LHC Machine Protection

B. Dehning

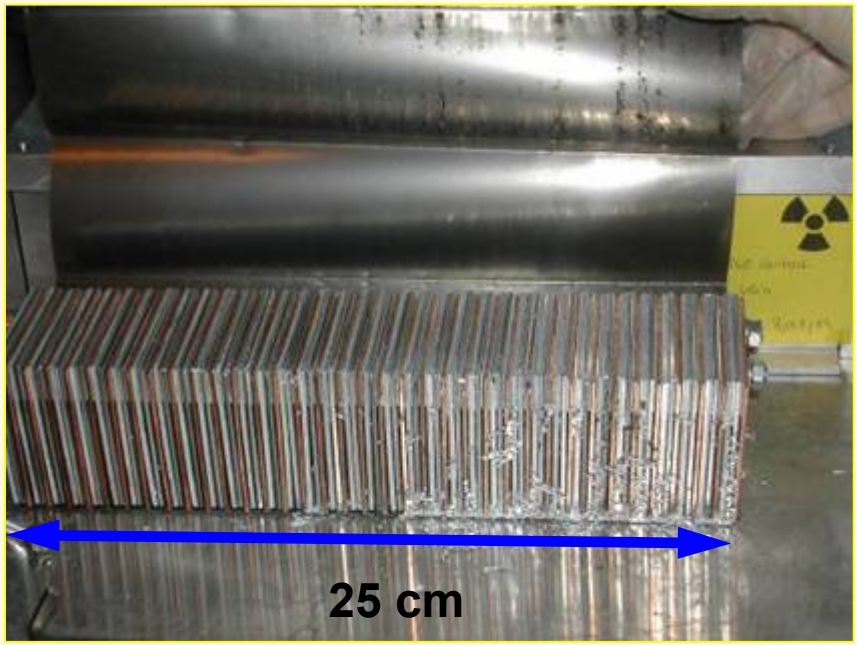
CERN AB/BI

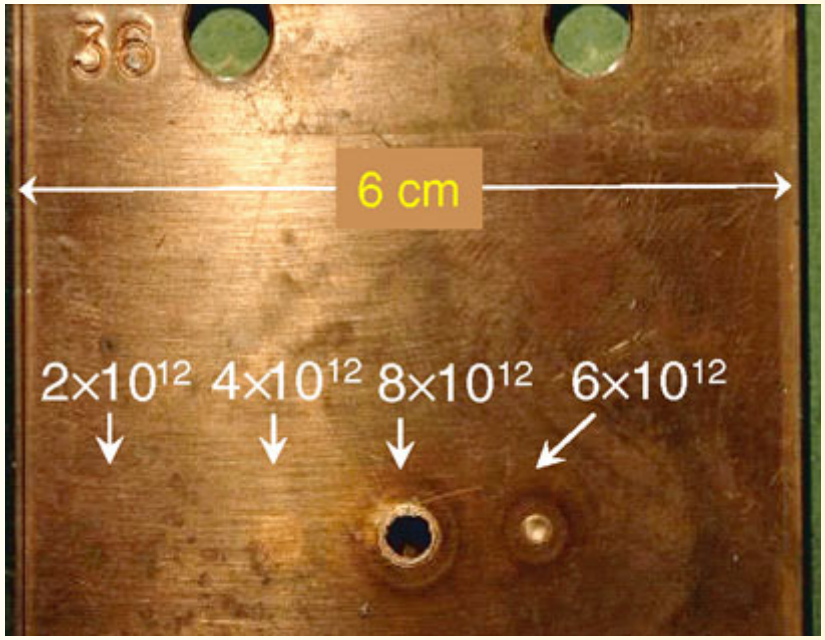
Contend

- Damage, Quench, Risk
- Protection Strategy
- Collimators
- Design approach
- Particularities of Superconducting Magnets
- Beam loss measurement System
- System settings and database
- Survey and tests
- Calculation and Simulation of damage risk and false dump

Material Damage Experiment at the SPS

V.Kain et al.



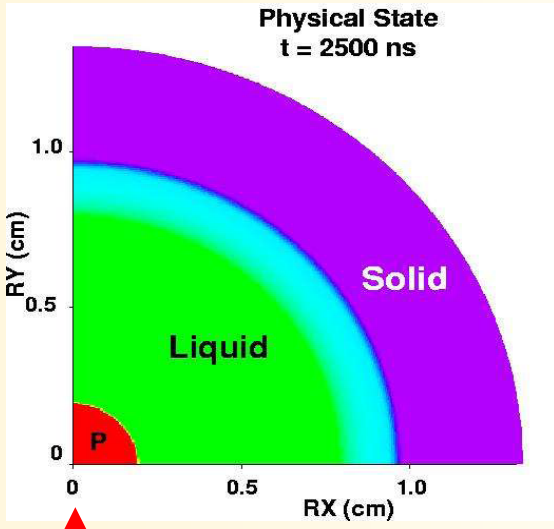


- Proton beam, 450 GeV, Cu, Fe sandwich target
- beam size $\sigma_{x/y}$ = 1.1mm/0.6mm
- $2 \cdot 10^{12}$ no damage
- $8 \cdot 10^{12}$ damage

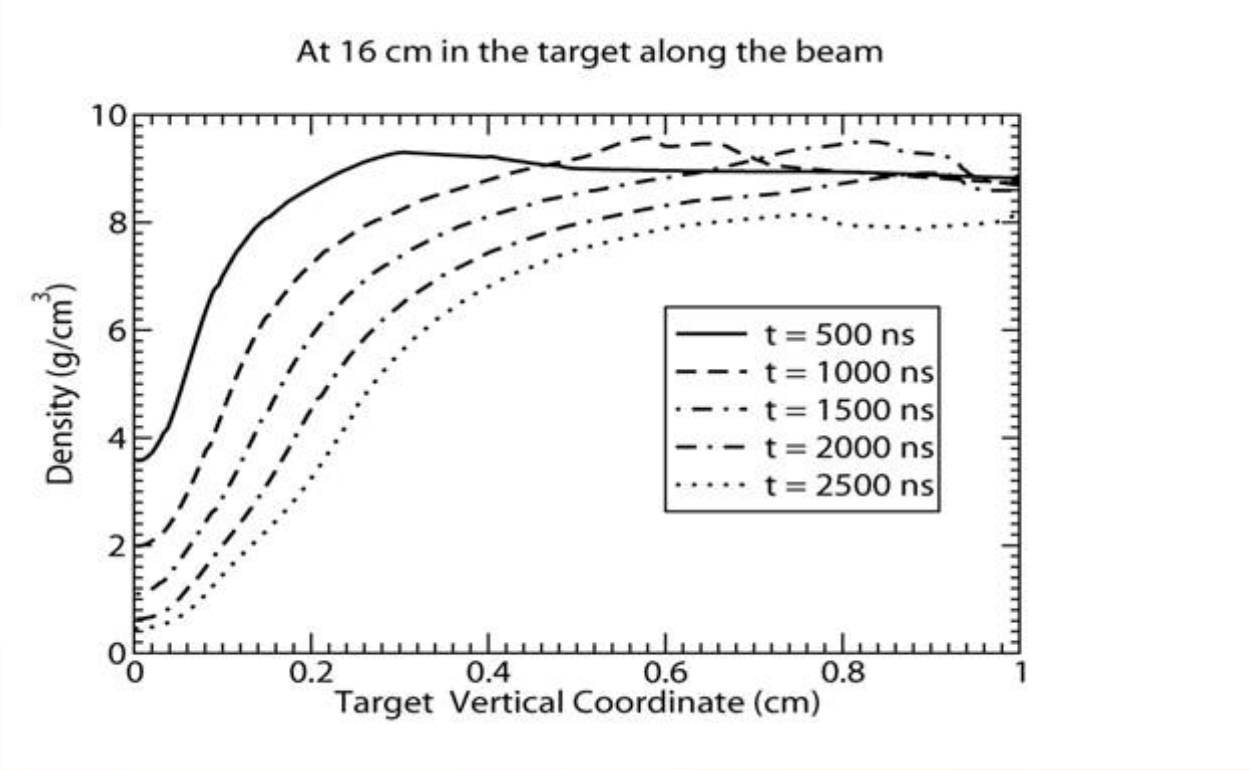
Safe at 0.6 % of full LHC intensity

Density Change in Target after Impact of 100 Bunches

Cross sectional view



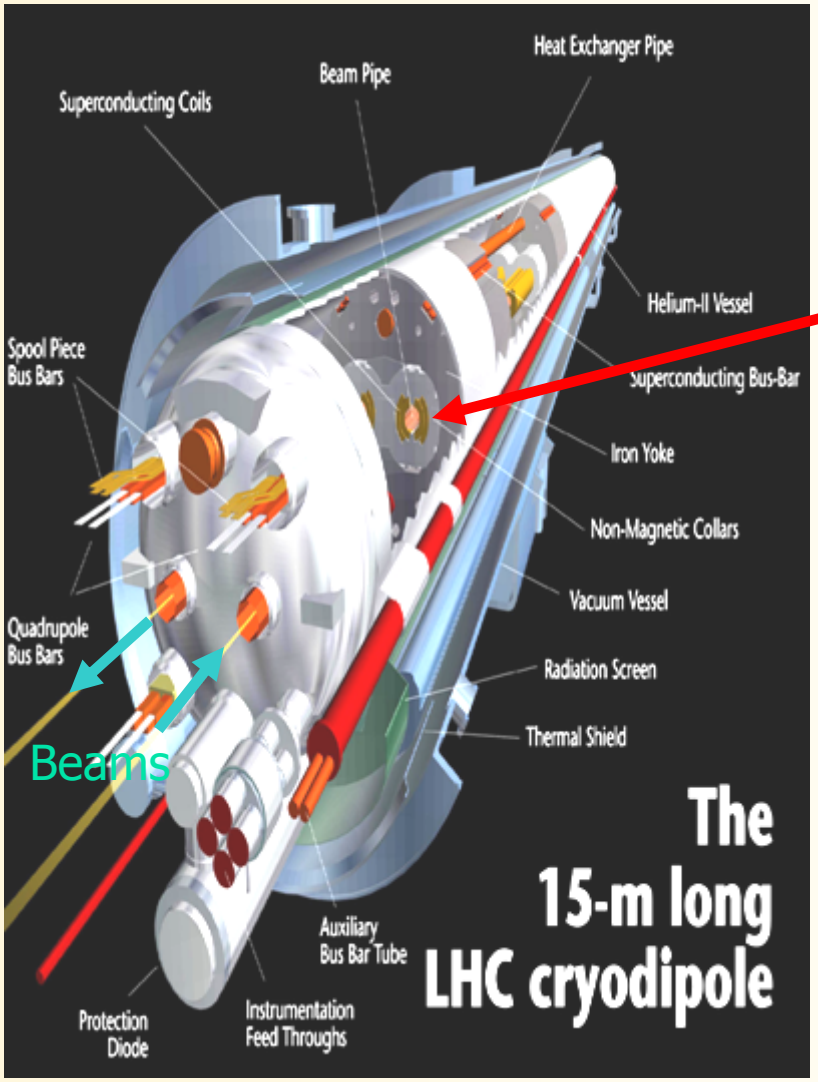
beam impact



2 dimensional hydrodynamic computer code, N.A. Tahir et al.

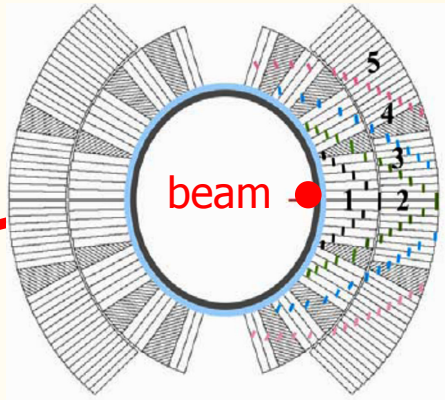
Reduction of density by a factor 10

Magnet Quenches



cross sectional view of coil

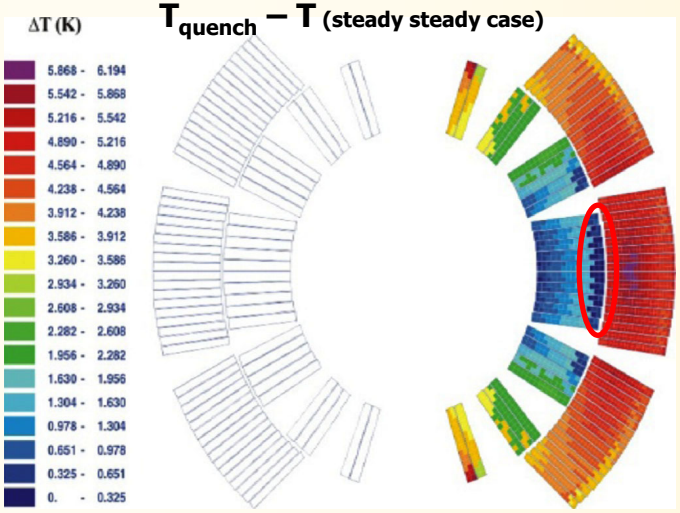
D. Bocian et al.



Energy deposition by the beam

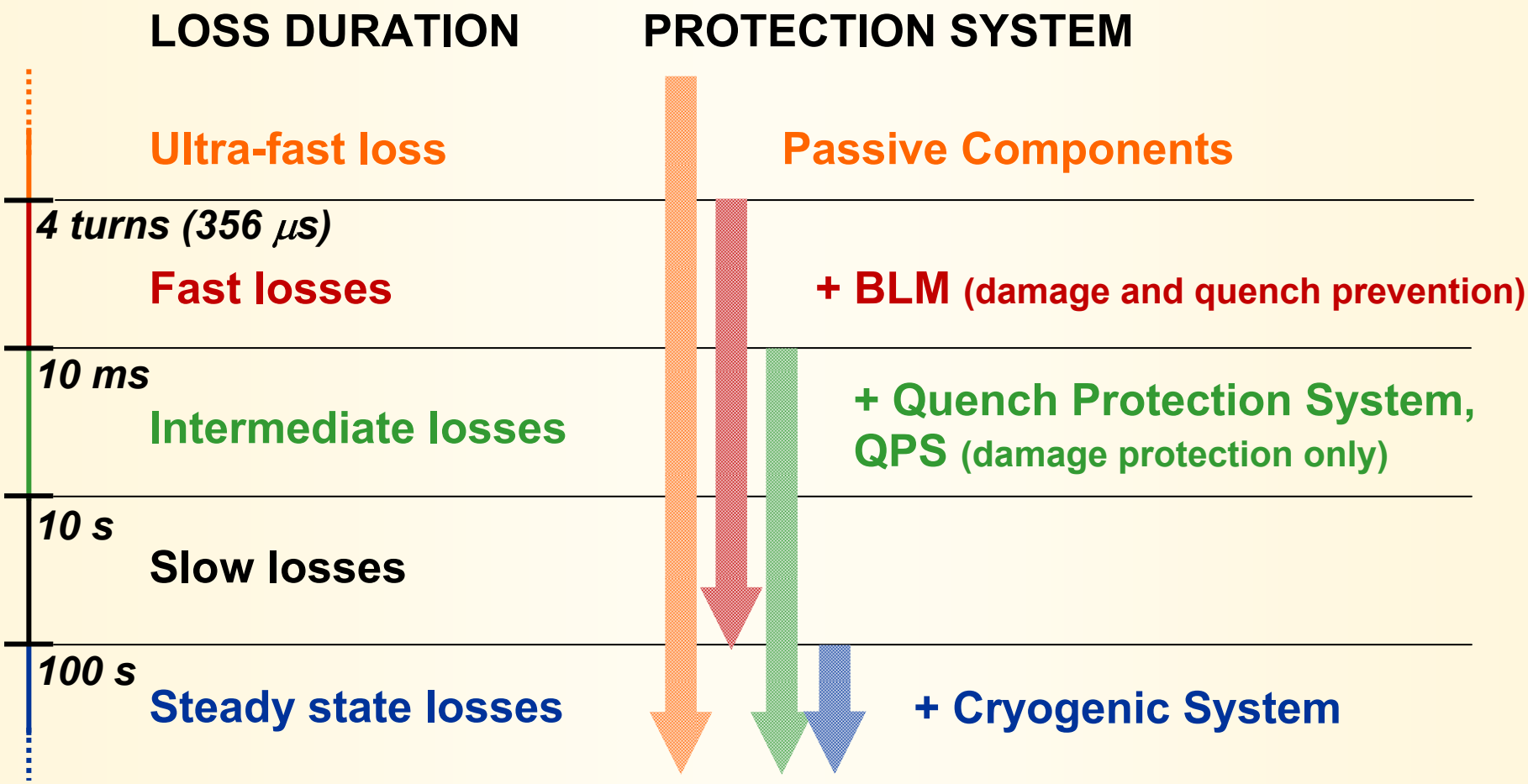
Temperature difference

$T_{quench} - T$ (steady steady case)



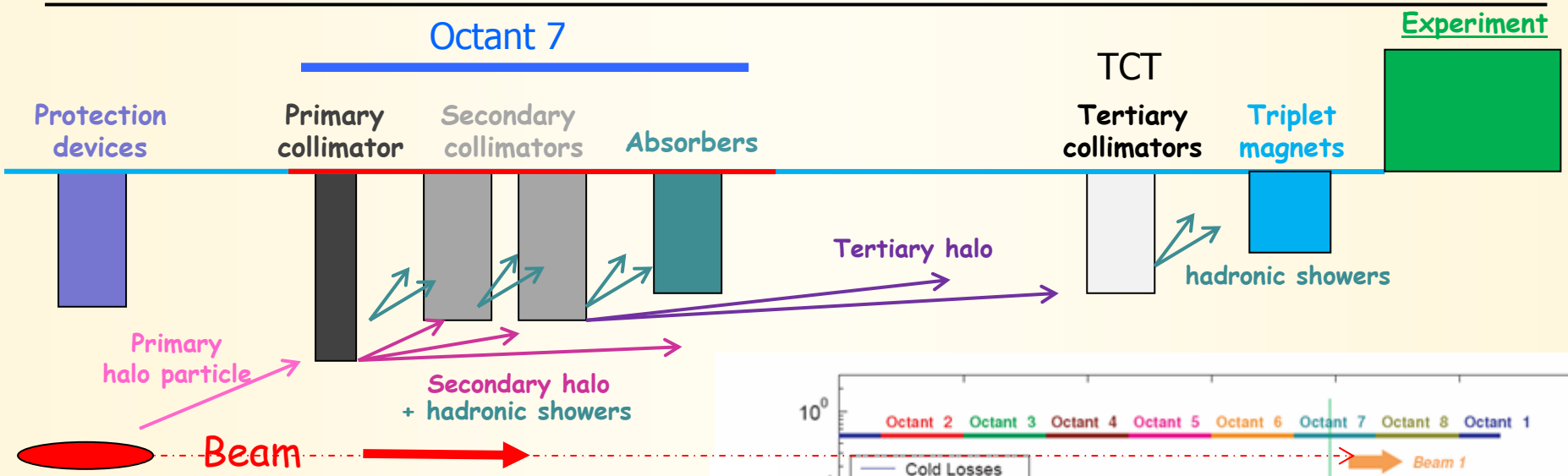
Location of QUENCH

Beam Loss Durations and Protection Systems

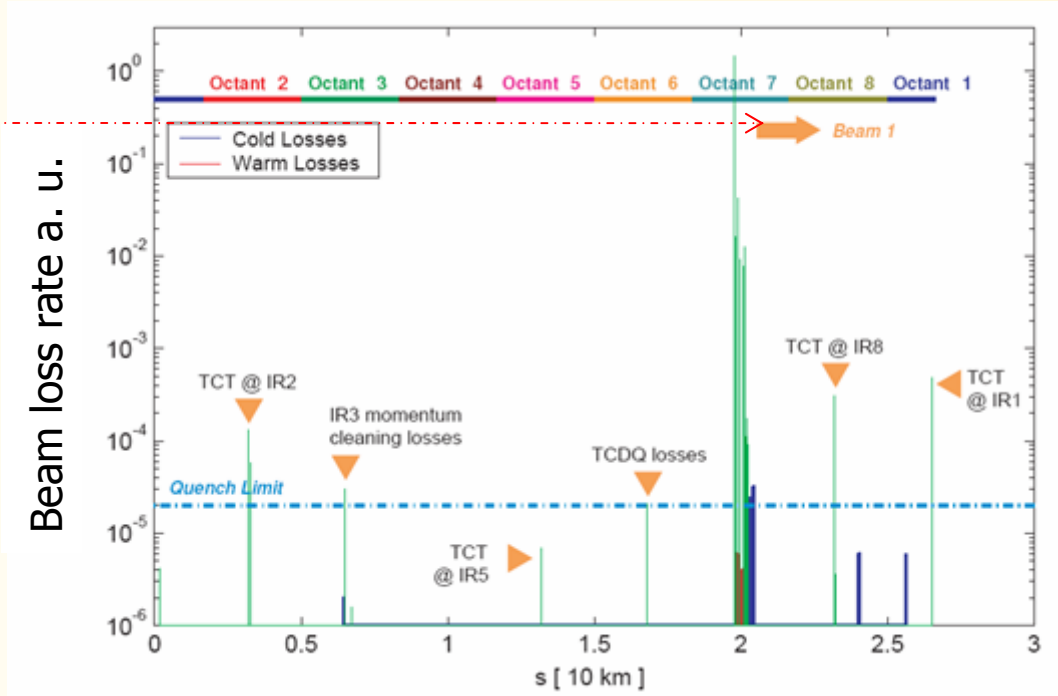


Since not active protection possible for ultra-fast losses => passive system

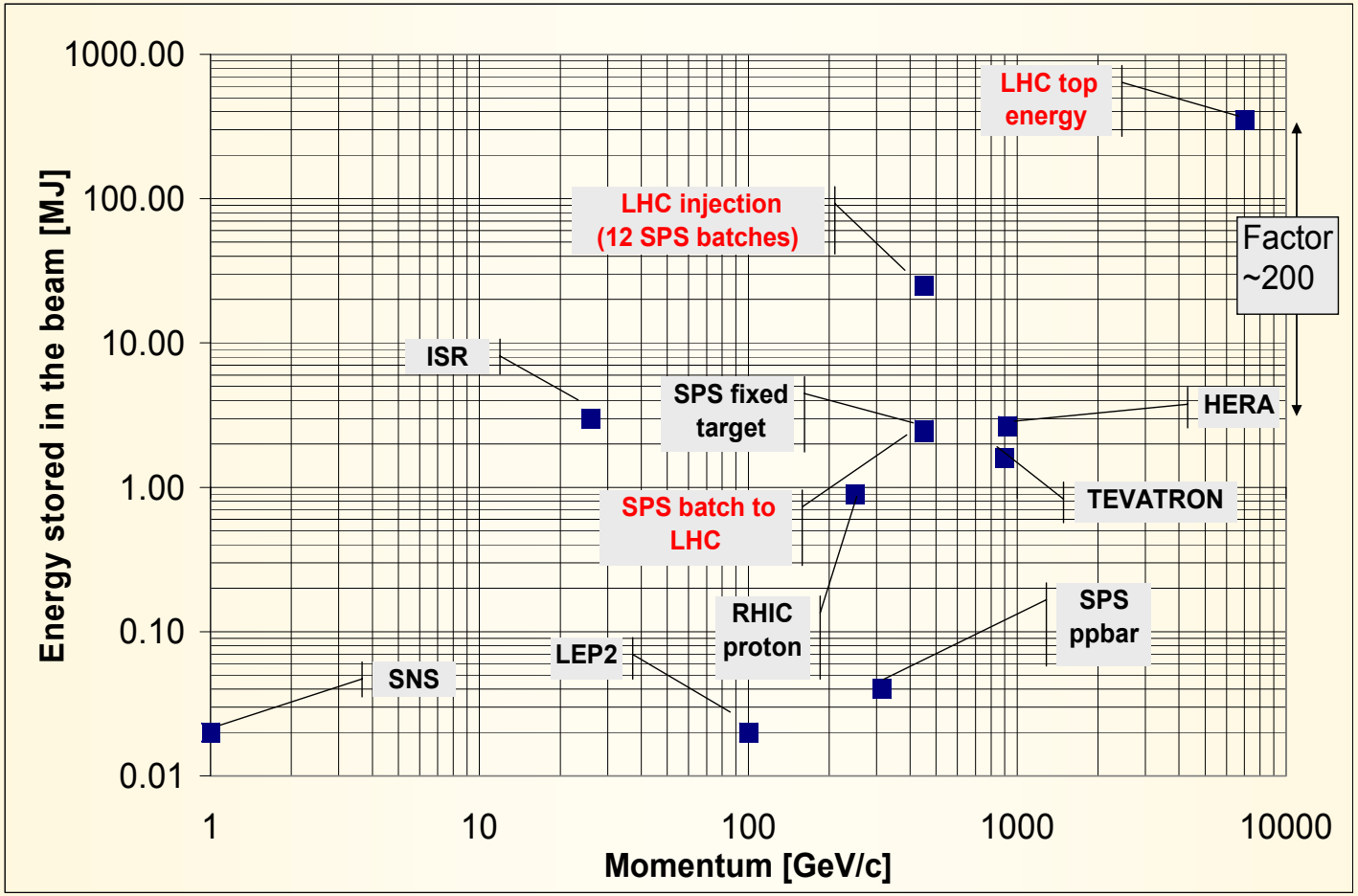
Collimators and Absorbers



- Distribution of collimators and absorbers along the ring to protect equipment against ultra-fast and up to steady state losses



Stored Beam Energies



LHC will be exceptional => High RISK

Safety System Design Approach

Risk → **Safety** → **Protection** → **Availability**

Methods:

Damage (system integrity)

Quench (operational Efficiency)

Failsafe
Redundancy
Survey
Functional Check

Stop of next injection

Extraction of beam

Reduction of operational efficiency

Systems:

Beam loss Monitors

Quench protection system

Interlock system

Dump system

Design issues:

Reliable components

Redundancy, voting

Monitoring of drifts

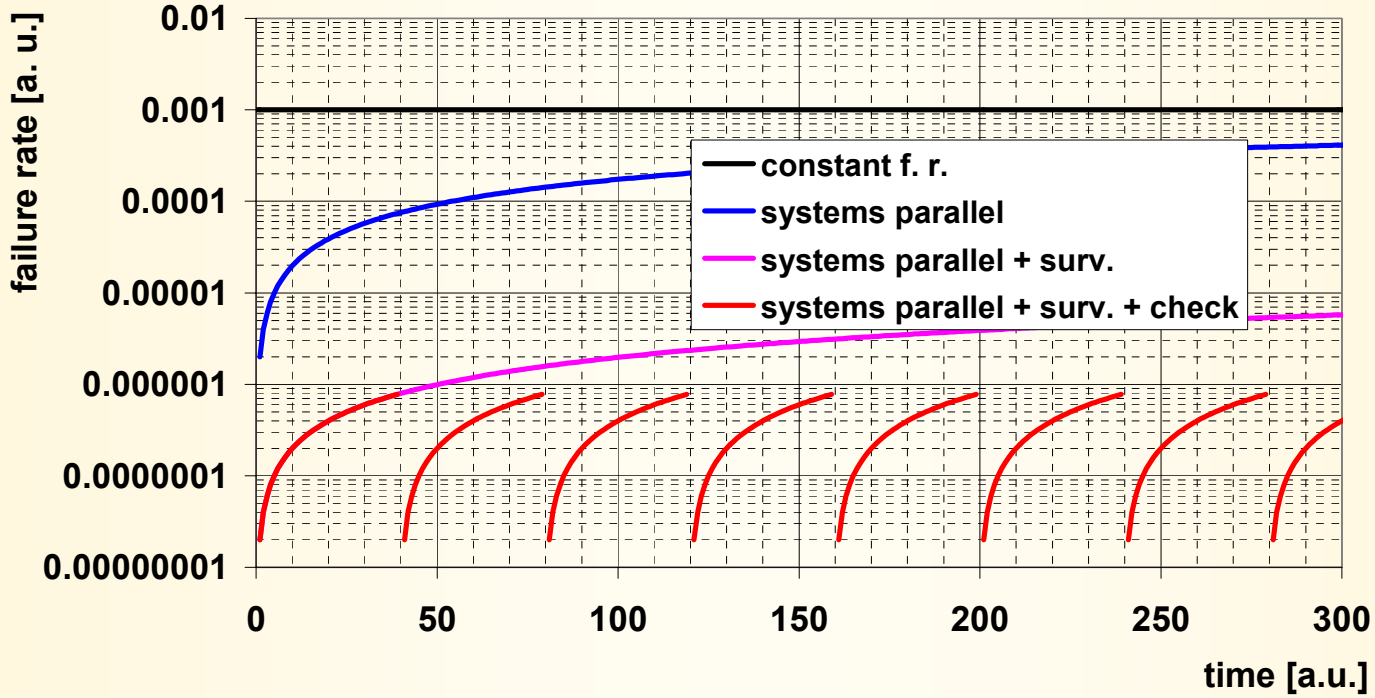
Scaling:

frequency of events x consequence → Mean time between failures → Systems

SIL
ALARP

$1\ 10^{-8}$ to $1\ 10^{-7}$ 1/h

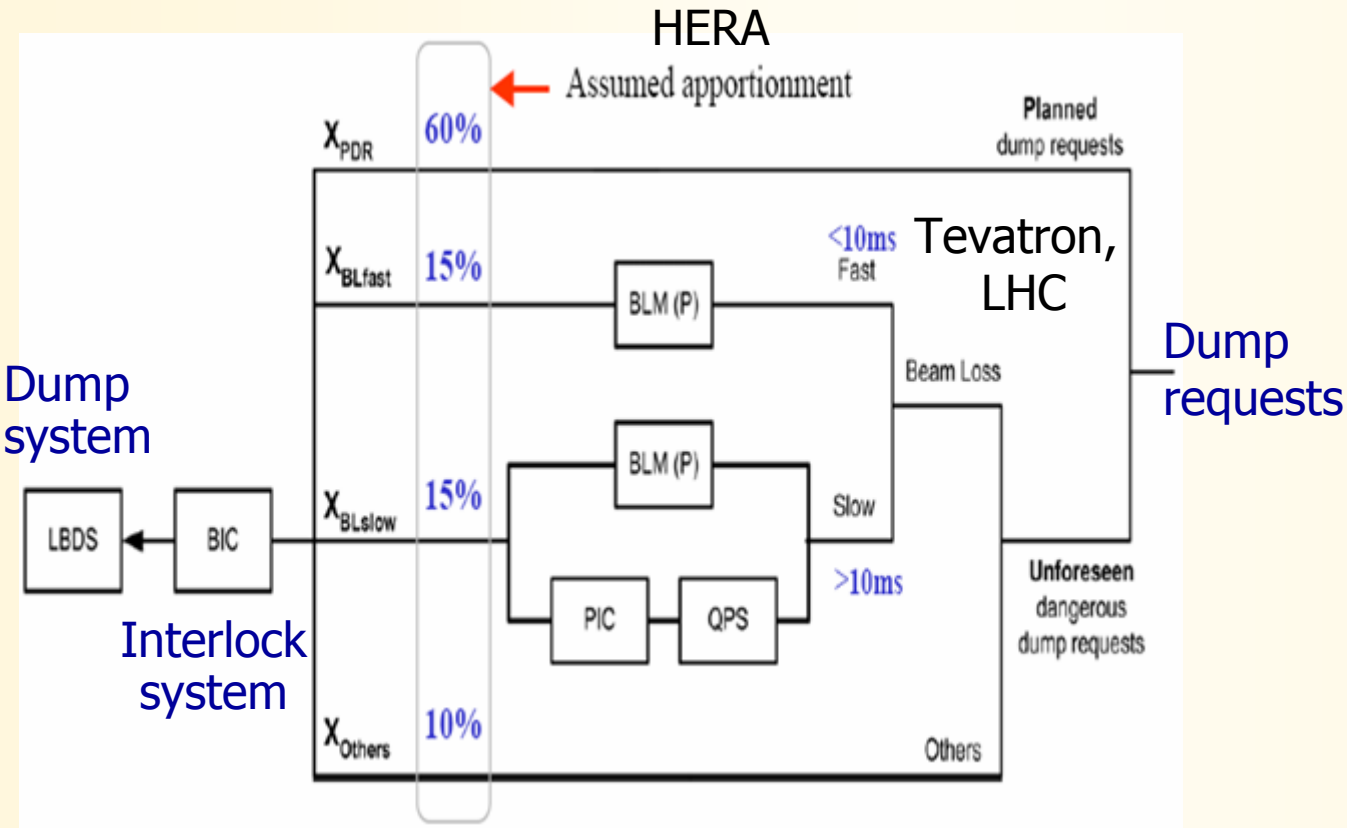
Failure Rate and Checks



Systems parallel + survey + functional check:

1. in case of system failure dump beam (failsafe)
2. verification of functionality: simulate measurement and comparison with expected result => as good as new

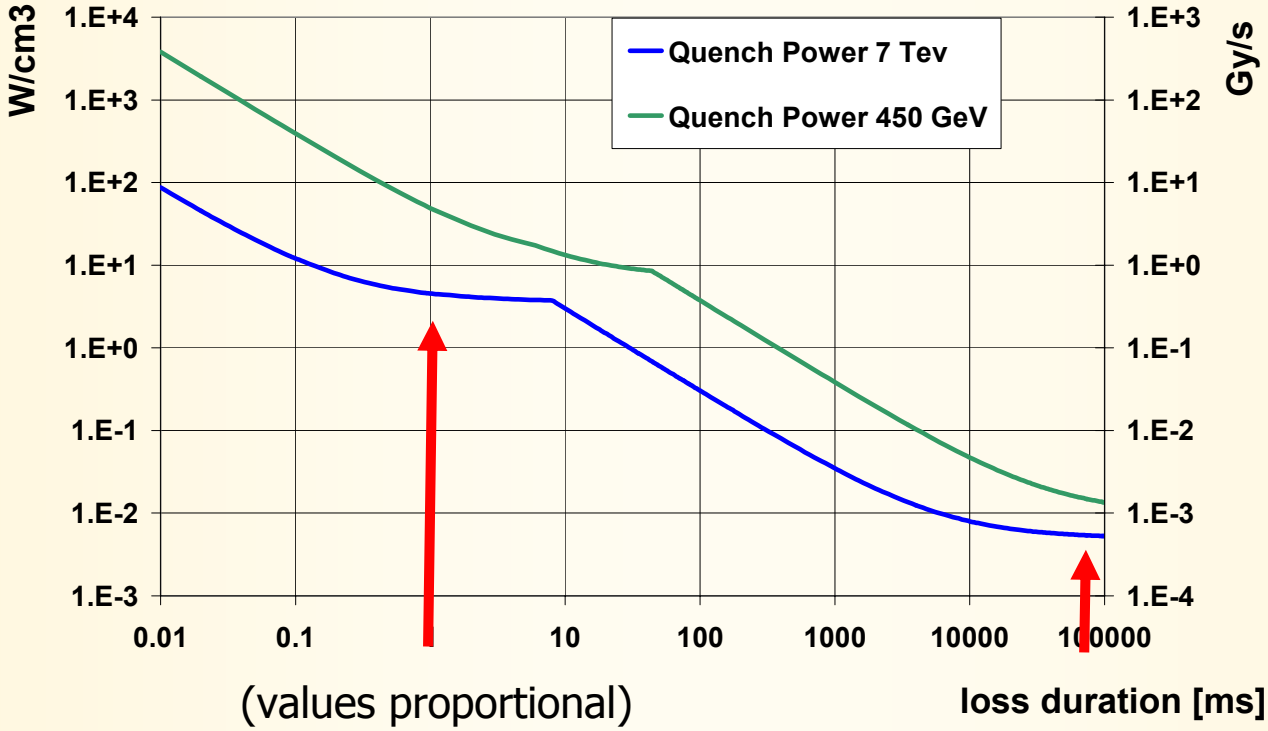
The Active Protection System



SOURCES of beam losses

1. User/operator
2. PC failures
3. Magnet failures
4. Collimators failures
5. RF failures
6. Obstacles
7. Vacuum
8. …

LHC Bending Magnet Quench Levels



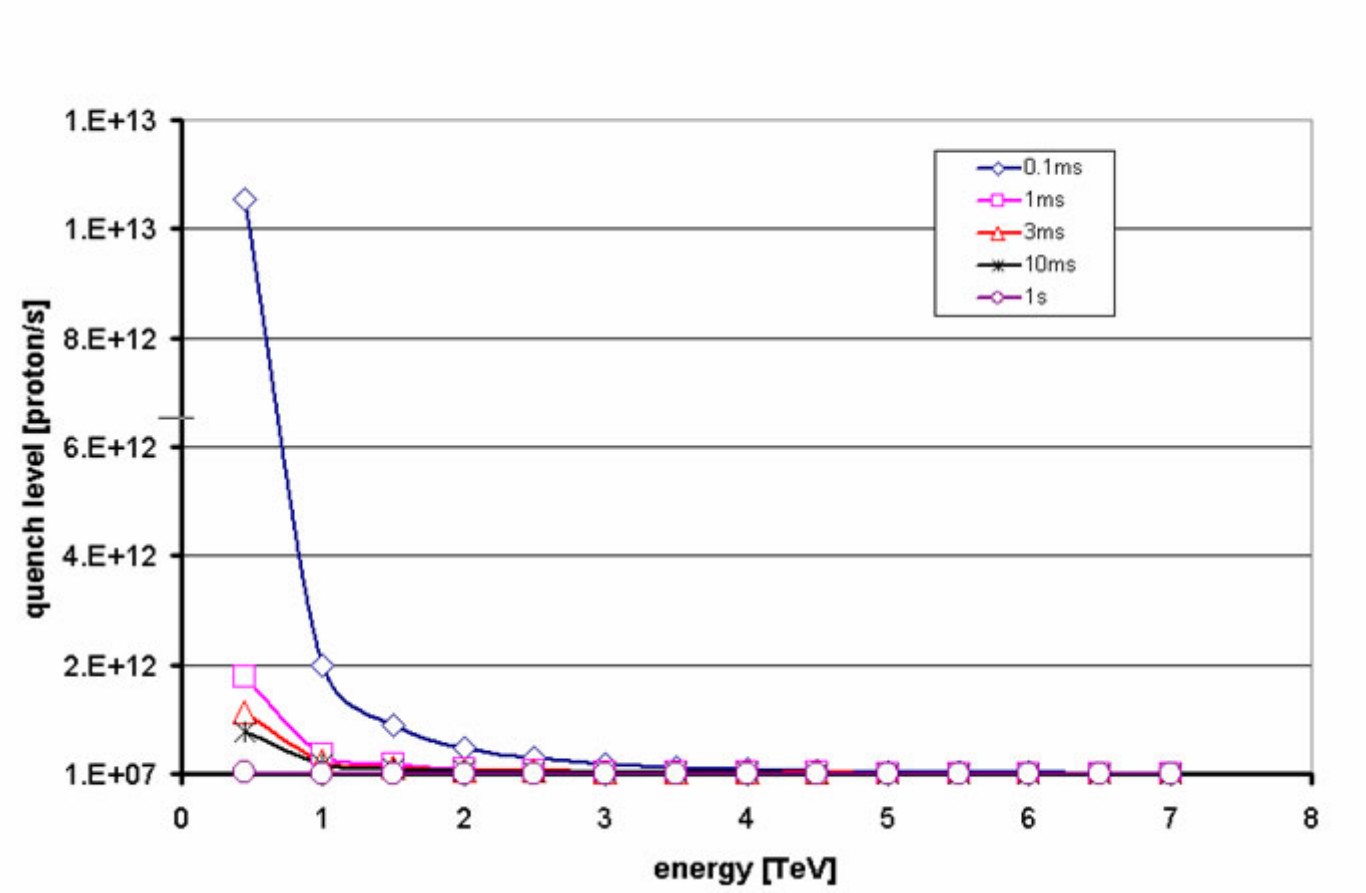
(values proportional)

13 us	J/cm3
Tevatron	4.50E-03
RHIC	1.80E-02
LHC	8.70E-04
DESY	2.6 – 6.6 E-03

steady state	W/cm3
Tevatron	7.47E-02
RHIC	7.47E-02
LHC	5.29E-03

LHC quench values are lowest

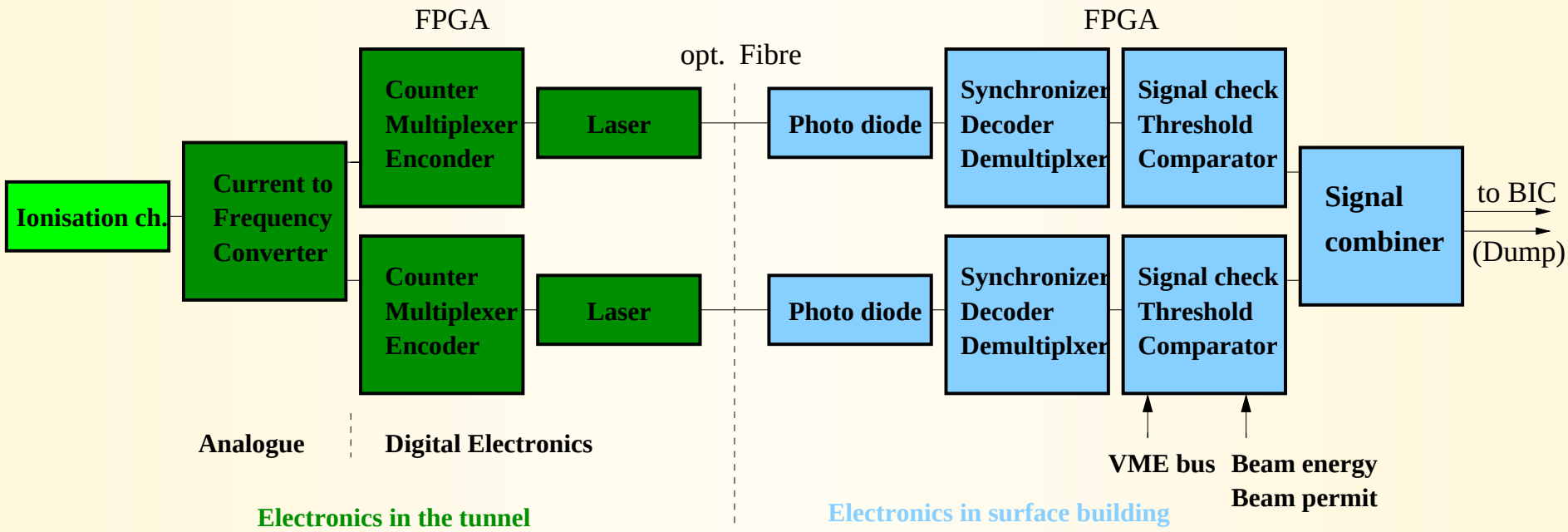
Quench Levels and Energy Dependence



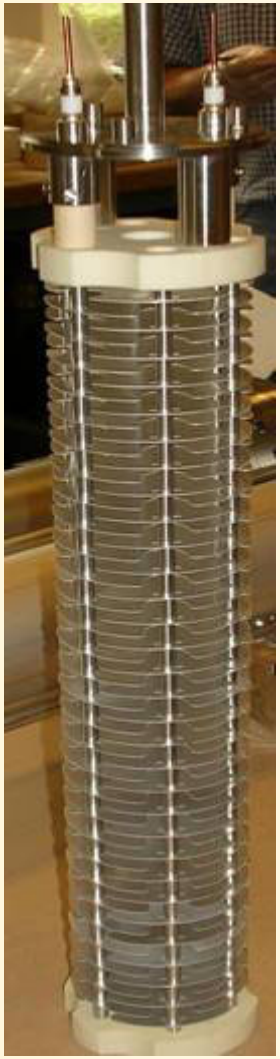
- Fast decrease of quench levels between 0.45 to 2 TeV
- Similar behaviour expected for damage levels

Beam Loss Measurement System Layouts

LHC



Ionisation Chamber and Secondary Emission Monitor



- Stainless steal cylinder
- Parallel electrodes distance 0.5 cm
- Diameter 8.9 cm
- Voltage 1.5 kV
- Low pass filter at the HV input

Signal Ratio: IC/SEM = 60000

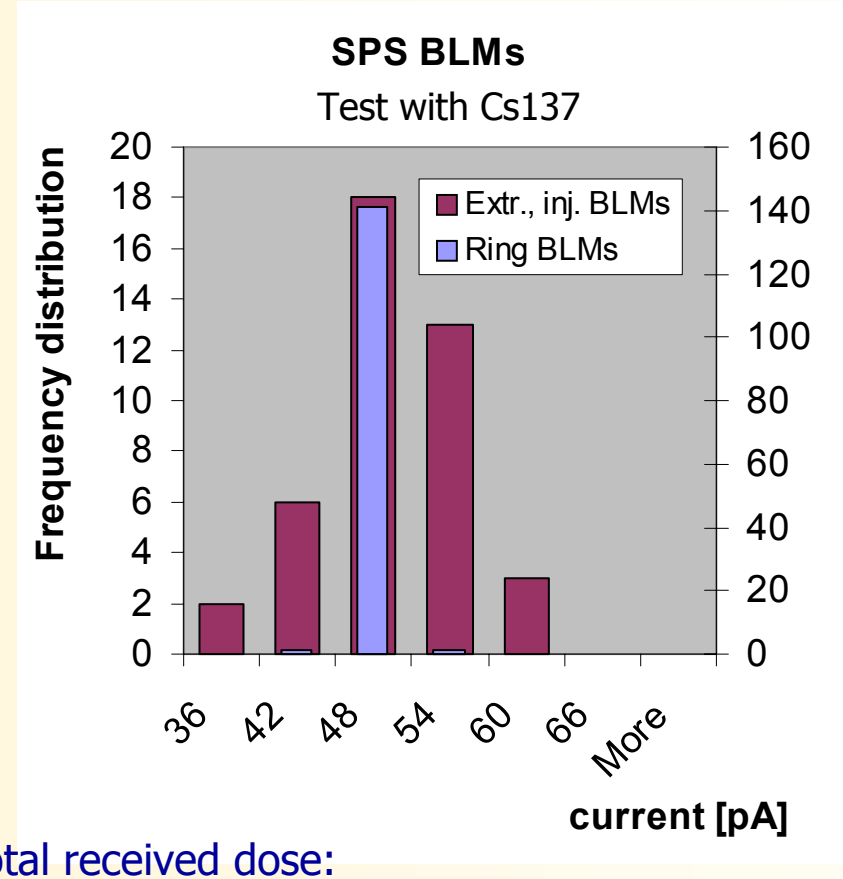
IC:

- Al electrodes
- Length 60 cm
- Ion collection time 85 us
- N_2 gas filling at 1.1 bar
- Sensitive volume 1.5 l

SEM:

- Ti electrodes
- Components UHV compatible
- Steel vacuum fired
- Detector contains 170 cm2 of NEG St707 to keep the vacuum < 10-4 mbar during 20 years

Gain Variation of SPS Chambers



Total received dose:

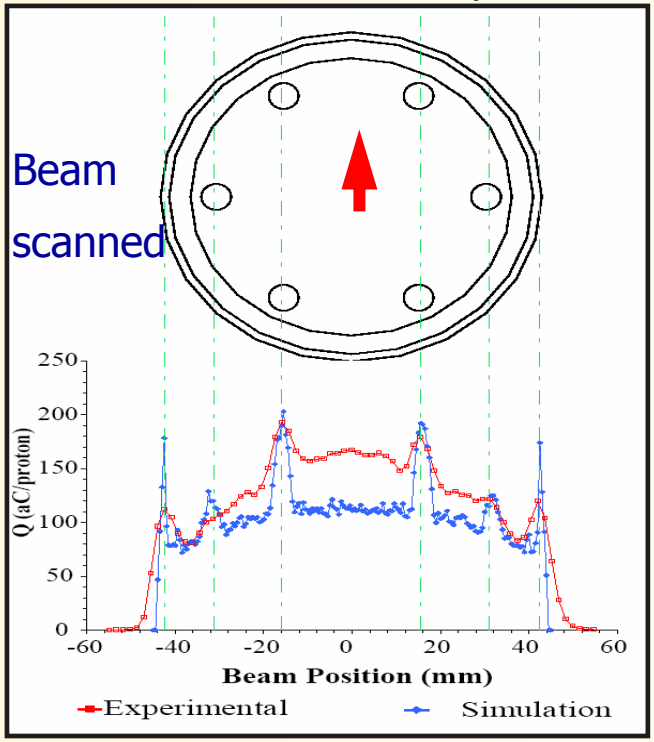
ring 0.1 to 1 kGy/year
extr 0.1 to 10 MGy/year

- 30 years of operation
- Measurements done with installed electronic
- Relative accuracy
  - $\Delta\sigma/\sigma$ < 0.01 (for ring BLMs)
  - $\Delta\sigma/\sigma$ < 0.05 (for Extr., inj. BLMs)
- Gain variation only observed in high radiation areas
- Consequences for LHC:
  - No gain variation expected in the straight section and ARC of LHC
  - Variation of gain in collimation possible for ionisation chambers

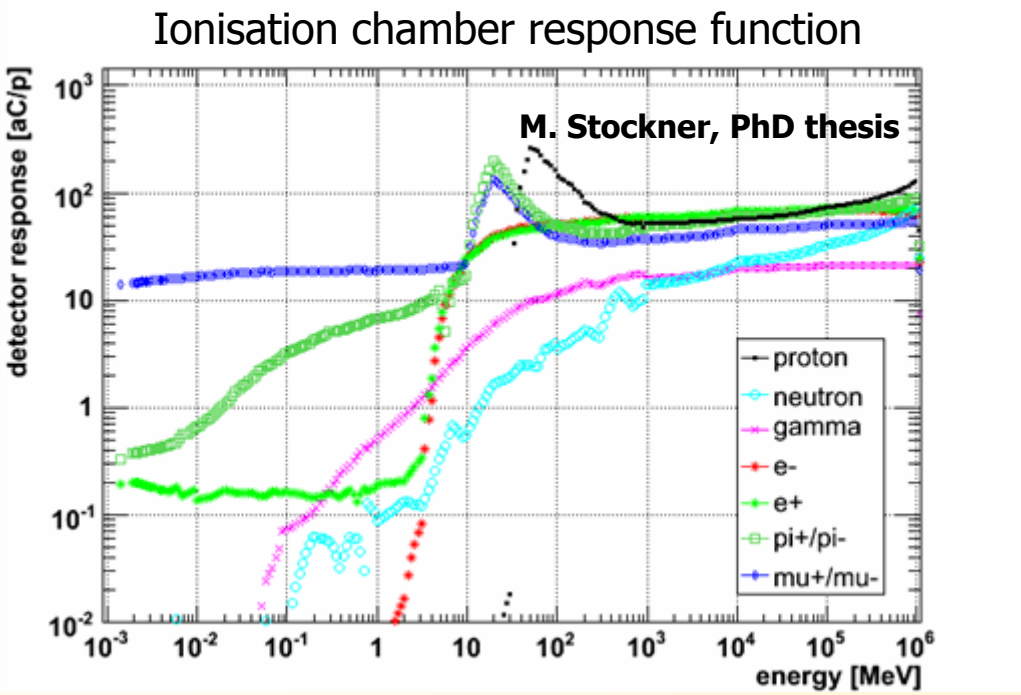
Reliable component

Ionisation Chamber Simulation and Measurements

Ionisation chamber top view



Ionisation chamber response function



- Comparison simulation measurements

	Rel. diff %	Error %
Proton	13.1	11.4
Gamma	14.3	12.1
neutron	37.4	13.9
Mixed field	20.5	11.4

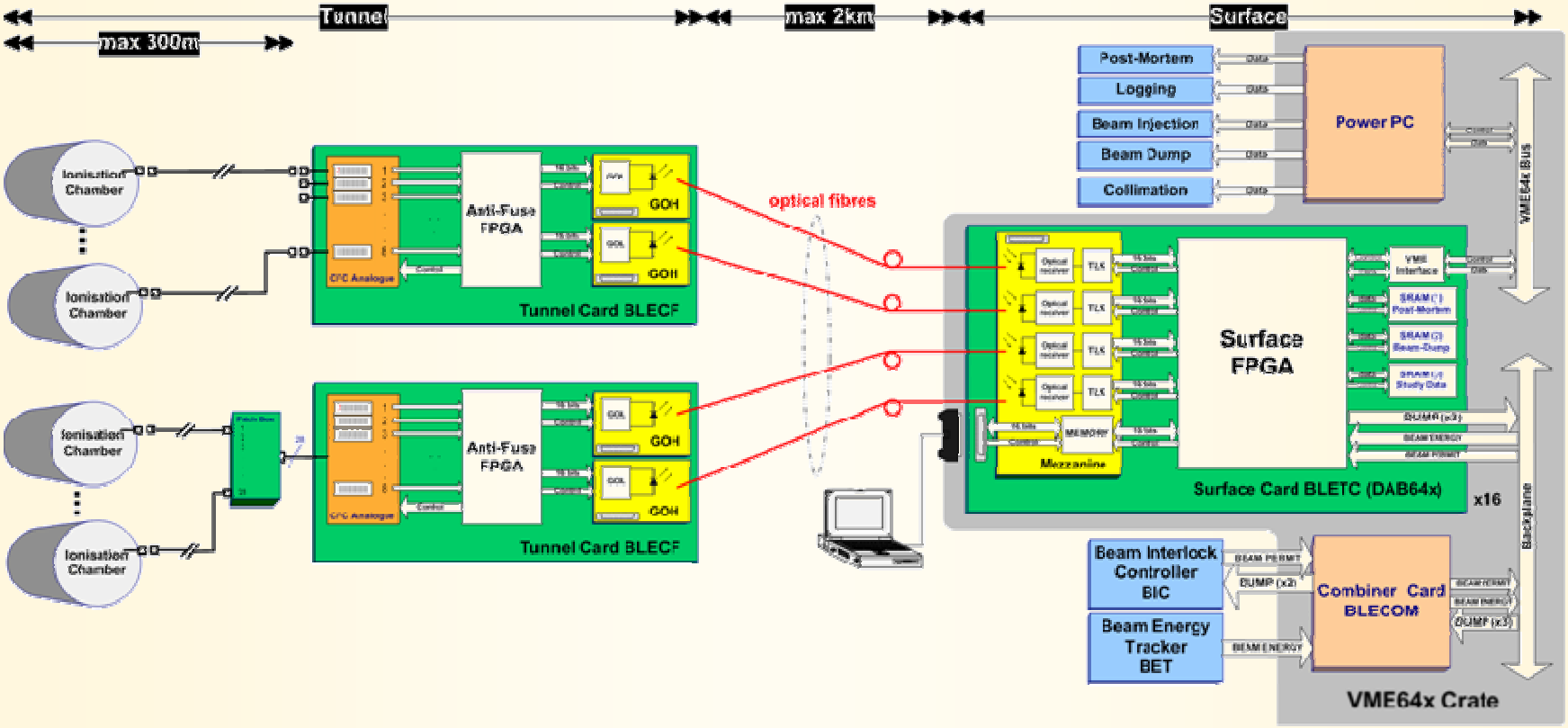
Good knowledge of behaviour =>

Reliable component

Ionisation chamber currents (1 litre, LHC)

Quench level ranges (min.)	450 GeV	100 s	12.5 nA
	7 TeV	100 s	2 nA
Dynamic range min., used for tuning	450 GeV	100 s	2.5 pA
	7 TeV	100s	80 pA

The BLM Acquisition System



Analog front-end FEE

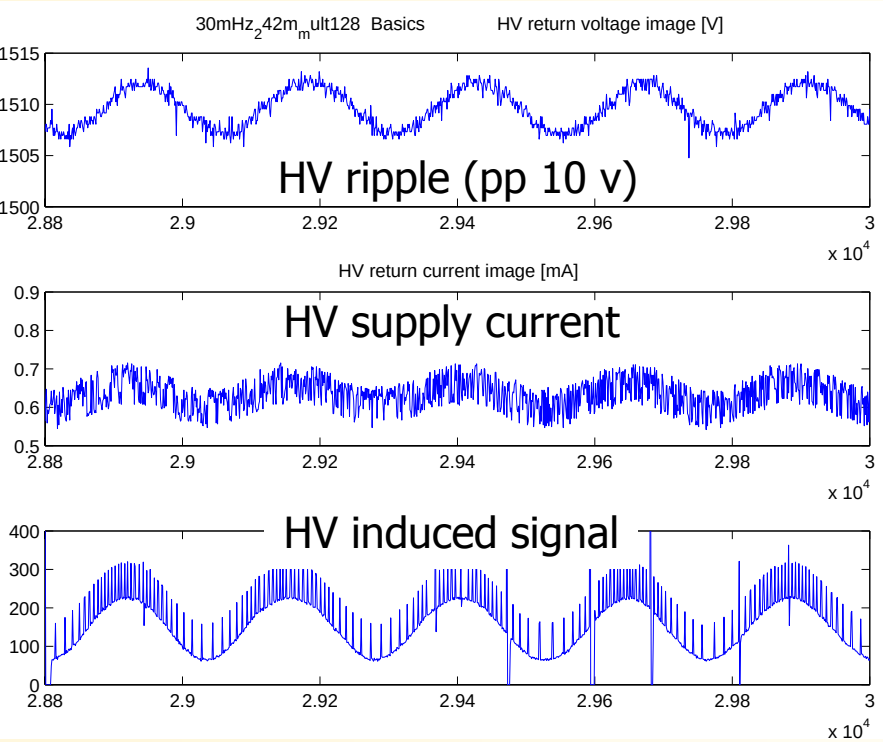
- **Current to Frequency Converters (CFCs)**
- **Analogue to Digital Converters (ADCs)**
- **Tunnel FPGAs:**
  Actel's 54SX/A radiation tolerant.
- **Communication links:**
  Gigabit Optical Links.

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**

Test Procedure of Analog Signal Chain

Modulation Example



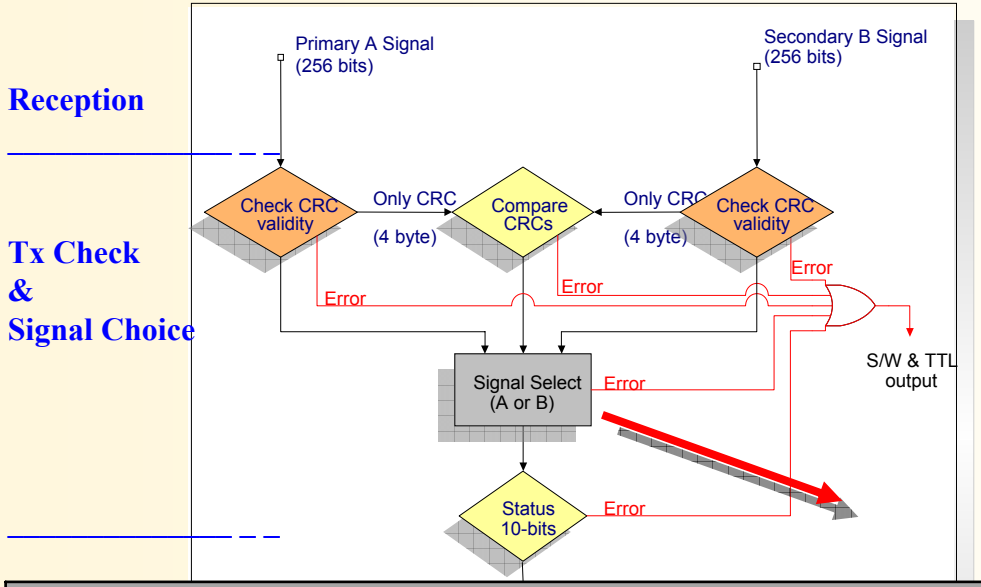
Basic concept:

Automatic test measurements in between of two fills

- Modulation of high voltage supply of chambers
  - Check of cabling
  - Check of components, R- C filter
  - Check of chamber capacity
  - Check of stability of signal, pA to nA (quench level region)
- Measurement of dark current
- Not checked: gas gain of chamber (only once a year with source)

Functional checks – Monitoring of drifts

Digital Transmission Line Check



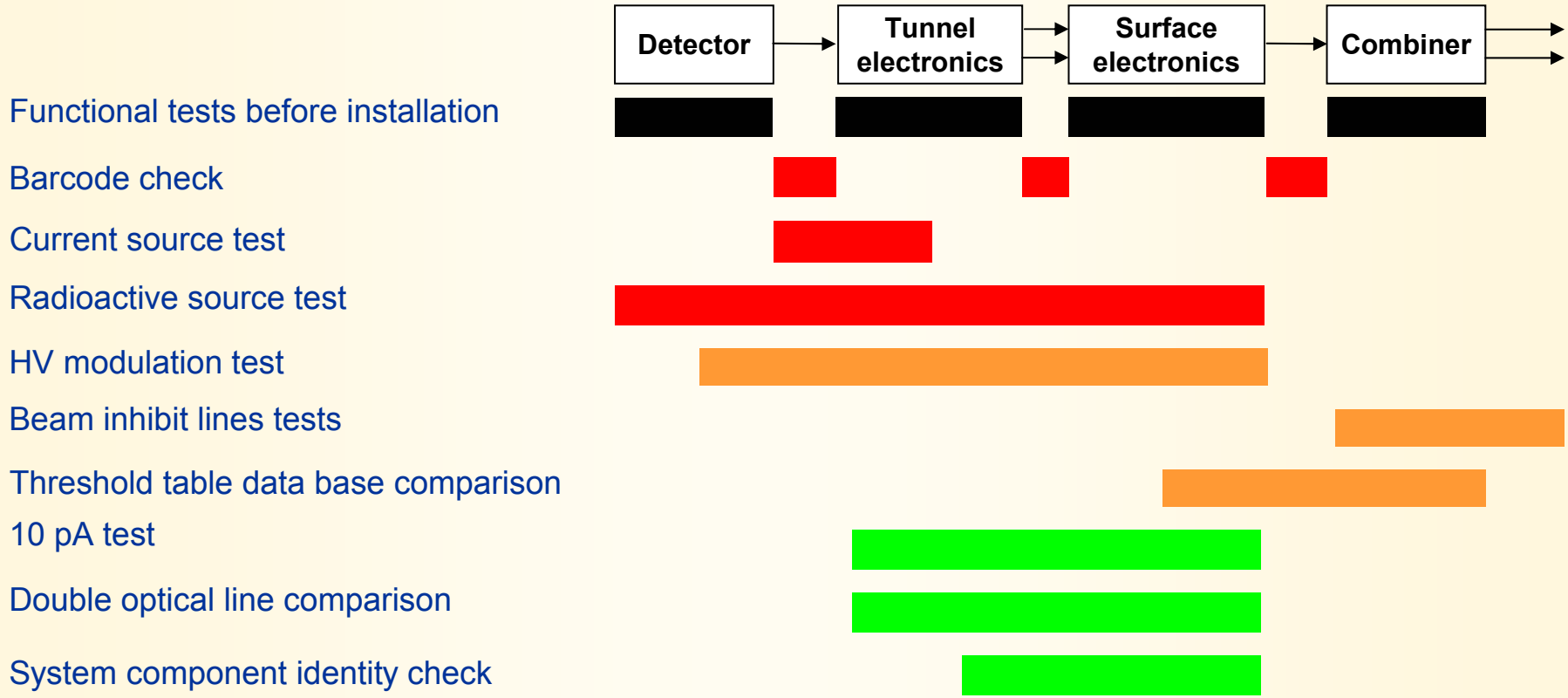
Signal Select Table				
CRC32 check		Comparison of 4Byte CRCs	Output	Remarks
A	B			
Error	**Error**	**Error**	Dump	**Both signals have error**
Error	**Error**	OK	Dump	**S/W trigger (CRCgenerate or check wrong)**
Error	OK	**Error**	Signal B	**S/W trigger (error at CRC detected)**
Error	OK	OK	Signal B	**S/W trigger (error at data part)**
OK	**Error**	**Error**	Signal A	**S/W trigger (error at CRC detected)**
OK	**Error**	OK	Signal A	**S/W trigger (error at data part)**
OK	OK	**Error**	Dump	**S/W trigger (one of the counters has error)**
OK	OK	OK	Signal A	By default (both signals are correct)

At the Surface FPGA:

- Signal CRC-32
  - Error check / detection algorithm for each of the signals received.
  - Comparison of the pair of signals.
  - Select block
  - Logic that chooses signal to be used
  - Identifies problematic areas.
- Tunnel's Status Check block
  - HT, Power supplies
- FPGA errors
  - Temperature

Functional Tests Overview

PhD thesis G. Guaglio

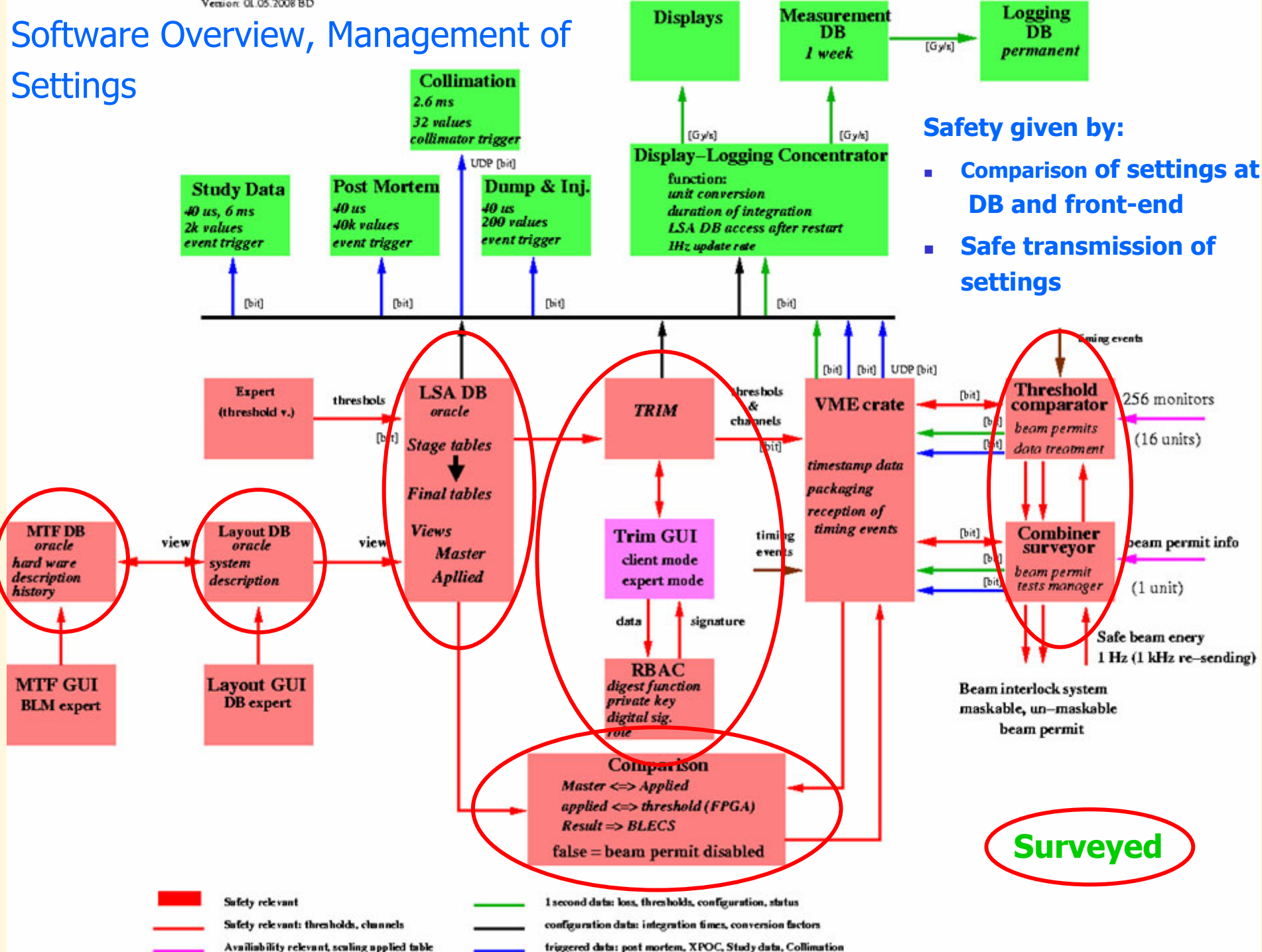


Inspection frequency:

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

Functional checks – Monitoring of drifts

Software Overview, Management of Settings

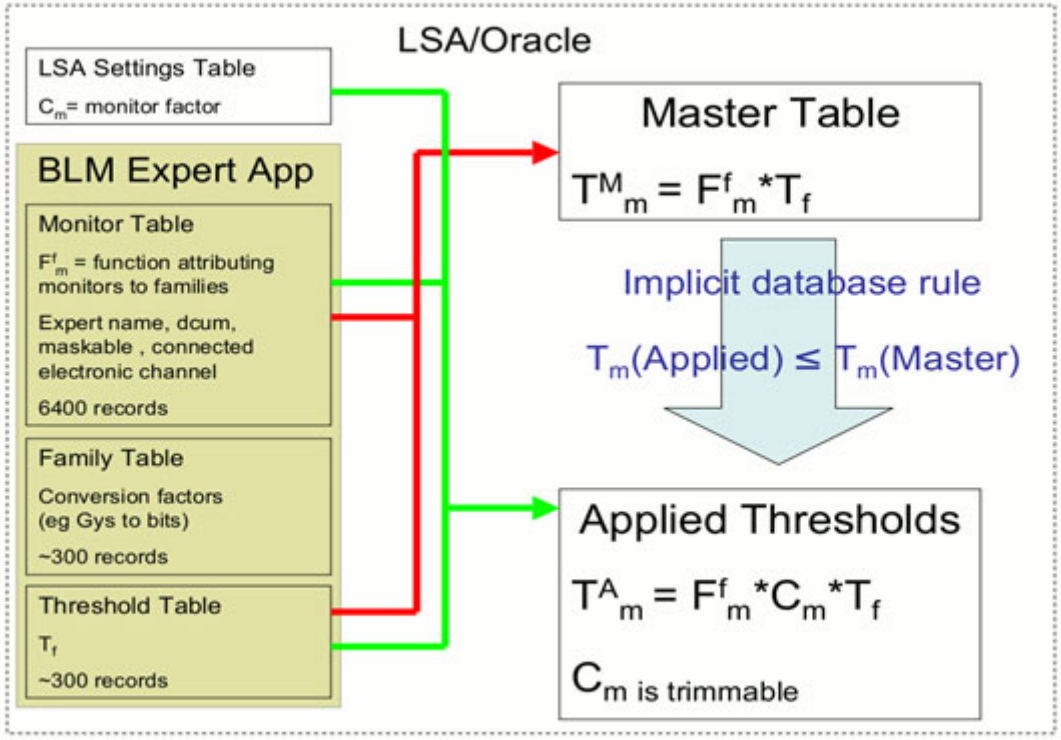


Safety given by:

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

Surveyed

Data Base Structure

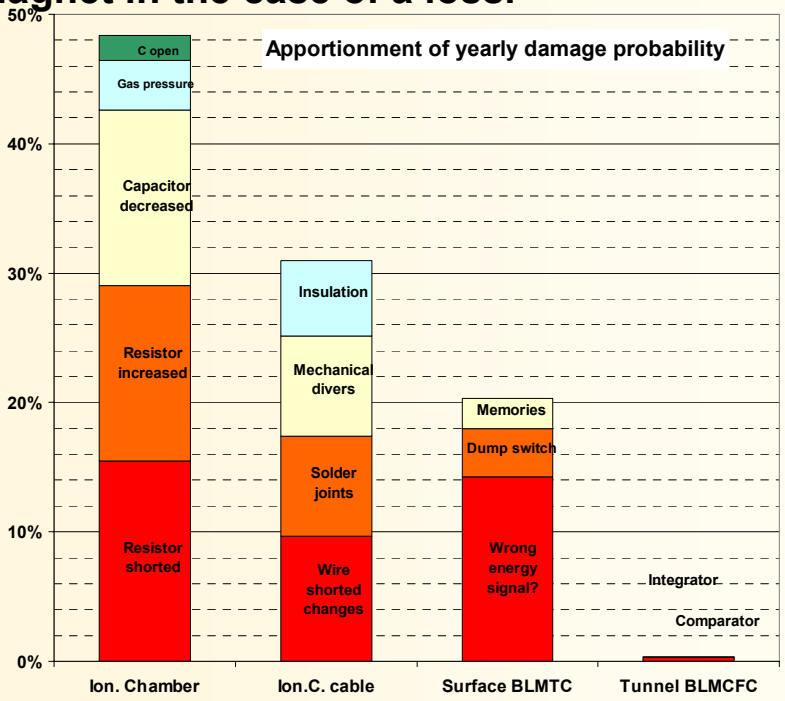


- Two layers
  - entry layer (stage tables)
  - validated layer (final tables)
- Concept of Master and Applied table – Comparison of Threshold values (Applied < Master)
  - Master: less frequent changes
  - Applied: change of thresholds possible with user interface

Failsafe

Reliability Study – Fault-Tree Approach

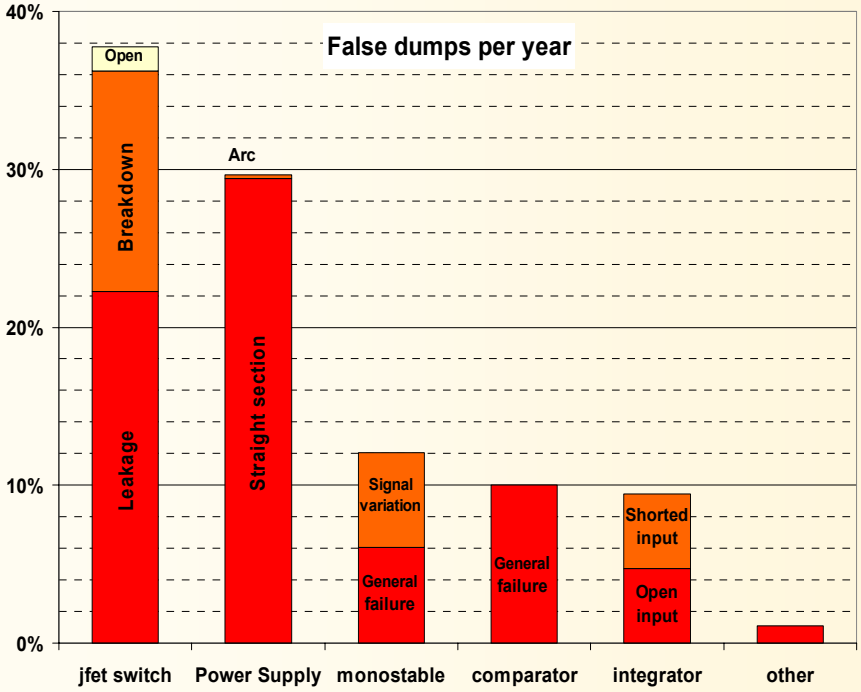
Relative probability of a system component being responsible for a damage to an LHC magnet in the case of a loss.



Highest damage probability given by the Ionisation chamber (80%) because:

1. Reduced checks
2. Harsh environment

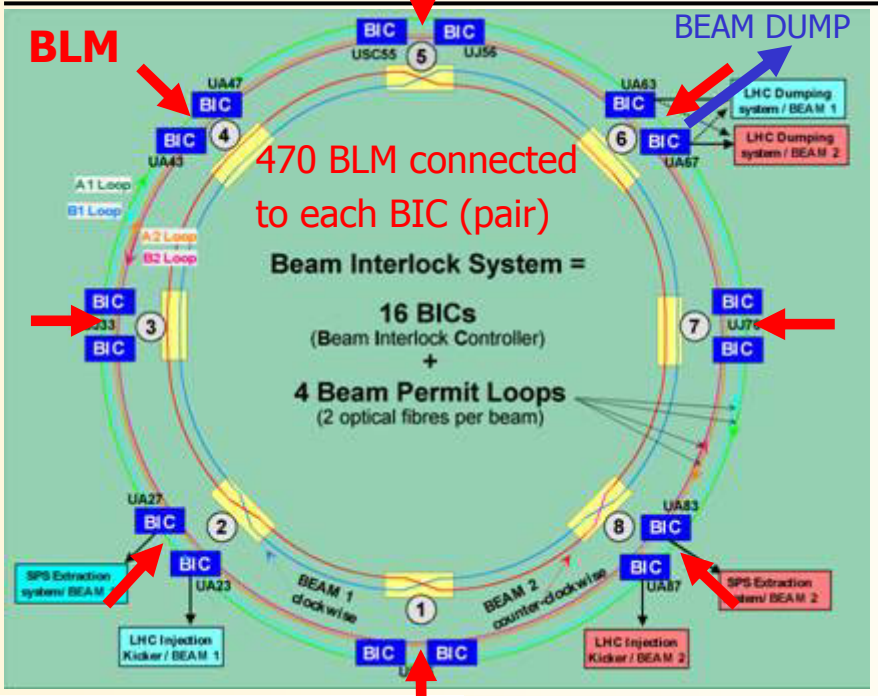
Relative probability of a BLM component generating a false dump. **by G. Guaglio**

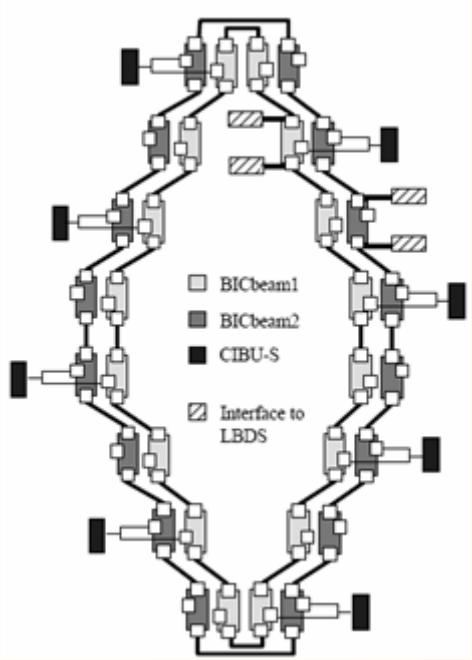


Most false dumps initiated by analog front end (98%) because:

1. Reduced check
2. Quantity
3. Harsh environment

Modelling of Machine Protection System





S. Wagner et al.
Laboratory for Safety Analysis, ETH Zurich

Combined model:

Fault Tree & Monte Carlo

Table 1: Number of components

i	Component i	Number n_i
1	IC	3744
2	FEE	624
3	BEE	312
4	Combiner Card	24
5	VME crate	24
6	CIBU-S	8
7	BICbeam1	16
8	BICbeam2	16
	Total	4768

BLM

Beam interlock

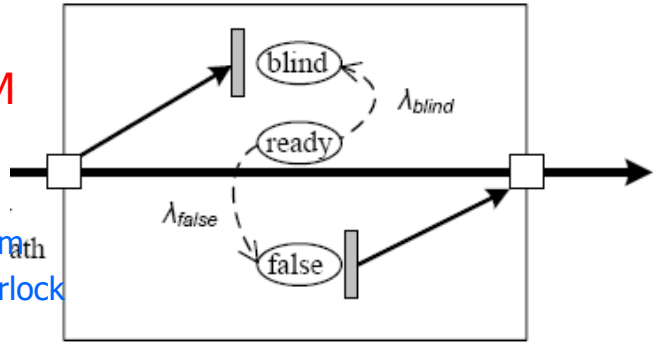


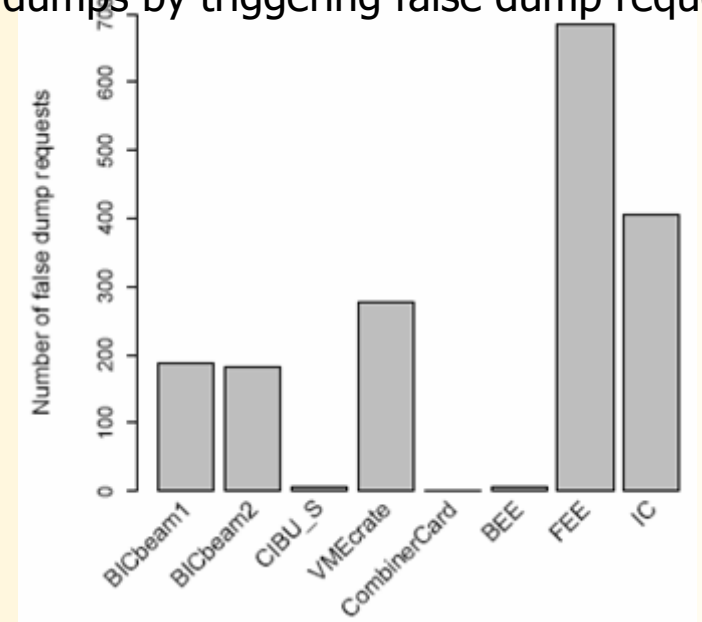
Table 2: Failure rates of the components

i	Component i	Rate λ_i^{false} 1/h	Rate λ_i^{blind} 1/h
1	IC	1E-7	1E-7
2	FEE	1E-6	1E-8
3	BEE	1E-8	1E-9
4	Combiner Card	1E-8	1E-9
5	VME crate	1E-5	1E-8
6	CIBU-S	1E-6	1E-13
7	BICbeam1	1E-5	1E-13
8	BICbeam2	1E-5	1E-13

First Modelling Results

- fraction of early ended missions triggered by beam loss event 11.3%
- false dump due to a false dump request by a component failure 1.7%

contribution of the components to false dumps by triggering false dump requests.



- Front electronics and BIC contribute with 40 %
- BLM system analysis reveals ARC power supply contribute most to FEE failure
- VME crate failure contribute significantly

Comparison between simulation and installed system => survey

Safety System Design Approach

Risk → **Safety** → **Protection** → **Availability**

Methods:

Damage (system integrity)

Quench (operational Efficiency)

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Survey
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SIL
ALARP

$1\ 10^{-8}$ to

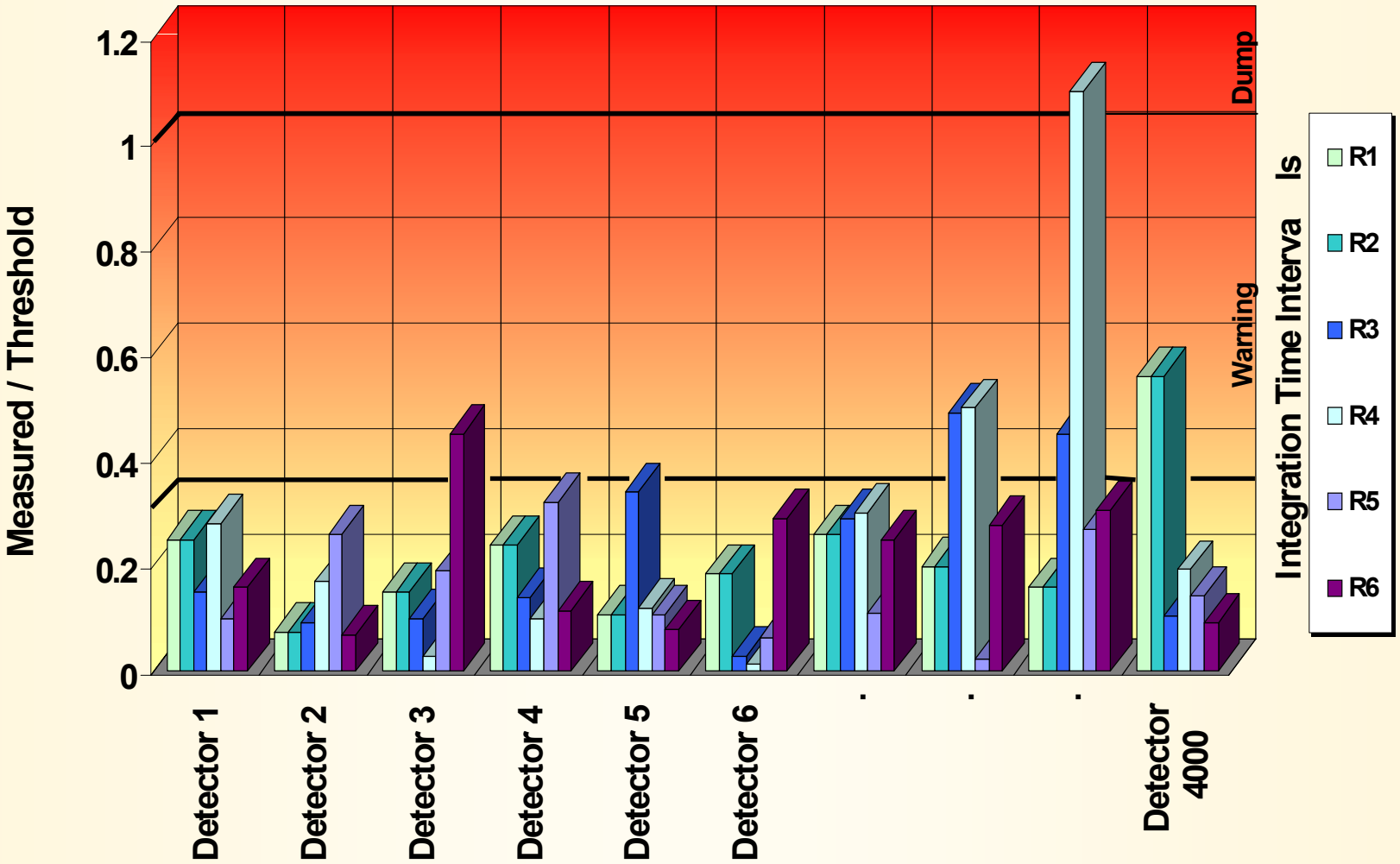
$1\ 10^{-7}$ 1/h

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

Beam Loss Display



Intensities

- Intensity one “pilot” bunch $5 \cdot 10^9$
- Nominal bunch intensity $1.1 \cdot 10^{11}$
- Batch from SPS (216/288 bunches at 450 GeV) $3 \cdot 10^{13}$
- Nominal beam intensity with 2808 bunches $3 \cdot 10^{14}$
- Damage level for fast losses at 450 GeV $1\text{-}2 \cdot 10^{12}$
- Damage level for fast losses at 7 TeV $1\text{-}2 \cdot 10^{10}$
- Quench level for fast losses at 450 GeV $2\text{-}3 \cdot 10^9$
- Quench level for fast losses at 7 TeV $1\text{-}2 \cdot 10^6$

Strategy for machine protection

- Definition of aperture by collimators.

Beam Cleaning System

- Early detection of failures for equipment acting on beams generates dump request, possibly before the beam is affected.

Powering Interlocks
Fast Magnet Current change Monitor

- Active monitoring of the beams detects abnormal beam conditions and generates beam dump requests down to a single machine turn.

Beam Loss Monitors
Other Beam Monitors

- Reliable transmission of beam dump requests to beam dumping system. Active signal required for operation, absence of signal is considered as beam dump request and injection inhibit.

Beam Interlock System

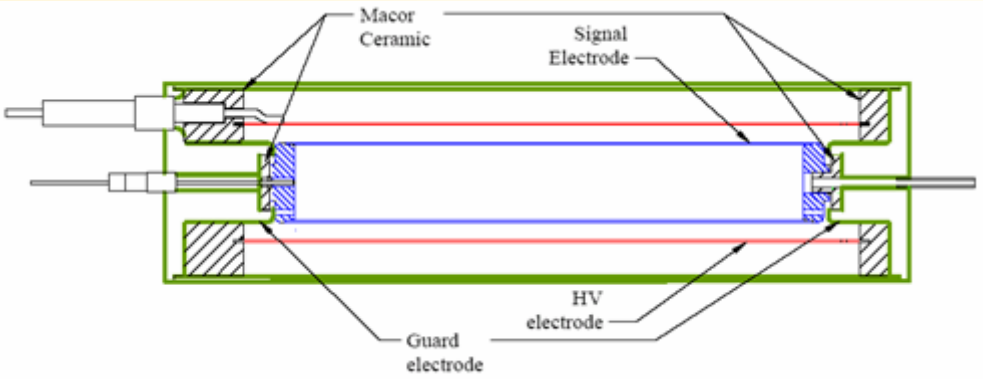
- Reliable operation of beam dumping system for dump requests or internal faults, safely extract the beams onto the external dump blocks.

Beam Dumping System

- Passive protection by beam absorbers and collimators for specific failure cases.

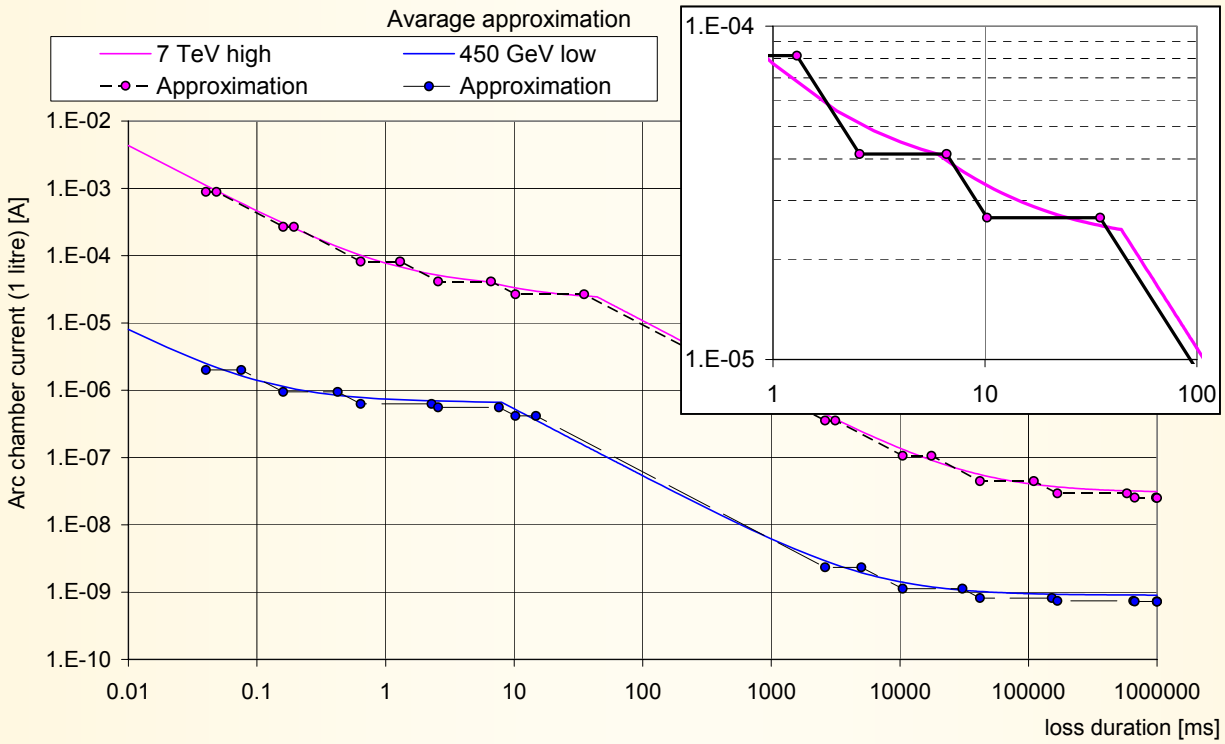
Beam Absorbers

Ionisation chamber SNS



- Stainless steal
- Coaxial design, 3 cylinder (outside for shielding)
- Low pass filter at the HV input
- Ar, N_2 gas filling at 100 mbar over pressure
- Outer inner electrode diameter 1.9 / 1.3 cm
- Length 40 cm
- Sensitive volume 0.1 l
- Voltage 2k V
- Ion collection time 72 us

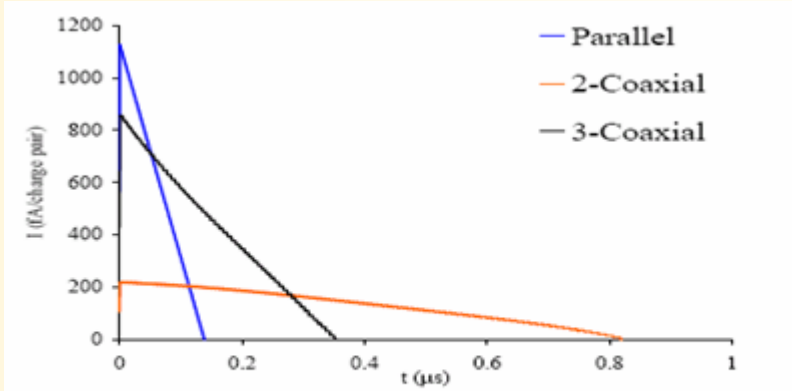
Approximation of Quench Levels (LHC)



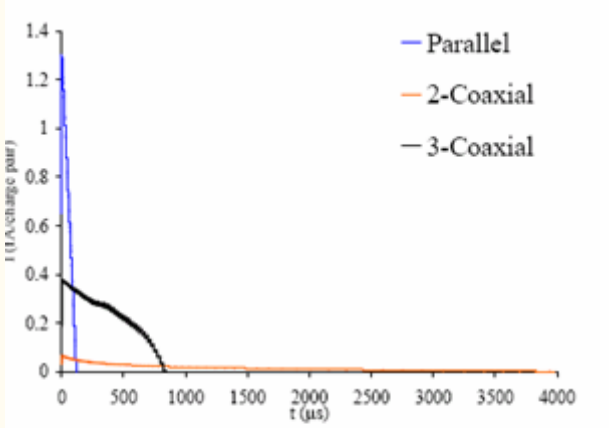
- Dump level tables are loaded in a non volatile RAM
- Any curve approximation possible
  - Loss durations
  - Energy dependence

Relative error kept < 20 %

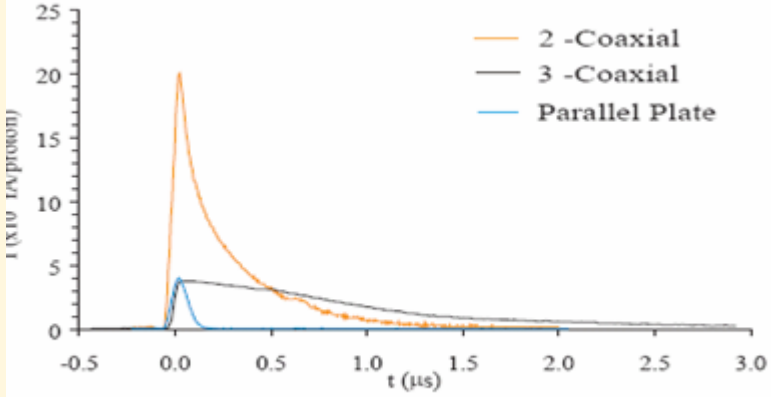
Drift times of electrons and ions (II)



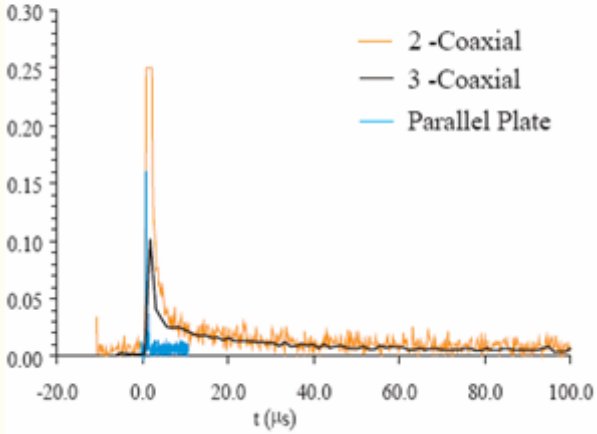
(a) *Simulated electrons*



(b) *Simulated ions*

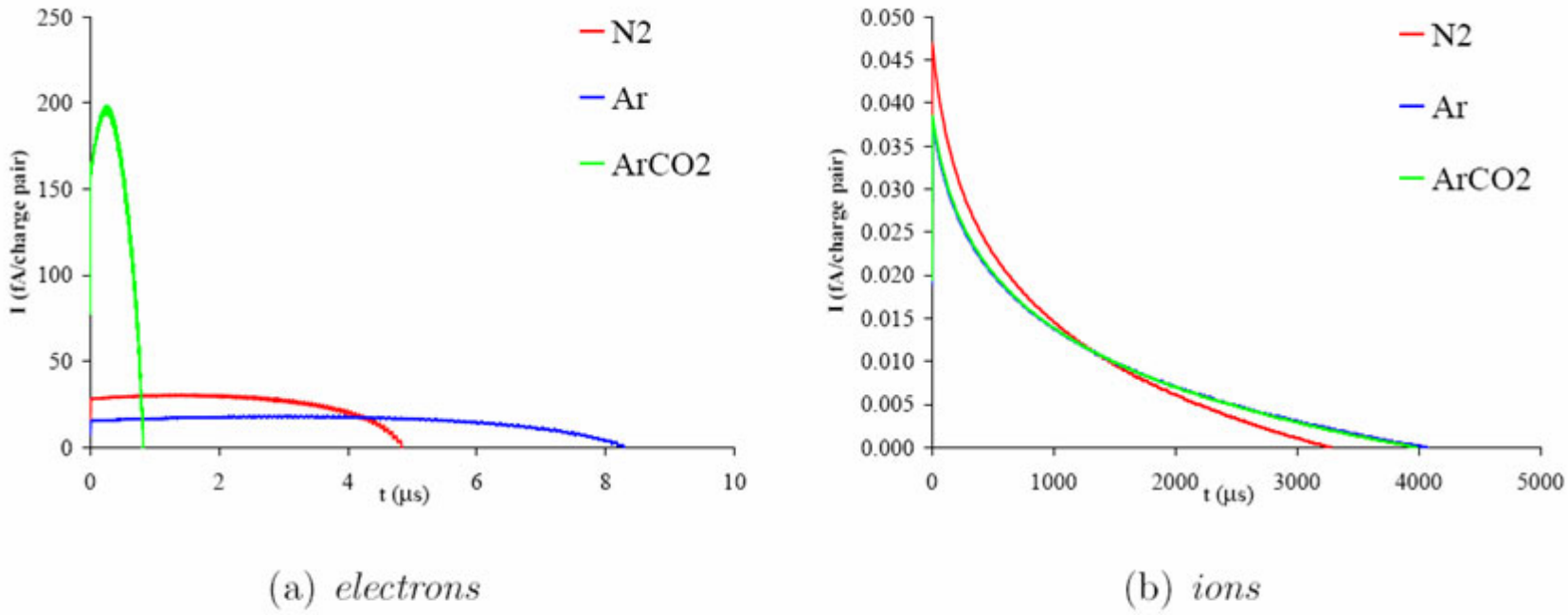


(c) *Experimental electrons*



(d) *Experimental ions*

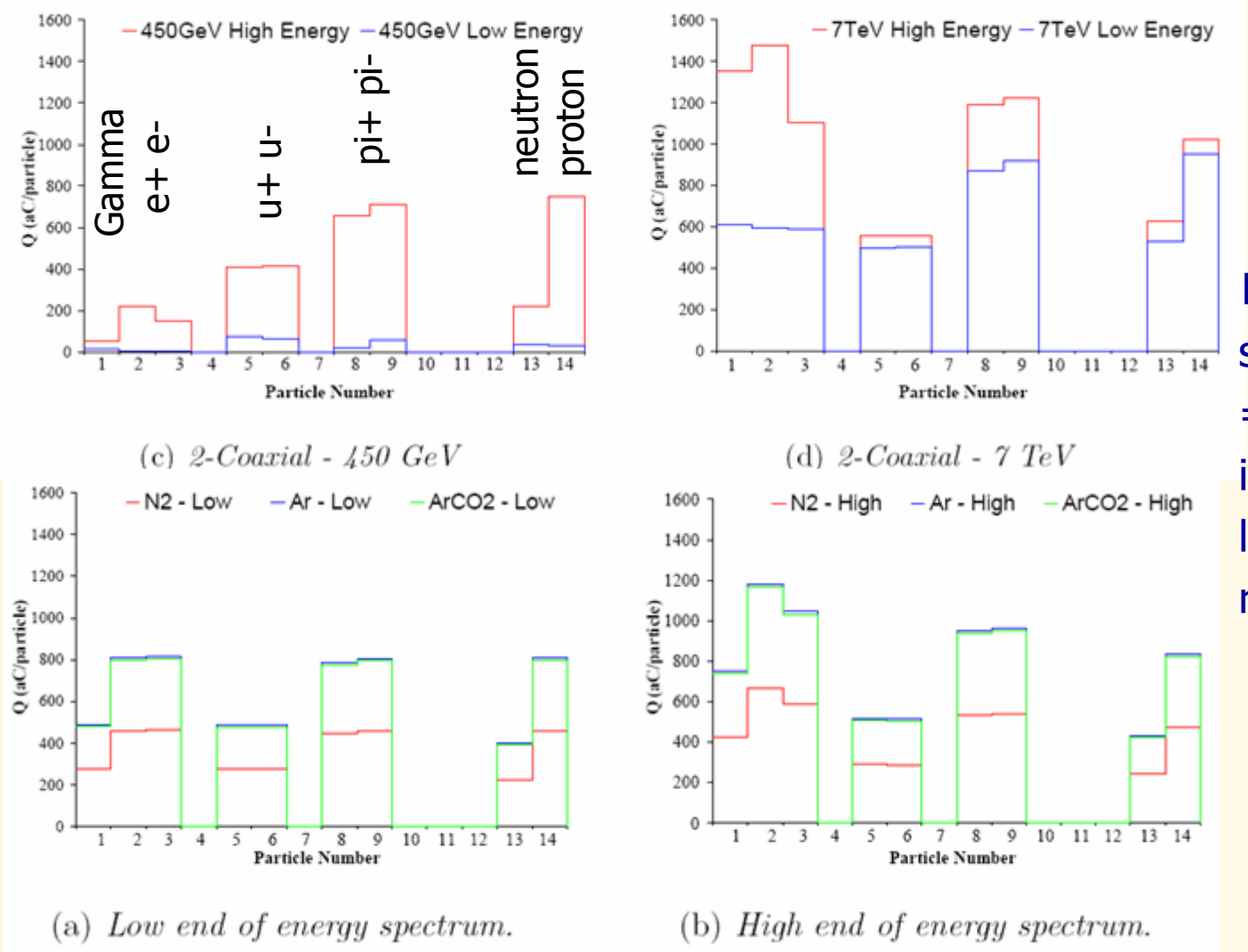
Drift times of electrons and ions (I)



(a) *electrons* (b) *ions*

Figure 6.12: *Simulated signal response of the 2-Coaxial ionisation chamber, filled with different gases. A homogeneous distribution was used.*

Response of ion chambers for different particle species



(c) *2-Coaxial - 450 GeV*

(d) *2-Coaxial - 7 TeV*

(a) *Low end of energy spectrum.*

(b) *High end of energy spectrum.*

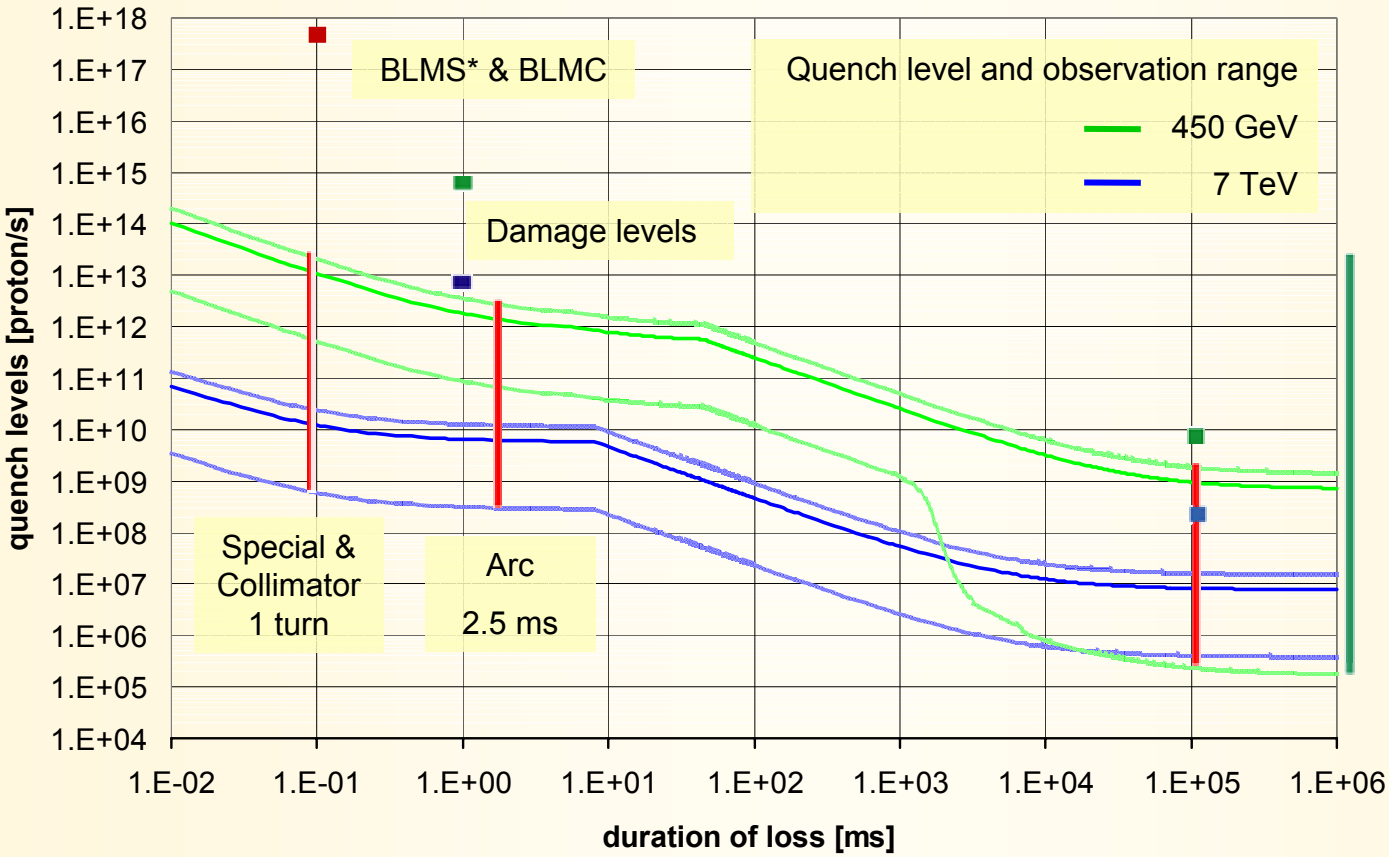
Due to attenuation of shower

=>

increase of non linearity of chamber response

Quench and Damage Levels

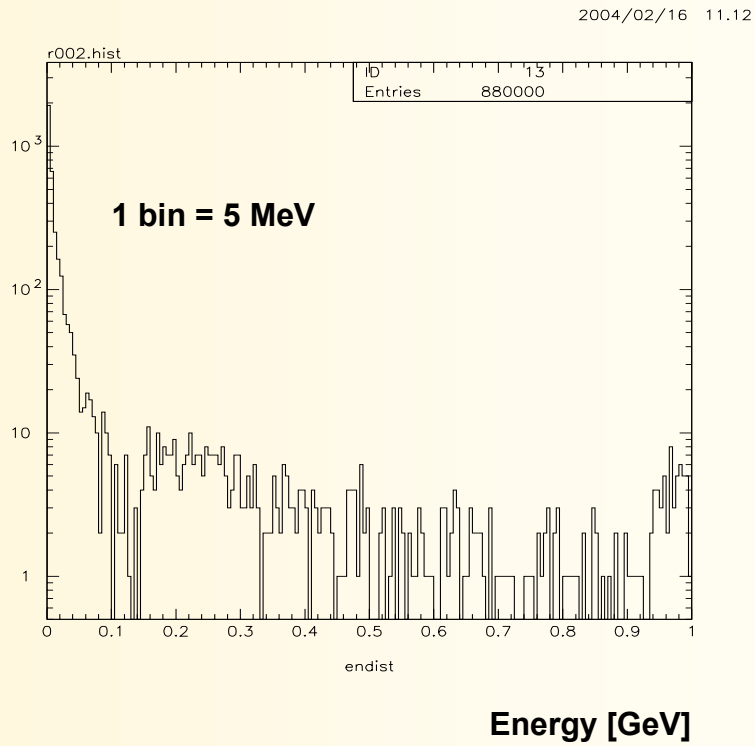
- Detection of shower particles outside the cryostat or near the collimators to determine the coil temperature increase due to particle losses



Dynamic
Arc: 10^8
Collimator: 10^{13}

Energy spectrum of shower particles outside of cryostat

- Energy spectrum:



- Number of charged particles and energy deposition simulated:

Average energy deposition in the detector (air):

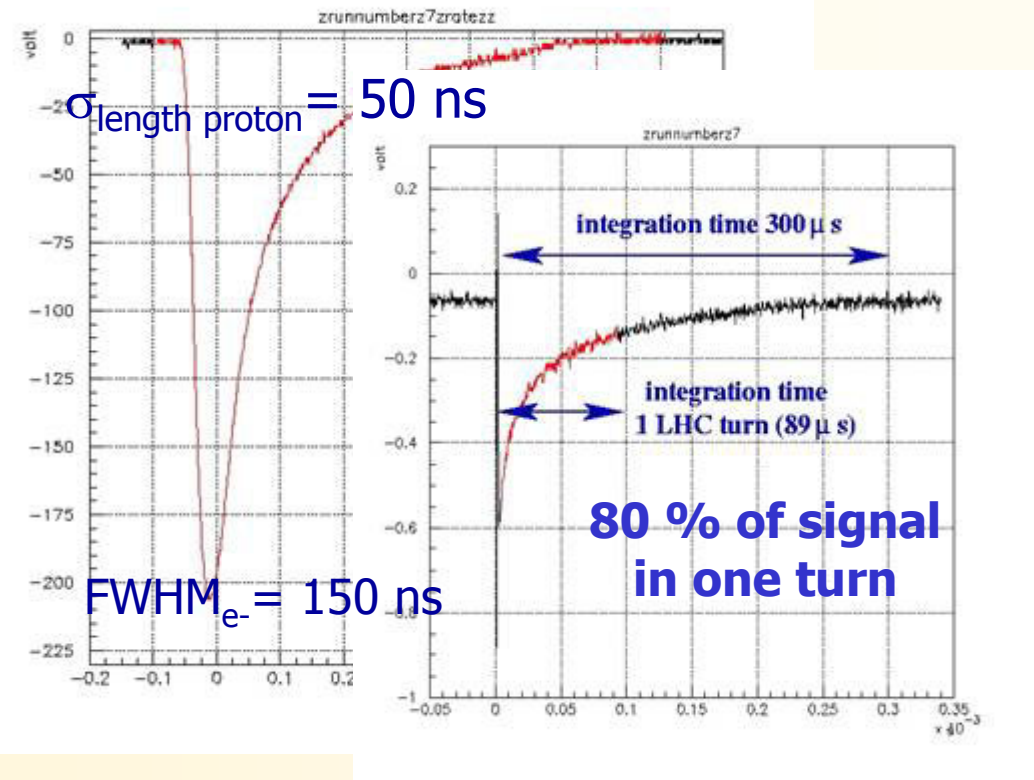
- **450 GeV: ~3.8 keV/cm**
- **7 TeV: ~4.3 keV/cm**

Shower particles in the detector per cm^2 and lost proton for point losses

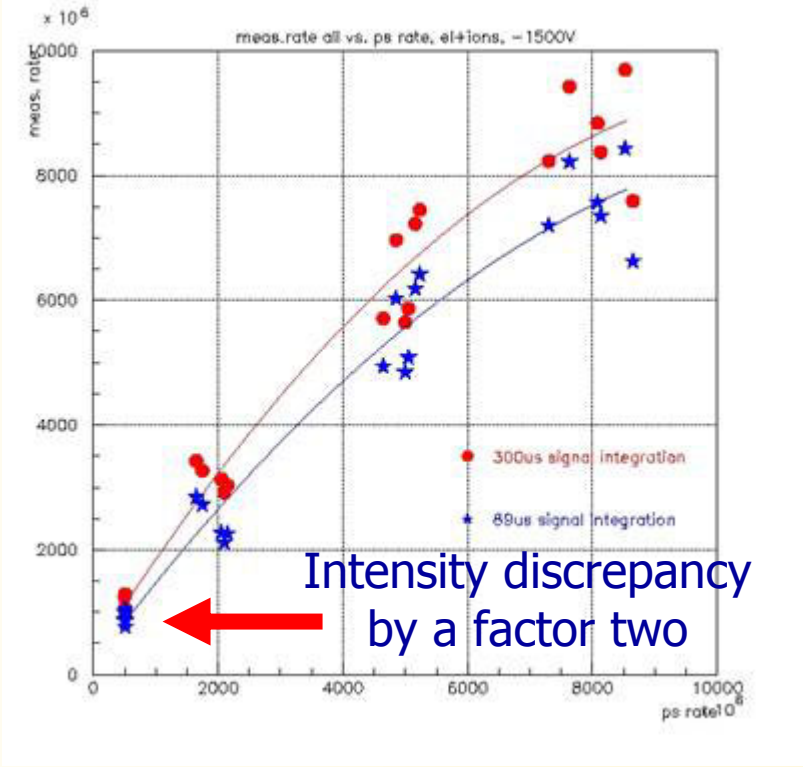
- **450 GeV: $5 \cdot 10^{-4}$ - $3 \cdot 10^{-3}$ part/p/cm^2**
- **7 TeV: $8 \cdot 10^{-3}$ - $4 \cdot 10^{-2}$ part/p/cm^2**

Ionisation Chamber Time Response Measurements (BOOSTER)

Chamber beam response

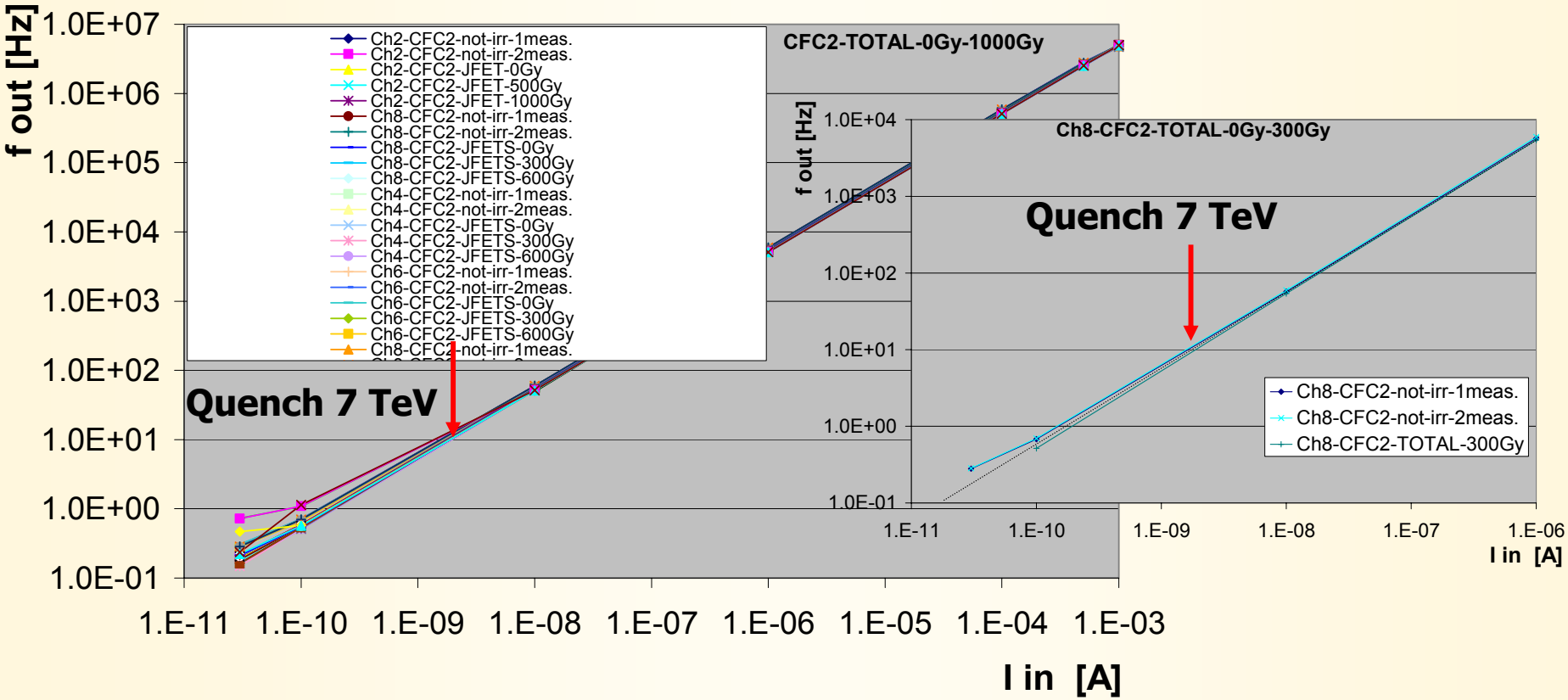


Chamber current vs beam current



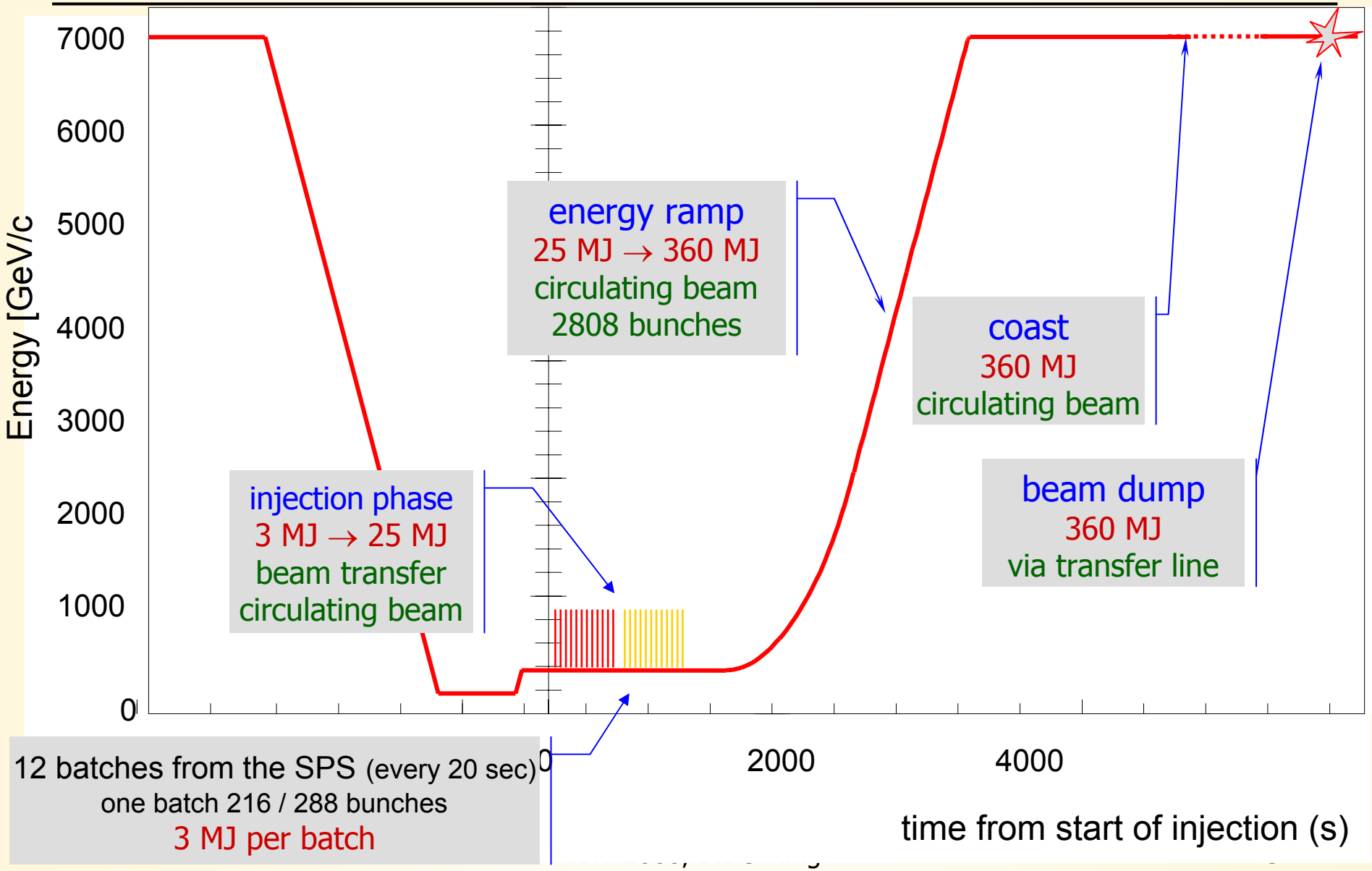
Intensity density: - Booster 6 10^9 prot./cm^2, two orders larger as in LHC

Current to Frequency Converter and Radiation

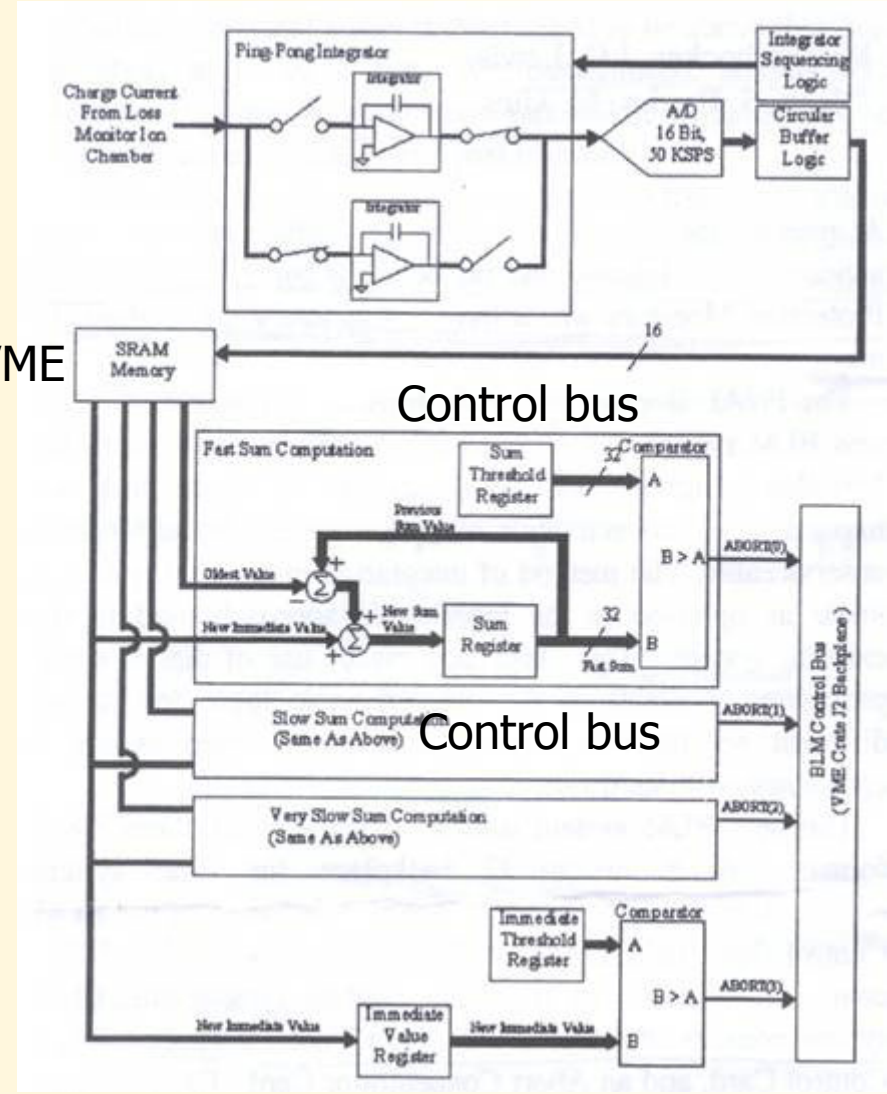


- Variation at the very low end of the dynamic range
- Insignificant variations at quench levels

LHC cycle and stored beam energy



FNAL beam loss integrator and digitizer

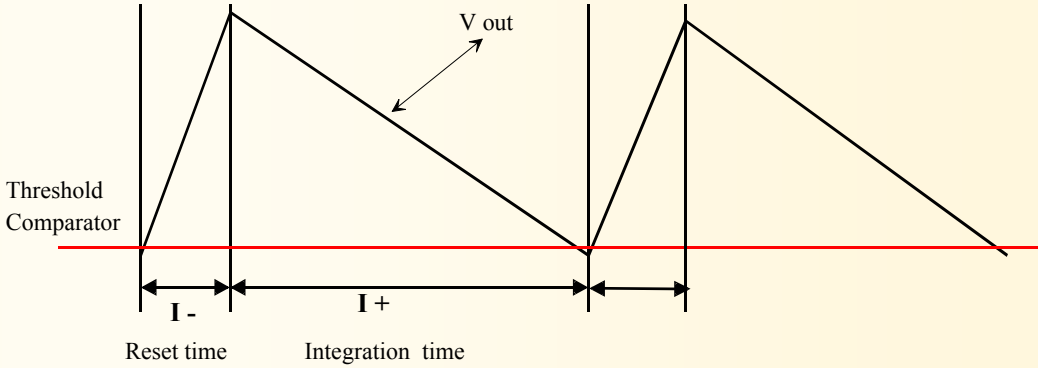


	FNAL	LHC
channels	4	16
Time resolution	21 μs	40 μs
# of running sums	3	11
windows	21 μs to 1.4 s	80 μs to 84 s
thresholds	4	12
Synchronized to machine timing	yes	no
post mortem buffer	4k values	1k values

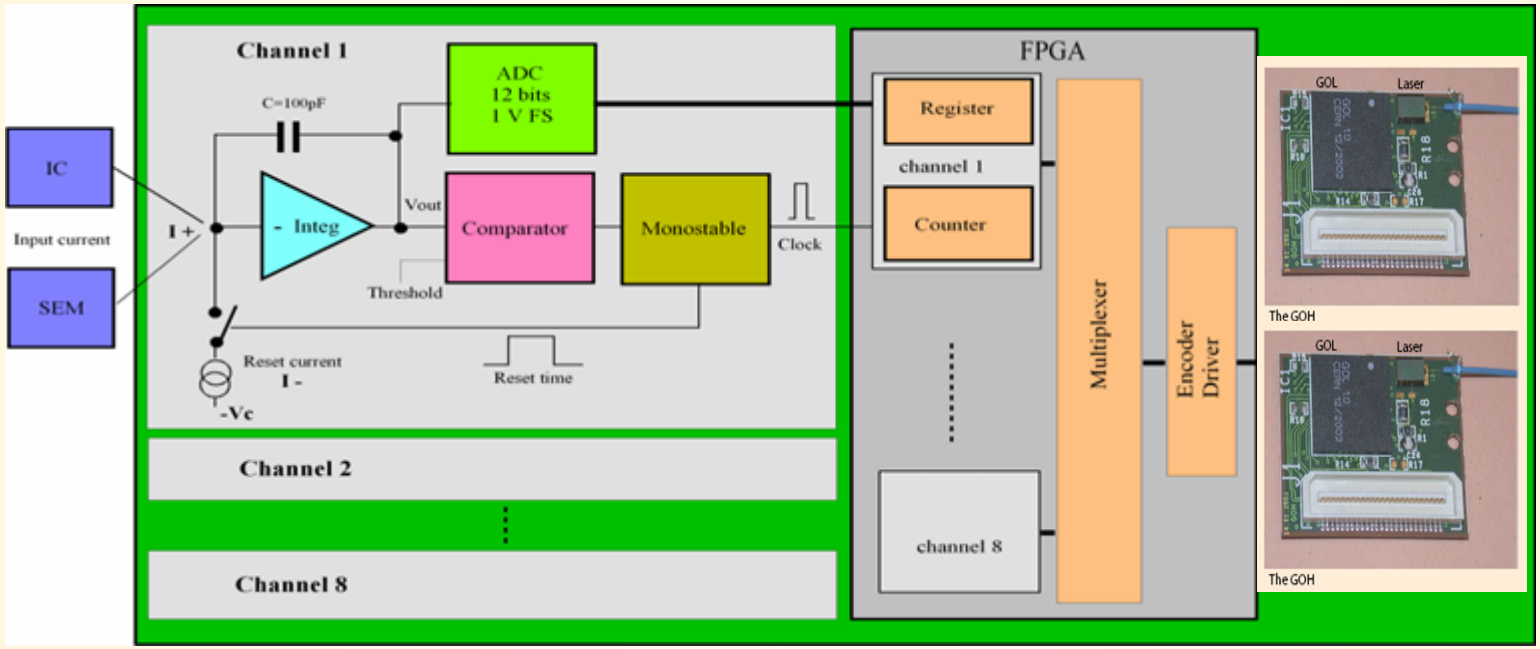
- Independent operation form crate CPU (FNAL, LHC)
- Thresholds managed by control card over control bus (LHC combined)

LHC tunnel card

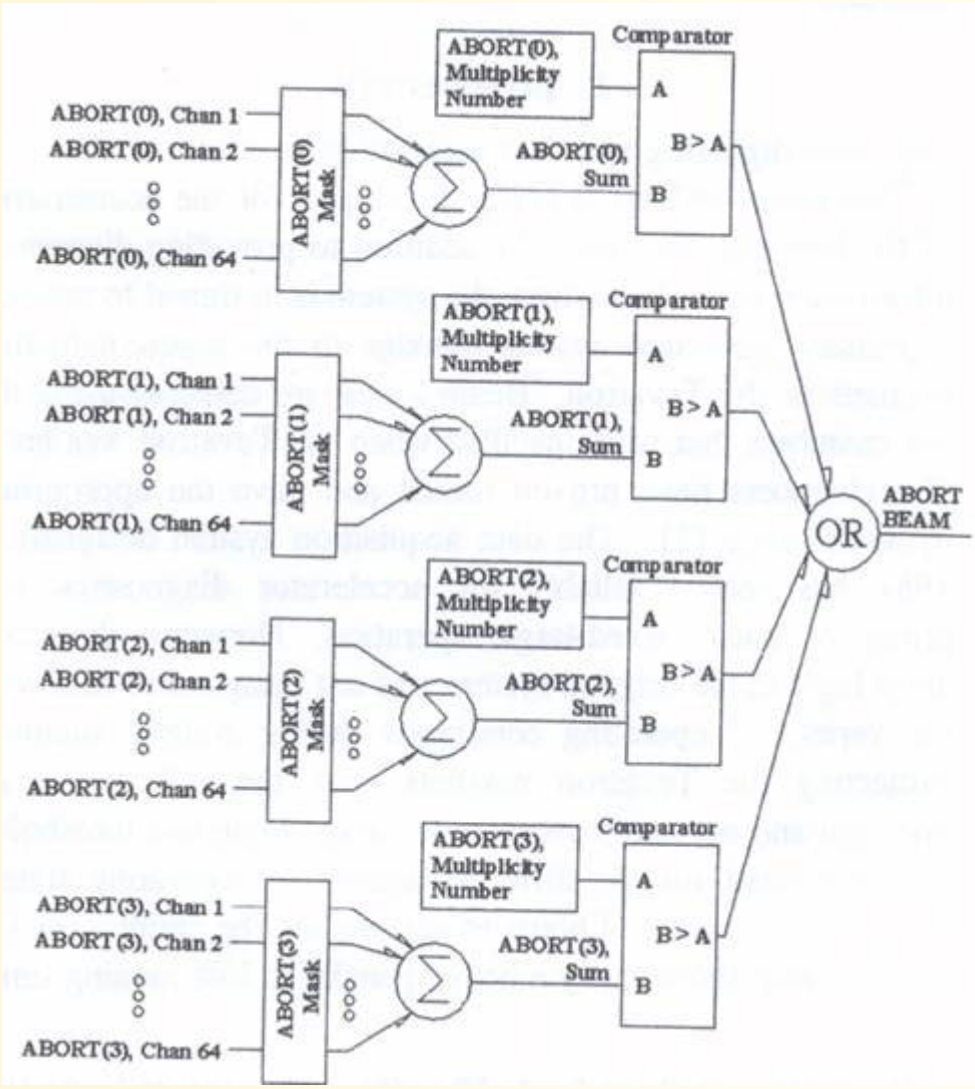
- Not very complicated design "simple"
- Large Dynamic Range (8 orders)
  - Current-to-Frequency Converter (CFC)
  - Analogue-to-Digital Converter
- Radiation tolerant (500 Gy, 5 10^8 p/s/cm^2)
  - Bipolar
  - Customs ASICs
  - Triple module redundancy



100 ns 100 ns to 100 s



FNAL abort concentrator



- Measurements and threshold are compared every 21 μs (fastest) (LHC 80 μs)
- Channels can be masked (LHC yes)
- Aborts of particular type are counted and compared to the required multiplicity value for this type (LHC: single channel will trigger abort, channel can be masked depending on beam condition)
- Ring wide concentration possible (LHC no)