Loss Monitoring an Overview

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CERN BE/BI

Content

- Project planning
  - Functional Specification
  - Technical specification result of several simulations:
      - loss of proton loss
      - shower location
      - quench level
      - reliability study of system
  - Budget, Personal, schedule
  - Project reviews with (internal, external, private companies)
- The systems
  - Detectors
    - Ionisation chambers
    - Photo multiplier (Aluminum Cathode, Cherenkov radiator, fibre)
    - Secondary emission monitor
  - Acquisition chain (analog front-end, digitalization, data treatment)
    - New high dynamic range current measurements
    - Digital design overview
  - Management of Settings
    - Organization of data bases
    - Procedure of setting validations
  - Data presentations

Specification Functional

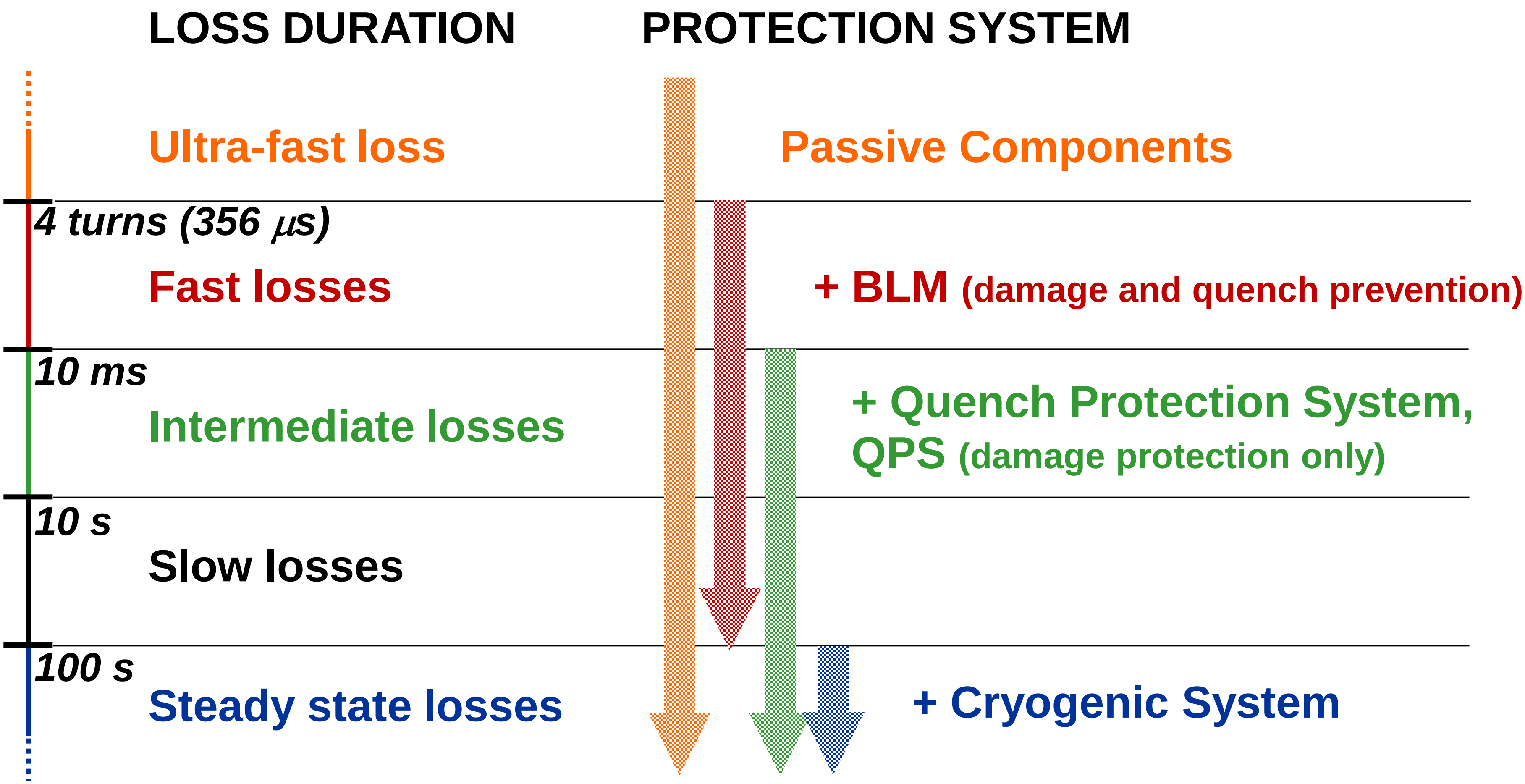
LHC Project Document No.
LHC-BLM-ES-0001 Rev 2.0

Table of Contents

General description of physical processes, over half of the text

1. Important to have basic process described which should be monitored, because of changes in functional requirements may change and reason for monitoring not clear
2. Complete requirements very useful to be defined, including description of measurement, reliability consideration, data presentation and logging, …; all may have an influence of the system design

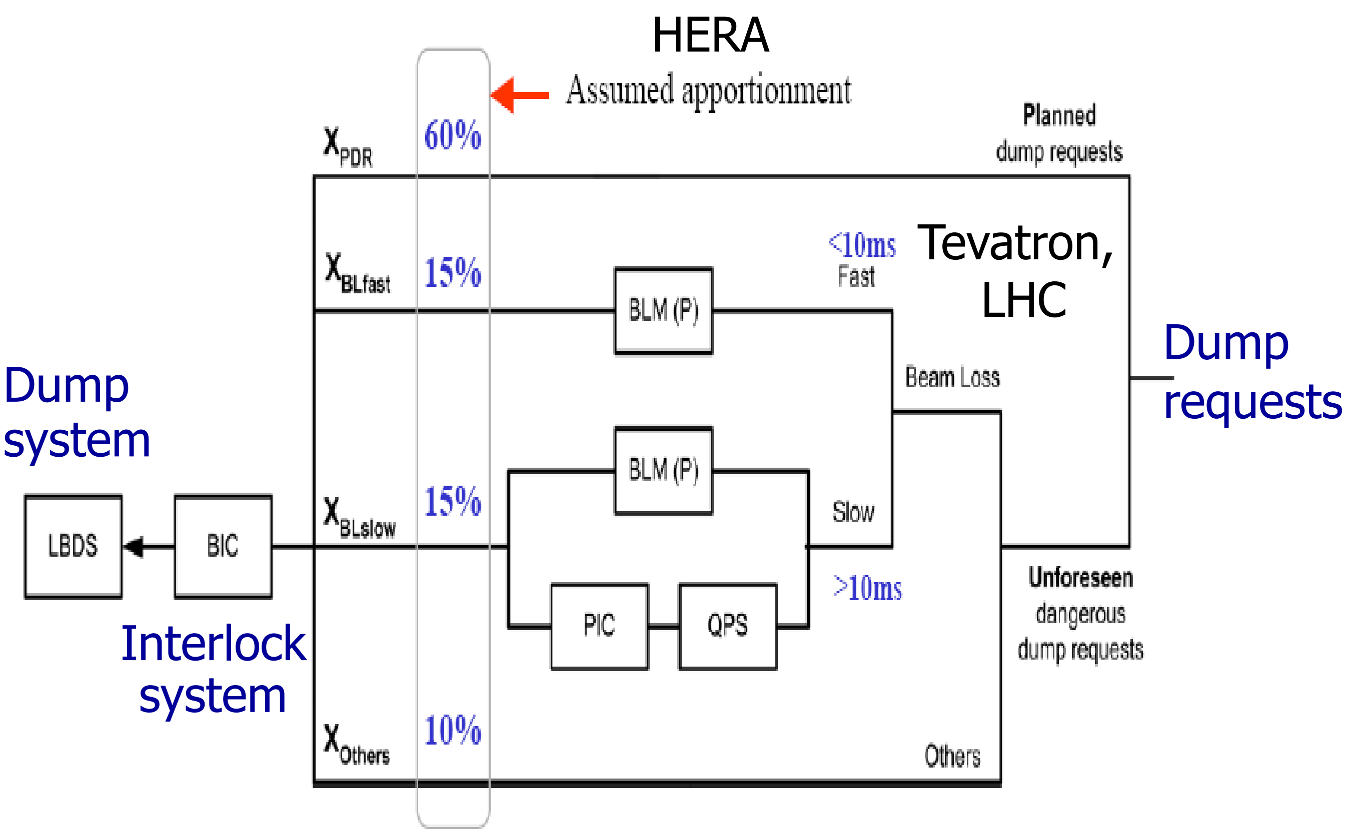
Specification: Beam Loss Durations and Protection Systems



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

Classification loss signals to be used for functional and technical specification

Specification: The Active Protection System and Involved Systems



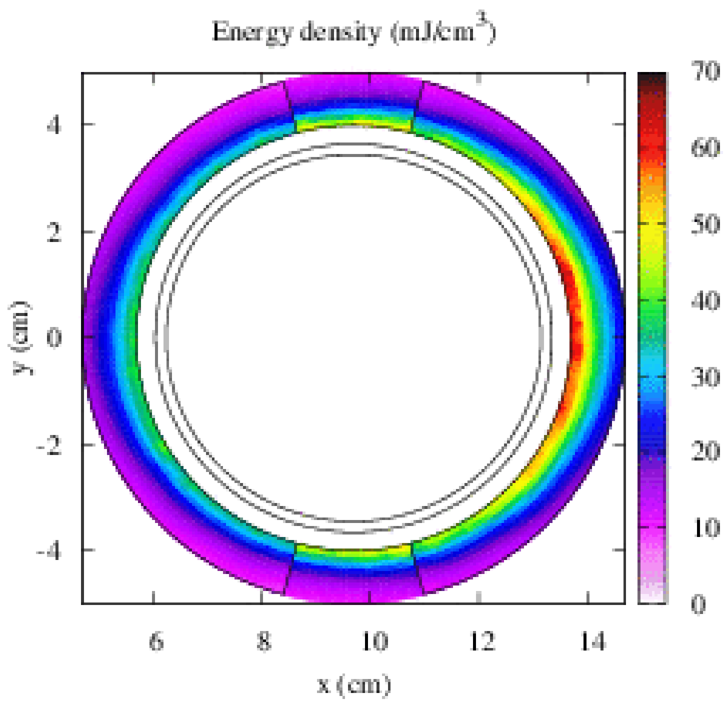
SOURCES of beam losses

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

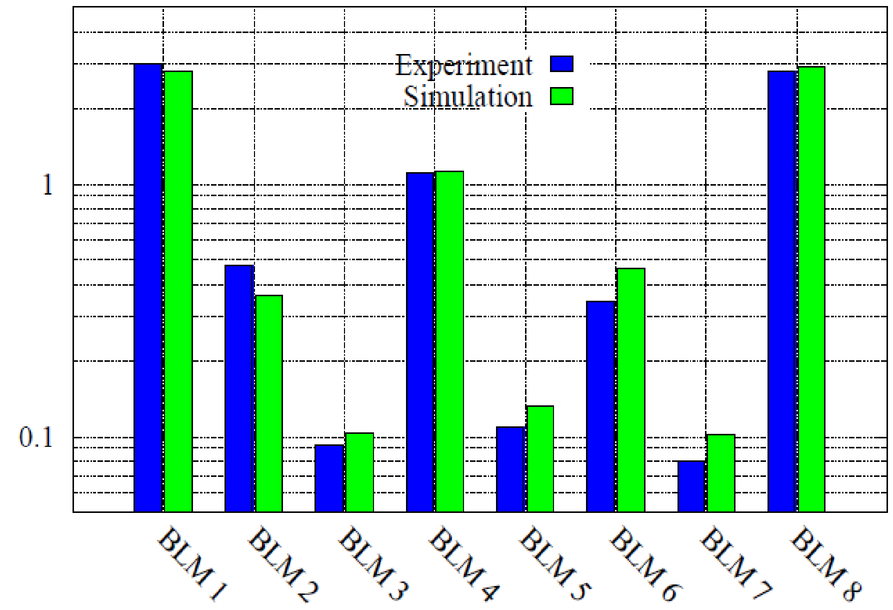
Study of equivalent system to be used for functional and technical specification

Particle shower simulations

One of the most spectacular quench tests: generate millisecond scale losses using with Wire Scanner at 3.5 TeV.



FLUKA simulations



Max E_{dep}
FLUKA: 62.5 mJ/cc
QP3: 38 mJ/cc (preliminary)
we call it a good agreement

Shower simulation could be accurate to few 10% in transverse tails of 20 to 30 cm

Reliability: Safety System Design Approach

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

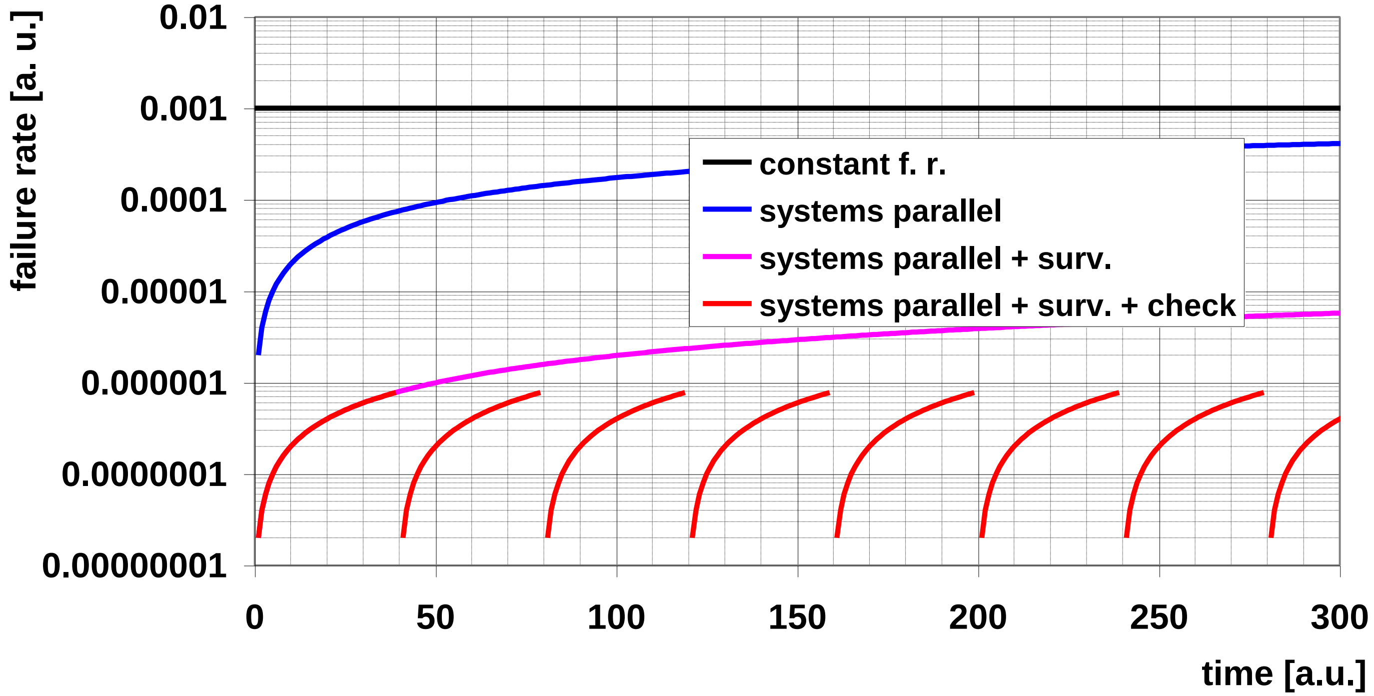
Scaling:

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

SIL ALARP

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

Reliability: Failure Rate and Checks



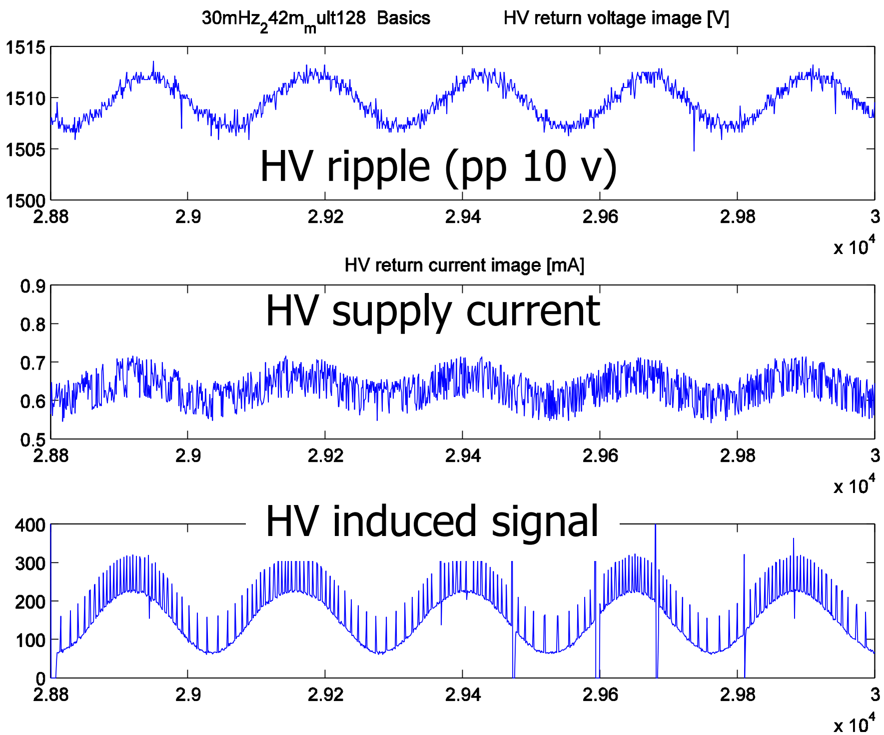
Systems parallel + survey + functional check:

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

Key implementation to obtain low failure rate

Reliability: Check of Analog Signal Chain

Modulation Example



Basic concept:

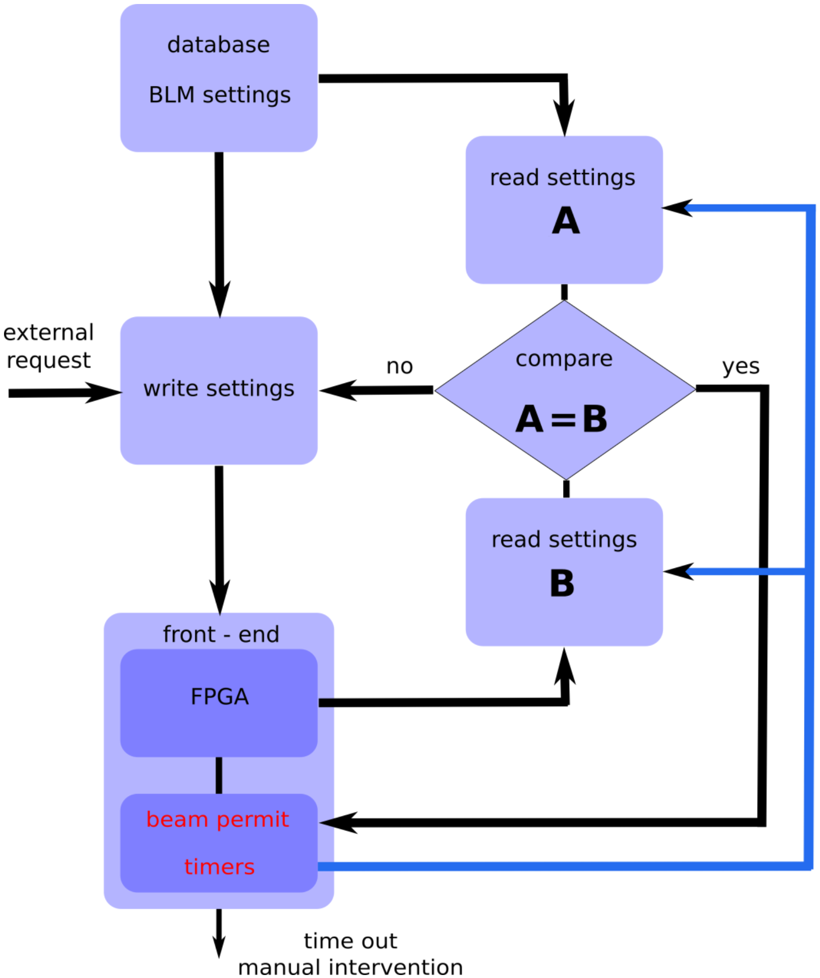
Automatic test measurements in between of two fills (LHC), new systems: continuous check during operation (0.05 Hz)

- 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

Reliability: Settings and Checks from Database to Frontend

Corruption in frontend are more likely as in reference database, therefore =>



- Setting storage in Oracle database
- Settings:
  - Threshold values
  - Voltages, currents, phase limits for automatic test
  - Serial numbers for ever equipment in the acquisition chain
  - Software version numbers
- Comparison of frontend settings with database every 12 hours or after every update
  - If positive hardware base beam permit given
  - If negative after retry, manual intervention (no beam permit)

Request for comparison issued by front-end, most reliable (no software layers in between)

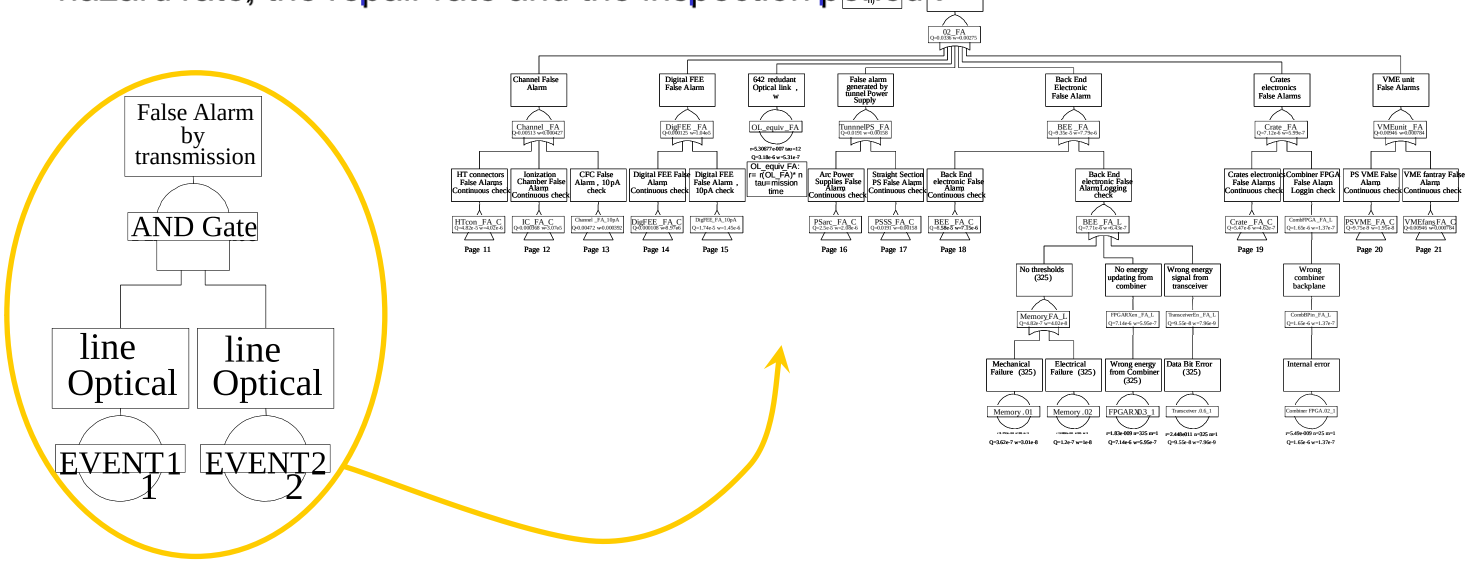
Reliability: Fault Tree Analysis

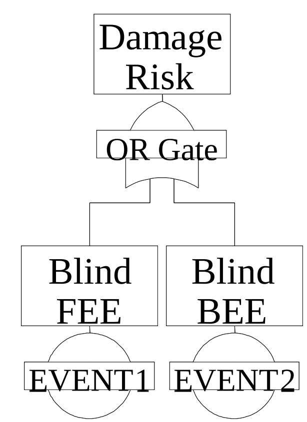
- Almost 160 Failure Modes have been defined for the BLMS using the FMD-97 standard.

Three Ends Effects:

1. Damage Risk: probability not to be ready in case of dangerous loss.
2. False Alarm: probability to generate a false alarm.
3. Warning: probability to generate a maintenance request following a failure of a redundant component.

- The probability to have an Failure Mode A, Pr{A}, is calculated per each Failure Modes of the FMECA, given the hazard rate, the repair rate and the inspection period.





Several (commercial) programs are available, which include component catalogue

Comments to Project Planning I

- Specification (LHC observations)
  - Specification changes (mainly technical, few functional changes) during project time due to knowledge increase (deeper understanding, reviews)
  - Iterative specification approach was needed to in cooperate continuously the specification changes not compromising the protection functionality and other requirements
- Budget (LHC observations):
  - Not enought contingencies included => every time when more budget was needed lengthy discussion, sometimes resulting in compromises without considering a complete system review. Reliability and functional degradation possible.
  - LHC BLM 33% cost overrun, reasons:
    - increase of functionality (knowledge gain during design process) (30%)
    - Unknown costs during planning phase (30%)
    - Wrong costs estimates (30%)
- Reviews (about 10 for the LHC system)
  - Main comments: Missing written operating procedures and documentation
  - Internal review: viewpoint of referees not independent enough, some times conflict of interest
  - External review: often to short, referees become not enough familiar with the system
  - Company review: introduce knowledge from different field (safety)

Comments to Project Planning II

- Reliability:
  - 2010+2011: 4 beam aborts due to internal BLM failure (4000 monitors, simulated failure per year 15)
  - Failure rate estimate need frequent recalculation, because of design changes (iterative process)
  - Data corruption in frontends observed due to radiation induced single events (at surface), unreliable electrical connections (soldering), …

Beam Loss Detectors used at CERN

Aluminium Kathode

+

PM

ACEM
(current)

Ionisation chambers

LIC
N2 @ 0.4 bar

LHC BLM
N2 @ 1.2 bar

Secondary
Emission
effect

SEM

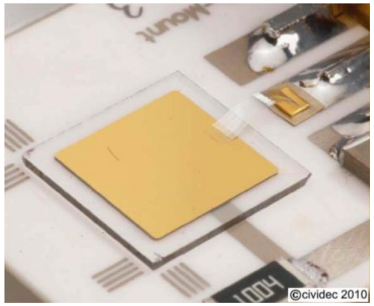
PEP-II BLM

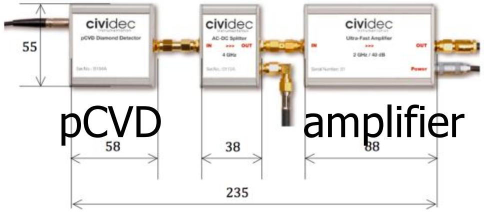
Cherenkov Light + PM

Courtesy of
U. Wienands
(SLAC)

Optical fibre
+
SiPM (array)
CLIC
+
Proton transfer

Diamond
pCVD
+
sCVD

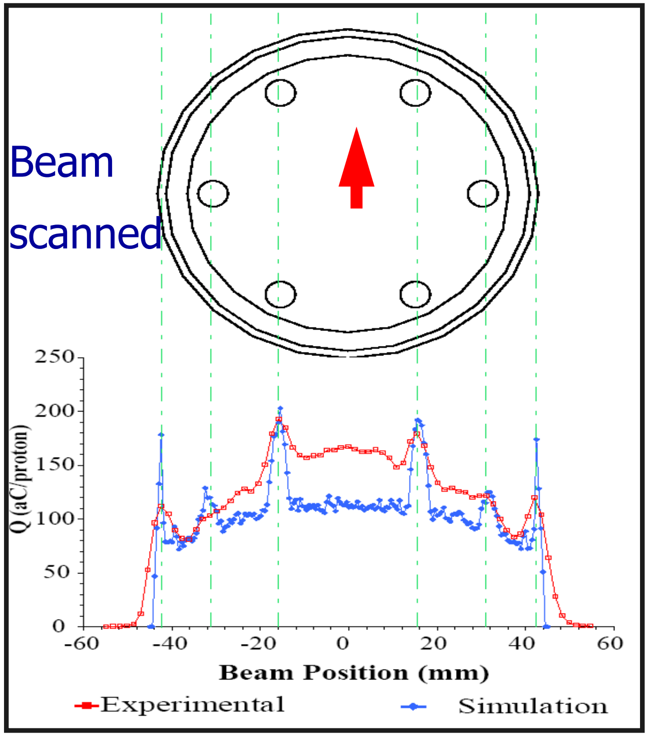




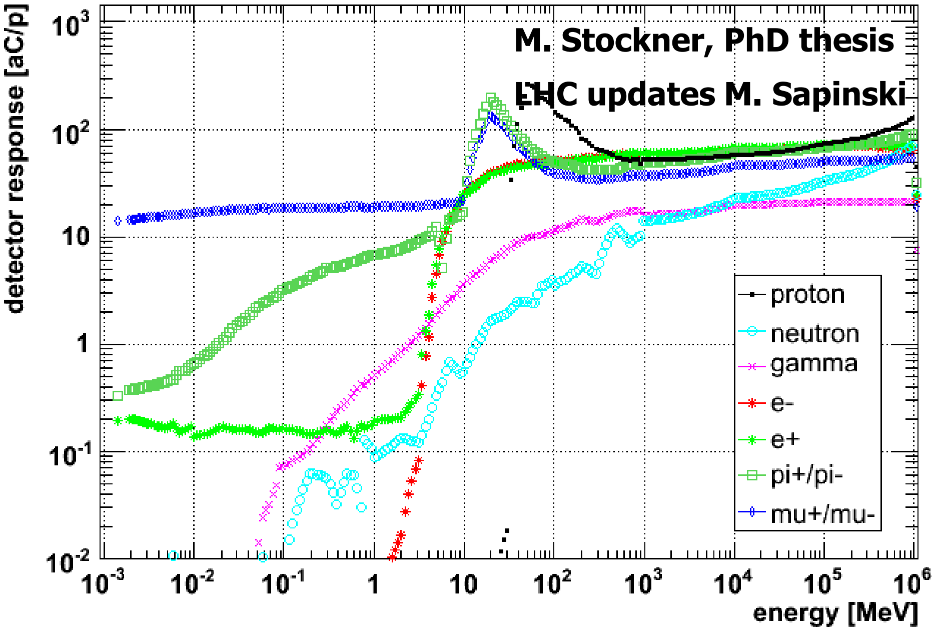
pCVD
amplifier

Ionisation Chamber Simulation and Measurements

Ionisation chamber top view



Ionisation chamber response function

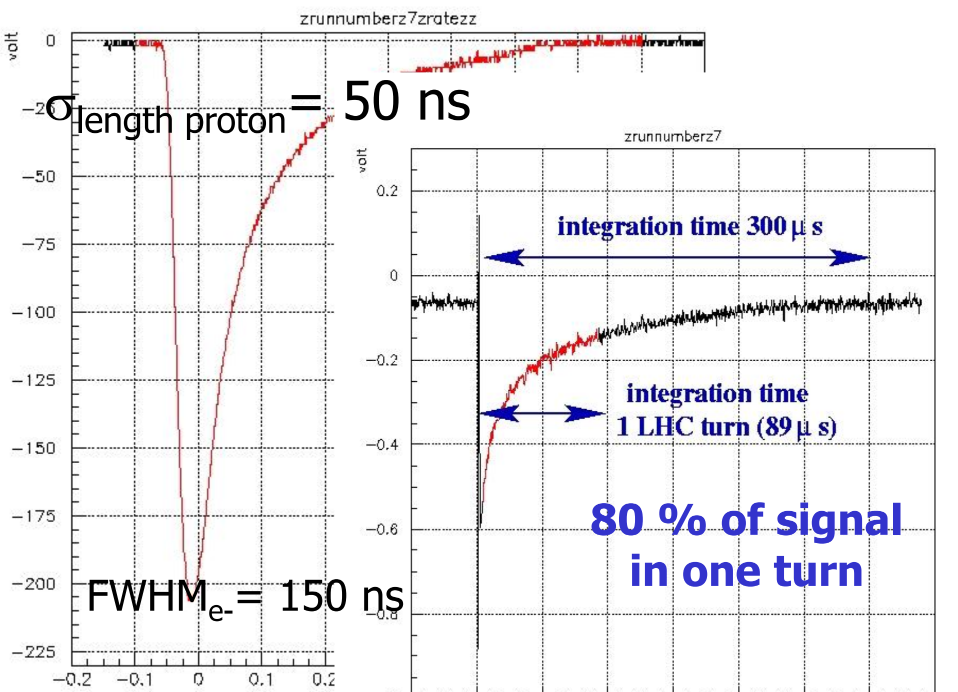


- Comparison simulation measurements

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

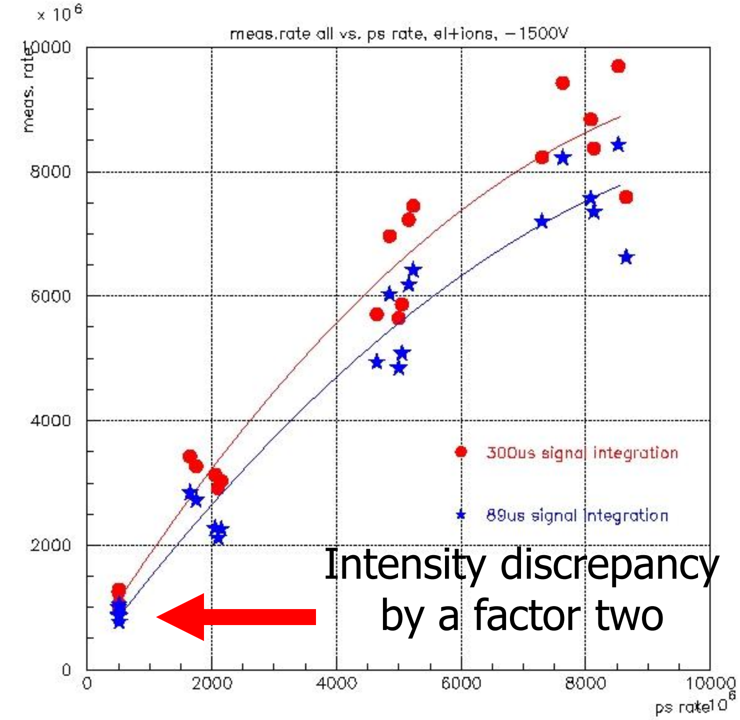
Good knowledge of behaviour => Reliable component

Chamber beam response



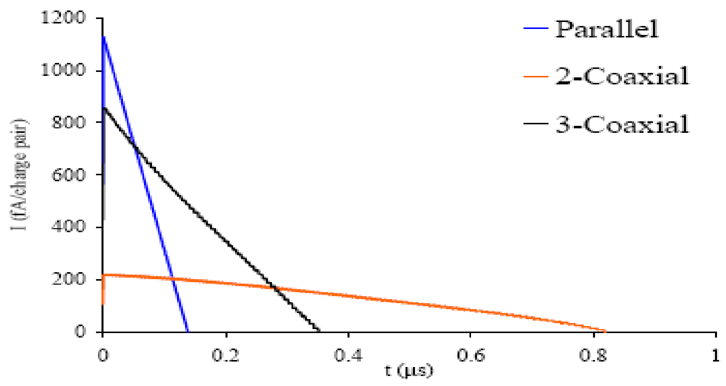
Peak current 50 A

Chamber current vs beam current

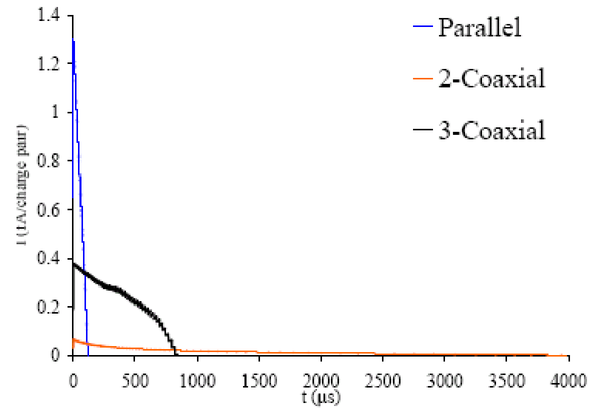


Intensity density: - Booster 6 10^9 prot./cm^2, two orders larger as in LHC

Simulations Ionisation chambers

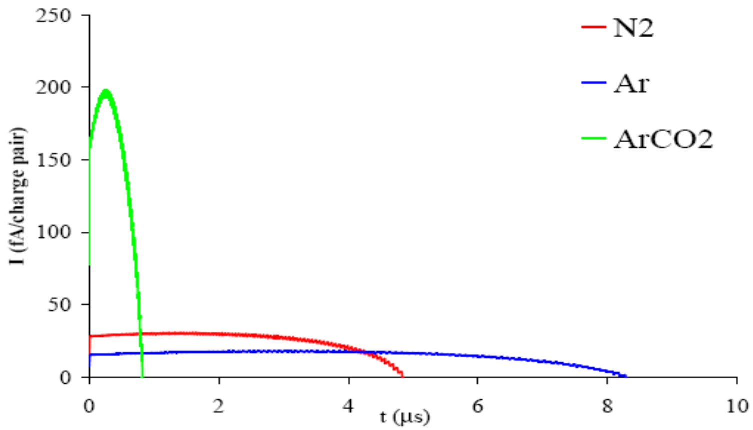


(a) *Simulated electrons*

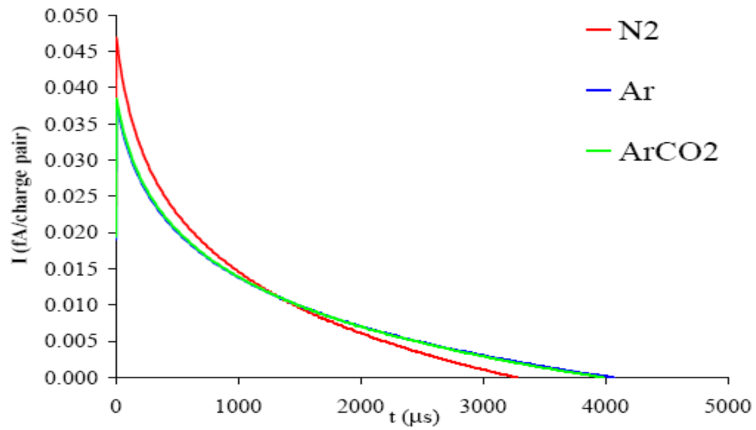


(b) *Simulated ions*

Coaxial Chamber

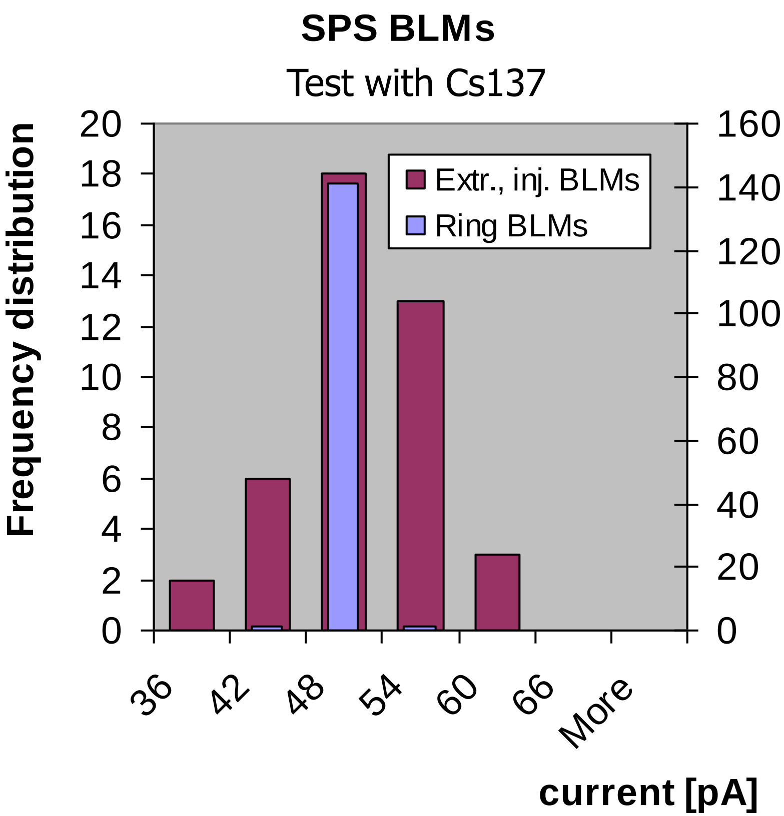


(a) *electrons*



(b) *ions*

Gain Variation of Ionisation 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, N2 gas filling

(Roughly) Estimated Sensitivities

- **Ionization chamber:** **70 µC/Gy** CERN IC 54 uC/Gy
  1 liter argon
  S ≈ active mass · charge per ionization energy ≈ $V \cdot \rho \cdot e/E_{ion}$ ≈ 1 l · 1.8 g/l · e / 26 eV LIC 1.4 uC/Gy
- **Long ionization chamber:** **20 µC/Gy**
  1 meter length, 1 cm radius, argon
  S ≈ active mass · charge per ionization energy ≈ $\pi r^2 \cdot L \cdot \rho \cdot e/E_{ion}$ ≈ 314 cm³ · 1.8 g/l · e / 26 eV
- **PIN diode:** **6 µC/Gy**
  1 cm² surface, 100 µm depletion depth
  S ≈ active mass · charge per excitation energy ≈ $A \cdot d \cdot \rho \cdot e/E_{ion}$ ≈ 10 mm³ · 2.3 g/cm³ · e / 3.6 eV
- **Secondary emission monitor:** **500 pC/Gy** CERN
  100 cm² surface, 0.01 average secondary emission yield (SEY)
  S ≈ surface · SEY · electron charge · density of primaries per dose ≈ A · SEY · e · (ρ/(dE/dx))
  ≈ 100 cm² · 0.01 · e · 1/(2 MeV·cm²/g)
- **Aluminum cathode electron multiplier:** **5 µC/Gy** CERN
  10 cm² surface, 0.01 average secondary emission yield (SEY), tube gain 10^5
  S ≈ surface · SEY · electron charge · density of primaries per dose · gain ≈ A · SEY · e · (ρ/(dE/dx)) · G
  ≈ 10 cm² · 0.01 · e · 1/(2 MeV·cm²/g) · 10^5
- **PMT with organic scintillator:** **200 C/Gy** ← Radiation damage problematic!
  1 liter scintillator, 60% collection efficiency, 30% photocathode efficiency, tube gain 10^5
  S ≈ active mass · photon yield per energy · collection efficiency · photocathode efficiency · gain · electron charge
  ≈ V · ρ · Y · C · P · G · e = 1 l · 1 g/cm³ · 1/(100 eV) · 0.6 · 0.3 · 10^5 · e
- **Bare PMT (Čerenkov light):** **4 mC/Gy**
  10 cm² surface, 1 mm thick, 30% photocathode efficiency, tube gain 10^5
  S ≈ active volume · density of primaries per dose · photon yield per length · photocath. efficiency · gain · electron charge
  ≈ A · d · ρ · (ρ/(dE/dx)) · Y · P · G · e ≈ 1 cm³ · 1/(2 MeV·cm²/g) · 260/cm · 0.3 · 10^5 · e
- **PMT with Čerenkov fiber:** **2 µC/Gy**
  1 meter length, 100 µm radius, 2% collection efficiency, 30% photocathode eff., tube gain 10^5
  S ≈ active volume · density of primaries per dose · photon yield per length · coll. eff. · photoc. eff. · gain · electron charge
  ≈ πr^2 · L · ρ · (ρ/(dE/dx)) · Y · C · P · G · e ≈ 31 mm³ · 1/(2 MeV·cm²/g) · 260/cm · 0.02 · 0.3 · 10^5 · e

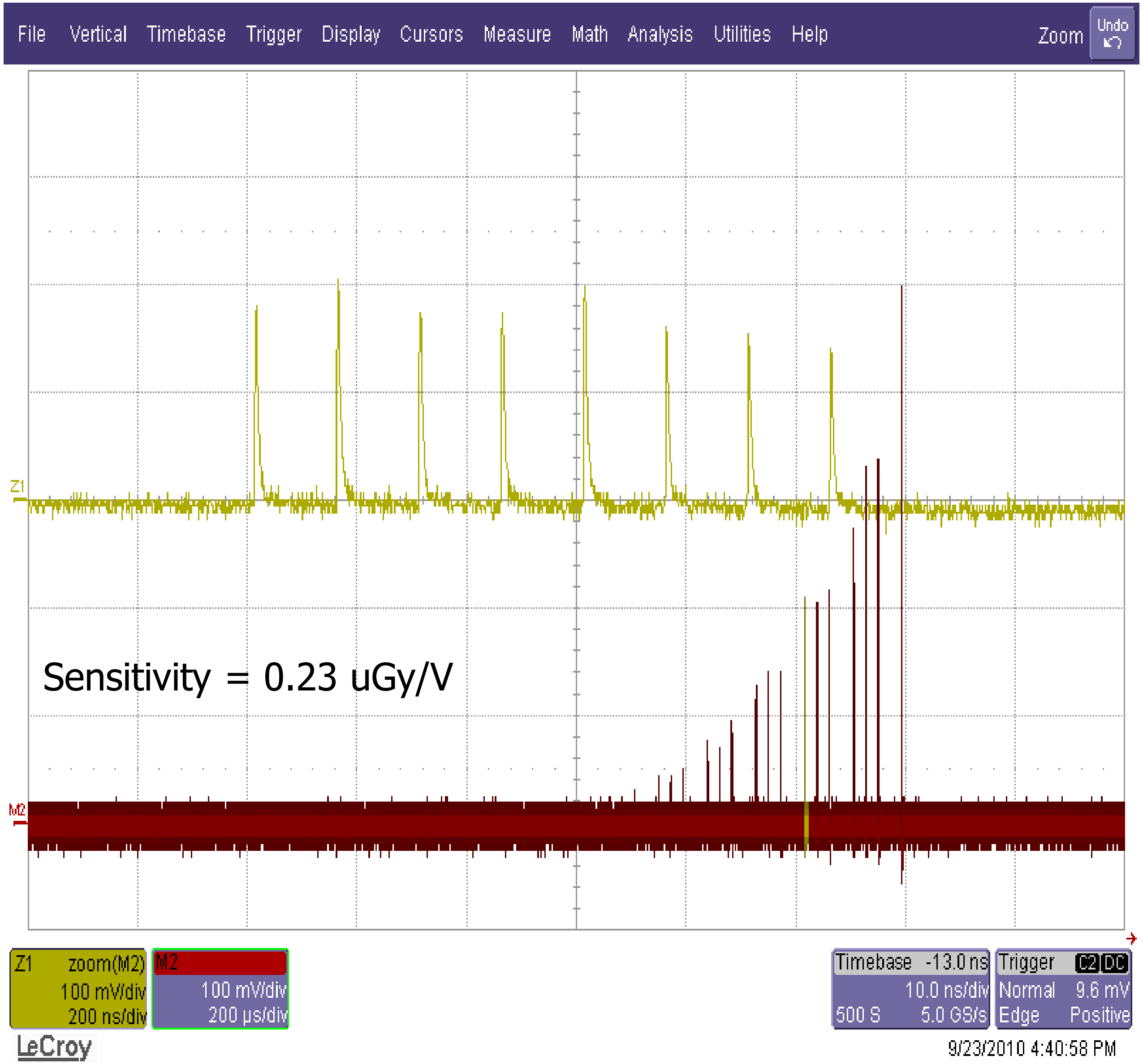
Flexible gain → linearity and calibration problematic!

Diamonds: Beam LHC Loss Signal

Diamond detector at a collimator

150 ns bunch spacing

Hypothesis:
Loss due to macro dust particle



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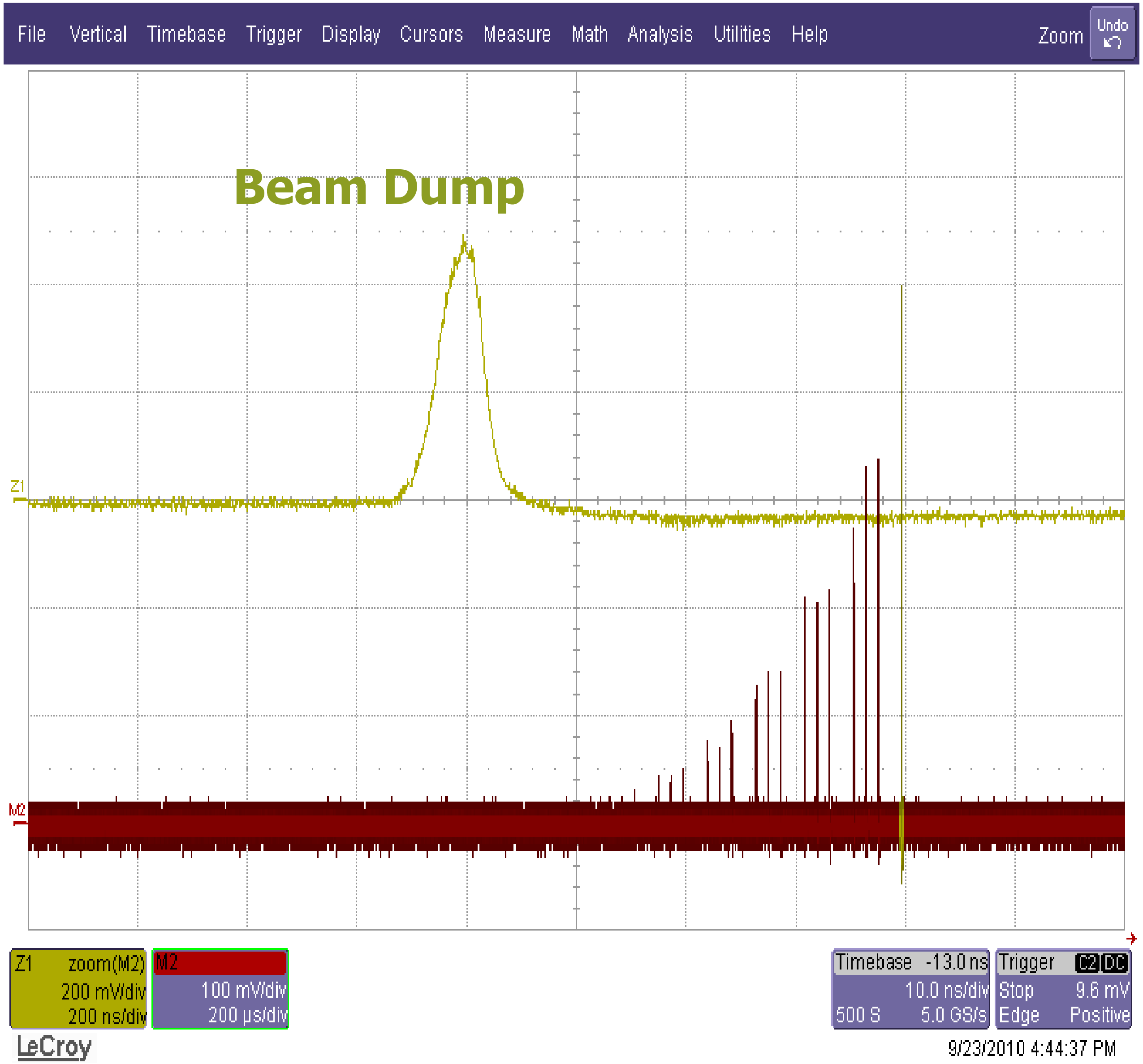
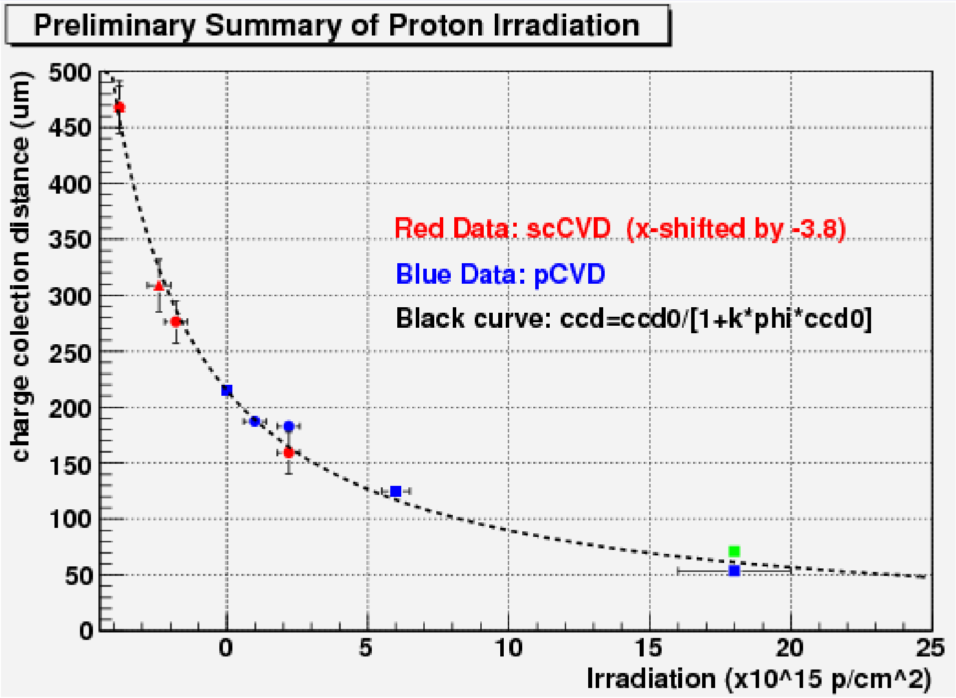
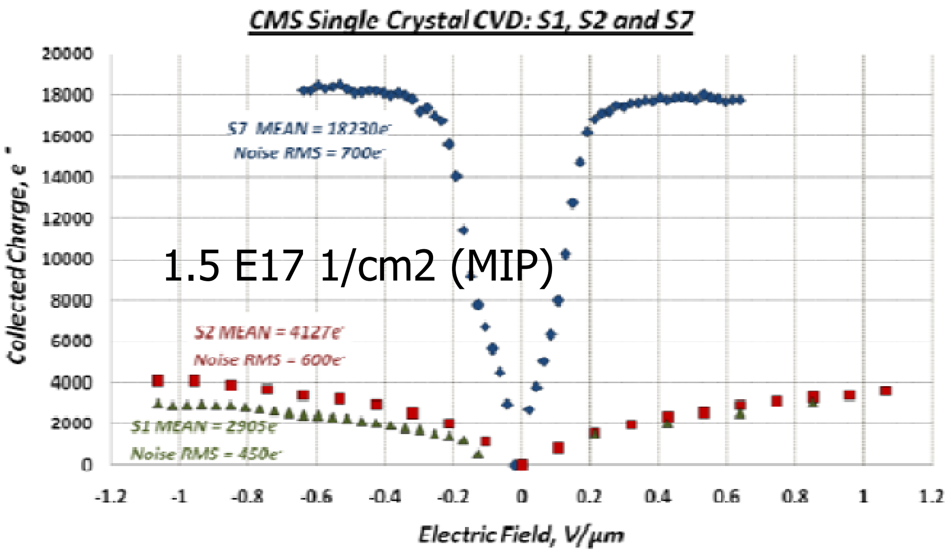


Diamond and Radiation Hardness

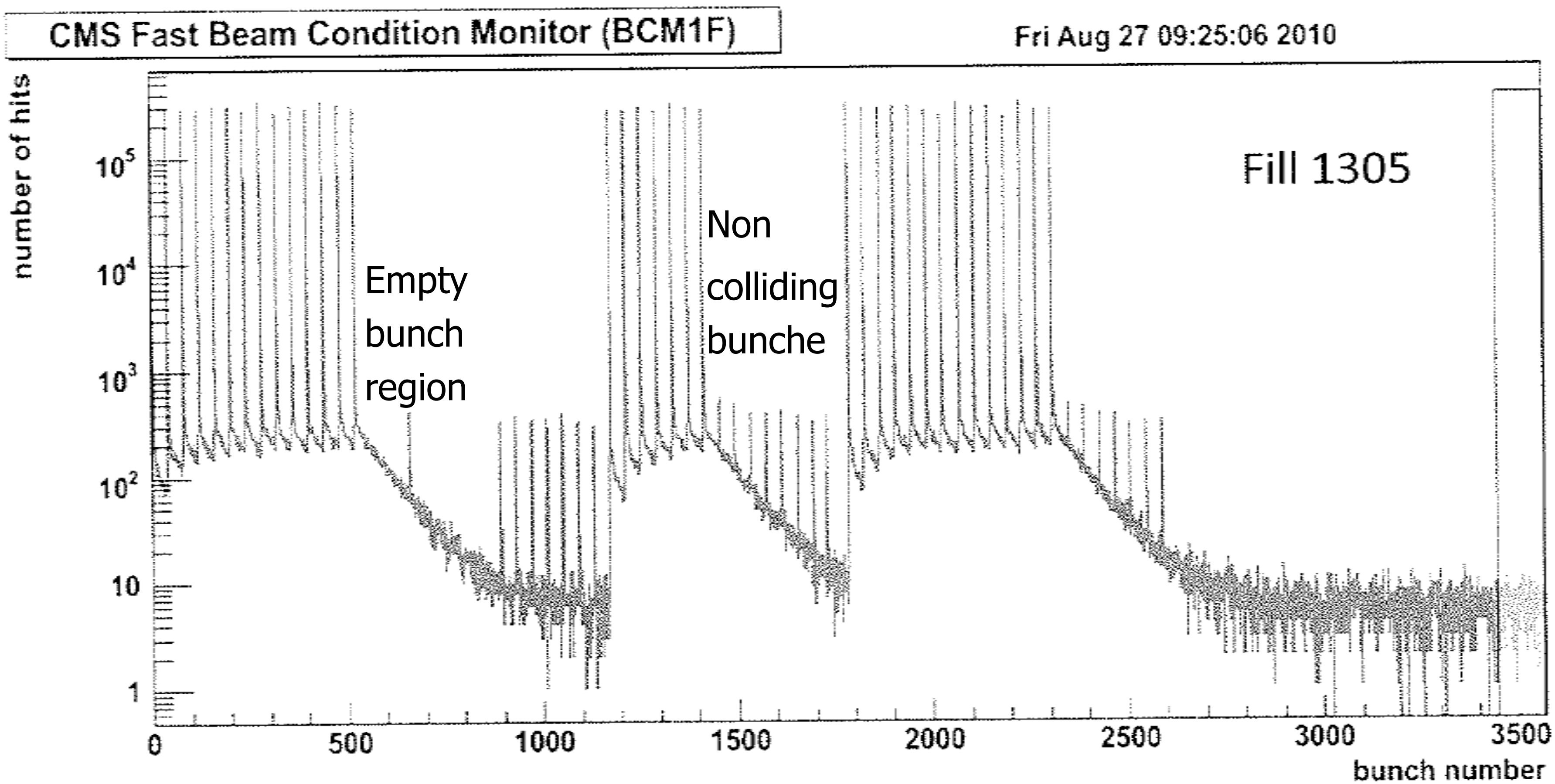




- Top: sCVD shifted to the left to show that it follows the same degradation parameterization as pCVD
- Bottom: sCVD irradiation loss 20 % of initial signal and drop of signal to noise from 26 to 7

Open question: DC noise increase with irradiation

Diamonds in Counting Mode

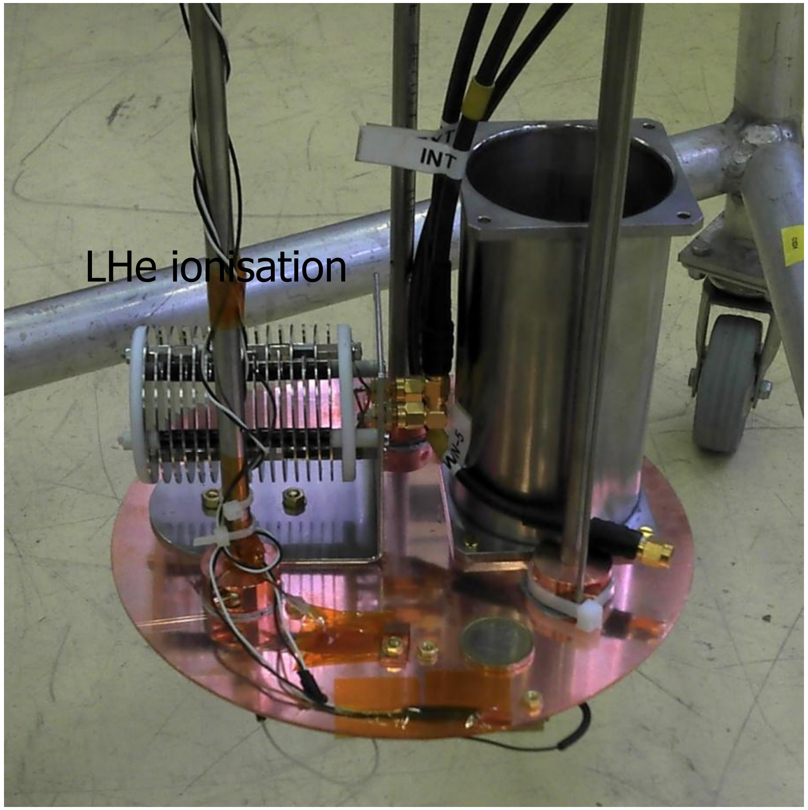


Detection system under construction for loss detection after LHC collimator

Measurement of bunch filling scheme with high dynamic

1.8 Kelvin Loss Detection

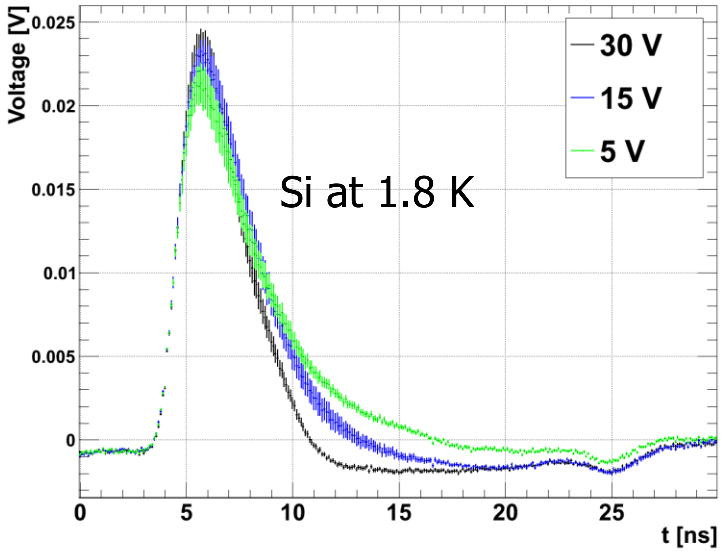
Single Particle beam test at CERN PS (20 GeV)

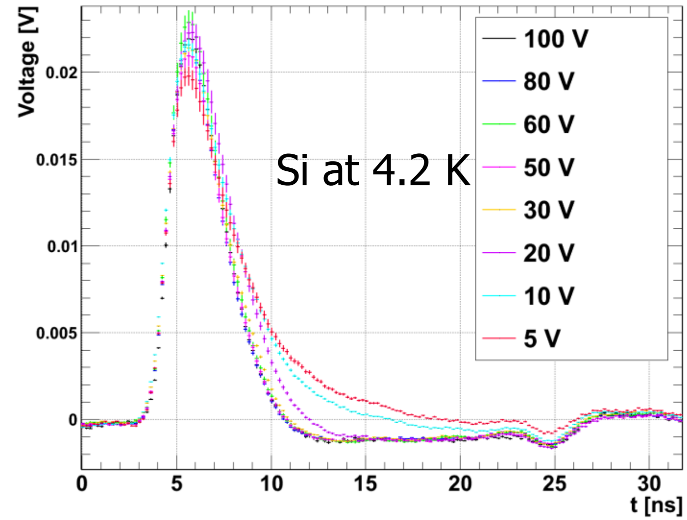


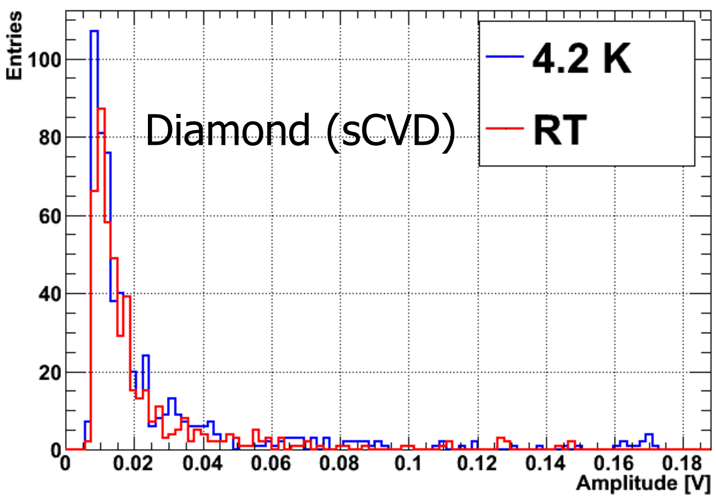
Under test: sCVD, Si, and LHe ionisation chamber

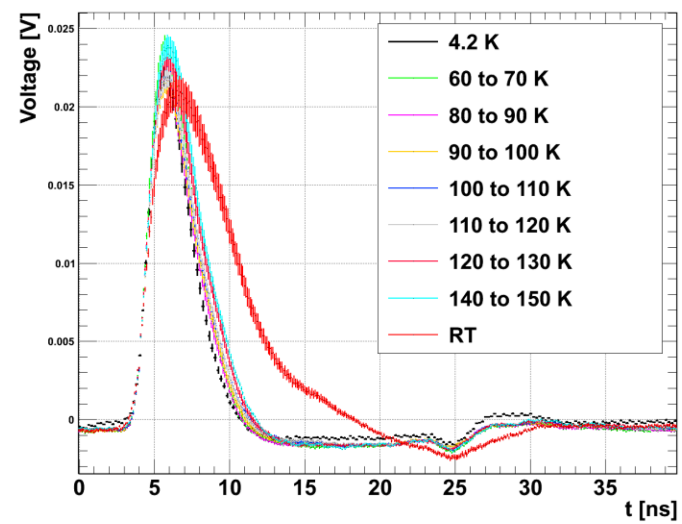
Next year: radiation test up to 1 MGy with online monitoring at CERN PS

1.8 Kelvin Loss Detection



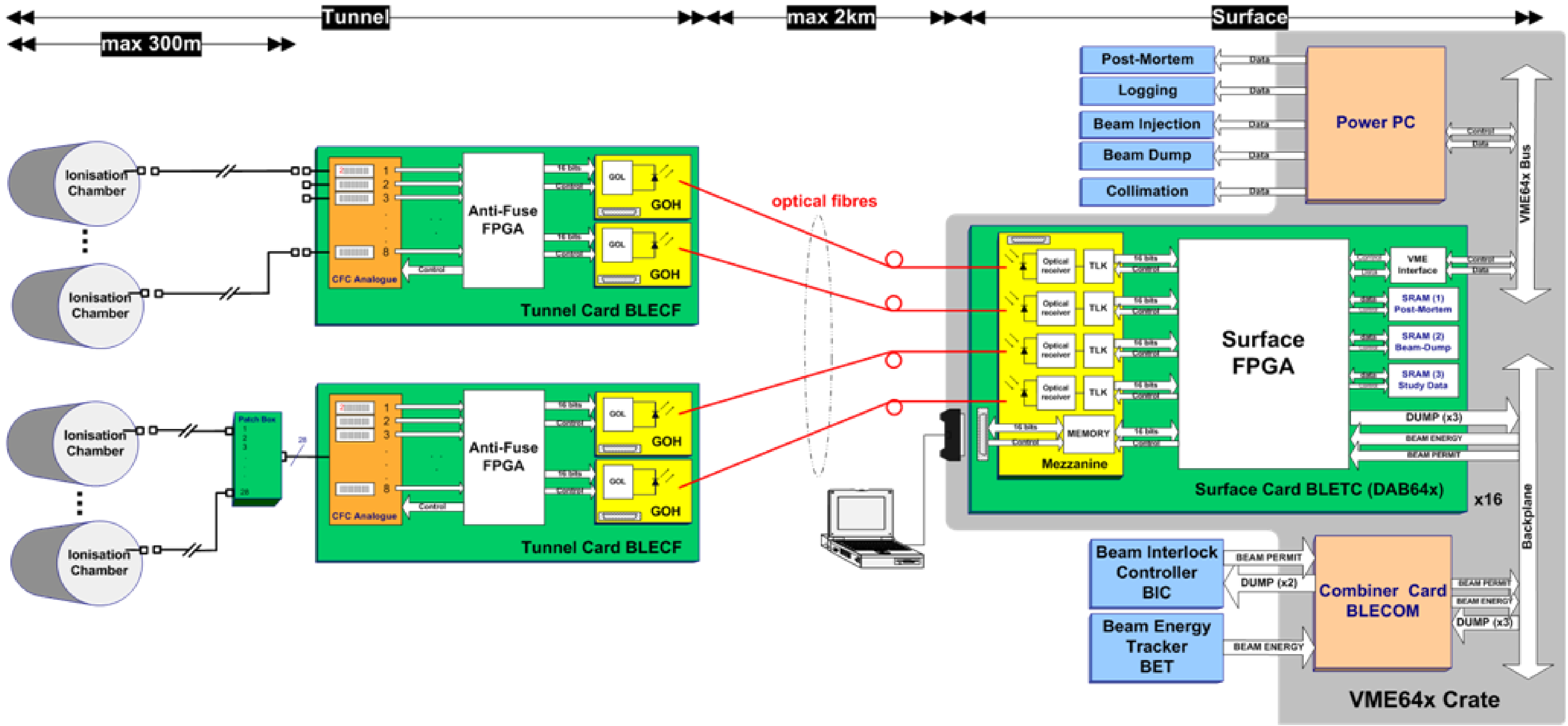






Open questions: radiation hardness, DC current value, non linearity effects for high losses

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**

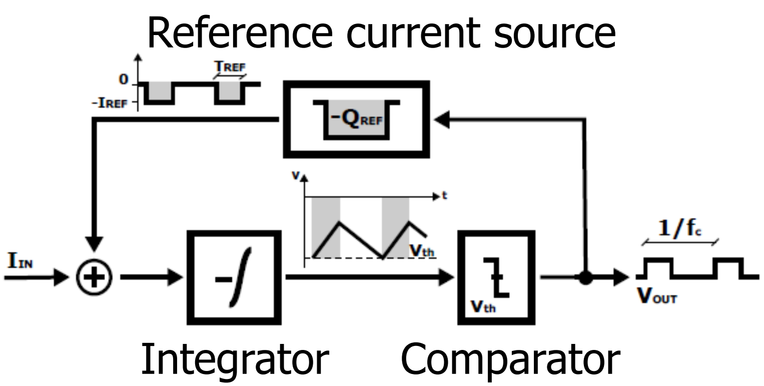
Fully Differential Current to Frequency Converter Principle

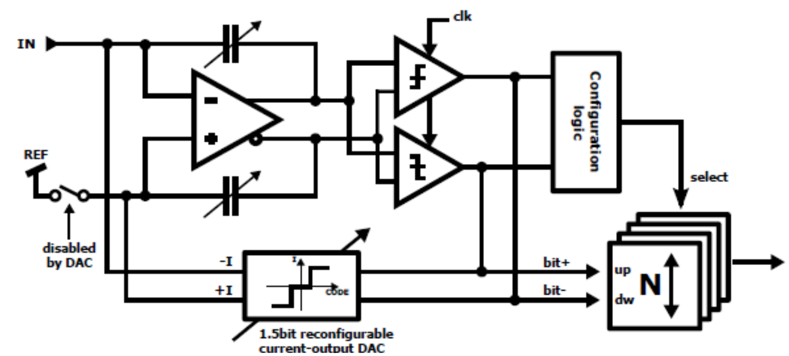
LHC current to frequency converter:

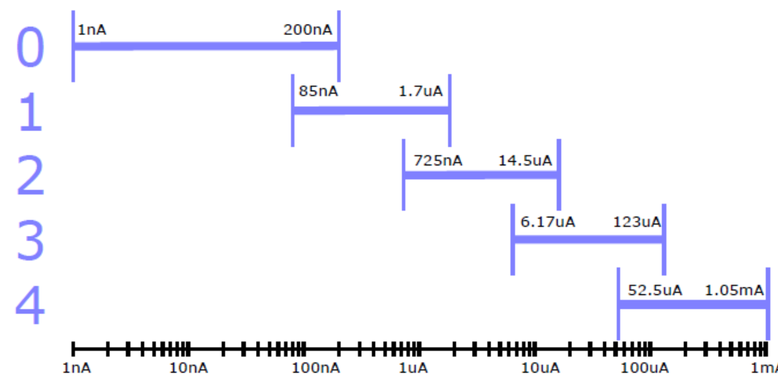
1. only positive signals (limitation in case of signal under shoots)
2. 500 Gy radiation tolerance

	Parameter	Value	Units	Comments
ASIC	Dynamic range	six decades		positive and negative currents
		nine decades		*(indirect measurement)*
	Minimum detected current	1	nA	(user selectable, minimum value)
	Linearity error	$< \pm 10$	%	relative error $\Delta I/I$
	Integration window	40	µs	
	Total integrated dose	1×10^4	Gy	in 20 years
	Target technology	CMOS 0.25 µm		

Six decades to be covered with a direct measurement → 20 bit

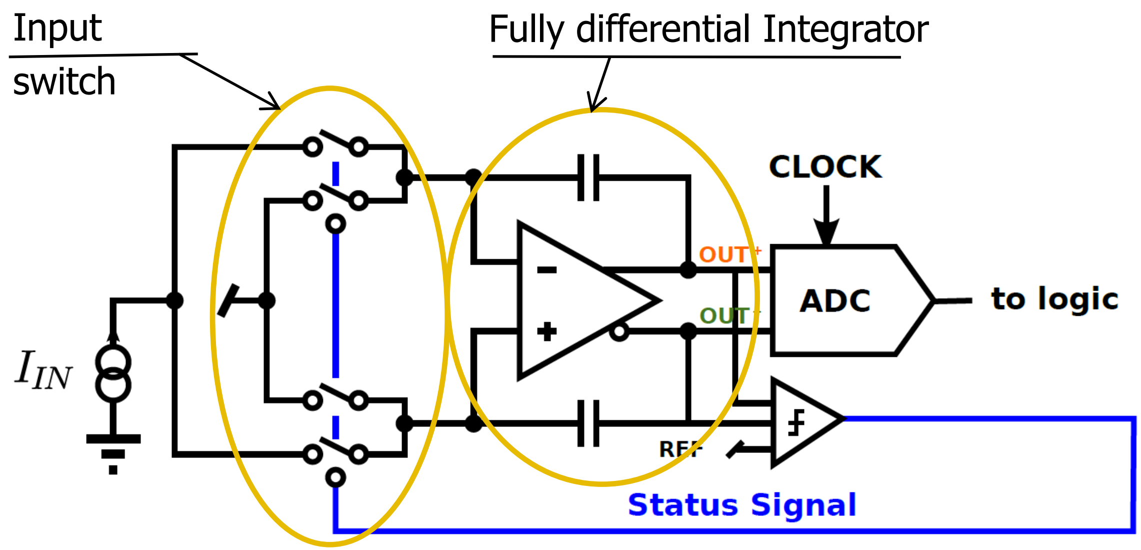


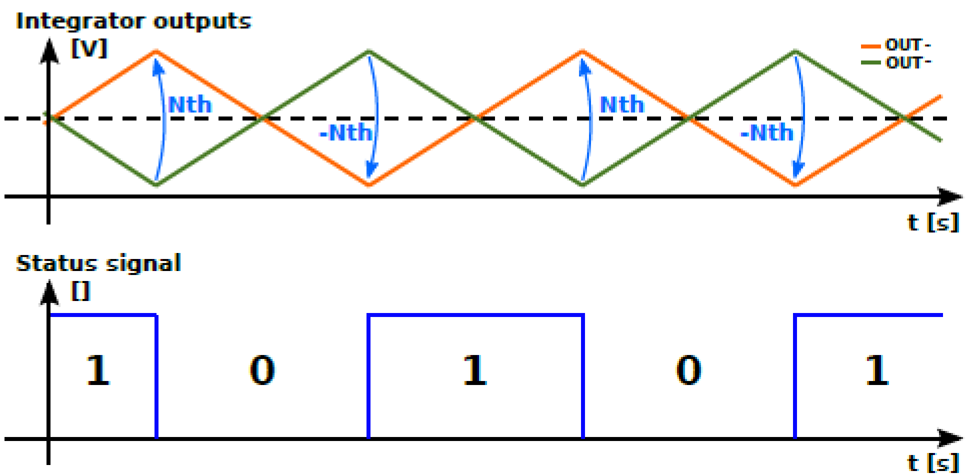




f = Iinput / (Qref * Tref)

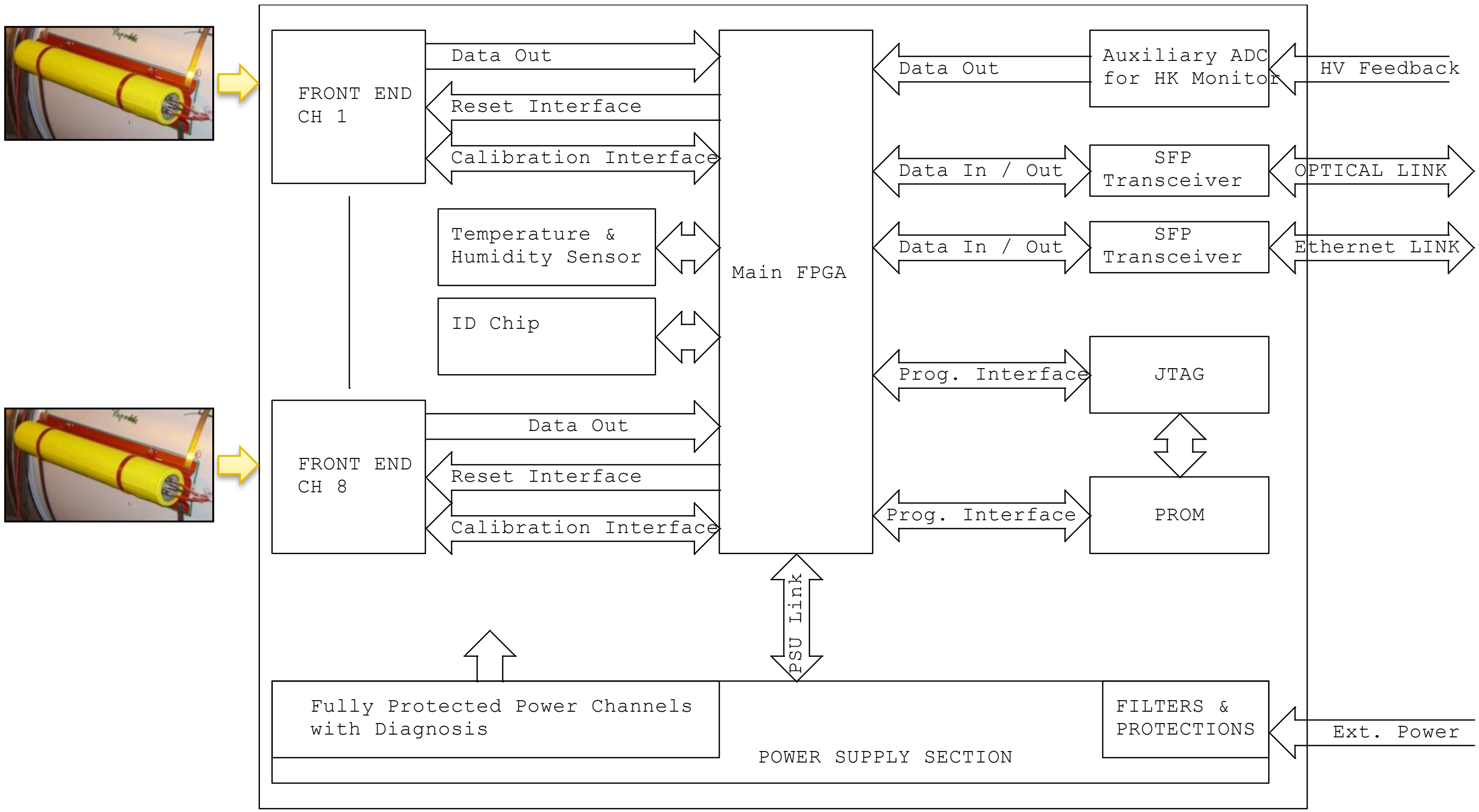
Fully Differential Current to Frequency Converter Principle





1. Specifications:
   1. Dynamic range 7 orders
   2. Integration window 2 us 1nA to 200mA
   3. Integration window 1 s 10pA to 200mA
2. A status signal selects in which branch of a fully deferential stage the input current is integrated.
3. Two comparators check the differential output voltage against a threshold, whenever is exceeded, the status signal changes to the complementary value (0 ! 1 or 1 ! 0) and the input current is integrated in the other branch.

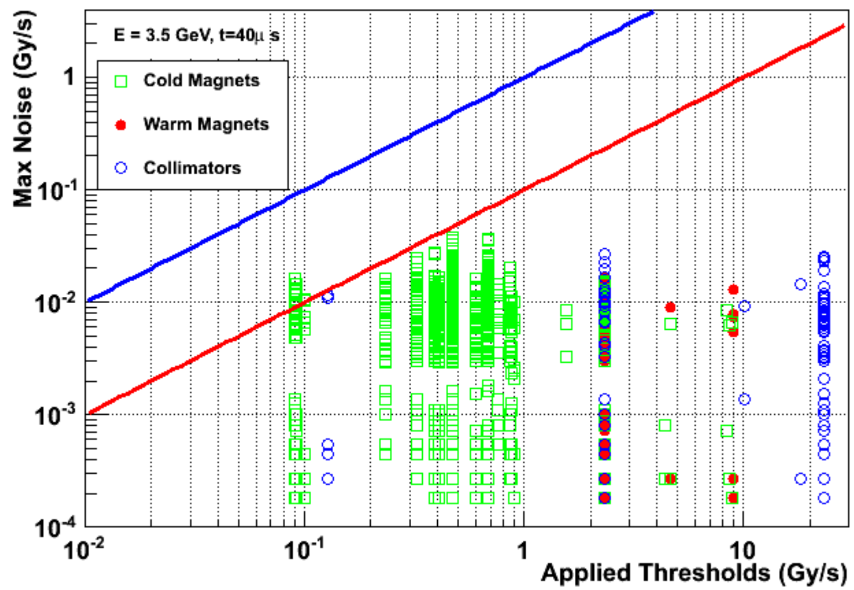
Differential Current to Frequency Converter

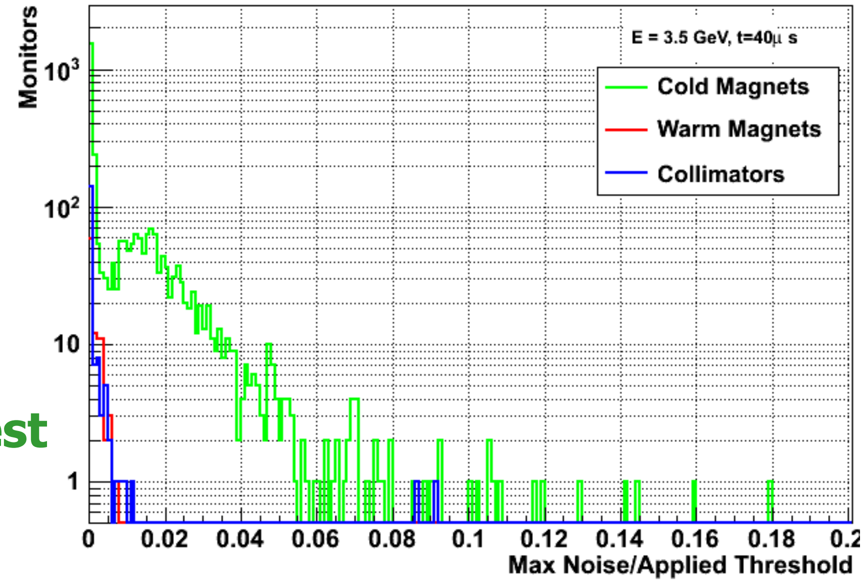


Available Resources: 8 Input Analog Interfaces; FPGA local or remote programming; bidirectional optical and Ethernet link; power supplies with protection and diagnosis; temperature and humidity measurement; ID Chip; Auxiliary ADC for Housekeeping Monitor.

Noise

- Important for availability (false dumps) and dynamic range
- Main source of noise: long cables (up to 800 m in straight section)
- Aim: factor 10 between noise and threshold
- Thresholds decrease with increasing energy → noise reduction before 7 TeV
  - Single pair shielded cables, noise reduction: > factor 5
  - **Development of kGy radiation hard readout to avoid long cables**





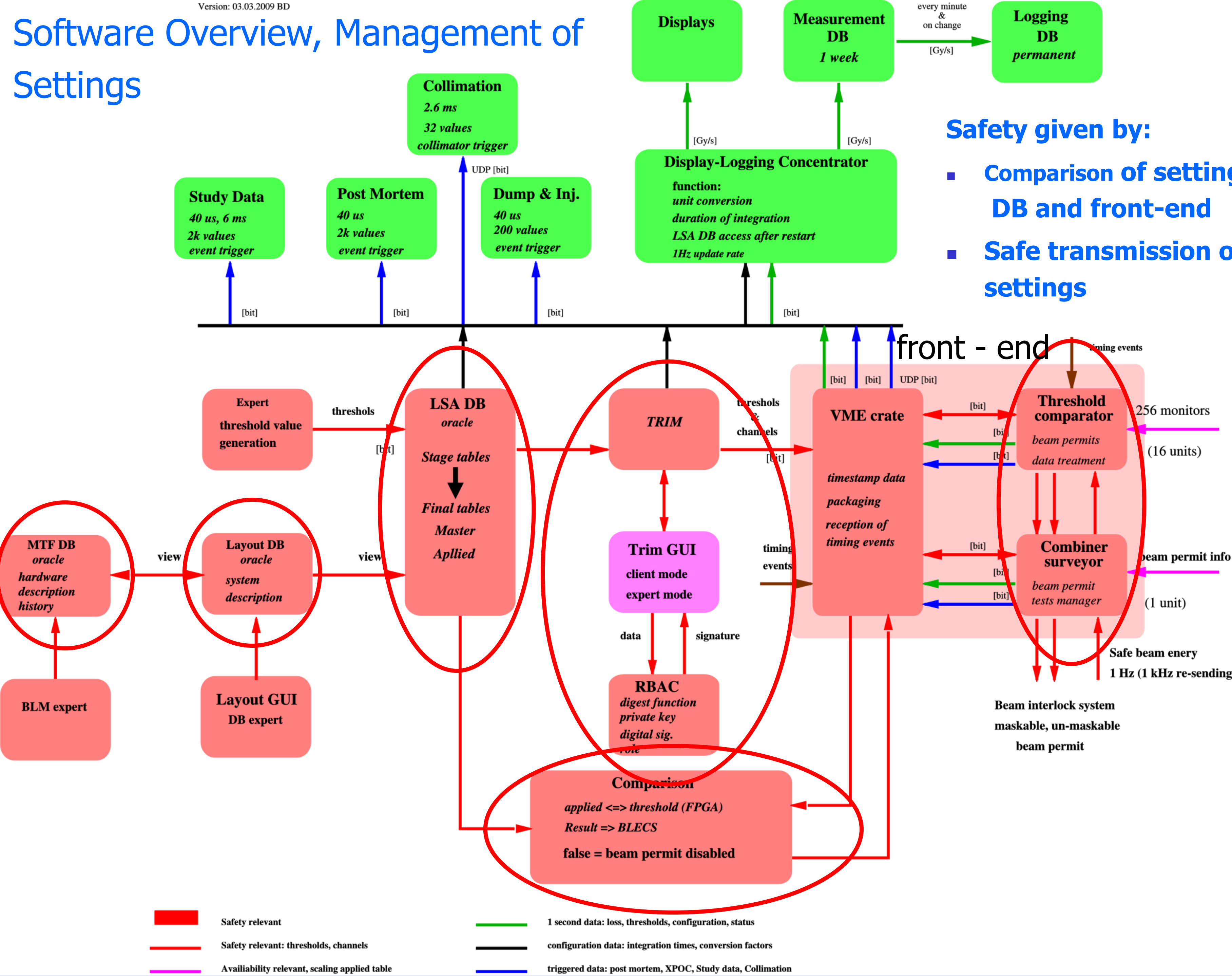
Noise estimate in design phase with test installations at comparable locations

Version: 03.03.2009 BD

Software Overview, Management of Settings

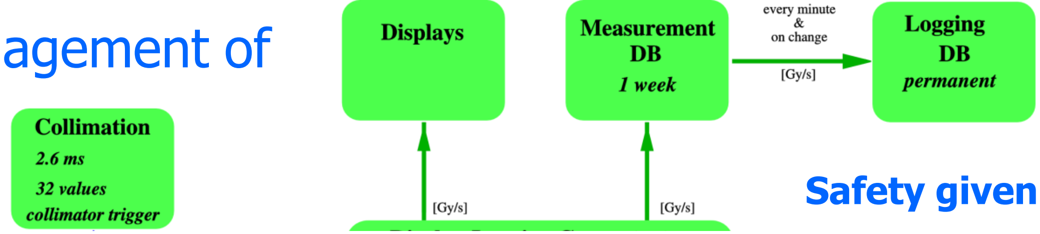
Safety given by:

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



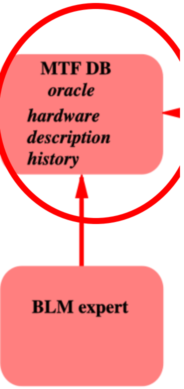
Version: 03.03.2009 BD

Software Overview, Management of Settings



Safety given by:

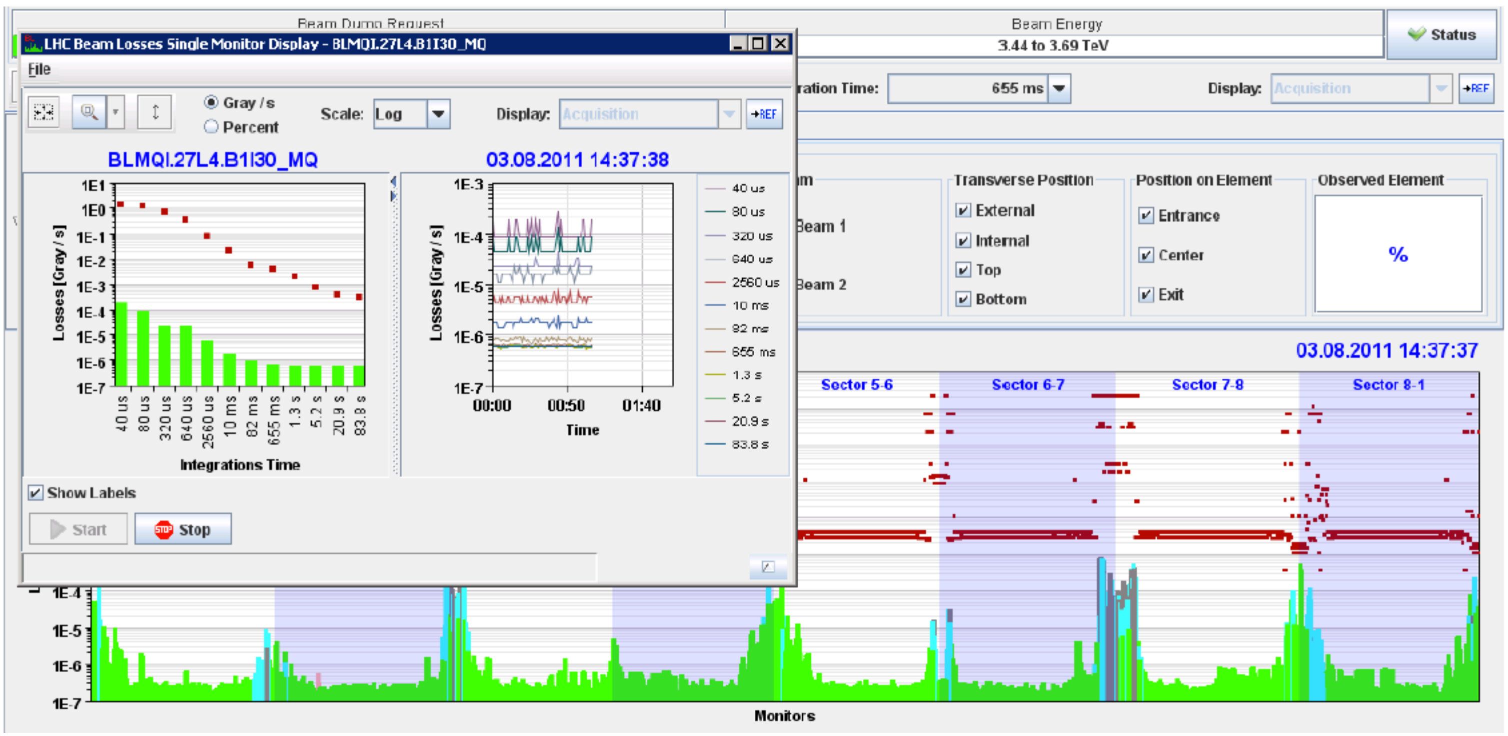
1. Modular design of data base very useful (if changes are needed limited impact)
   1. MTF: history of equipment e.g. ionisation chamber, electronic cards, …
   2. Layout: description of links between equipment
   3. LSA: reference for all data needed in the front-end (some imported from MTF and Layout)
2. Storage of data in frontend in FPGA memory (even here corruptions observed)
3. Master for comparison is the front-end (this allows immediate beam inhibit)
4. Design very early defined in PhD thesis on reliability (root was followed during project)
5. Issue of design: protection and measurement functionality are implemented in same front-end (review remark).
   1. Critical, because of upgrades are more often needed on measurement functionality compared to protection functionality
   2. New design: locking of FPGA firmware, which has protection functionality (partial solution)
   3. Occupation of FPGA by firmware too large, first estimate of occupation will be about 30% for new BLM systems



Availiability relevant, scaling applied table   triggered data: post mortem, XPOC, Study data, Collimation

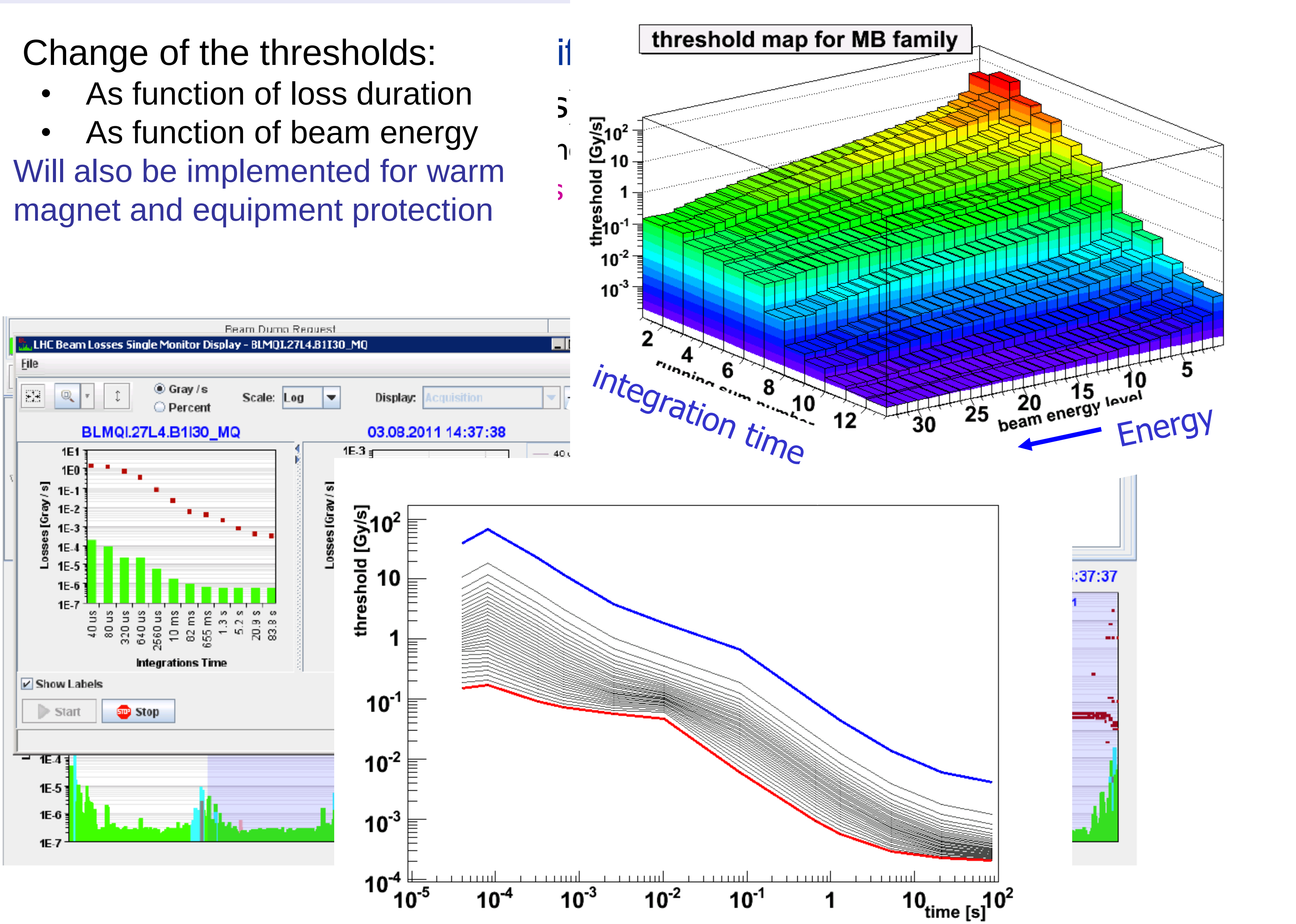
BLM Published Data – Logging Data – Online Display

- Extensively used for operation verification and machine tuning
- 1 Hz Logging (12 integration times)
  - Integration times < 1s: maximum during the last second is logged
    → short losses are recorded and loss duration can be reconstructed (20% accuracy)
  - Also used for Online Display



BLM Published Data – Logging Data – Online Display

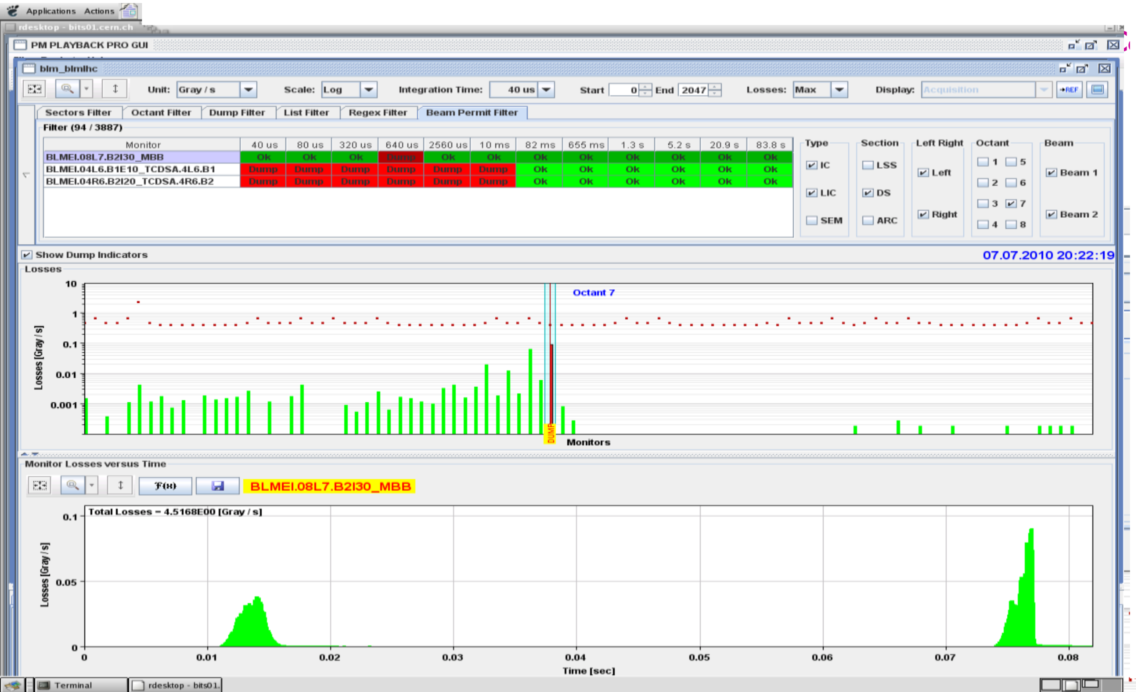
- Change of the thresholds:
  - As function of loss duration
  - As function of beam energy
- Will also be implemented for warm magnet and equipment protection

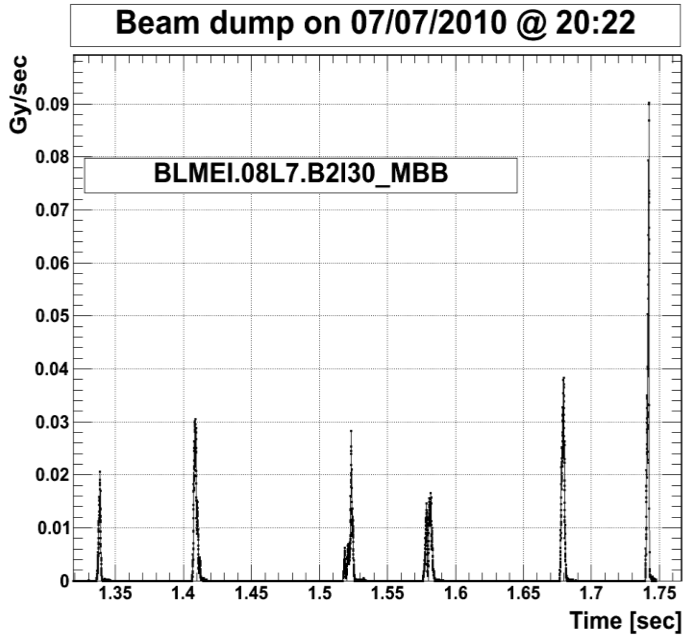


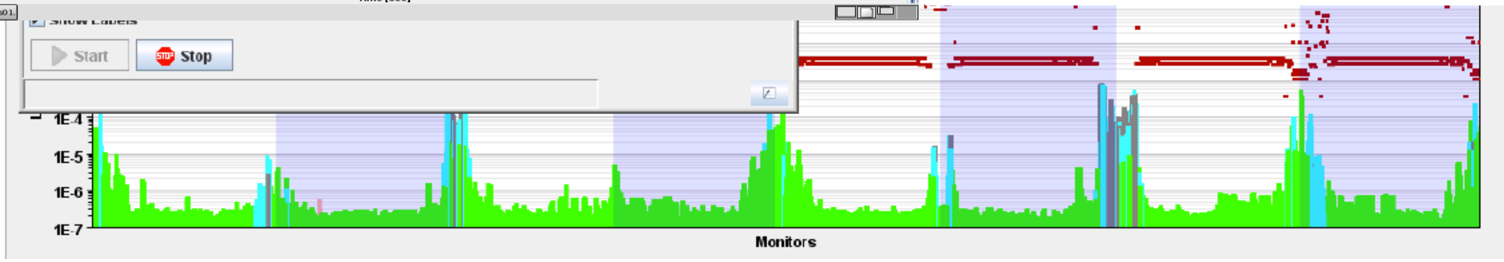
BLM Published Data – Logging Data – Online Display

Post Mortem Data: Event triggered read out of all acquisition buffers

1. Online (after 10 s 2000 values with 40 us integration time
2. Off line 43000 values







BLM Published Data – Logging Data – Online Display

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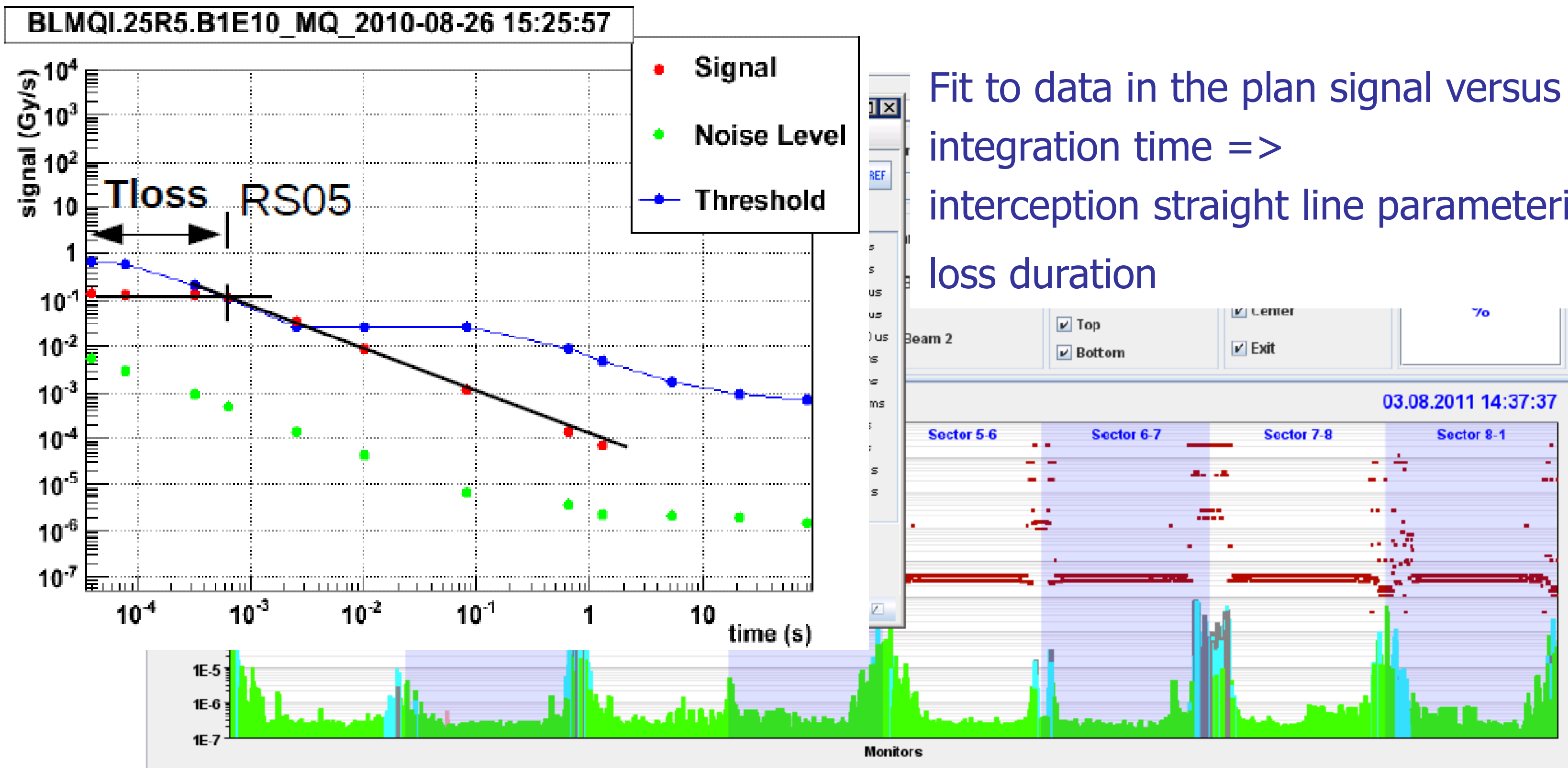
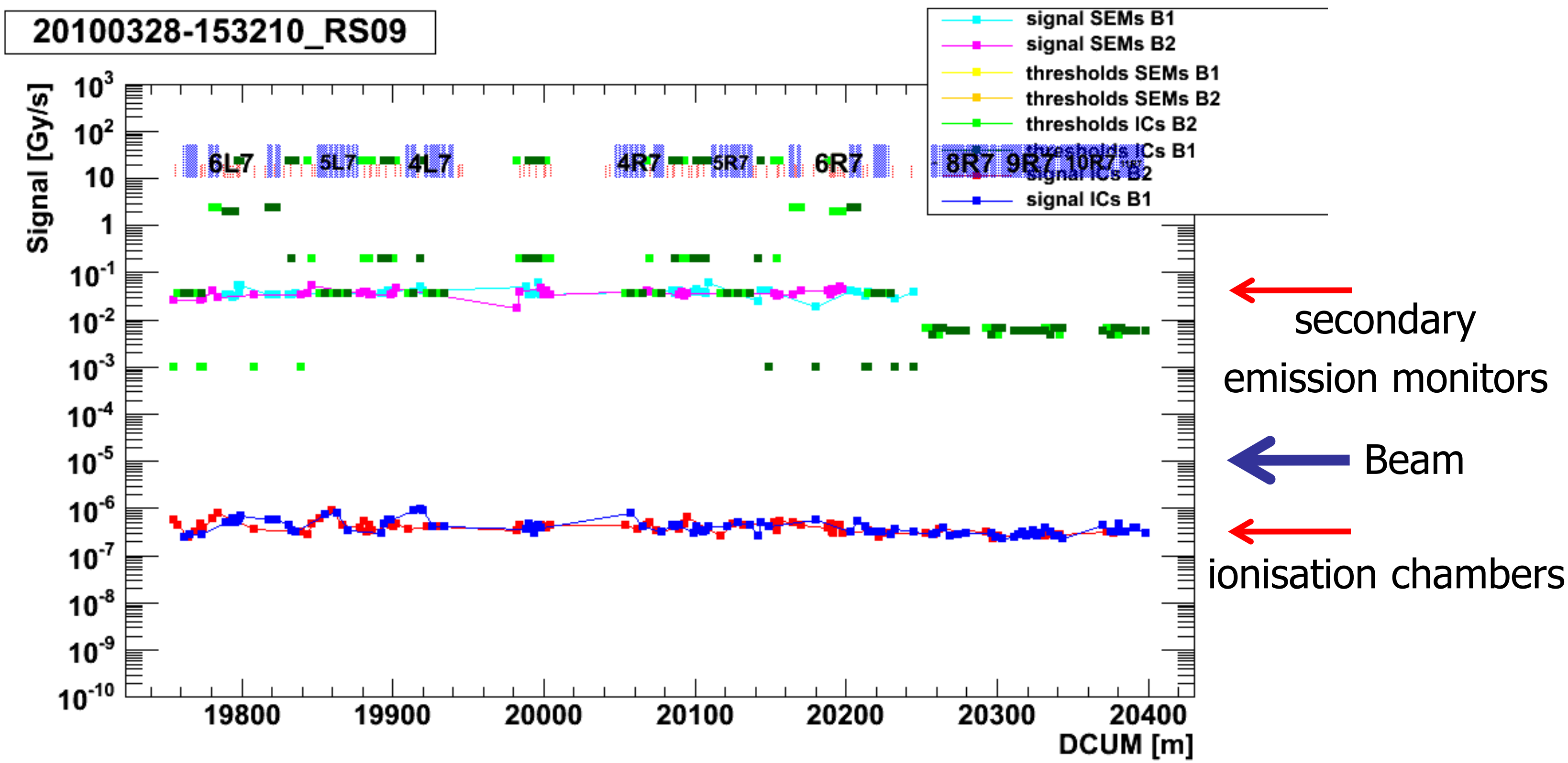


Fit to data in the plan signal versus integration time => interception straight line parameterization => loss duration

Storage of several running sums allows reconstruction of duration of loss event (reduction of network traffic and data storage place)

Resonance Crossing – SEM signal Issue



No signal from secondary emission monitors expected: due to ionisation in air at non insulated wire connection (patch boxes)

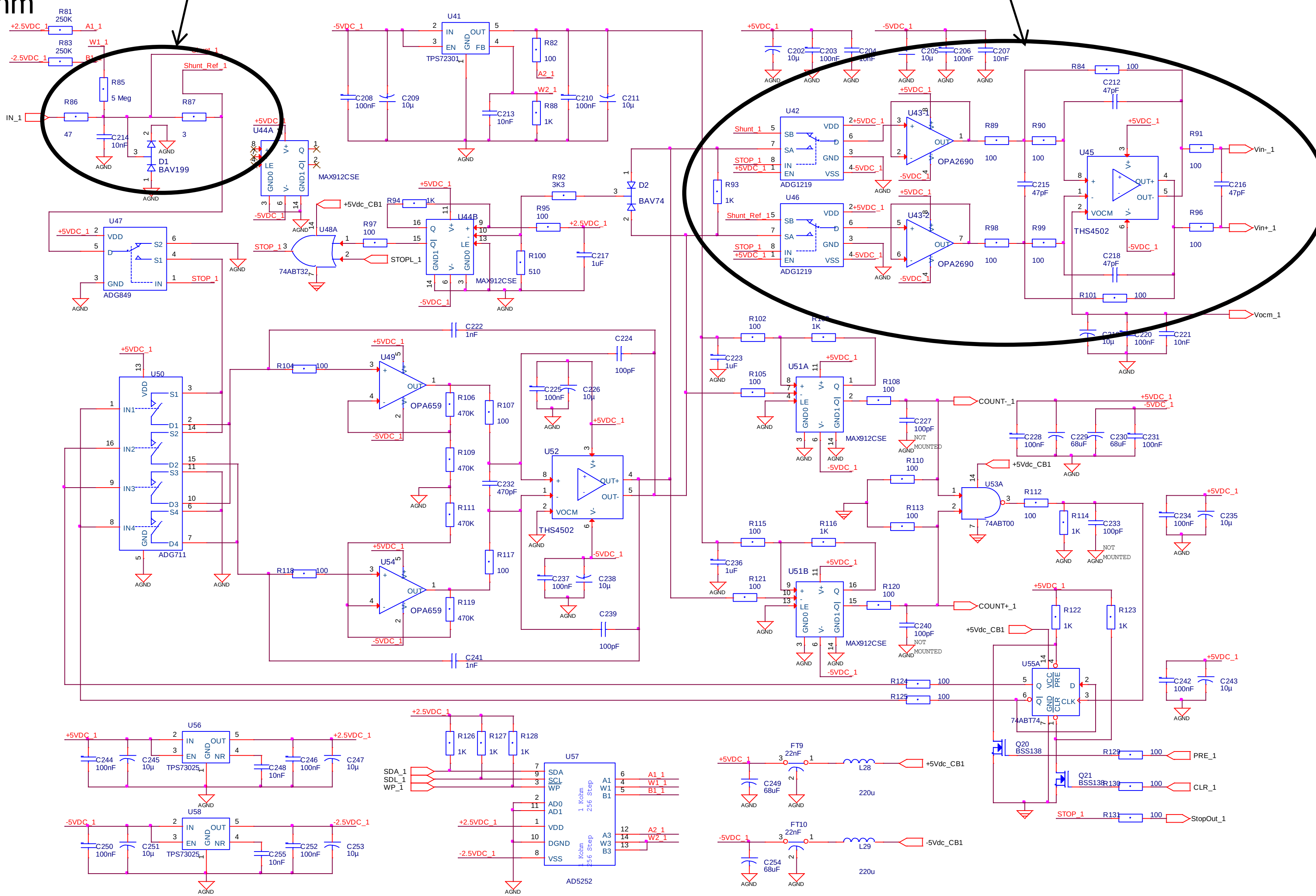
Optimized tools are very help full during commissioning (design during test phases)

Reserve Slides

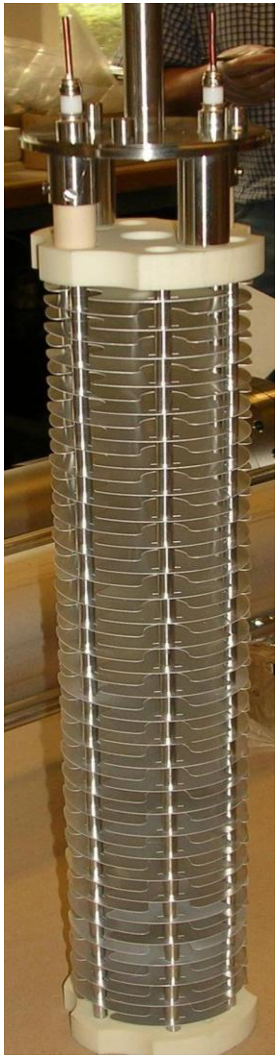
DADC Principle

Input 50 ohm resistor split in two: 47 + 3 ohm

Re-routing on the ADC buffer amplifier

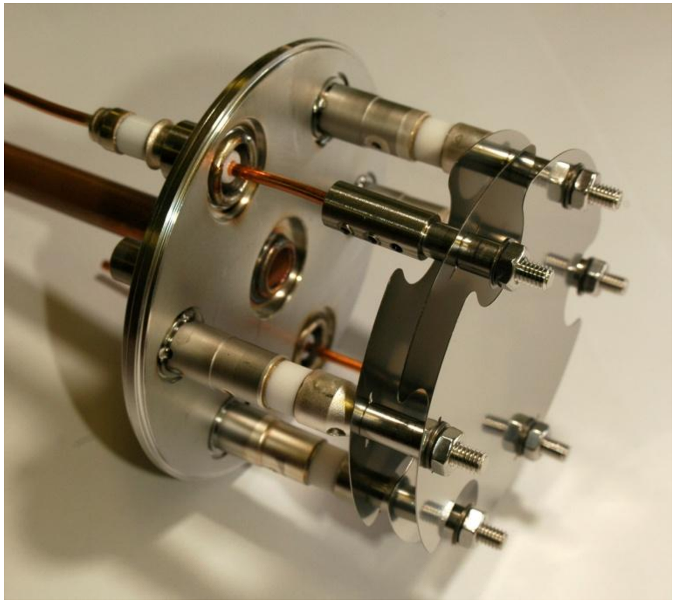


Ionisation Chamber and Secondary Emission Monitor



- 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

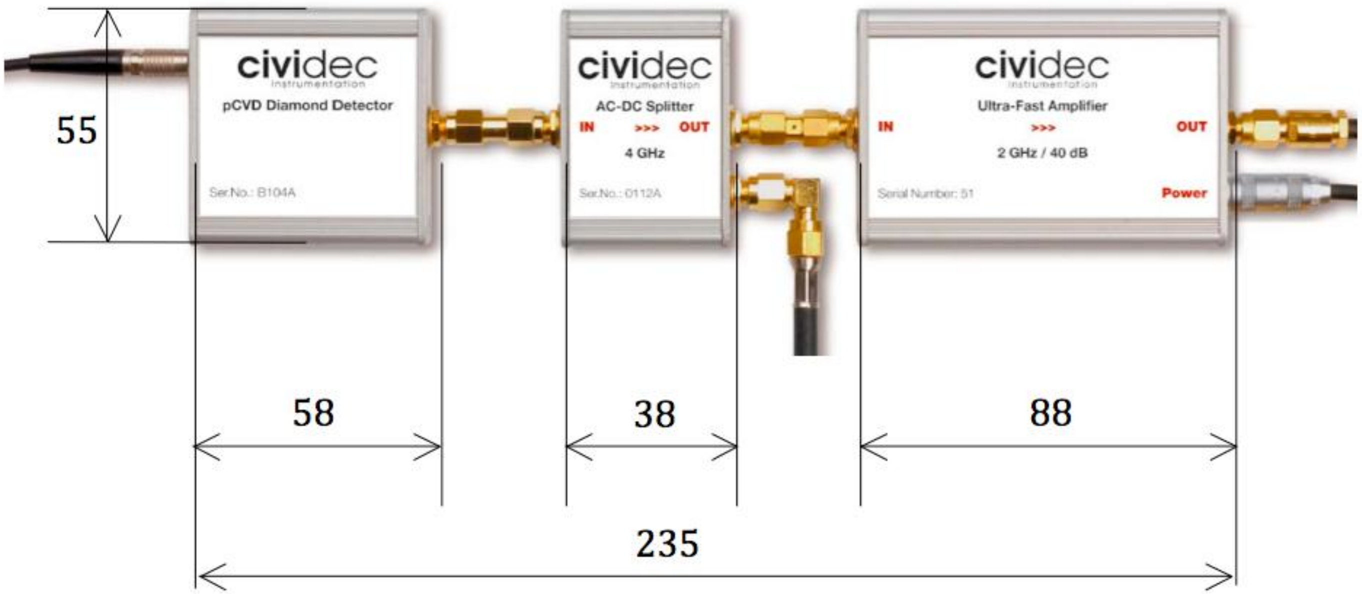
SEM:

- 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

4 Diamond BLMs for Observation

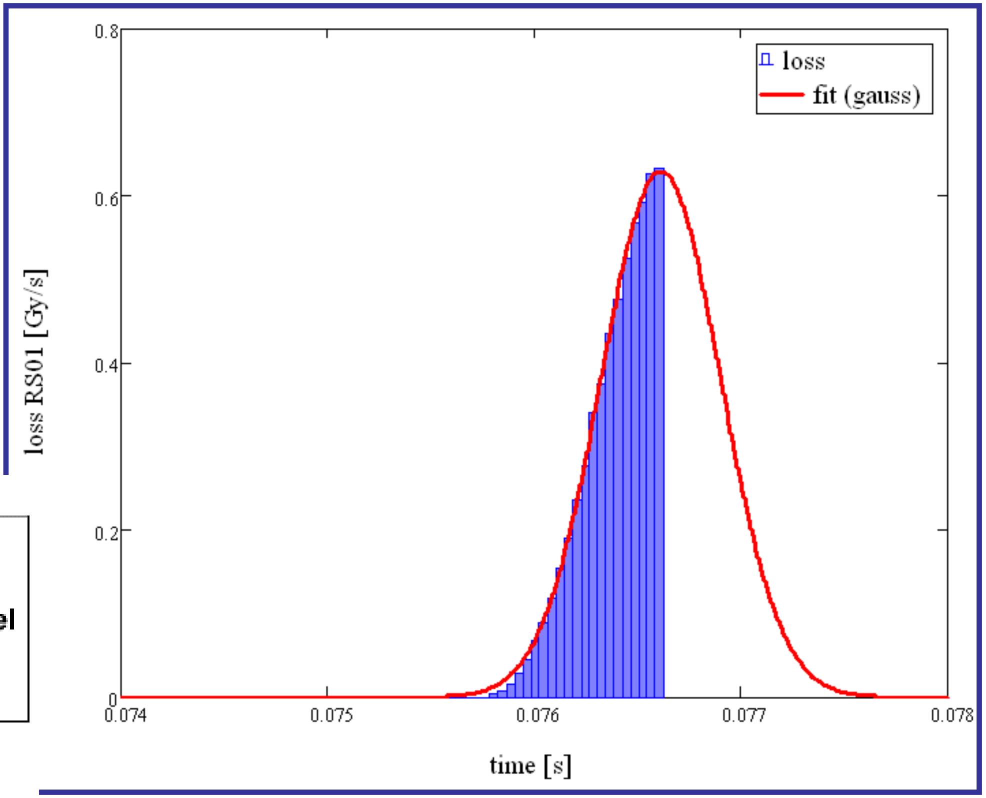
ATS/Note/2011/048 (TECH), B. Dehning et al.

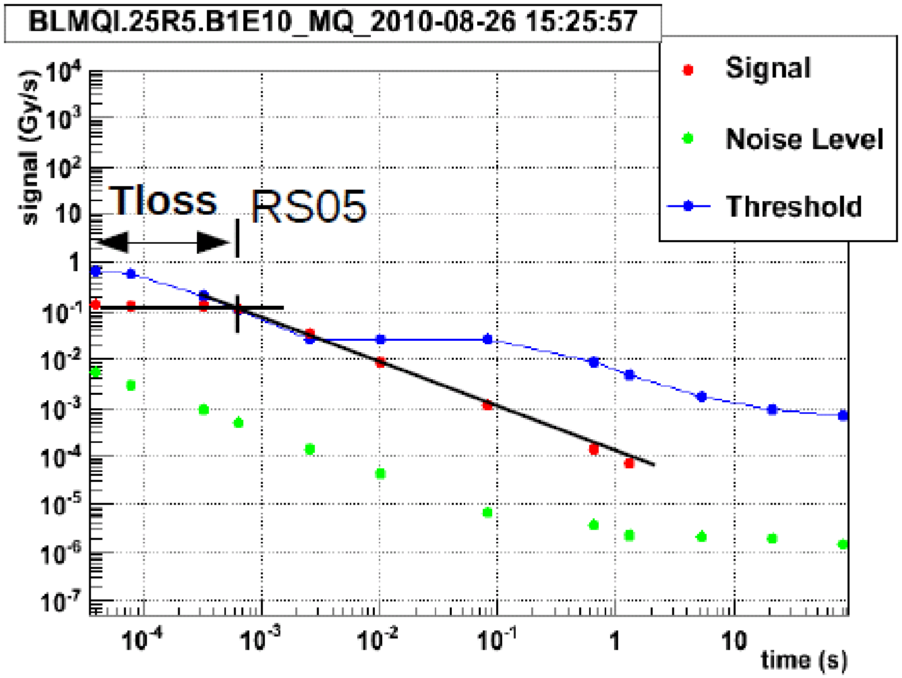
- Chemical Vapour Deposition (CVD) diamond
- IP7 collimators (TCP) – one per beam
    - All sizable local losses also seen at collimators
- Ir

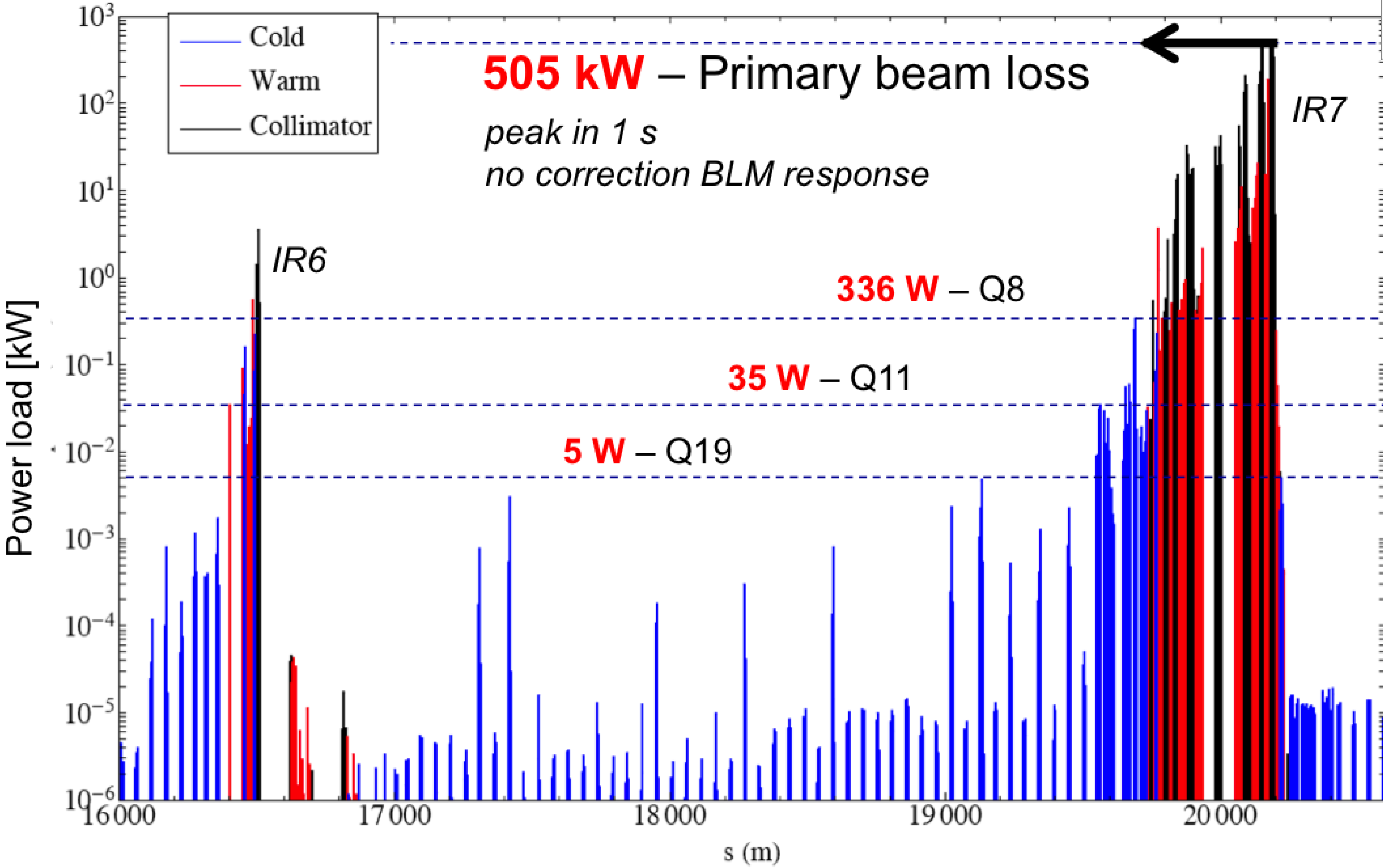


Dump on 01.05.2011

- From fit of PM data
- (BLMEI.05L2.B1E10_MKI.D5L2.B1):
- *Amplitude: 0.63 Gy/s*
- *Width: 0.29 ms*



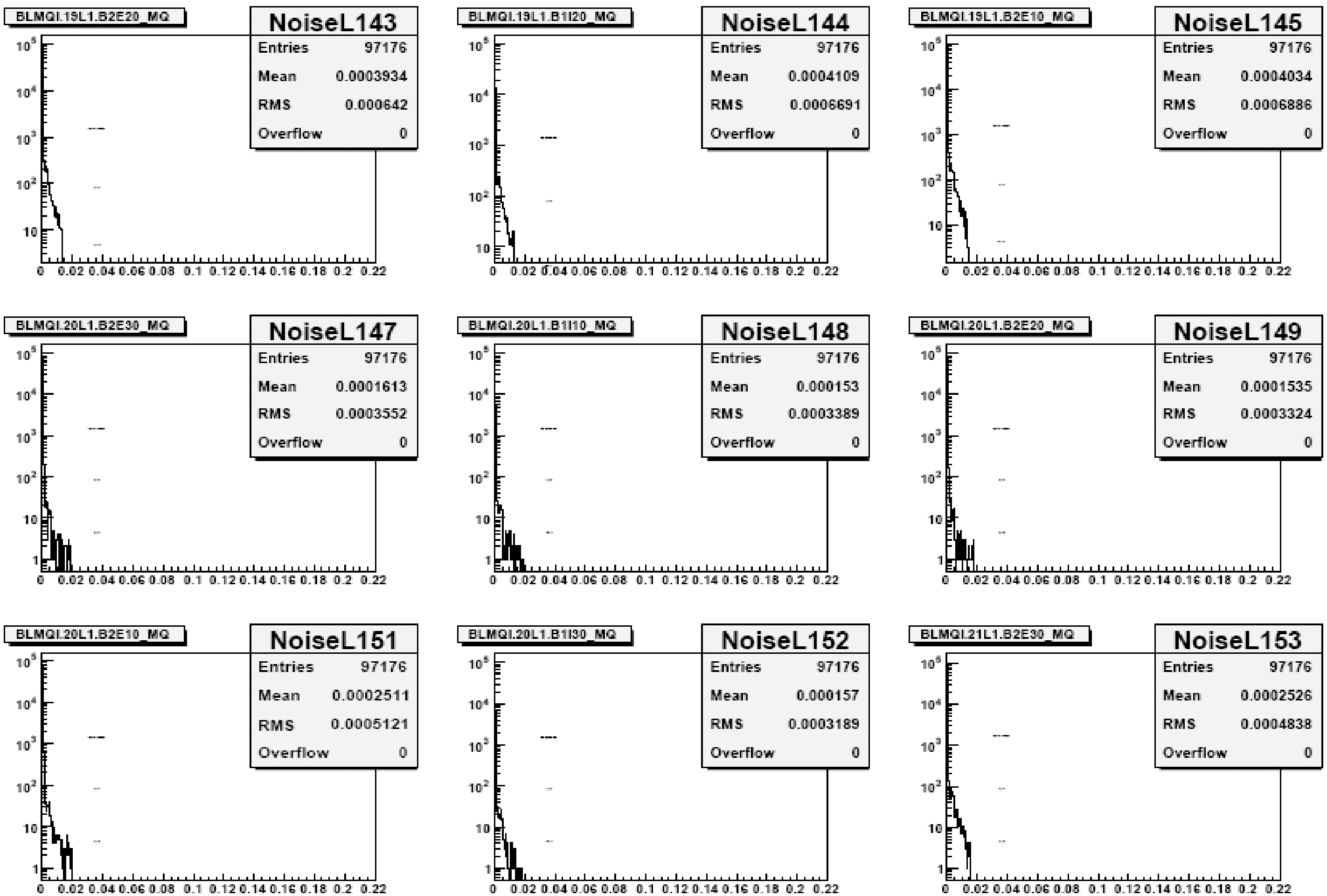




3.5 TeV operational collimator settings (not best possible)

No quench – consistent with BLM thresholds (64% of assumed quench level)

Noise Level Distributions



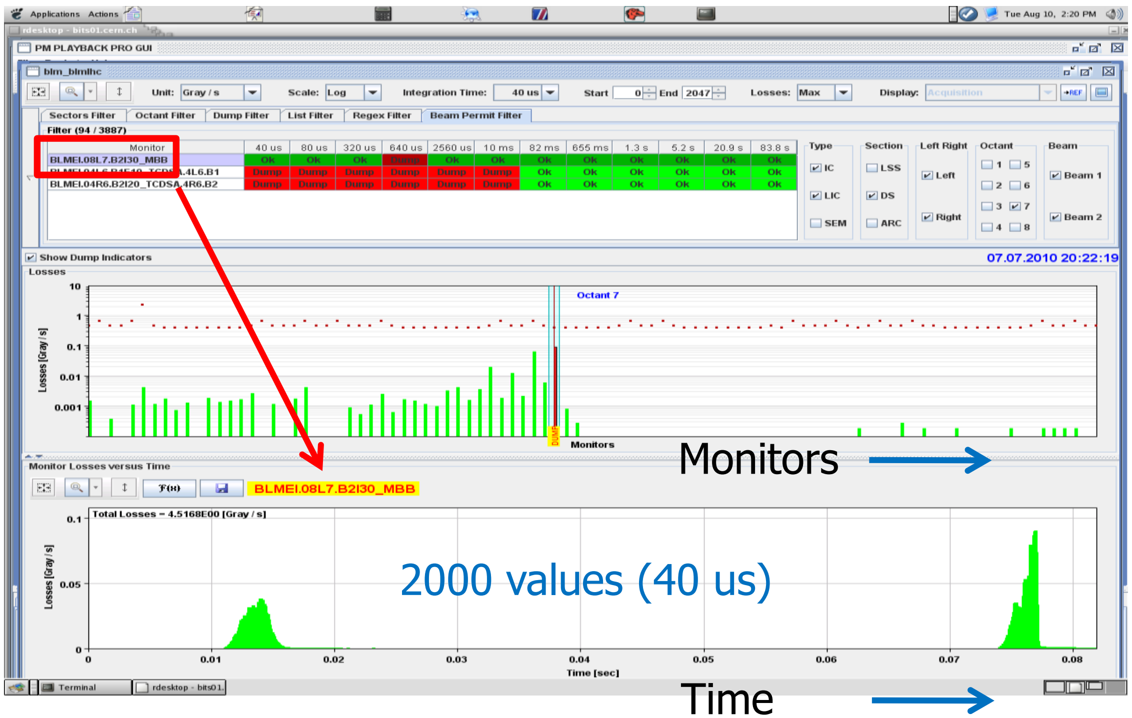
- Procedure:
  - require data during nominal operation conditions of LHC
  - Choose most sensitive integration intervals
  - Set histogram max value to lowest quench threshold level (MB-magnet)
- Overflows are interpreted as false signals

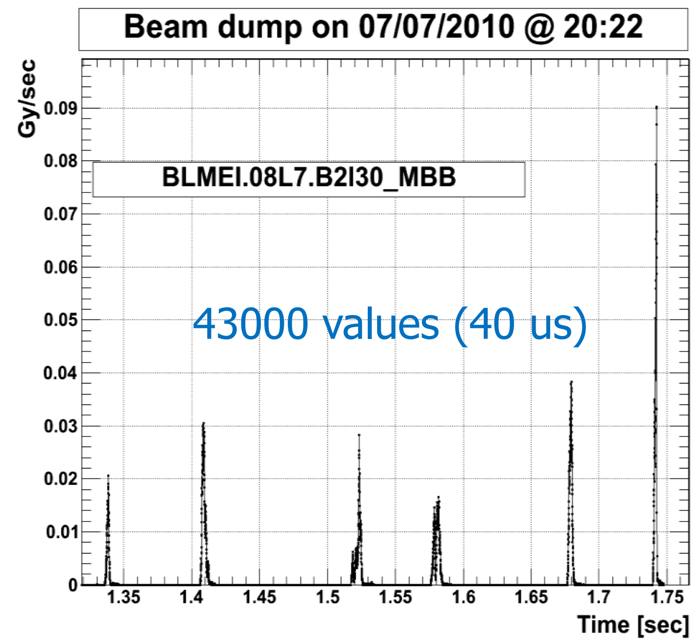
Post Mortem Data (some examples)

Loss in a bending magnet

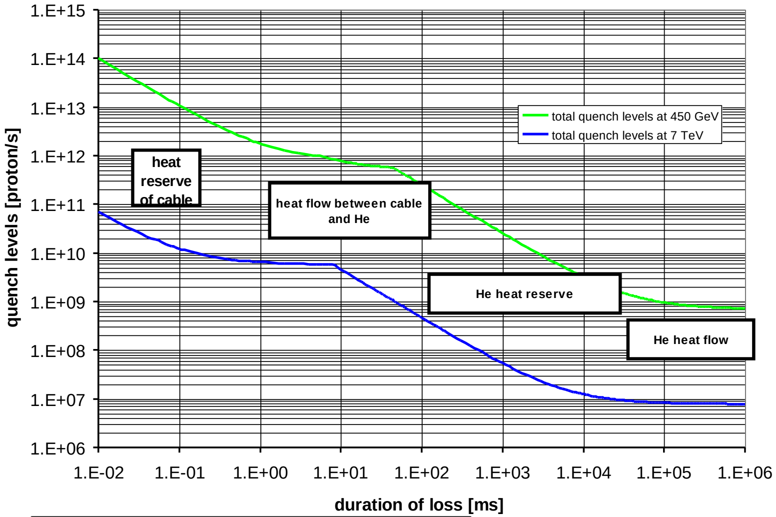
PM application: BLM data of 0.082 sec
online available

Longer PM buffer: BLM data of 1.72 sec
offline available

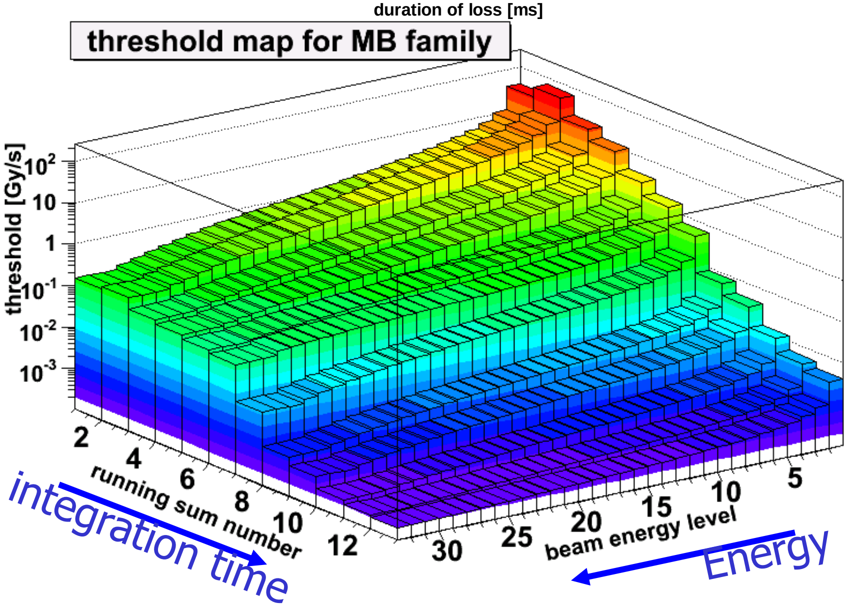


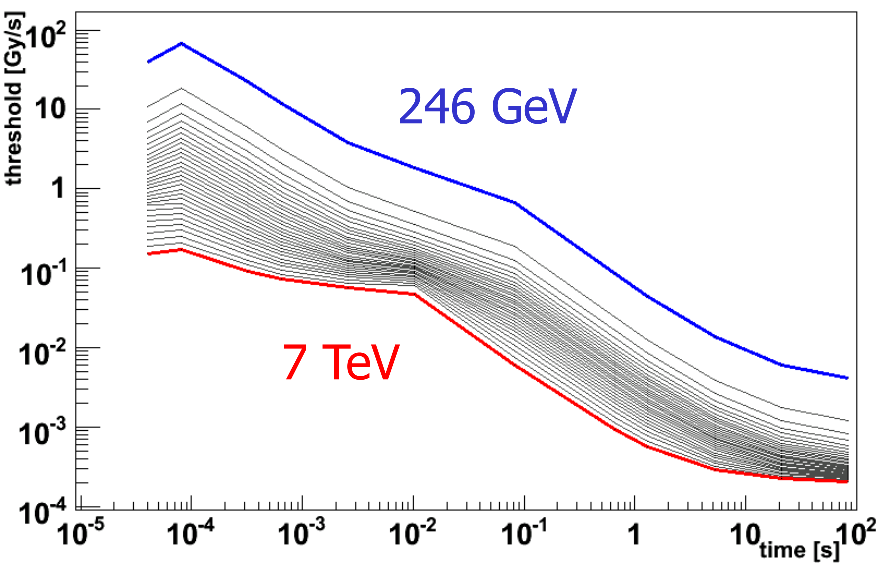


Quench and Damage Levels



- High dynamic range dynamic
  - Arc: 10^8
  - Collimation: 10^{13} second detector
- Change of the



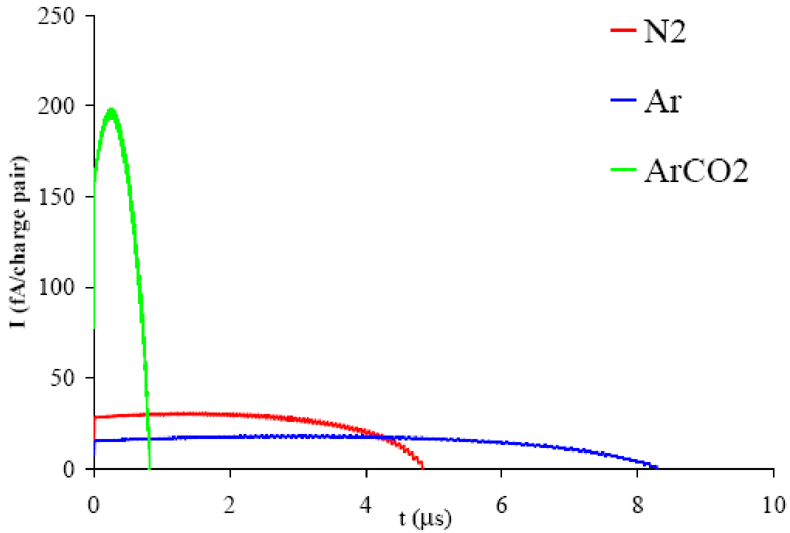


Literature

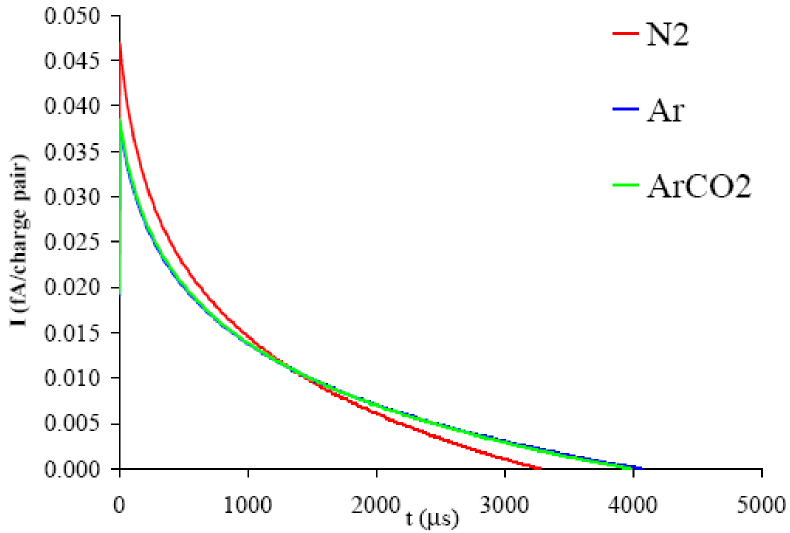
- http://cern.ch/blm
- LHC
  - Reliability issues, thesis, G. Guaglio
  - Reliability issues, R. Filippini et al., PAC 05
  - Front end electronics, analog, thesis, W. Friesenbichler
  - Front end electronics, analog-digital, E. Effinger et al.
  - Digital signal treatment, thesis, C. Zamantzas
  - Balancing Safety and Availability for an Electronic Protection System, S. Wagner et al., to be published, ESREL 2008

Drift times of electrons and ions (I)

Coaxial Chamber

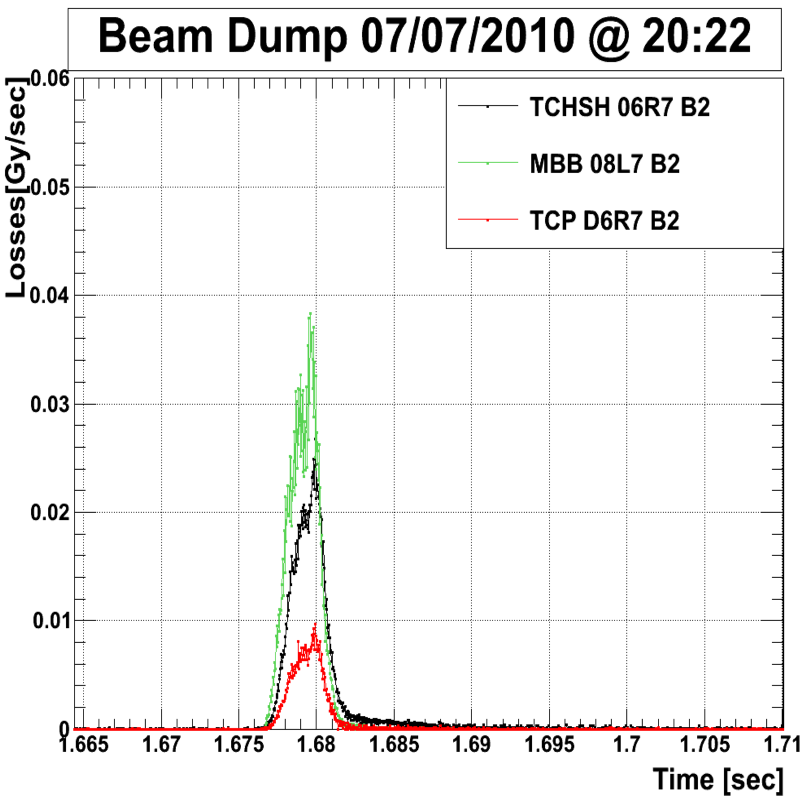


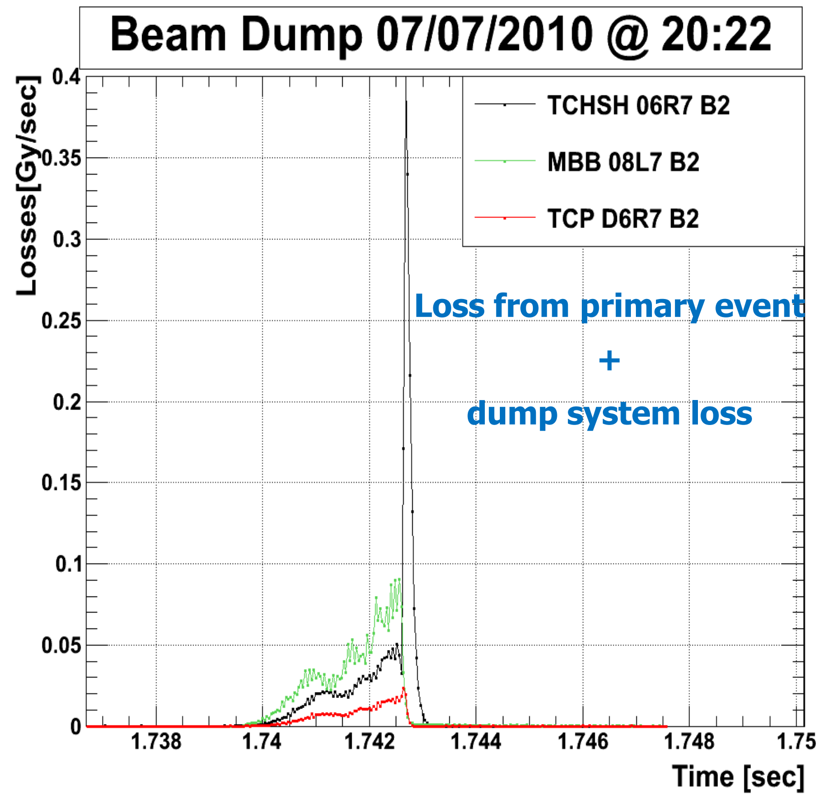
(a) *electrons*

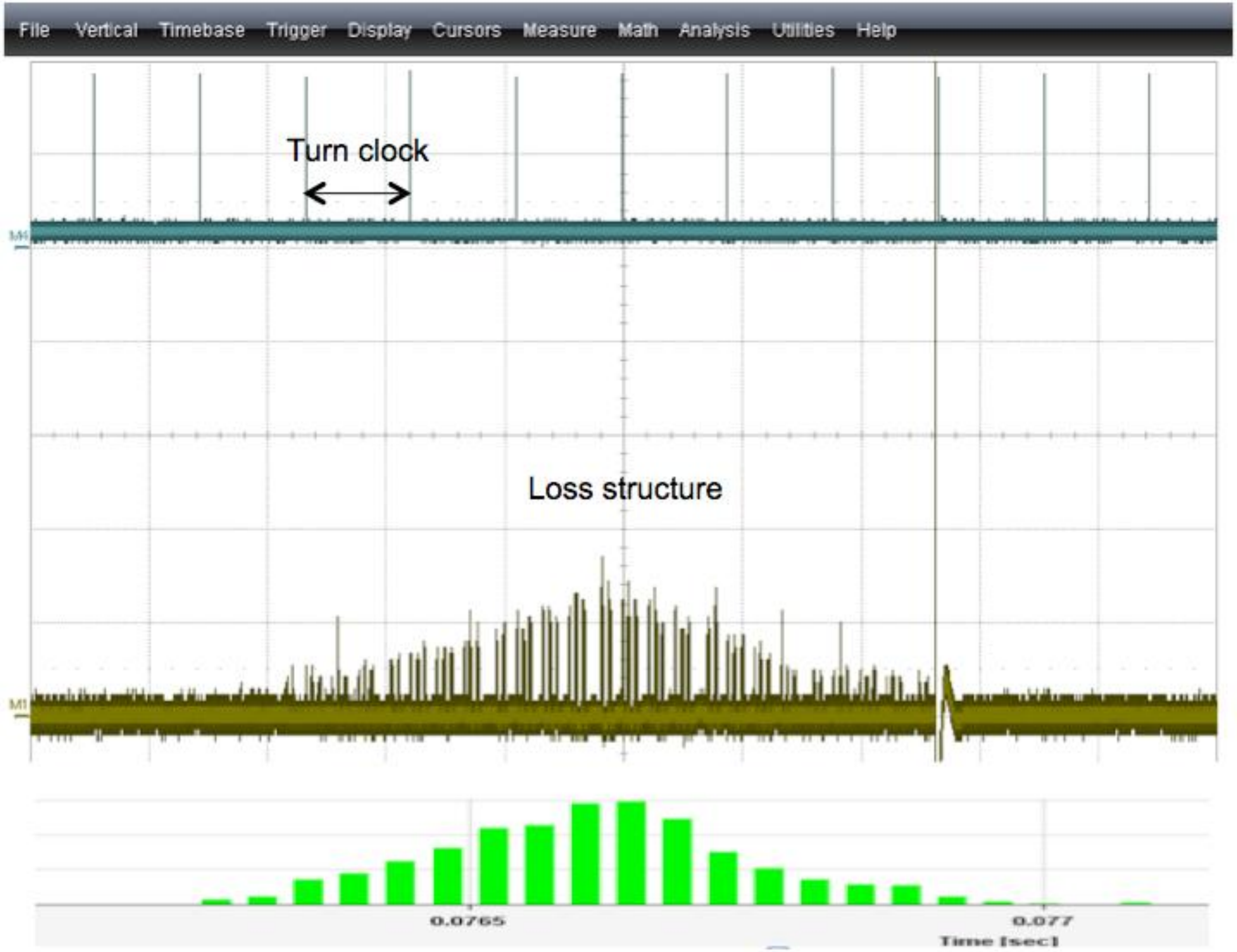


(b) *ions*

Post Mortem Data (some examples), Zoom



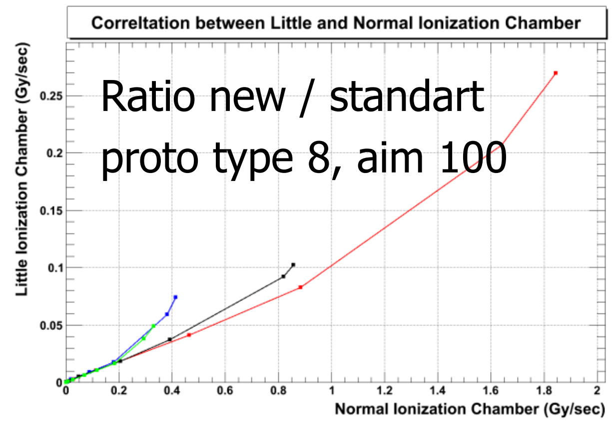




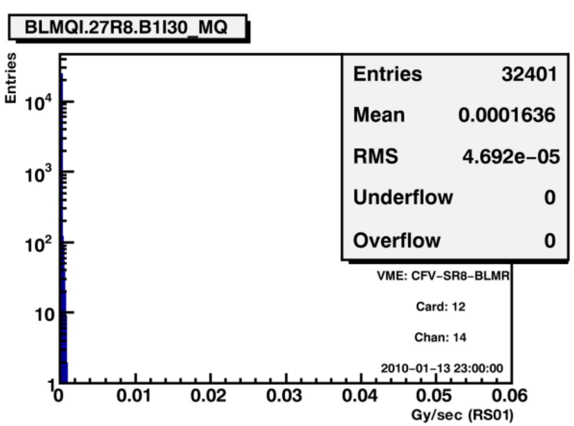
File
Vertical
Timebase
Trigger
Display
Cursors
Measure
Math
Analysis
Utilities
Help
Turn clock
Loss structure
0.0765
0.077
Time [sec]

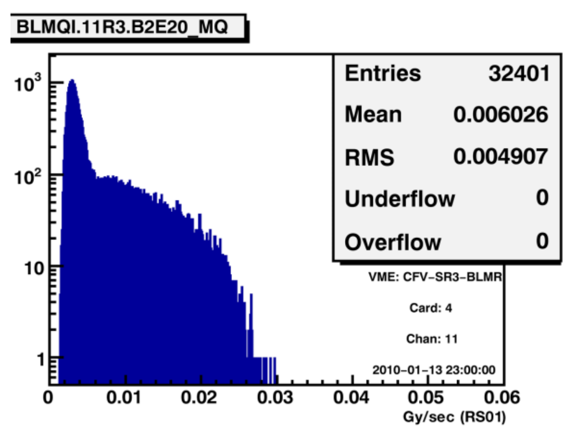
BLM System Upgrades

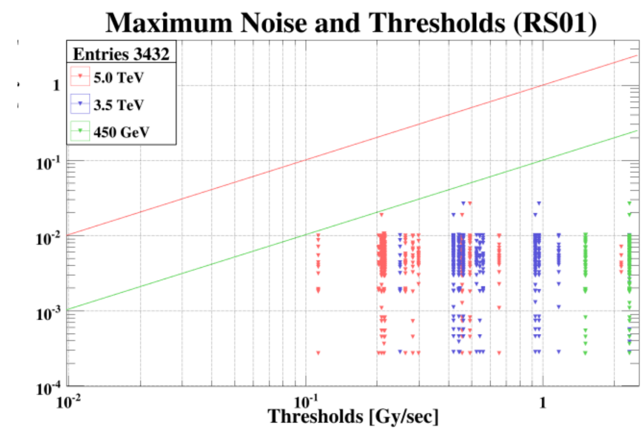
- Online program predicting loss characteristics and likely loss origin, PhD
- Long cable issue in IP3
- Development of an Detector with intermediate measurement range
- New cables for noise channels (7 TeV operation)



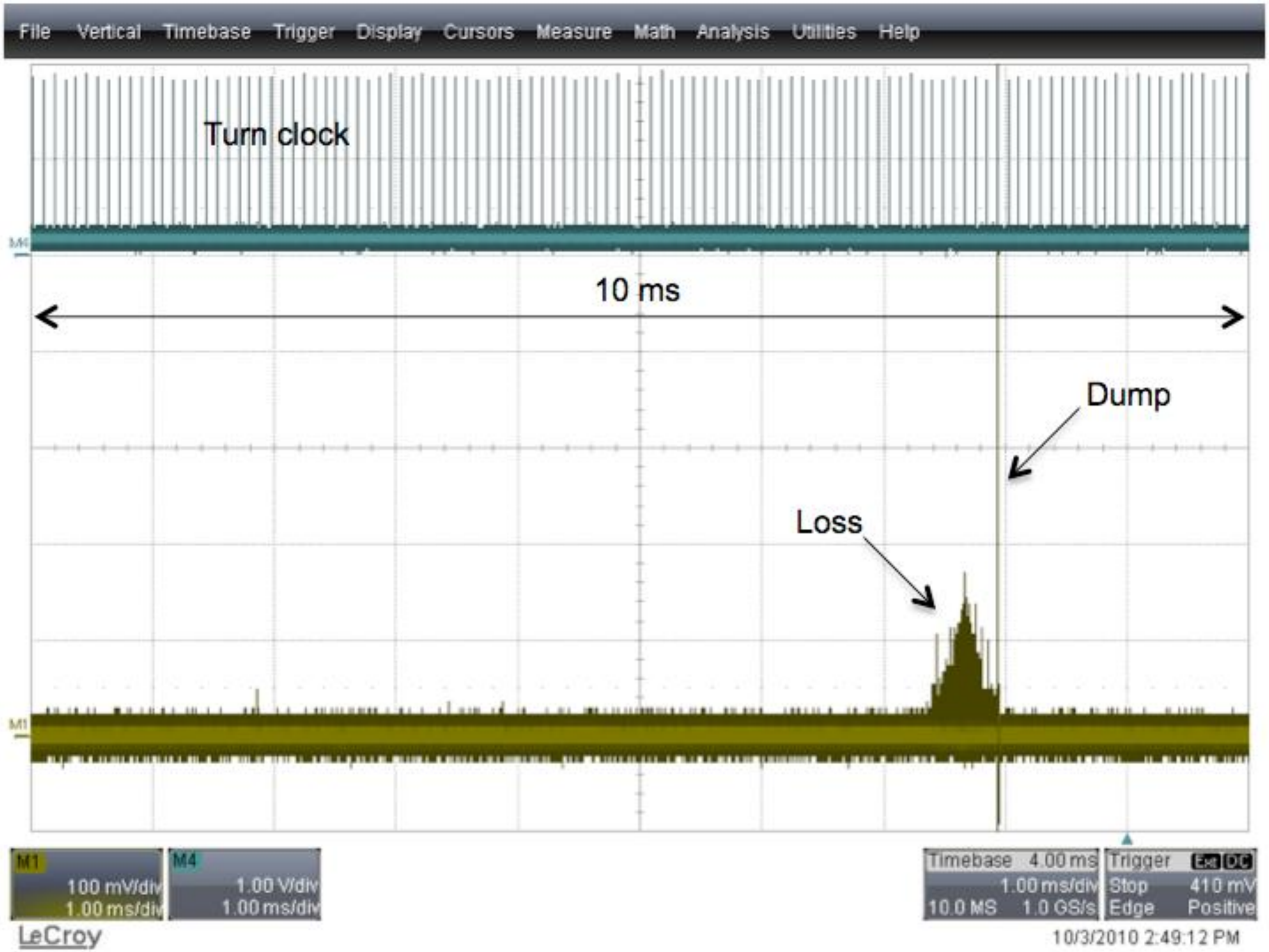
Data set: 8.1.2010-15.1.2010

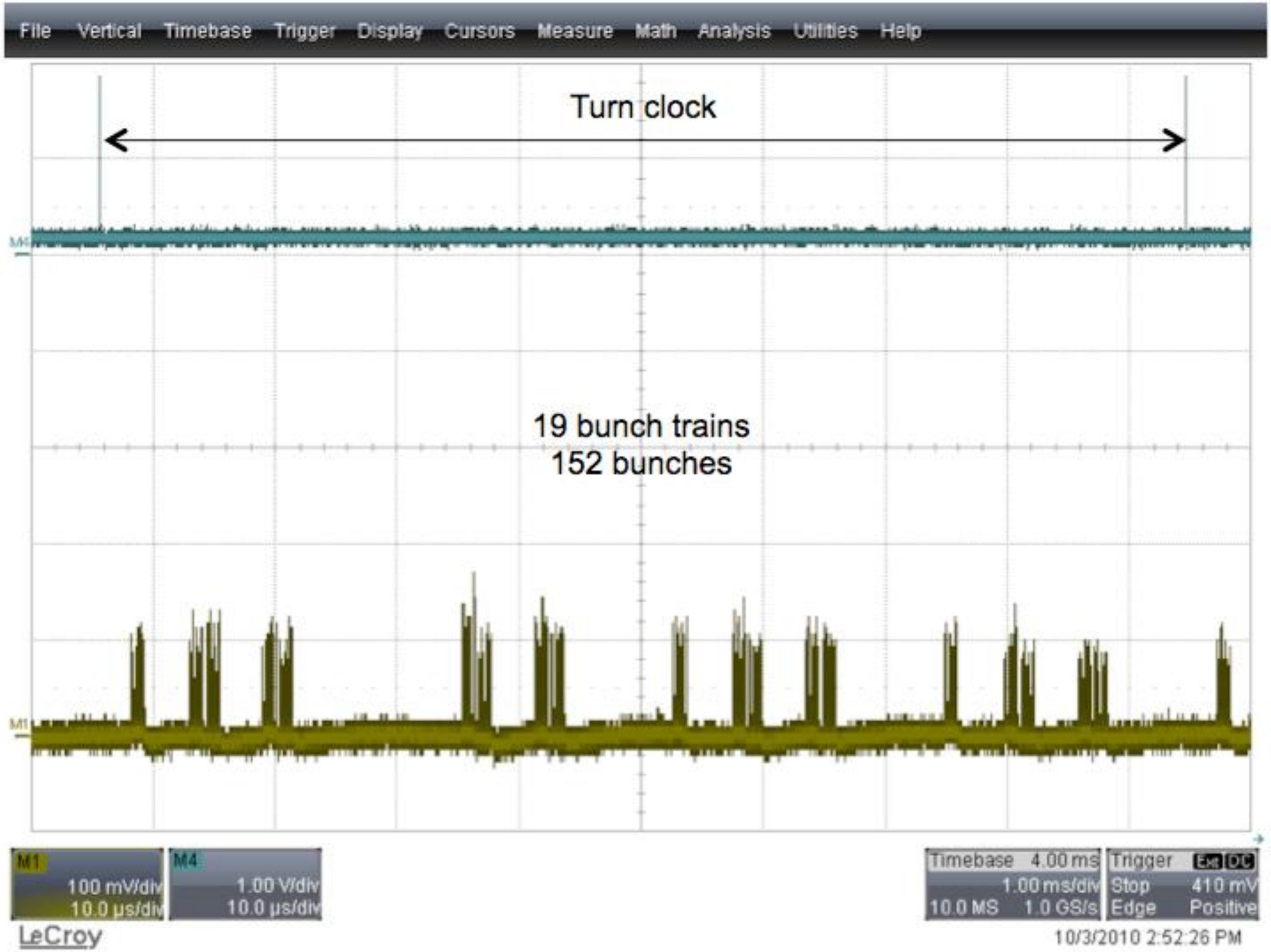


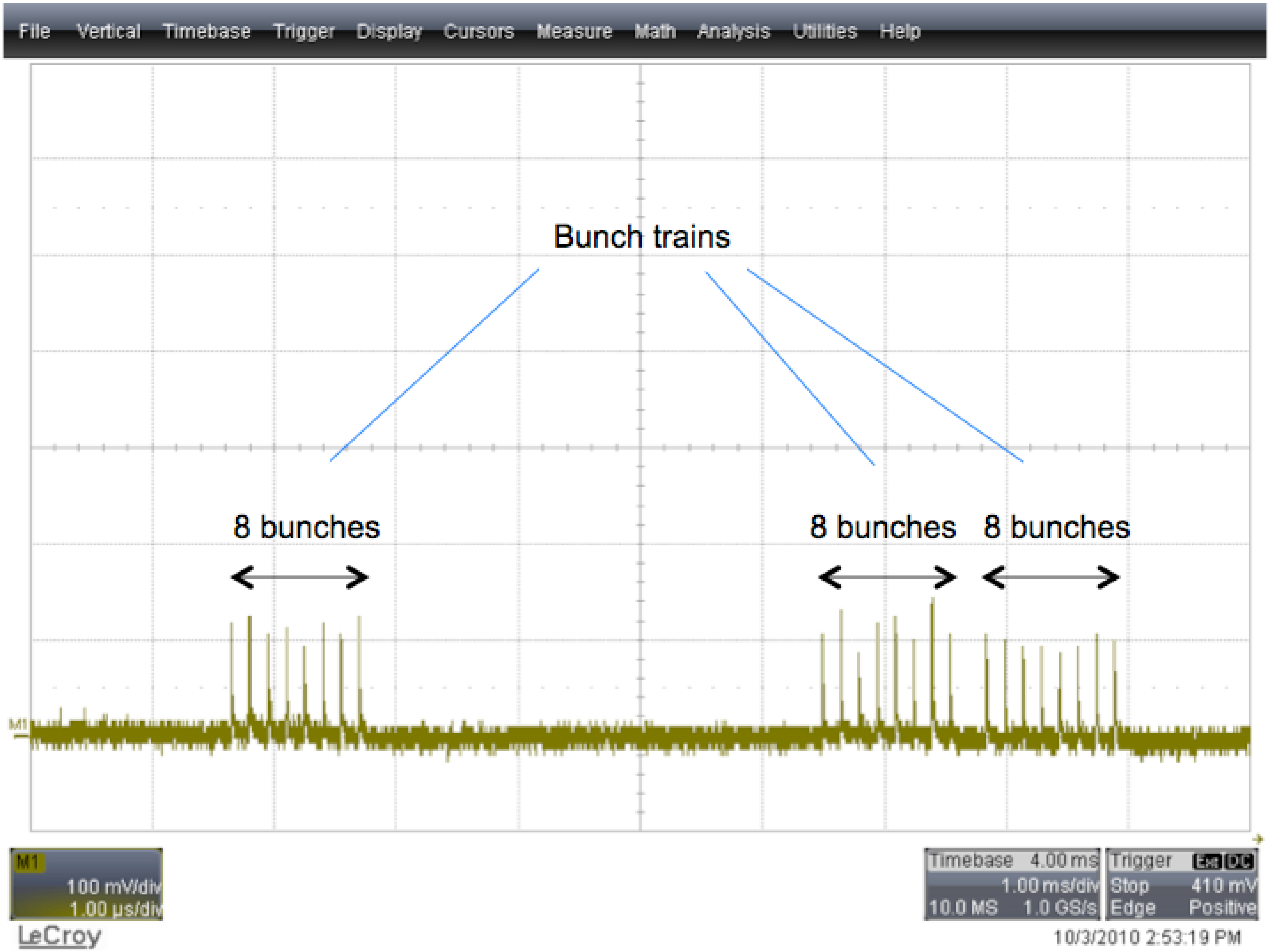




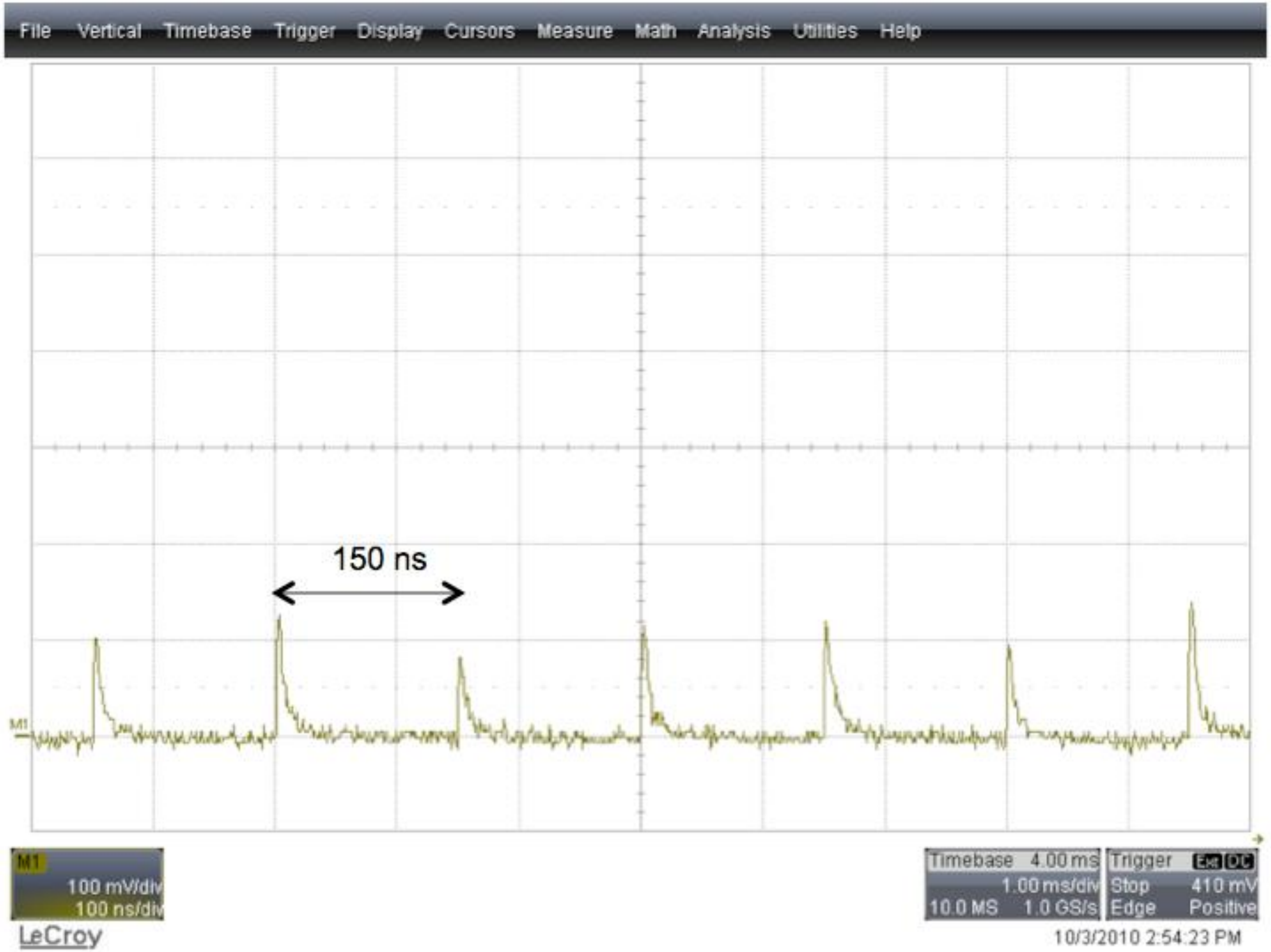
Date: 3/10/2010 12h18, 152 bunches, 150ns bunch spacing




File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help
Turn clock
19 bunch trains
152 bunches
M1
100 mV/div
10.0 µs/div
M4
1.00 V/div
10.0 µs/div
LeCroy
Timebase 4.00 ms
1.00 ms/div
10.0 MS 1.0 GS/s
Trigger
Stop 410 mV
Edge Positive
10/3/2010 2:52:26 PM



File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help
Bunch trains
8 bunches
8 bunches
8 bunches
M1
M1
100 mV/div
1.00 µs/div
LeCroy
Timebase 4.00 ms
1.00 ms/div
10.0 MS 1.0 GS/s
Trigger Ext DC
Stop 410 mV
Edge Positive
10/3/2010 2:53:19 PM


File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help
150 ns
M1
M1
100 mV/div
100 ns/div
LeCroy
Timebase 4.00 ms
1.00 ms/div
10.0 MS 1.0 GS/s
Trigger
Stop 410 mV
Edge Positive
10/3/2010 2:54:23 PM