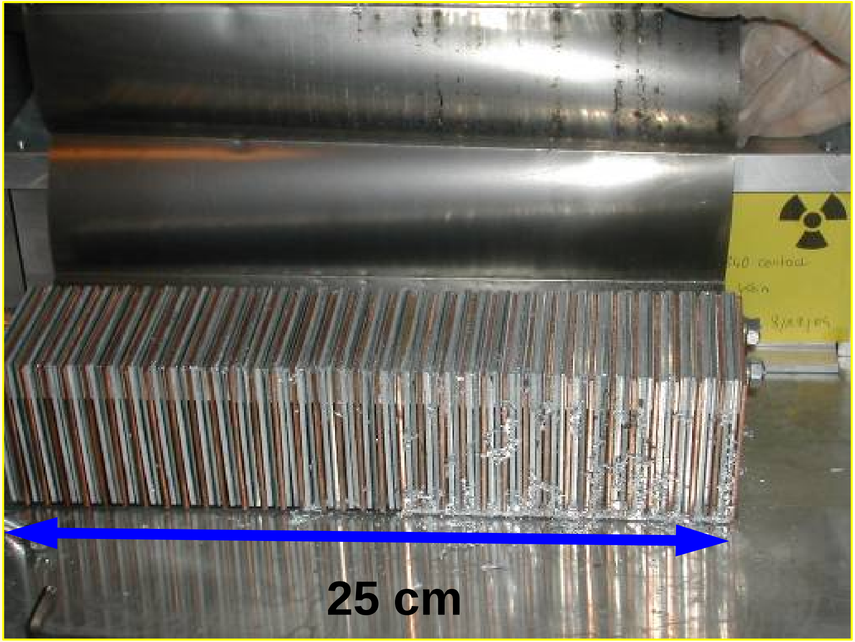
LHC Machine Protection

B. Dehning
CERN AB/BI

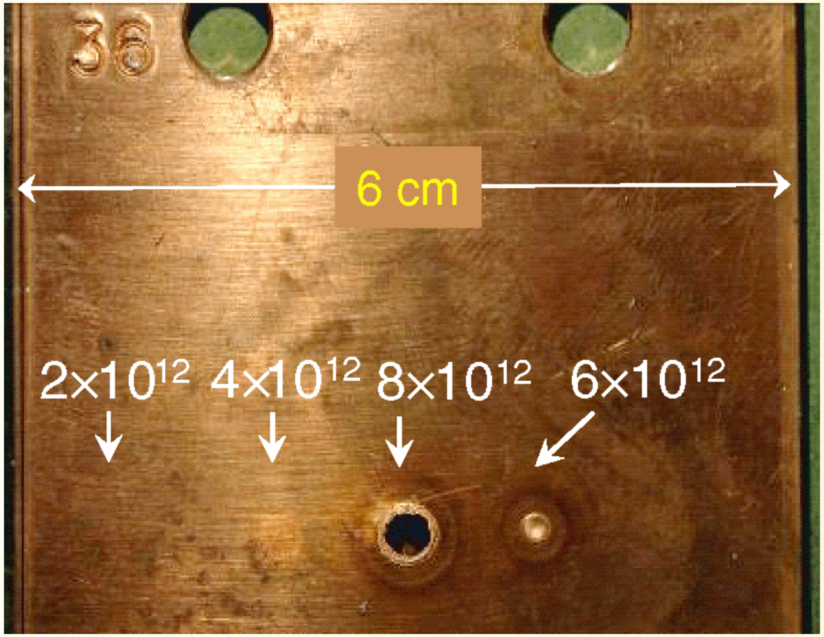
Contend

- 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.

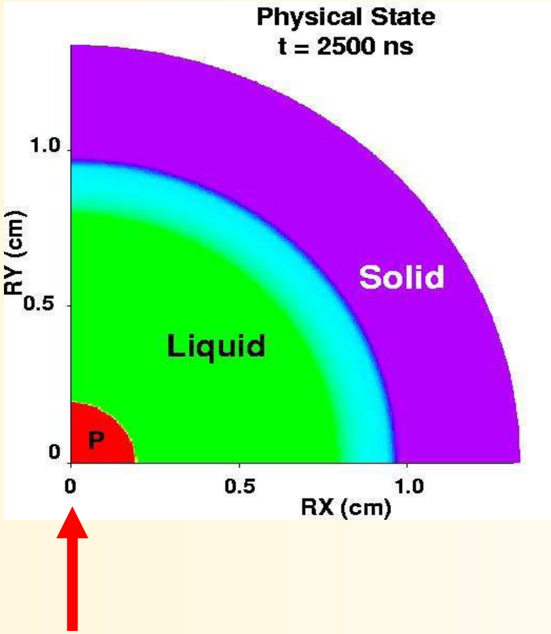


- Proton beam, 450 GeV, Cu, Fe sandwich target
- beam size $\sigma_{x/y}$ = 1.1mm/0.6mm
- $2 \cdot 10^{12}$ no damage
- $8 \cdot 10^{12}$ damage

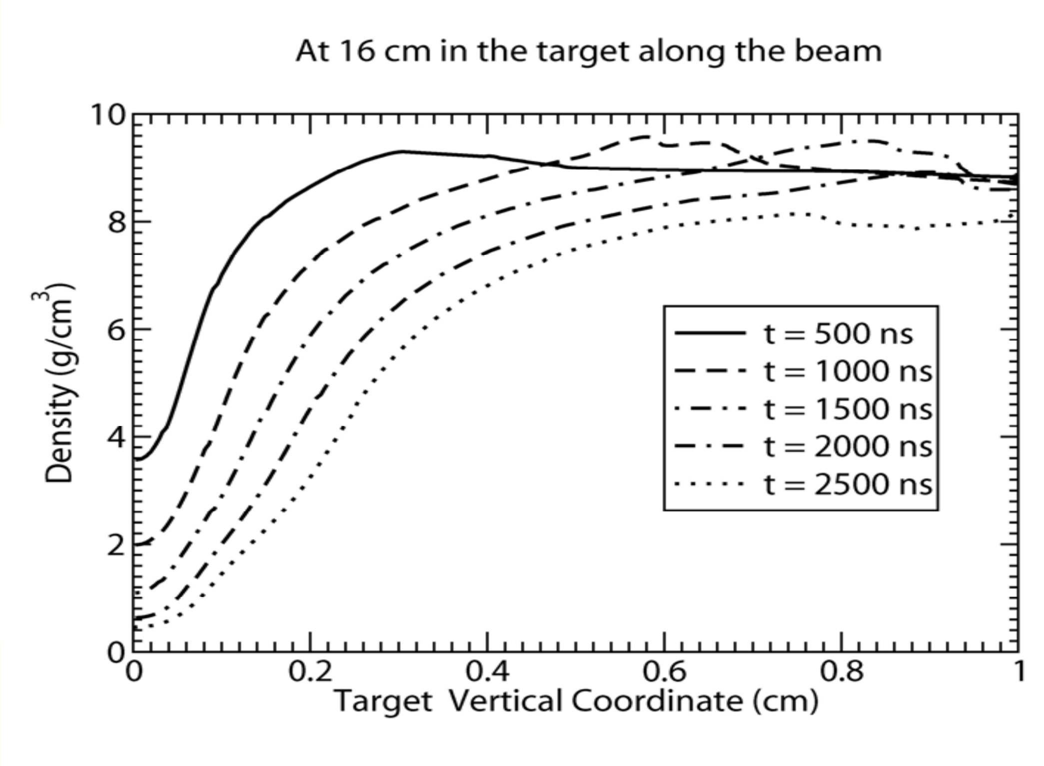
Safe at 0.6 % of
full LHC intensity

Density Change in Target after Impact of 100 Bunches

Cross sectional view



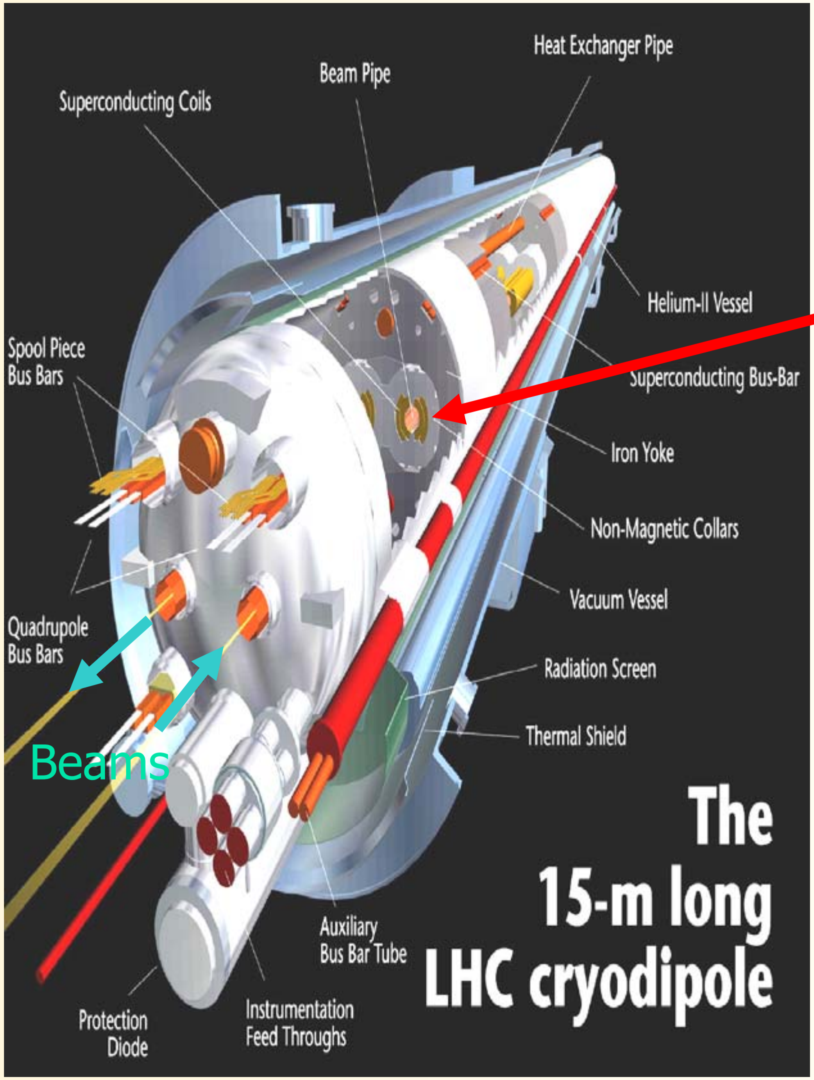
beam impact



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

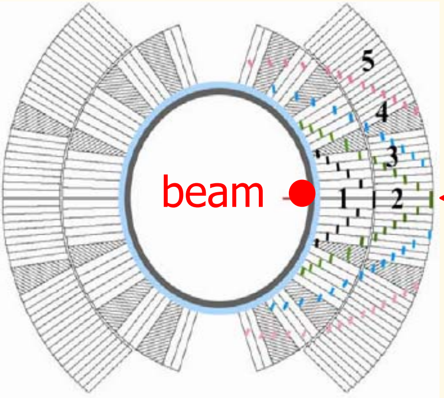
Reduction of density by a factor 10

Magnet Quenches



cross sectional view of coil

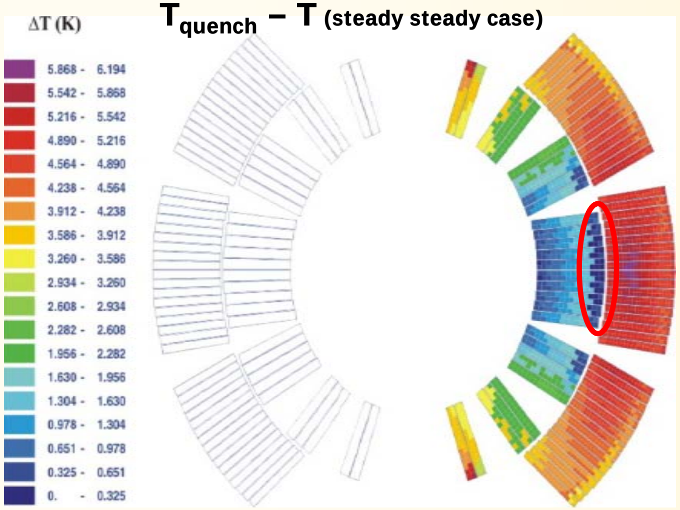
D. Bocian et al.



Energy deposition by the beam

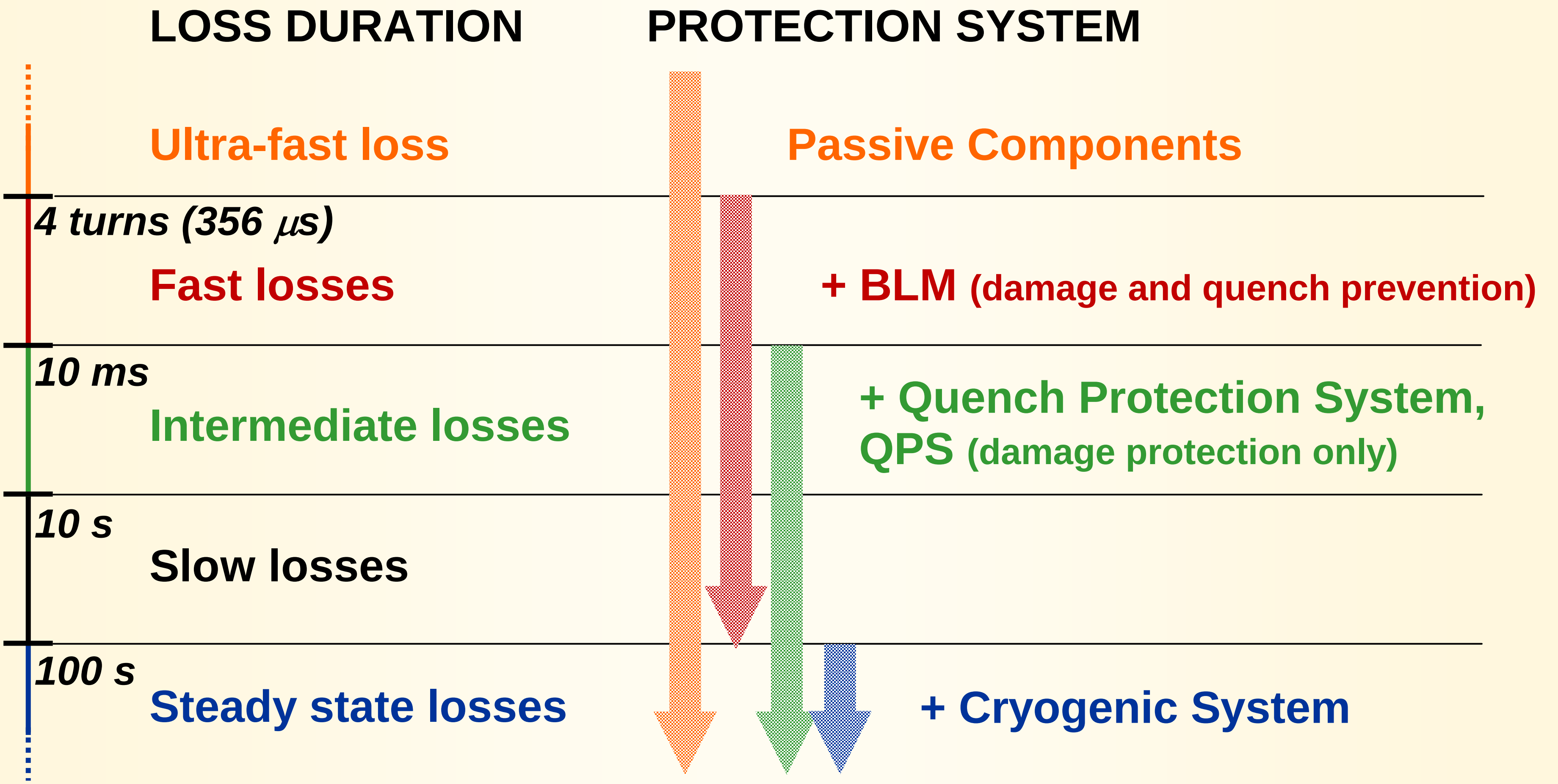
Temperature difference

T_{quench} – T (steady steady case)



Location of QUENCH

Beam Loss Durations and Protection Systems



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

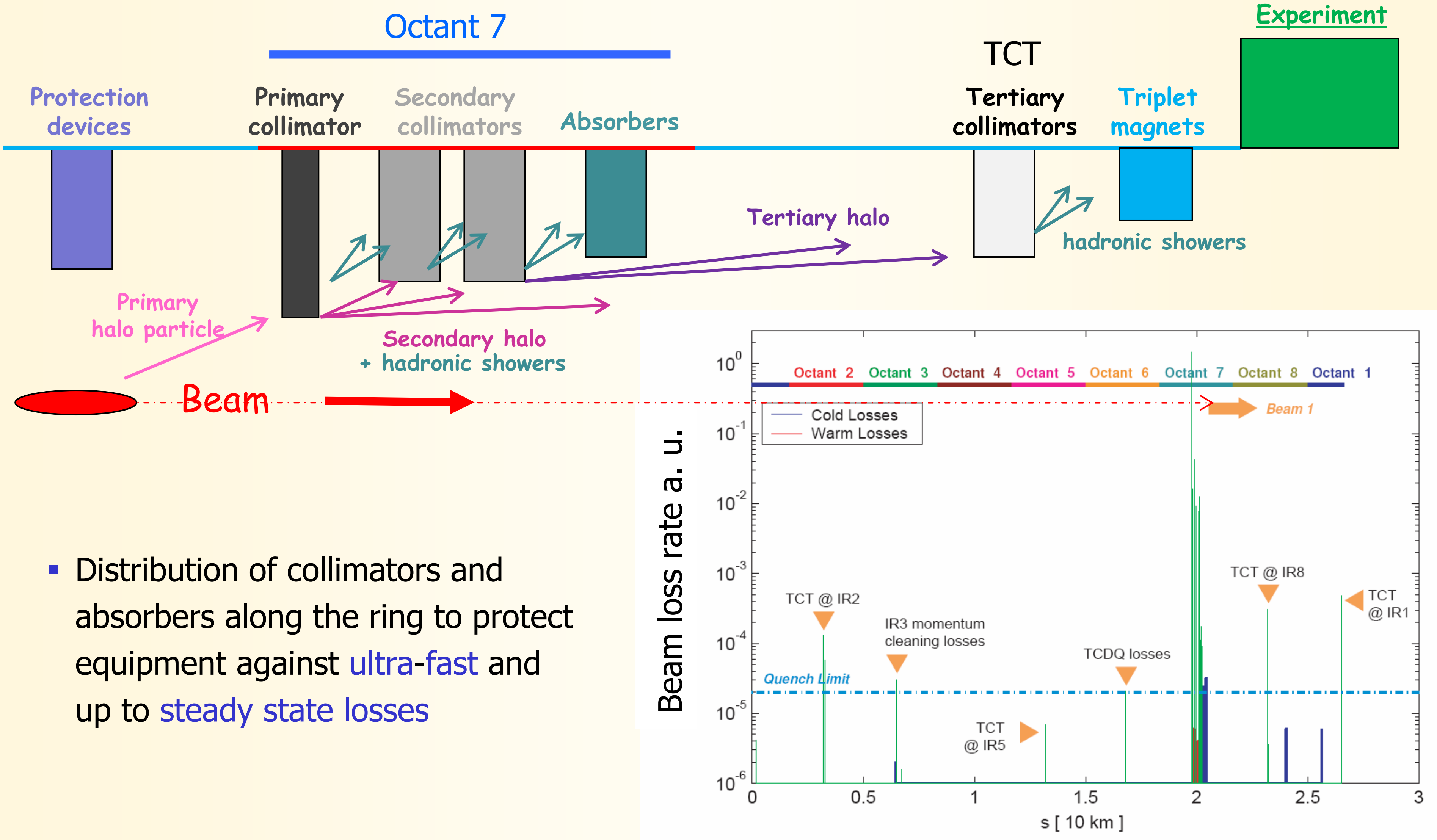
Slow losses

100 s

Steady state losses **+ Cryogenic System**

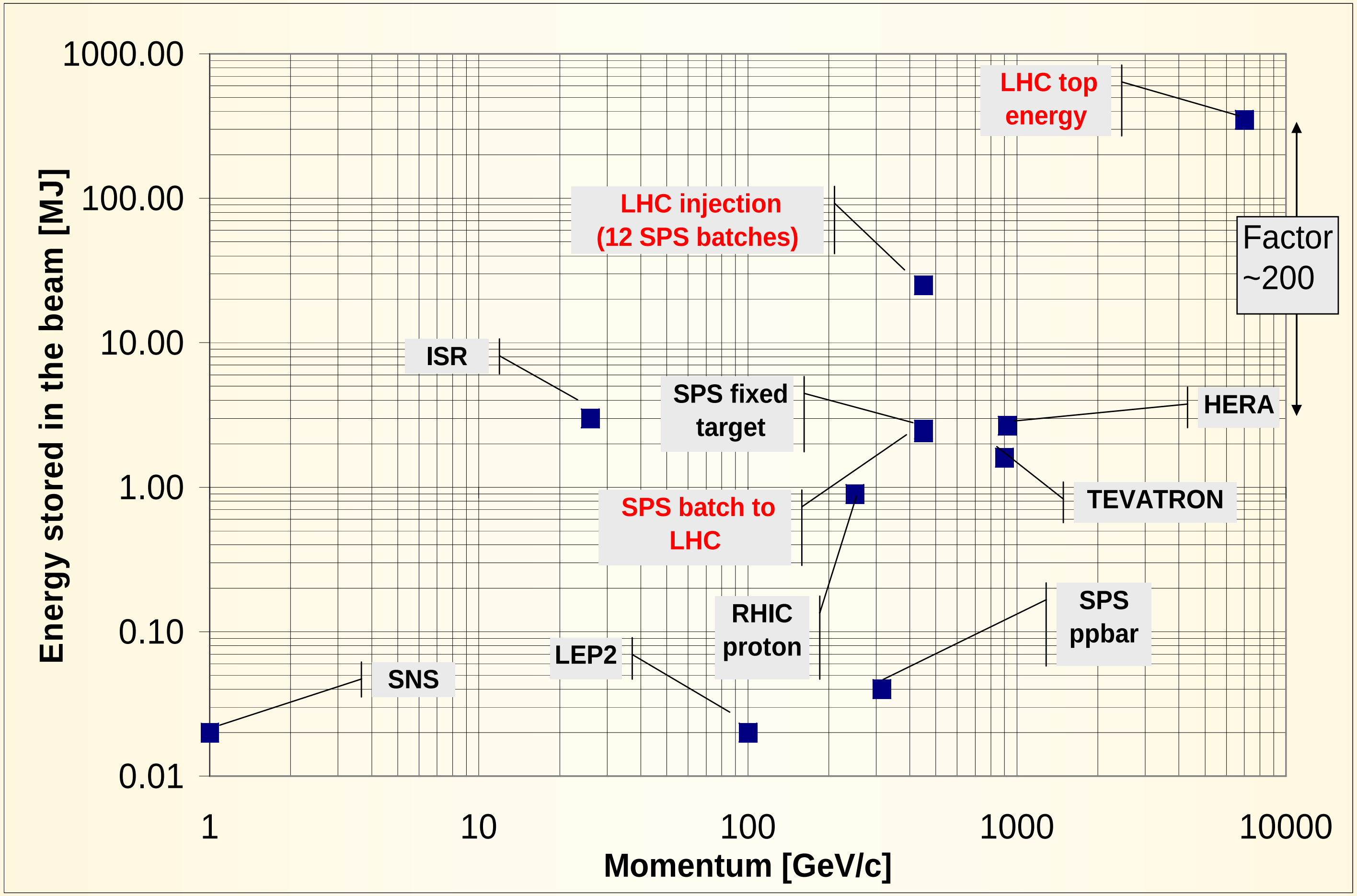
Since not active protection possible for ultra-fast losses => passive system

Collimators and Absorbers



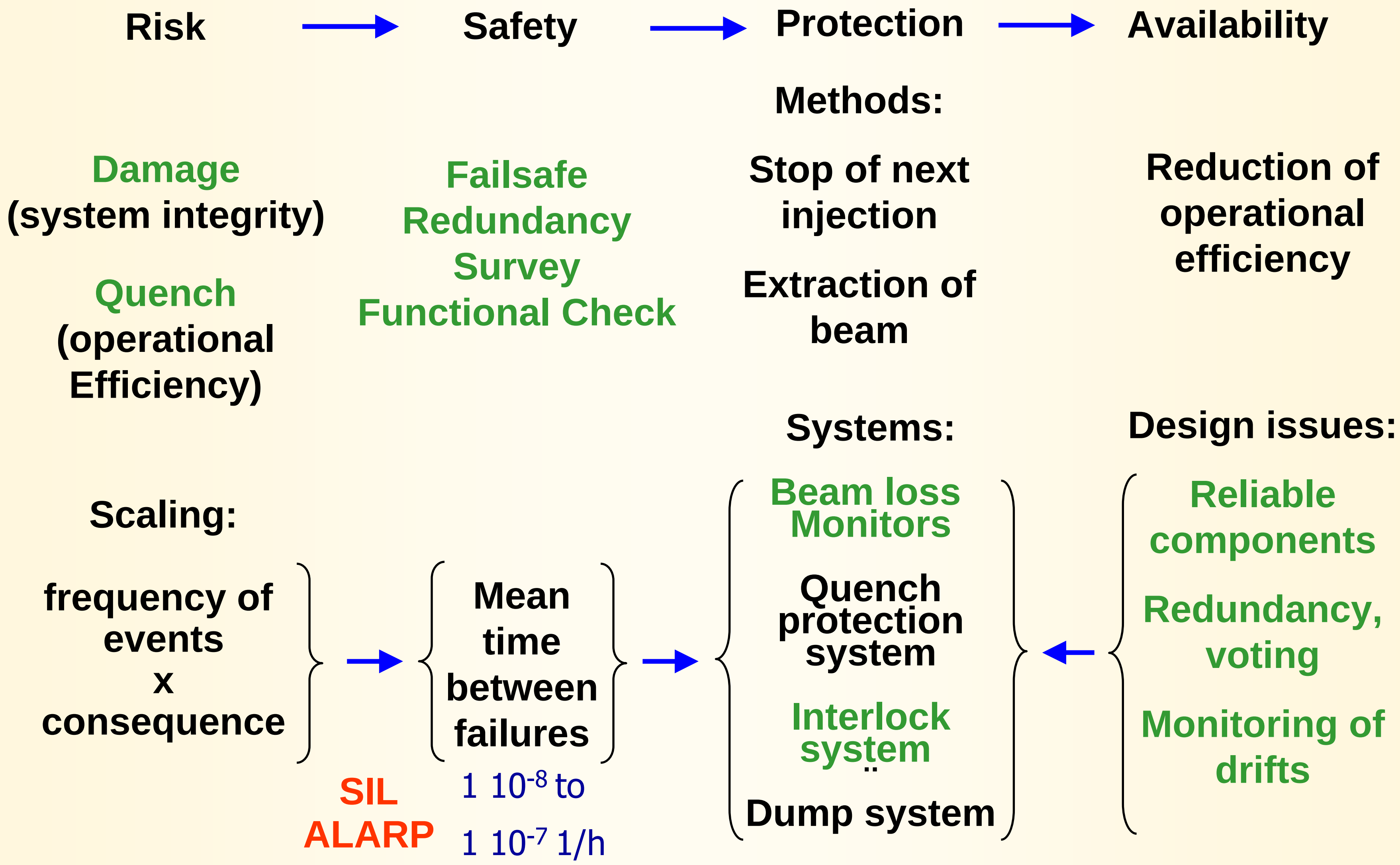
- Distribution of collimators and absorbers along the ring to protect equipment against ultra-fast and up to steady state losses

Stored Beam Energies



LHC will be exceptional => High RISK

Safety System Design Approach



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

Methods:

Risk	Safety	Protection	Availability
Damage (system integrity) Quench (operational Efficiency)	Failsafe Redundancy Survey Functional Check	Stop of next injection Extraction of beam	Reduction of operational efficiency

Scaling:

frequency of events x consequence → Mean time between failures → Beam loss Monitors, Quench protection system, Interlock system, Dump system ← Reliable components, Redundancy, voting, Monitoring of drifts

SIL
ALARP

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

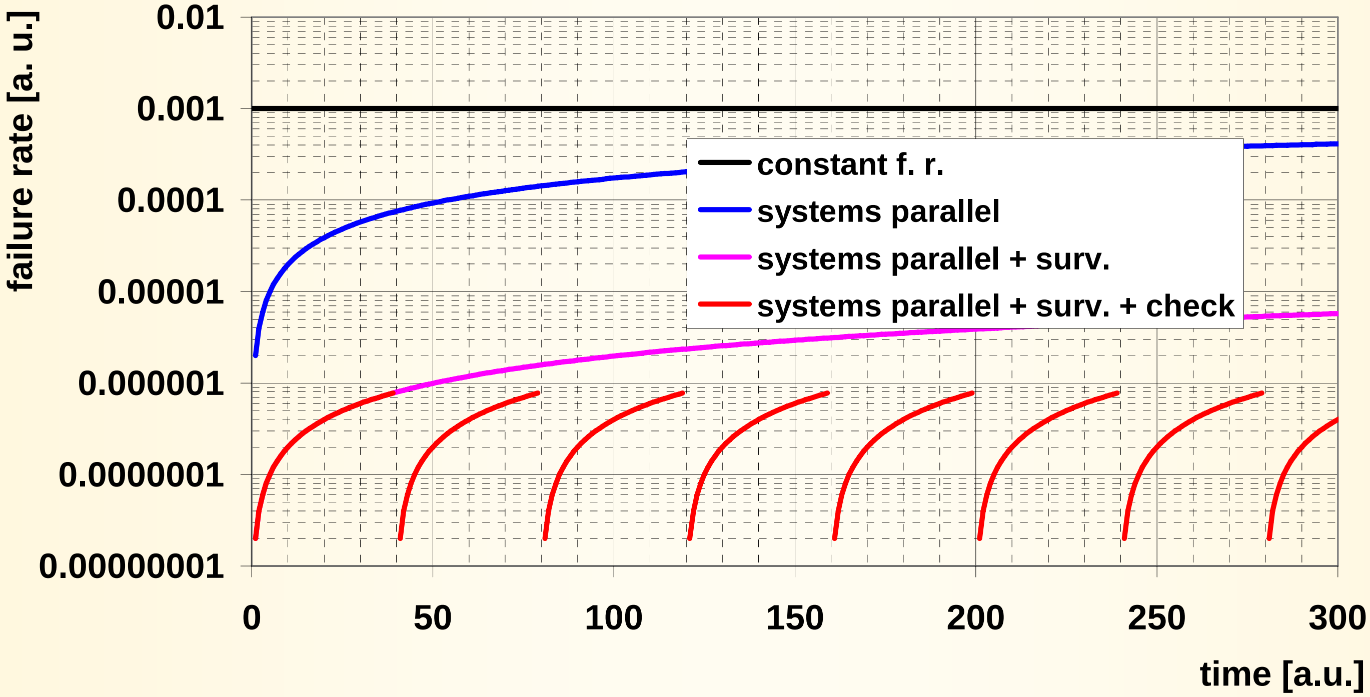
Systems:

- Beam loss Monitors
- Quench protection system
- Interlock system
- Dump system

Design issues:

- Reliable components
- Redundancy, voting
- Monitoring of drifts

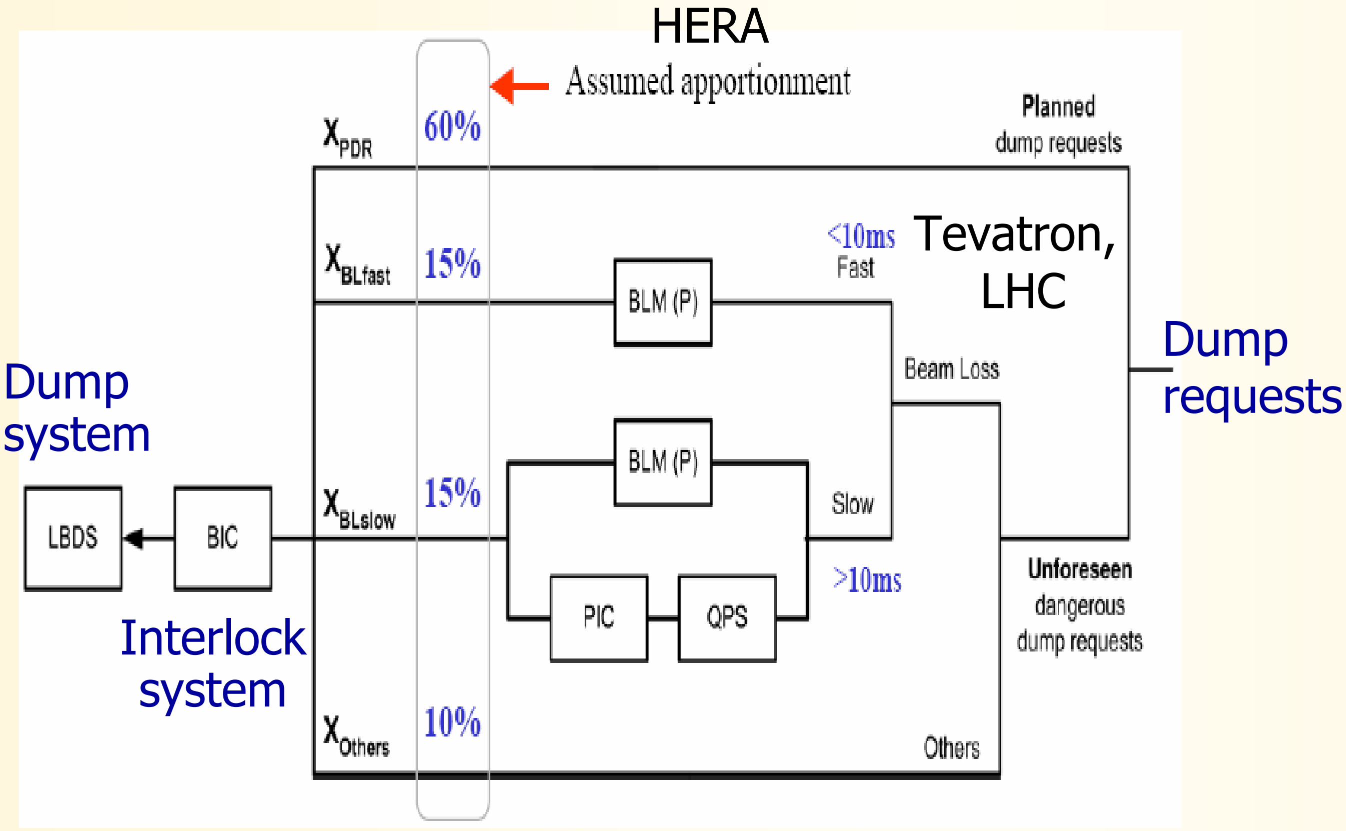
Failure Rate and Checks



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

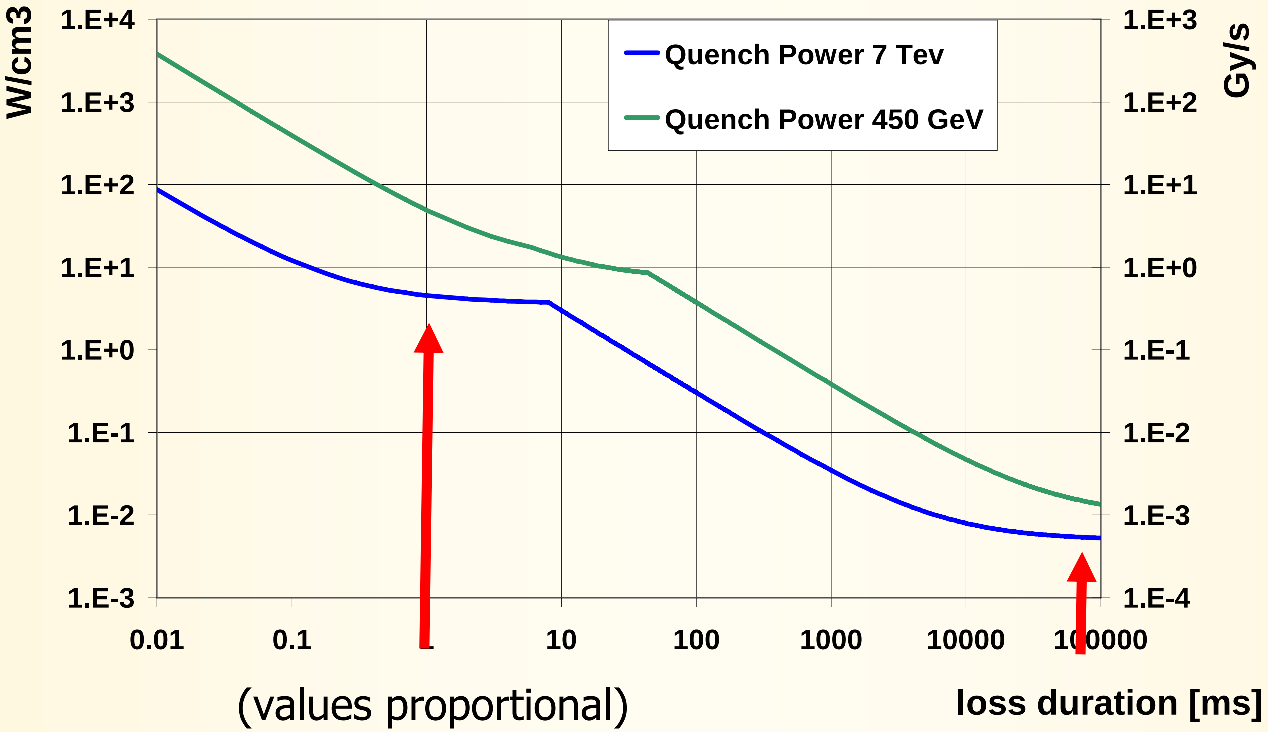


SOURCES of

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



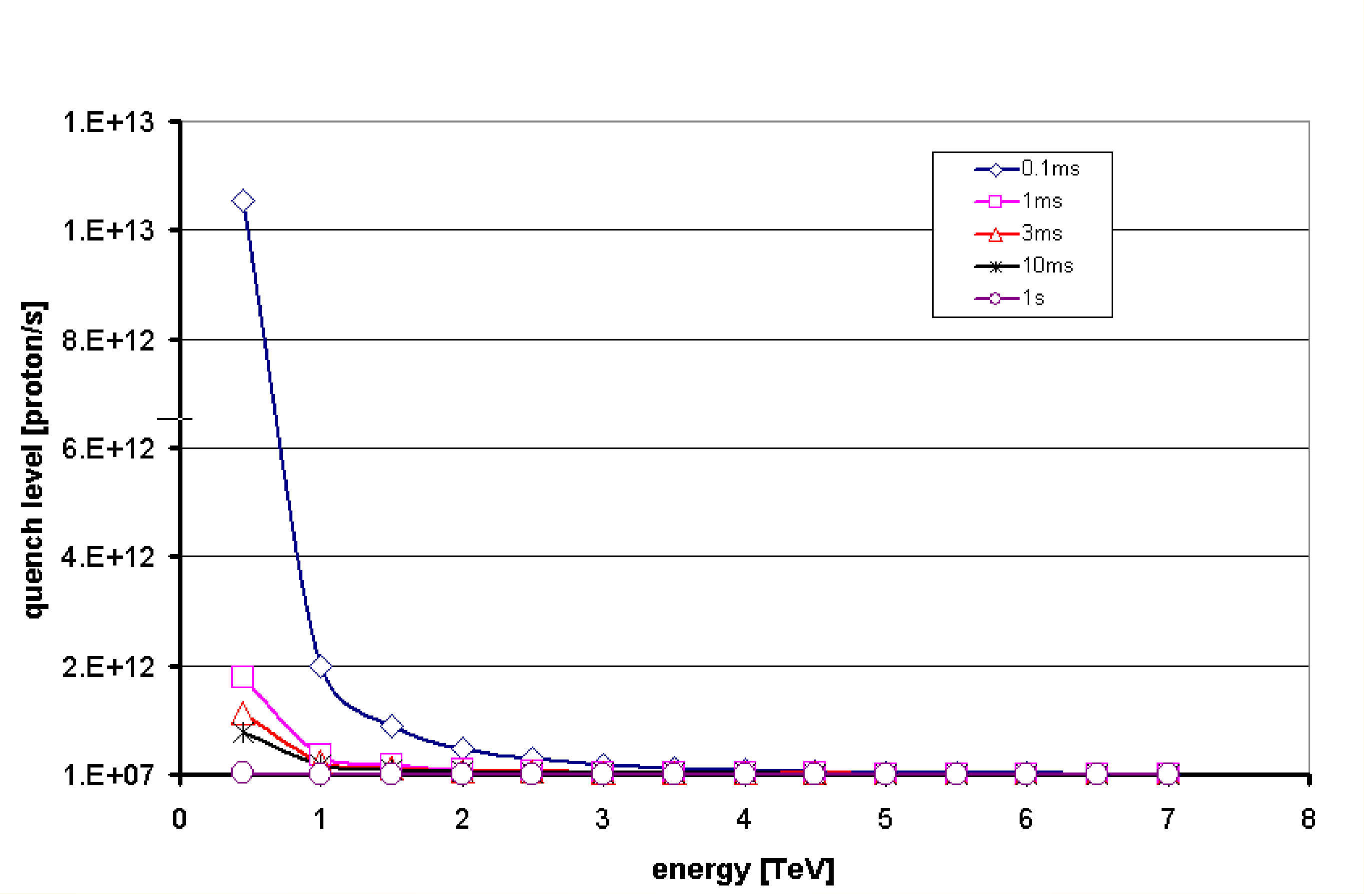
(values proportional)

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

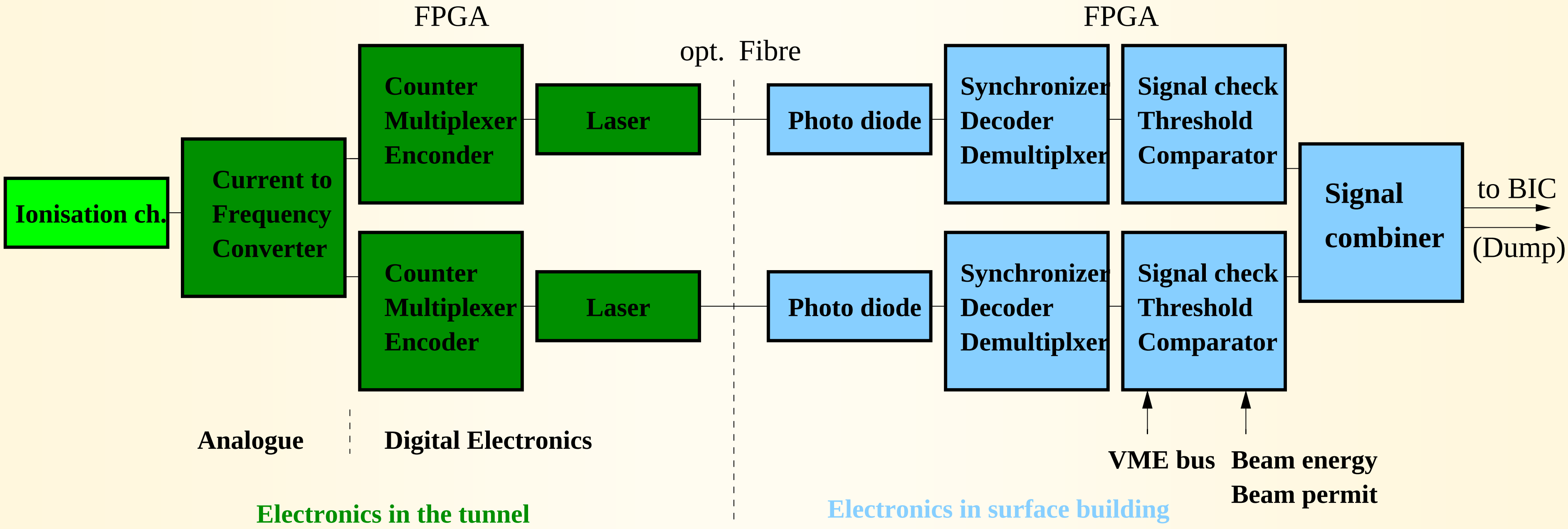
Quench Levels and Energy Dependence



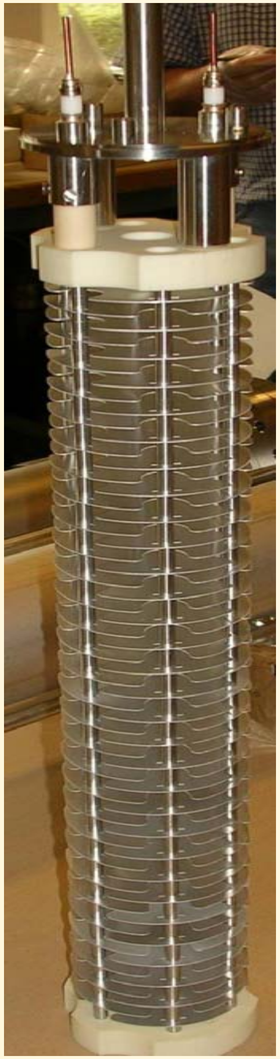
- Fast decrease of quench levels between 0.45 to 2 TeV
- Similar behaviour expected for damage levels

Beam Loss Measurement System Layouts

LHC



Ionisation Chamber and Secondary Emission Monitor

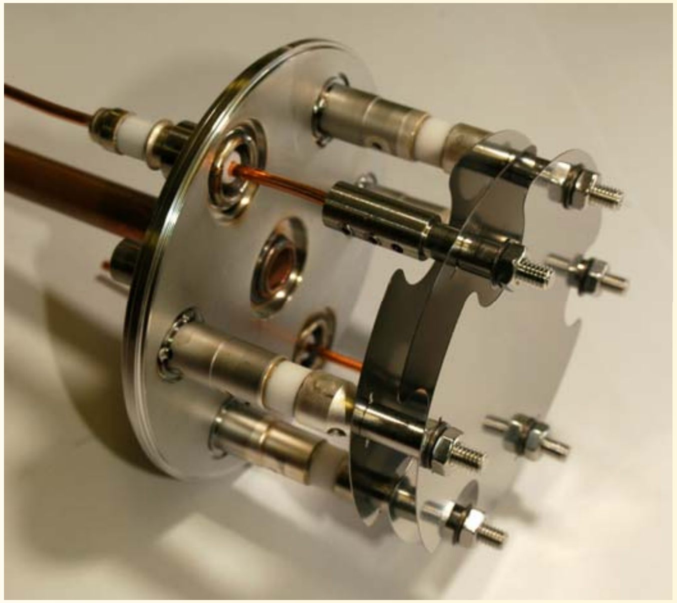


- Stainless steal cylinder
- Parallel electrodes distance 0.5 cm
- Diameter 8.9 cm
- Voltage 1.5 kV
- Low pass filter at the HV input

Signal Ratio: IC/SEM = 60000

IC:

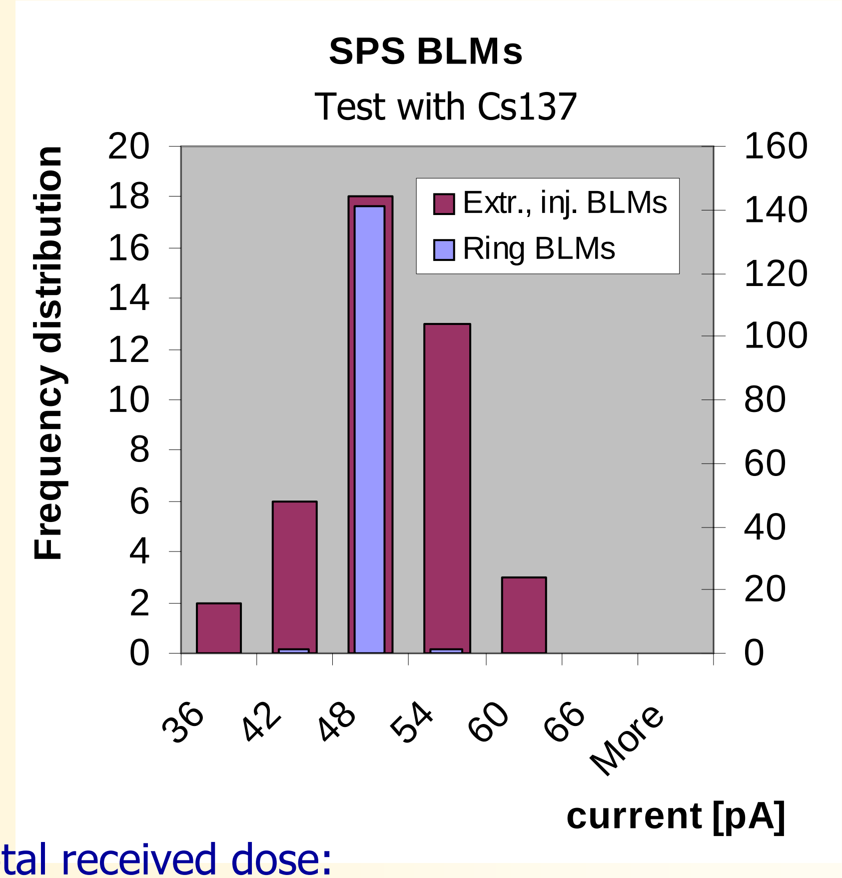
- Al electrodes
- Length 60 cm
- Ion collection time 85 us
- N_2 gas filling at 1.1 bar
- Sensitive volume 1.5 l



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

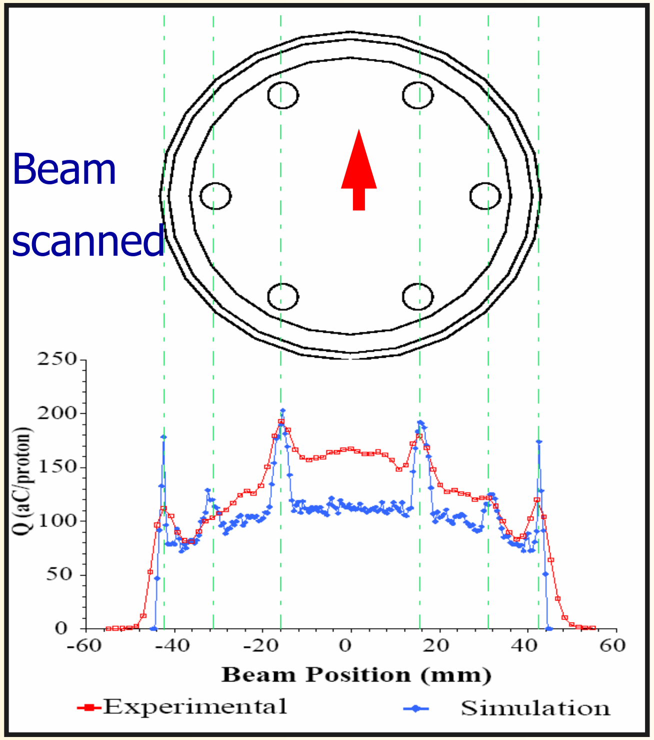
extr 0.1 to 10 MGy/year

- 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

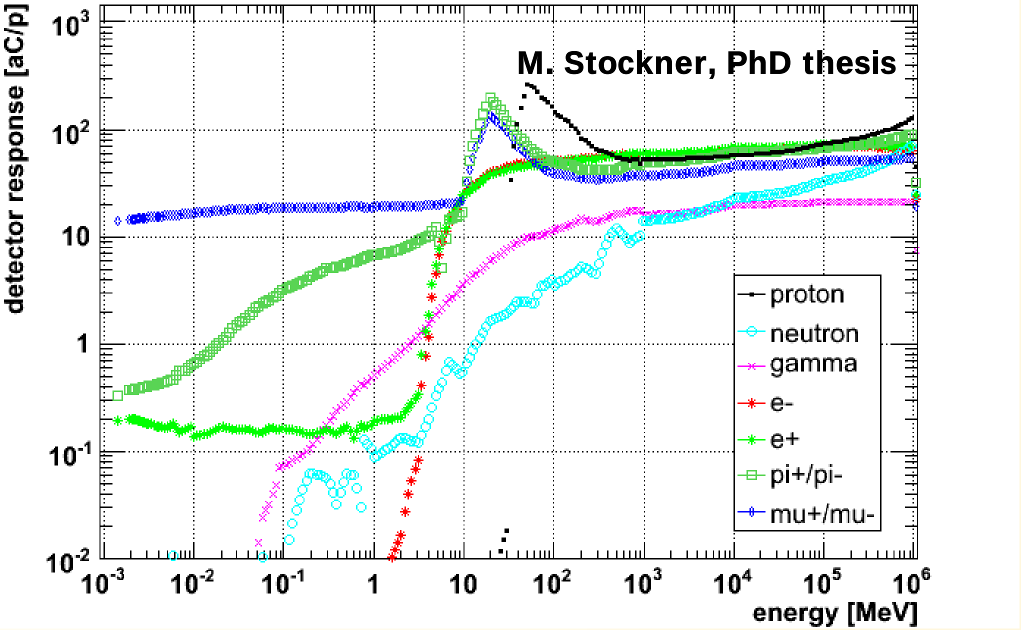
Reliable component

Ionisation Chamber Simulation and Measurements

Ionisation chamber top view



Ionisation chamber response function


M. Stockner, PhD thesis

- Comparison simulation measurements

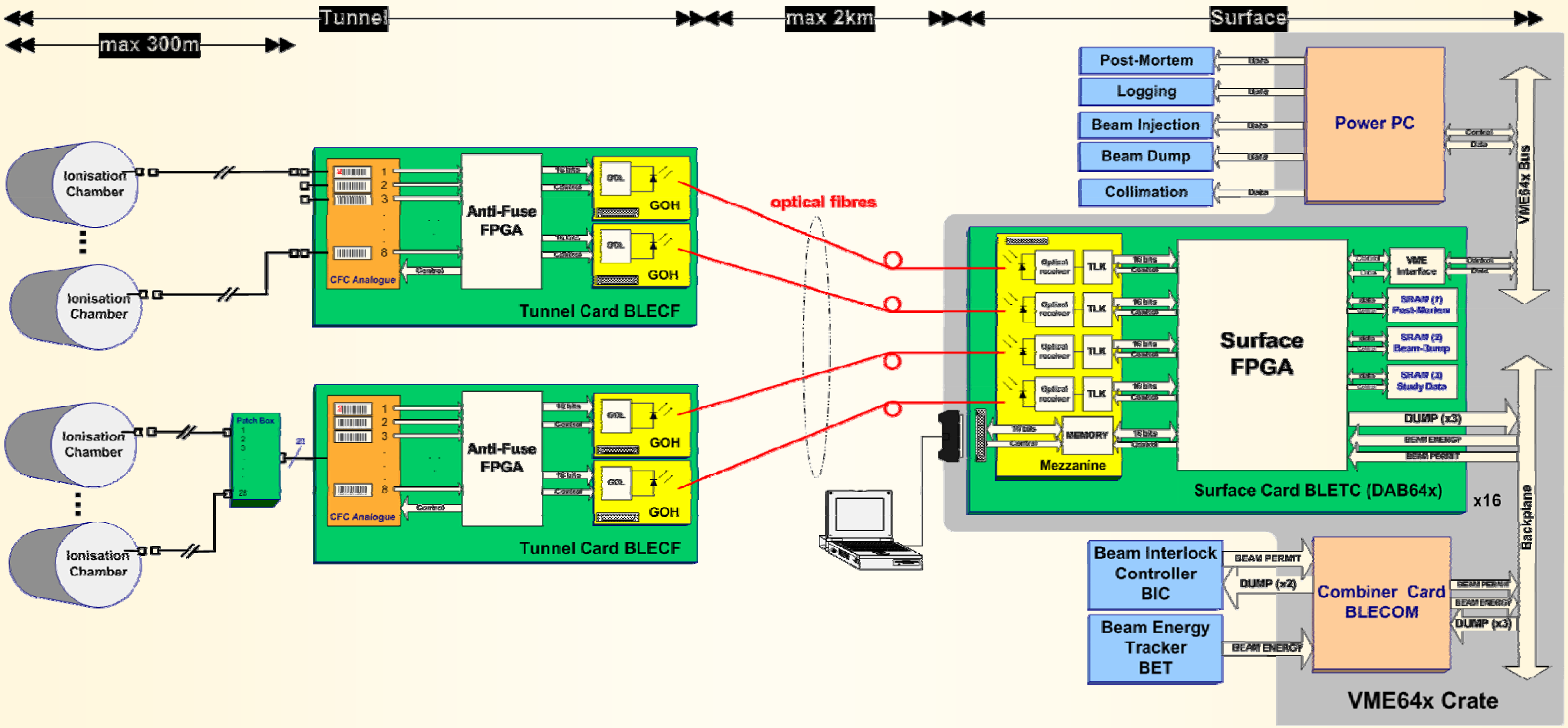
	Rel. diff %	Error %
Proton	13.1	11.4
Gamma	14.3	12.1
neutron	37.4	13.9
Mixed field	20.5	11.4

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

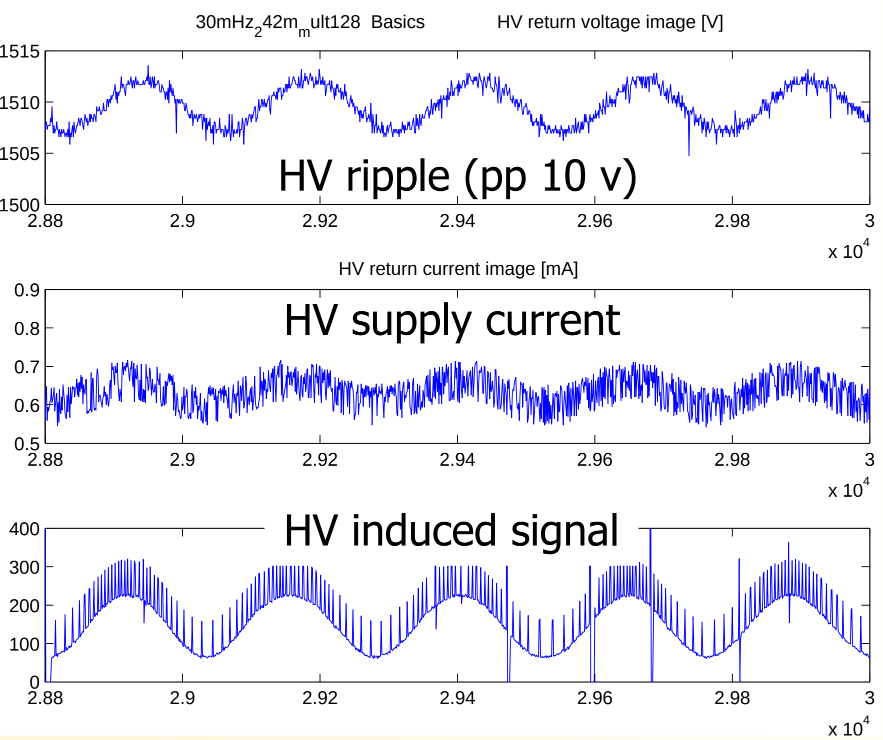
- **Current to Frequency Converters (CFCs)**
- **Analogue to Digital Converters (ADCs)**
- **Tunnel FPGAs:**
  Actel's 54SX/A radiation tolerant.
- **Communication links:**
  Gigabit Optical Links.

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



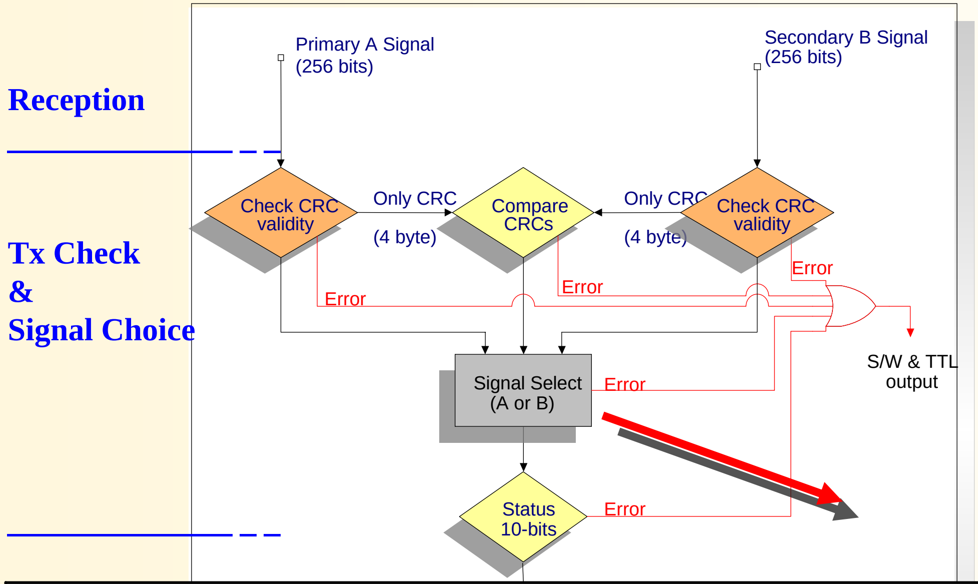
Basic concept:

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

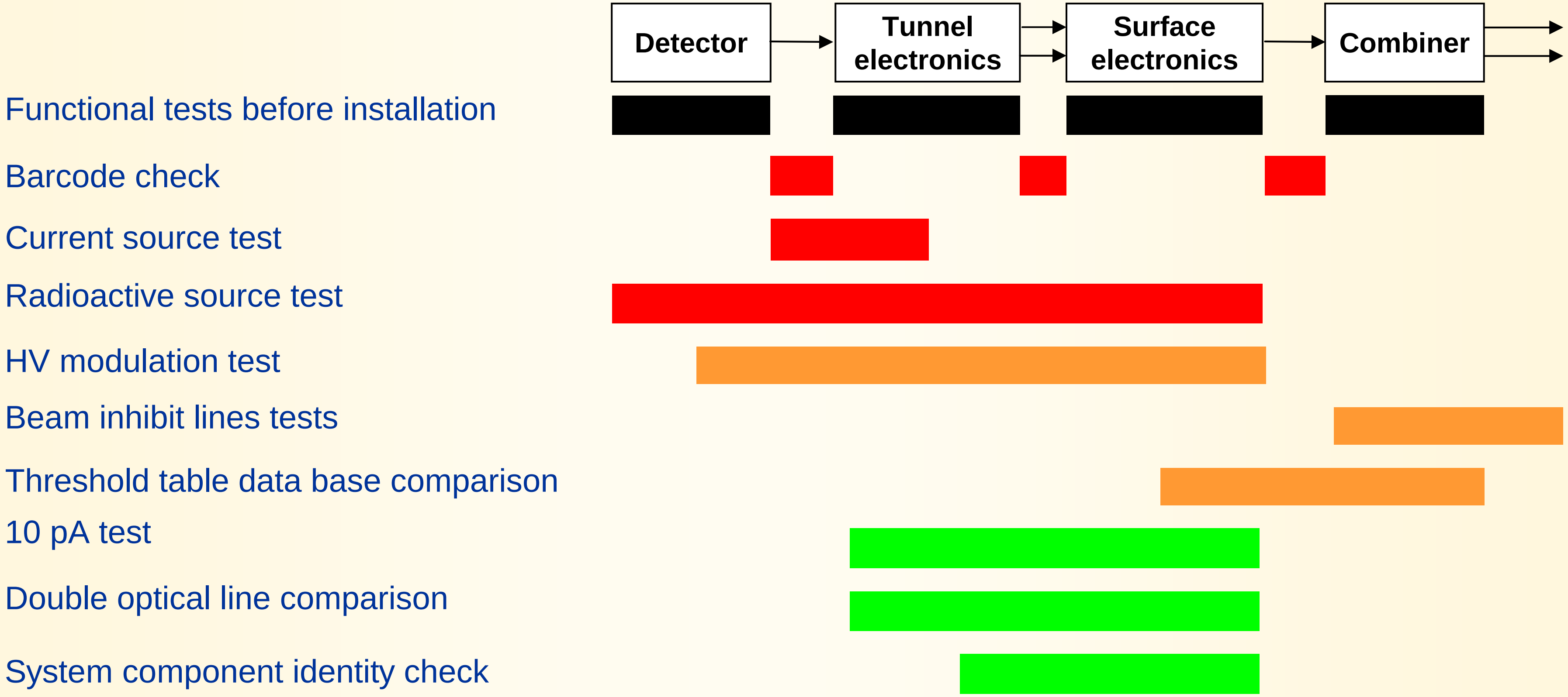
CRC32 check		Comparison of 4Byte CRCs	Output	Remarks
A	B			
Error	**Error**	**Error**	Dump	**Both signals have error**
Error	**Error**	OK	Dump	**S/W trigger (CRCgenerate or check wrong)**
Error	OK	**Error**	Signal B	**S/W trigger (error at CRC detected)**
Error	OK	OK	Signal B	**S/W trigger (error at 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



Detector → Tunnel electronics → Surface electronics → Combiner

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:

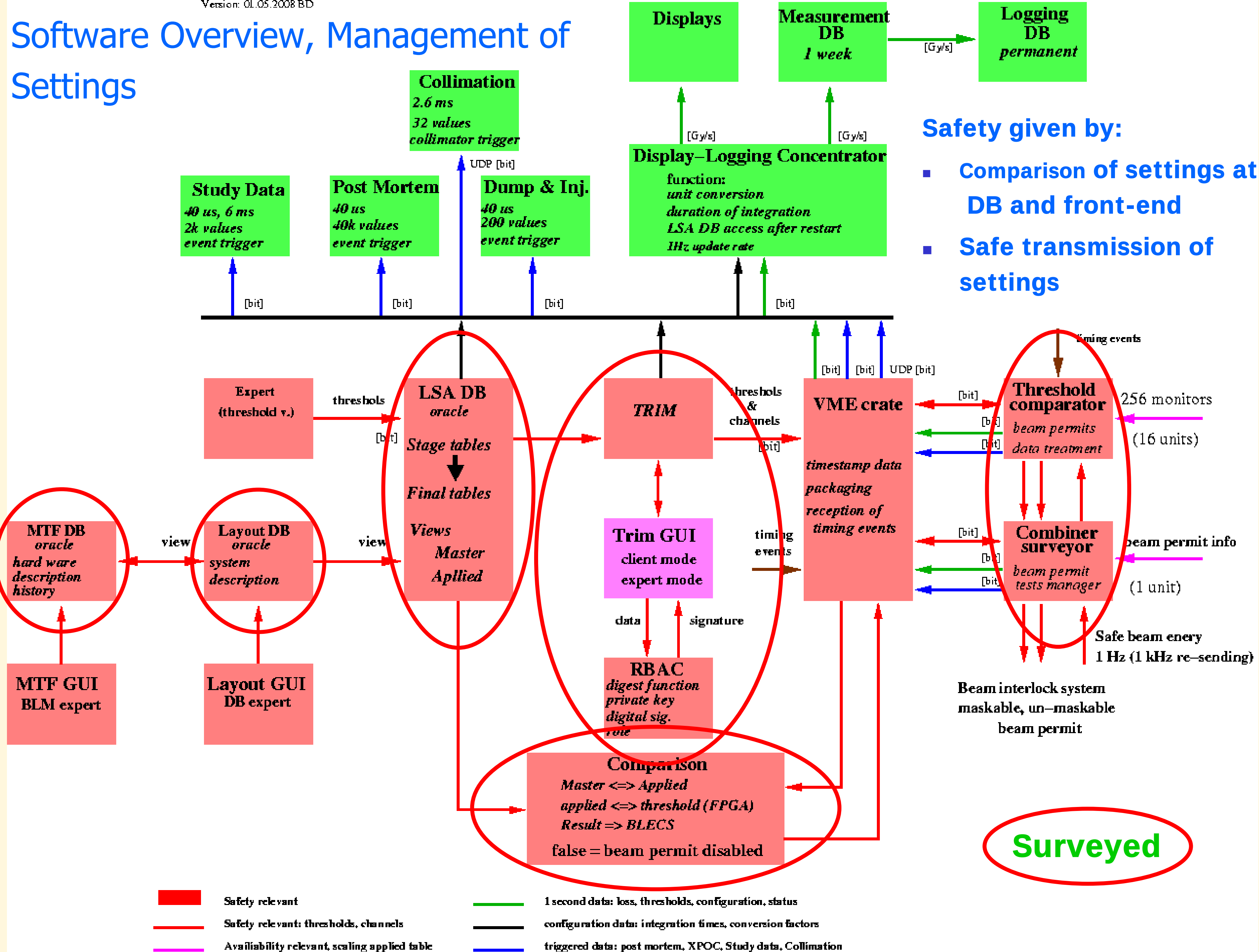
⬛ Reception 🟥 Installation and yearly maintenance 🟧 Before (each) fill 🟩 Parallel with beam

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



🟥 Safety relevant

Safety relevant: thresholds, channels

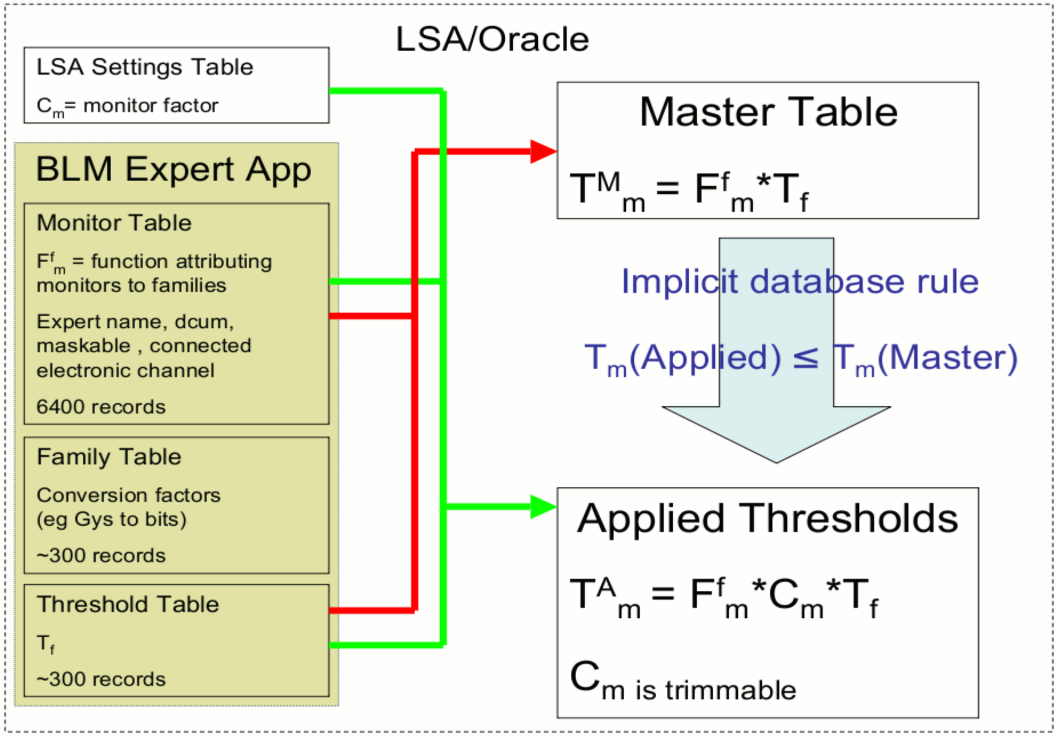
Availiability relevant, scaling applied table

1 second data: loss, thresholds, configuration, status

configuration data: integration times, conversion factors

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

Data Base Structure



LSA/Oracle

LSA Settings Table

C_m= monitor factor

BLM Expert App

Monitor Table

F^f_m = function attributing monitors to families

Expert name, dcum, maskable , connected electronic channel

6400 records

Family Table

Conversion factors (eg Gys to bits)

~300 records

Threshold Table

T_f

~300 records

Master Table

$T^M_m = F^f_m * T_f$

Implicit database rule

$T_m(\text{Applied}) \leq T_m(\text{Master})$

Applied Thresholds

$T^A_m = F^f_m * C_m * T_f$

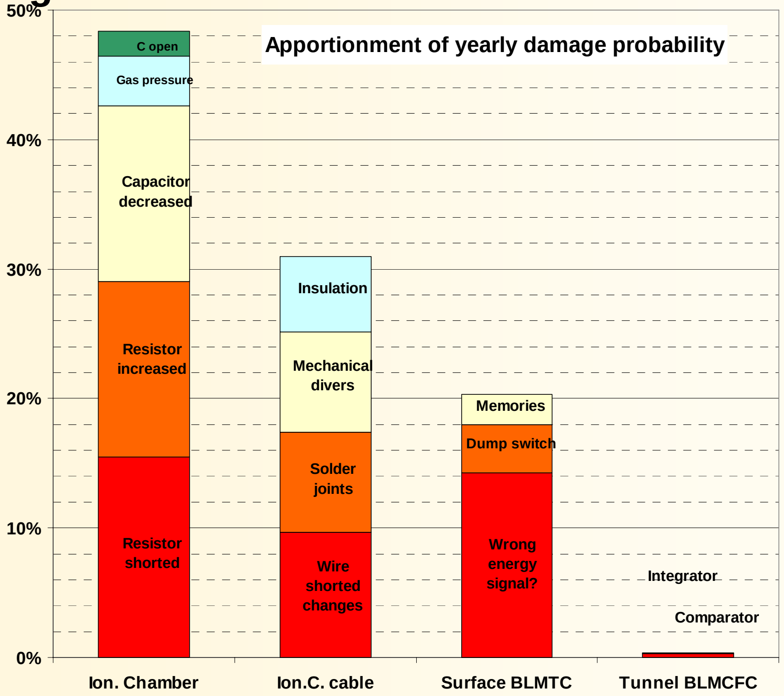
C_m is trimmable

Failsafe

- 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

Reliability Study – Fault-Tree Approach

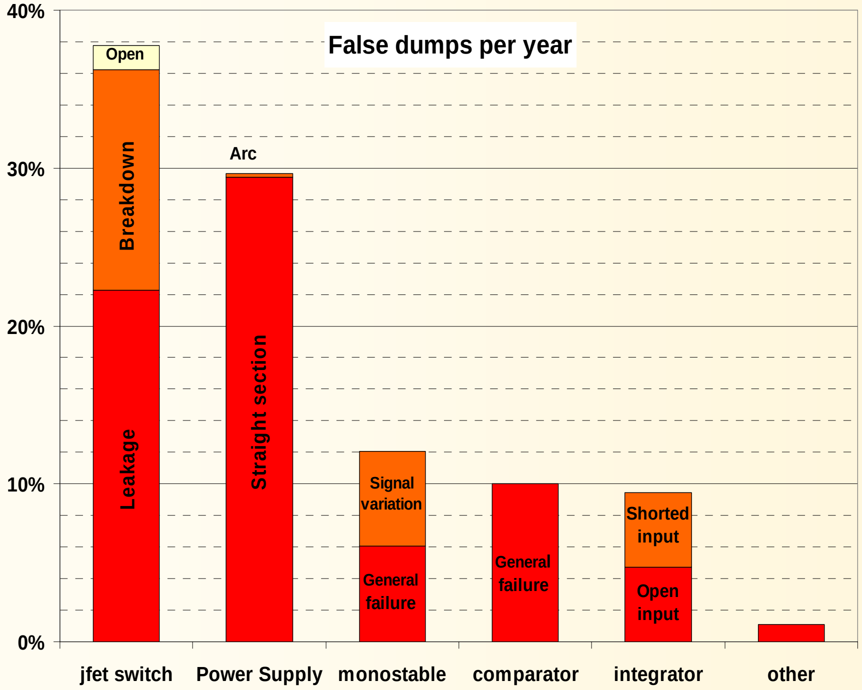
Relative probability of a system component being responsible for a damage to an LHC magnet in the case of a loss.



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

1. Reduced checks
2. Harsh environment

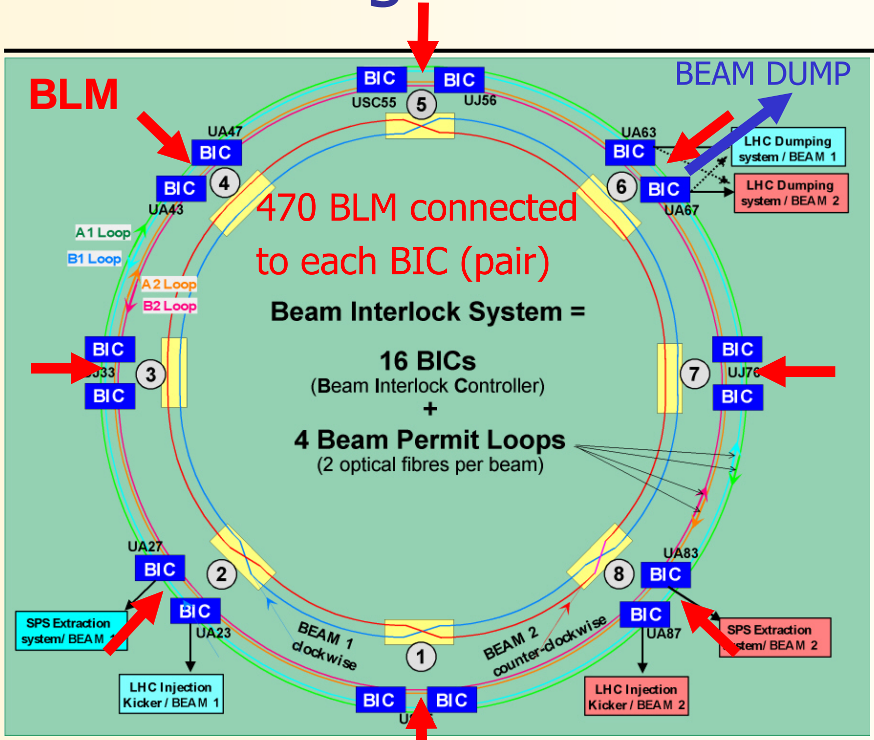
Relative probability of a BLM component generating a false dump. by G. Guaglio

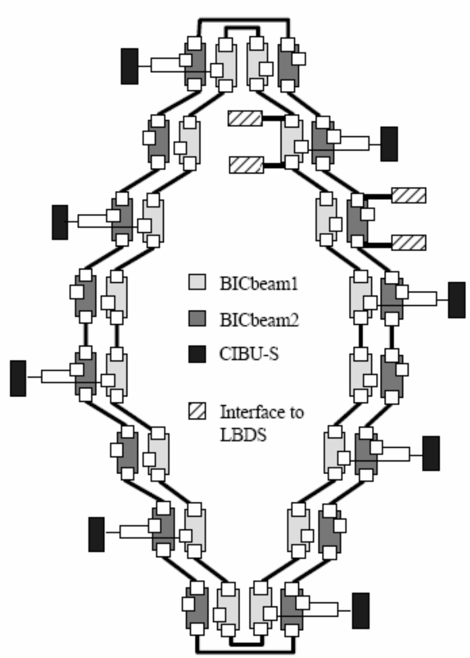


Most false dumps initiated by analog front end (98%) because:

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

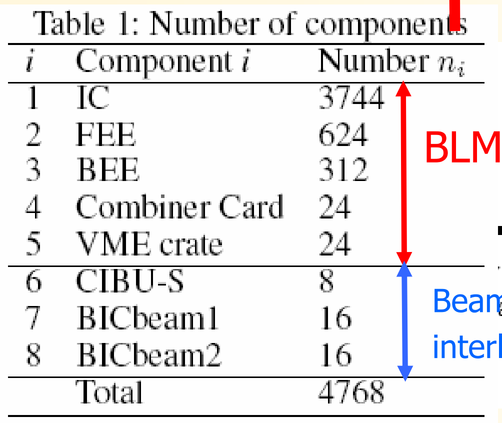
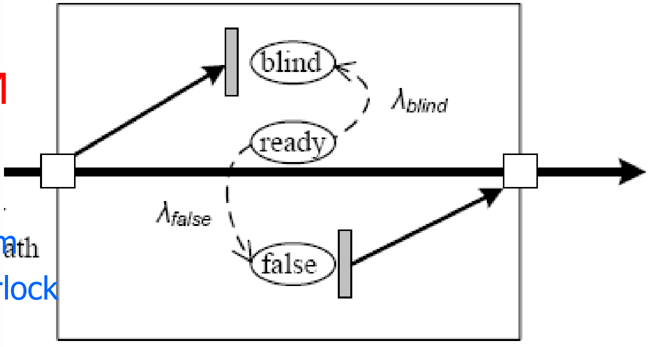


Table 1: Number of components

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



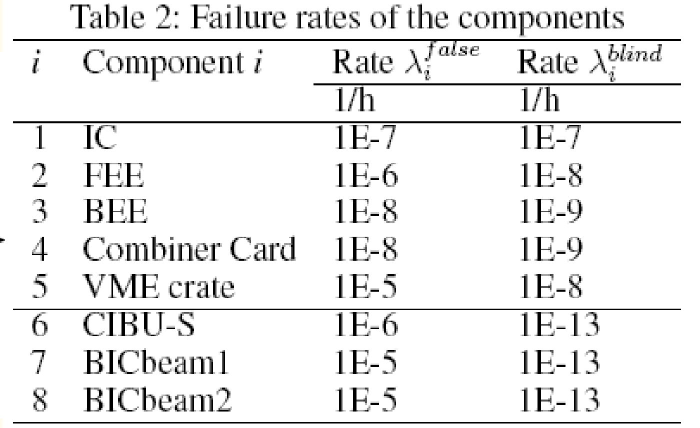


Table 2: Failure rates of the components

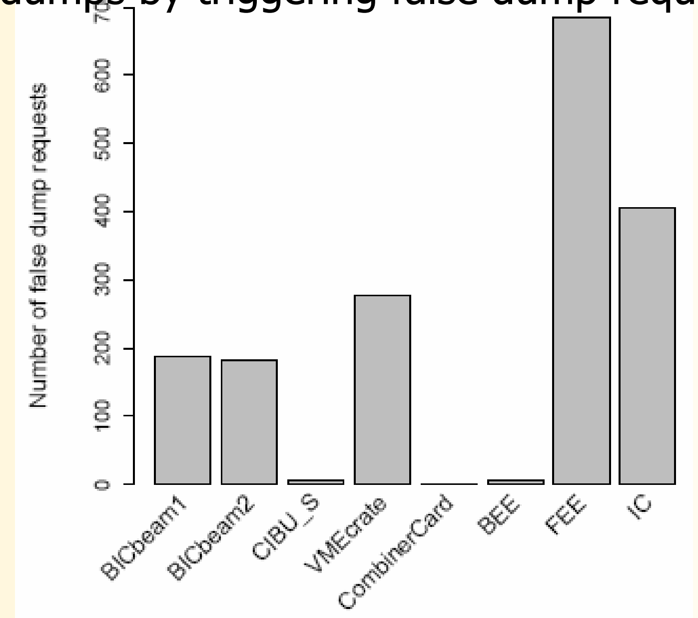
i	Component i	Rate λ_i^{false}	Rate λ_i^{blind}
		1/h	1/h
1	IC	1E-7	1E-7
2	FEE	1E-6	1E-8
3	BEE	1E-8	1E-9
4	Combiner Card	1E-8	1E-9
5	VME crate	1E-5	1E-8
6	CIBU-S	1E-6	1E-13
7	BICbeam1	1E-5	1E-13
8	BICbeam2	1E-5	1E-13

First Modelling Results


Mission Distribution

- 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%

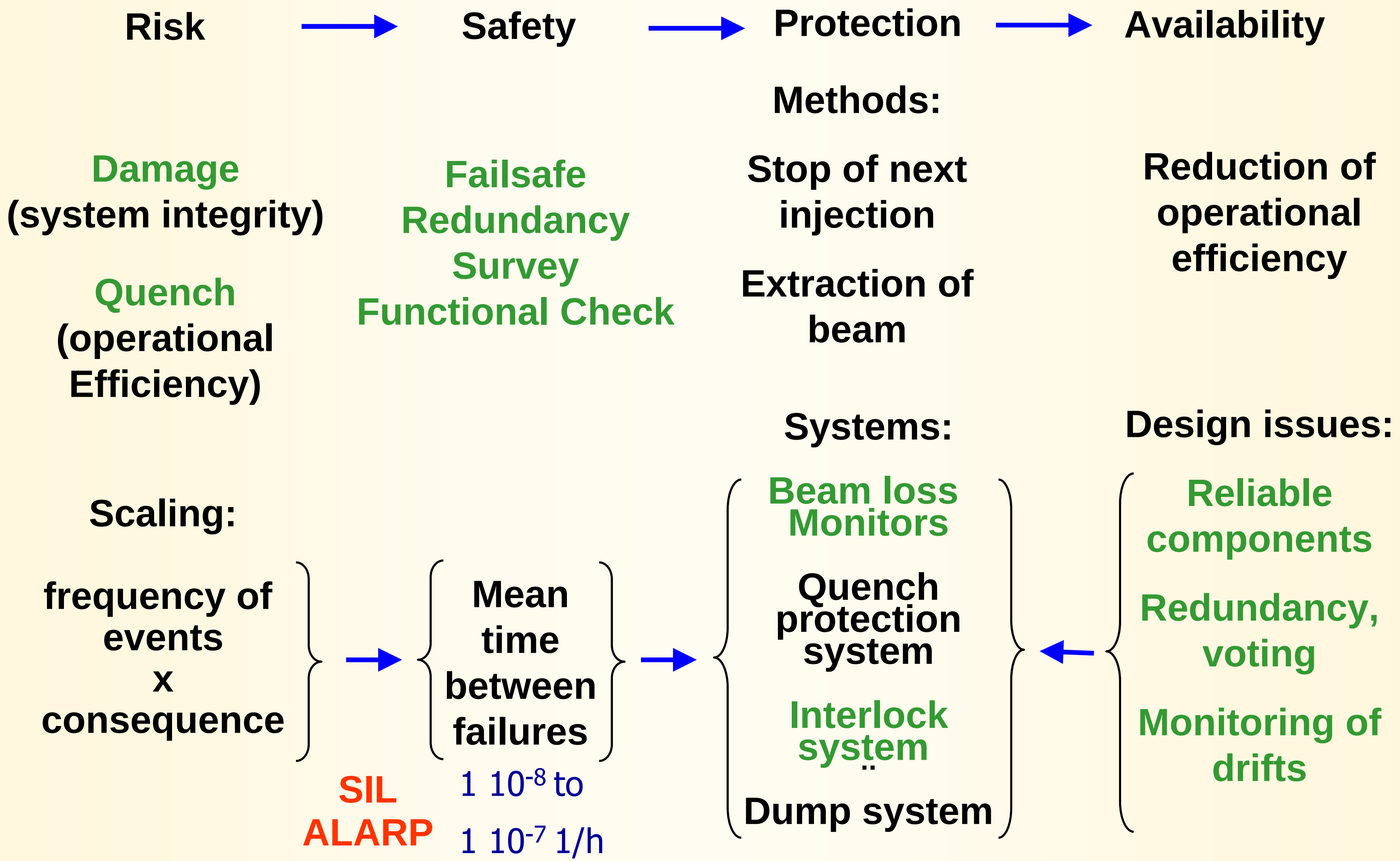
contribution of the components to false dumps by triggering false dump requests.



- 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**

Damage
(system integrity)

Quench
(operational Efficiency)

Failsafe
Redundancy
Survey
Functional Check

Methods:

Stop of next injection

Extraction of beam

Reduction of operational efficiency

Scaling:

frequency of events
x
consequence

→

Mean time between failures

SIL
ALARP

$1\ 10^{-8}$ to

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

→

Systems:

Beam loss Monitors

Quench protection system

Interlock system

Dump system

←

Design issues:

Reliable components

Redundancy, voting

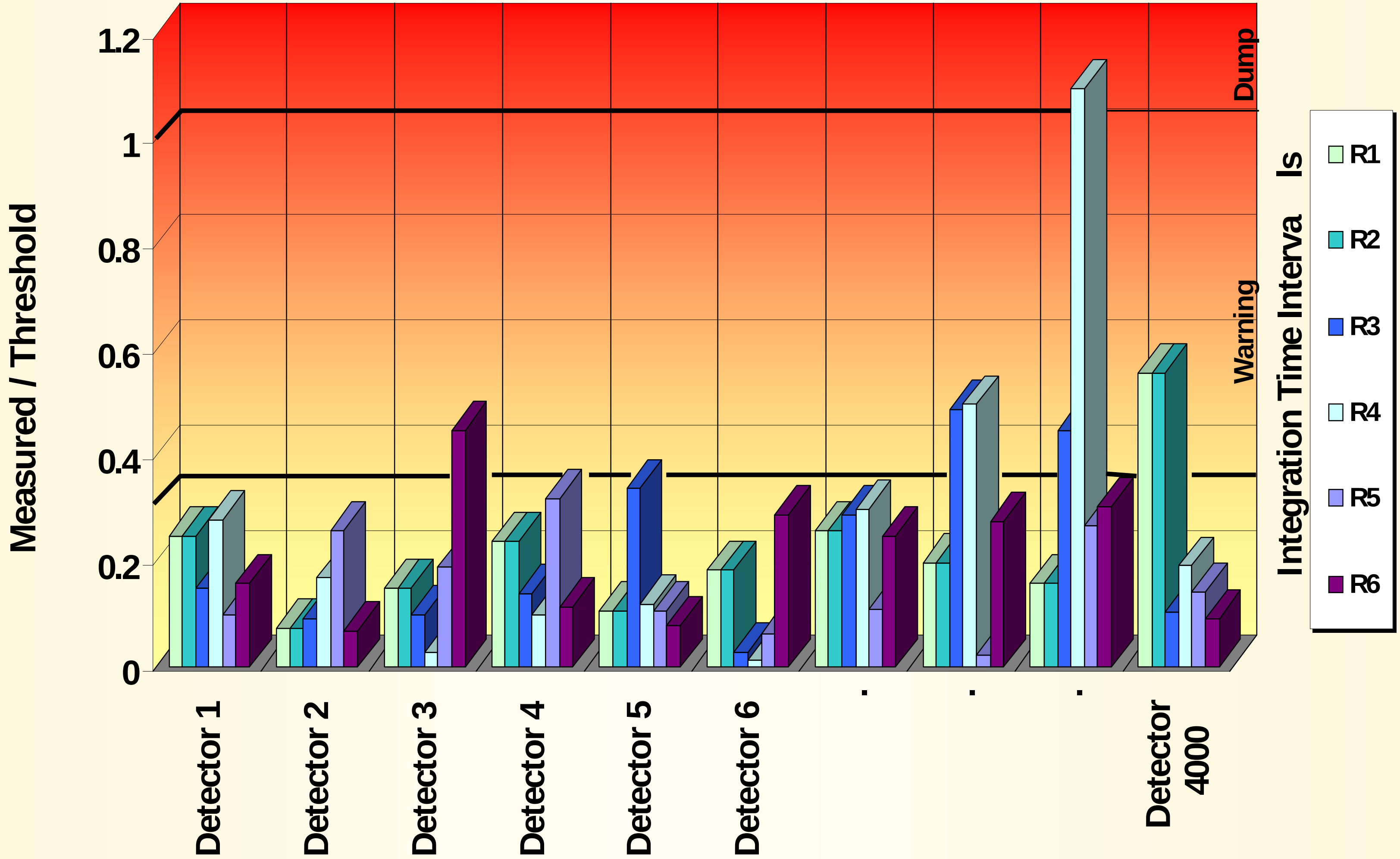
Monitoring of drifts

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



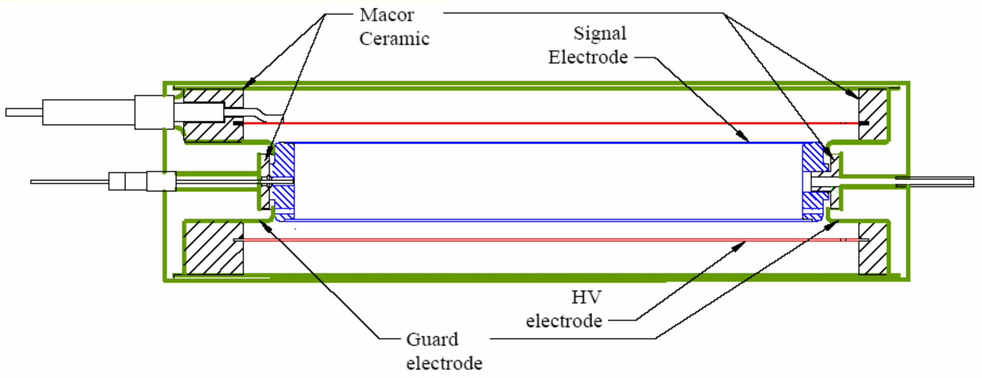
Intensities

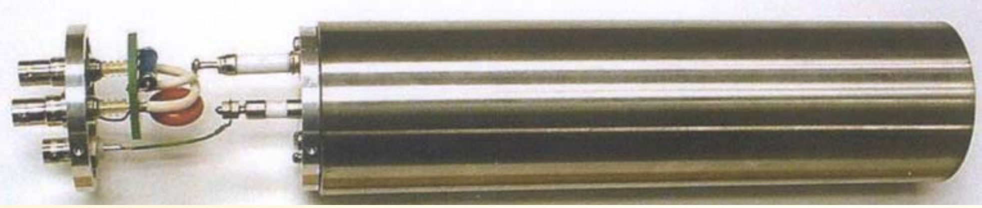
- Intensity one “pilot” bunch $5\cdot10^{9}$
- Nominal bunch intensity $1.1\cdot10^{11}$
- Batch from SPS (216/288 bunches at 450 GeV) $3\cdot10^{13}$
- Nominal beam intensity with 2808 bunches $3\cdot10^{14}$
- Damage level for fast losses at 450 GeV $1\text{-}2\cdot10^{12}$
- Damage level for fast losses at 7 TeV $1\text{-}2\cdot10^{10}$
- Quench level for fast losses at 450 GeV $2\text{-}3\cdot10^{9}$
- Quench level for fast losses at 7 TeV $1\text{-}2\cdot10^{6}$

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**

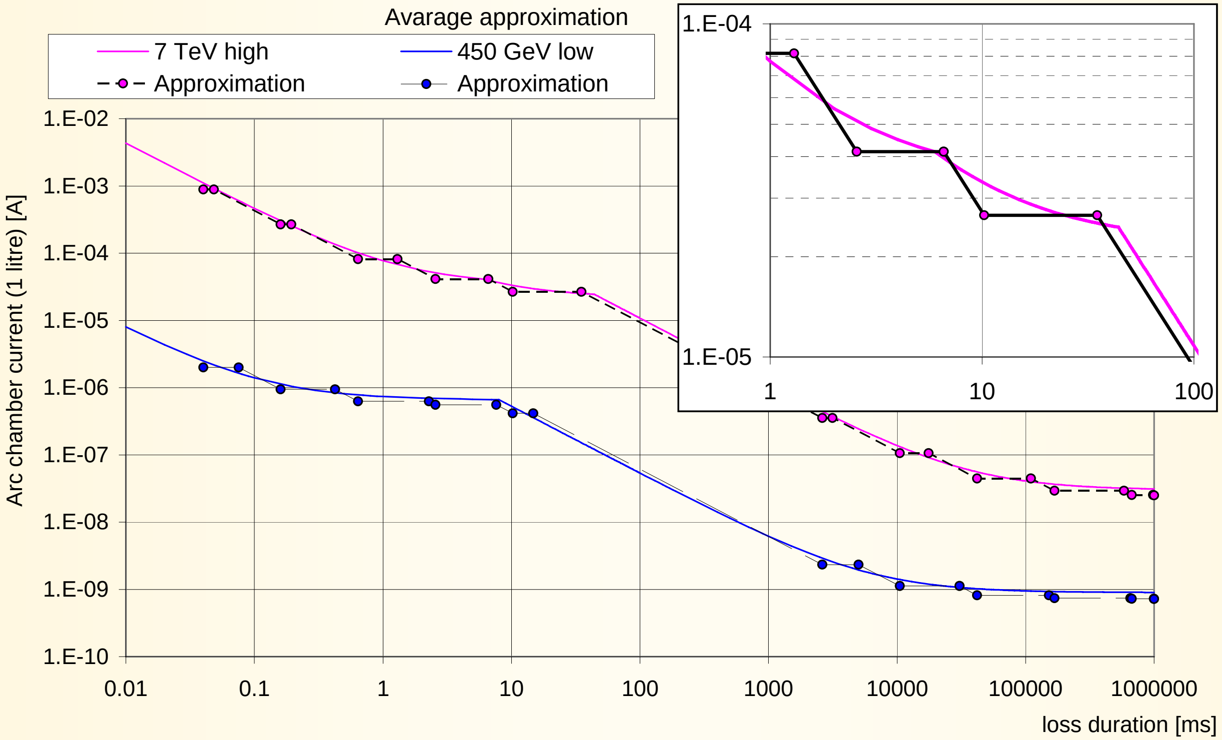
Ionisation chamber SNS





- 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

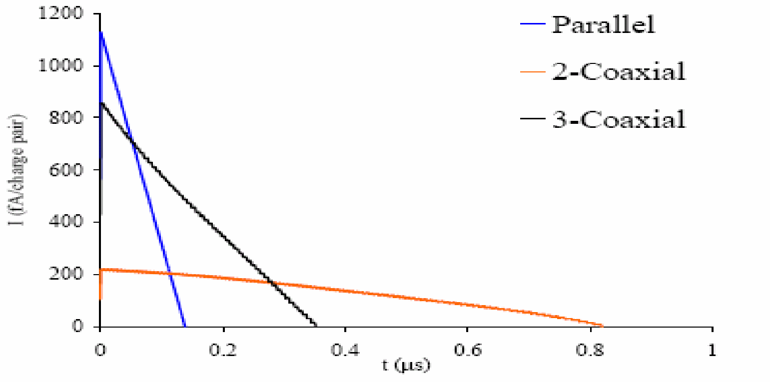
Approximation of Quench Levels (LHC)



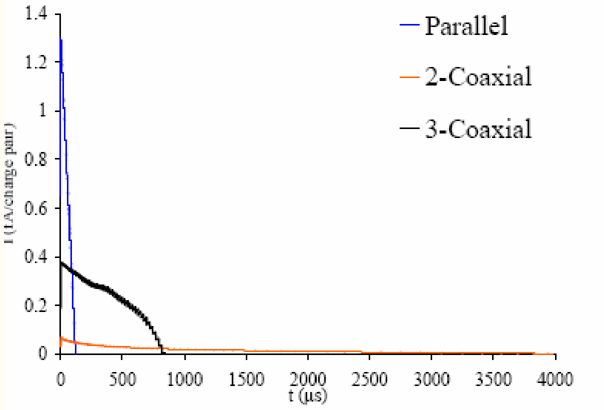
- Dump level tables are loaded in a non volatile RAM
- Any curve approximation possible
  - Loss durations
  - Energy dependence

Relative error kept < 20 %

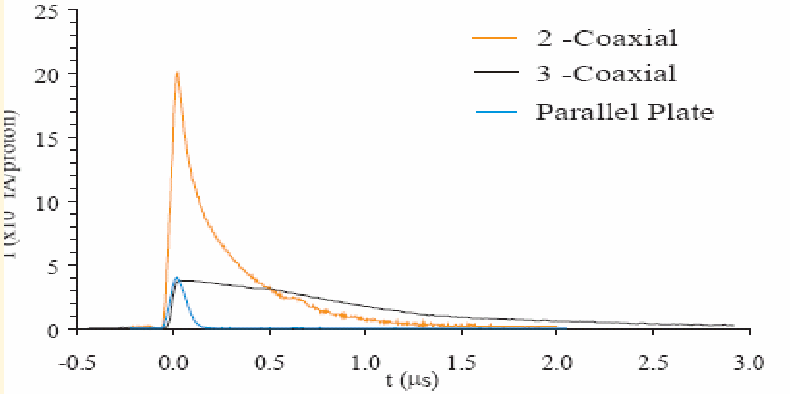
Drift times of electrons and ions (II)



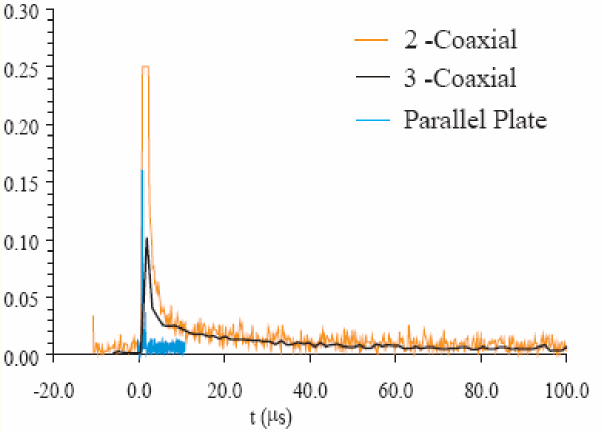
(a) *Simulated electrons*



(b) *Simulated ions*

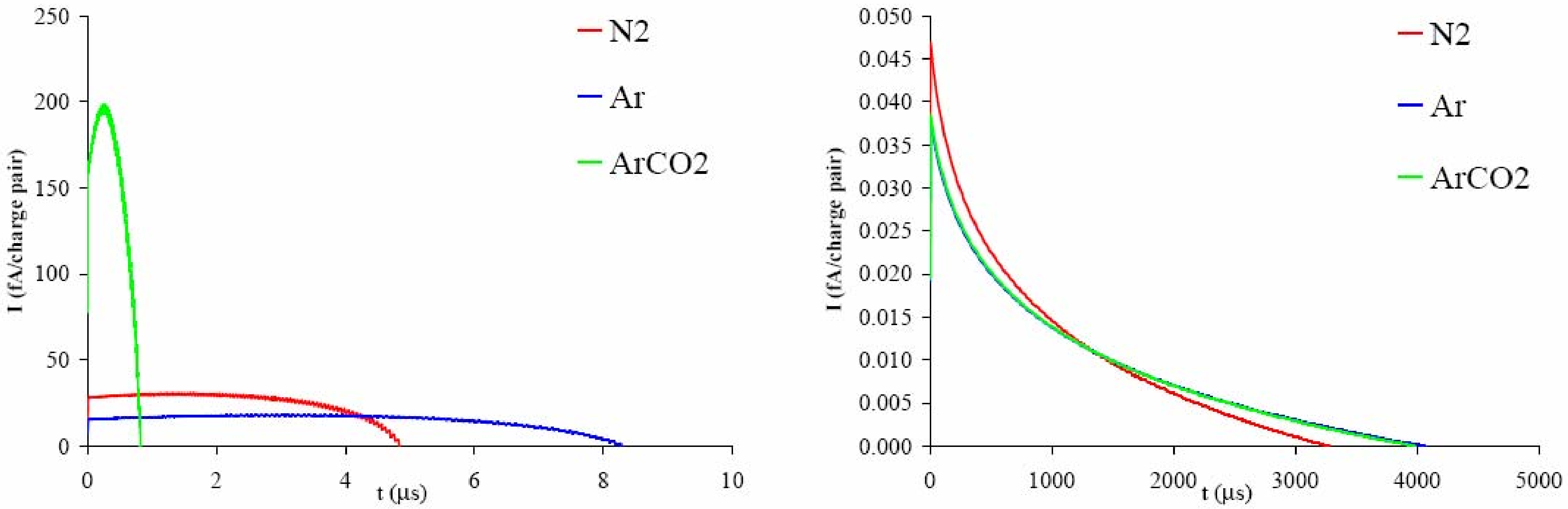


(c) *Experimental electrons*



(d) *Experimental ions*

Drift times of electrons and ions (I)

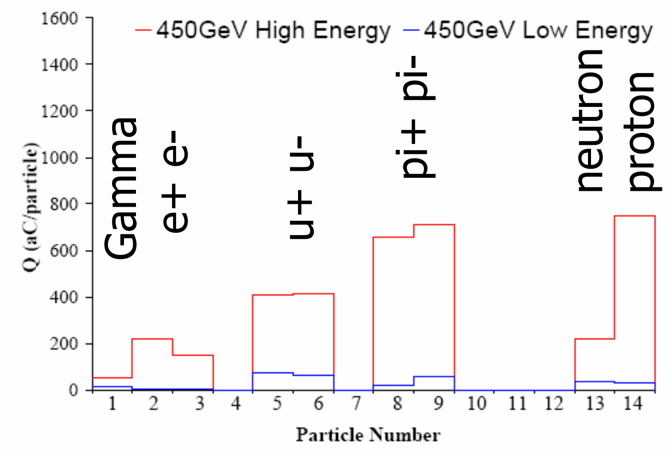


(a) *electrons*

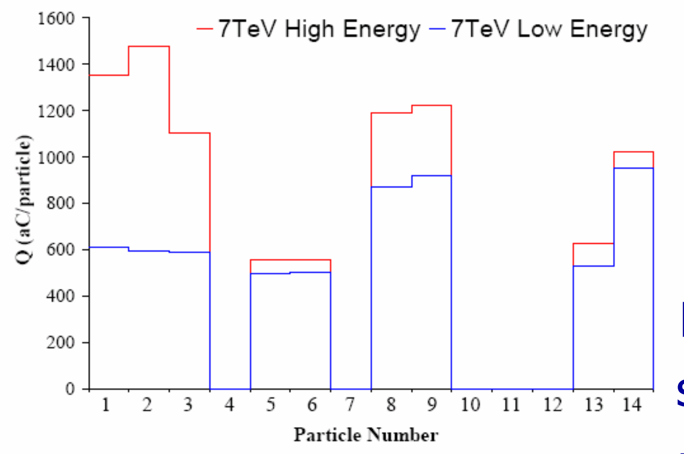
(b) *ions*

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

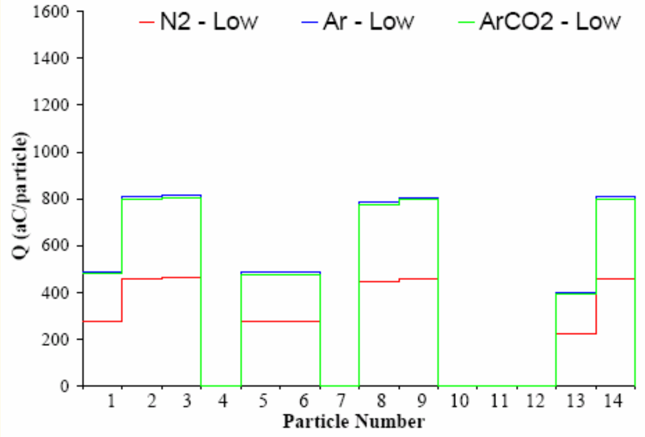
Response of ion chambers for different particle species



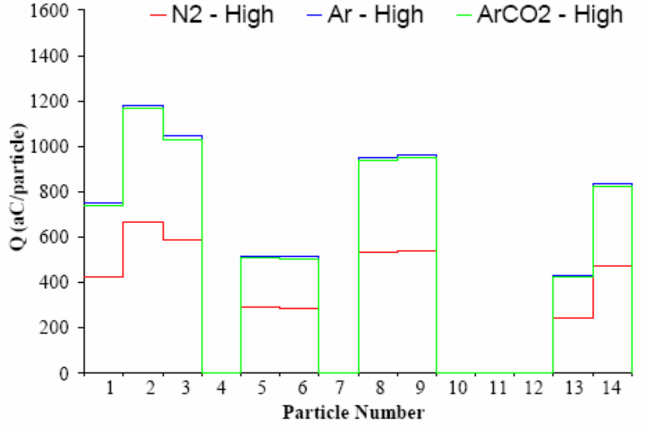
(c) *2-Coaxial - 450 GeV*



(d) *2-Coaxial - 7 TeV*



(a) *Low end of energy spectrum.*



(b) *High end of energy spectrum.*

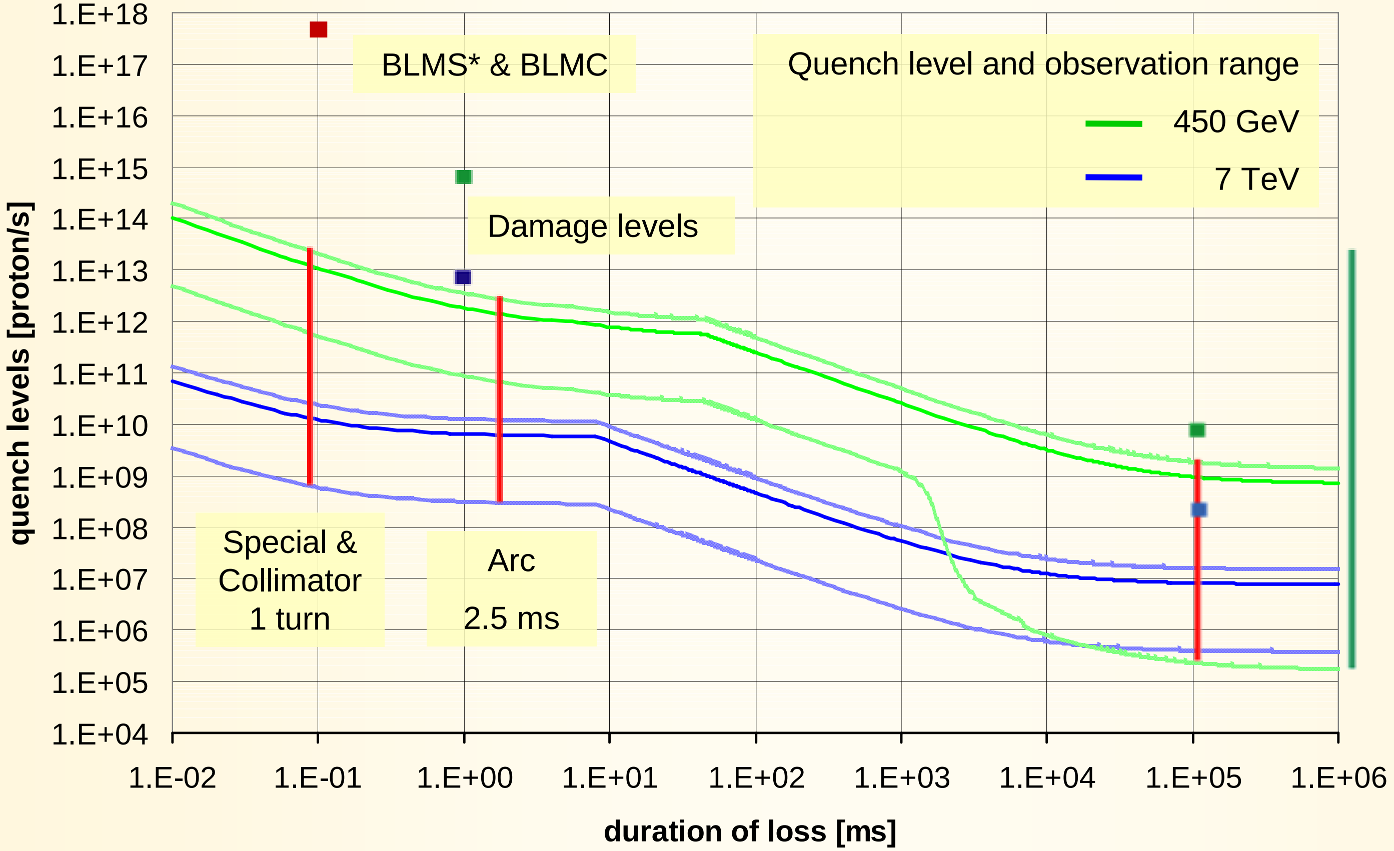
Due to attenuation of shower

=>

increase of non linearity of chamber response

Quench and Damage Levels

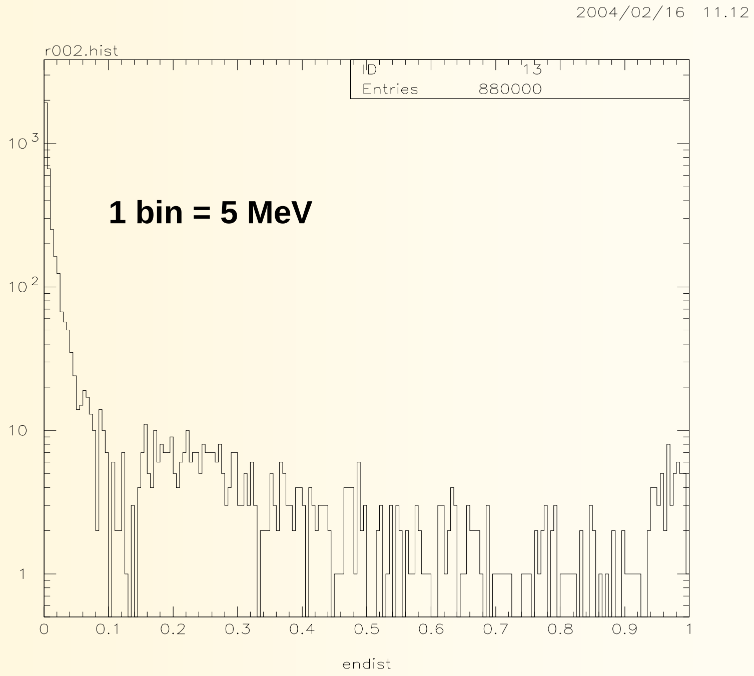
- Detection of shower particles outside the cryostat or near the collimators to determine the coil temperature increase due to particle losses



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

Energy spectrum of shower particles outside of cryostat

- Energy spectrum:



1 bin = 5 MeV

Energy [GeV]

- Number of charged particles and energy deposition simulated:

Average energy deposition in the detector (air):

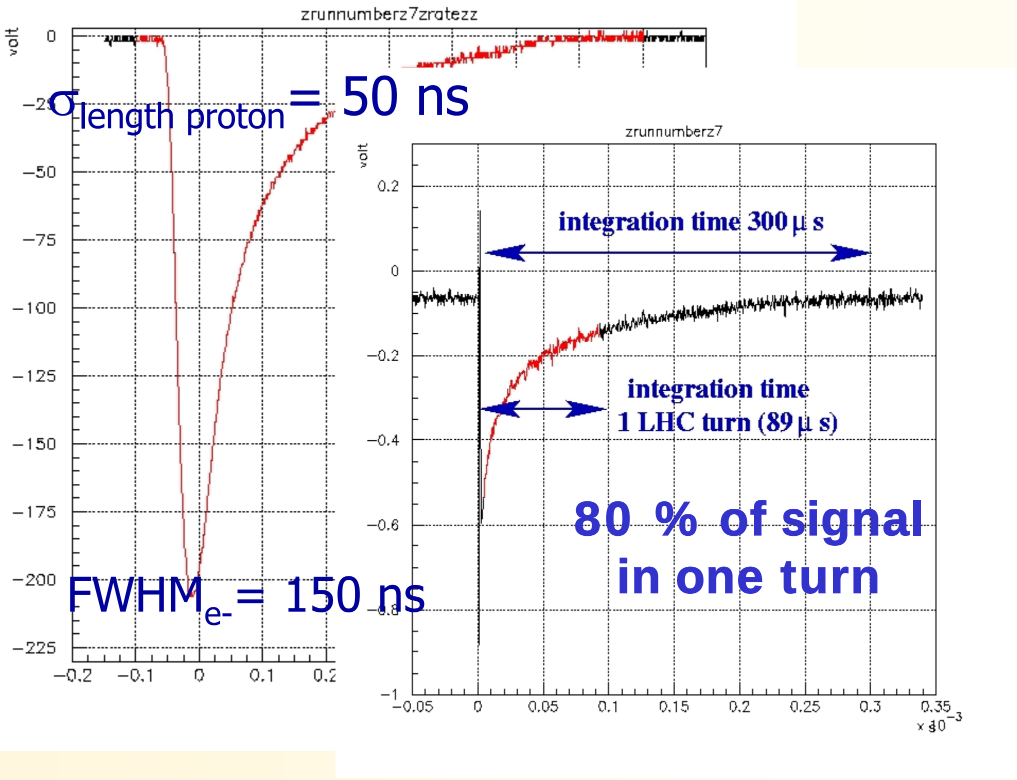
- **450 GeV: ~3.8 keV/cm**
- **7 TeV: ~4.3 keV/cm**

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

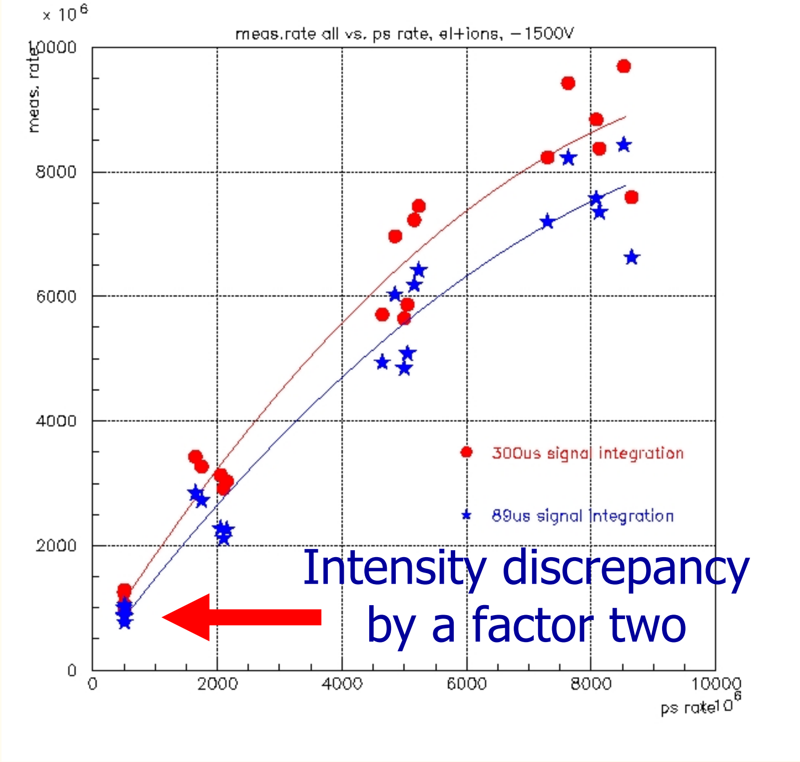


$\sigma_{\text{length proton}}$ = 50 ns

FWHM_{e-} = 150 ns

80 % of signal in one turn

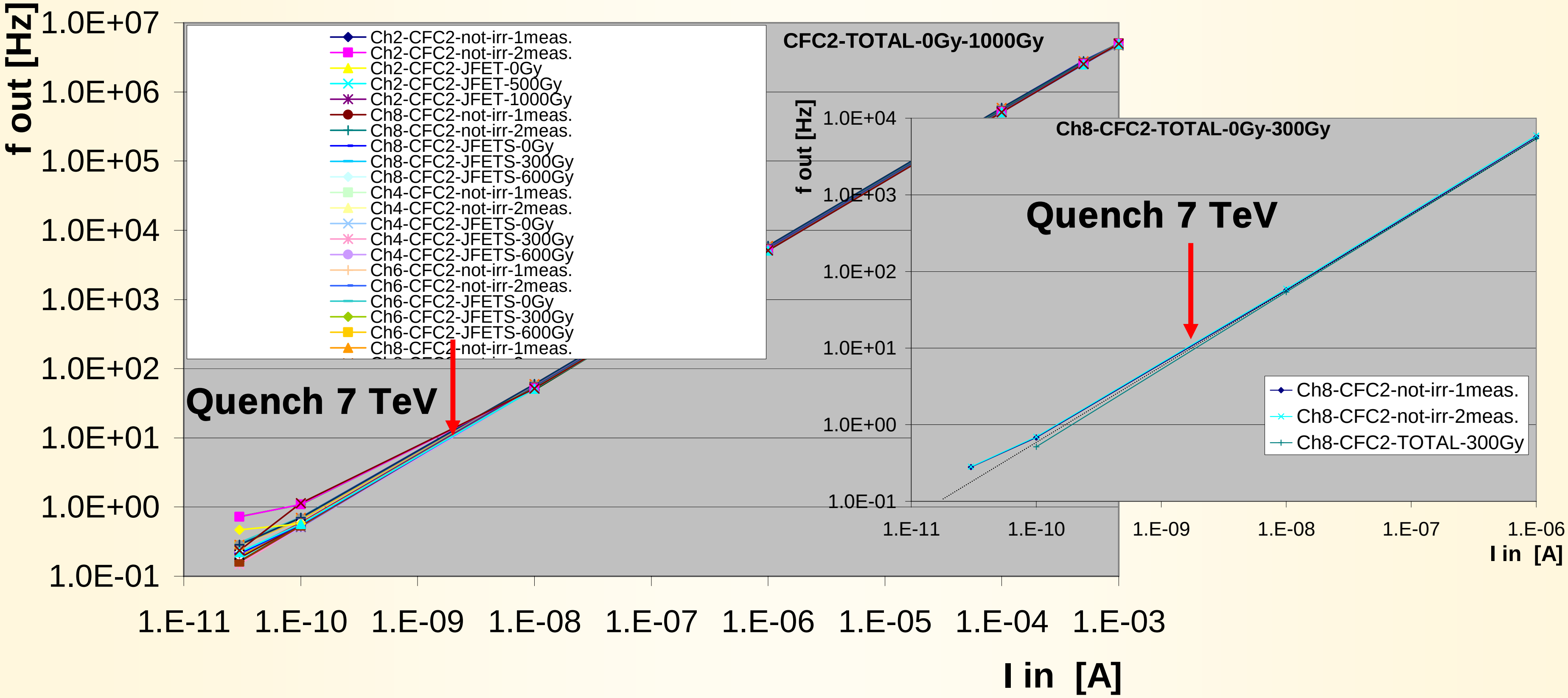
Chamber current vs beam current



Intensity discrepancy by a factor two

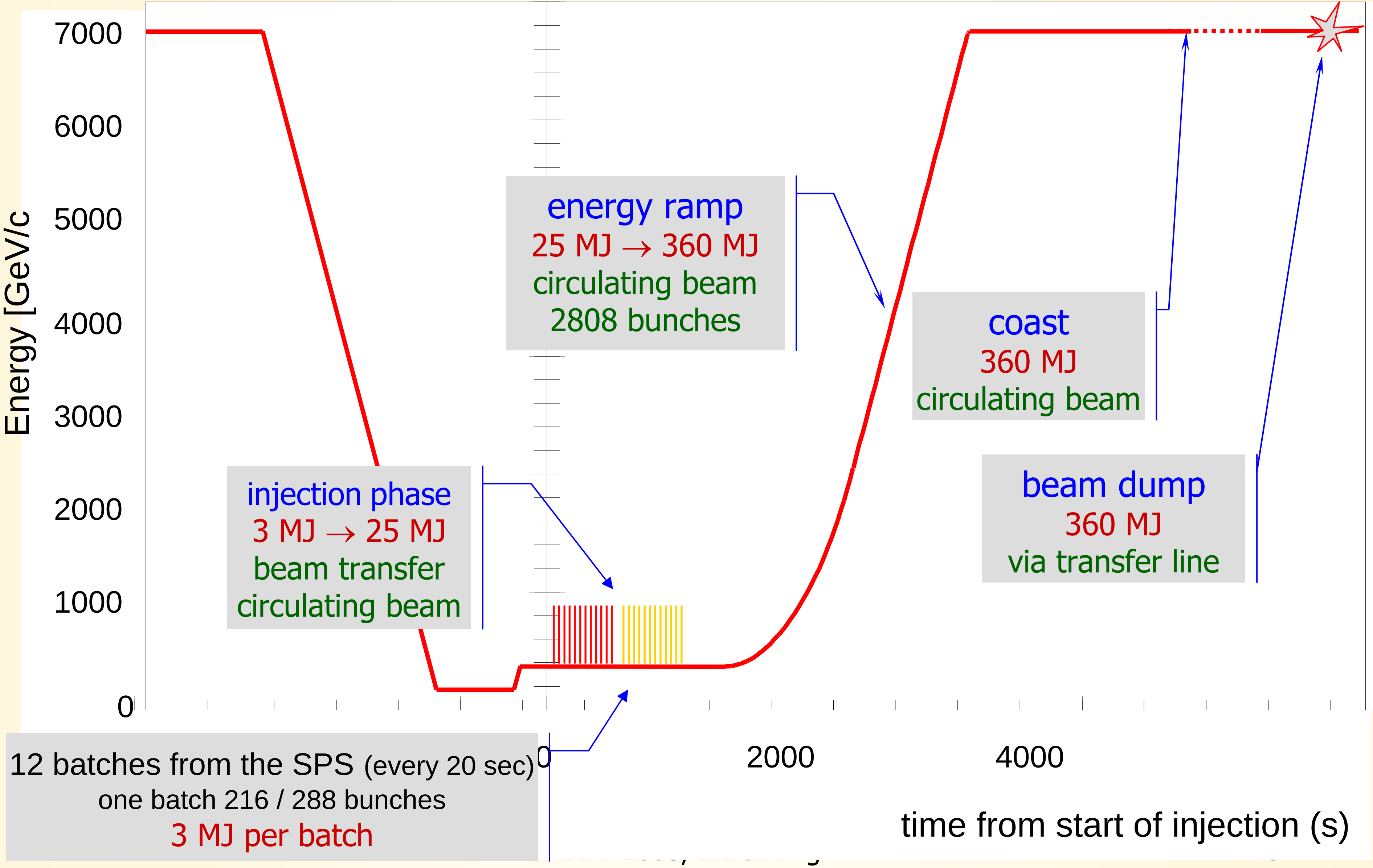
Intensity density: - Booster 6 10^9 prot./cm^2, two orders larger as in LHC

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



energy ramp
25 MJ → 360 MJ
circulating beam
2808 bunches

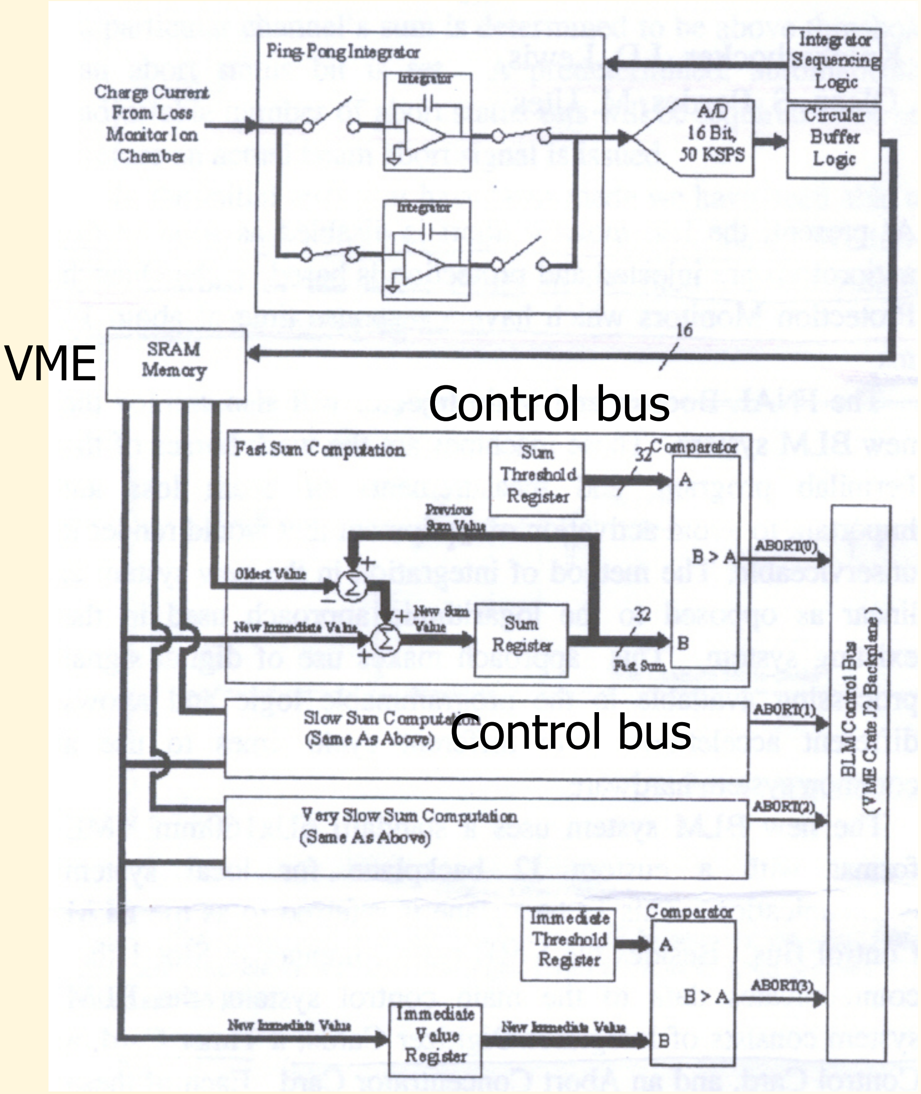
coast
360 MJ
circulating beam

beam dump
360 MJ
via transfer line

injection phase
3 MJ → 25 MJ
beam transfer
circulating beam

12 batches from the SPS (every 20 sec)
one batch 216 / 288 bunches
3 MJ per batch

FNAL beam loss integrator and digitizer

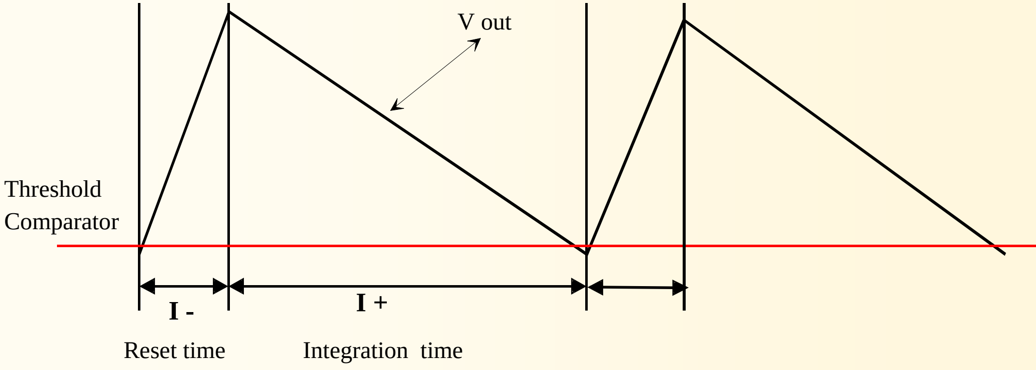


	FNAL	**LHC**
channels	4	16
Time resolution	21 µs	40 µs
# of running sums	3	11
windows	21 µs to 1.4 s	80 µs to 84 s
thresholds	4	12
Synchronized to machine timing	yes	no
post mortem buffer	4k values	1k values

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

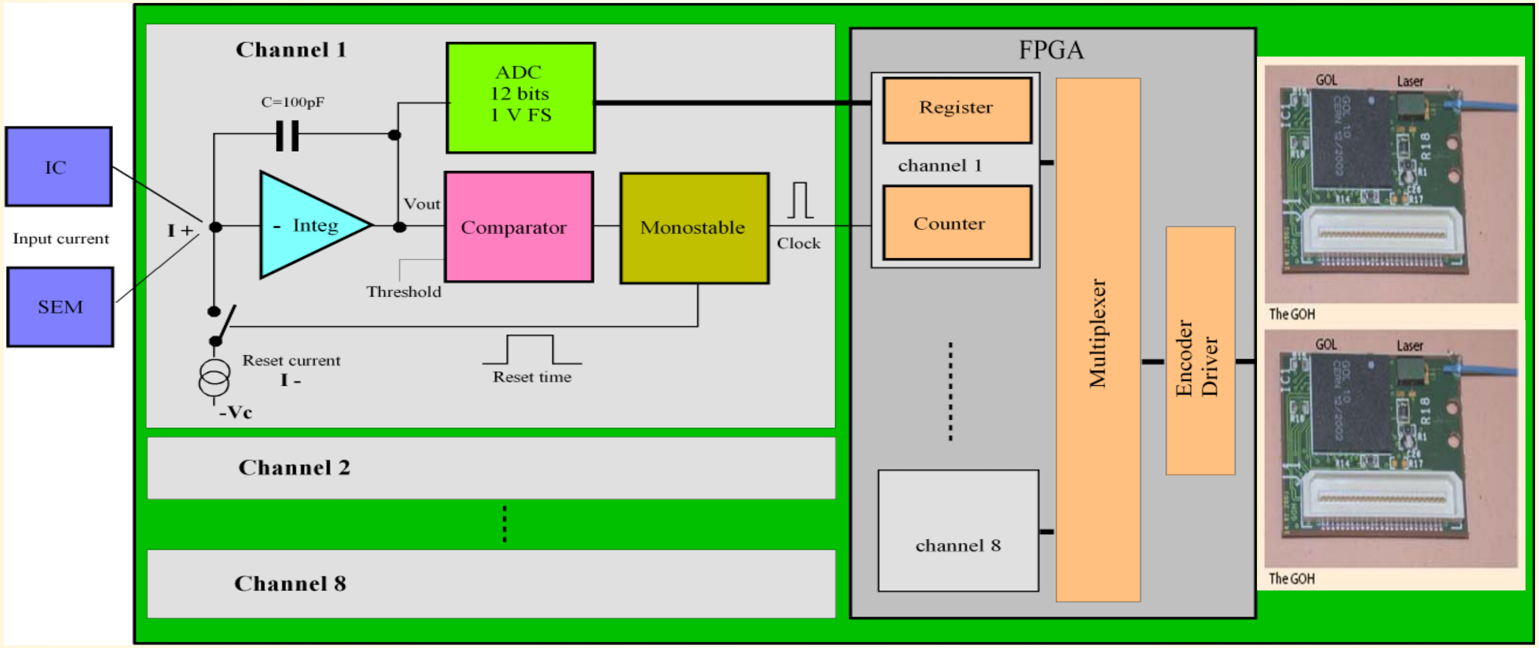
LHC tunnel card

- 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

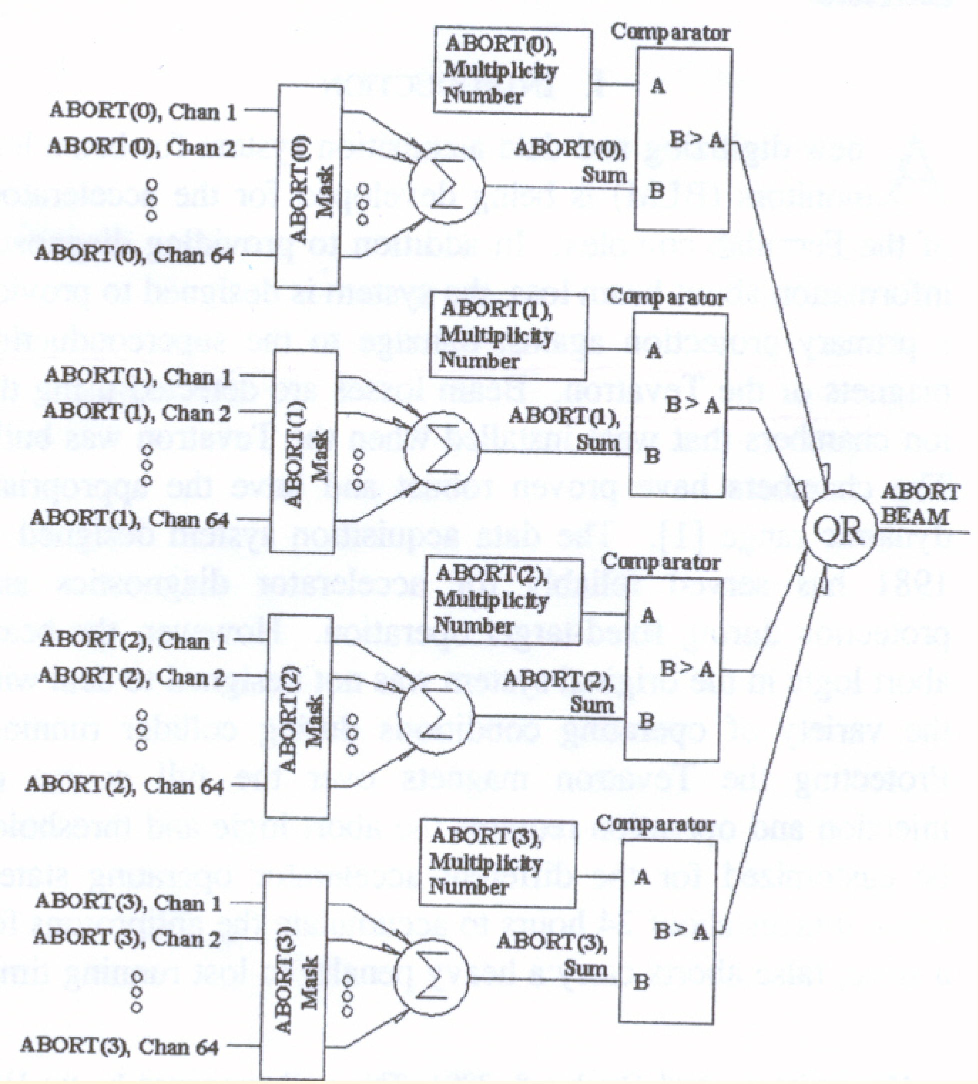


100 ns

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)