Machine Protection system: Lessons learnt from LHC

Eva Barbara Holzer, CERN

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- How to design a Machine Protection System?
- LHC Machine Protection (MP) and Beam Loss Monitoring (BLM)
- Differences to CLIC and consequences for MP?
- Summary

1) Start early to determine:

1. Damage (quench) thresholds of exposed components as a function of loss duration in the relevant physical quantity:
   - Energy (e.g. heat capacity)
   - Energy density (e.g. local damage)
   - Power (e.g. global cooling power)
   - Poser density (e.g. local cooling power)

Single shot

Continuous losses

2. Time constants of failure scenarios and destruction potential
3. Reaction time needed (or achievable) of the sub-systems
   - Failure scenarios covered by system reaction times?
   - Need of additional or redundant protection system?
   - Passive protection for fastest losses

2) Start the MP design early!

- Integration of protection system in machine layout required
  - e.g. space requirement of passive components
- MP system design will yield the technical specifications of the MP related aspects of the sub-systems:
  - Beam dump system
  - Collimators and absorbers
  - Beam interlock system
  - Beam Loss Monitoring
  - Beam Current Monitoring
  - Beam Position Monitoring
  - Power converter monitoring
  - Fast magnet current change monitor (normal conduction magnets)
  - System operational checks (kickers, RF, cryogenics, vacuum, etc.)
  - Interlocks on movable objects, beam parameters (Energy, Intensity), etc.
  - Interlocks from experiments, access system, etc.
  - …

Example: Fast magnet current change monitor

- Operational experience at HERA (DESY):
  - Infrequent events
  - Uncontrolled total loss of proton beam
  - Too fast for their beam loss measurement system
- Identified source
  - Power failure on warm magnets
- Built the fast current change monitors which measure directly at the magnet coil the voltage change
- Beam could be dumped in time to avoid uncontrolled losses around the machine
- Investigated the LHC
  - Identified the possibility of such failures at the limit of BLM quench protection capability
- Several warm magnets (D1, septa, etc.) will be equipped with such monitors

3) Make a dependability (colloquially: reliability) analysis

- It will yield allocation of “budgets” to the sub-systems

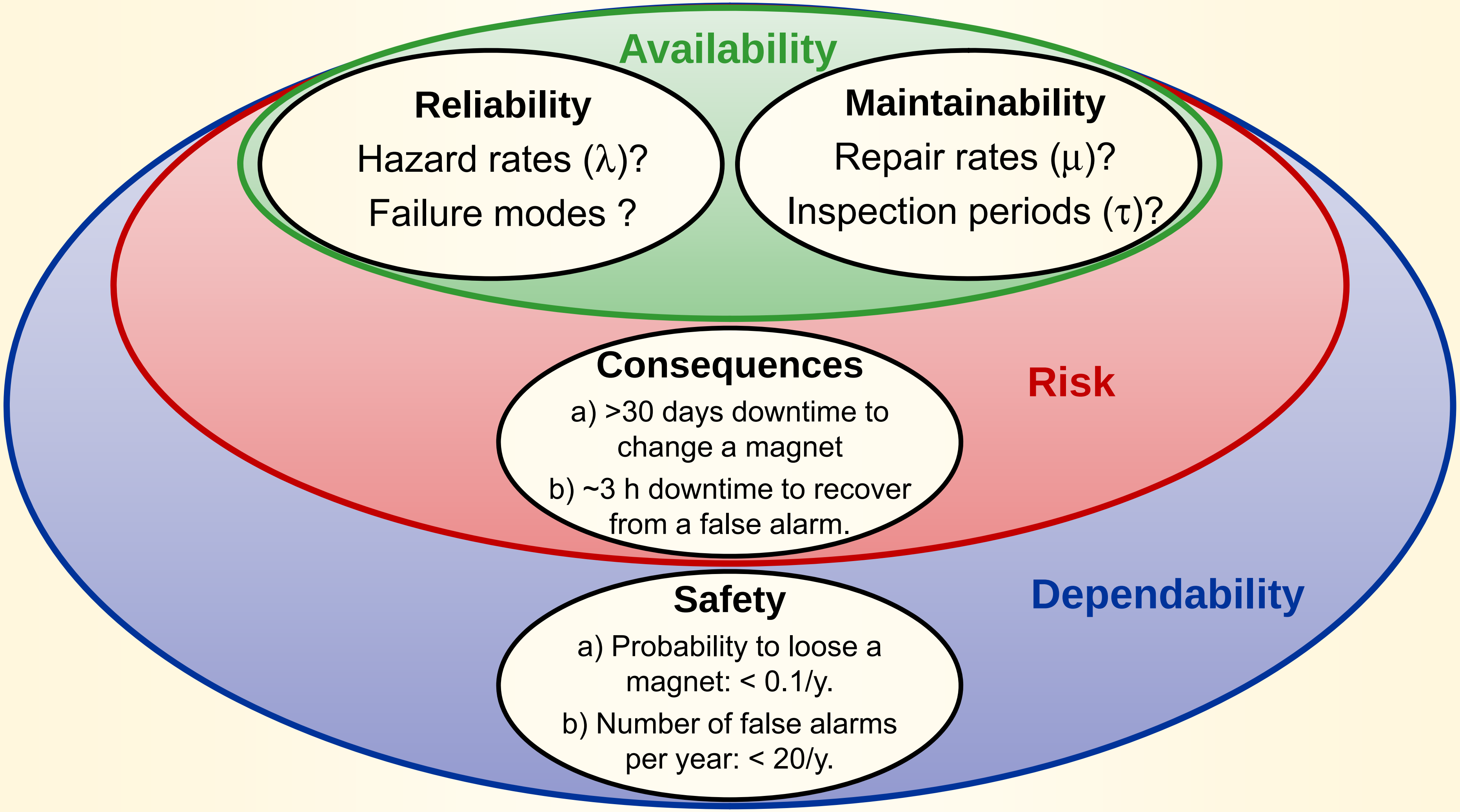
“budget”:

  - Probability of component damage due to malfunctioning
  - Downtime due to false alarms
  - Downtime due to maintenance

Inherent conflict between these budgets, e.g. added redundancy:

  - Damage probability ↓
  - False dumps ↑
  - Maintenance ↑

Dependability



Definitions I

- Reliability: probability of an element to operate under designated operating conditions up to a designated period of time. Usually indicated by R(t), where t is an interval!
- Maintainability: probability that a given active maintenance action, for an item under given conditions of use, can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources. Usually indicated by G(t), where t is an interval!

- Hazard rates of the components:

  “How often does a component fail?”
- Failure modes of the components:

  “How does a component fail?”

Definitions II

- Availability: is the probability of an element to operate under designated operating conditions at a designated time or cycle. Usually indicated by A(t), where t is an instant!
- Risk: Product of the probability to have a damage times the «cost» of the damage. The availability analysis gives the damage probability, the risk analysis gives the cost of the damage.
- Safety: the likelihood of an element to maintain throughout its life cycle an acceptable level of risk that may cause a major damage to the product or its environment. Definition very vague!
- Dependability: ensemble of reliability, availability, maintainability and safety. Also called RAMS (Reliability, Availability, Maintainability, Safety). It is a purist term. Reliability is the term improperly used to indicate “dependability”.

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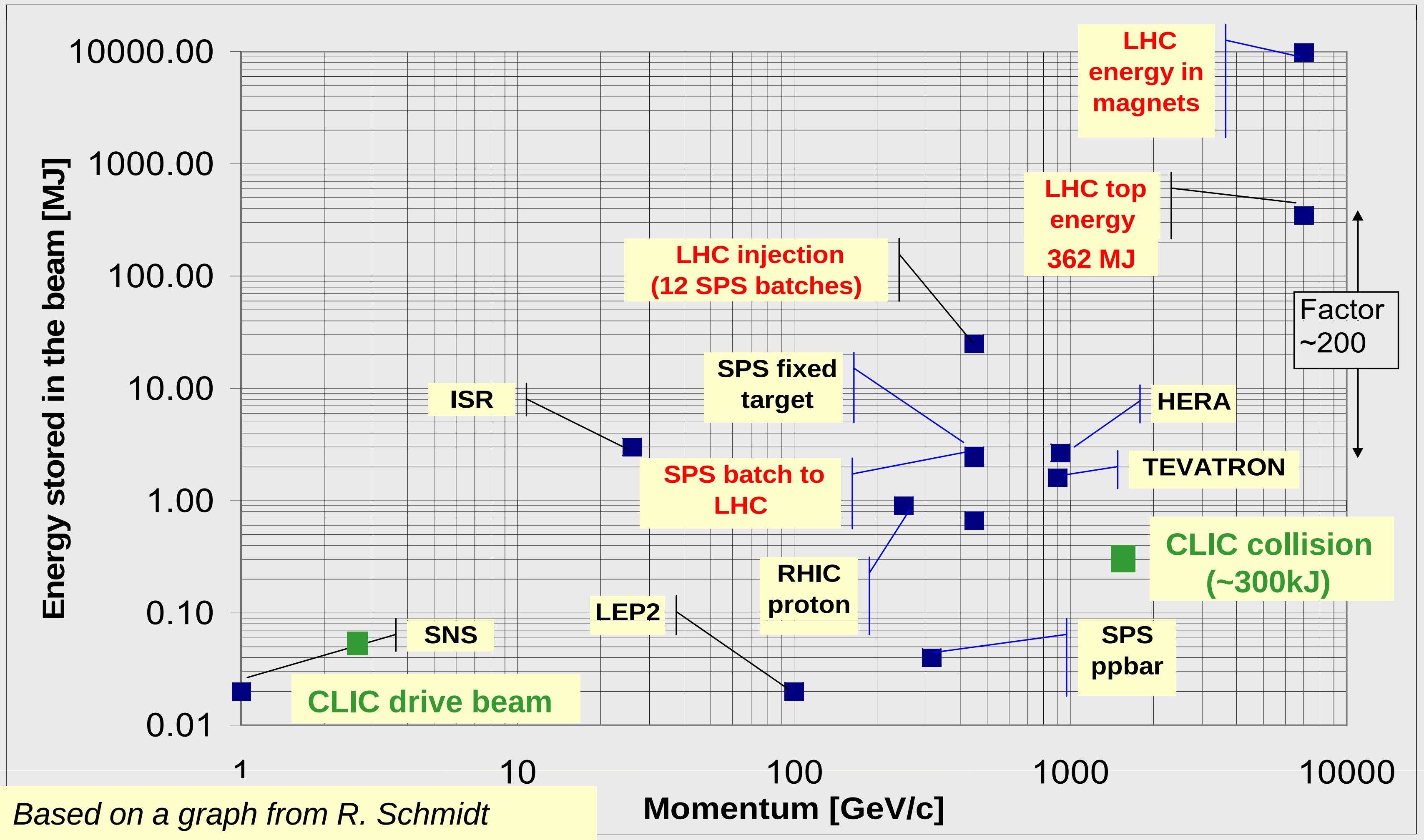
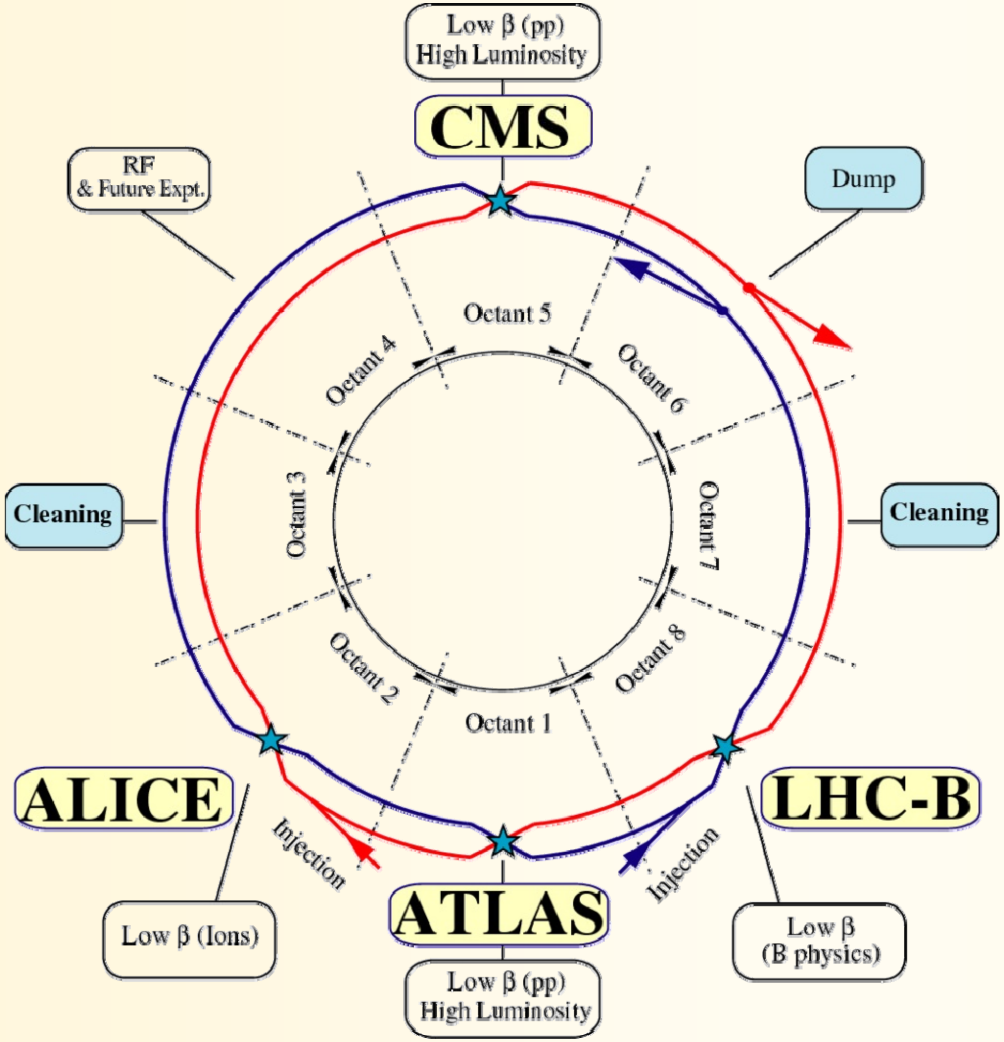
MP relevant parameters: Stored energies

- 362 MJ of energy in the each p beam (~200 times higher than existing hadron machines)
- 10 GJ of energy in the electric circuits



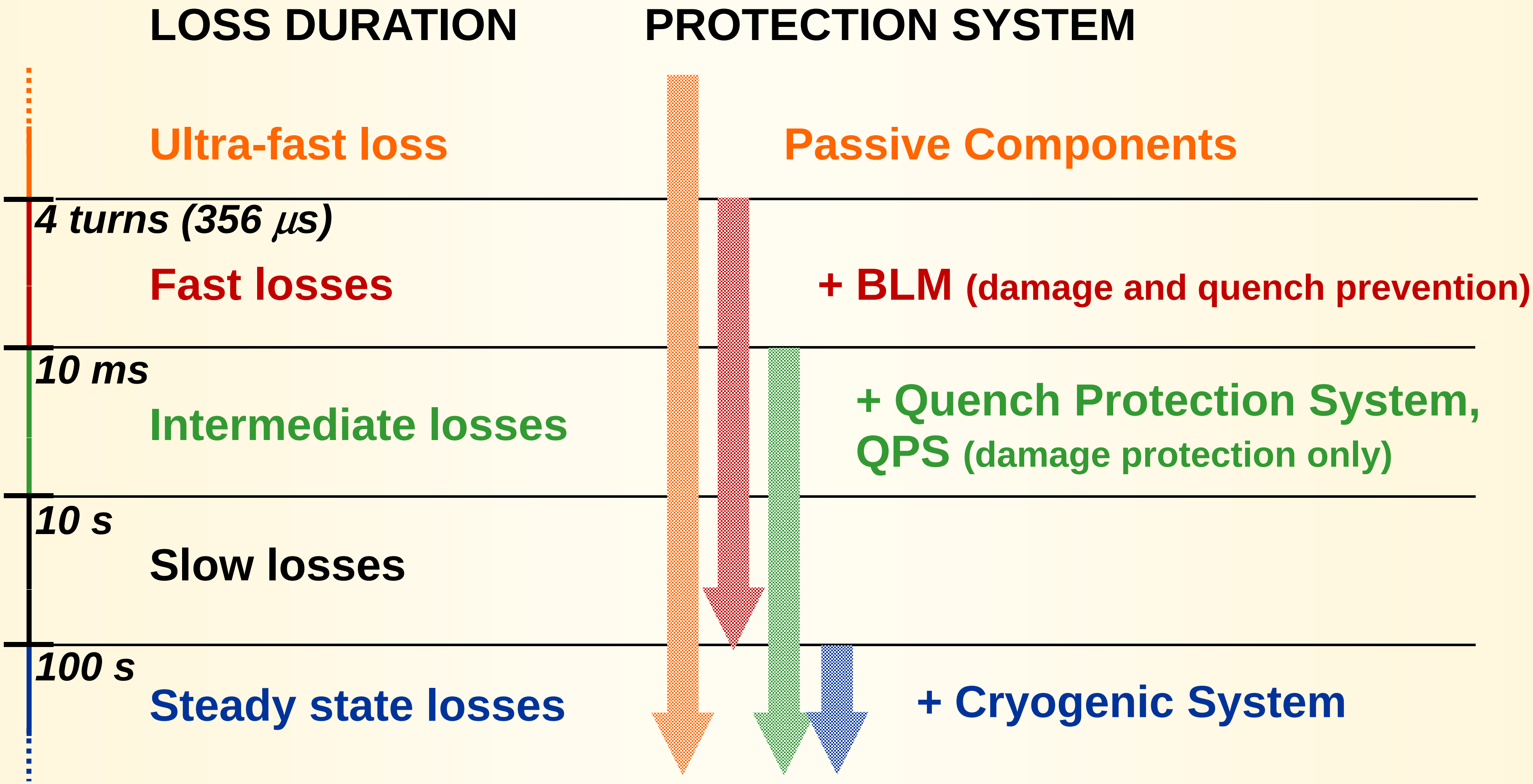
Based on a graph from R. Schmidt

Other MP relevant parameters



- Superconducting magnets:
  - ~500 main quadrupoles
  - ~1200 main dipoles
- Quench levels ~5-20 times lower than existing hadron machines
- ~130 collimators and absorbers (phase 1)
- ~320 other movable objects
- pp and PbPb

Beam loss durations classes



LOSS DURATION **PROTECTION SYSTEM**

Ultra-fast loss **Passive Components**

4 turns (356 μs)

Fast losses **+ BLM (damage and quench prevention)**

10 ms

Intermediate losses **+ Quench Protection System, QPS (damage protection only)**

10 s

Slow losses

100 s

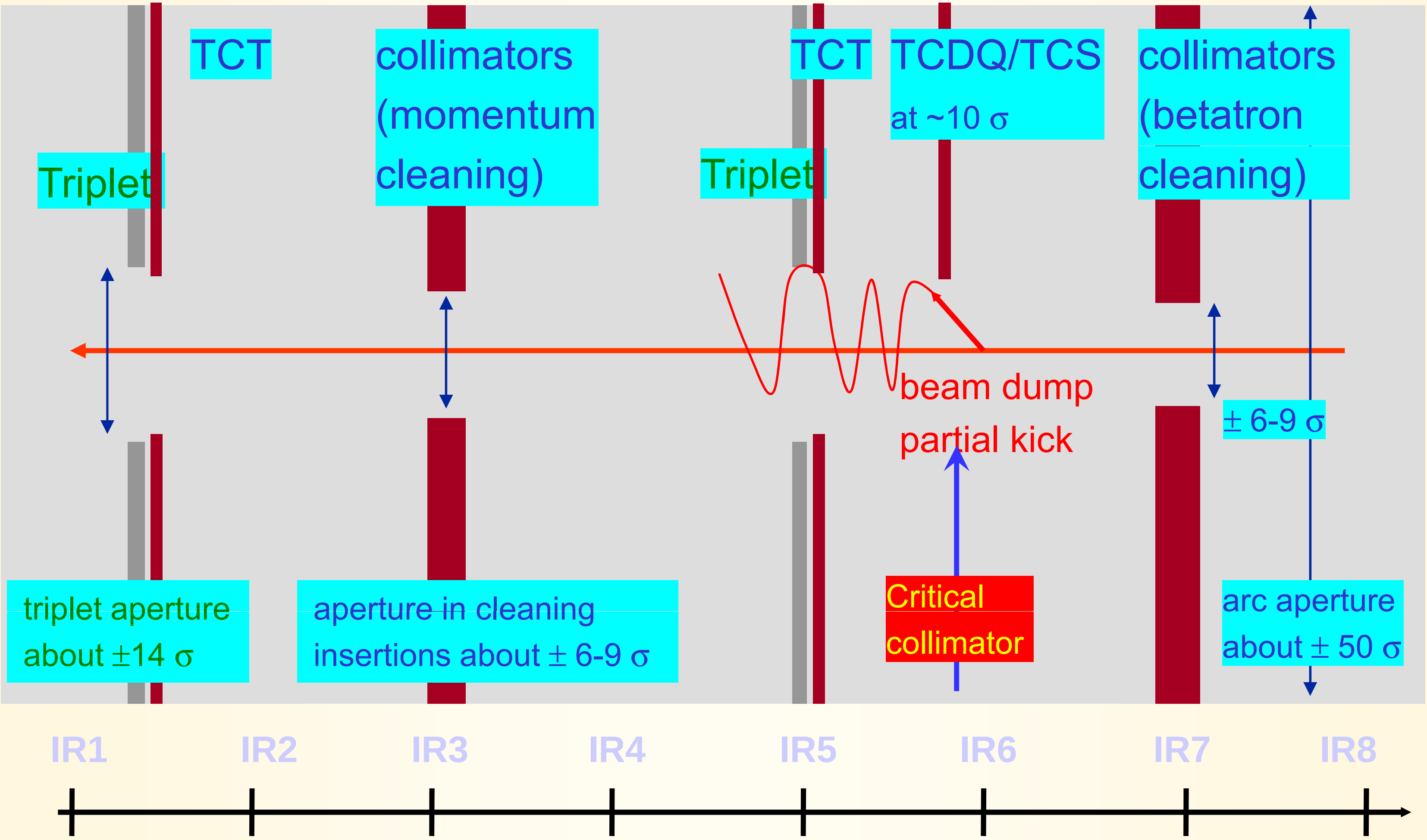
Steady state losses **+ Cryogenic System**

- The BLM is the main active system to prevent magnet damage from all the possible multi-turn beam losses.
- Prevention of quench only by BLM system

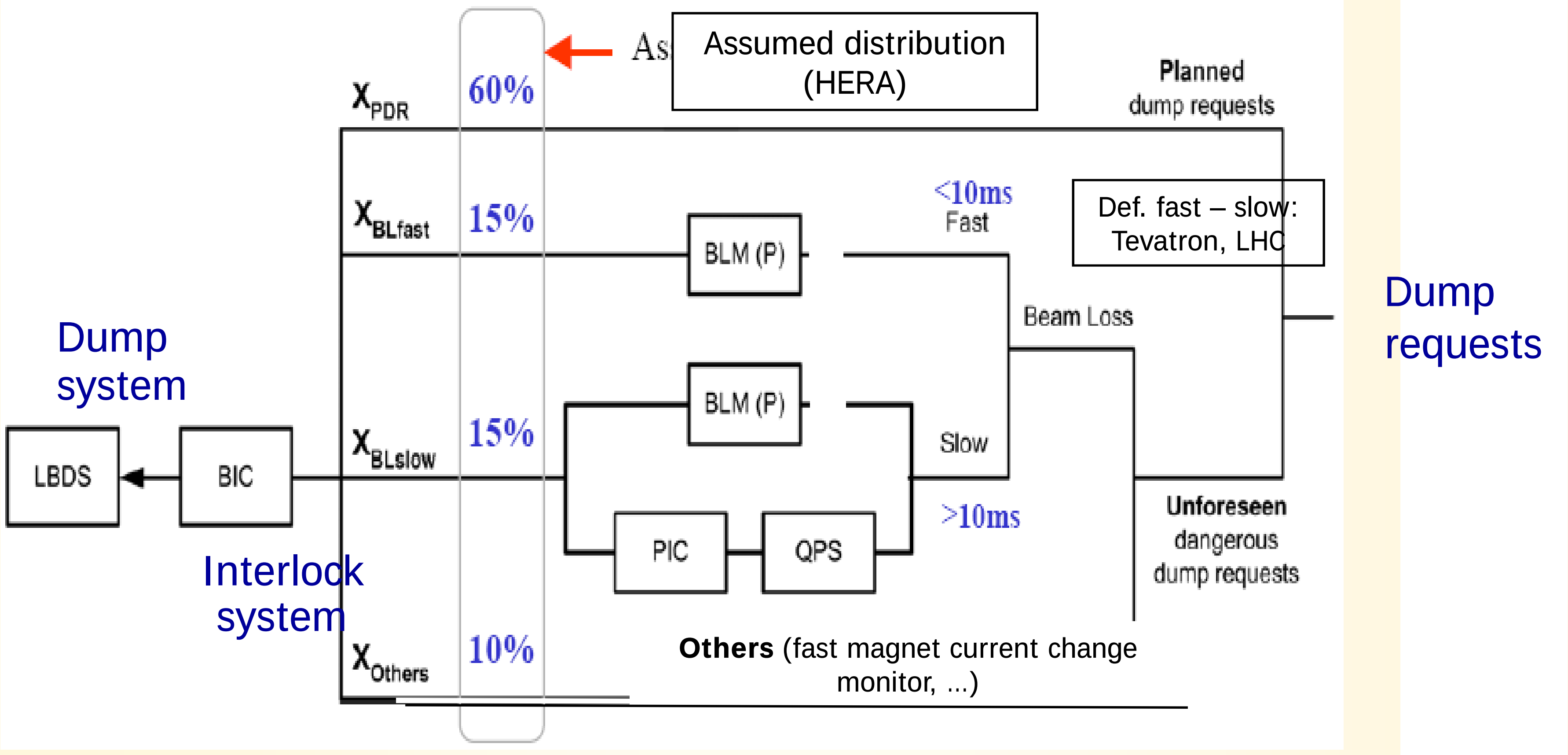
Passive Protection - Define critical aperture limits

- Critical apertures around the LHC (illustration drawing) in units of beam size σ for 7 TeV and β* = 0.55 m in IR1 and IR5

R. Schmidt



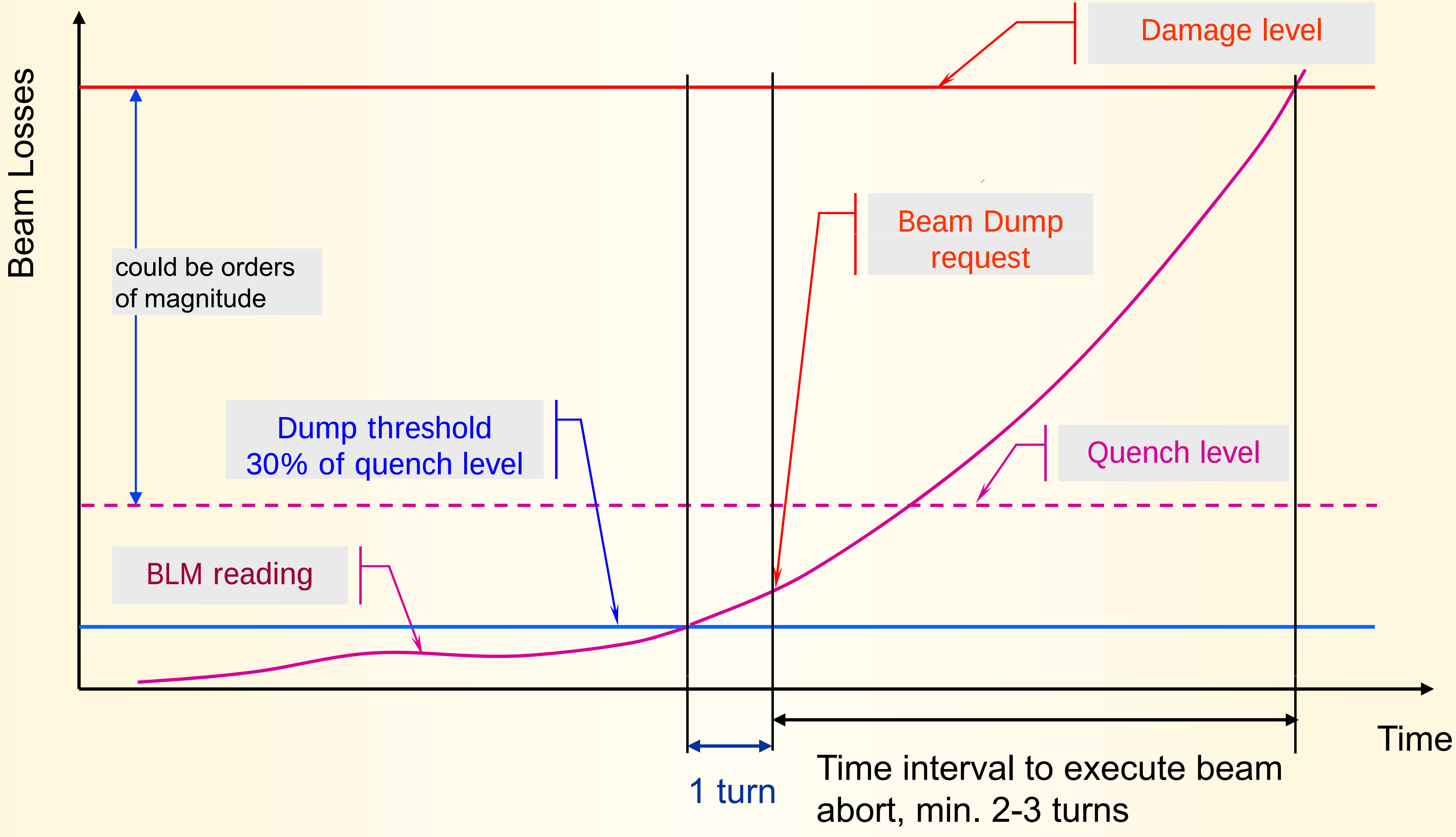
Active Protection Overview



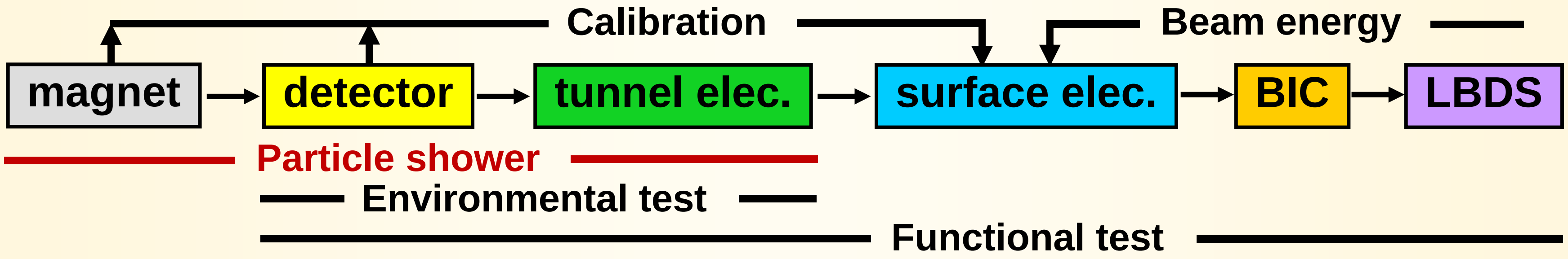
- Active protection between 0.4 and 10 ms (multi-turn losses) mainly given by BLM system
- Prevention of quench only by BLM system
- QPS system contributes to damage protection

Example: Beam Abort Sequence – Fast Beam Loss

(Based on graph from R. Schmidt)



Dependability design of BLM system



Calibration

Beam energy

magnet → detector → tunnel elec. → surface elec. → BIC → LBDS

Particle shower

Environmental test

Functional test

PhD thesis (*G. Guaglio, Reliability of the Beam Loss Monitors System for the Large Hadron Collider at CERN, PhDThesis, Universit´e Clermont Ferrand II - Blaise Pascal, 2005.)*

Fail safe design: *"The most probable failure of the component does not generate the worst consequence (= risk to damage a magnet)."*

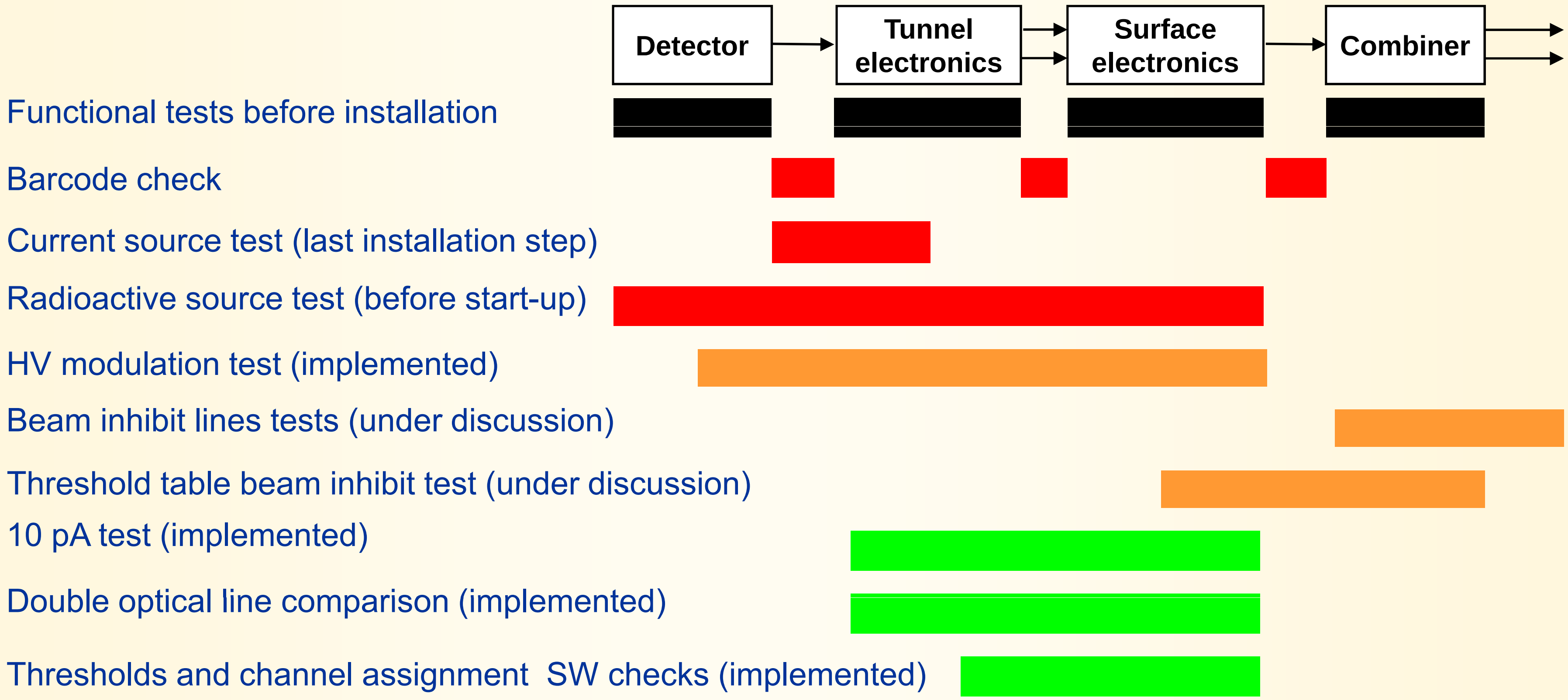
1. Choice of reliable and radiation tolerant components
   - environmental tests of tunnel electronics:

Temperature	15 – 50 degree
Dose & single event	no single event effects observed during tests, dose corresponding to 20 years of operation

2. Redundancy and voting (when single components are not reliable enough)
3. Constant monitoring of availability and drift of readout channels (Functional Tests)

Functional Tests

PhD thesis G. Guaglio



Detector → Tunnel electronics → Surface electronics → Combiner →

Functional tests before installation

Barcode check

Current source test (last installation step)

Radioactive source test (before start-up)

HV modulation test (implemented)

Beam inhibit lines tests (under discussion)

Threshold table beam inhibit test (under discussion)

10 pA test (implemented)

Double optical line comparison (implemented)

Thresholds and channel assignment SW checks (implemented)

Inspection frequency:

⬛ Reception 🟥 Installation and yearly maintenance 🟧 Before (each) fill 🟩 Parallel with beam

BLM Dependability Calculation Results

PhD thesis G. Guaglio

	Per year	Weakest components	Notes
Damage Risk	$5\cdot10^{-4}$ (100 dangerous losses)	Detector (88%) Analogue electronics (11%)	Detector likely overestimated (no failure in ~20 years SPS), all other components checked constantly
False Alarm	13 ± 4	Tunnel power supplies (57%) VME fans (28%)	Tunnel power supplies likely underestimated
Warning	35 ± 6	Optical line (98%) VME PS (1%)	LASER hazard rate likely overestimated (conservative data)

- Assuming 100 dangerous losses per year (detectably by only one BLM channel) this corresponds to the required SIL3 (Safety Integrity Level) - 1 magnet lost in 20 years due to BLM failure
- False alarm / year < 20 required
- Warning: safe to keep running, but repair ASAP

LHC Dependability Calculation Results

System	Damage Risk / year	False dumps/y Average Std.D.
LBDS	1.8×10^{-7}(2x)	3.4(2x) +/-1.8
BIC	1.4×10^{-8}	0.5 +/-0.5
BLM	1.44×10^{-3} (BLM_1)	17 +/-4.0
	0.06×10^{-3} (BLM_2)	
PIC	0.5×10^{-3}	1.5 +/-1.2
QPS	0.4×10^{-3}	15.8 +/-3.9
Overall results		
MPS	2.3×10^{-4}	41.6 +/-6.2

- Results depend on assumed LHC dump requests distribution (slide 15), operational details, system redundancies etc. (Damage risk and errors do not sum up)
    - Slightly different numbers than on previous slide due to different model assumptions
    - Still corresponds to SIL3 for damage risk

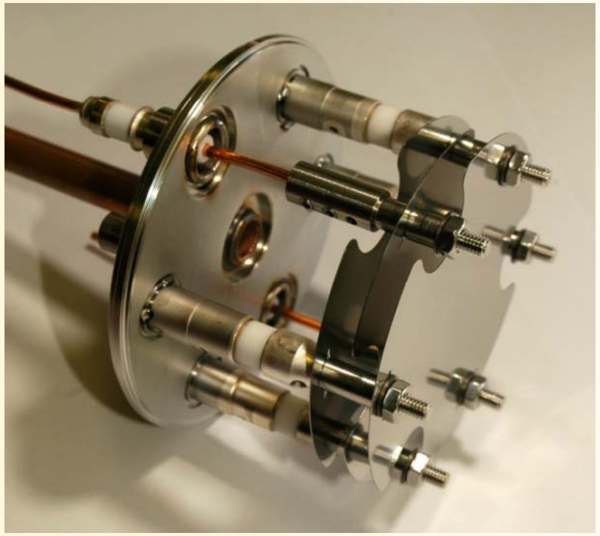
R. Filippini et al., Reliability Assessment of the LHC Machine Protection system, PAC 2005.

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).

Secondary Emission Monitor:

- Length 10 cm
- $P < 10^{-7}$ bar
- ~ 30000 times smaller gain

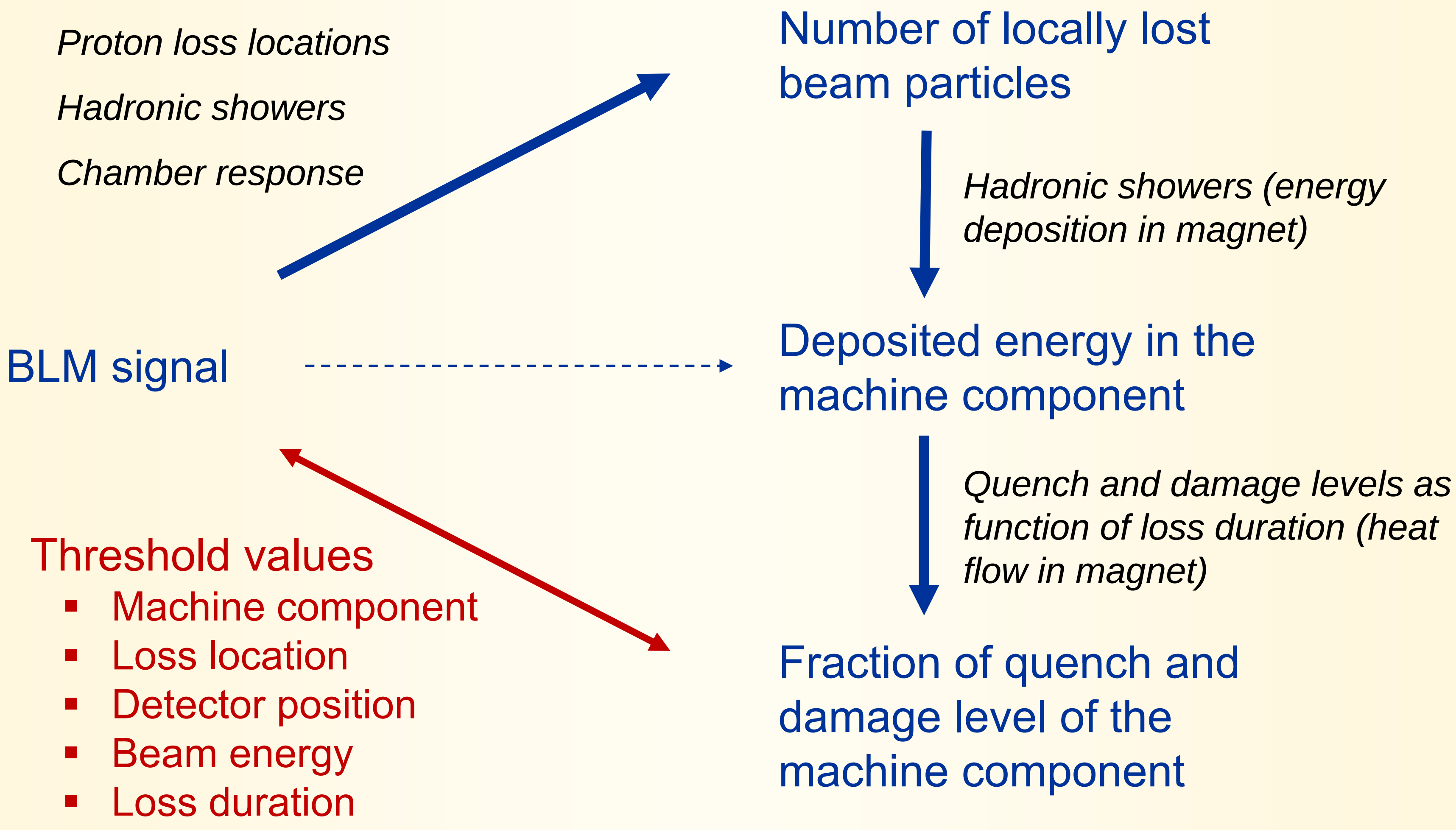


Ionization chamber:

- N_2 gas filling at 100 mbar over-pressure
- Length 50 cm
- Sensitive volume 1.5 l
- Ion collection time 85 μs

- Both monitors:
  - Parallel electrodes (Al, SEM: Ti) separated by 0.5 cm
  - Low pass filter at the HV input
  - Voltage 1.5 kV

Calibration / Threshold determination



Proton loss locations

Hadronic showers

Chamber response

Number of locally lost beam particles

Hadronic showers (energy deposition in magnet)

BLM signal

Deposited energy in the machine component

Quench and damage levels as function of loss duration (heat flow in magnet)

Threshold values
- Machine component
- Loss location
- Detector position
- Beam energy
- Loss duration

Fraction of quench and damage level of the machine component

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Differences to CLIC and consequences for MP?

- Total beam energy ~ 10^4 lower
- No superconducting magnets
  - Higher damage levels
  - No quench risk
- Damage might come more abrupt
  - No “pre-warning” from quenches
  - Smaller beam sizes (from 0 to 100% in small distance)
- MP systems need to inhibit next injection → MP system reaction time of 20ms needed
- Possibility to dump the beam during a shot? → reaction time?
- Dynamic range required for BLMs? Given by the range from pilot beam to full intensity. Adjust so that:
  - Pilot beam (or low intensity) and no losses observable → extrapolation to full intensity → safely below damage limit; or
  - Pilot → intermediate; intermediate → full intensity
- Very different background radiation composition; synchrotron light

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Summary

1. Start designing the MP system before designing the sub-systems:
    1. Analyze damage levels of components and the destruction potential of the beam
    2. Analyze reaction times required and achievable
    3. Specify MP relevant sub-systems
    4. Integrate protection system in machine layout

2. Calculate:
    1. Damage probability
    2. Downtime due to false alarms
    3. Downtime due to maintenance

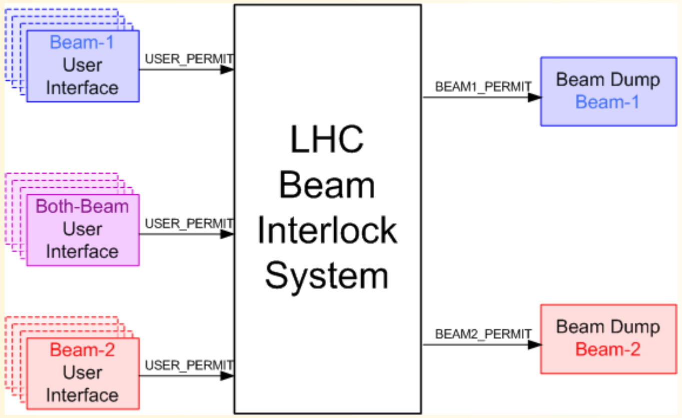
SOME MORE SLIDES

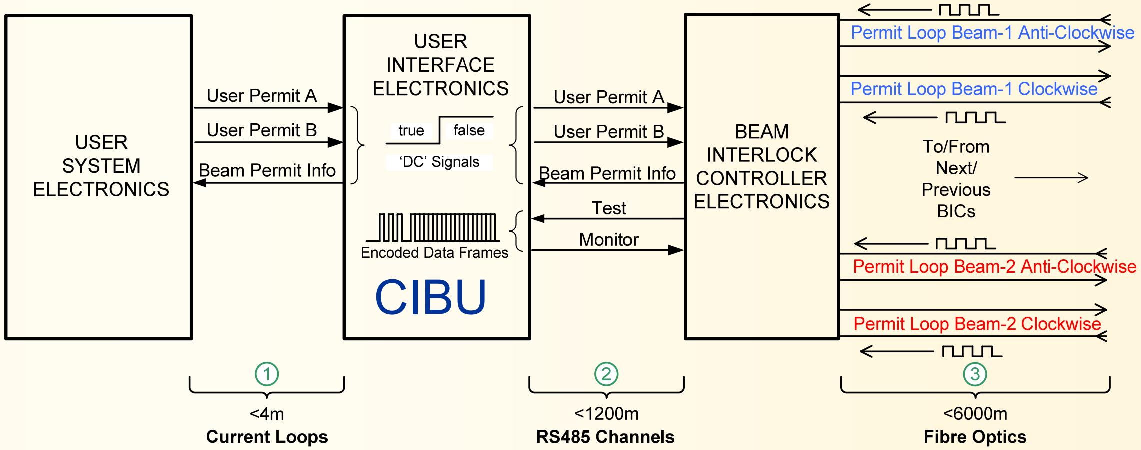
BLM System Challenges

- Reliable (tolerable failure rate 10^{-7} per hour per channel) → 10^{-3} magnets lost per year (assuming 100 dangerous losses per year)
  - Reliable components, radiation tolerant electronics
  - Redundancy, voting
  - Monitoring of availability and drift of channels
- Less than 2 false dumps per month (operation efficiency)
- High dynamic range (10^8, 10^{13} – two monitor types at the same location)
- Fast (1 turn, 89 μs) trigger generation for dump signal - protect against losses of 4 turns or more
- Quench level determination with an uncertainty of a factor 2
  - Calibration
  - Dynamically changing threshold values

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.

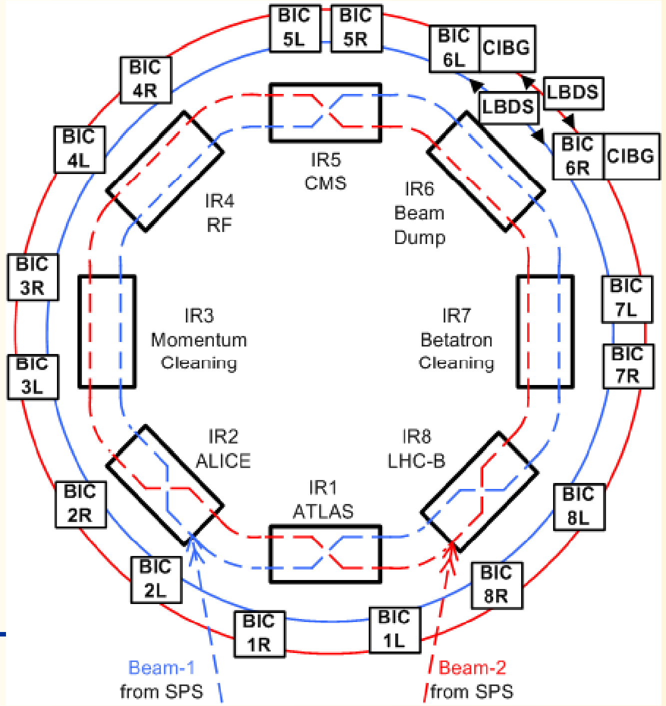
The BIS Architecture





Three ring-type systems:
- LHC Beam 1 & Beam 2
- SPS

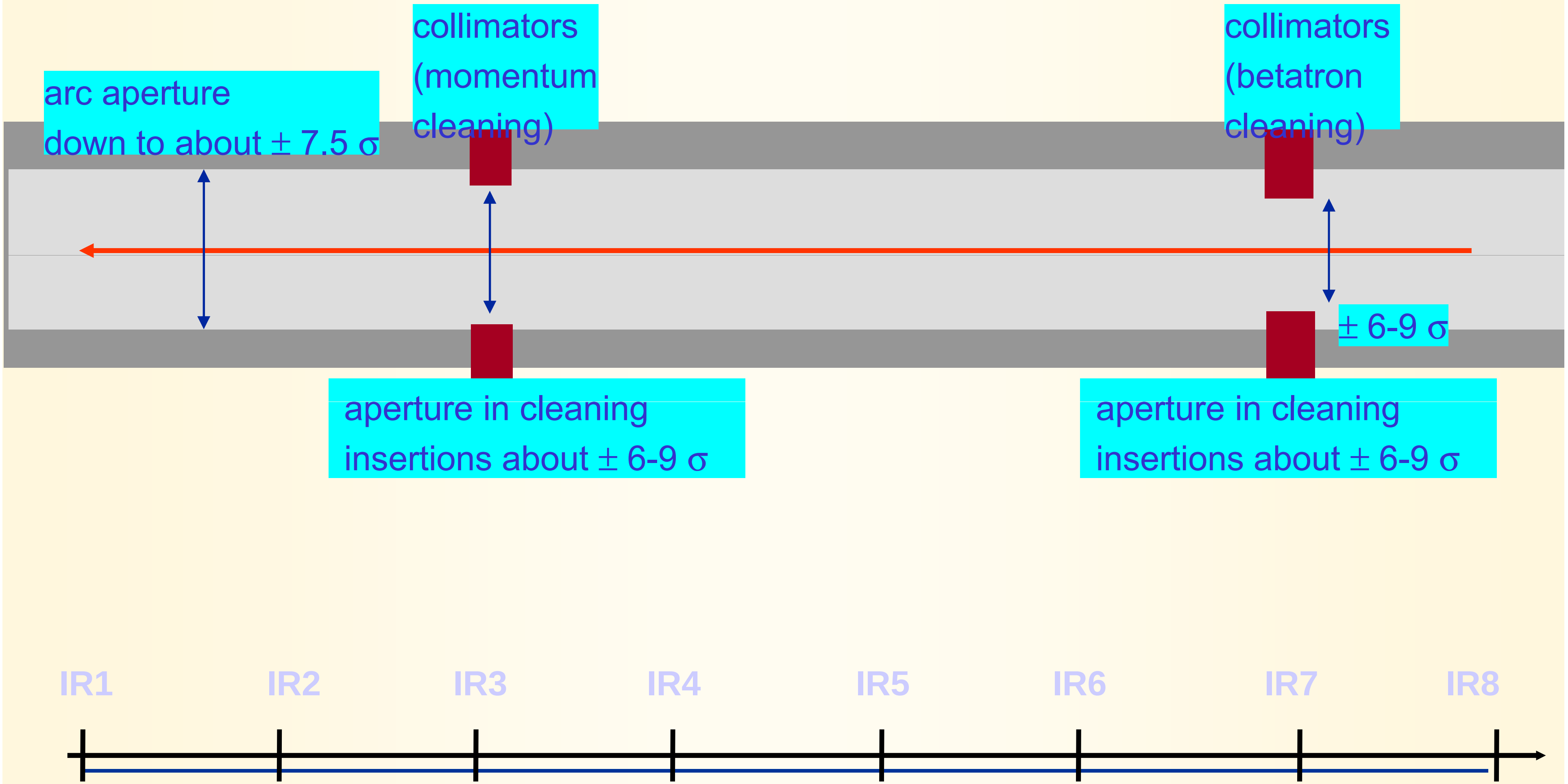
Four tree-type systems:
- LHC injection (Beam 1 & 2)
- SPS extraction (BA4 & BA6)



Critical apertures around the LHC

(illustration drawing)

in units of beam size σ at 450 TeV



arc aperture
down to about ± 7.5 σ

collimators
(momentum
cleaning)

collimators
(betatron
cleaning)

± 6-9 σ

aperture in cleaning
insertions about ± 6-9 σ

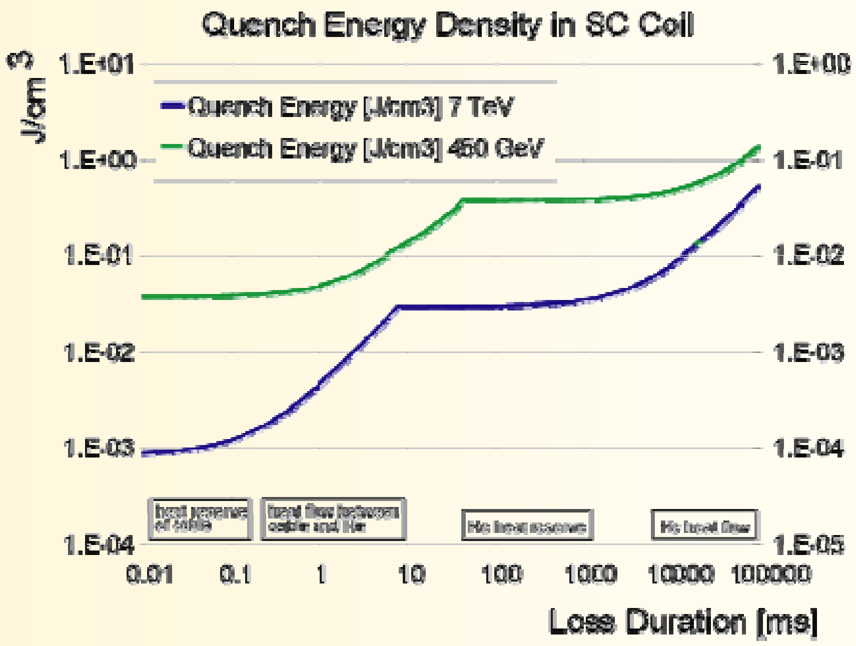
aperture in cleaning
insertions about ± 6-9 σ

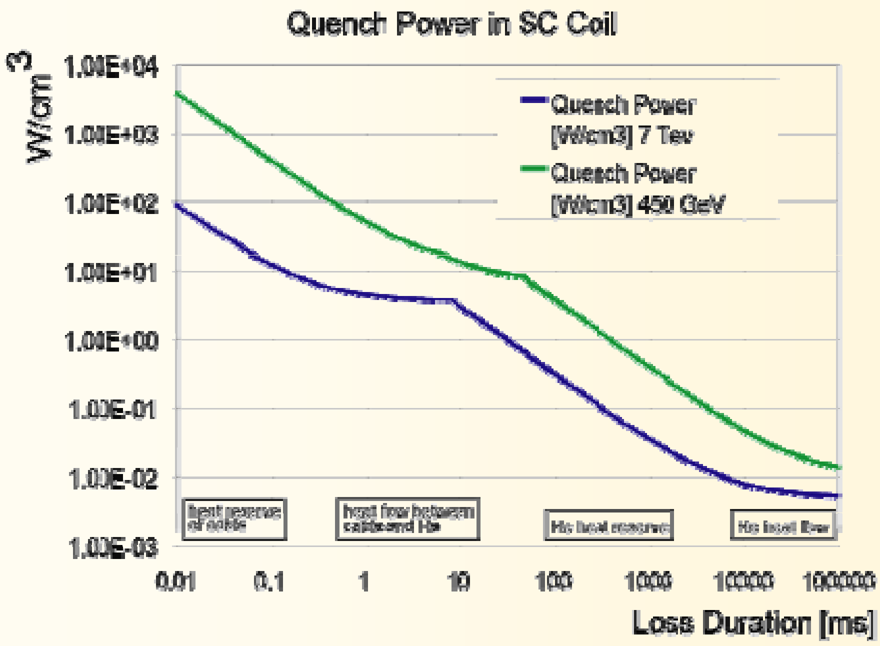
Families of BLM's

Number	*Locations*	*Main Purpose*	*Maskable (Dynamic Range)*
~3000	Arc quadrupoles (6 per magnet)	Protection of superconducting magnets	Yes (10^8)
~400	Critical aperture limits or critical positions	Machine protection and diagnostics of losses	No (10^8 or 10^{13})
~150	Collimators and absorbers	Set-up the collimators and monitor their performance	No (10^{13})
Movable (up to ~170)	Any location possible (~1300 channels)	Studies, cover unforeseen loss locations	As needed

- Maskable: Beam abort signal can be ignored, when the stored energy in the beam is below the damage limit
- All non-maskable monitors have to be available before injection

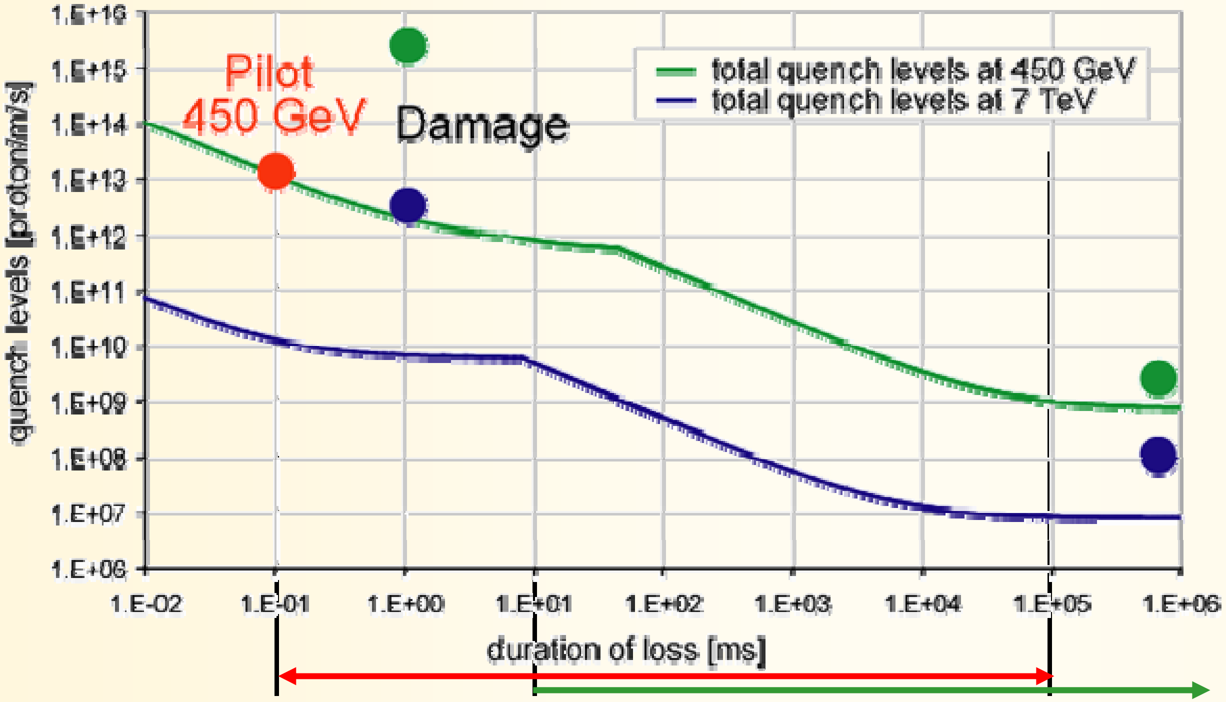
LHC Bending Magnet Quench Levels





LHC Project Report 44

Damage and Quench Levels



BLM system (damage and quench protection)

Quench protection system (damage protection)

Relative loss levels for ***fast*** **/** ***slow*** *losses*		
	450 GeV	7 TeV
Damage level	**320** **5 (?)**	**1000** **25**
Quench level	**1** **1**	**1** **1**
Dump threshold	**0.3** **0.3**	**0.3** **0.4**

- Ratio damage to quench:
  - Fast losses: large ⇒ abort of beam at quench level ensures safety for damage
  - Slow losses: small ⇒ two systems detect losses *(new estimates needed for damage levels!)*
- Pilot bunch at:
  - 450 GeV: on quench limit (assuming losses distributed over 5 m)
  - 7 TeV: 50 times the damage limit (assuming losses distributed over 5 m)

Other Beam Loss Scenarios

- Movable object (~450) other than primary collimator touches beam
- Beam orbit moves into aperture (outside collimator sections)
- Secondary or tertiary collimator becomes primary collimator
- …

  → *Some of them can be very fast!*

- Damage level reached within less than 10 turns after the beam abort signal
  - Injection and extraction kickers (too fast for BLM)
  - Aperture kickers (too fast for BLM)
  - Some warm magnets (D1 and few others)
    - Fast magnet current change monitor (DESY and CERN development)
    - BLM can prevent damage
  - General power failure
    - Also covered by the concerned fast magnet current monitors
  - Others?

Calibration - Threshold Determination

- Detection of shower particles outside the cryostat to determine the coil temperature increase due to particle losses
    - comparison BLM signal with threshold → beam dump if exceeded
- Beam dump threshold set to 30% of the magnet quench level
- Specification:

Absolute precision (calibration)	factor 2 (final) factor 5 (initial)
Relative precision for quench prevention	< 25%

- Calibration of Thresholds:
    - Before start-up:
        - Based on simulations
        - Cross-checked by measurements when possible
    - After start-up, in case of too many false beam aborts or magnet quenches:
        - Analysis of logging and post mortem data
        - Beam quench tests might be necessary to reach the required precision
- 4000 monitors * 32 energy intervals * 11 time intervals = $1.4 * 10^6$ threshold values!

Calibration Steps II

- Complex simulations and measurements - effort of many people over the last ~ 8 years!
    - Proton loss locations
        - MAD-X, SIXTRACK, BeamLossPattern
        - measurements: LHC beam
    - Hadronic showers through magnets
        - GEANT
        - measurements: HERA/DESY, LHC beam
    - Magnet quench levels as function of proton energy and loss duration
        - SPQR
        - measurements: Laboratory, LHC beam
    - Chamber response to the mixed radiation field in the tail of the hadronic shower
        - GEANT, GARFIELD
        - measurements: booster, SPS, H6, HERA/DESY

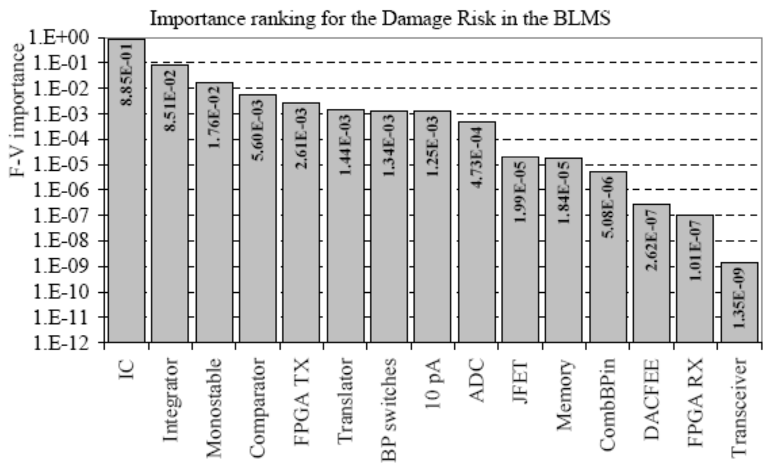


Figure 4.12: Relative importance of the event for the Damage Risk expositio

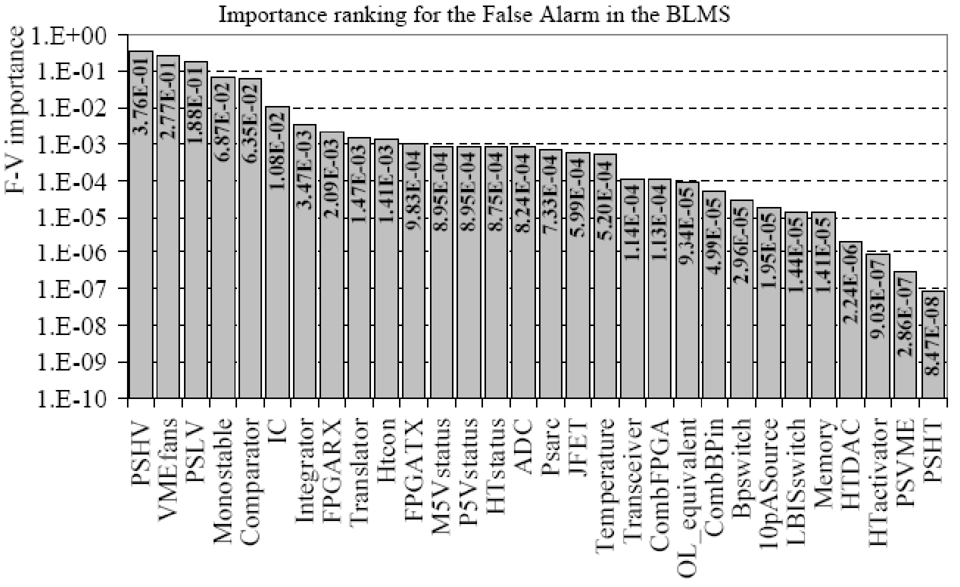


Figure 4.14: Fussell-Vesely importance for the False Alarm generation in the BLMS. Note the logarithmic scale.