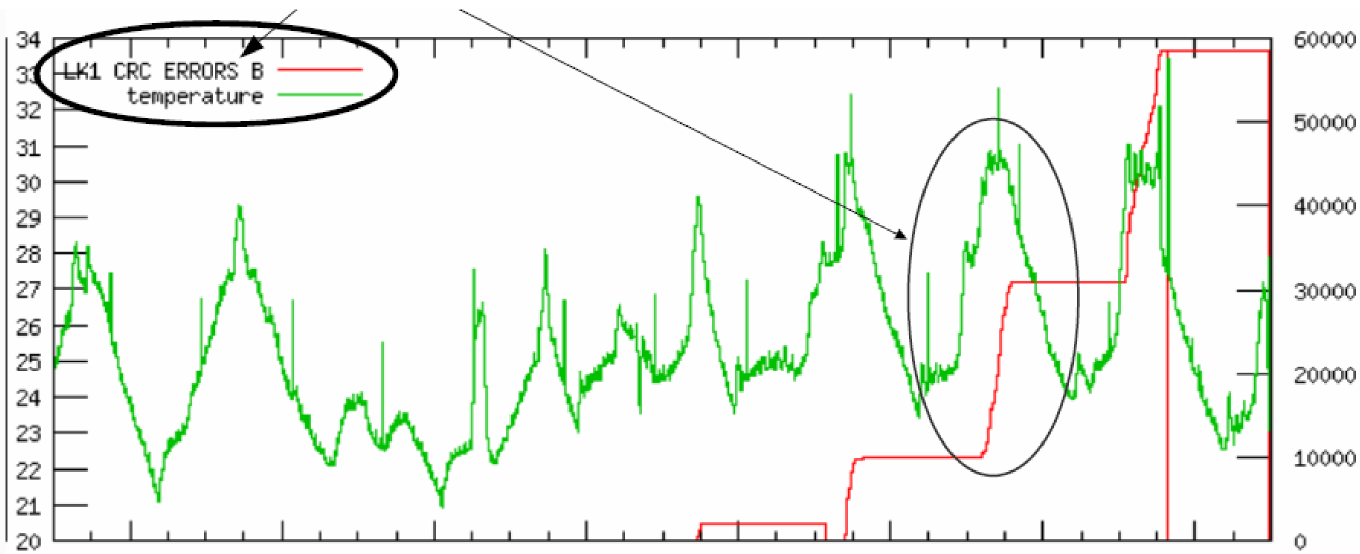
a) constantly low error rate

b) increasing error rate: critical, take action!

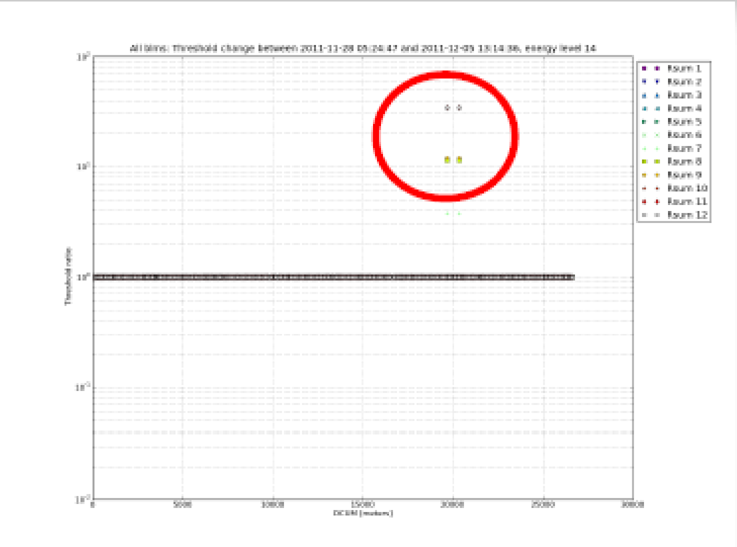
Daily Optical Link Check Results — from 2011-05-08 12:00:00 to 2011-05-09 12:00:00 (local time)

Card	*Card-Serial numbers* BLECF Serial	BLETC Serial	BLECS Serial	CRC COMP A	CRC COMP B	LK1 ERRORS A	LK1 ERRORS B	LK2 ERRORS A	LK2 ERRORS B	LK1 LOST A	LK1 LOST B	LK2 LOST A	LK2 LOST B	FID COMP A	FID COMP B
SR1-L 12	0282 0241	9511602473975246337	12177733450726613761	71	0	71	0	0	0	0	0	0	0	0	0
SX4-R 14	0040 0230	8574853751483037953	11096869540207459585	224	0	225	0	0	0	0	0	0	0	0	0
SR7-L 14	0580 0426	10952754354734524415	16429131499061498881	18	0	18	0	0	0	0	0	0	0	0	0
SR8-C 12	0278 0267	4899916455551403009	4755801264793850881	0	571	0	27762	0	0	0	999999	0	0	0	1

Temperature and failure rate

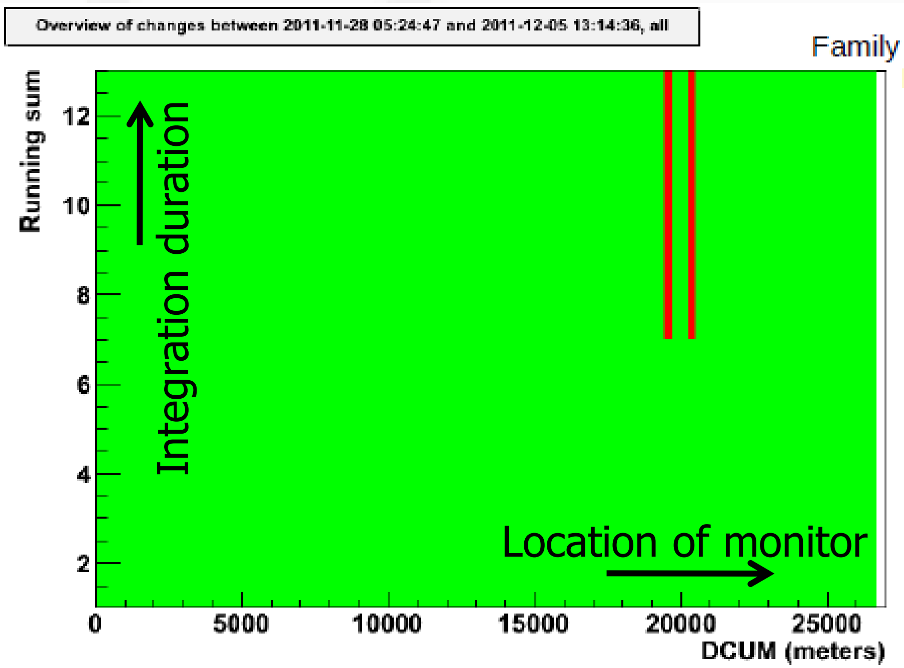


Survey of BLM thresholds



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

Example of weekly report:



Family THRI.DS.B1.1_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

Detailed Analysis of Modulation Result – Preventive Action

Example: Connectivity Check – Results from Shape Analysis

from 2010-10-21 00:00 to 2010-10-22 00:00

Expert Name	Hardware Channel	Cable conn.	BIS conn.	$\frac{\chi^2}{NDF}$	Gain min	Gain meas.	Gain max	Phase min	Phase meas.	Phase max
BLMQI.04R6.B1E10_MQY	6.R.01.02	True	True	73	2628	3772	4880	46	66	84
BLMQI.18R6.B2I30_MQ	6.R.07.01	True	True	87	2823	3973	5241	45	63	81
BLMQI.18R6.B1E10_MQ	6.R.07.02	True	True	92	2881	4052	5351	45	63	81

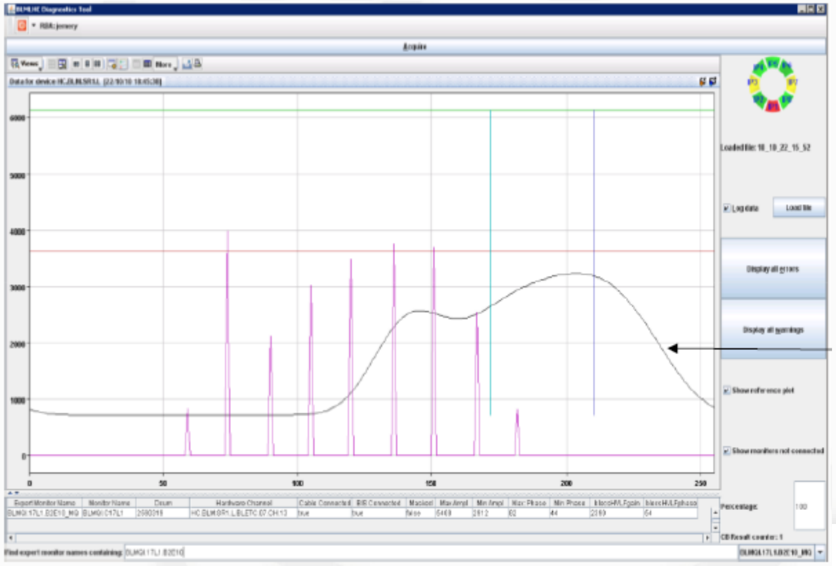
Connectivity check on 2010-10-21 19:00:27

Connectivity Check Results (High Voltage Modulation) from 2010-10-21 00:00 to 2010-10-22 00:00 (1 tests run)

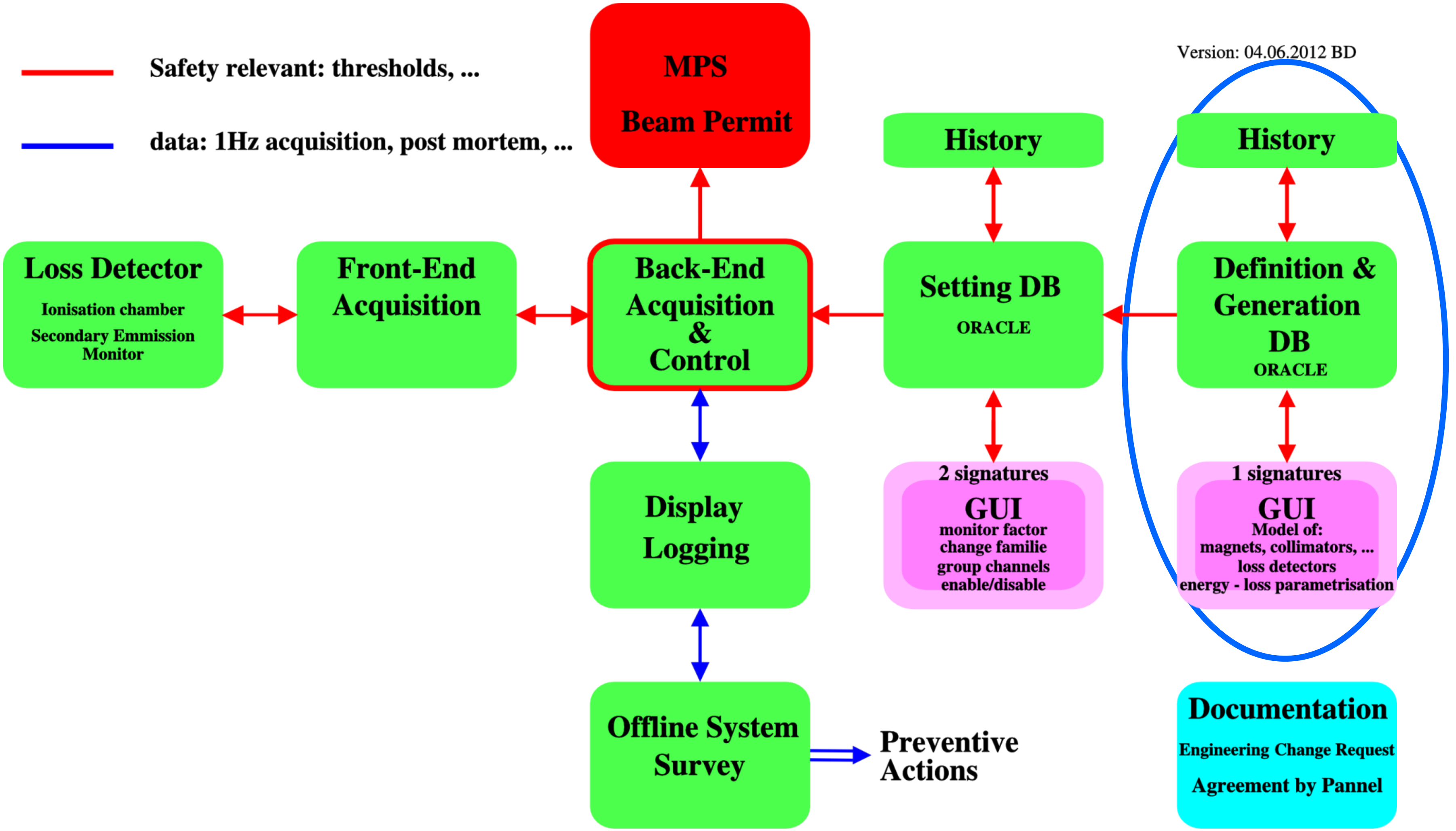
Example: Summary on Connectivity Check Measurement Results

Expert name	Gain min	Gain max	Phase min	Phase max	spare channel
Failures					
BLMQI.10R1.B2I10_MQML	1	0	0	0	0
BLMEL.06R7.B2I20_TCSG.A6R7.B2	1	0	0	0	0
BLMEL.06R7.B2I21_TCSG.A6R7.B2	1	0	0	1	0
BLMEL.06R7.B2I22_TCSG.A6R7.B2	0	1	0	1	0
Warnings					
BLMCC.08R3.A8R3_BATT	1	0	0	0	—
BLMCC.06R3.A6R3_BATT	1	0	0	0	—
BLMCC.06R3.A6R3_HV	1	0	0	0	—
BLMES.06R3.B2E10_TCAPA.6R3.B2	1	0	0	0	—

Summary table



BLM System Information Flow



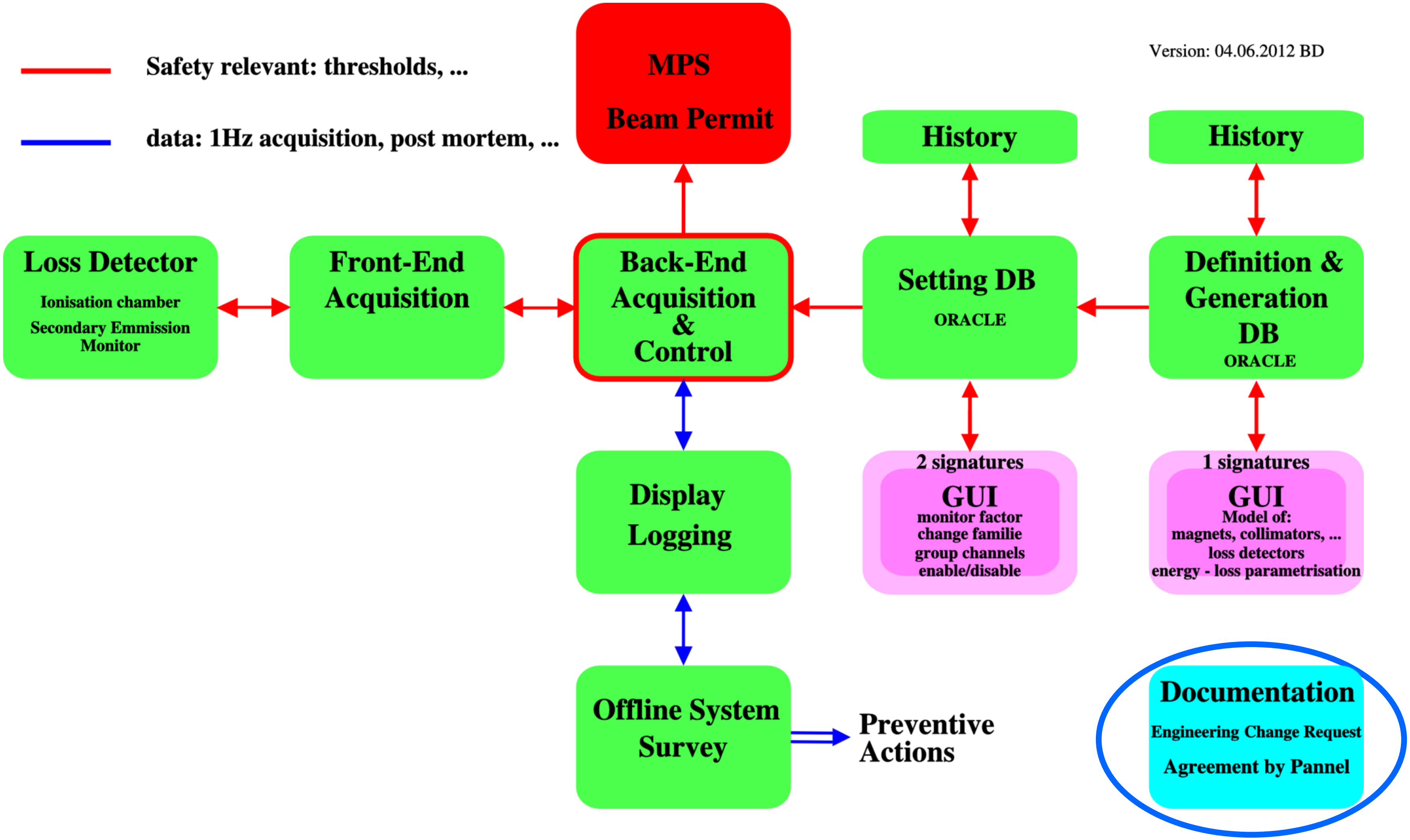
Now: C++ program and SVN storage   Future: all values and functional dependence in ORACLE

Beam Abort Threshold Table Concept

Stage working level	200 Families
Final becoming operational	
Master operational	4000 Channels
Applied applied < master	

- 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

BLM System Information Flow



Concluding Remarks

- 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.
  - Digital signal treatment, thesis, C. Zamantzas
  - 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

BLM Buffer (IC & SEM)		Integration Time	Buffer Length
Post Mortem		40µs	80ms online 1.72s offline
Collimation Buffer		2.6ms	80ms
Extraction Validation Buffer		40µs	80ms
Capture Data (2 modes)	Injection Quality Check (IQC) – 8 crates only	40µs	20ms
	Study (event triggered: for example UFO study)	80µs	Dynamical, currently up to 350ms

Event triggered	Sampling Rate	Integration Time	Buffer Length
Post Mortem	0.2 ns	≈ 2ns	1ms

Hardware Failures (since Feb. 2010)

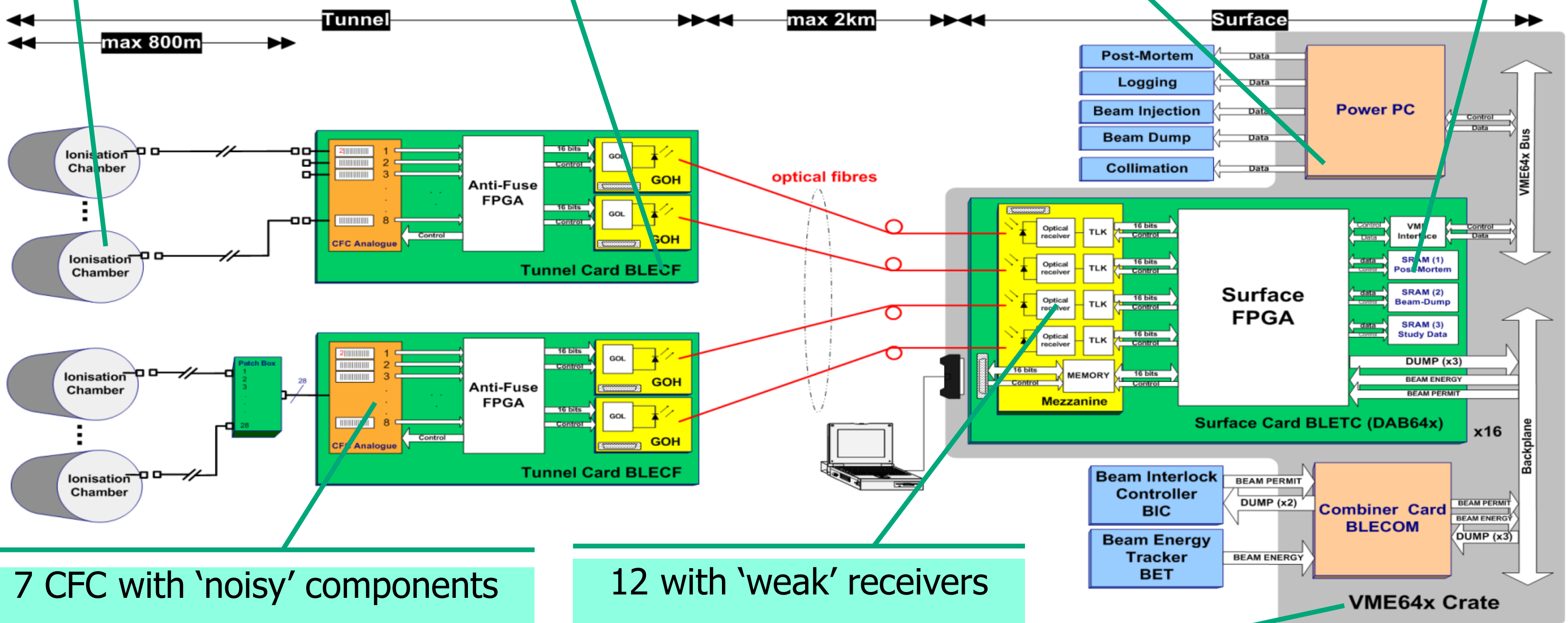
- Mostly, onset of system degradation detected by regular offline checks before malfunction
- Number of failures regarded manageable (no availability issue)

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

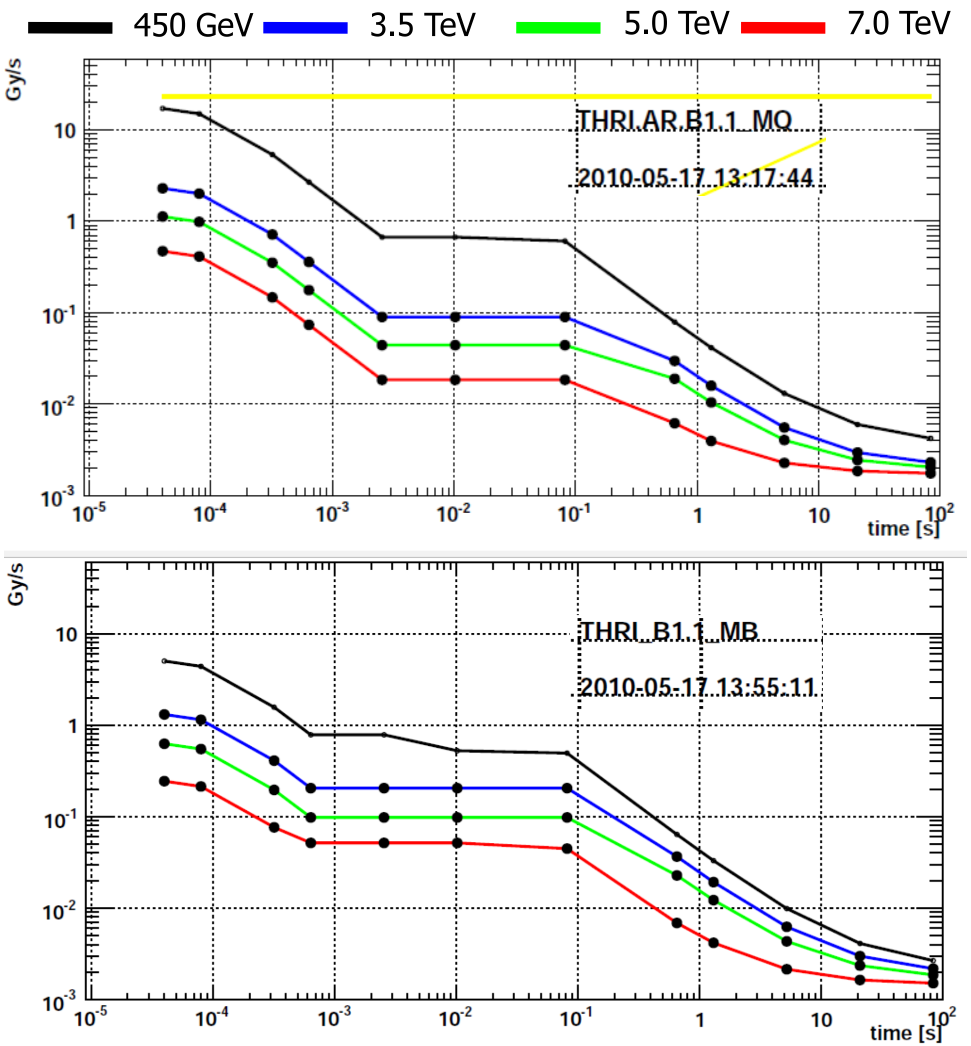
Fault Statistic

Table 4: Hardware interventions due to channel degradation or failure since february 2010

Element	Details	Number	Out of total installed
IC	bad soldering	12	3600
tunnel electronics	noisy analogue component (CFC)	7	359
tunnel electronics	bad soldering	2	720
tunnel electronics	low power optical transmitter (GOH)	9	1500
tunnel electronics	damaged connector	1	1500
surface electronics	weak optical receiver	12	1500
surface electronics	failed SRAM	2	350
VME64x Crate	failed CPU RIO3	3	25
VME64x Crate	failed power supply	1	25

Quench and Damage Levels

Quadrupole and bending magnet thresholds

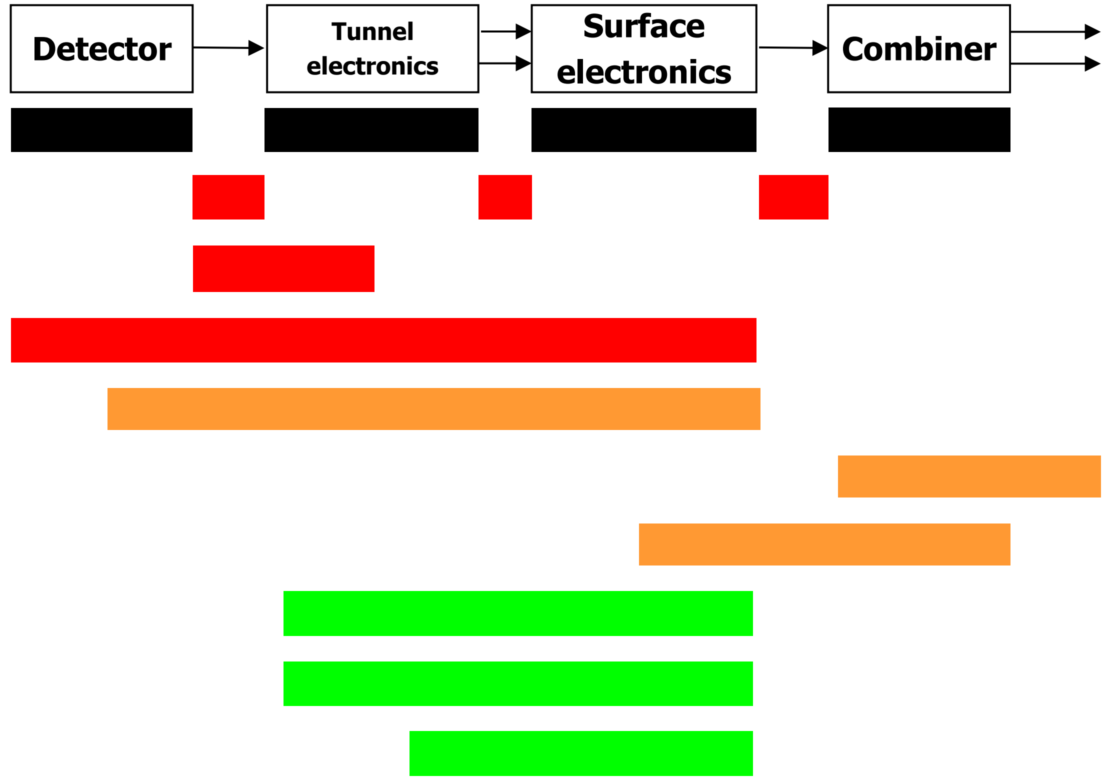


Specifications

- 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

PhD thesis G. Guaglio



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)

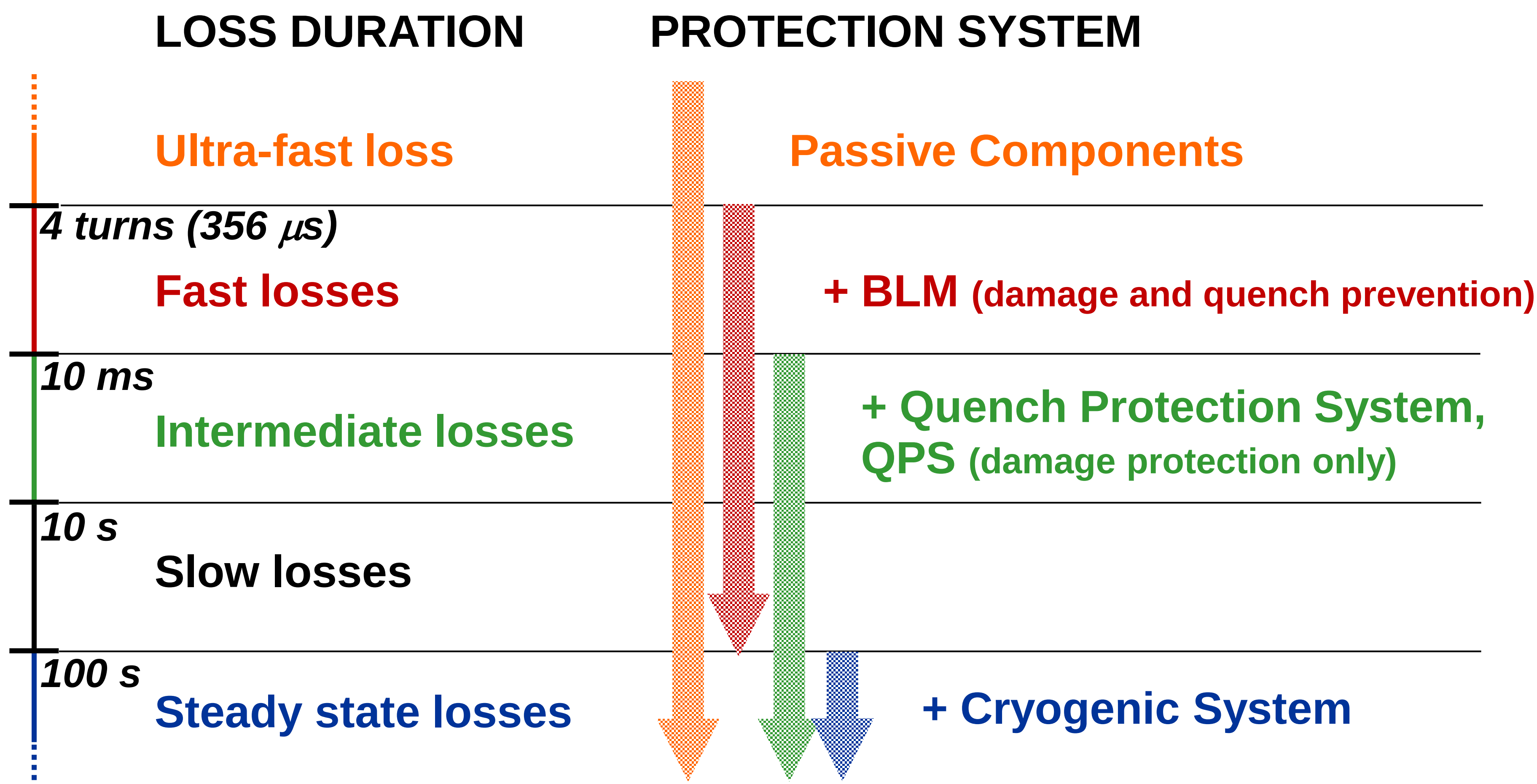
Double optical line comparison

System component identity check

Inspection frequency:

Reception   Installation and yearly maintenance   Before (each) fill   Parallel with beam

Specification: Beam Loss Durations and Protection Systems



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

Classification loss signals to be used for functional and technical specification

Combiner card inside the LHC BLM system

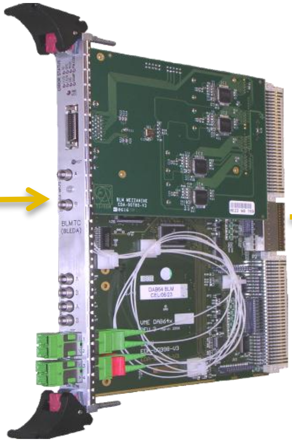
Beam Loss Monitors (4000)

around the LHC ring

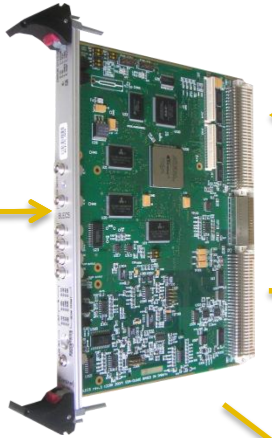
Tunnel Cards (700)

Tunnel Card test benches (5)

Threshold Comparators (350)

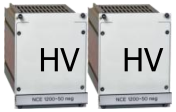


Combiner and Survey (25)

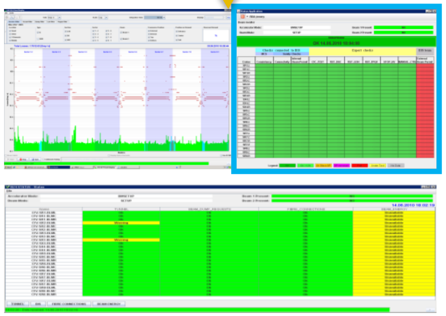


Beam Energy Receivers (8)
[CISV]
Hardware:
BE-CO-HT (P. Alvarez)
Responsible:
TE-MPE-MI (B. Puccio)
Energy measurements:

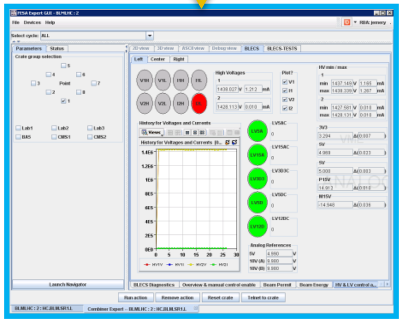
Interlock Interfaces (16)
[CIBUS] TE-MPE-MI
(B. Puccio, B. Todd)



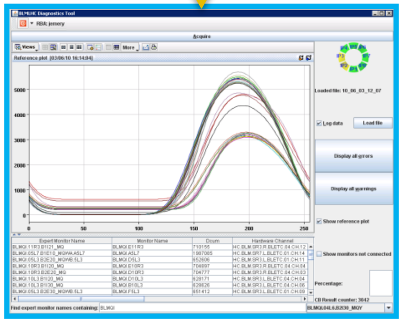
BLM HV supplies



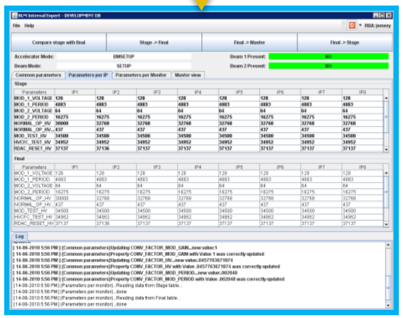
Operational applications (2)



Expert applications (2)

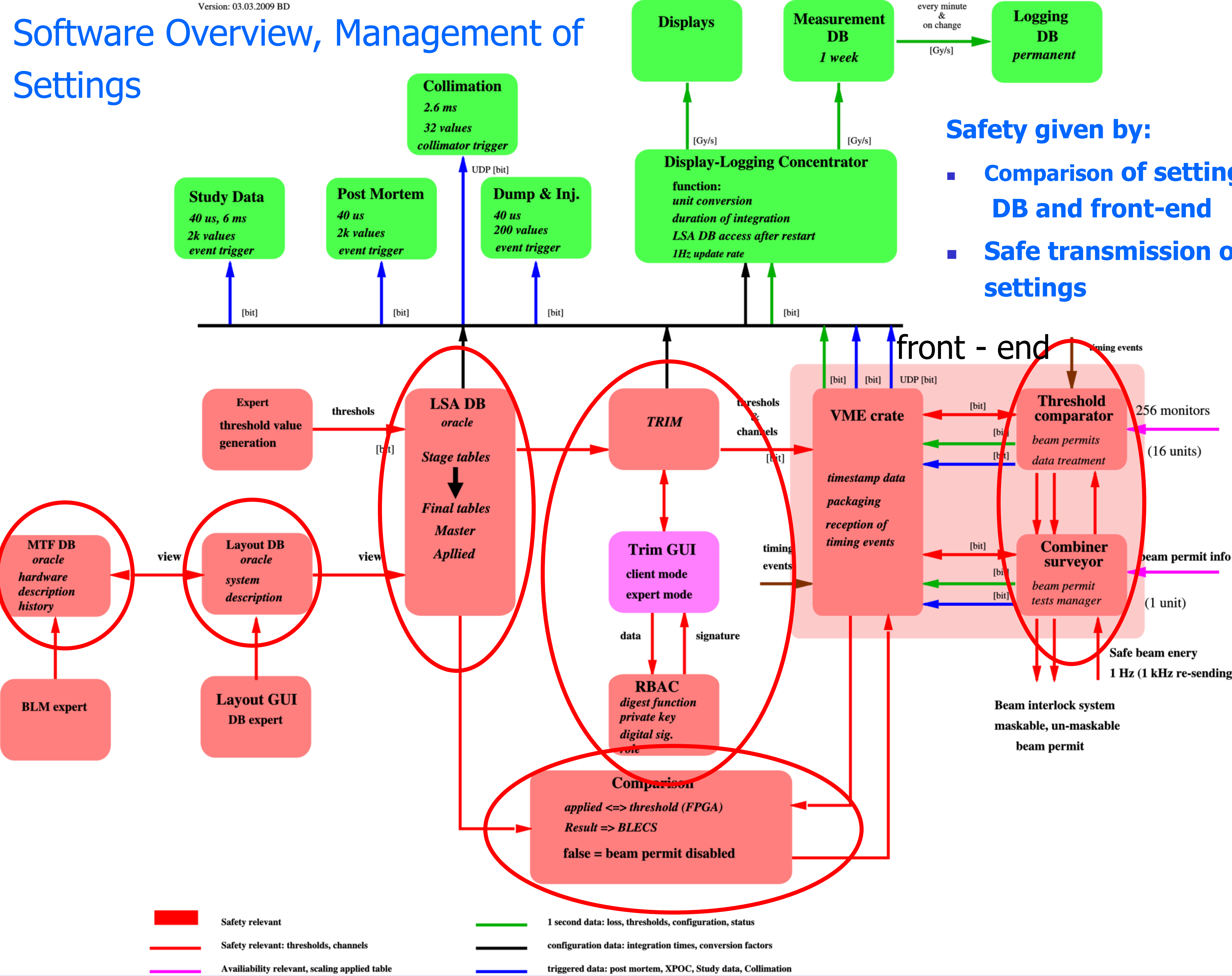


Diagnostics application, phase and amplitude for the connectivity check



Settings applications (2)

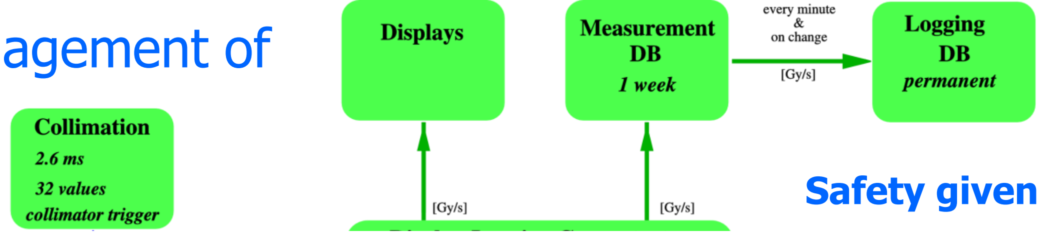
Software Overview, Management of Settings



Safety given by:

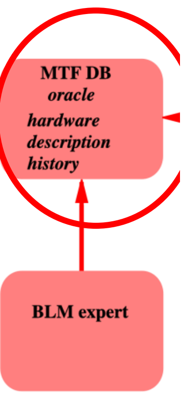
- Comparison of settings at DB and front-end
- Safe transmission of settings

Software Overview, Management of Settings



Safety given by:

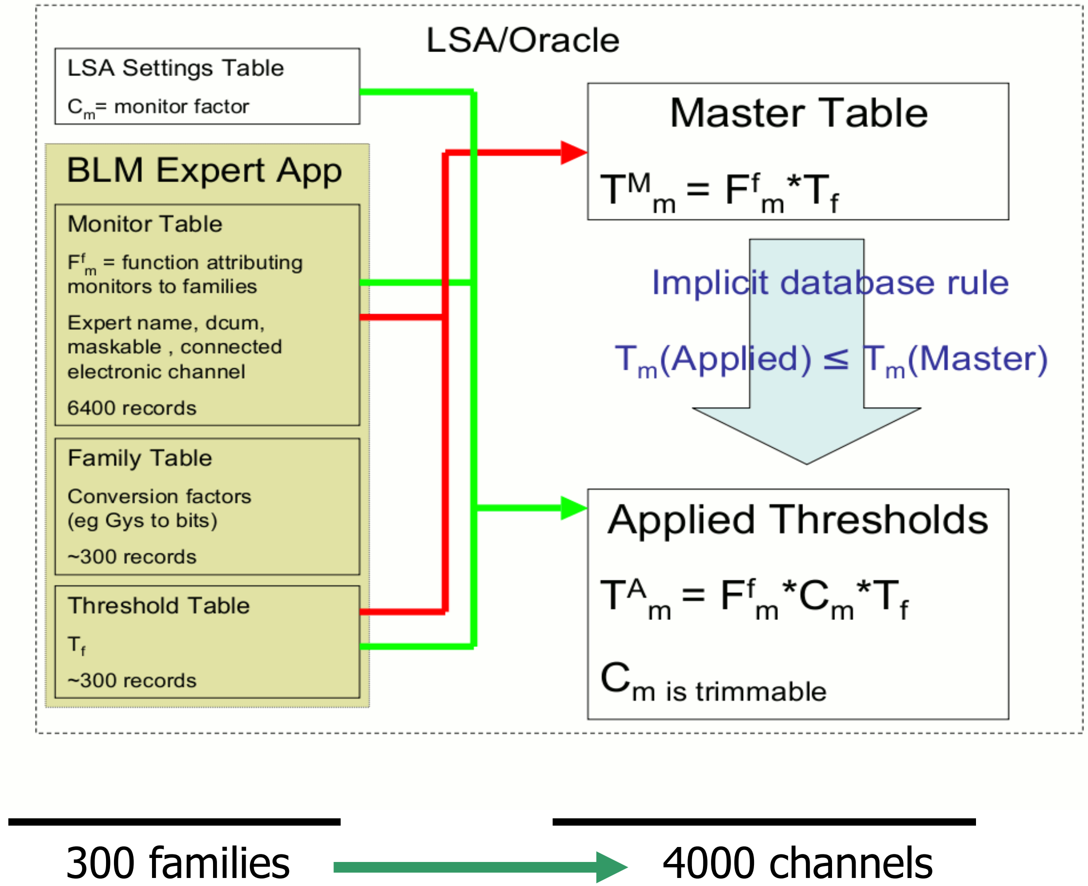
1. Modular design of data base very useful (if changes are needed limited impact)
    1. MTF: history of equipment e.g. ionisation chamber, electronic cards, …
    2. Layout: description of links between equipment
    3. LSA: reference for all data needed in the front-end (some imported from MTF and 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



Availiability relevant, scaling applied table

triggered data: post mortem, XPOC, Study data, Collimation

LSA Data Base Structure



Two layers

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

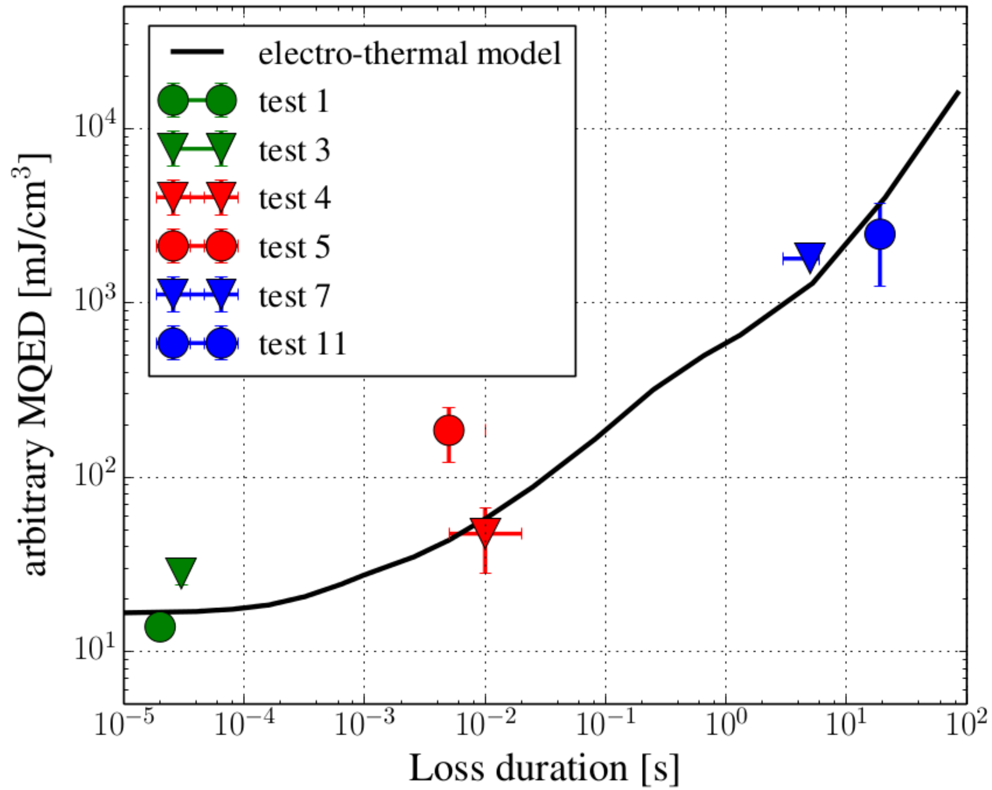
Concept of Master and Applied table – Comparison of Threshold values (Applied < Master)

- Master: less frequent changes
- Applied: change of thresholds possible with user interface

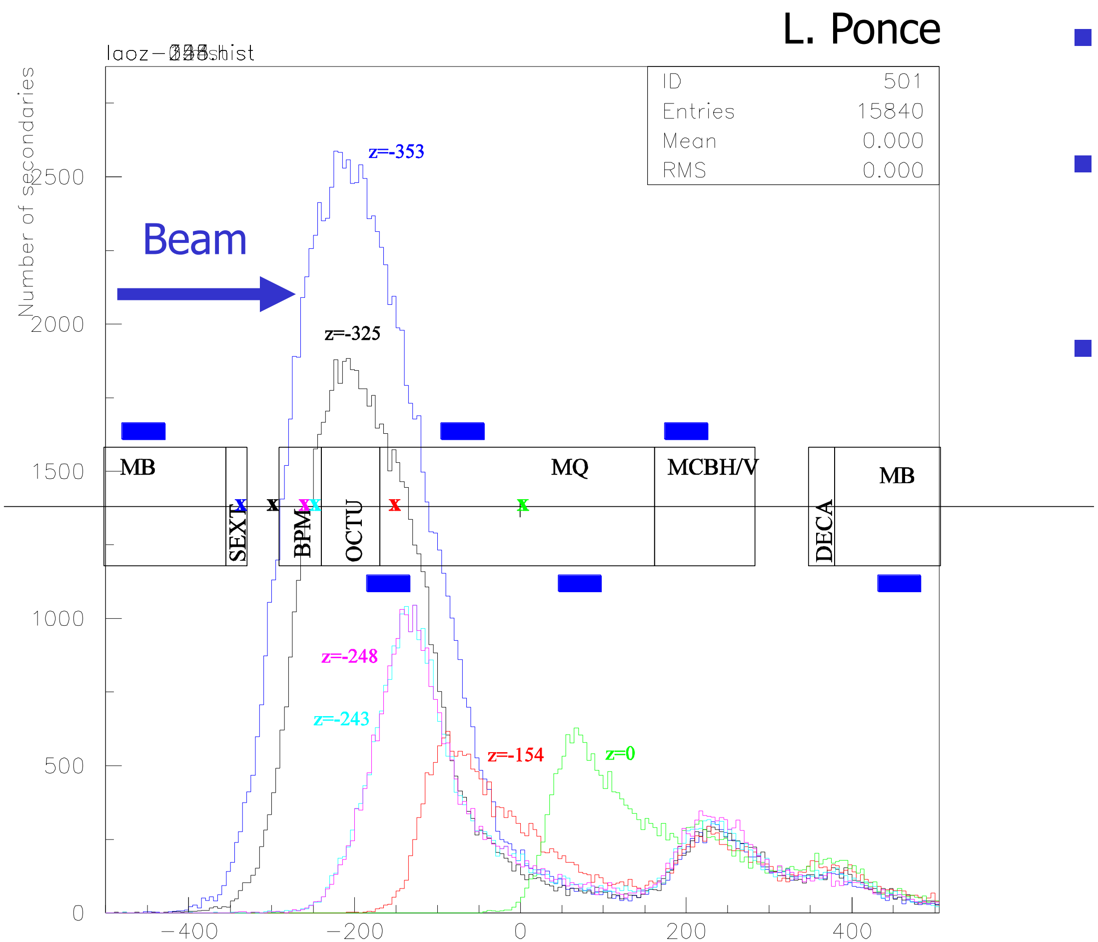
Results and conclusions

- 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

No	Date	Regime	Method	Type	Temp. [K]	I/I_{nom} [%]	beam energy [TeV]
1	2008.09.07	short	kick	dipole	1.9	6	0.45
2	2011.07.03	short	collimation	-	-	-	0.45
3	2013.02.15	short	collimation	quadrupole	4.5	46/58	0.45
4	2010.11.01	intermediate	wire scanner	dipole	4.5	50	3.5
5	2013.02.16	intermediate	orbit bump	quadrupole	1.9	54	4
6	2010.10.06	steady-state	dyn. orbit bump	quadrupole	1.9	?	0.45
7	2010.10.17	steady-state	dyn. orbit bump	quadrupole	1.9	?	3.5
8	2011.05.08	steady-state	collimation	-	-	-	3.5
9	2011.12.06	steady-state	collimation	-	-	-	3.5
10	2013.02.15	steady-state	collimation	-	-	-	4
11	2013.02.16	steady-state	orbit bump	quadrupole	1.9	54	4



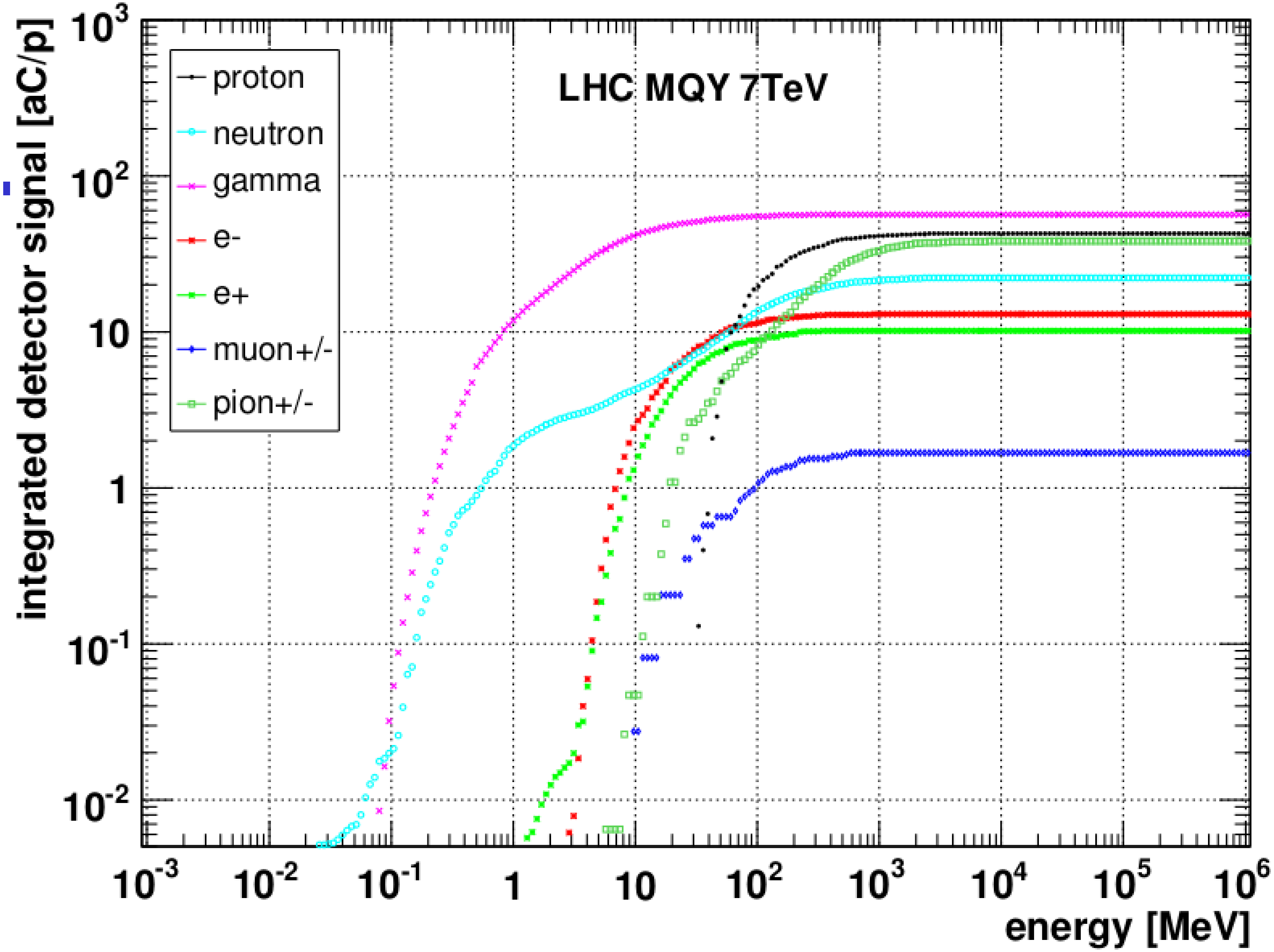
Particle Shower in the Cryostat



- Impact position varied along the MQ
- Black impact position corresponds to peak proton impact location
- Position of detectors optimized
  - to catch losses:
    - 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



Comparison of Reliability Tools

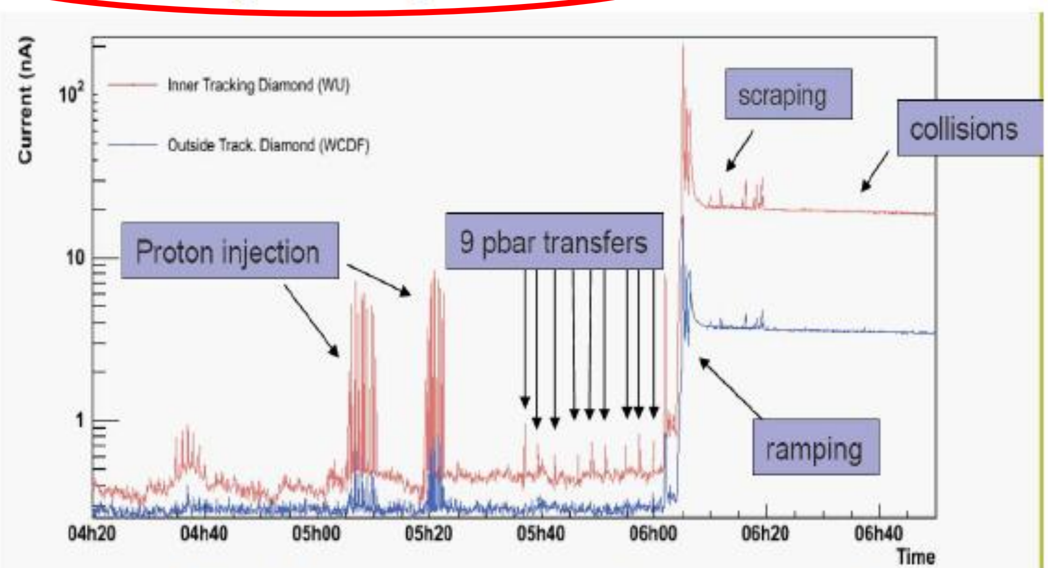
Tool	Pros	Cons
Spreadsheet	Previously used by SNS, good source of data	Interface difficult to use, lack of visualization, error prone
AvailSim (free)	Previously used for ILC, many accelerator specific concepts	No GUI
Sapphire (semi-commercial)	Widely used by NASA and nuclear industries, developed by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

Lit: S. Bhattacharyya, IPAC12

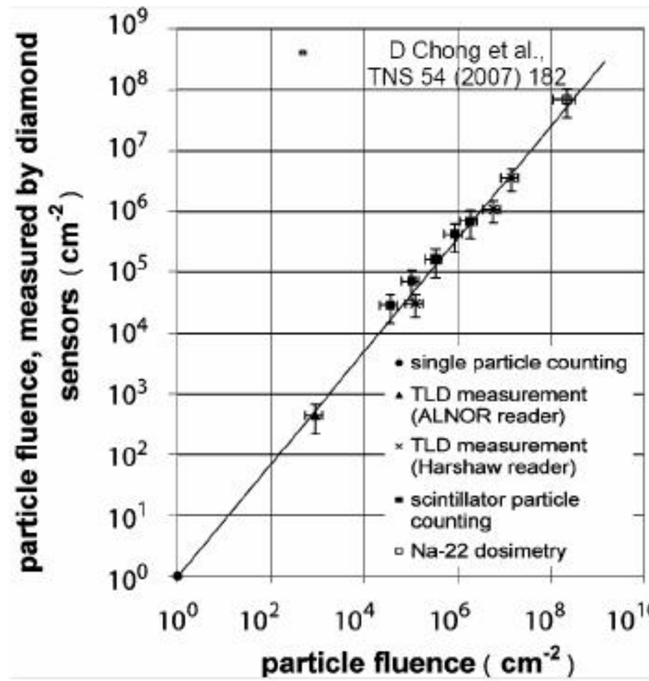
Why CVD Diamond?

- 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

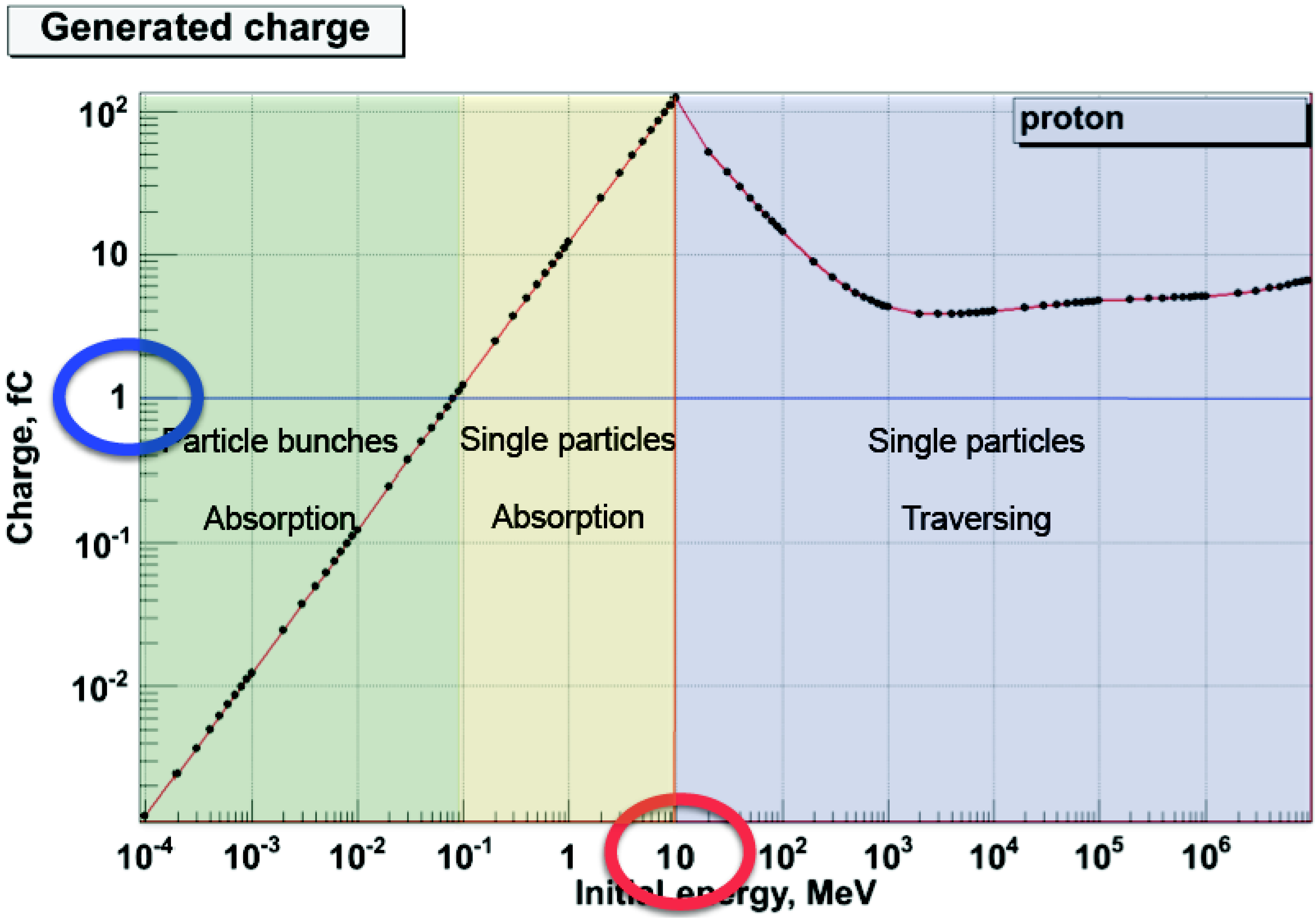
1. **Nano second response time**
2. **Large dynamic range**
3. **Operation at 1.8 Kelvin**



CDF pCVD diamonds at r=3cm and r=10.7cm

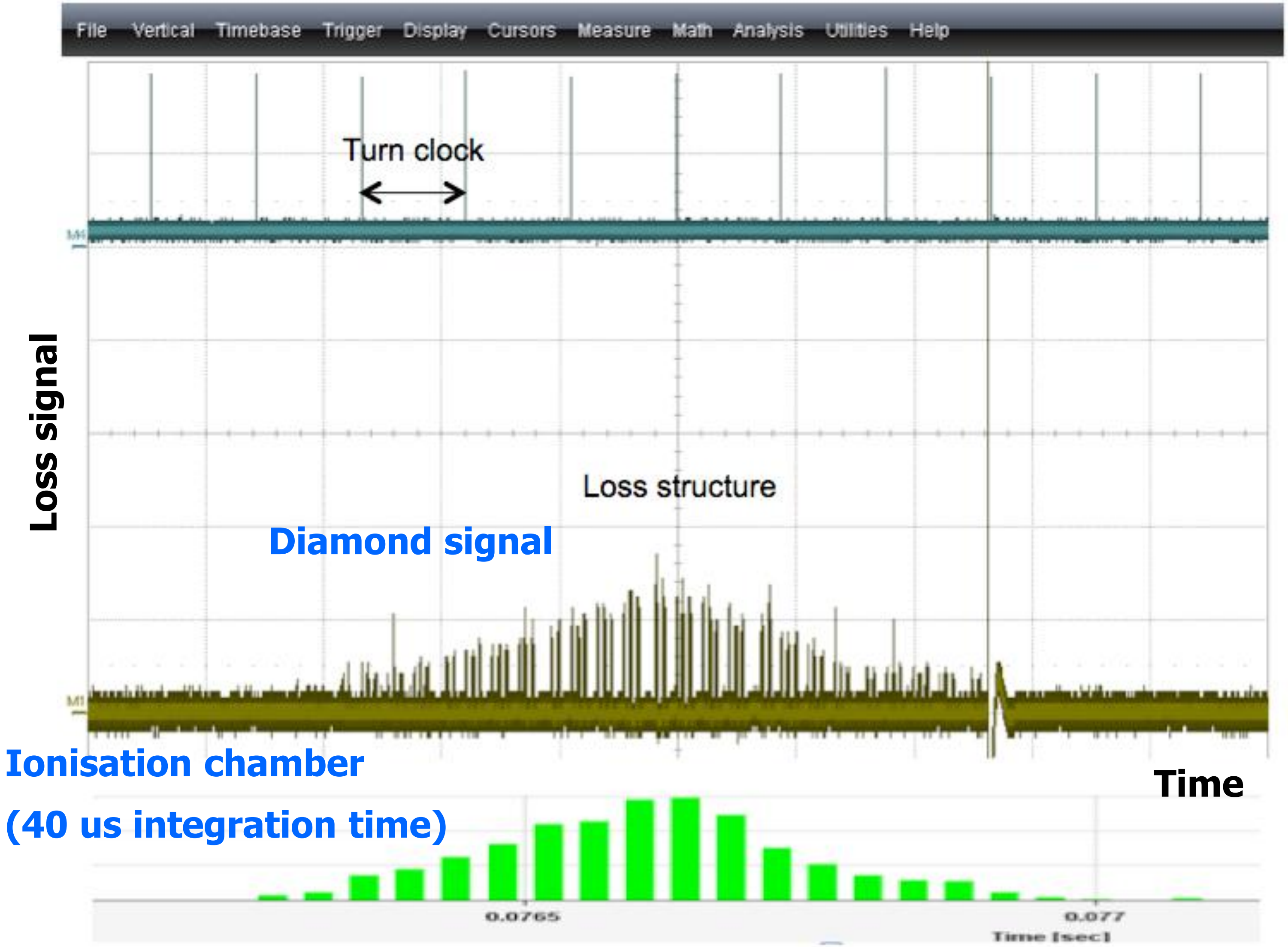


Ionisation Characteristics in 500 um sCVD

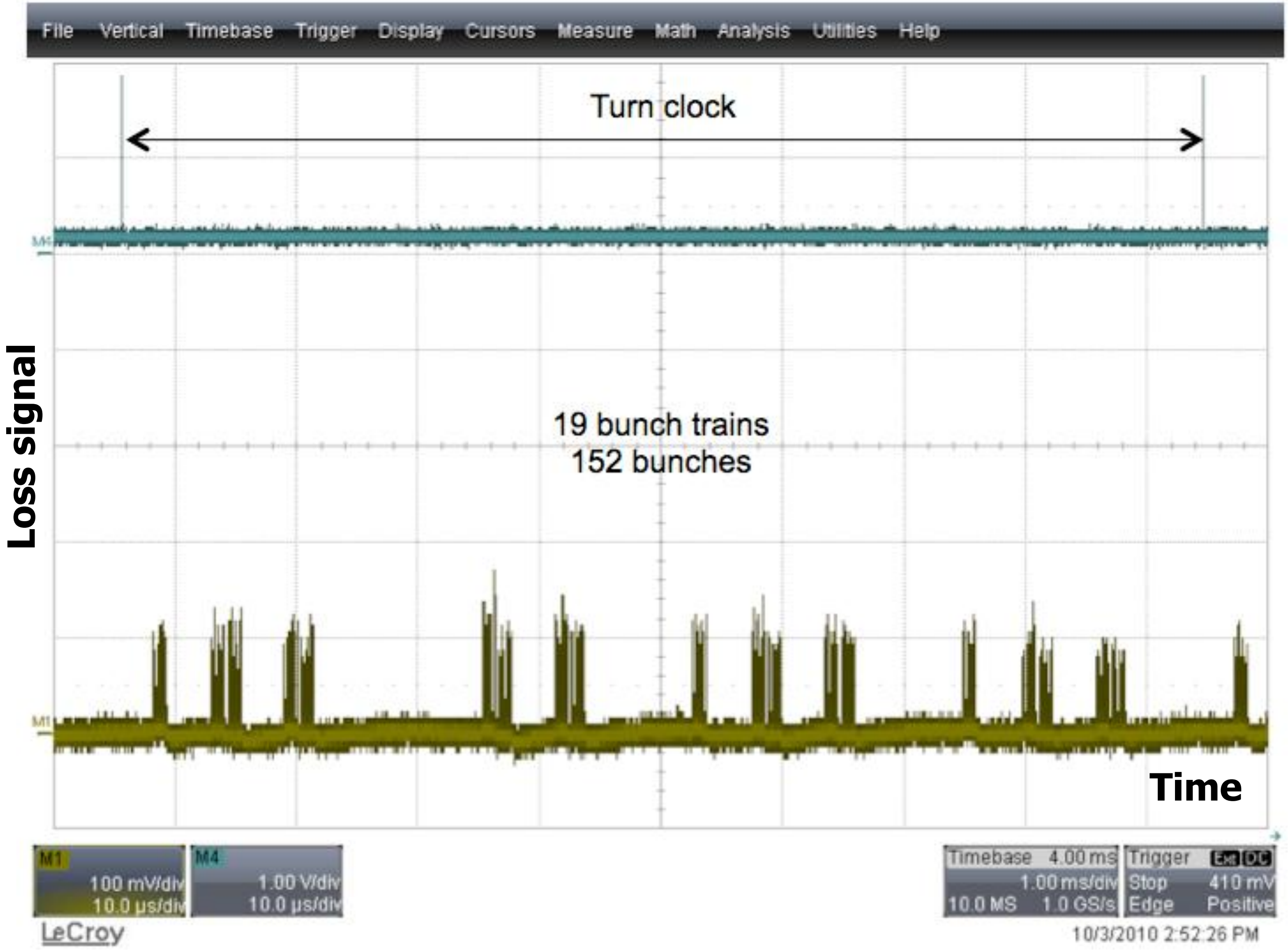


Courtesy to E. Griesmayer

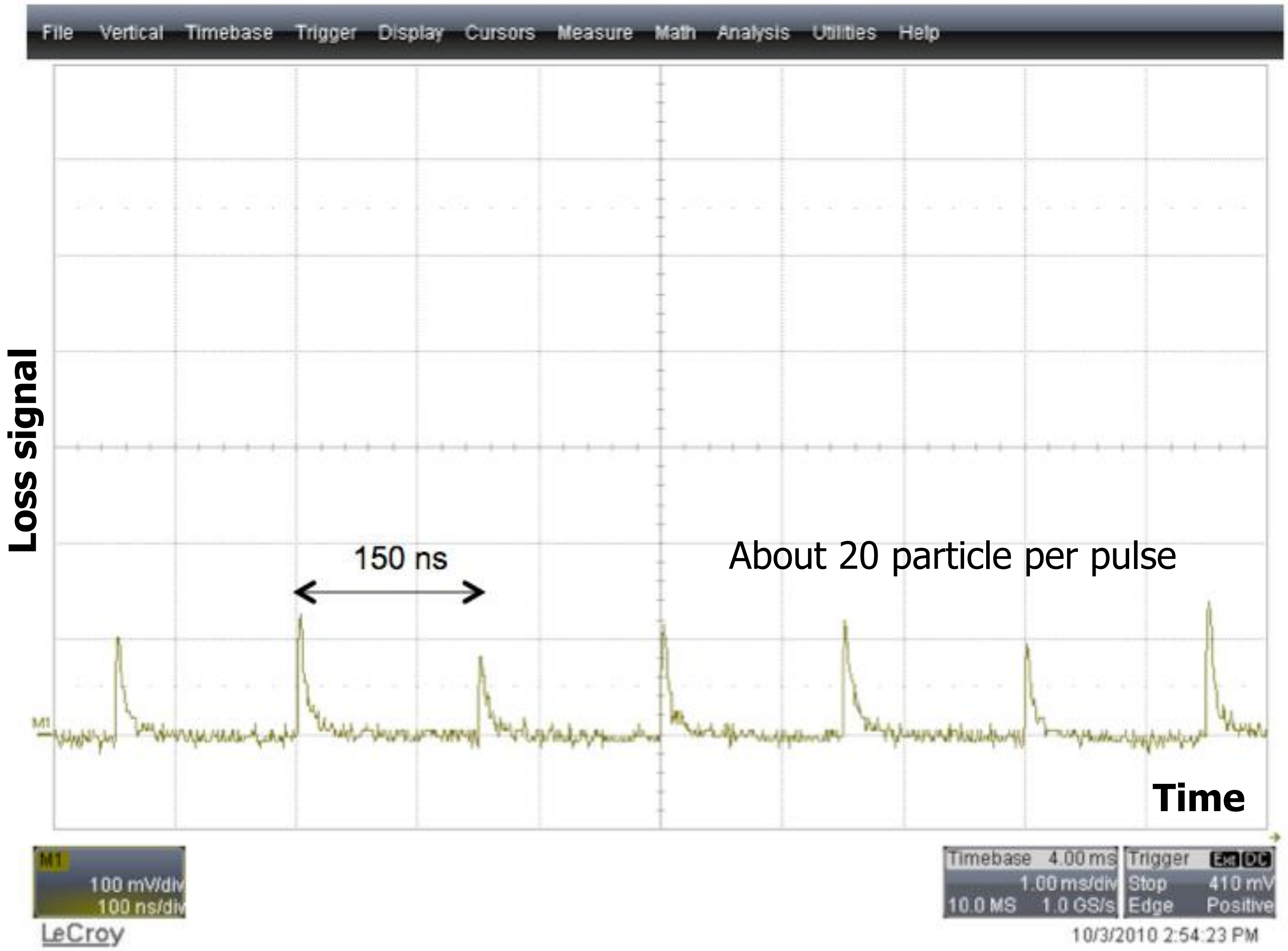
LHC: 152 bunches, 150ns bunch spacing (3/10/2010 12h48)



LHC: 152 bunches, 150ns bunch spacing (3/10/2010 12h48)

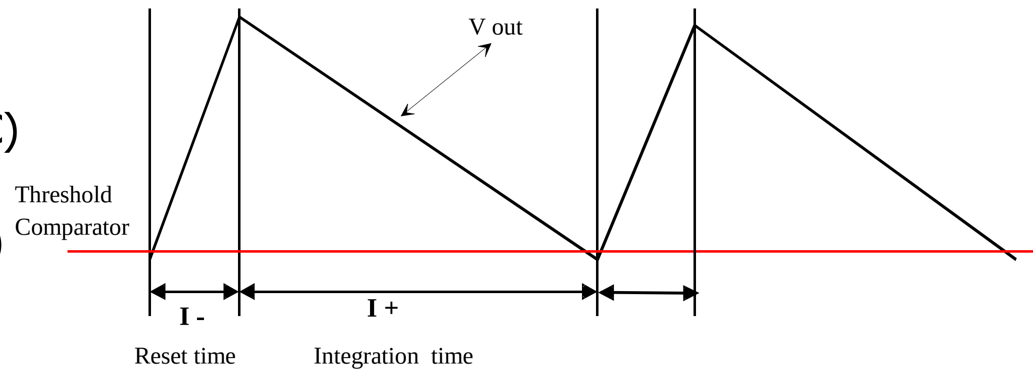


LHC: 152 bunches, 150ns bunch spacing (3/10/2010 12h48)

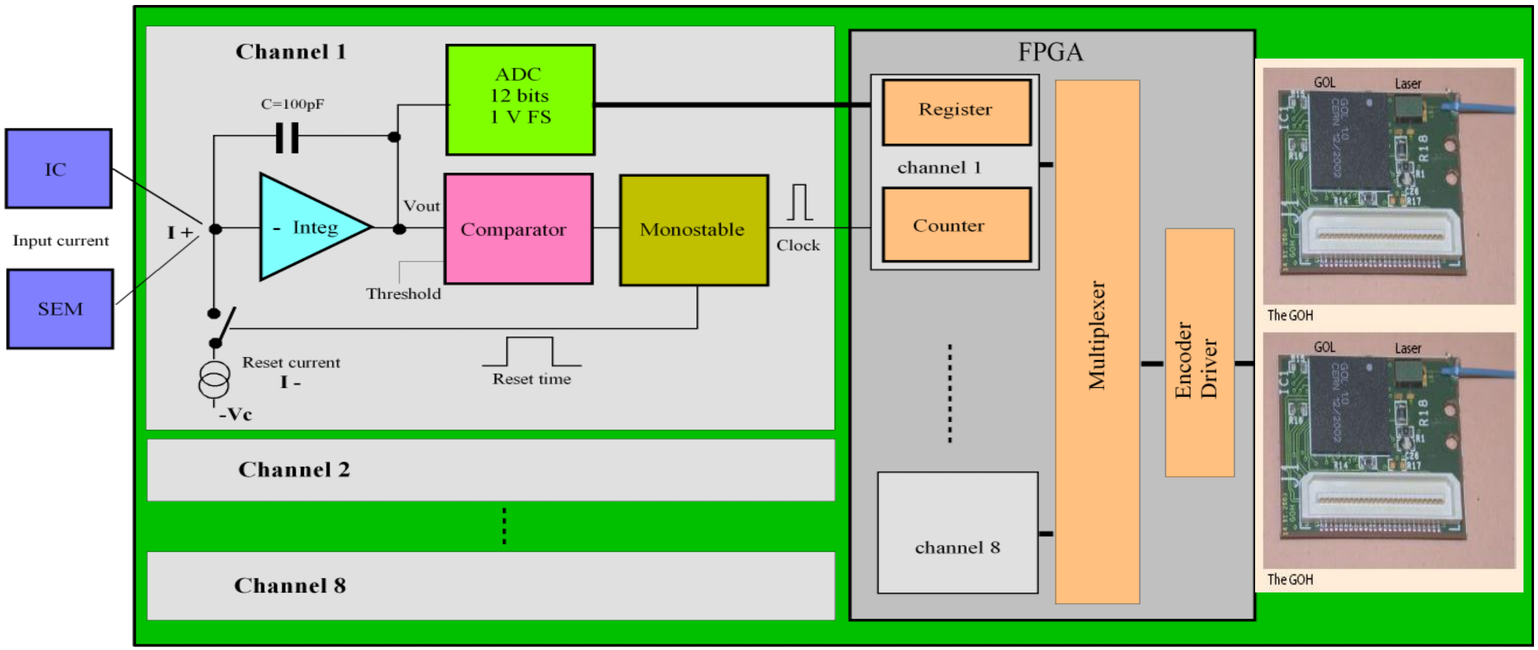


LHC tunnel card

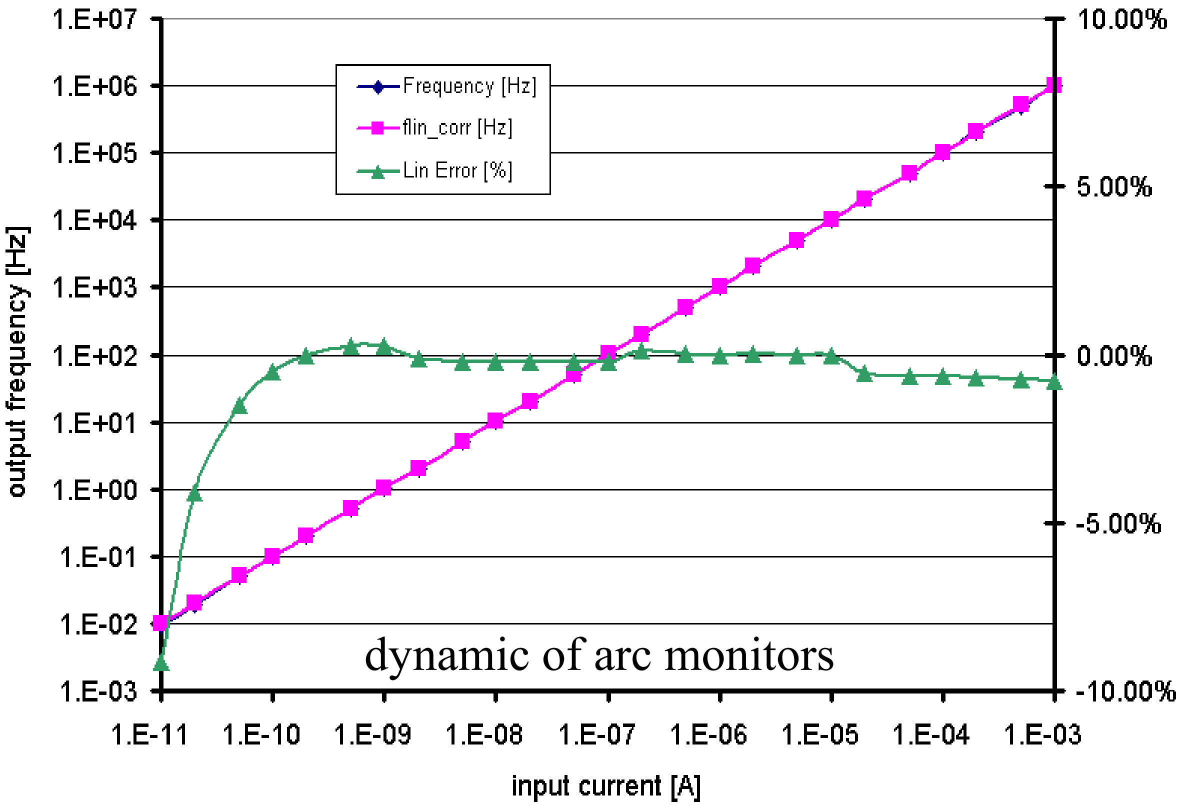
- Not very complicated design "simple"
- Large Dynamic Range (8 orders)
  - Current-to-Frequency Converter (CFC)
  - Analogue-to-Digital Converter
- Radiation tolerant (500 Gy, 1 10^7 p/s/cm^2)
  - ADC custom ASIC
  - Triple module redundancy



100 ns   100 ns to 100 s



Current to Frequency Converter



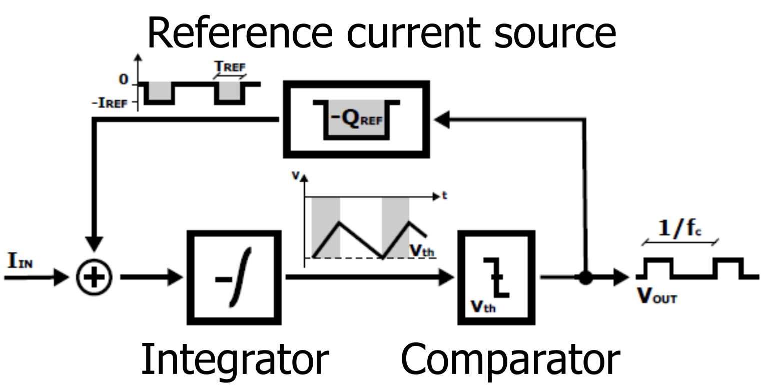
circuit limited by:

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:

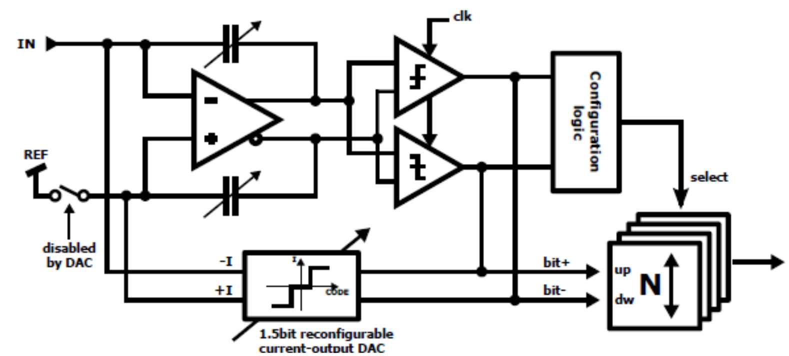
1. only positive signals (limitation in case of signal under shoots)
2. 500 Gy radiation tolerance

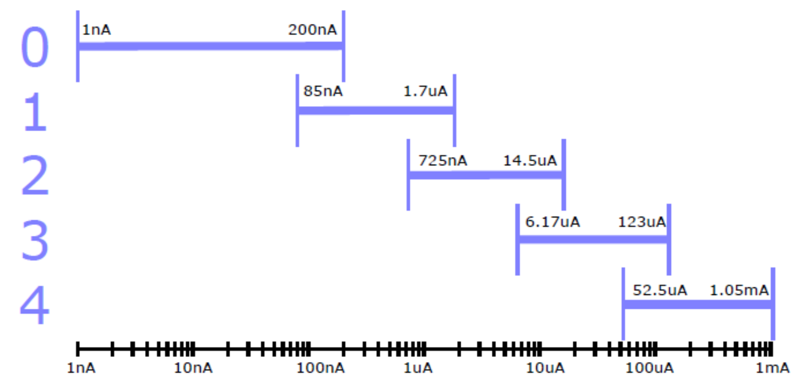


$$f = I_{input} / (I_{ref} * T_{ref})$$

	Parameter	Value	Units	Comments
ASIC	Dynamic range	six decades		positive and negative currents
		nine decades		*(indirect measurement)*
	Minimum detected current	1	nA	(user selectable, minimum value)
	Linearity error	$< \pm 10$	%	relative error $\Delta I / I$
	Integration window	40	µs	
	Total integrated dose	1×10^4	Gy	in 20 years
	Target technology	CMOS 0.25 µm		

Six decades to be covered with a direct measurement → 20 bit





Advanced Current to Frequency Converter Principle

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ASIC

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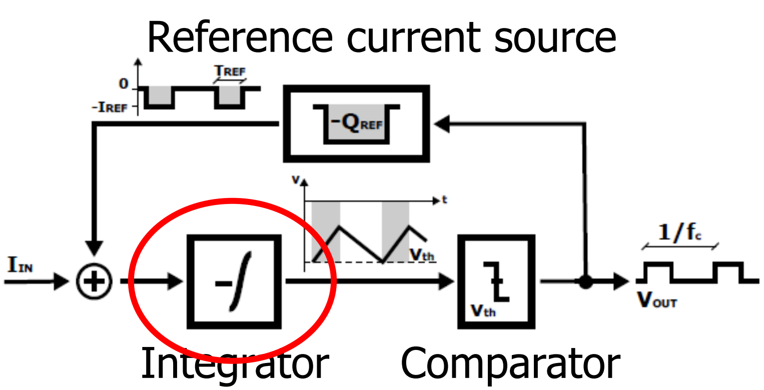

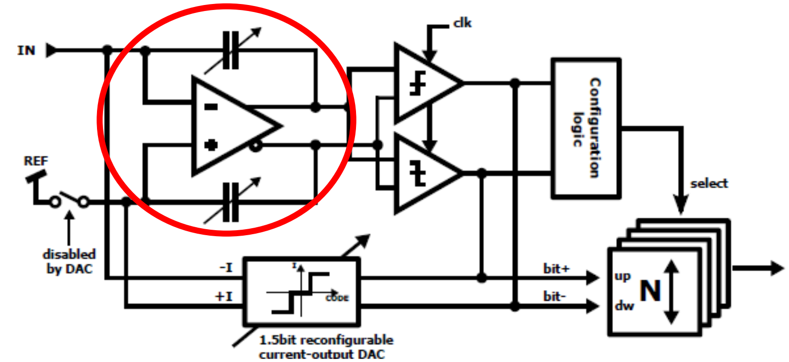

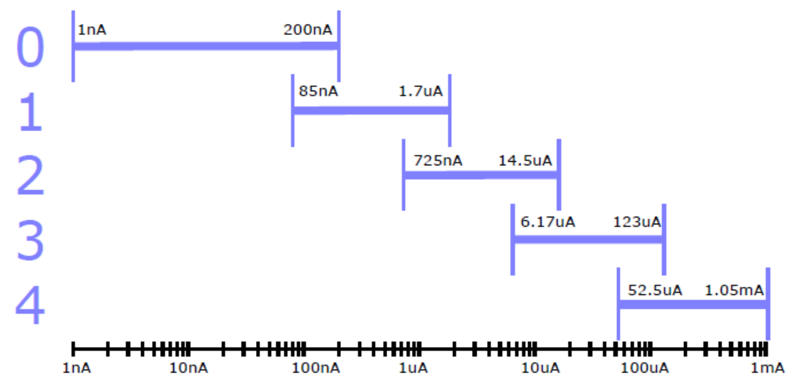

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Advanced Current to Frequency Converter Principle

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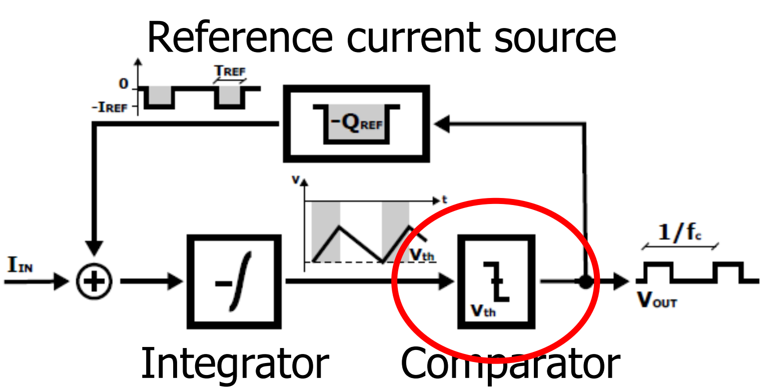
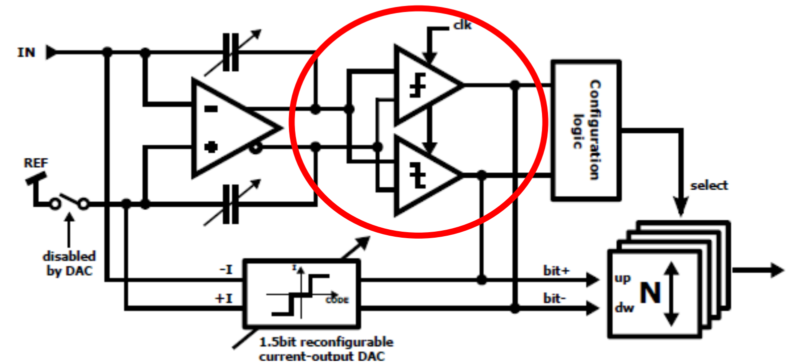
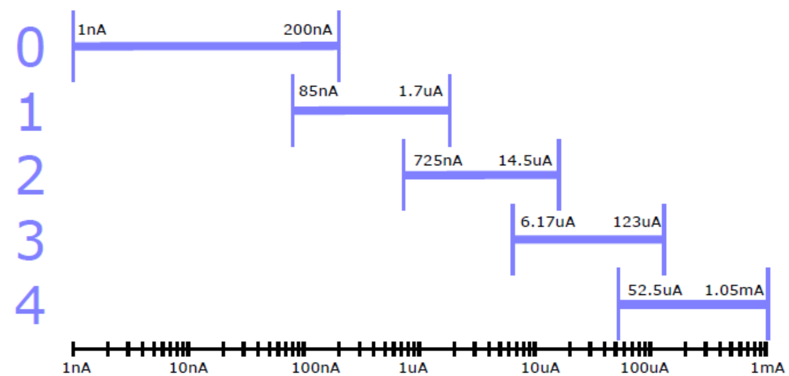


Six decades to be covered with a direct measurement → 20 bit





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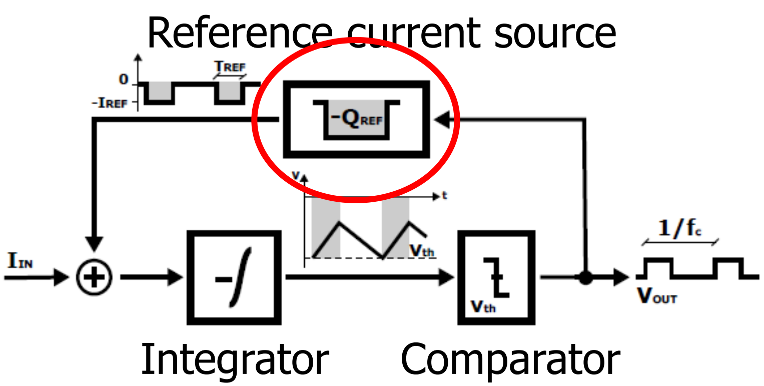
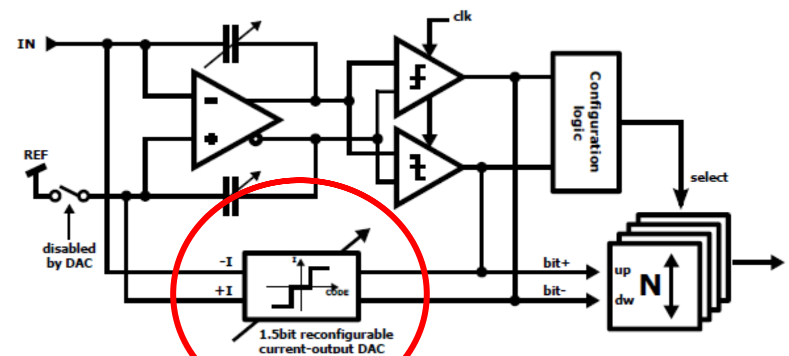
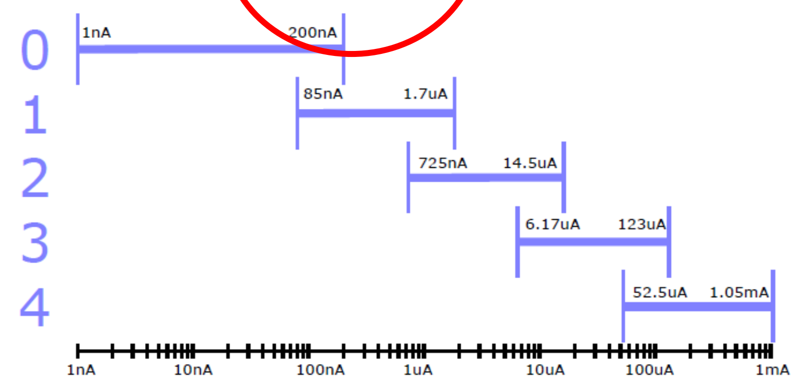


$$f = I_{input} / (I_{ref} * T_{ref})$$

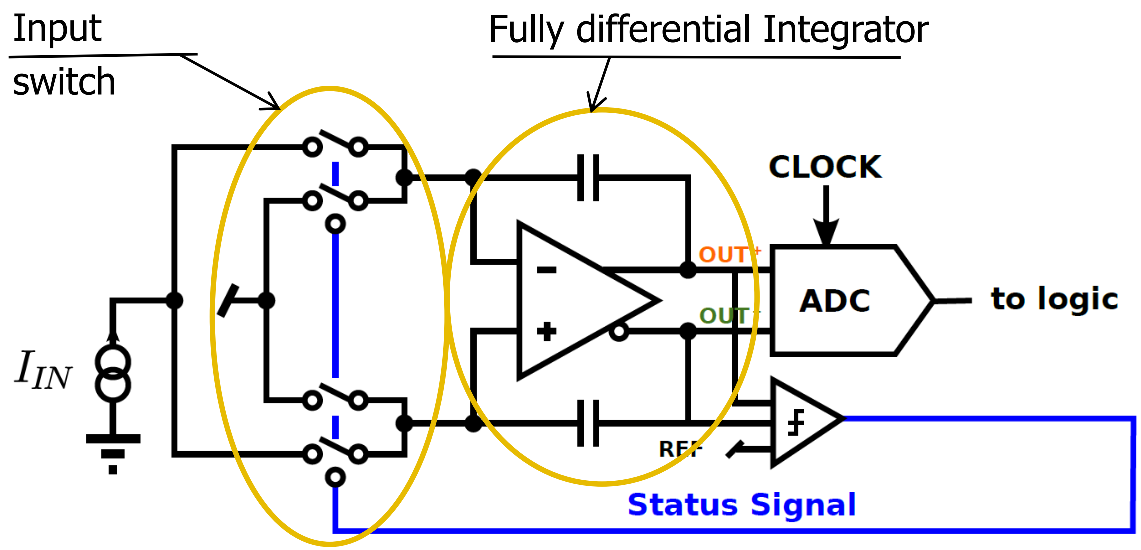
Six decades to be covered with a direct measurement → 20 bit

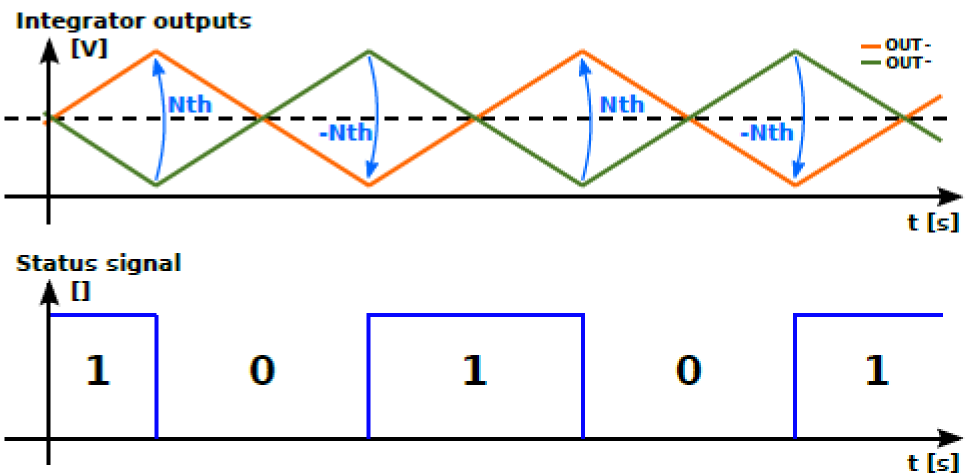




Fully Differential Current to Frequency Converter Principle

Discrete components: not radiation tolerant





1. Specifications:
   1. **Dynamic range 7 orders integration window 2 us 1nA to 200mA**
   2. **Dynamic range 9 orders** integration window 1 s 10pA to 200mA
2. A status signal selects in which branch of a fully deferential 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