



Beam Loss Monitoring in the Context of Machine Protection

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CERN, Geneva, Switzerland

**OPAC Topical Workshop on Beam Loss
Monitors 2016**

Barcelona

- Role of Beam Loss Monitoring (BLM) in machine protection
 - Risk
 - Damage
 - through energy / power / power density of beam
 - through uncontrolled release of stored energy (quench of superconductive magnet, RF structure)
 - Operational efficiency: recovery time from quenches
 - Long term integrity and maintainability: reduce total dose to equipment and intervention teams
 - Actions of Machine Protection (MP) system: Abort or block injection
 - Threshold determination
- Design of LHC machine protection
- Special BLM roles in set-up and monitoring of safe machine settings:
 - Collimator set-up
 - Injection and extraction
 - LHC ion operation
- Dependability driven design, implementation and testing
 - Test procedures
 - 24 hour surveillance and automatic notification
 - Post-operational verifications and system re-design if necessary

Further Reading

- Joint International Accelerator School on “Beam Loss and Accelerator Protection”, Nov 5-13, 2014
<http://uspas.fnal.gov/programs/JAS/JAS14.shtml>
<https://indico.cern.ch/event/287647/>
CERN yellow report: <https://cds.cern.ch/record/1641418>
- <https://cas.web.cern.ch/cas/>

Role of BLM in Machine Protection

- Risk

Damage Potential of the Beams

Synchrotrons, storage rings – example LHC

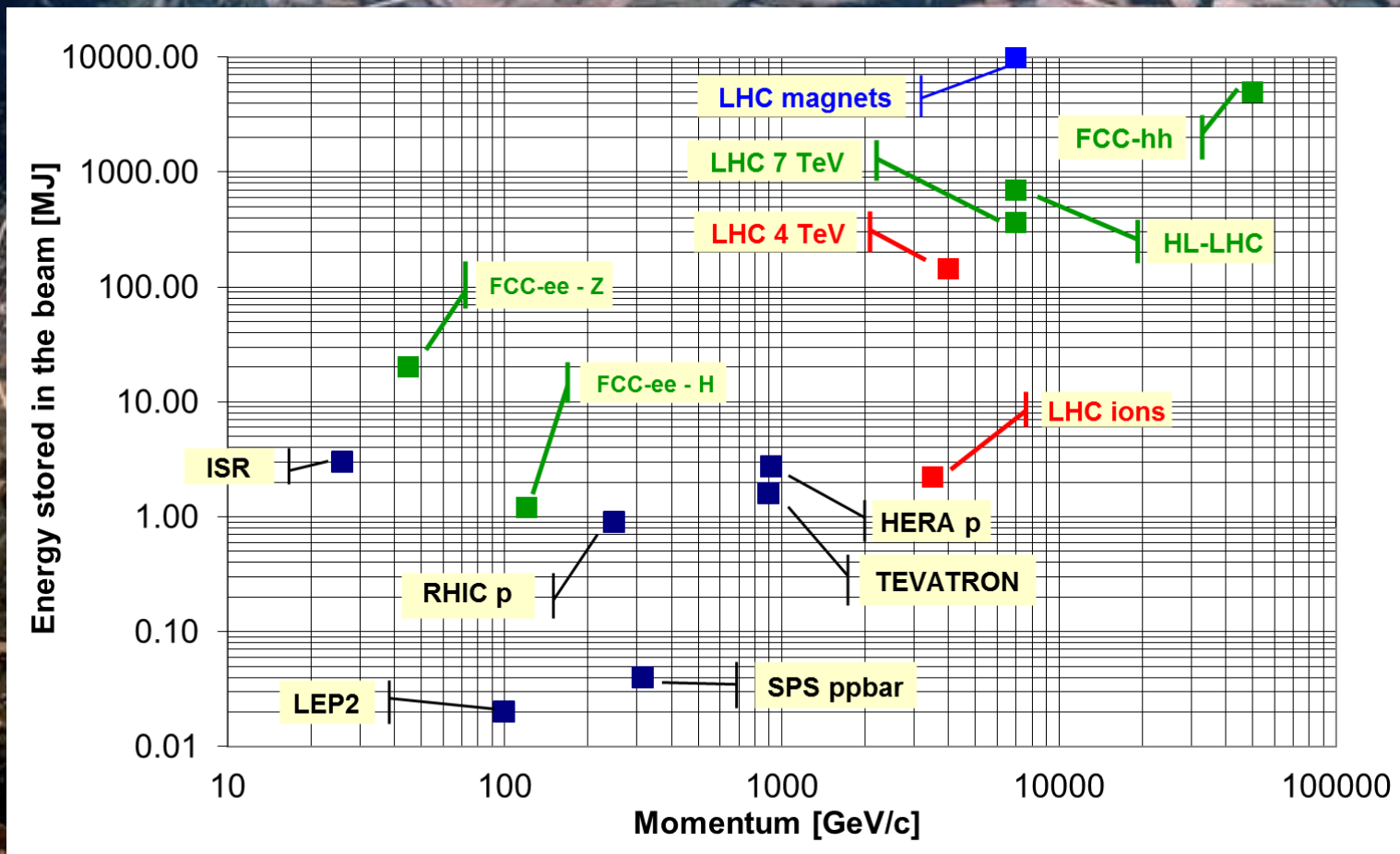
Highest beam damage potential

stored energy

Damage Potential of the Beams

LHC at 7 TeV 360 MJ

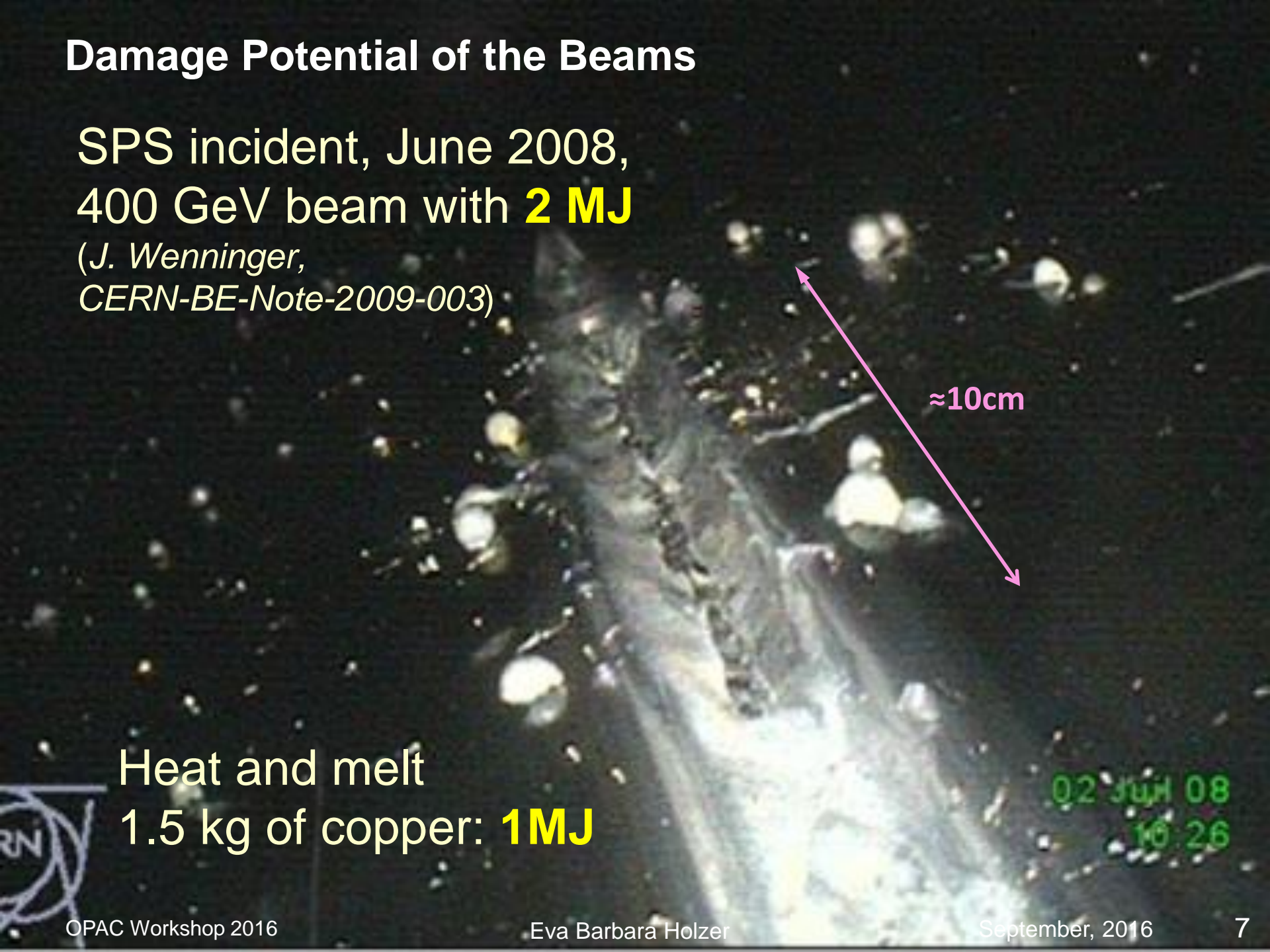
Pilot bunch (5×10^9 p) at 7 TeV close to damage level



Damage Potential of the Beams

SPS incident, June 2008,
400 GeV beam with **2 MJ**

(J. Wenninger,
CERN-BE-Note-2009-003)



Heat and melt
1.5 kg of copper: **1 MJ**

Damage Potential of the Beams

Linear accelerators and fast cycling machines
– examples SNS, J-PARC, ESS

Highest beam damage potential

beam power

ESS average power **5 MW**

Damage Potential of the Beams

In case of very small beam sizes – examples
ILC, CLIC, XFEL

Highest beam damage potential

energy or power density

European XFEL: power density
80 GW/cm²

> 10⁶ times power density of arc welding

Risk to the Machine

Damage

Direct beam damage OR through uncontrolled release of stored energy
(quench of superconductive magnet, RF structure)

Quench – Operational Efficiency

Activation / Aging / Human Exposure

Energy Stored in Superconductive Structures

- Release of **600 MJ**, LHC 2008, without beam
 - Electrical arc provoked a He pressure wave **damaging** ≈ 600 m of LHC
- LHC magnets at 7 TeV: **10 GJ**
- Heating by beam loss could trigger magnet damage (weakness of quench protection system, pre-damaged structure)

Over-pressure



Arcing at interconnection



Magnet displacement



Risk to the Machine

Damage

Quench – Operational Efficiency

Activation / Aging / Human Exposure

Risk to the Machine

Damage

Quench – Operational Efficiency

Activation / Aging / Human Exposure

Role of BLM in Machine Protection

- Risk
- Actions of MP system

Protection Roles by BLM System

- Extract beam to external or internal beam dump
 - LHC:
 - Dump beam when loss exceeds threshold on any of ≈ 3600 detectors
 - ≈ 1.5 million thresholds depend on
 - Detector location
 - Beam energy
 - Integration time ($40\mu\text{s}$ – 84s)
- Prevent subsequent injection by blocking beam at the source (at low energy) or by deviating to a beam dump
 - Linear accelerators or fast cycling machines
 - CLIC, remove “next cycle permit”, when potentially dangerous beam losses are detected
 - LHC injection
- Based on individual monitors a combination of monitors
 - e.g. HERA: 3 monitors above threshold

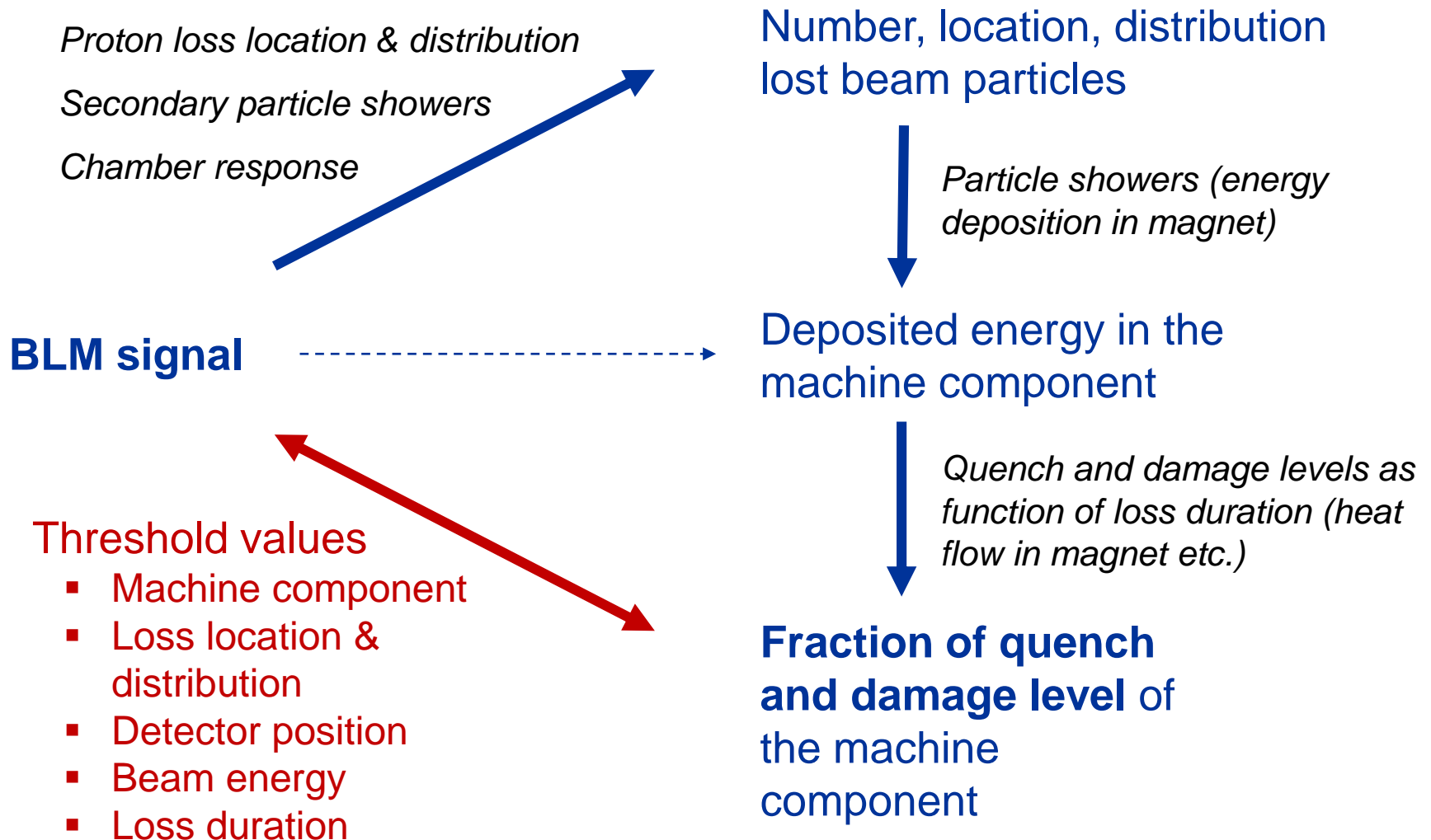
Role of BLM in Machine Protection

- Risk
- Actions of MP system
- **Threshold Determination**

Threshold Determination

- What?
 - Thresholds for beam abort request
 - Thresholds for injection inhibit
 - Thresholds for issuing a warning – typically a defined level below the dump / inhibit thresholds
- How?
 - Empirically based on “good” machine settings plus some tolerance
 - Attempt to calibrate loss signal to beam particles lost and establish “absolute” safe limits

LHC BLM Threshold Determination



LHC Thresholds on Cold Magnets

- BLM signal at quench:

$$\text{BLMSignal@Quench}(E, t) = \frac{\text{BLMResponse}(E, t) * \text{QuenchLevel}(E, t)}{\text{EnergyDeposit}(E, t)}$$

FLUKA

QP3

- The **master threshold** is a multiple of the BLMSignal@Quench

$$\text{MasterThreshold}(E, t) = N * \text{BLMSignal@Quench}(E, t) * \text{AdHoc}(t)$$

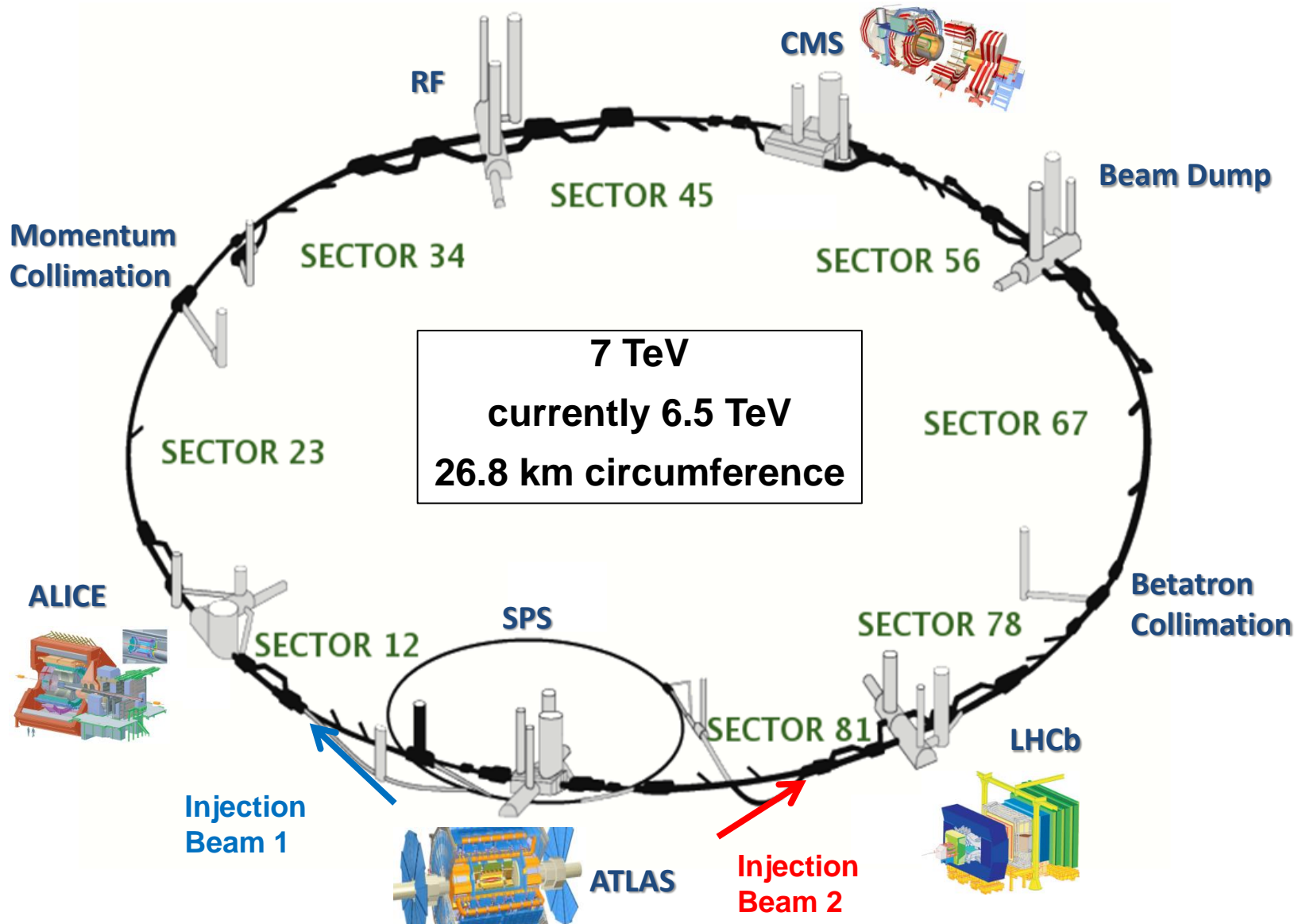
Operational experience and
quench tests

- For **operational flexibility**:

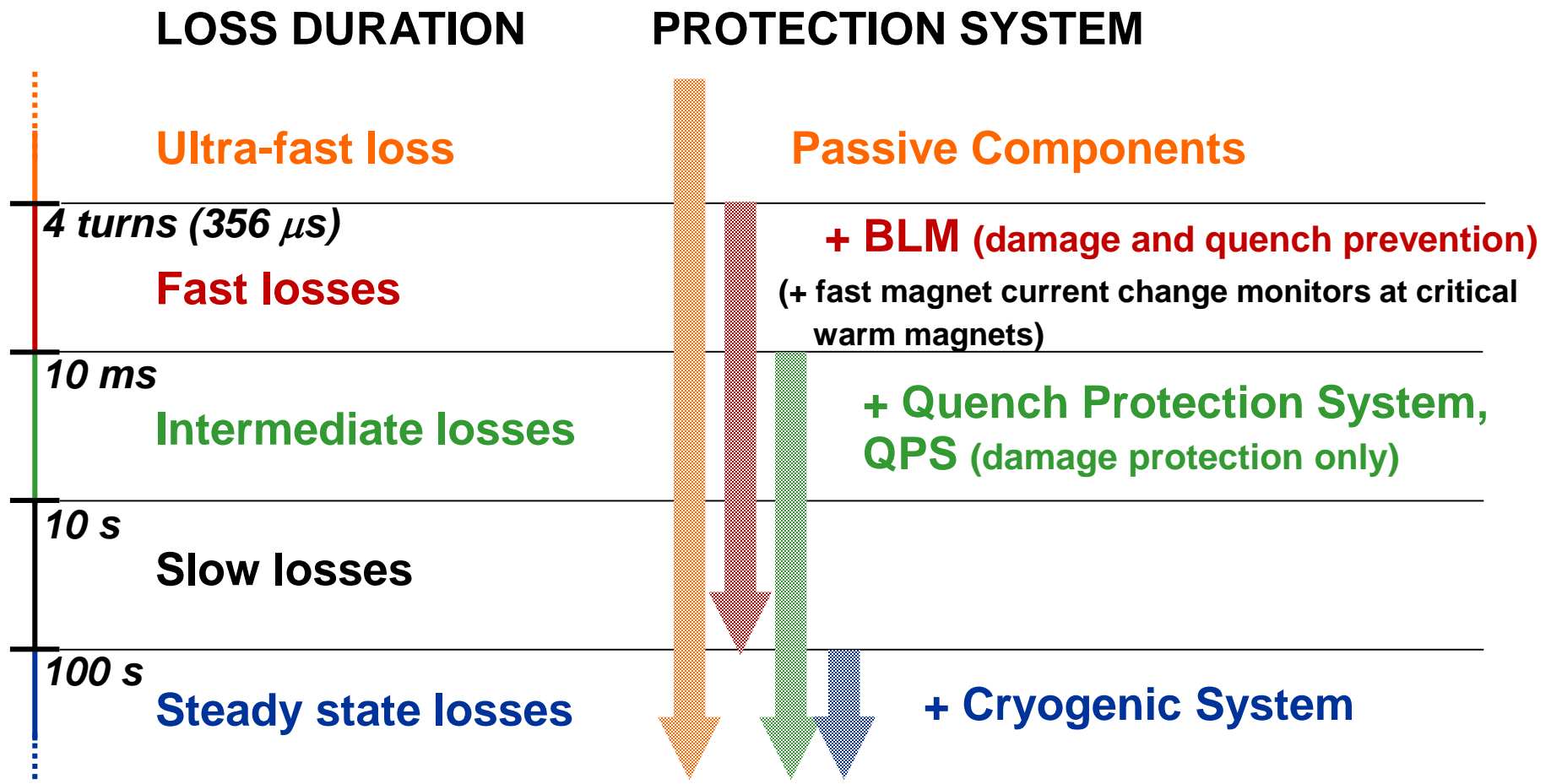
$$\text{Applied threshold} = \text{master threshold} * \text{monitor factor}$$

Design of LHC Machine Protection

LHC: pp, PbPb and pPb Collisions



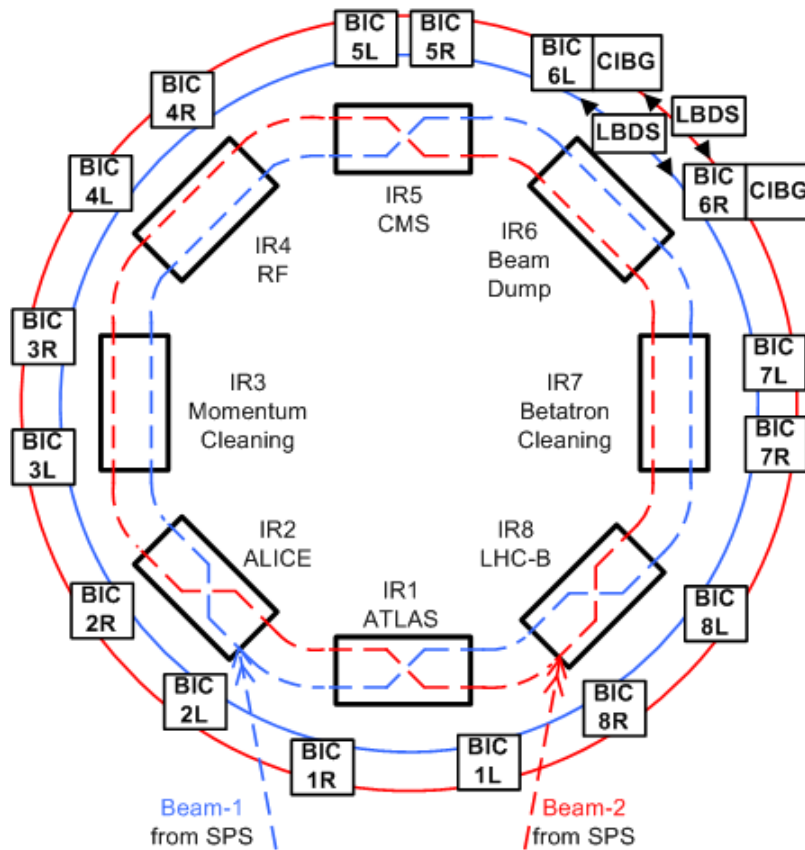
LHC – Beam Loss Durations Classes



The BLM is the main system to prevent magnet damage from multi-turn beam losses

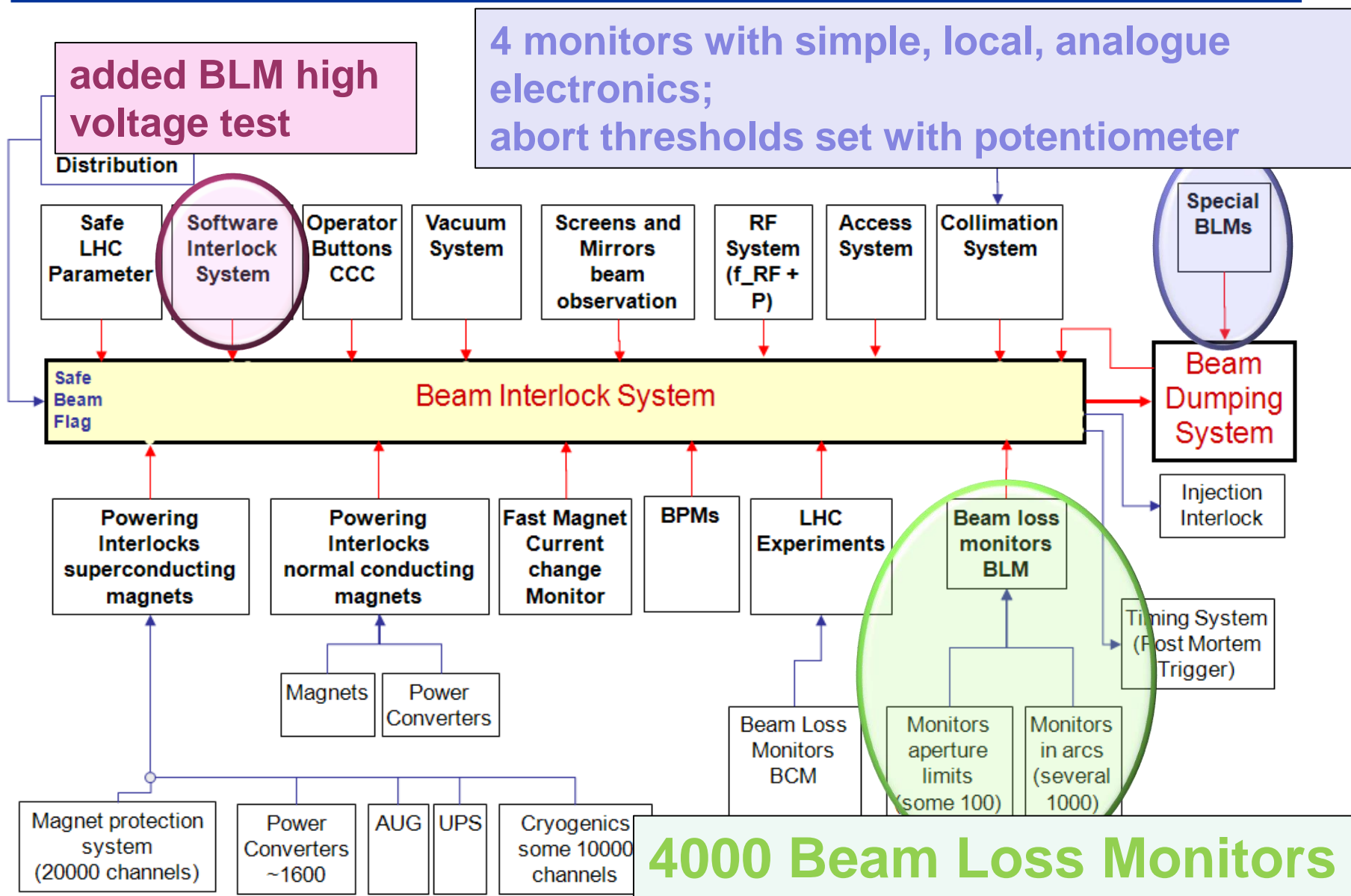
Prevention of quench only by BLM system

The BIS (Beam Interlock System) Layout



- 4 beam permit loops, 2 per beam
- Direct link to LHC injection and SPS extraction
 - beam permit
 - injection/extraction
- BLM beam dump delay up to $\approx 3-4$ turns ($\approx 0.3-0.4$ ms)

Machine Protection System



Special BLM Roles in Set-up and Monitoring of Safe Machine Settings

Example LHC

Collimation

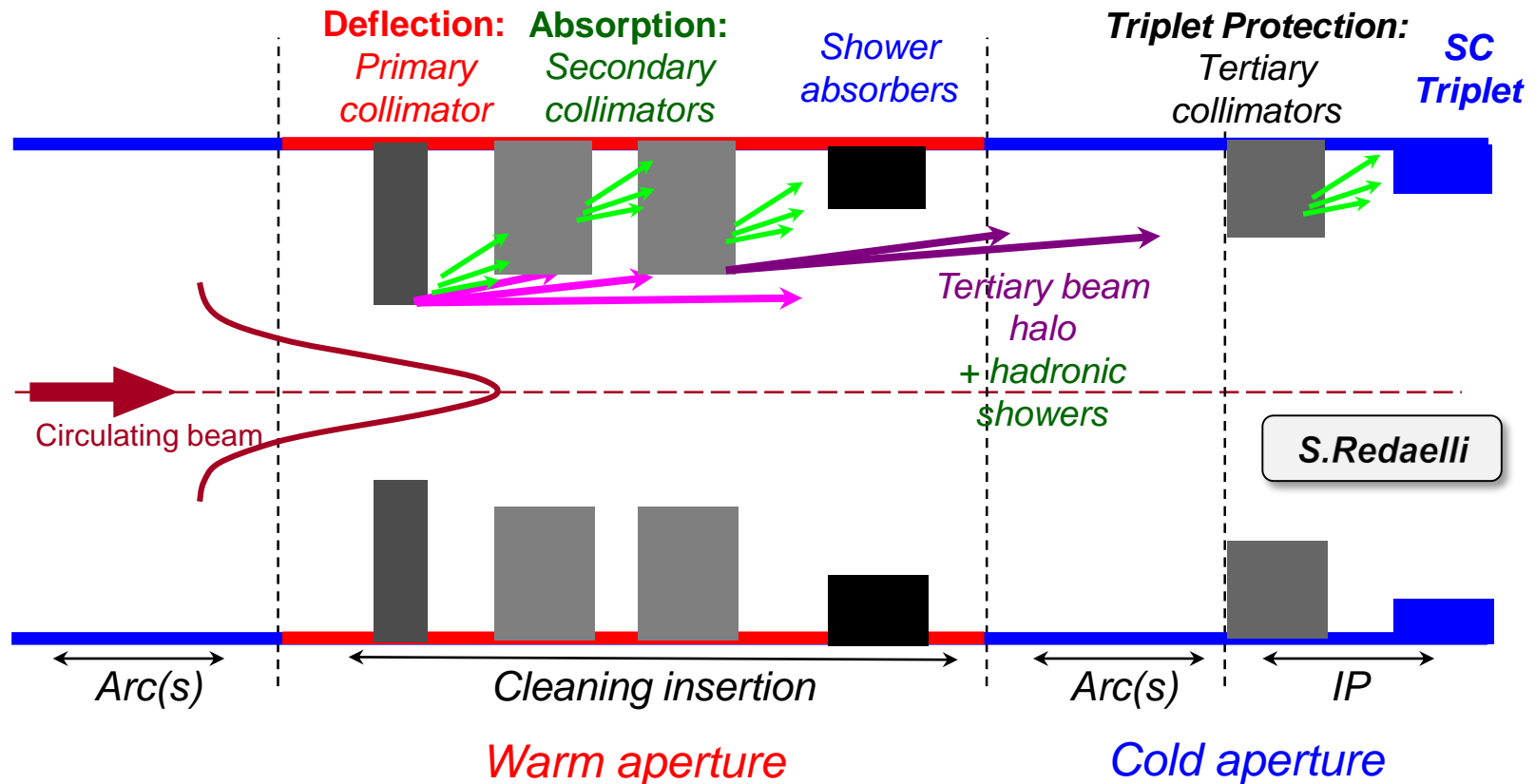
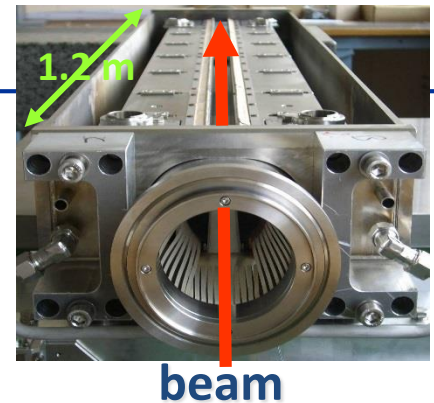
Injection and Extraction

Heavy Ion Operation

Three Stage Collimation System

≈100 collimators and absorbers

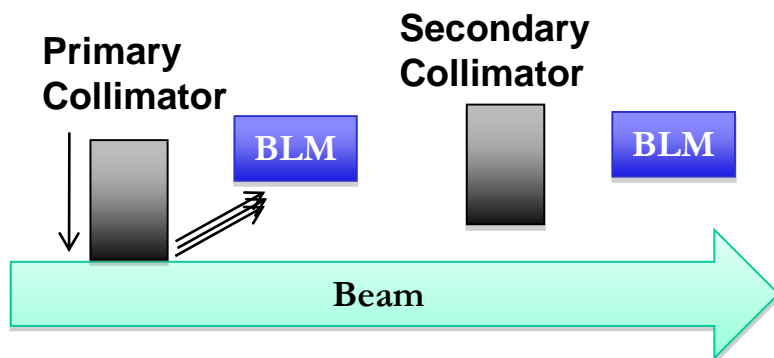
Including special dump and injection protection collimators



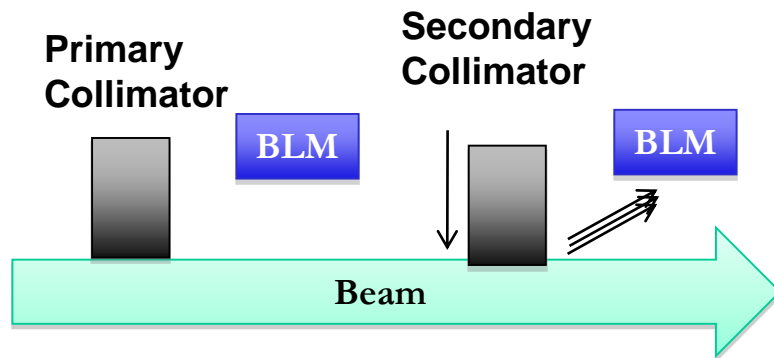
Collimator Set-Up

G. Valentino
D. Wollmann

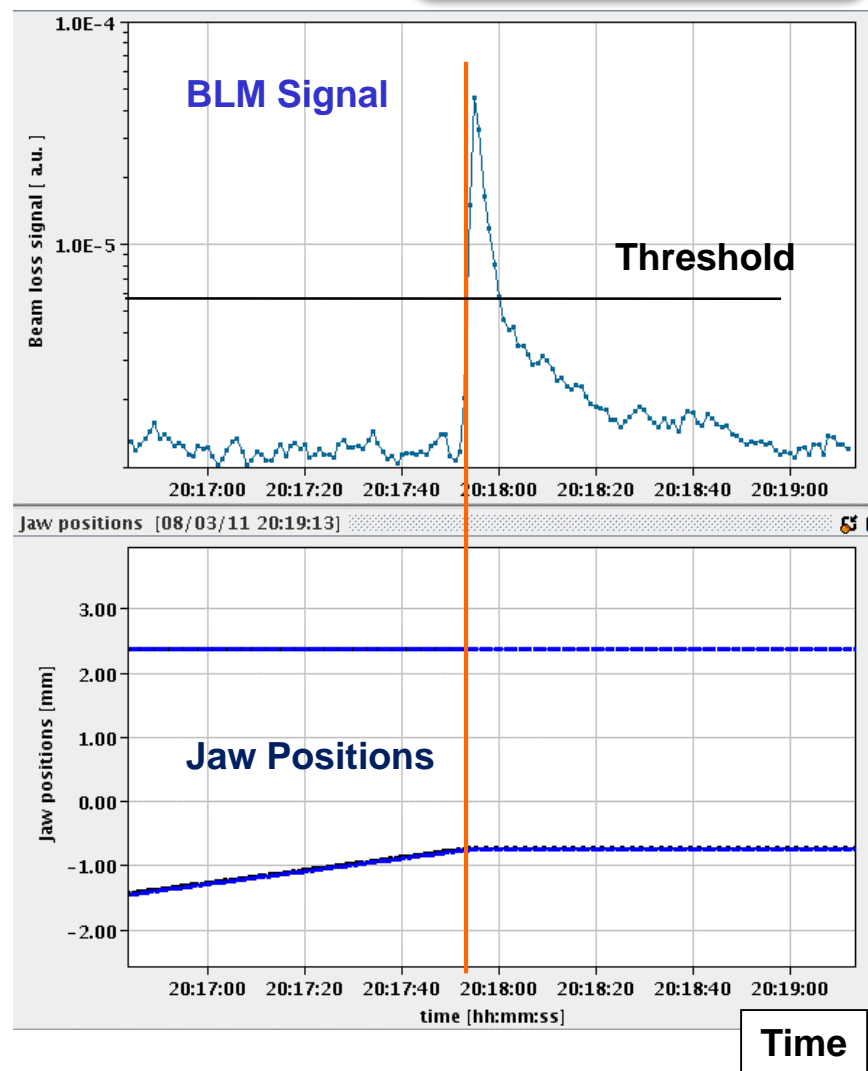
1.



2.



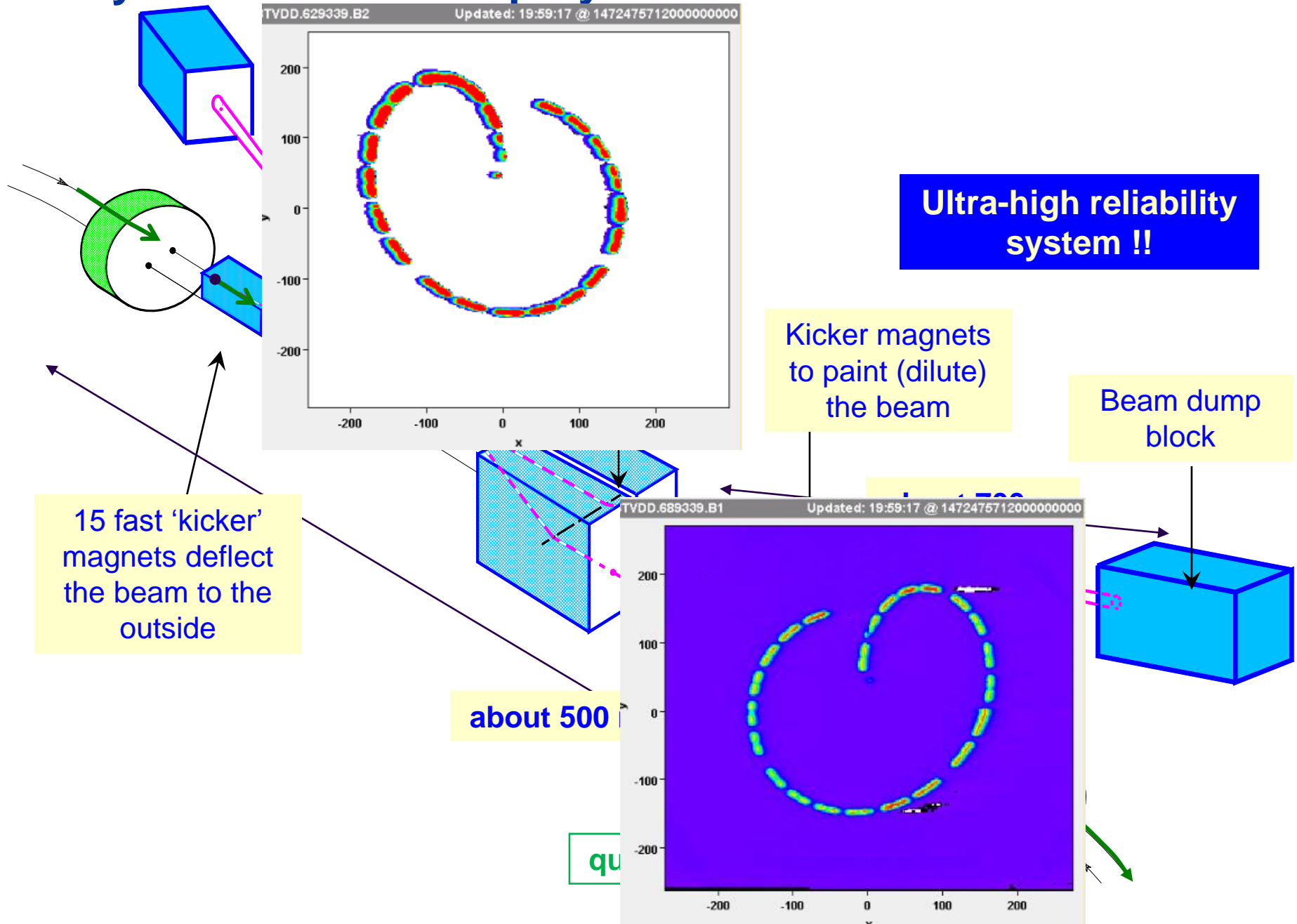
Find center and relative size of beam at collimator location using BLM signal



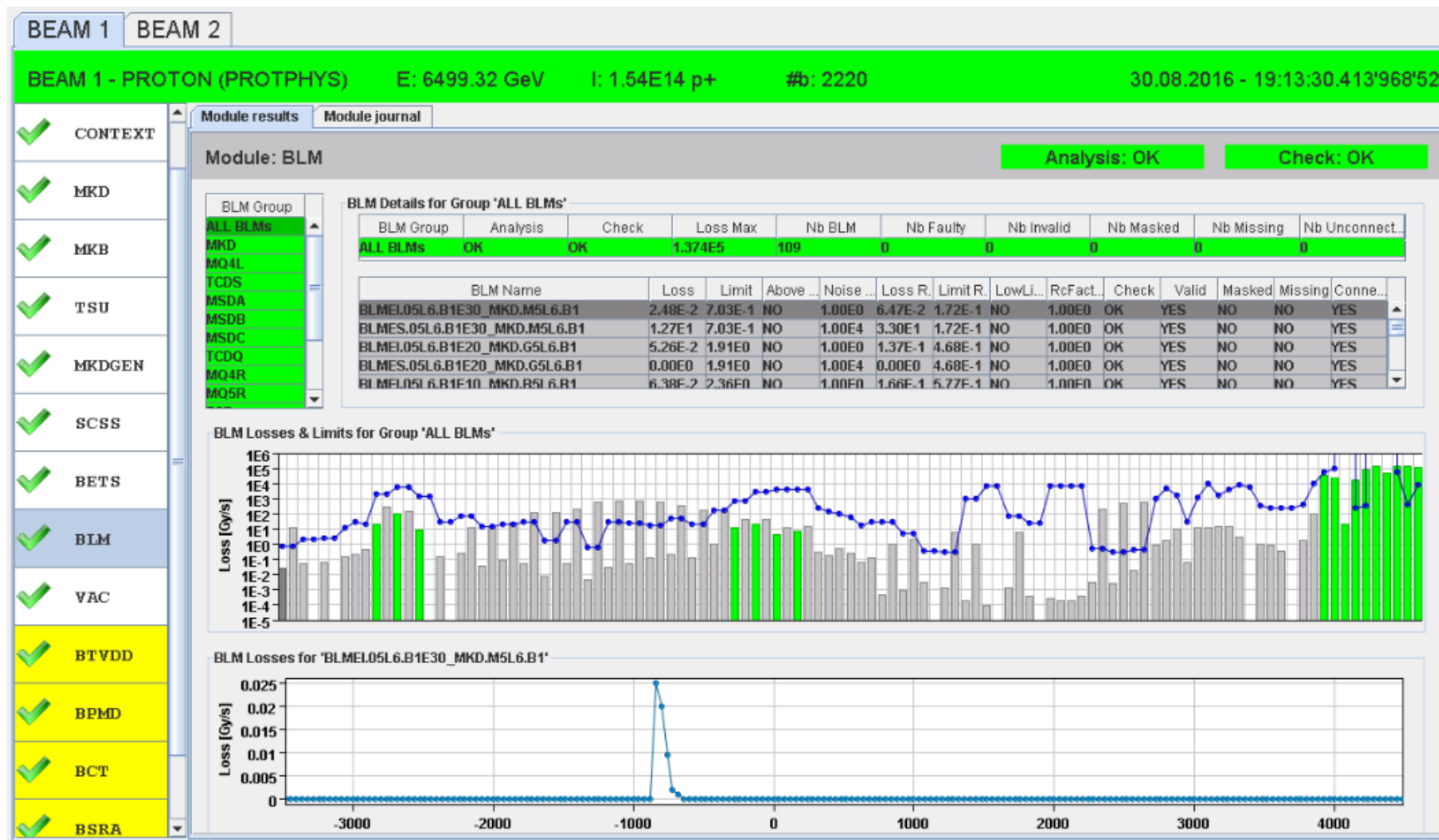
Injection Quality Checks



Layout of Beam Dump System in IR6

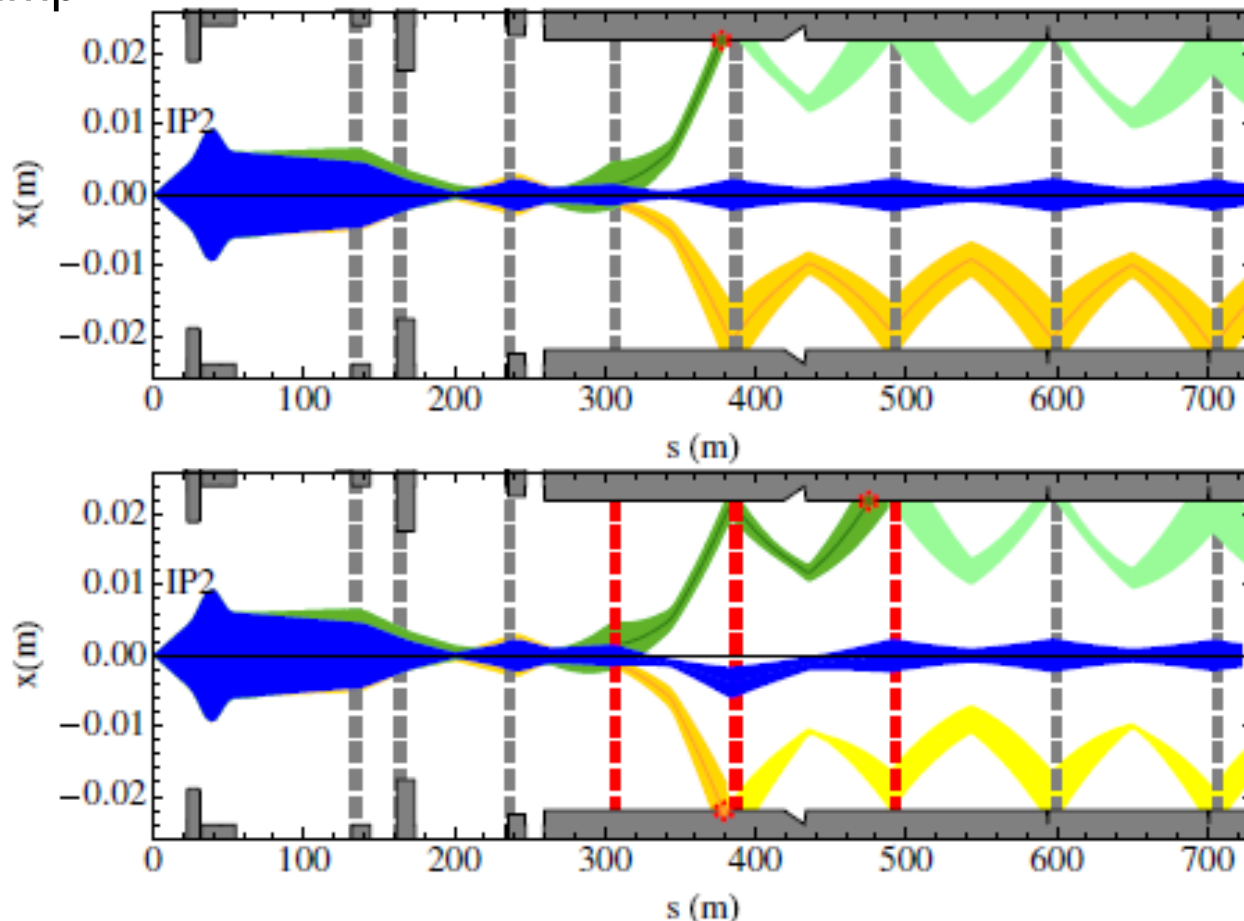


Beam Extraction Quality Checks



Ion Losses

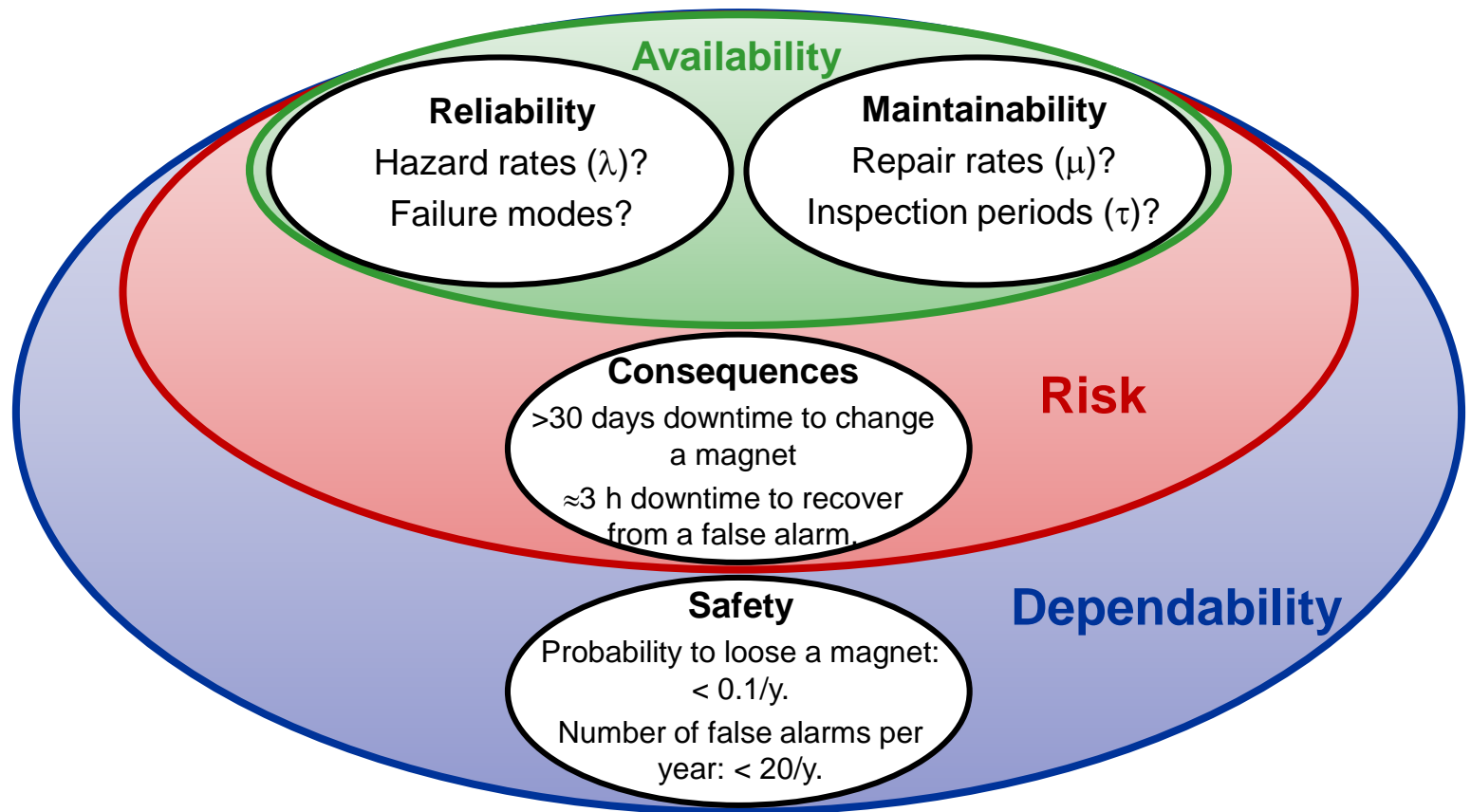
- Secondary ion beams from IPs and collimation → very localized losses in the dispersion suppressor → special BLMs
- Distribute losses longitudinally and over more cells by introducing an orbit bump



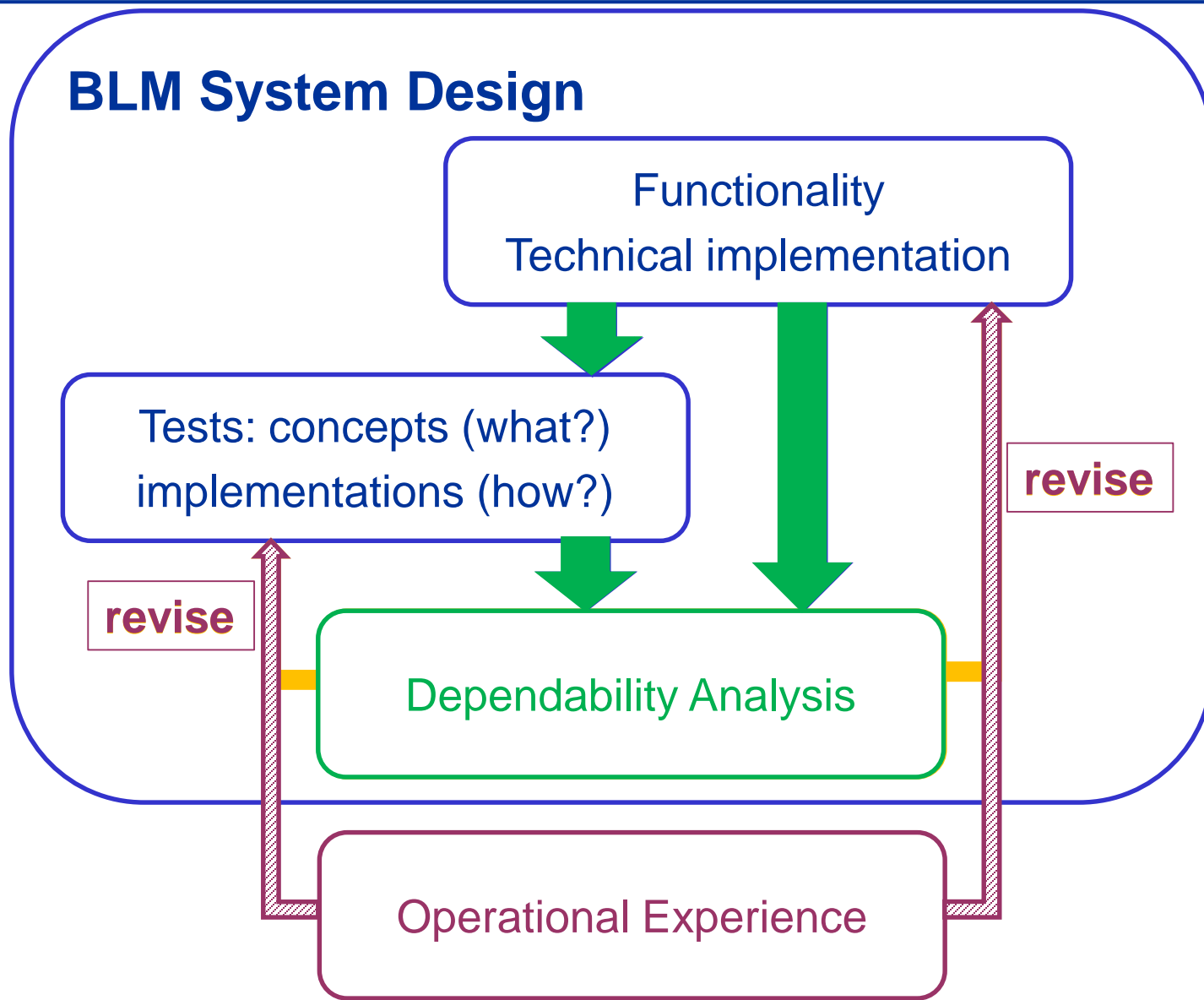
Dependability Driven Design, Implementation and Testing

Dependability (colloquially: reliability) Analysis

- Machine protection system must be integrated in the machine design
- Dependability (**reliability, availability, maintainability and safety**) analysis → allowances for
 - Probability of component damage due to malfunctioning
 - Downtime due to false alarms
 - Downtime due to maintenance



Iterations in the System Design



Dependability Design of the LHC BLM System

LHC BLM Design Specifications include:

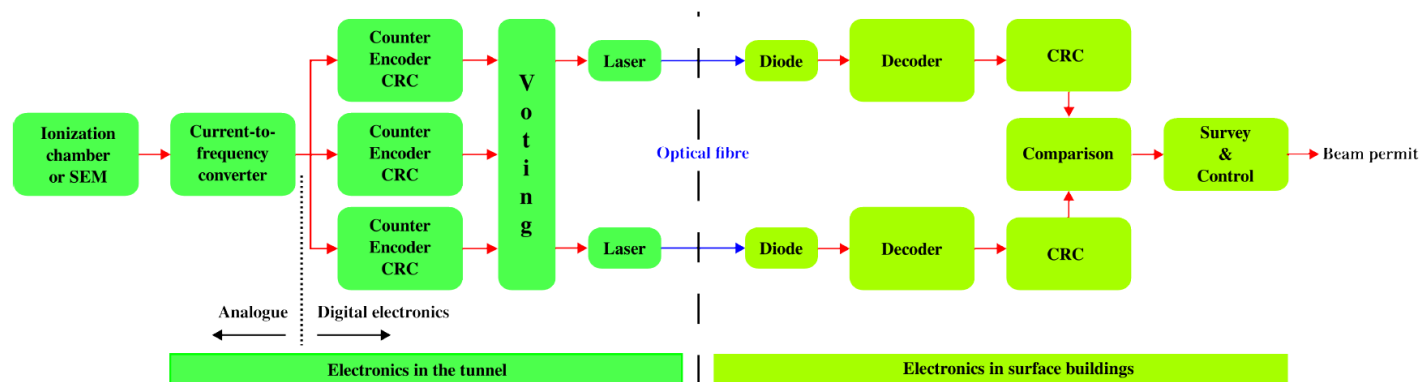
- Reliable (tolerable failure rate 10^{-7} per hour per channel) → 10^{-3} magnets lost per year (assuming 100 dangerous losses per year)
- Less than 2 false dumps per month (operation efficiency)

1. Reliable and radiation tolerant components

- Environmental tests of tunnel electronics:
 - temperature: 15 – 50 °C
 - no single event effects observed during tests for a dose corresponding to 20 years of operation

2. Redundancy and voting (when single components are not reliable enough)

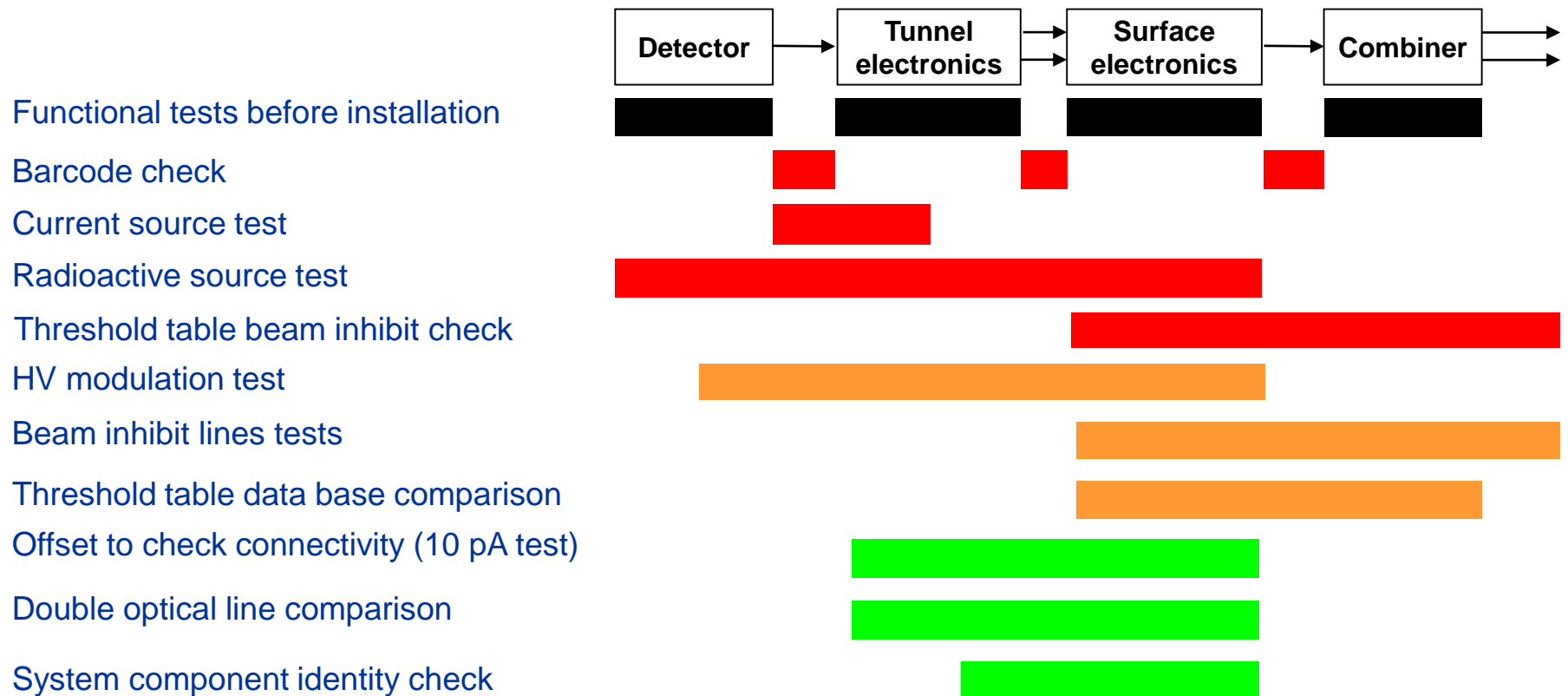
3. Monitoring of availability and drift of readout channels (functional tests)



Test Procedures

- What can go wrong?
- Devise a test for all conceivable failure scenarios

LHC BLM Validation Tests – Design



PhD thesis Gianluca Guaglio

Inspection frequency:

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

Test Procedures

- What can go wrong?
- Devise a test for all conceivable failure scenarios
- Periodically review and update the tests!

Test Procedures – What can go wrong?

- Forgot one?
- LHC BLM:
 - High voltage cable supplying ionisation chambers was cut on the surface (no beam in LHC).
 - No immediate drop of voltage due to high capacitances in the circuit, but HV supply only tested before each fill.
 - → added software interlock, now HV on chambers is monitored continuously.

24 Hour Surveillance and Automatic Notification

- **Verify system integrity**
- **Proactive maintenance**

Threshold Validation – Automatic Reporting

- Detailed daily report on changes to thresholds, and monitor / filter layout of the system

Report of changes on LSA between 2016-08-19_07:05:03 and 2016-08-20_07:05:04

BLM Basic Info BLM position means its connection to the crate: card-channel, BLMs without old values are new monitors or monitor with new expert names.

Table 1: Changes of BLM info in LSA

Expert Name	Position		Family				Dcum	
	old	new	old		new		old	new
BLMBI.08L2.BOT10_MBB-MBA_07L2	-	-	THRI.ARDS_MBMB_RC_CRITS12		THRI.ARDS_MBMB_CRITS12		-	-
BLMBI.09L2.BOT10_MBB-MBA_08L2	-	-	THRI.ARDS_MBMB_RC_CRITS12		THRI.ARDS_MBMB_CRITS12		-	-

BLM Flags Only flags with new values are listed, unchanged flag values are listed as '-', BLMs without old values are new monitors or monitor with new expert names.

Table 2: Changes of BLM flags in LSA

Expert Name	Cable		BIS		MASK		Capacitor	
	old	new	old	new	old	new	old	new
BLMBI.08L2.BOT10_MBB-MBA_07L2	-	-	-	-	-	-	2200	0
BLMBI.09L2.BOT10_MBB-MBA_08L2	-	-	-	-	-	-	2200	0

BLM Applied Thresholds BLM removed from a family will not be listed, BLM with changed expert name will be listed although its thresholds may be unchanged.

Table 3: Changes of BLM thresholds in LSA

Family Name	# of blms with new thr.	Total # of blms
THRI.ARDS_MBMB_CRITS12	2	101

Applied threshold ratios (new/old):

Changed threshold are marked as yellow cells

Family: THRI.ARDS_MBMB_CRITS12

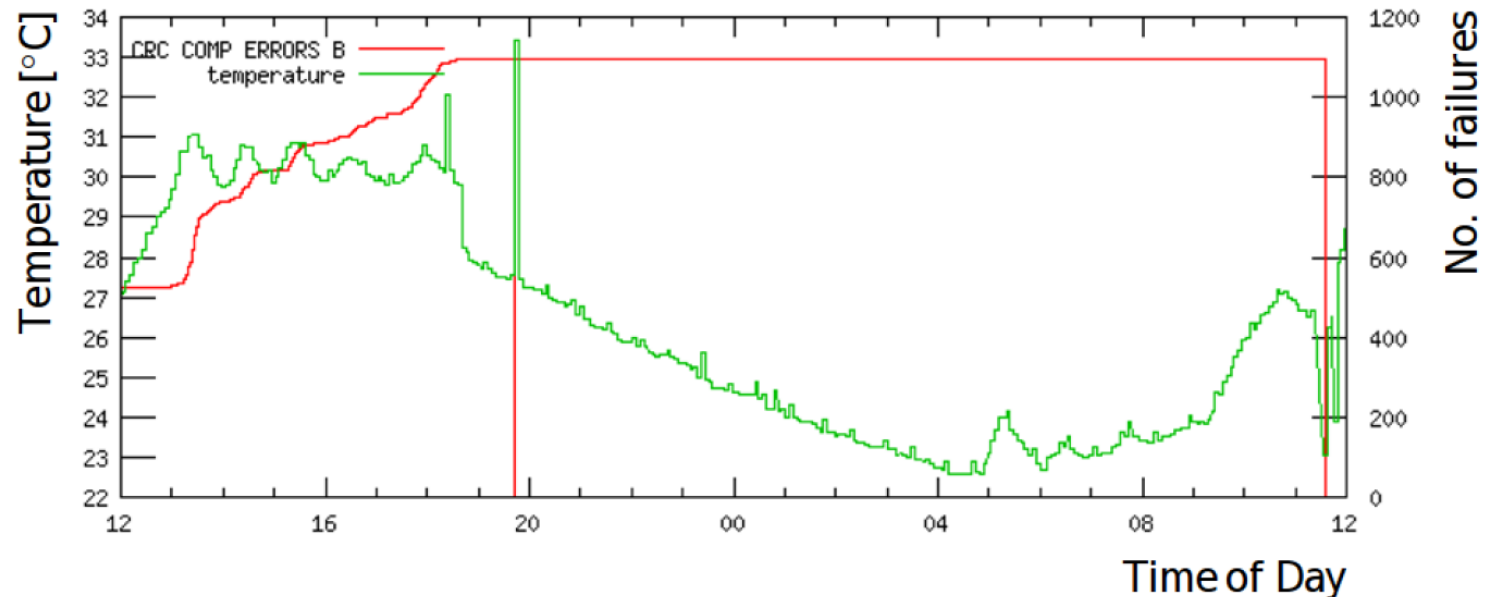
BLMBI.08L2.BOT10_MBB-MBA_07L2 (32)

RS	1	2	3	4	5	6	7	8	9	10	11	12
450 GeV	1.66	1.62	1.62	1.62	1.39	1.01	1	1	1	1	1	1
4 TeV	20.2	17.9	7.84	4.64	1.57	1.01	1	1	1	1	1	1
6.5 TeV	4.08	7.39	8.01	5.4	2.34	1.01	1	1	1	1	1	1

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24 Hour Crate Temperature

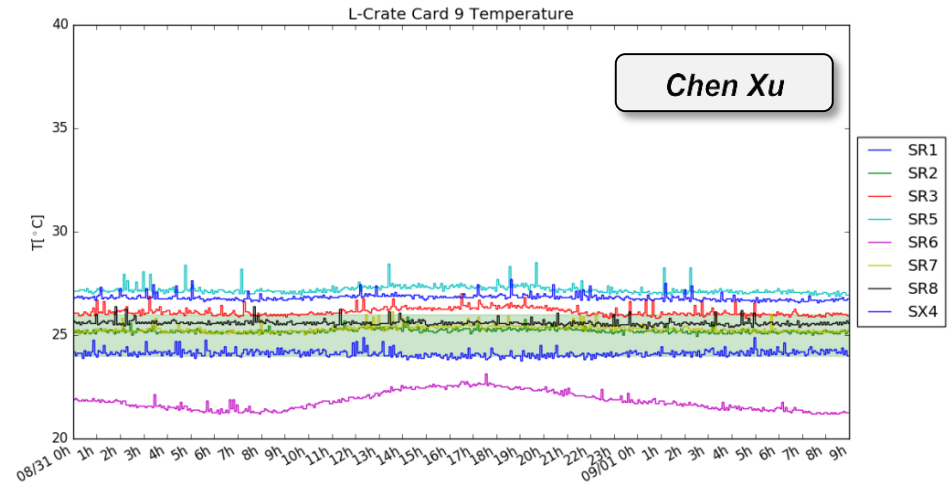
- Run1: observed optical link failures correlated with electronics card temperature



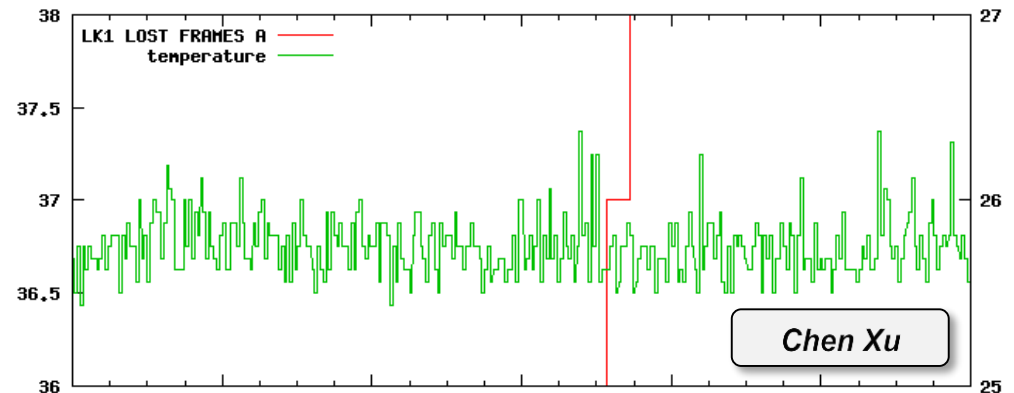
- temperature control and 24 hour monitoring of all surface electronics card temperatures

Automatic Reports – 24 Hour Surveys

- Temperature of the surface cards



- Optical link error: Check for lost data frames and for CRC (cyclic redundancy check) errors



- If optical link failure → automatically generate trend over the last 20 days → if number of errors increases → exchange

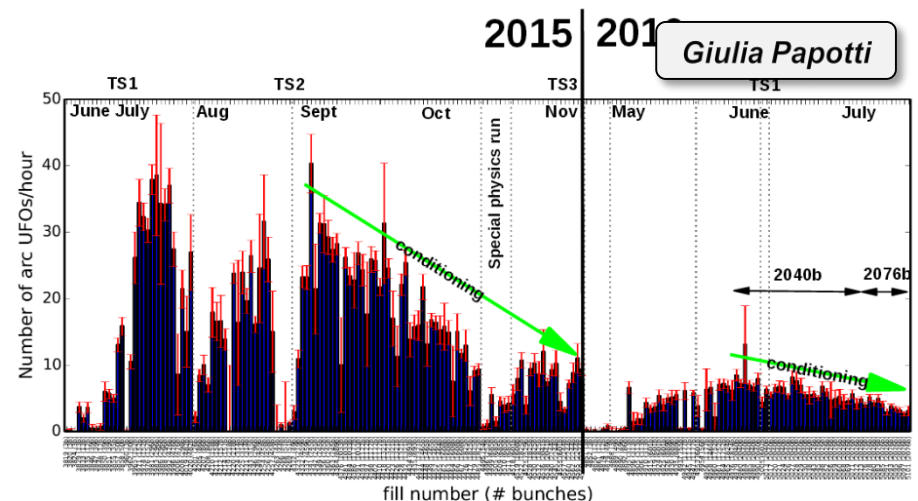
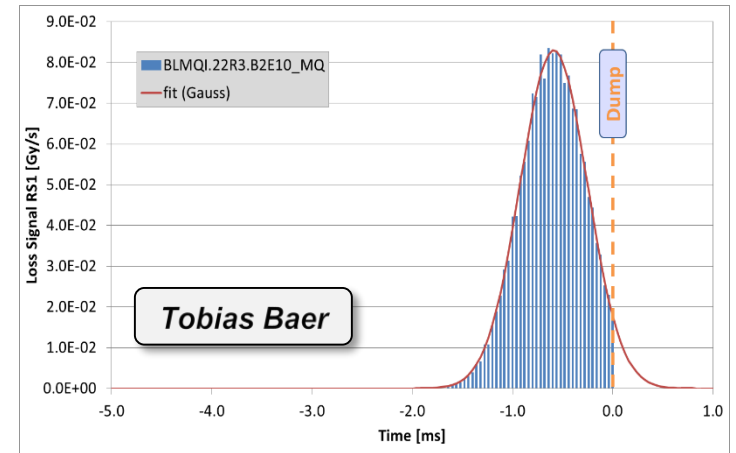
Post-operational Verifications and System Re-design if Necessary

- HV software interlock
- Temperature controlled racks
- Injection losses – hardware and threshold modifications, injection inhibit of the interlock?
- UFOs → massive relocation of monitors
- Abort thresholds not static

UFOs – Causing Quenches at 6.5 TeV



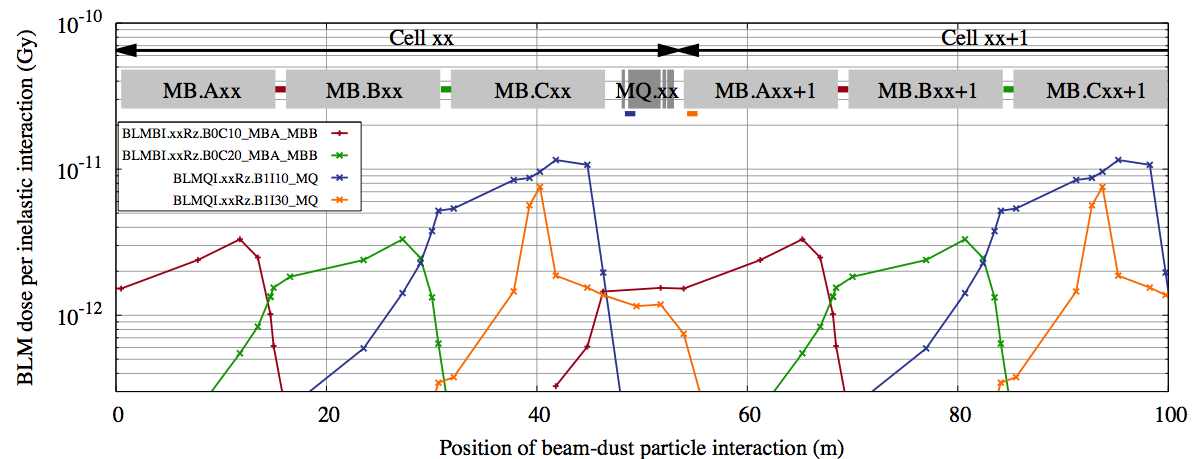
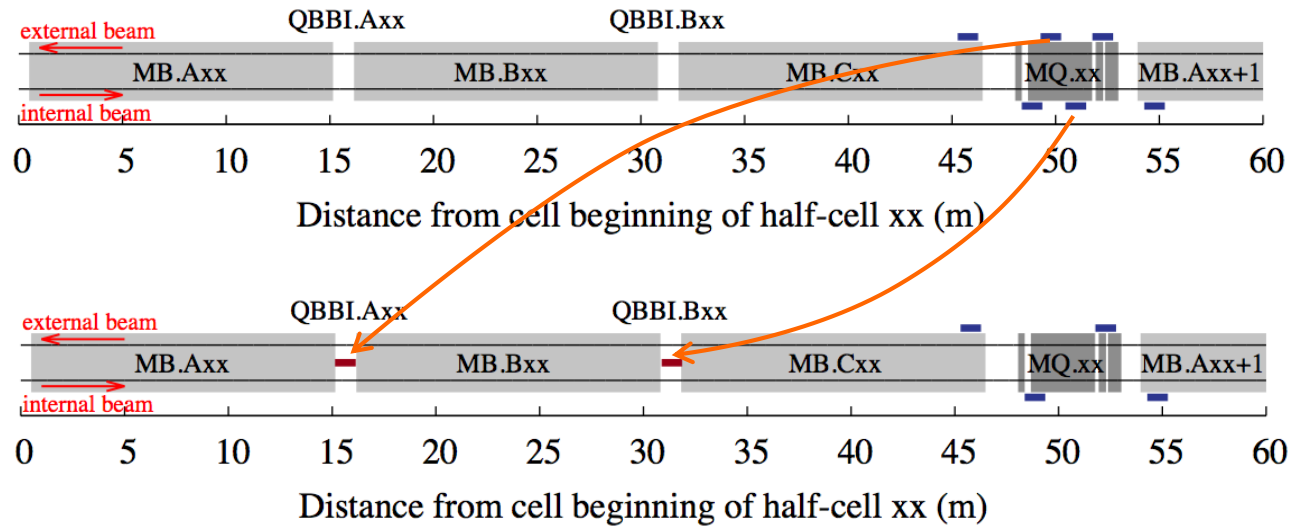
- Fast and localised losses all around the ring believed to be caused by macro particles interacting with the beam
- “UFO”: Unidentified Falling Objects
- No quenches at 4 TeV
 - Less heat deposited
 - Lower magnetic field
 - Conservative BLM thresholds
- 6.5 TeV: thresholds set to and **above** the quench limit
→ quenches occurred



Relocation of 1/3 of Arc Detectors (Long Shutdown 1)



- Coverage post-LS1: increases sensitivity by a factor 30 → 100% coverage can be achieved



A. Lechner, Workshop on Beam-Induced Quenches, CERN, 2014

LHC Example: Are Beam Abort Thresholds Static?

- Concept phase:
 - Eventually, YES → change only by physical intervention at the threshold comparator card
 - But only once tuned properly → allow (HW jumper) remote download of new thresholds
- Experience: NO
 - Loss pattern depend on: Beam energy, particle type, beam optics, collimator settings, luminosity, cleanness of injection etc.
 - Completely revised loss scenarios after Run1 (e.g. UFO)
- Recently:
 - Urgent and massive BLM system changes required to compensate for problems with other systems:
 - Injection kicker length needed shortening – higher losses
 - Suspicion of magnet weakness (inter turn short) – reduce probability of magnet quench in one sector
- **Conclusion: If the machine is static – well tuned thresholds will be static!**

Buzz Phrases

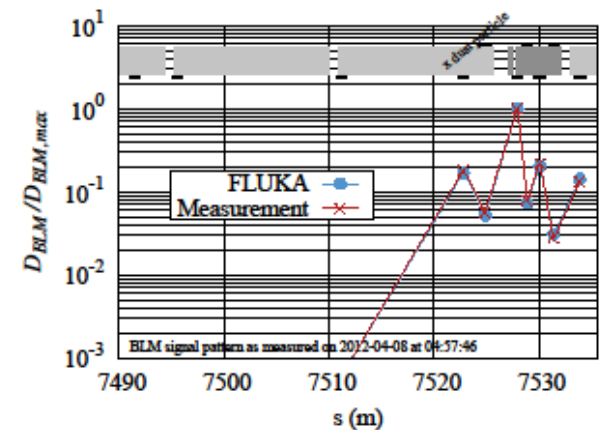
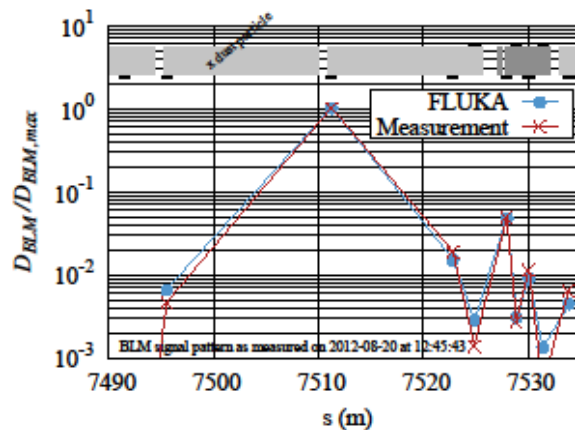
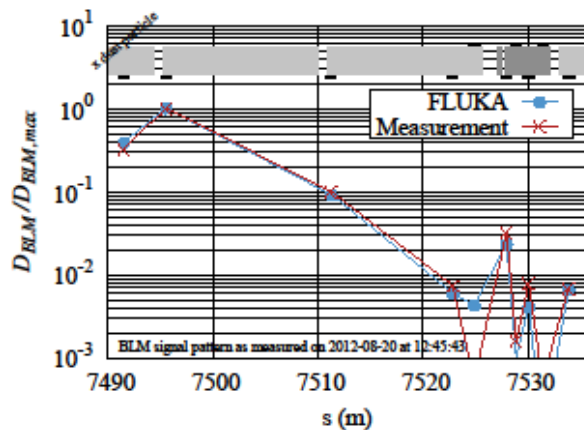
- Protection roles of the BLM system depend on machine type and criticality
- Thresholds are based on the most critical and/or most likely loss scenarios
- Dependability analysis outcome might modify system design
- Test Procedures are part of system design

**Thank You
for Your
Attention**

UFO Losses: Comparison Simulation — Measurement

Anton Lechner

- If several detectors record the loss: Determine the loss position and magnitude with the help of simulations
 - Loss position: ± 1 m
 - Number of inelastic proton-dust particle interactions: factor 2

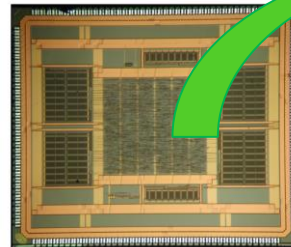
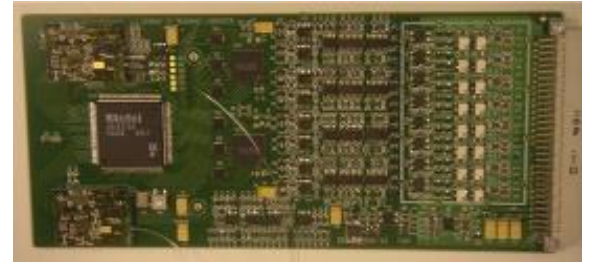


- $1-4 \times 10^6$ inelastic proton-dust particle interactions in this cell
- Other cells 10–100 times higher

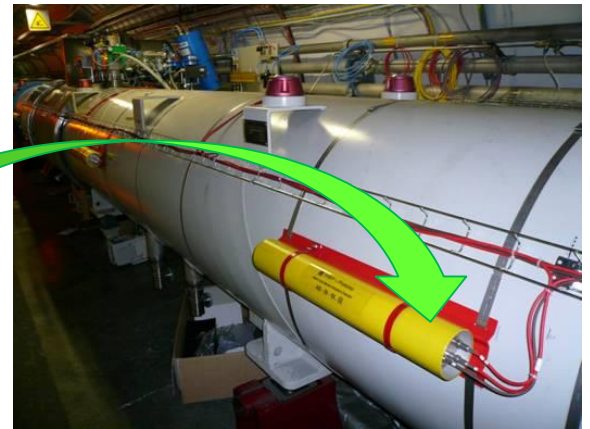
A. Lechner, Workshop on Beam-Induced Quenches, CERN, 2014

Radiation Tolerant Readout

- LHC BLM front-end: charge-to-frequency converter
 - 500 Gy certified — ok for arcs
 - Insertion regions:
up to 300–800 m long cables
- New development: radiation hard Application Specific Integrated Circuit (ASIC)
 - Dynamic range 10^6
 - Bipolar input current
 - Certified up to 100 kGy



G. Venturini



LHC BLM System

- Main purpose: **prevent damage and quench**
- Beam abort thresholds:
 - 12 integration intervals:
40 μ s to 84s
 - 32 energy levels
→ **1.5 Million threshold values**
- Each monitor aborts beam
 - One of 12 integration intervals over threshold
 - Internal test failed



Monitor types

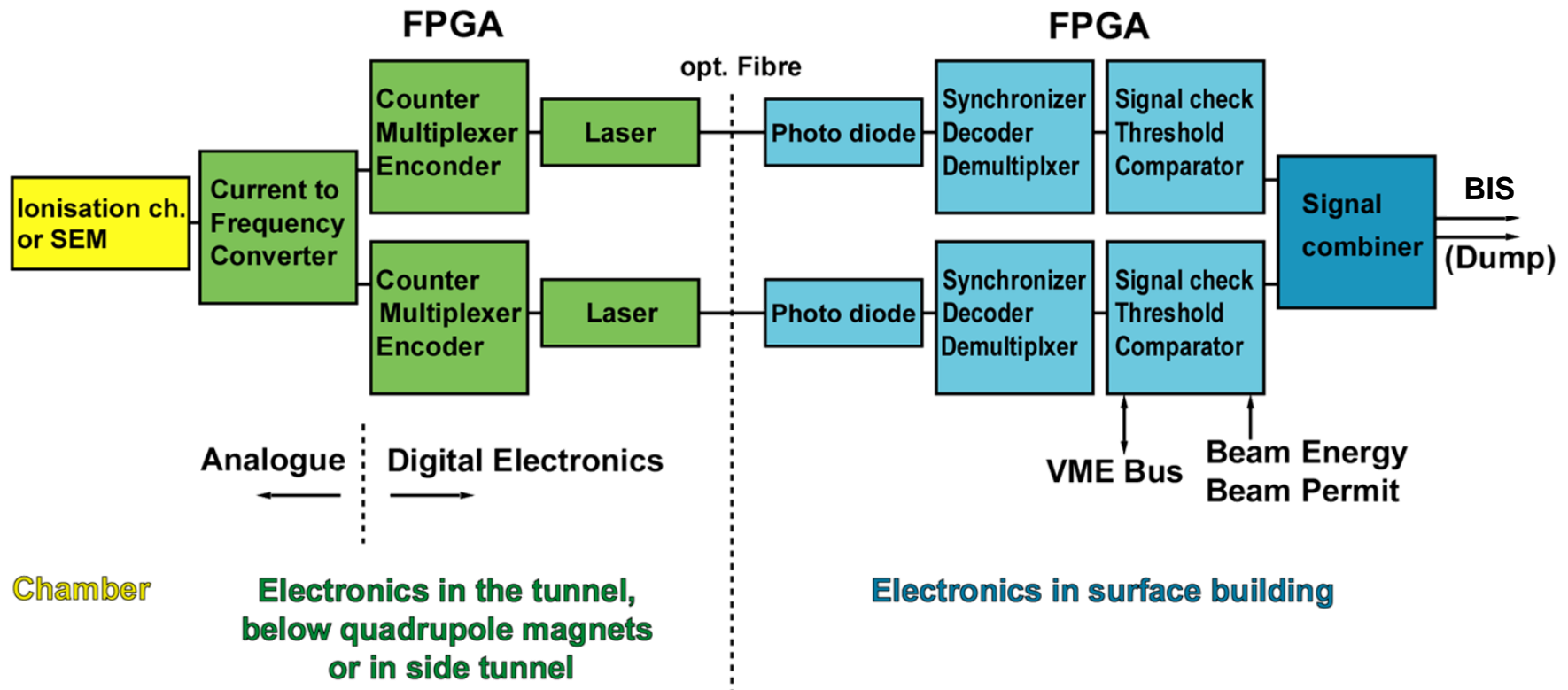
- Design criteria: Signal speed and robustness
- Dynamic range ($> 10^9$) limited by leakage current through insulator ceramics (lower) and saturation due to space charge (upper limit).
- Parallel electrodes (Al, SEM: Ti) separated by 0.5 cm
- Voltage 1.5 kV
- Ionization chamber: IC
 - Standard LHC monitor
 - ~3600
 - N₂ gas filling at 1.1 bar
 - Length 50 cm
 - Sensitive volume 1.5 l
 - Ion collection time 85 μ s
- Secondary emission monitor: SEM
 - $P < 10^{-7}$ bar
- Little Ionization chamber: LIC
 - Mechanically nearly identical to SEM, 1.1 bar N₂



Requirements and Challenges

- Requirements and Challenges
 - Dependability
 - Tolerable failure rate 10^{-7} per hour per channel
 - Less than 2 false dumps per month
 - Threshold precision (ultimately: factor 2)
 - Reaction time 1-2 turns (100 – 200 μ s)
 - Dynamic range: 10^8 (at 40 μ s 10^5 achieved – 10^6 planned)
- Modify the dynamic range for short losses with signal delay filter
 - Small filter, SF, 2200 pF & 150 kOhm: factor 20
 - Big filter, BF, 47000 pF & 150 kOhm: factor 180

System Layout



Threshold Comparator: Losses integrated and compared to threshold table (12 time intervals and 32 energy ranges).

Master threshold and Applied threshold

- 12 integration intervals: 40 μ s ($\approx 1/2$ turn) to 84s (32 energy intervals)
→ 1.5 Million threshold values
- Give OP team certain tuning freedom on thresholds
 - Master thresholds:
 - Maximum thresholds which can be applied
 - Safety requirement:

Master thresholds < 10 * 'damage level' for integration times ≤ 100 ms

(integration times > 100ms: also covered by QPS + cryogenic system)

- Applied thresholds = Master thresholds * monitor factor (MF)
 - $MF \leq 1$ (enforced in LHC setting database)
- MF set individually for each monitor

Typically: thresholds set in conservative way at the start-up of LHC

Families and Protection Strategy

- **Family**: monitors with the same master thresholds
 - Similar/same:
 - Elements
 - Monitor location
 - Loss scenario
 - Between 1 and 360 monitors in one family
- **Each monitor** (connected to interlock system BIS) aborts beam:
 - One of 12 integration intervals **over threshold**
 - Internal **test failed**
- **Mostly: Local protection strategy**

LHC BLM Design Specifications

- Reliable (tolerable failure rate 10^{-7} per hour per channel) $\rightarrow 10^{-3}$ magnets lost per year (assuming 100 dangerous losses per year)
- Less than 2 false dumps per month (operation efficiency)
- Fast (1 turn, $89 \mu\text{s}$) trigger generation for dump signal - protect against losses of 4 turns or more
- Quench level determination with an ultimate uncertainty of a factor 2
 - Extensive simulations and measurements
 - Threshold values are a function of loss duration and beam energy

For a complete description of the BLM system see: *Beam Loss Monitoring System for the LHC*, E.B. Holzer et al., Nuclear Science Symposium Conference Record, 2005 IEEE, Volume 2:1052 – 1056.

Automatic Report – HV Modulation Tests

- Signal response to HV modulation tests most of the BLM system chain, including monitor type
- Performed before each fill (enforced after 24 hours to allow for a new injection)
- Daily reports:

HV connectivity test between 2016-08-31 00:00:00 and 2016-09-01 00:00:00

Total number of tests: 2

No Fails from the 2 tests.

Warnings are measurement results in the top or bottom 10% of defined limits.

Chen Xu

Table 1: Warnings from 2 tests

ExpertName	HW Ch	Gn min	Gn max	Ph min	Ph max	Cable	BIS
BLMDS.9775.B2C31_8.501_DUMP	6.C.08.06	3	0	0	0	1	0