

LHC Machine Protection

B. Dehning

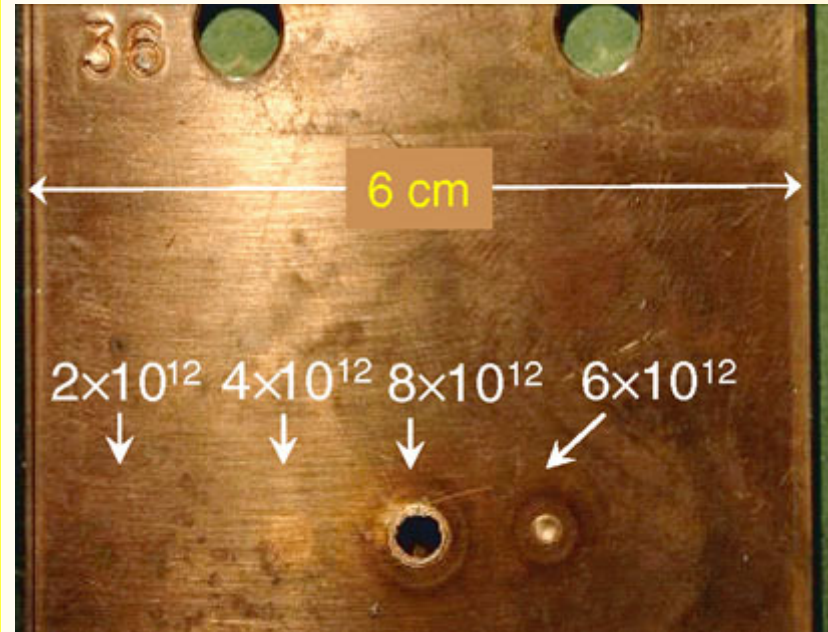
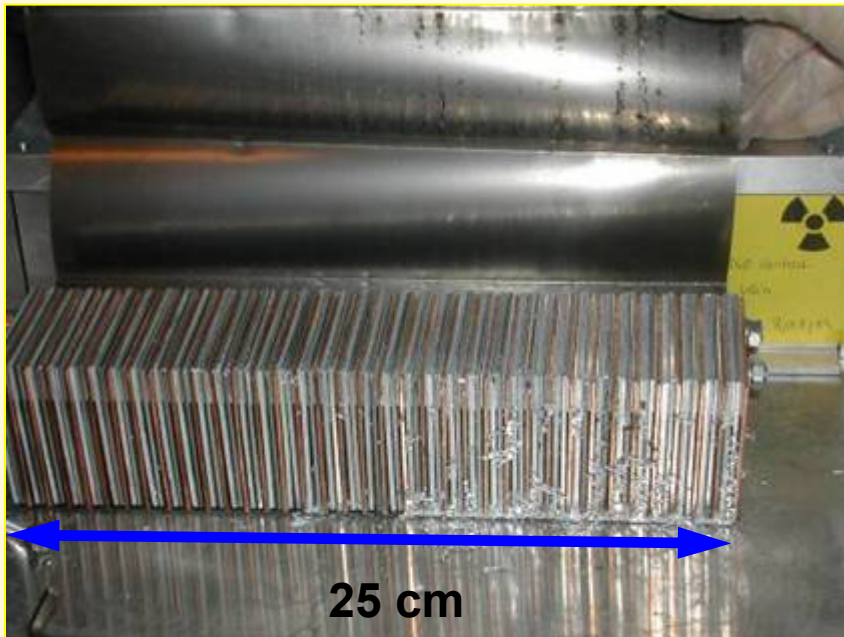
CERN AB/BI

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.

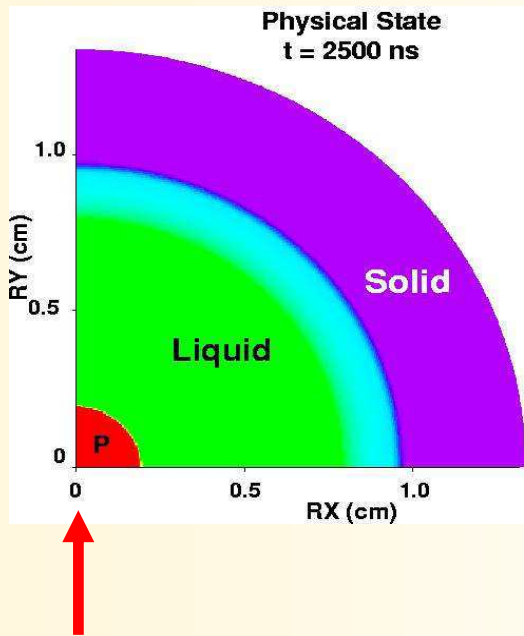


- Proton beam, 450 GeV, Cu, Fe sandwich target
- beam size $\sigma_{x/y} = 1.1\text{mm}/0.6\text{mm}$
- $2 \cdot 10^{12}$ no damage
- $8 \cdot 10^{12}$ damage

Safe at 0.6 % of
full LHC intensity

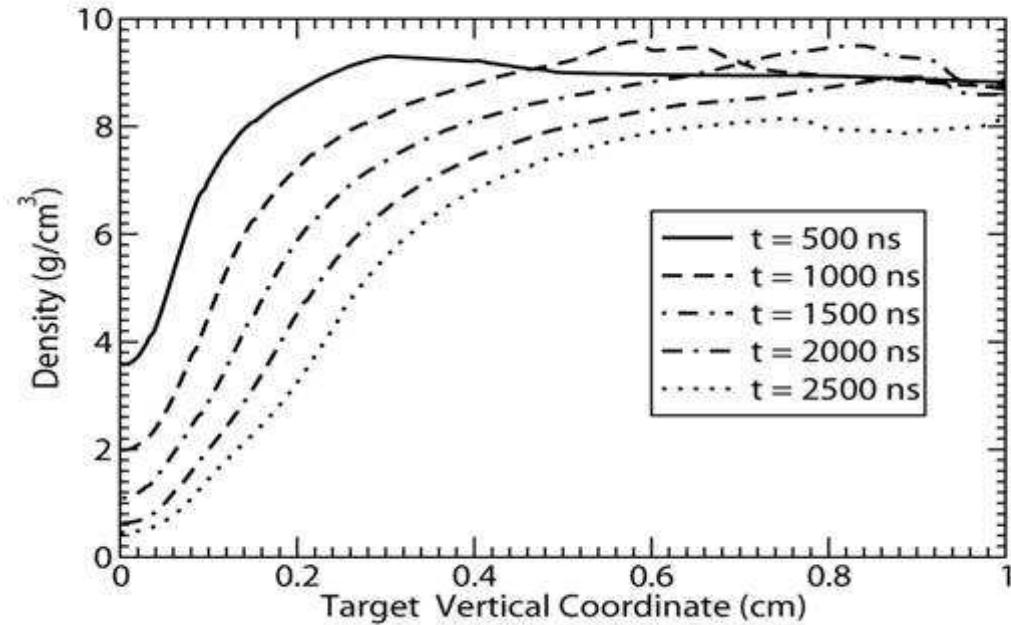
Density Change in Target after Impact of 100 Bunches

Cross sectional view



beam impact

At 16 cm in the target along the beam

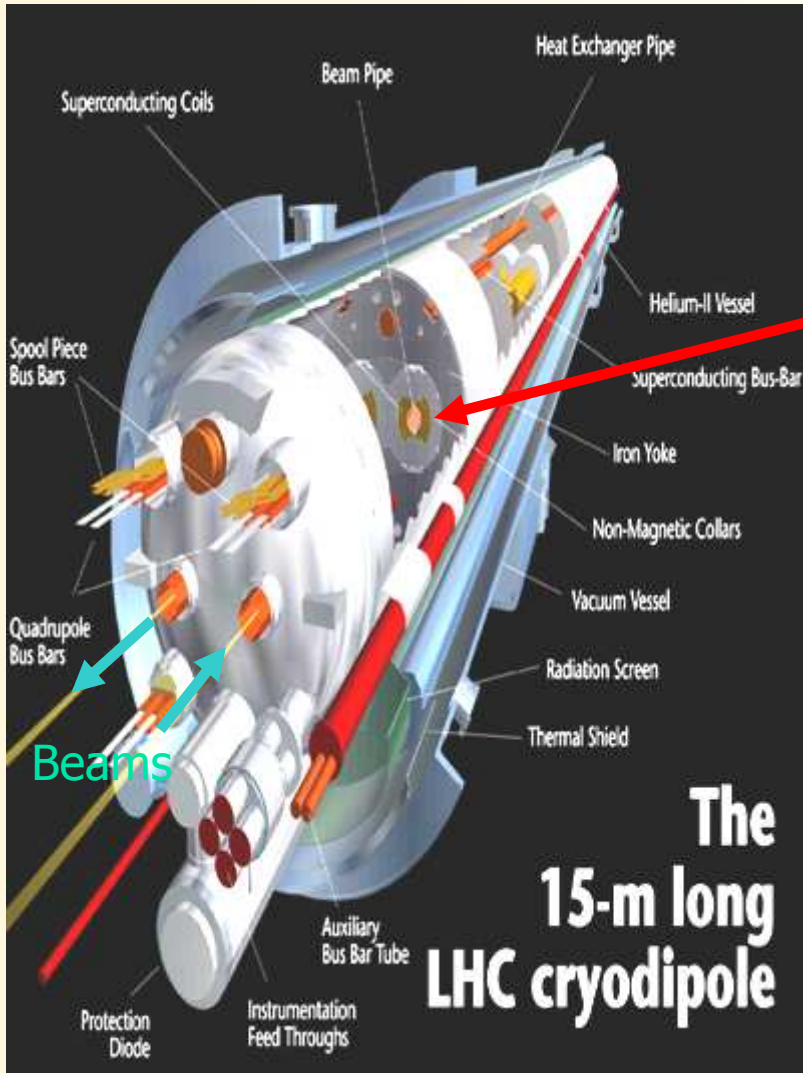


2 dimensional hydrodynamic computer code, N.A. Tahir et al.

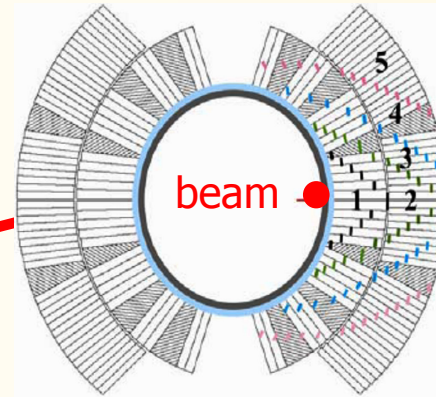
Reduction of density by a factor 10

Magnet Quenches

D. Bocian et al.



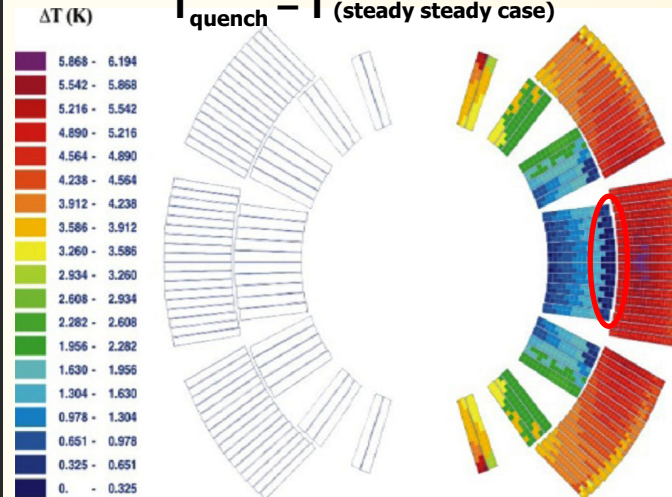
cross sectional view of coil



Energy deposition by the beam

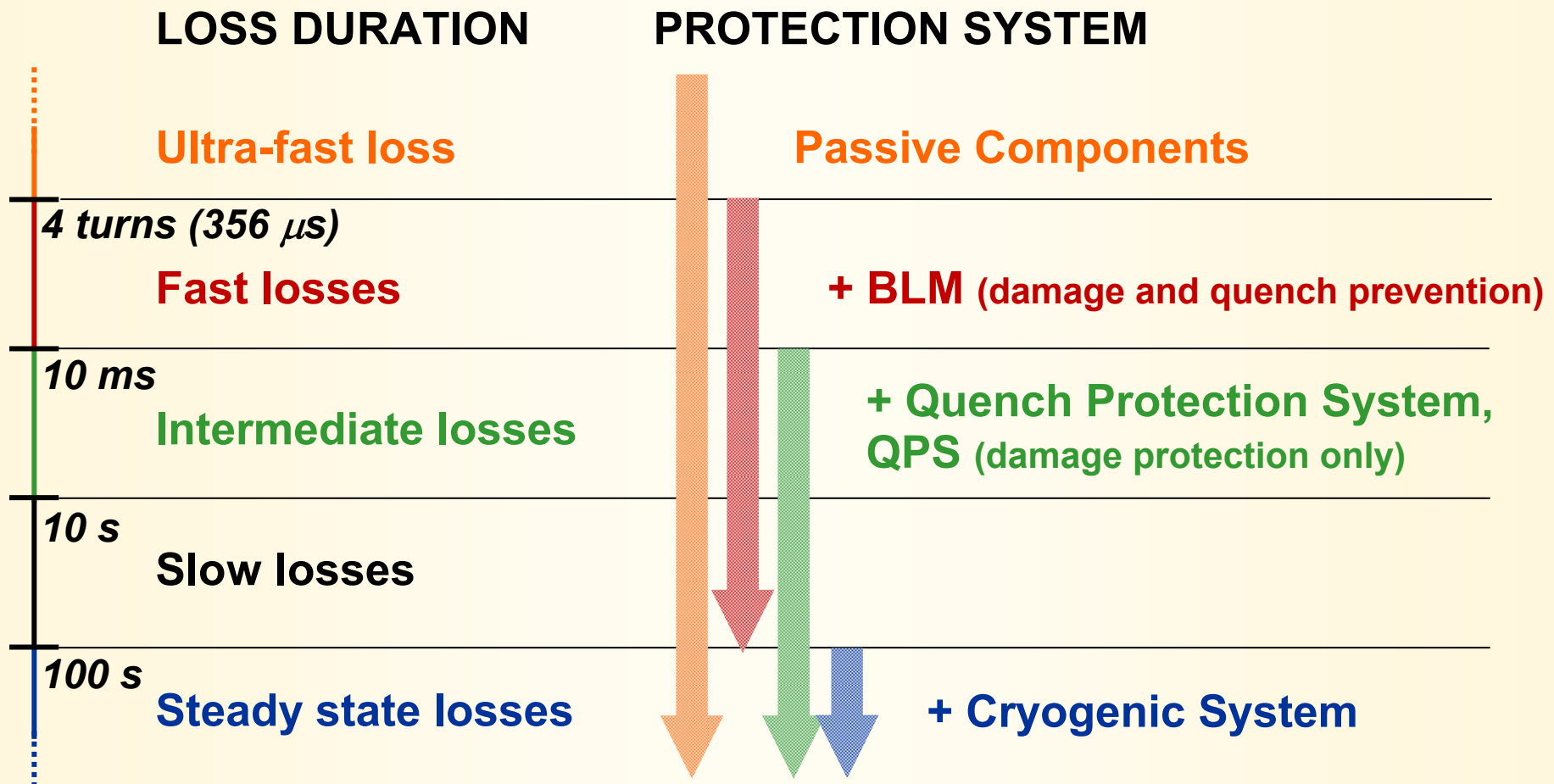
Temperature difference

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



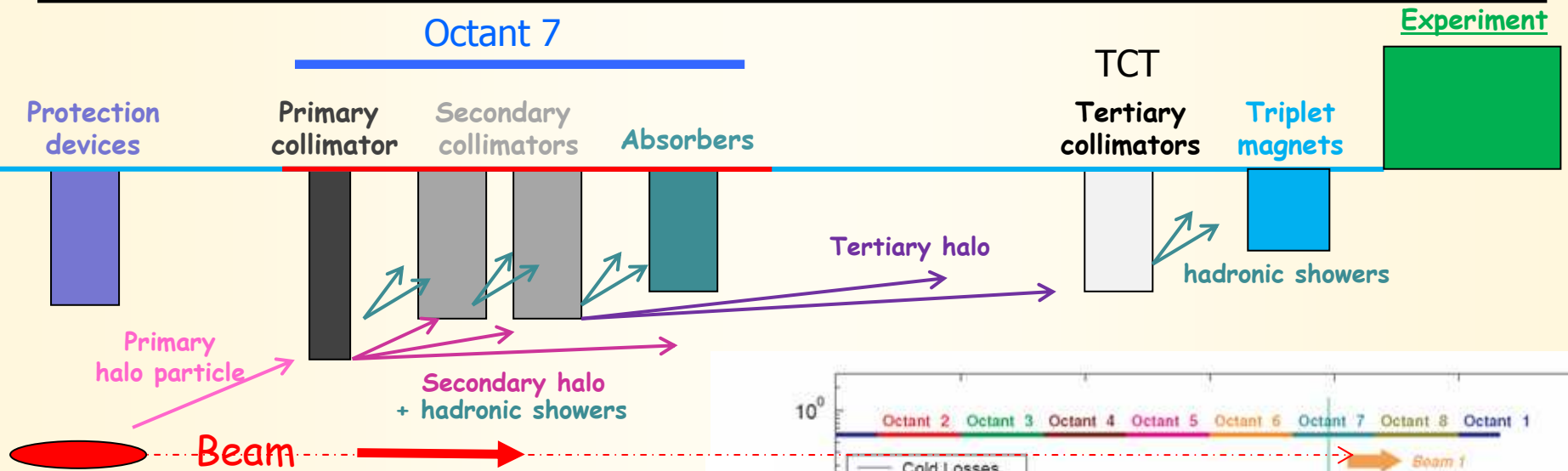
Location of QUENCH

Beam Loss Durations and Protection Systems

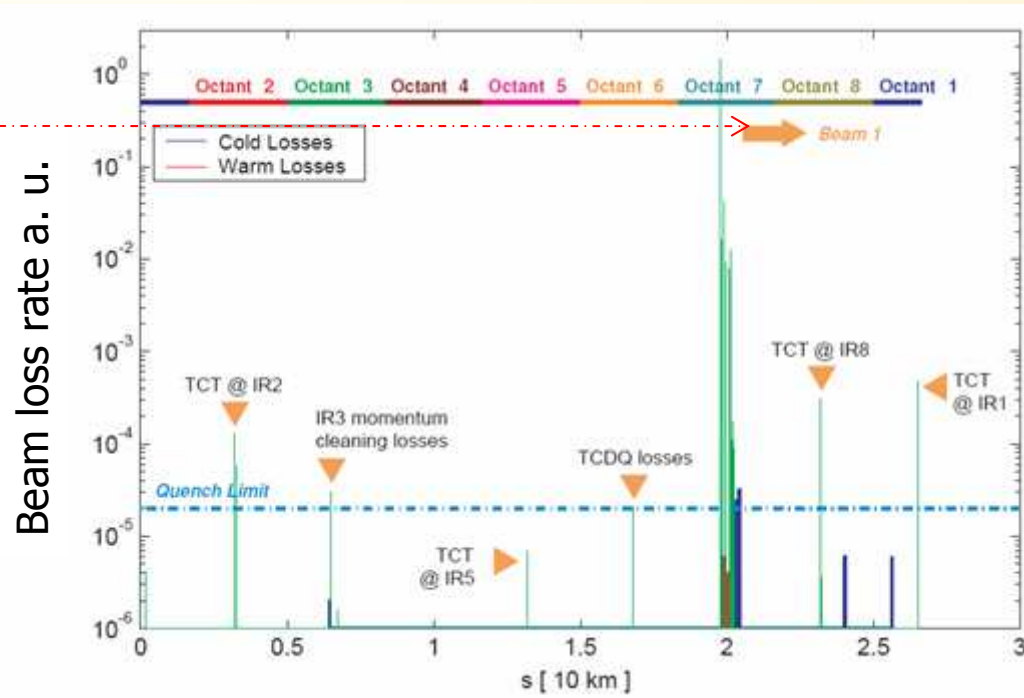


Since not active protection possible for ultra-fast losses => passive system

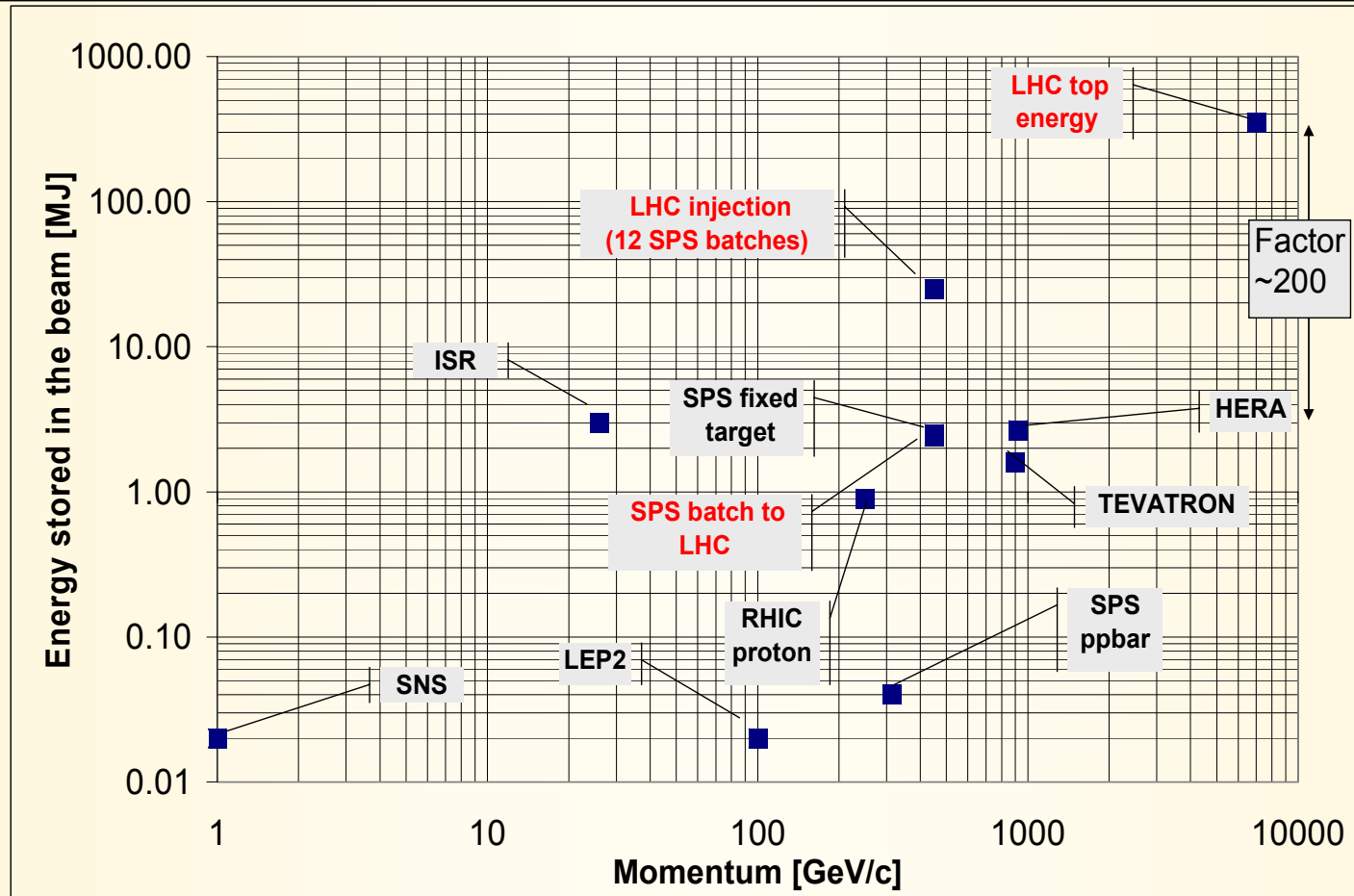
Collimators and Absorbers



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

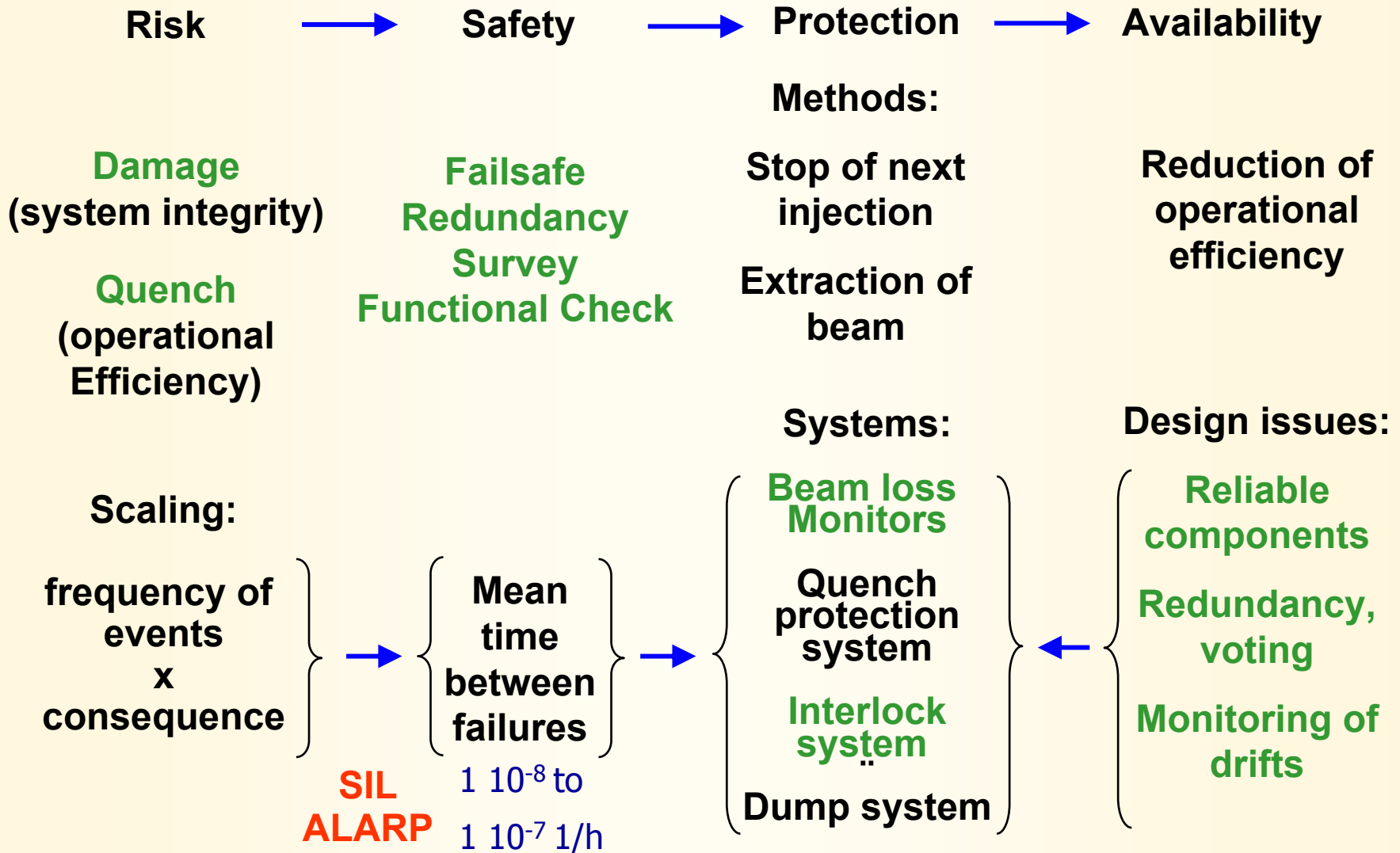


Stored Beam Energies

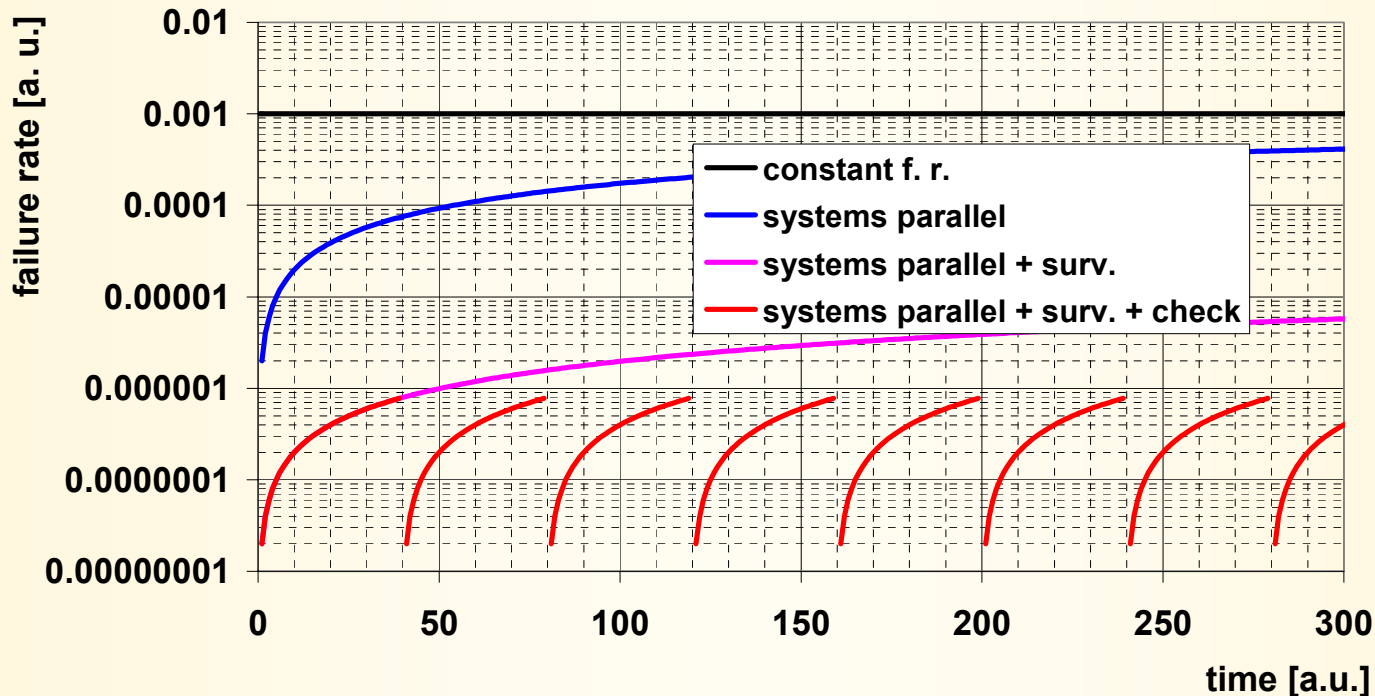


LHC will be exceptional => High RISK

Safety System Design Approach



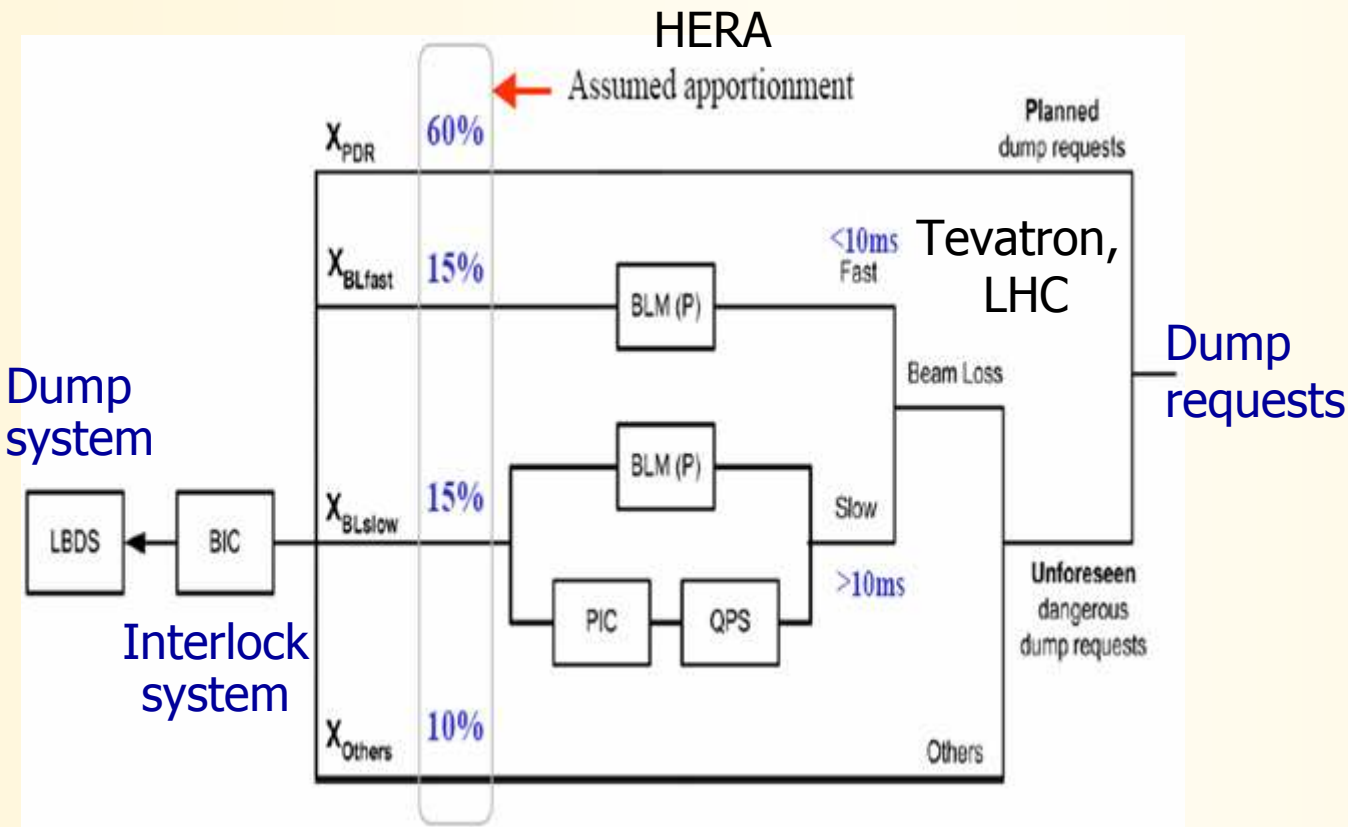
Failure Rate and Checks



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**

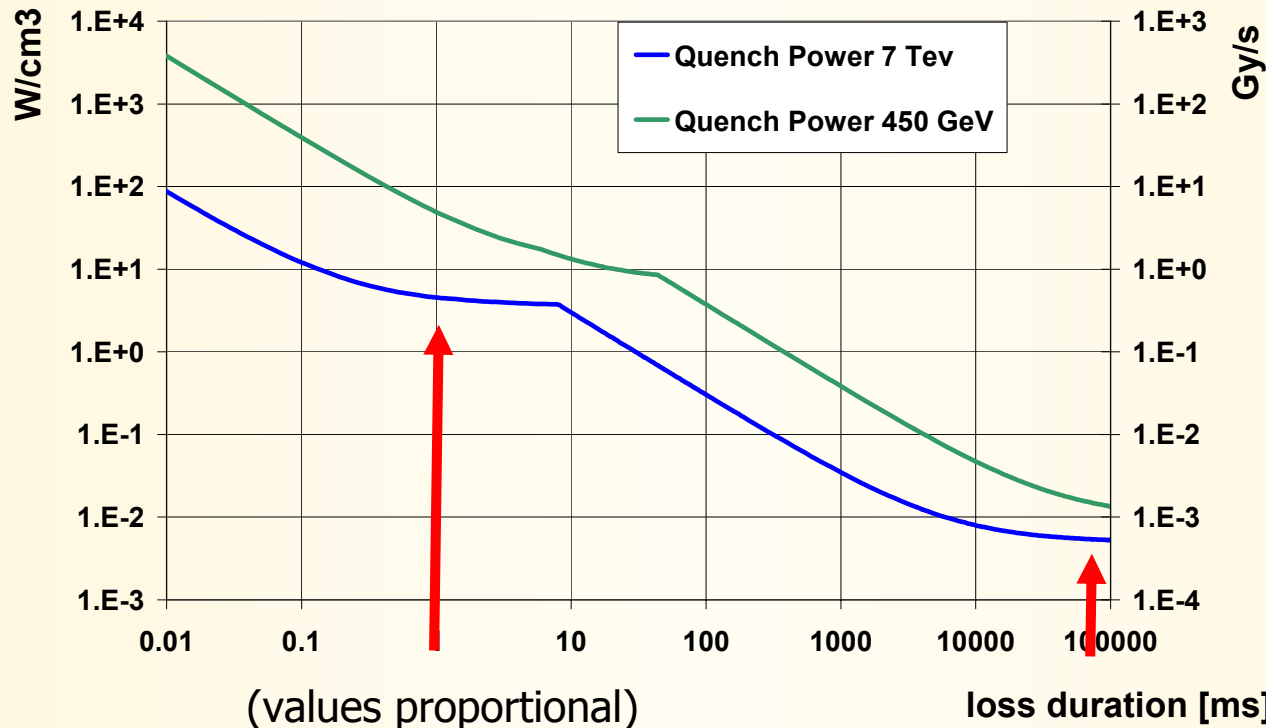
The Active Protection System



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)

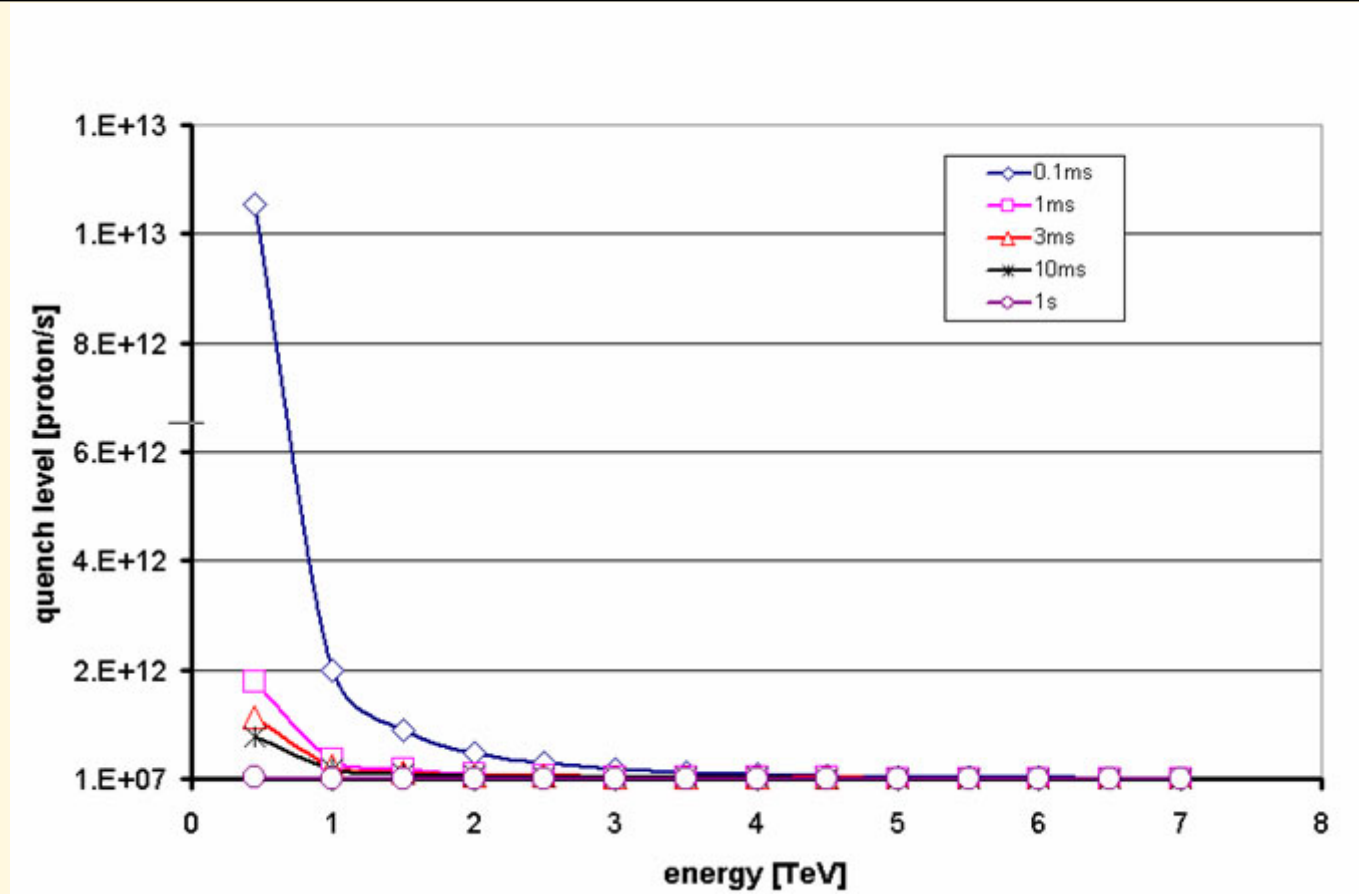
loss duration [ms]

loss duration	W/cm ³
13 us	4.50E-03
Tevatron	1.80E-02
RHIC	8.70E-04
LHC	2.6 – 6.6 E-03
DESY	

loss duration	W/cm ³
steady state	7.47E-02
Tevatron	7.47E-02
RHIC	5.29E-03
LHC	

LHC quench values are lowest

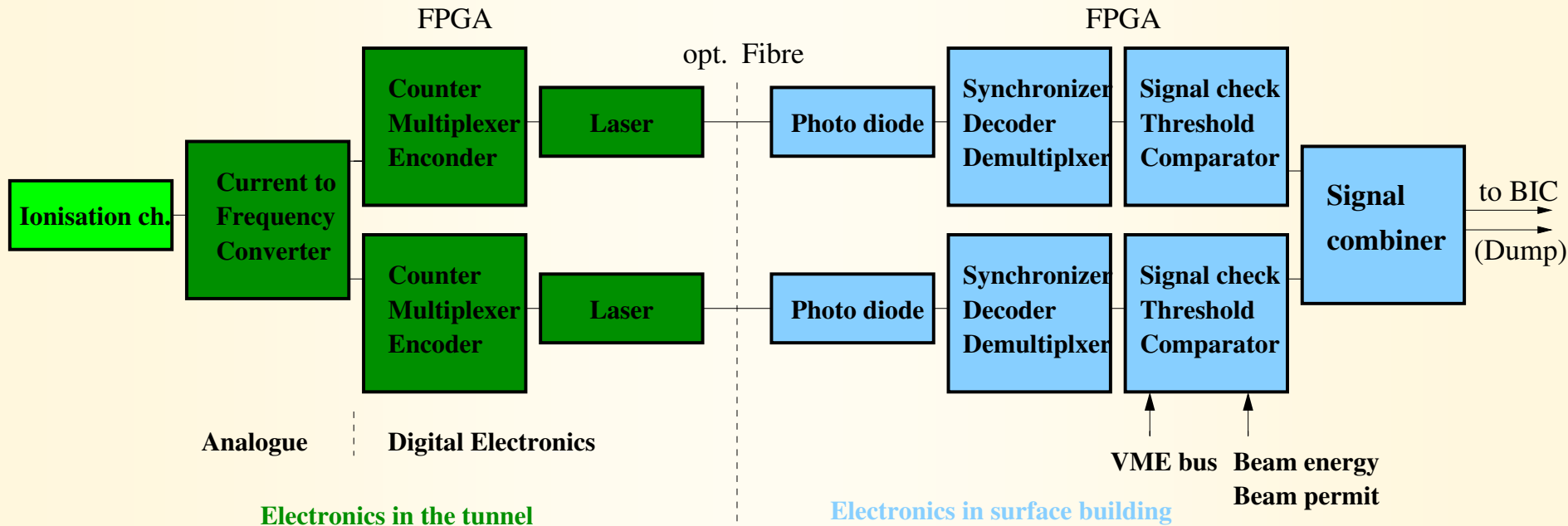
Quench Levels and Energy Dependence



- 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 steel 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:

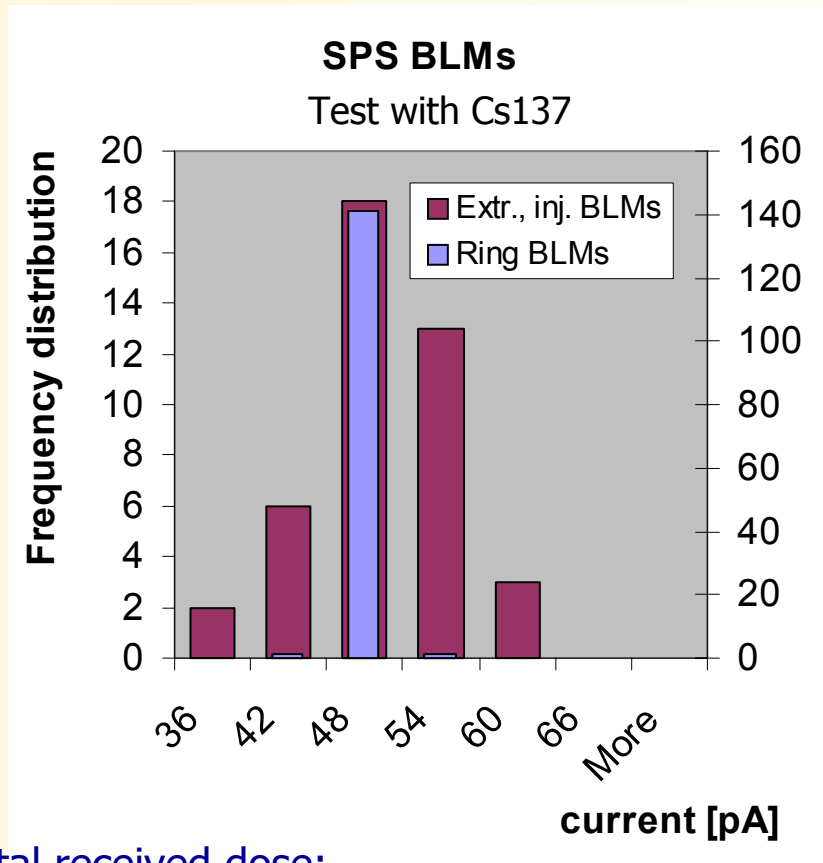
- Al electrodes
- Length 60 cm
- Ion collection time 85 us
- N₂ gas filling at 1.1 bar
- Sensitive volume 1.5 l

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:

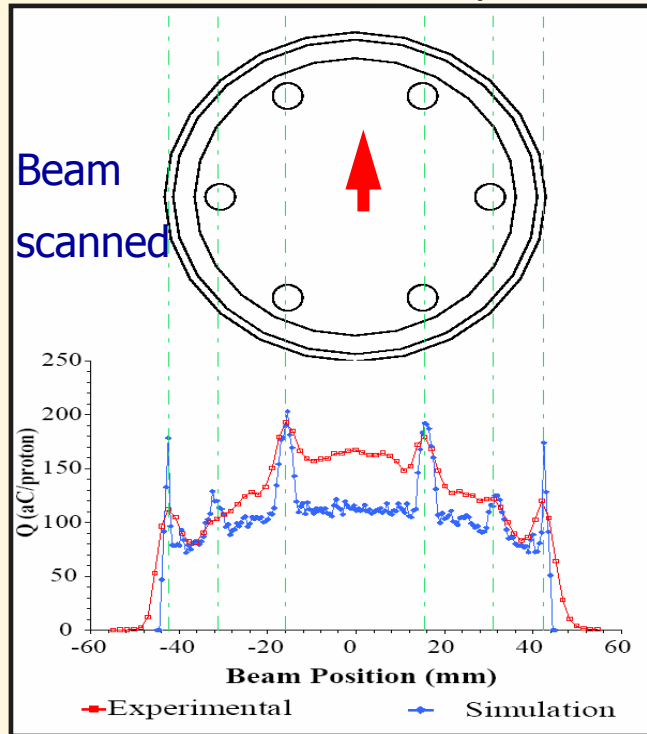
ring 0.1 to 1 kGy/year
extr 0.1 to 10 MGy/year

- 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

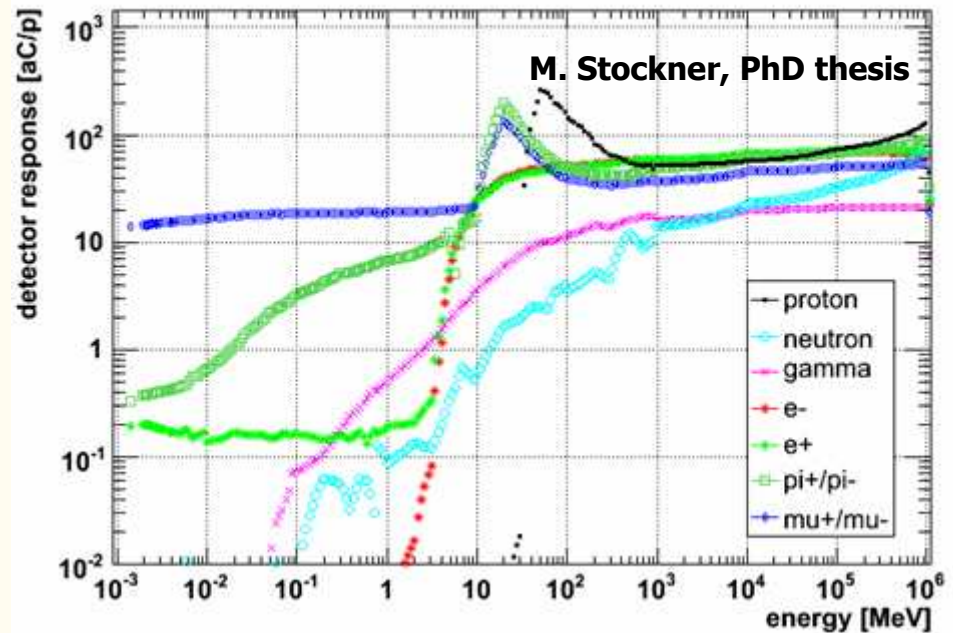
Reliable component

Ionisation Chamber Simulation and Measurements

Ionisation chamber top view



Ionisation chamber response function



■ Comparison simulation measurements

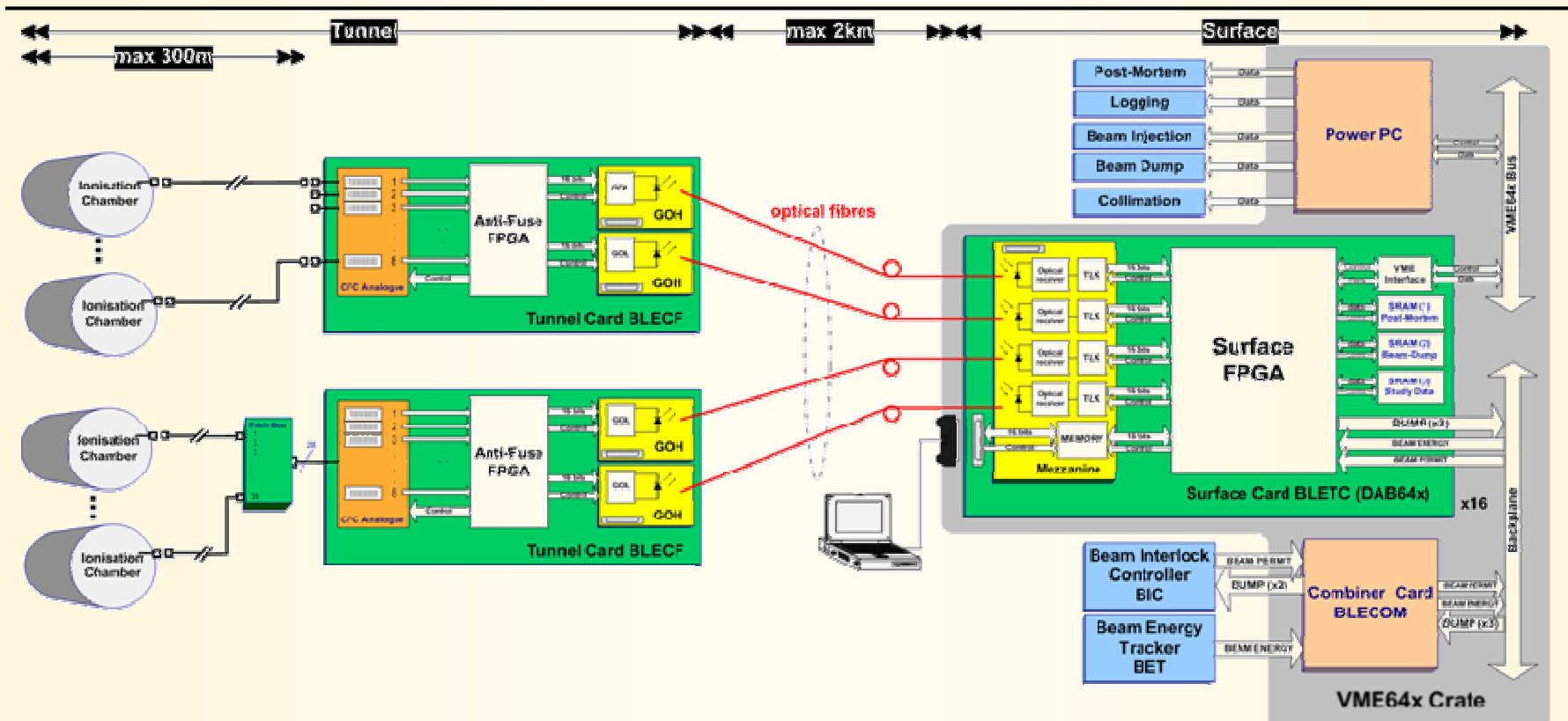
	Rel. diff %	Error %
Proton	13.1	11.4
Gamma	14.3	12.1
neutron	37.4	13.9
Mixed field	20.5	11.4

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

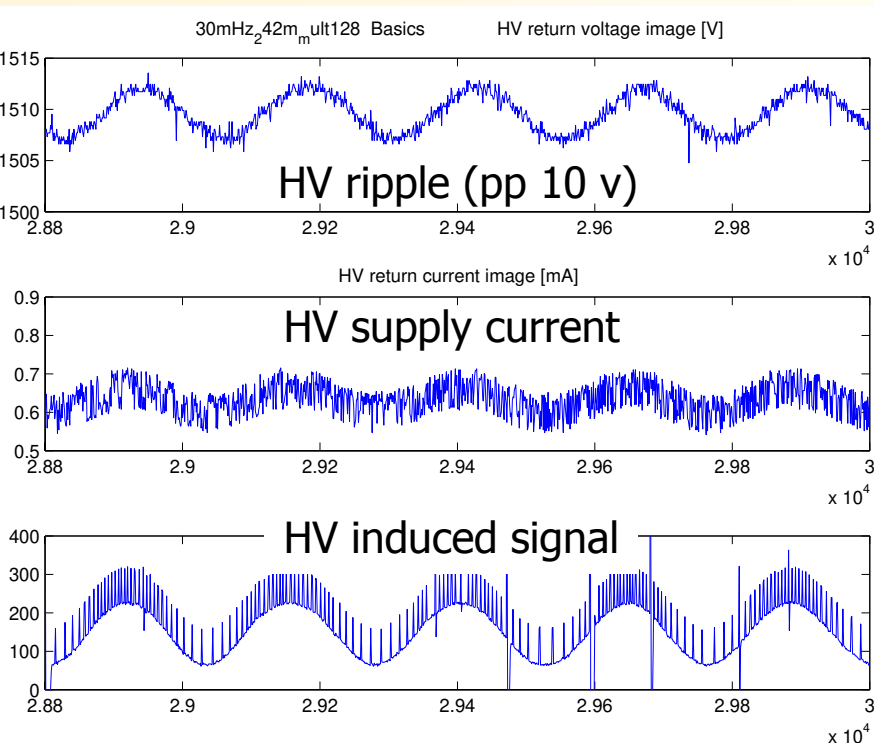
- Current to Frequency Converters (CFCs)
- Analogue to Digital Converters (ADCs)
- Tunnel FPGAs:
Actel's 54SX/A radiation tolerant.
- Communication links:
Gigabit Optical Links.

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



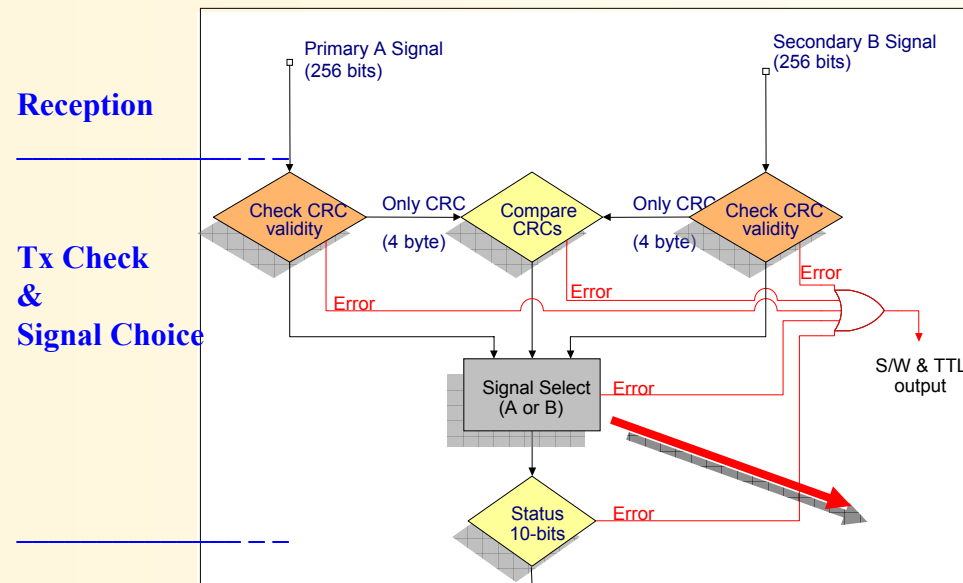
Basic concept:

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



At the Surface FPGA:

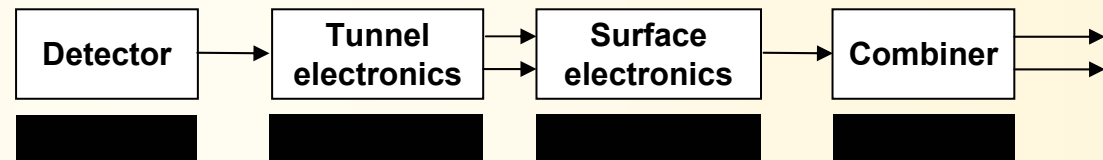
- **Signal CRC-32**
 - Error check / detection algorithm for each of the signals received.
 - Comparison of the pair of signals.
 - Select block
 - Logic that chooses signal to be used
 - Identifies problematic areas.
- Tunnel's Status Check block
 - HT, Power supplies
- FPGA errors
 - Temperature

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)

Functional Tests Overview

PhD thesis G. Guaglio



Functional tests before installation

Barcode check

Current source test

Radioactive source test

HV modulation test

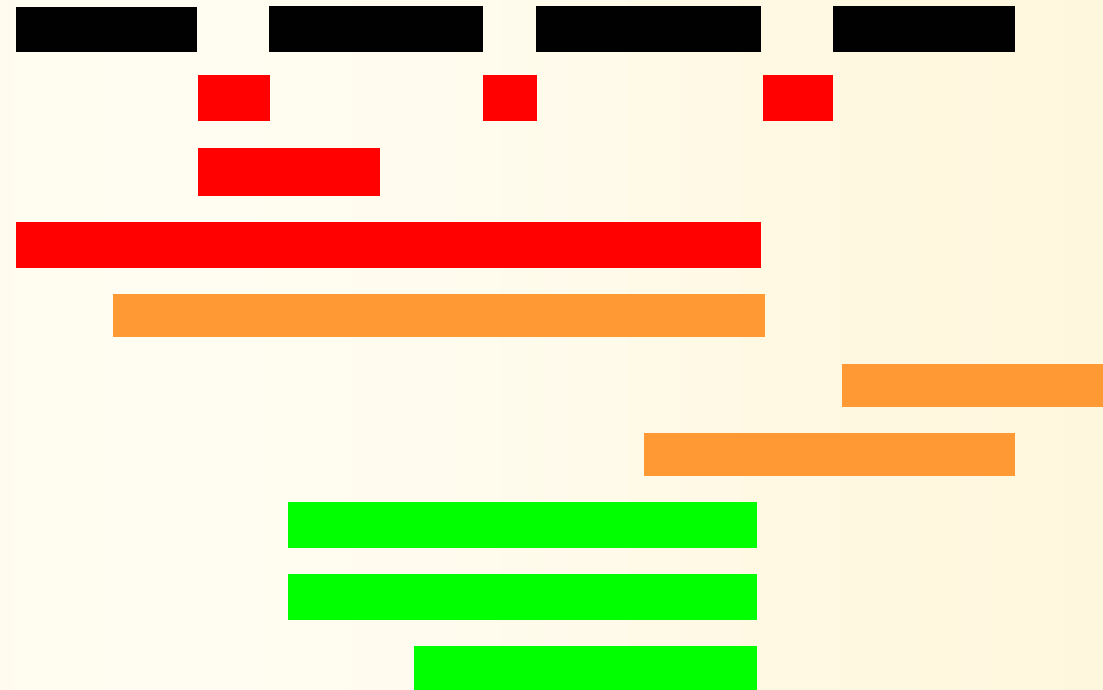
Beam inhibit lines tests

Threshold table data base comparison

10 pA test

Double optical line comparison

System component identity check

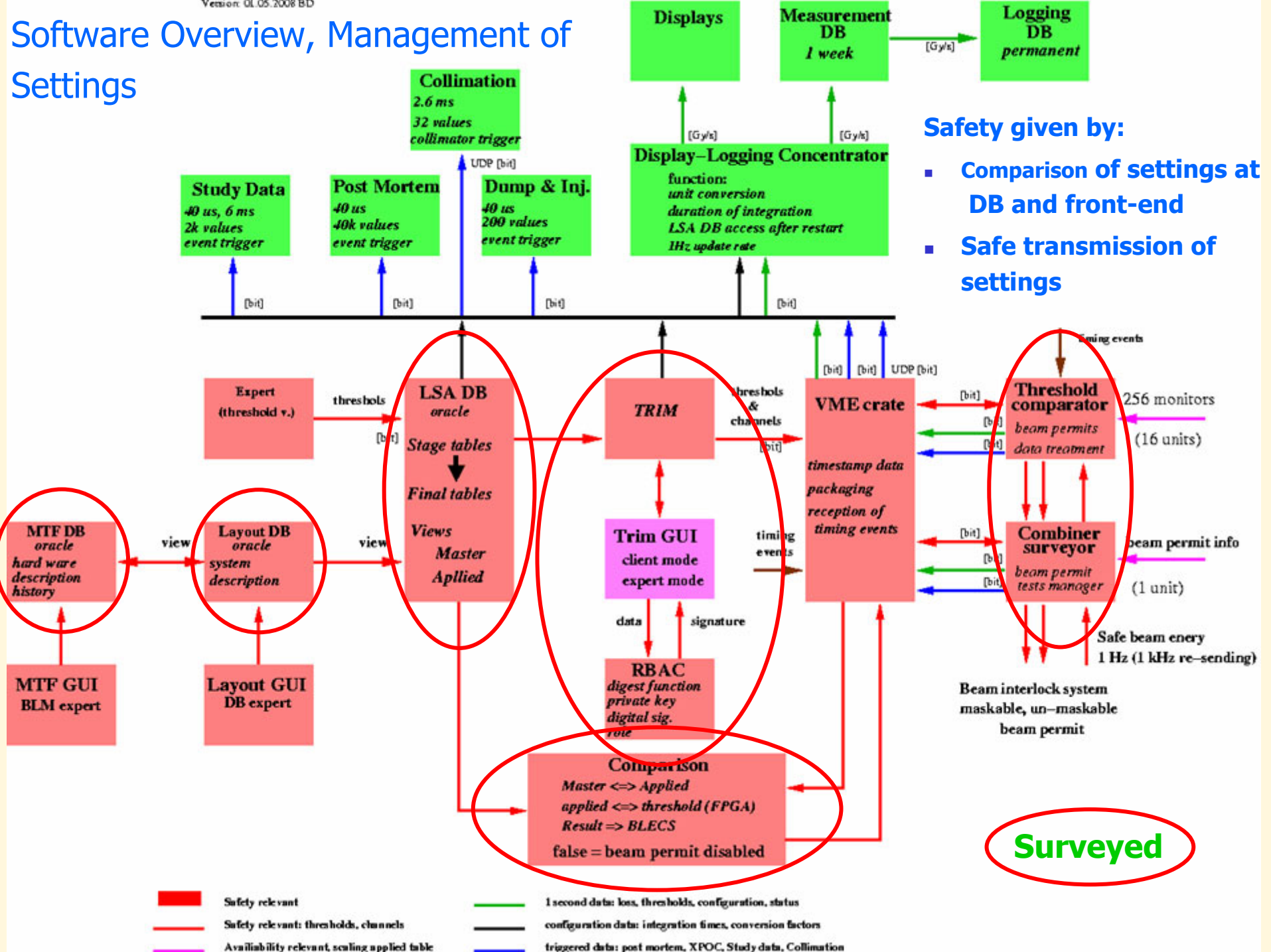


Inspection frequency:

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

Functional checks – Monitoring of drifts

Software Overview, Management of Settings

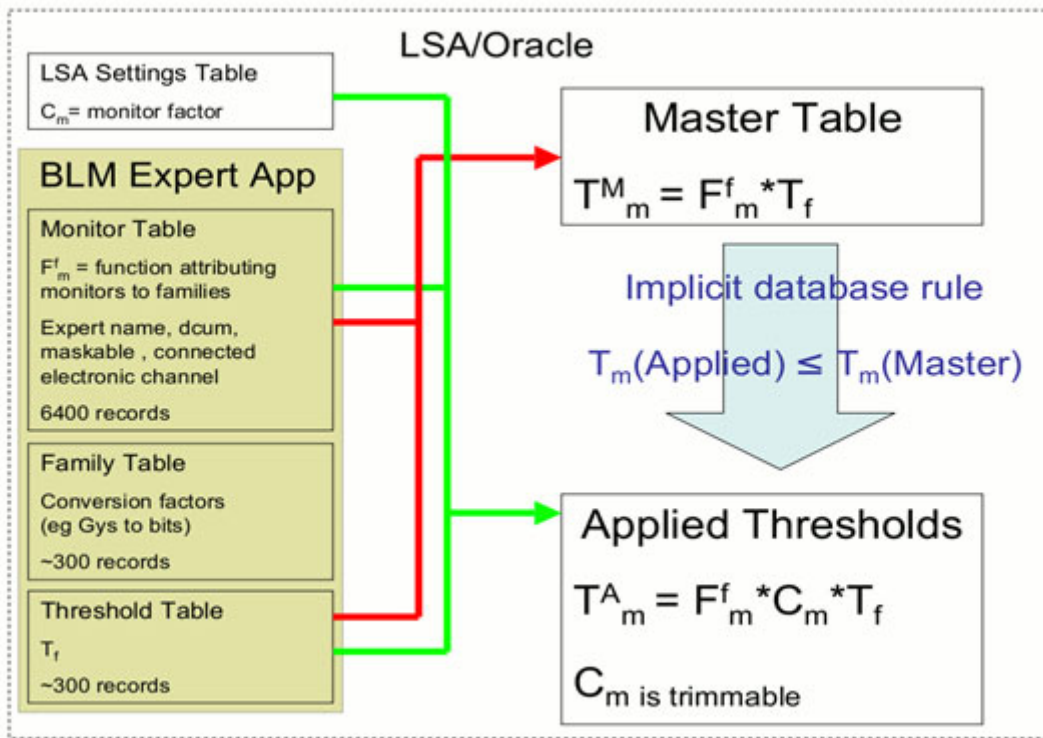


Safety given by:

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

Surveyed

Data Base Structure

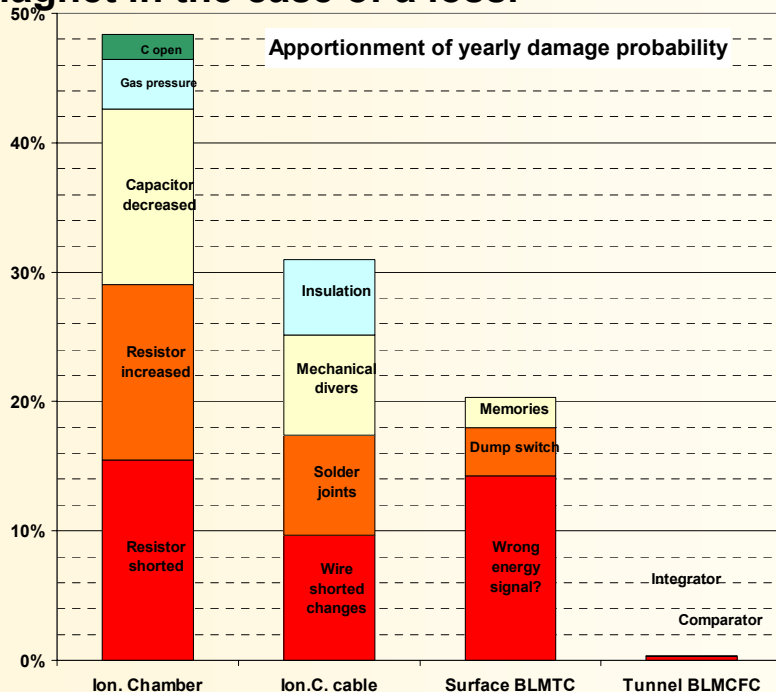


- Two layers
 - entry layer (stage tables)
 - validated layer (final tables)
- Concept of Master and Applied table – Comparison of Threshold values (Applied < Master)
 - Master: less frequent changes
 - Applied: change of thresholds possible with user interface

Failsafe

Reliability Study – Fault-Tree Approach

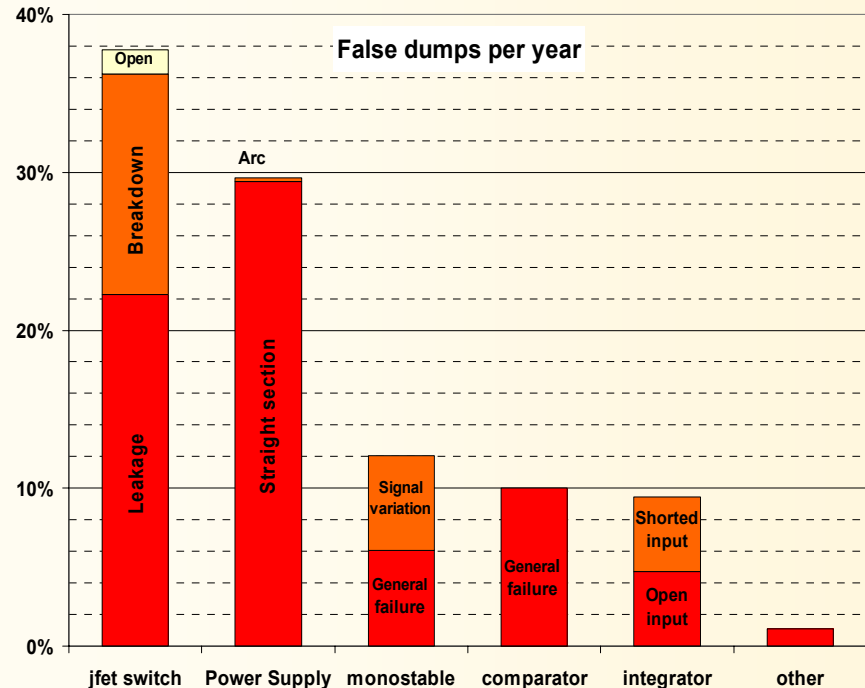
Relative probability of a system component being responsible for a damage to an LHC magnet in the case of a loss.



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

1. Reduced checks
2. Harsh environment

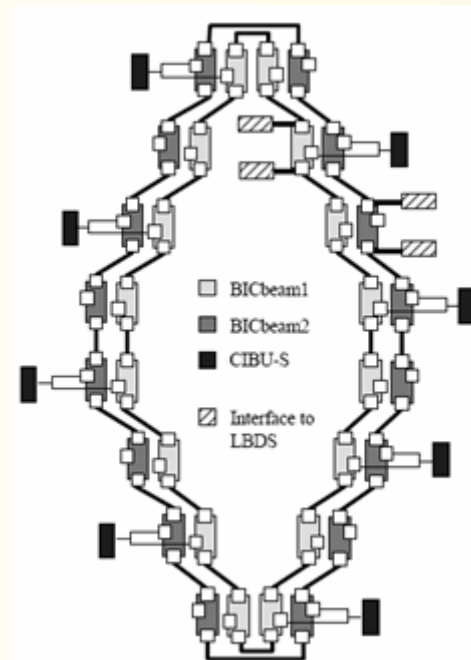
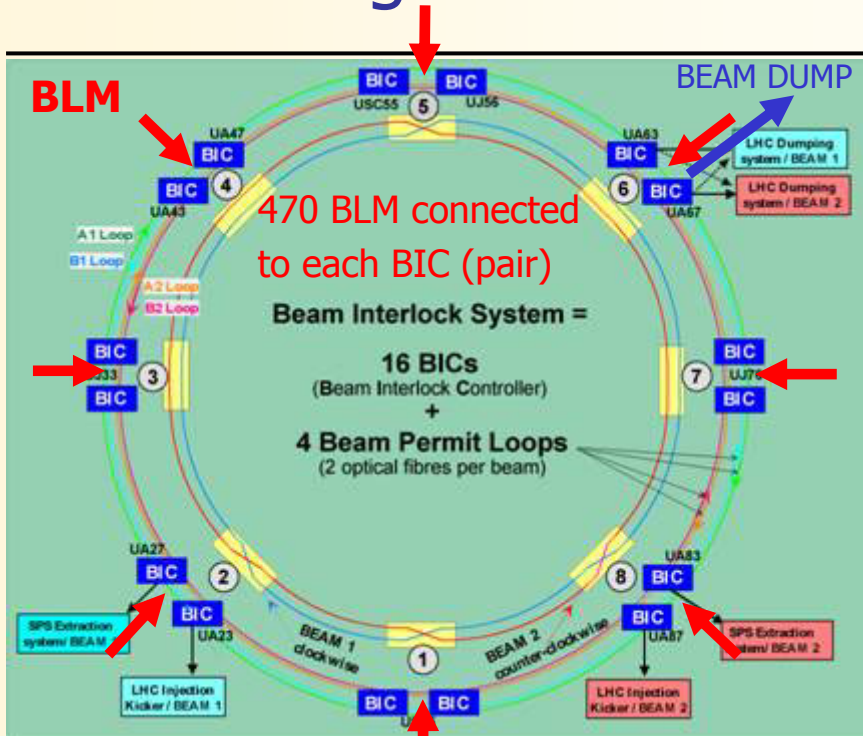
Relative probability of a BLM component generating a false dump. *by G. Guaglio*



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

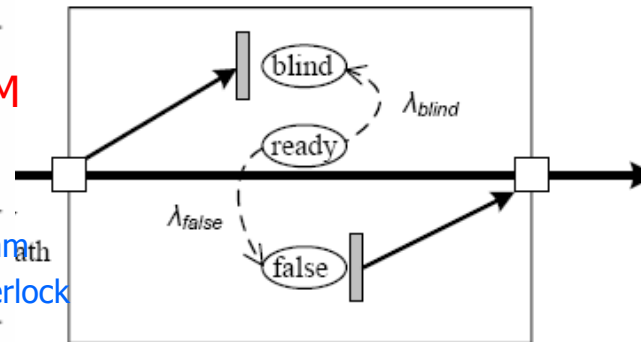
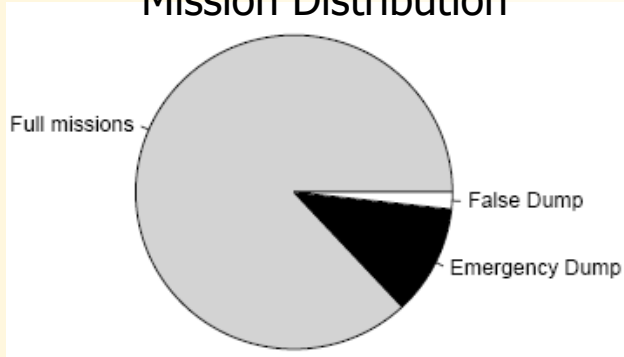


Table 2: Failure rates of the components

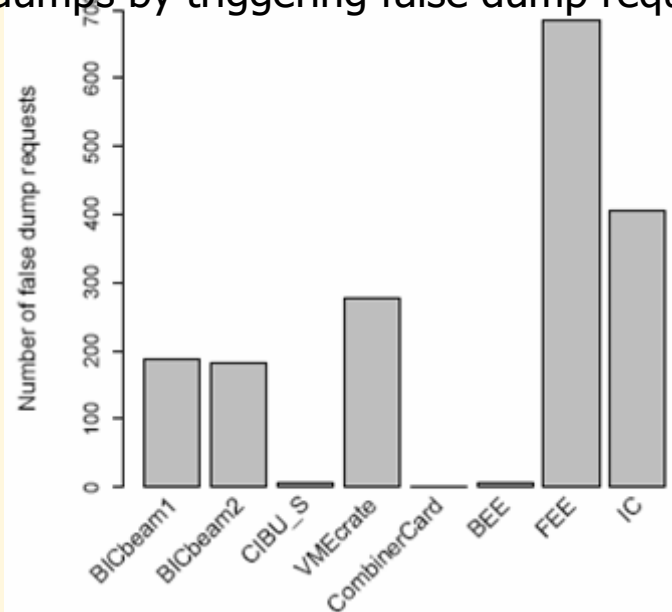
i	Component i	Rate λ_i^{false} 1/h	Rate λ_i^{blind} 1/h
1	IC	1E-7	1E-7
2	FEE	1E-6	1E-8
3	BEE	1E-8	1E-9
4	Combiner Card	1E-8	1E-9
5	VME crate	1E-5	1E-8
6	CIBU-S	1E-6	1E-13
7	BICbeam1	1E-5	1E-13
8	BICbeam2	1E-5	1E-13

First Modelling Results

Mission Distribution



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

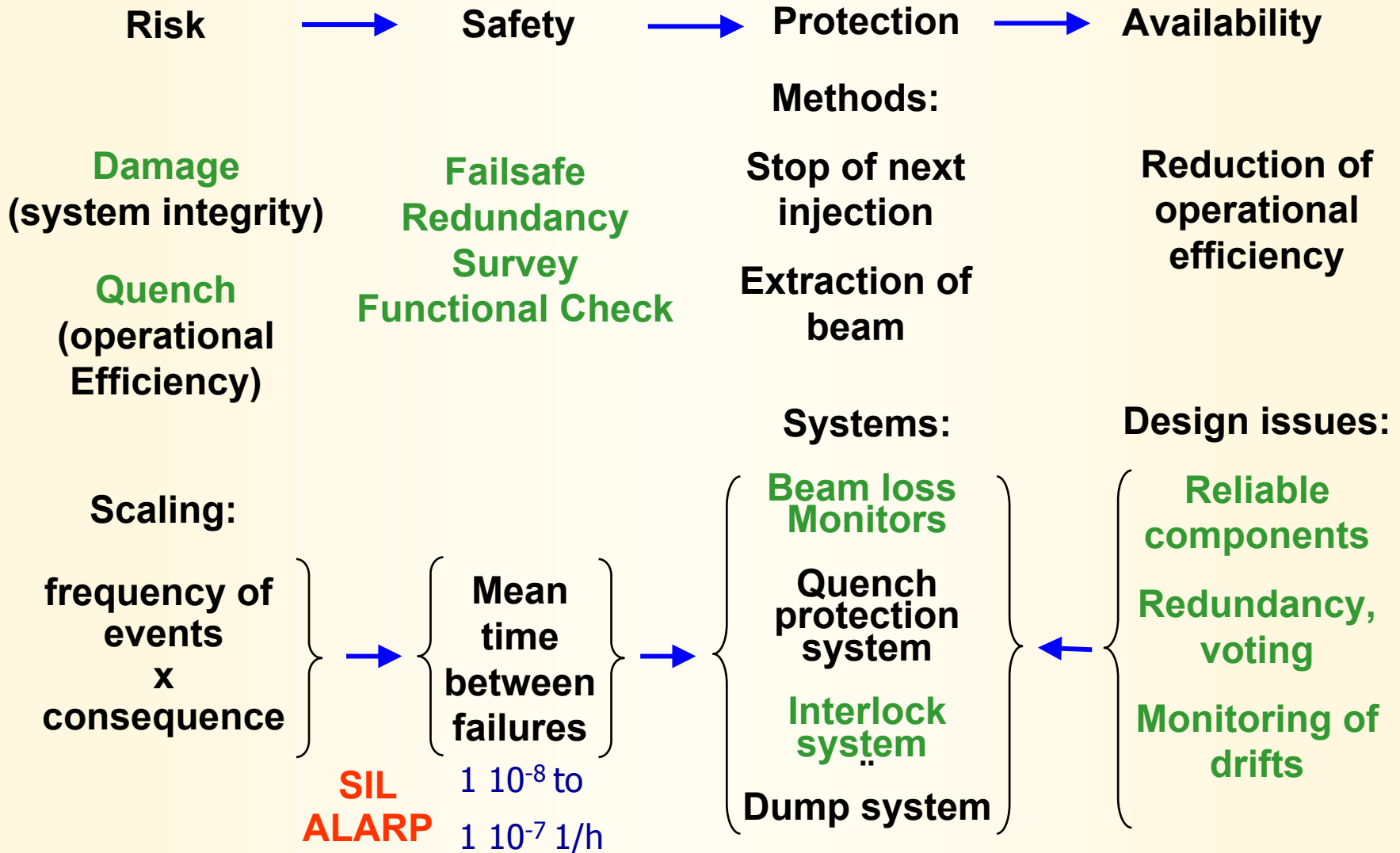


- fraction of early ended missions triggered by beam loss event **11.3%**
- false dump due to a false dump request by a component failure **1.7%**

- 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

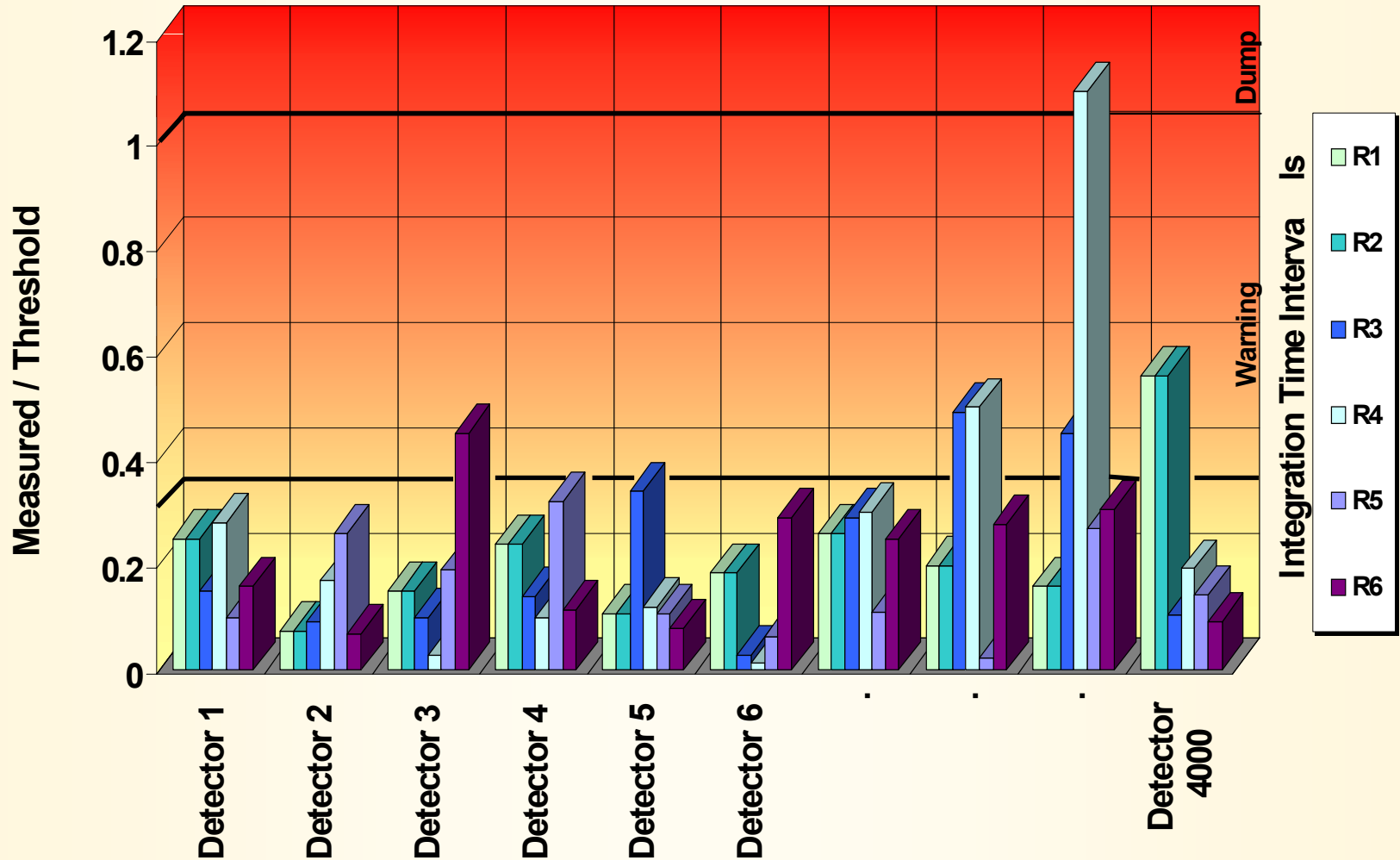


Literature

- <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 $1-2 \cdot 10^{12}$
- Damage level for fast losses at 7 TeV $1-2 \cdot 10^{10}$
- Quench level for fast losses at 450 GeV $2-3 \cdot 10^9$
- Quench level for fast losses at 7 TeV $1-2 \cdot 10^6$

Strategy for machine protection

- Definition of aperture by collimators.
- Early detection of failures for equipment acting on beams generates dump request, possibly before the beam is affected.
- Active monitoring of the beams detects abnormal beam conditions and generates beam dump requests down to a single machine turn.
- 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.
- Reliable operation of beam dumping system for dump requests or internal faults, safely extract the beams onto the external dump blocks.
- Passive protection by beam absorbers and collimators for specific failure cases.

Beam Cleaning System

**Powering Interlocks
Fast Magnet Current
change Monitor**

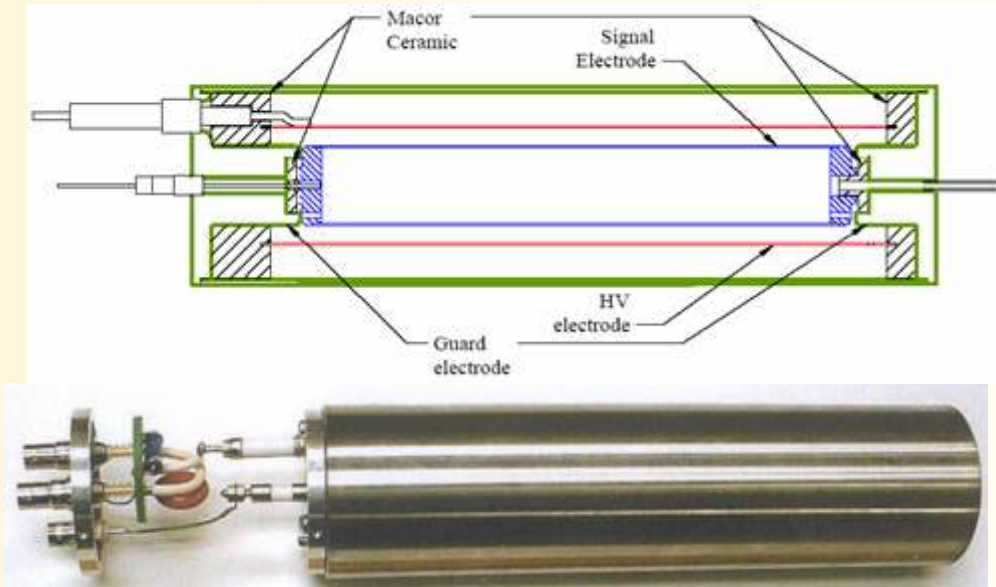
**Beam Loss Monitors
Other Beam Monitors**

Beam Interlock System

Beam Dumping System

Beam Absorbers

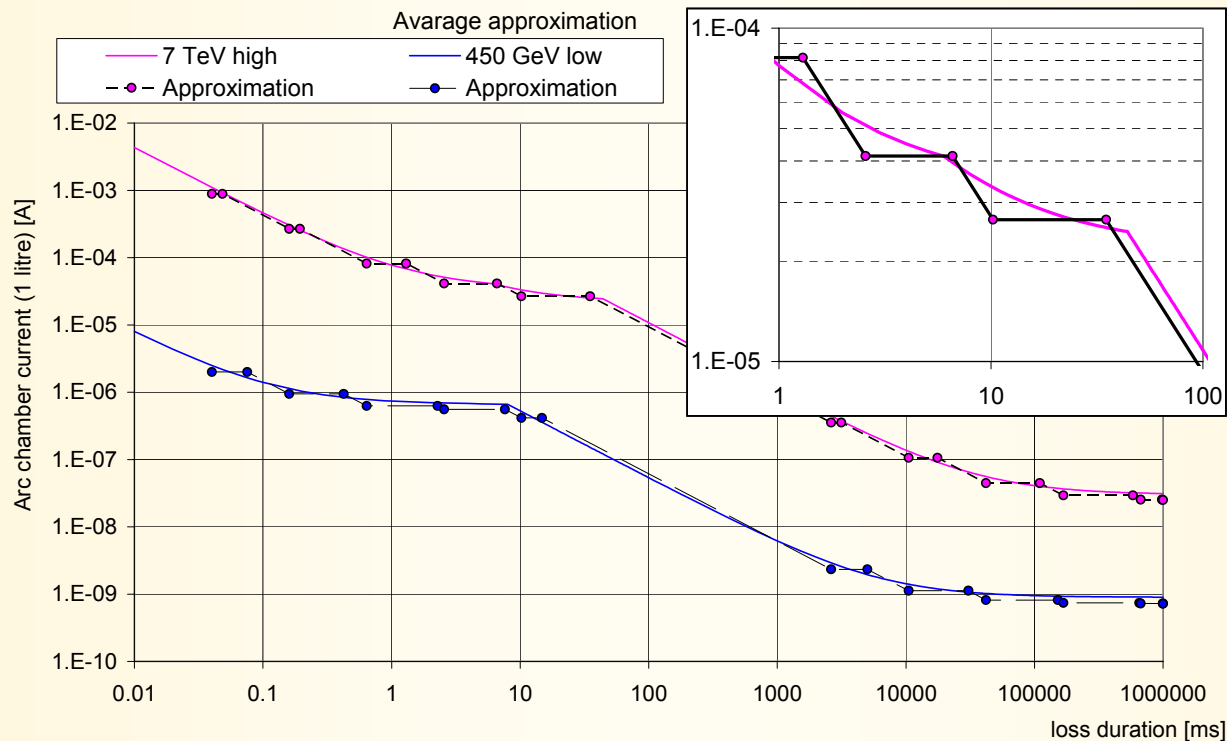
Ionisation chamber SNS



- Stainless steel
- Coaxial design, 3 cylinder (outside for shielding)
- Low pass filter at the HV input
- Ar, N₂ 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



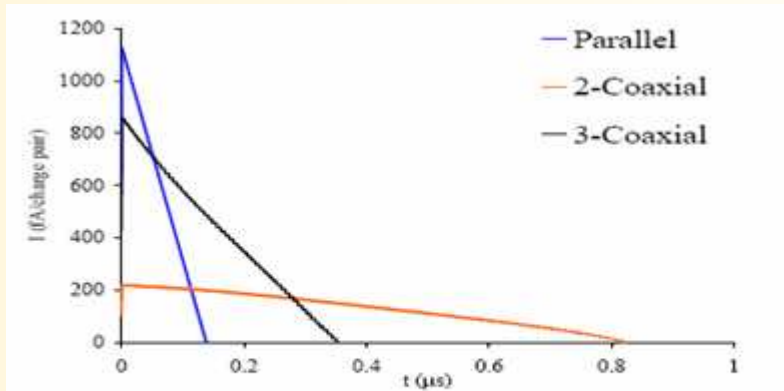
Approximation of Quench Levels (LHC)



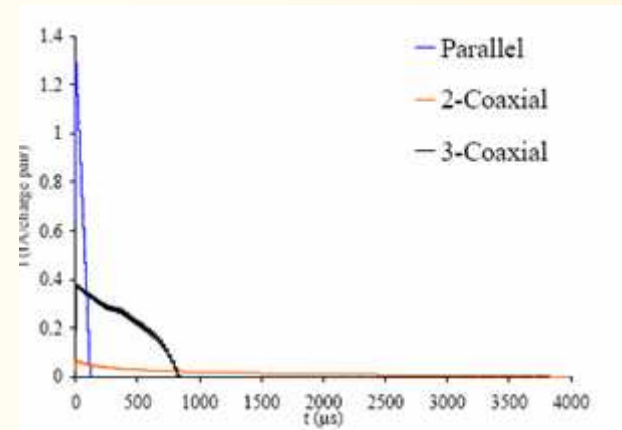
- Dump level tables are loaded in a non volatile RAM
- Any curve approximation possible
 - Loss durations
 - Energy dependence

Relative error kept
< 20 %

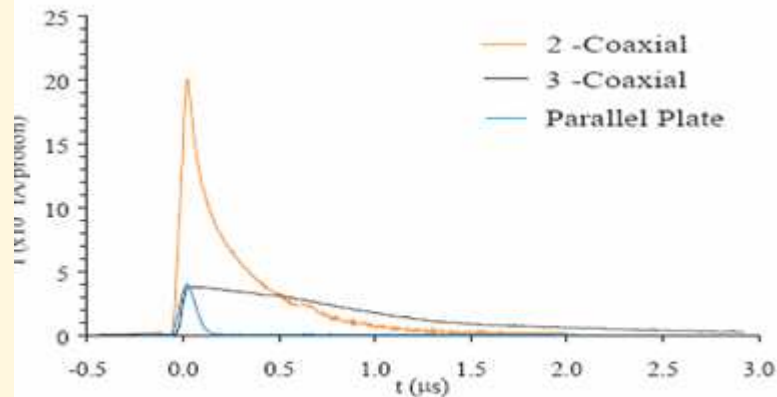
Drift times of electrons and ions (II)



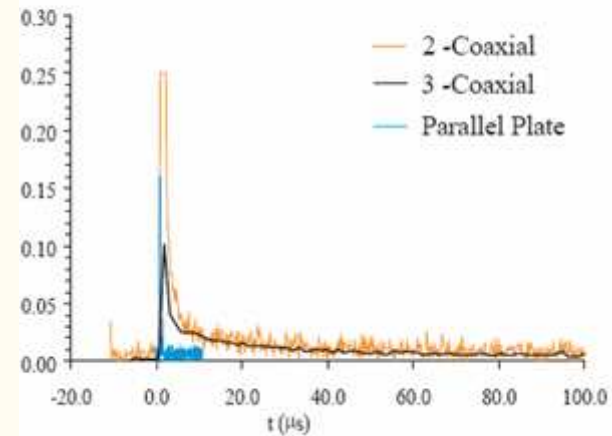
(a) *Simulated electrons*



(b) *Simulated ions*

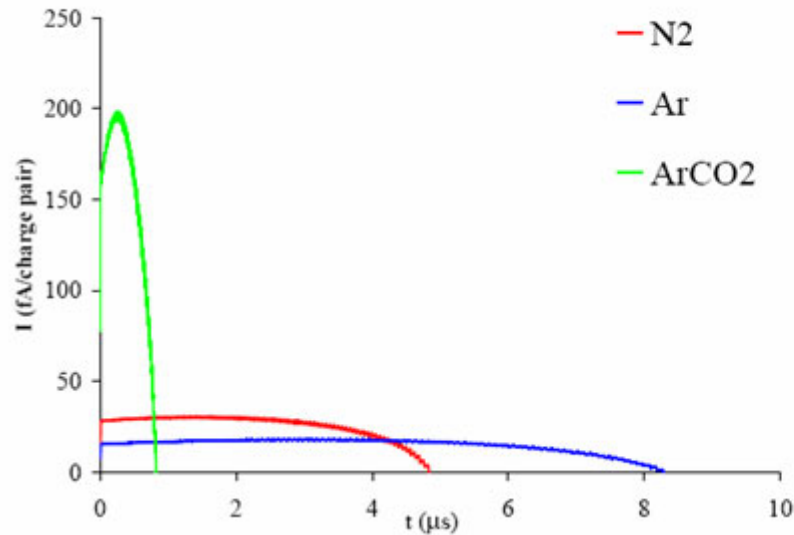


(c) *Experimental electrons*

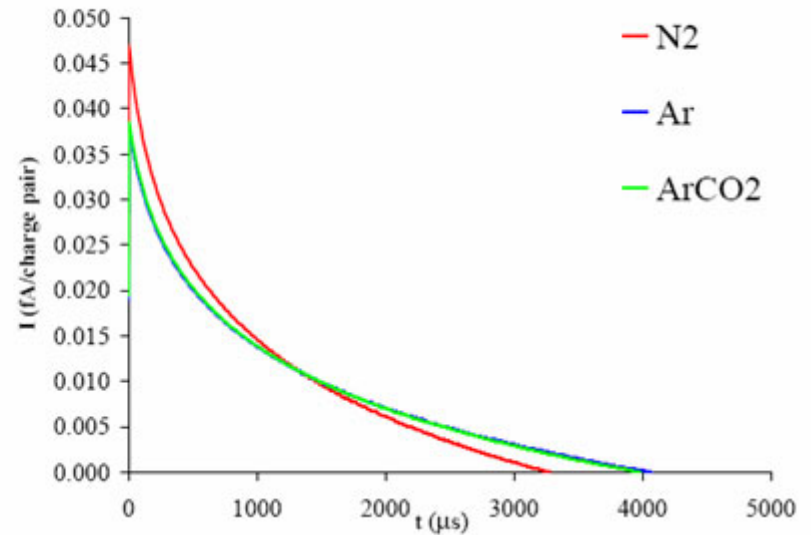


(d) *Experimental ions*

Drift times of electrons and ions (I)



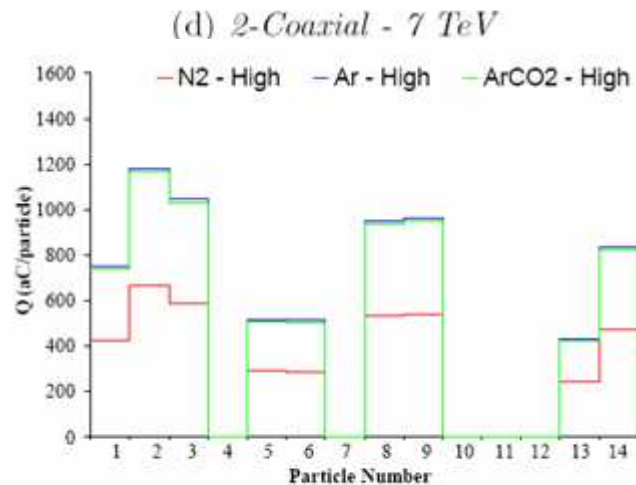
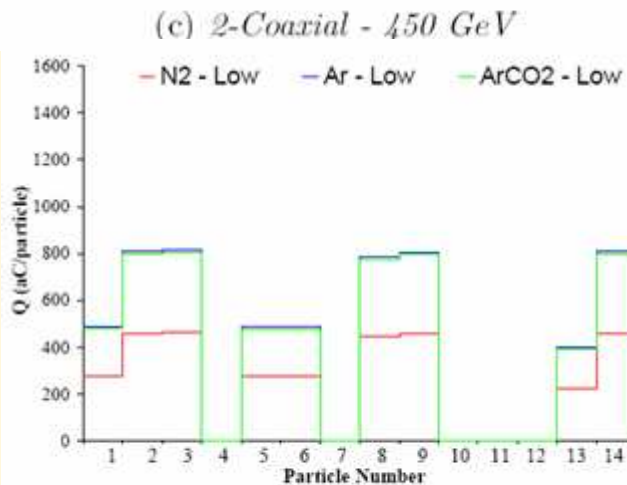
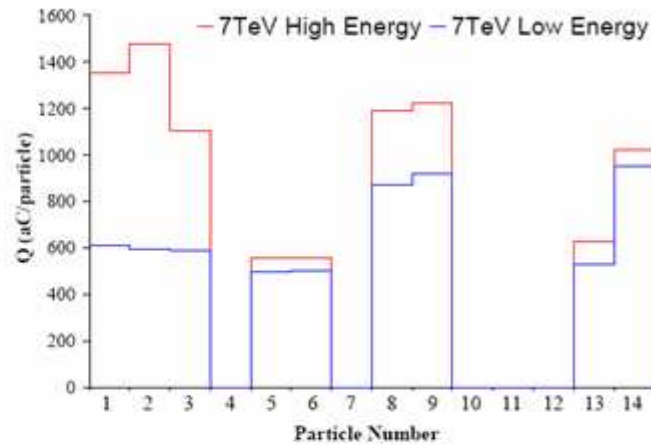
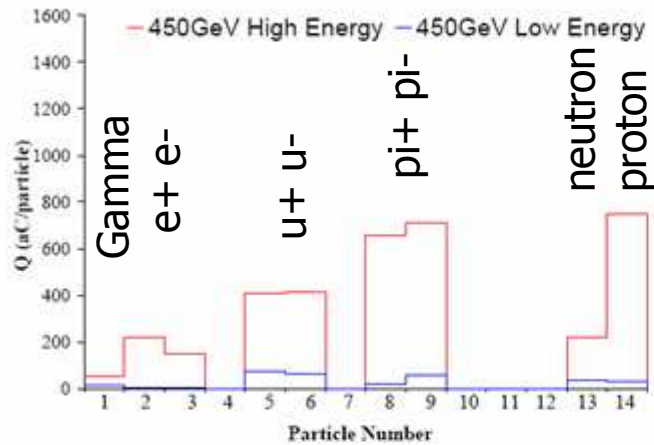
(a) *electrons*



(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



(a) Low end of energy spectrum.

(b) High end of energy spectrum.

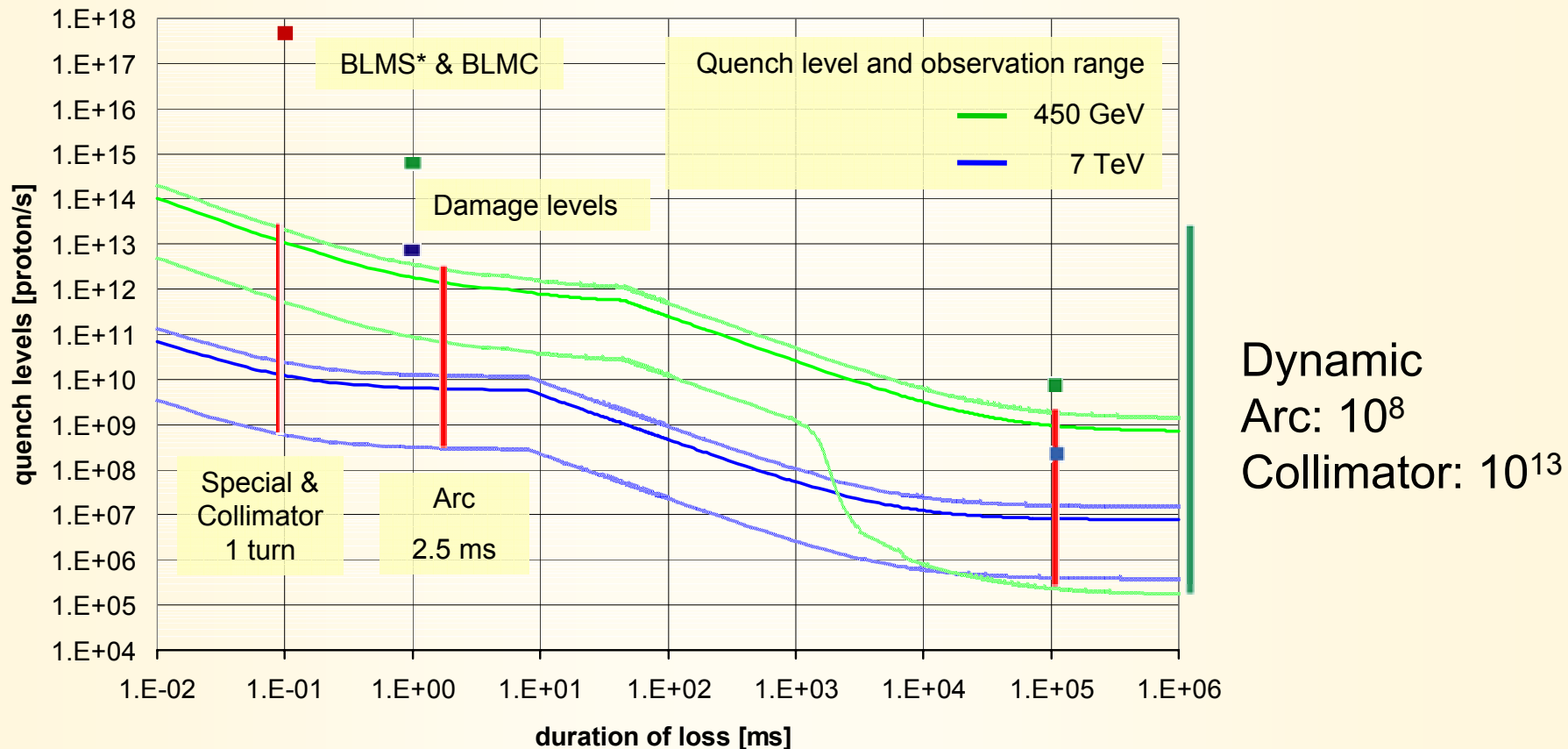
Due to attenuation of shower

=>

increase of non linearity of chamber response

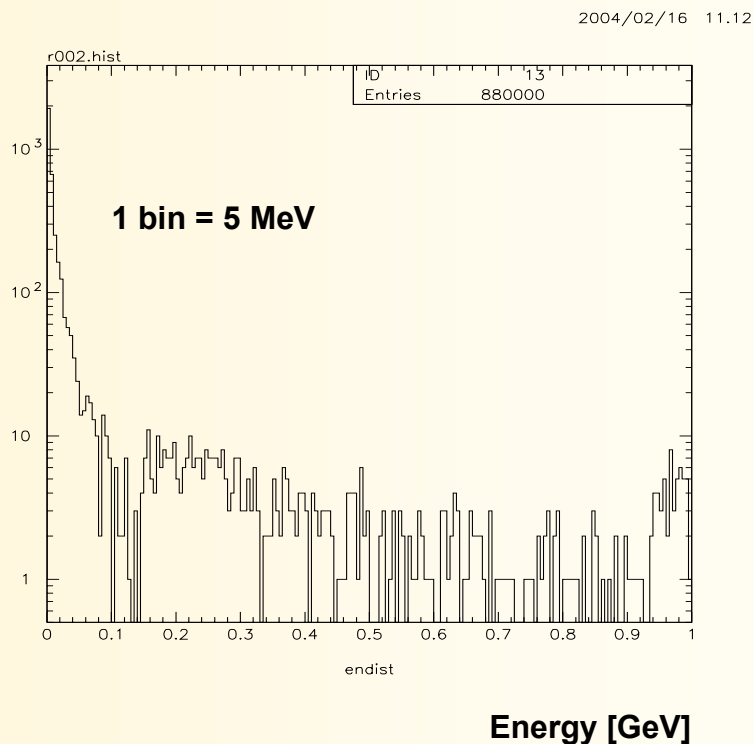
Quench and Damage Levels

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



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):

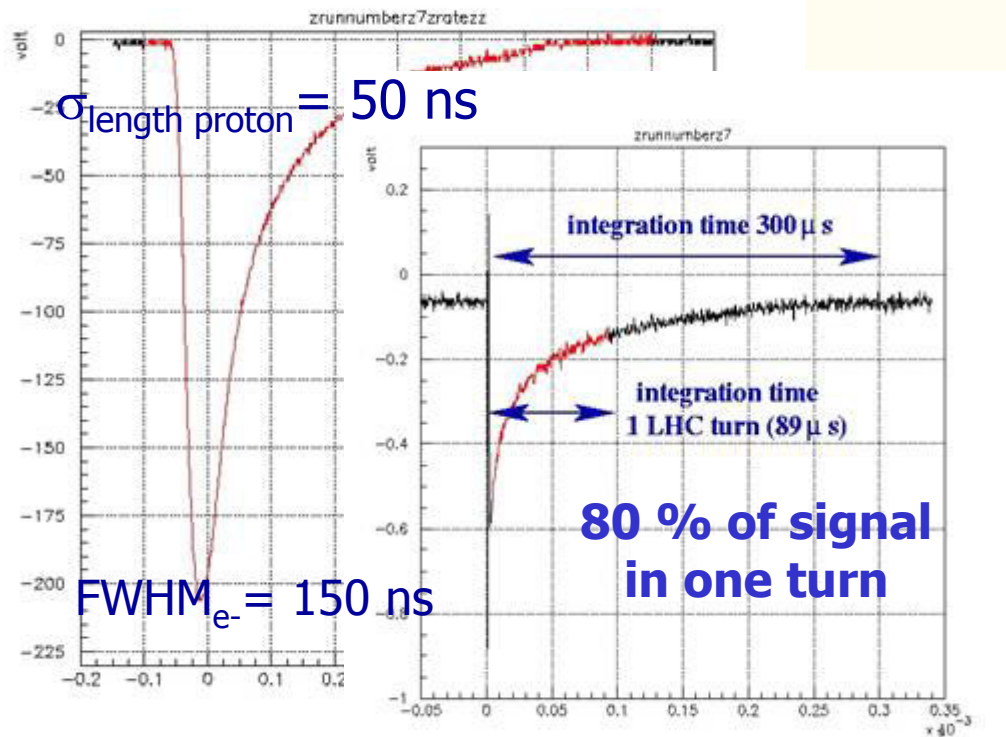
- **450 GeV: ~ 3.8 keV/cm**
- **7 TeV: ~ 4.3 keV/cm**

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

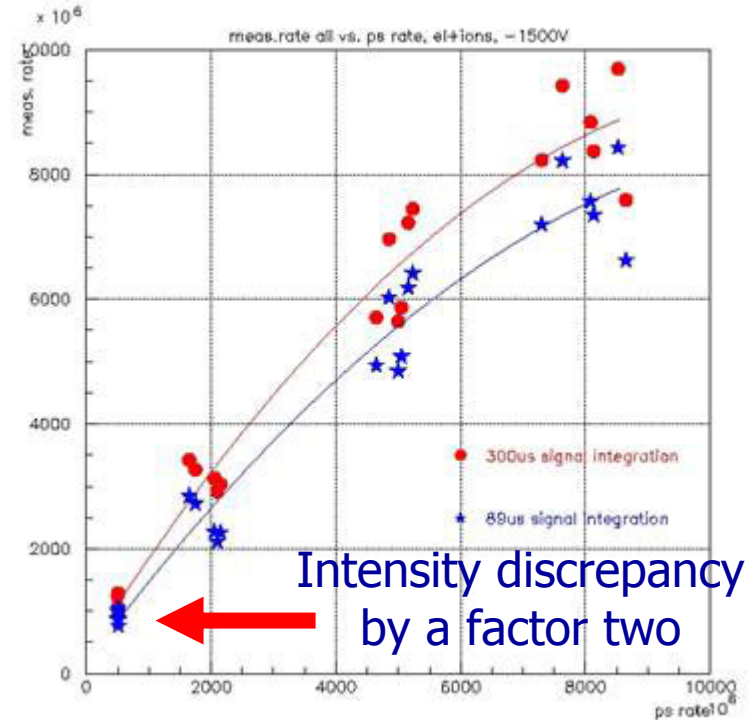
- **450 GeV: $5 \cdot 10^{-4} - 3 \cdot 10^{-3}$ part/p/ cm^2**
- **7 TeV: $8 \cdot 10^{-3} - 4 \cdot 10^{-2}$ part/p/ cm^2**

Ionisation Chamber Time Response Measurements (BOOSTER)

Chamber beam response

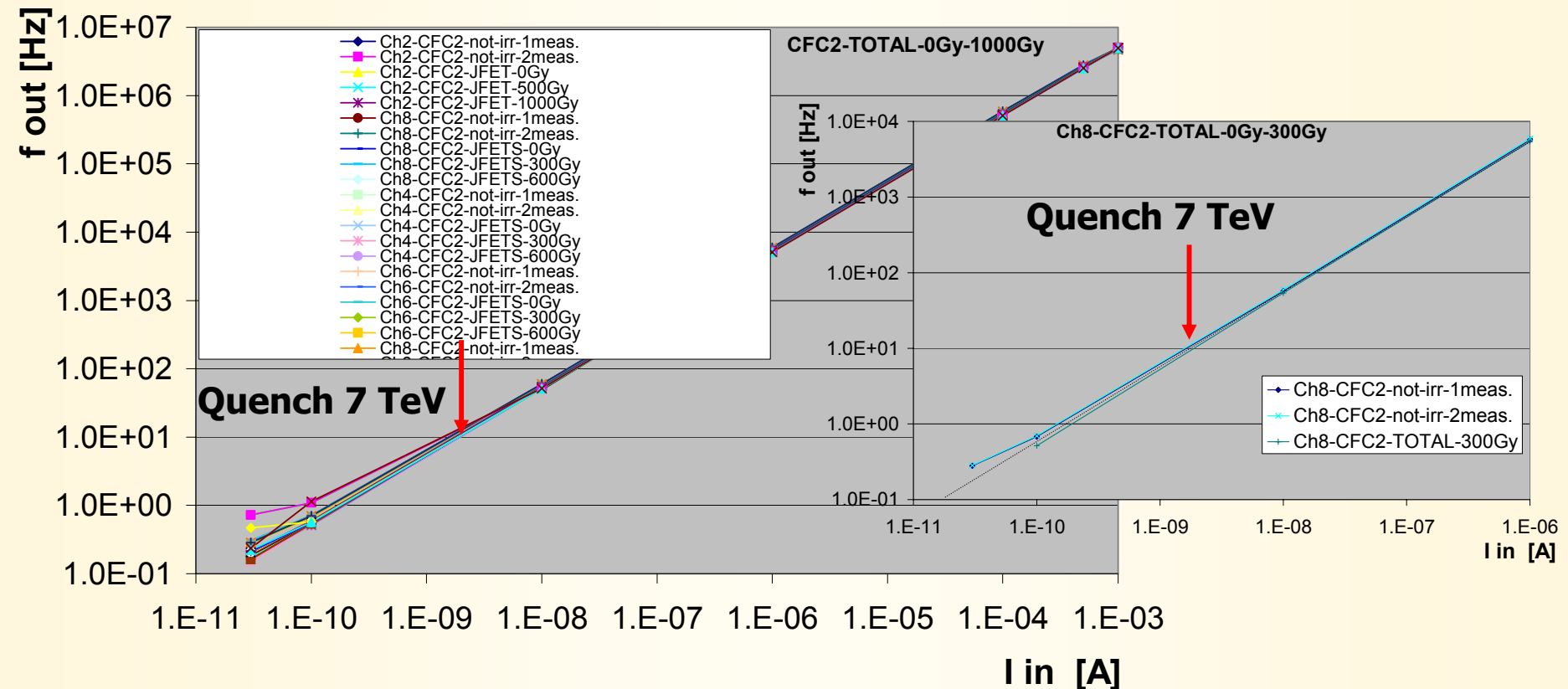


Chamber current vs beam current



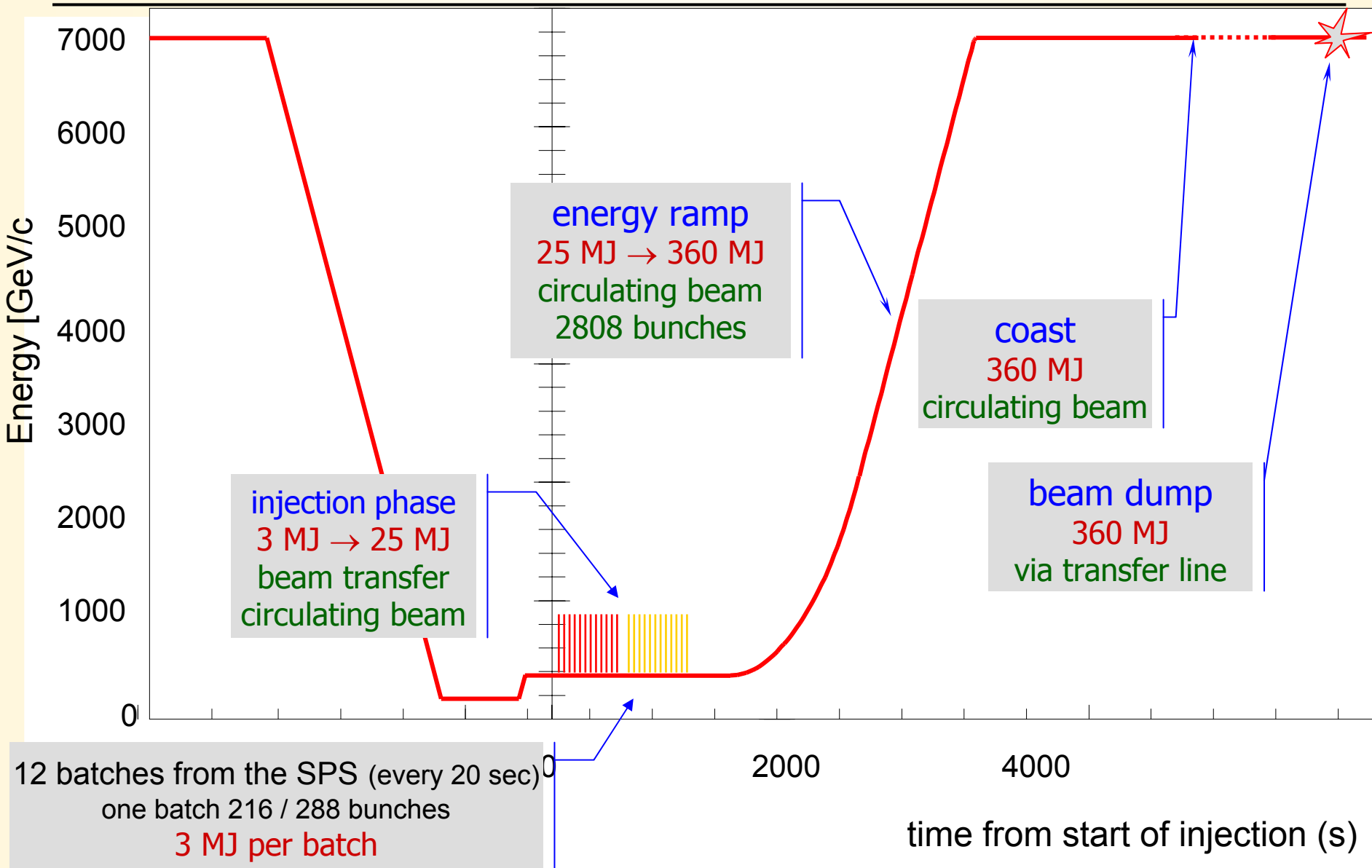
Intensity density: - Booster $6 \cdot 10^9 \text{ prot./cm}^2$, two orders larger as in LHC

Current to Frequency Converter and Radiation

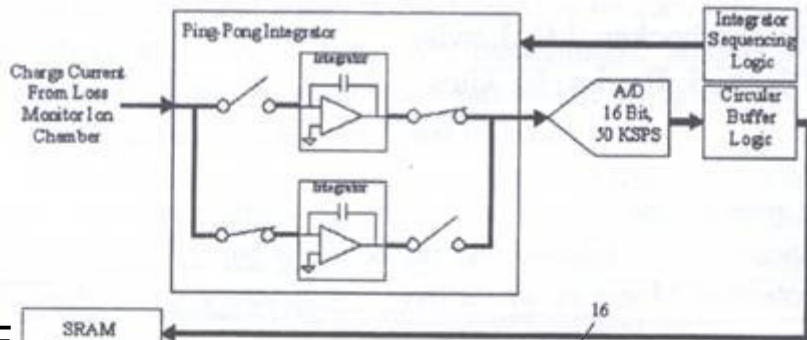


- Variation at the very low end of the dynamic range
- Insignificant variations at quench levels

LHC cycle and stored beam energy

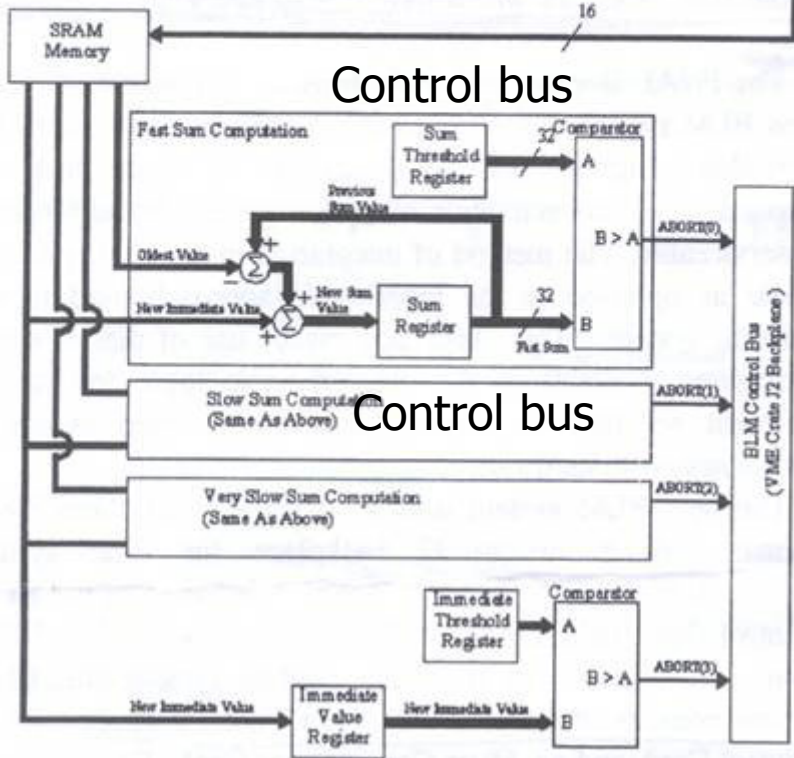


FNAL beam loss integrator and digitizer



VME

Control bus



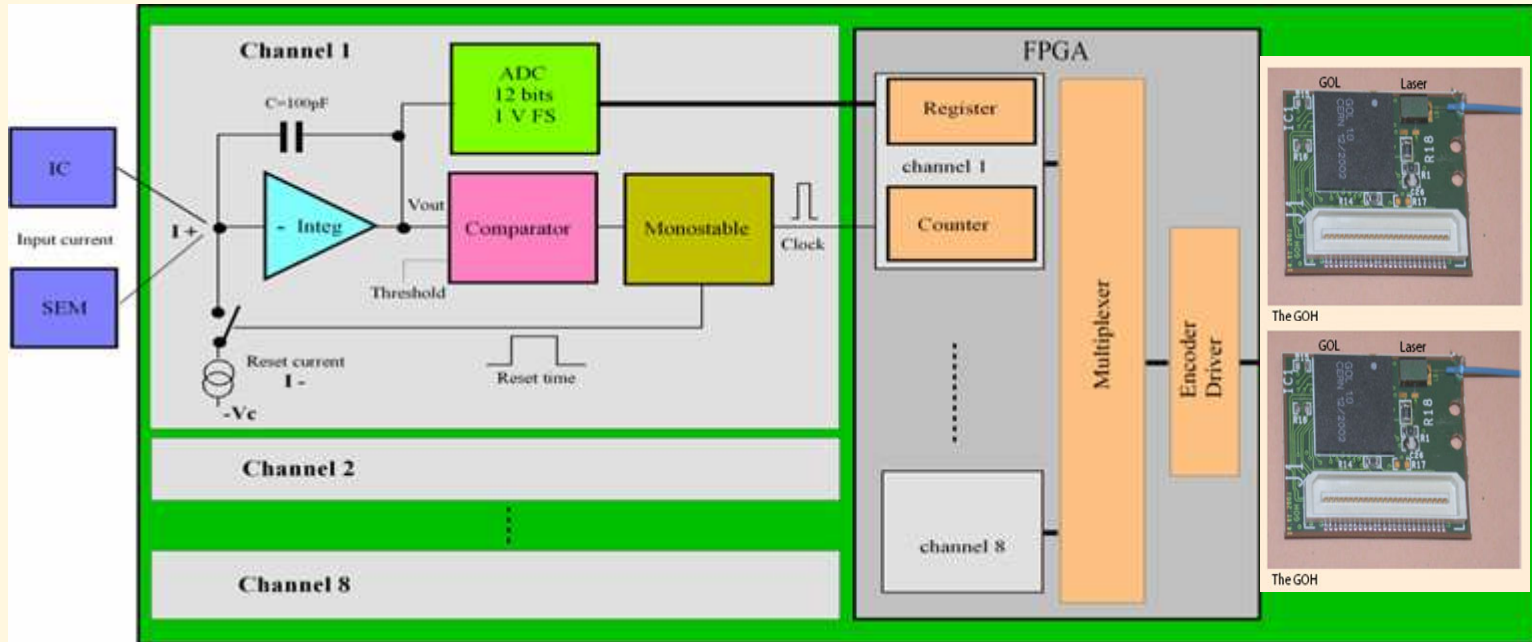
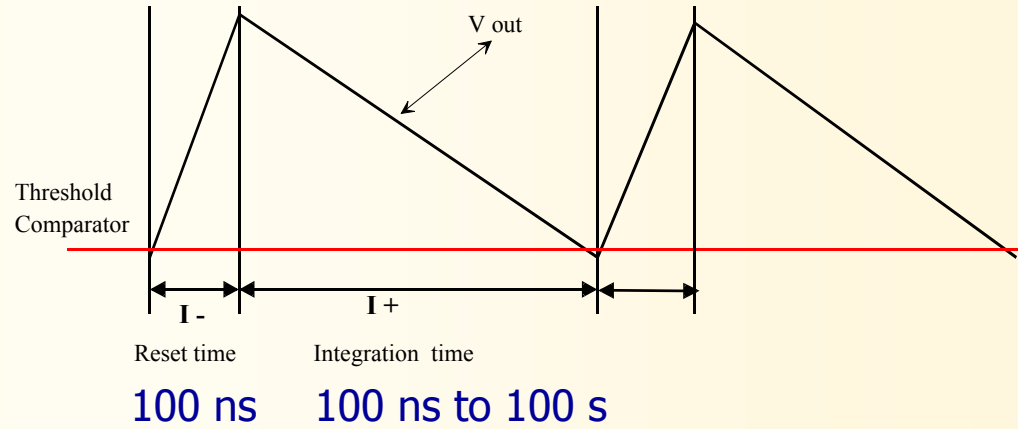
Control bus

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

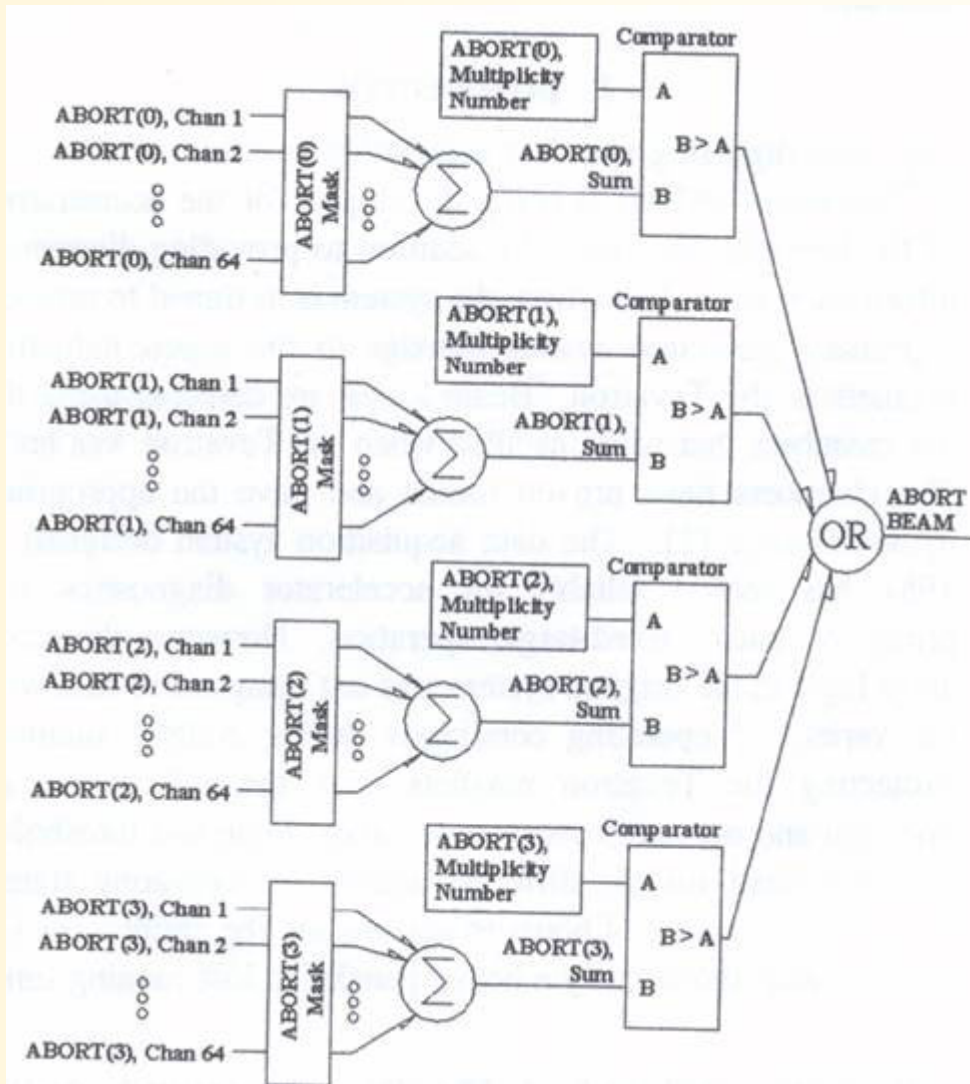
- Independent operation from crate CPU (FNAL, LHC)
- Thresholds managed by control card over control bus (LHC combined)

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, $5 \cdot 10^8$ p/s/cm²)
 - Bipolar
 - Customs ASICs
 - Triple module redundancy



FNAL abort concentrator



- Measurements and threshold are compared every $21 \mu\text{s}$ (fastest) (LHC $80 \mu\text{s}$)
- 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)