CERN

# State-of-the-art and future challenges for the quench detection and protection of accelerator superconducting magnet circuits

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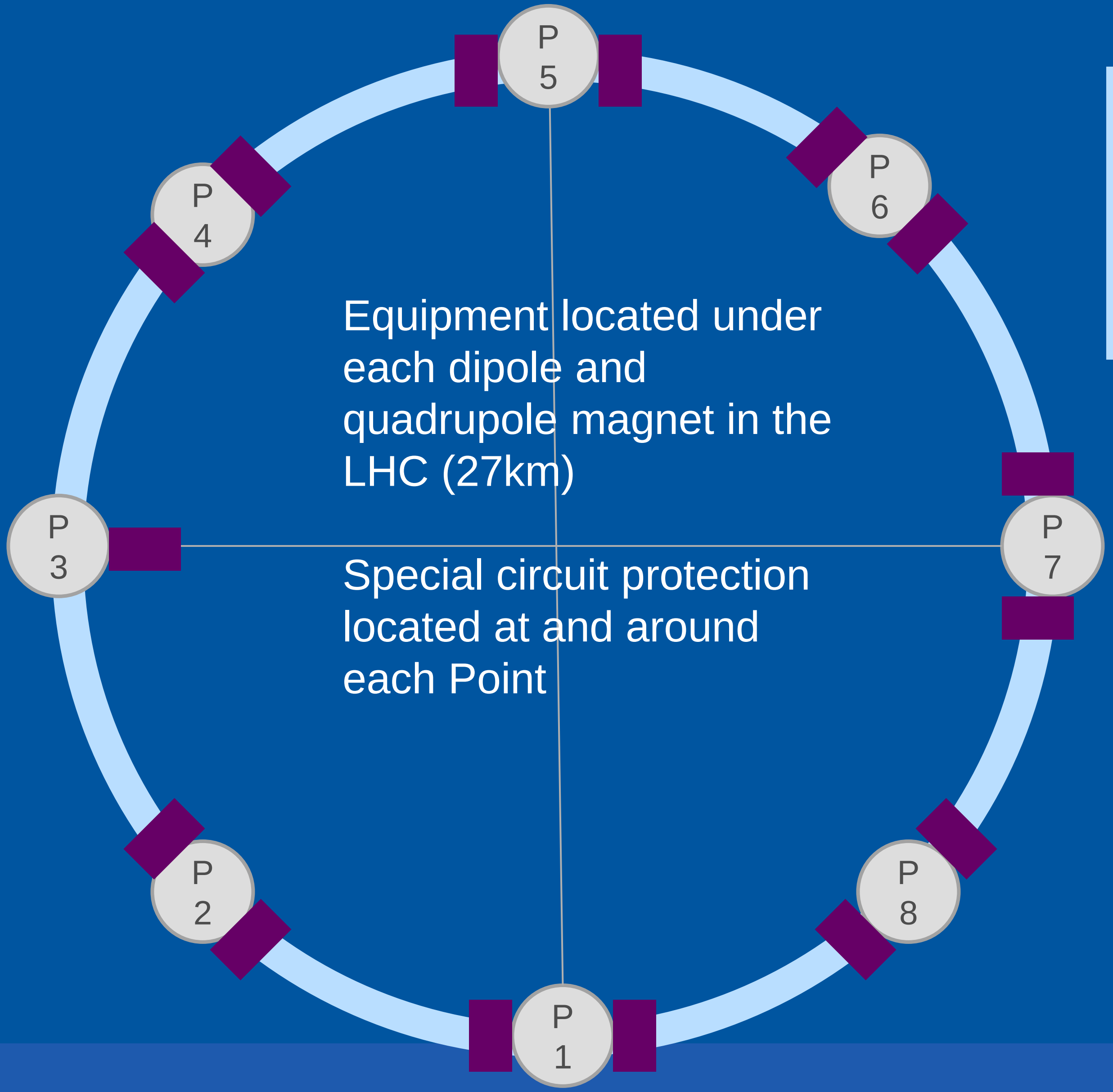
# Outline

- LHC quench detection technologies as an example of the state-of-the-art
- Performance of the main quench detector types
- Some limitations in real environment
- Future developments for the quench detection and magnet protection
- Conclusion

# Quench detection systems in LHC

- For the detection of quenches in the superconducting circuits of the LHC in total 7568 quench detection systems have been installed
  - 24 main circuits, 8 inner triplets, 94 insertion region and 418 corrector magnet circuits
  - Protection of magnets, HTS current leads and superconducting bus-bars
  - About 14000 hardwired interlocks and 2500 data acquisition systems for supervision
  - LHC quench detection systems are highly dependable systems. Due to the large number and the constraints during LHC operation (restricted access, ionizing radiation, electro-magnetic compatibility …), the design must not only focus on reliability but also optimize availability and maintainability

# Geographical distribution




Equipment located under each dipole and quadrupole magnet in the LHC (27km)

Special circuit protection located at and around each Point

75% of detectors
Main circuits protection (DQQDL/DS/BS) installed in the tunnel

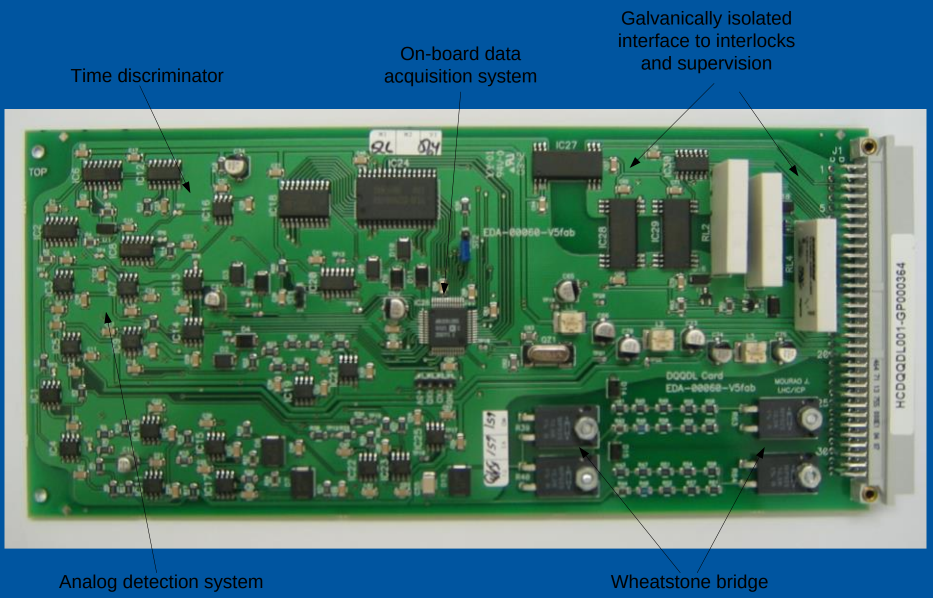
25% of detectors
IPQ/IPD/IT, 600A circuits protection EE systems (DQQDI/DT/DC/nDI/nDG)
installed in UA/UJ/RR

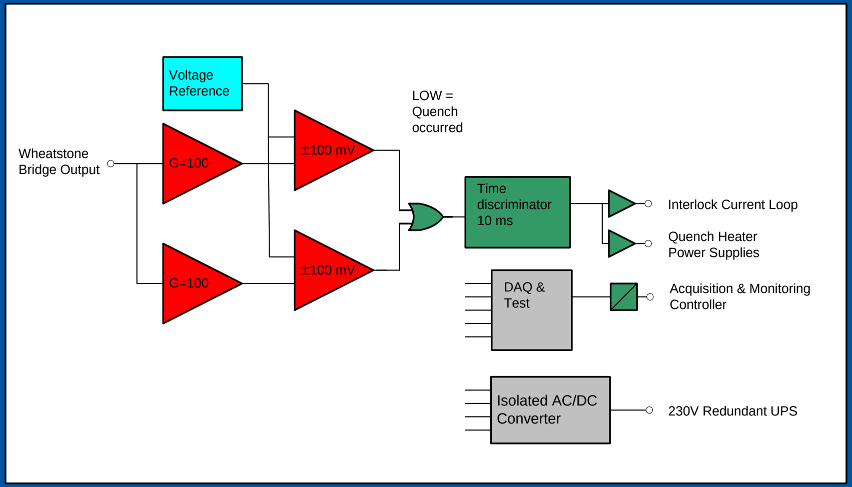
# Technologies of quench detection systems

- Classical systems are mostly using Wheatstone bridges in combination with linear amplifier, comparators and non-programmable digital logic
  - In some cases a programmable devices are used for data acquisition
  - The systems have restricted functionality but are normally extremely reliable and robust
  - Their protection functionality can be verified relatively easy
- Digital systems are actually mixed signal devices
  - Analog input stages based on instrumentation amplifiers for initial signal conditioning, filtering and circuit protection
  - Analog to digital converters for signal digitization
  - Programmable logic devices for the implementation of the detection logic
    - Complex detection algorithms, parameter based dynamic detection settings, non-linear filters etc.
    - Detection functionality not easy to verify
  - Electrical insulation is always provided in the digital signal path

# Local quench detector for LHC main magnets

- Analog bridge detector based on state of the art instrumentation amplifiers
- (2 out of 2) || (2 out of 2) hardwired multi-channel evaluation scheme
- Radiation tolerant
- Resolution < 125 µV @ +/- 250mV
- Adjustment free – fixed threshold detector ($U_{TH}$ = ±100 mV)
- Digitally isolated interface – detector circuit on magnet potential
- On-board data acquisition system
- Very reliable operation with 4032 circuit boards installed in LHC



# Digital high precision quench detection systems

- Based on ADuC834™ microcontroller with integrated 24 Bit ∑Δ analog to digital converter ADC
  - High resolution < 15 nV @ +/-12.5mV
  - Minimum reaction time $t_{EVAL}$ = 100 ms
- Originally developed for the protection of hybrid HTS current leads, these detection systems are meanwhile also in use for the protection of the bus-bar splices in the LHC main circuits (3266 redundant systems installed in total)
  - Reliable operation with detection thresholds as low as 500 µV
  - Measurement of bus-bar splice resistance with ΔR ≤ 1 nΩ
  - Programmable gain based version used for circuit protection and diagnostics during the Copper Stabilizer Continuity Measurement (CSCM) campaigns

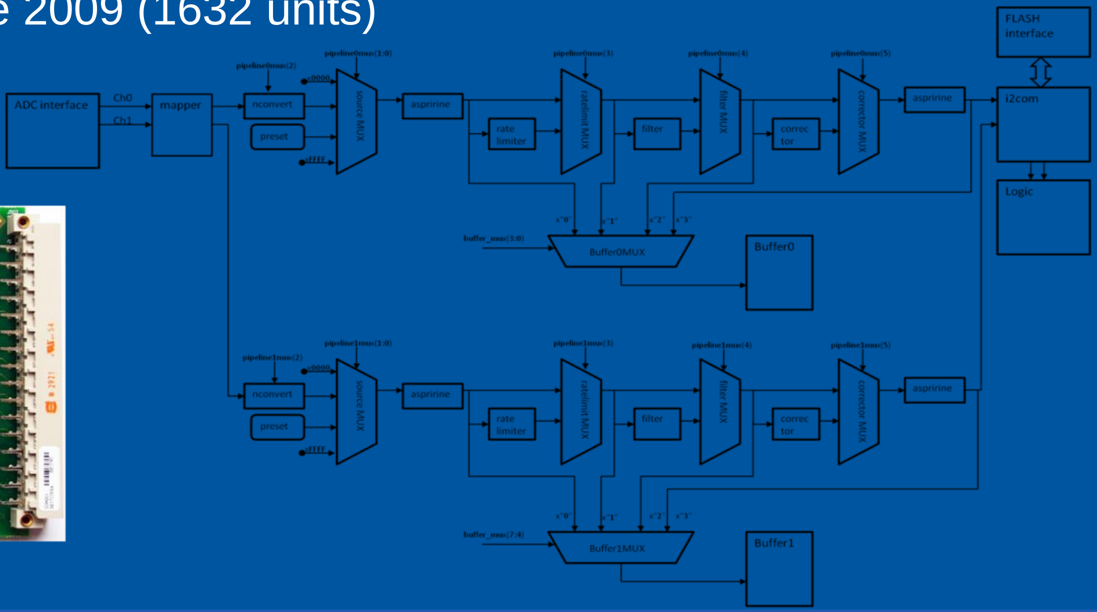
# Fast digital quench detection systems – 1st generation

- The first LHC general purpose digital detection board has been developed for the protection of insertion region magnets, inner triplets and corrector magnet circuits. It is based on a digital signal processor DSP of the TI TMS320C6211™ and 14 bit successive approximation (SAR) ADC.
  - The design is not radiation tolerant as not required at the time of the development
  - Resolution < 1 mV @ +/-10V
  - Minimum reaction time $t_{EVAL}$ = 20 ms
- The DSP based approach turned out to be crucial for the commissioning of the corrector magnet circuits as it allowed to implement the complex inductive voltage compensation.
  - A part the inherent sensibility to radiation induced faults, the performance of the system is excellent with respect to reliability and availability

- The lack of radiation tolerance and the obsolescence of key components called for a system upgrade
  - Major part replaced during LS1, to be completed over the next years

# Fast digital quench detection systems – $2^{nd}$ generation

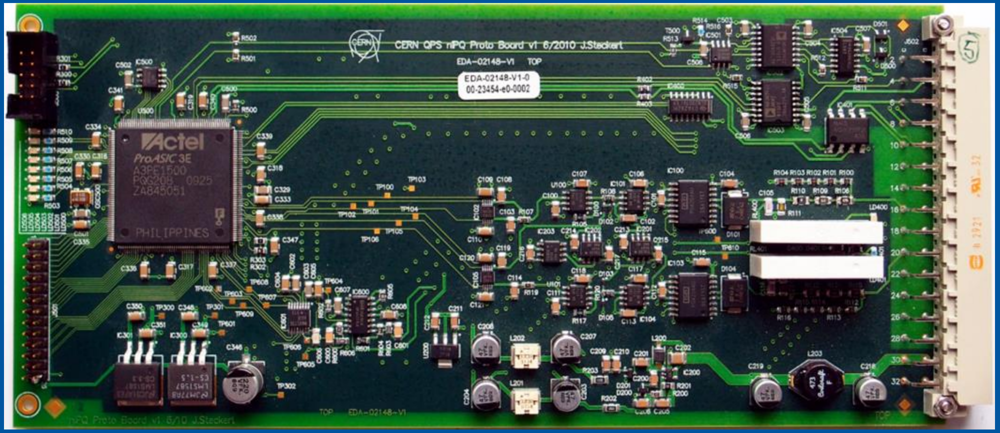
- Radiation tolerant fast digital quench detection systems have been developed for the symmetric quench detection in LHC main dipoles and quads.
  - Based on Microsemi ProAsic3™ field programmable gate array (FPGA) and 16 Bit SAR ADC
  - Resolution < 500 µV @ +/-10V
  - Minimum reaction time $t_{EVAL}$ = 20 ms
  - All critical components extensively tested for radiation tolerance
  - 4 isolated input channels (ADC on magnet potential) for the comparison of different magnet voltages
  - Successful operation since 2009 (1632 units)

# Fast digital quench detection systems – 2nd generation v2

- Based on the experience gained during the development of symmetric quench detection board a variety of detection and data acquisition systems has been produced and deployed during LHC LS1.
- The detection boards are used for the protection of insertion region magnets; the latest development will be used for the 600 A corrector magnet circuits.
  - Resolution < 20 µV @ +/-10V
  - Minimum reaction time $t_{EVAL}$ = 20 ms

  - This board makes use of a larger FPGA and fast high resolution 24 Bit ∑Δ ADCs allowing to replace a complex analog/digital feedback loop used in the original device
  - Qualification of the ADC and the development of efficient error correction algorithms has been a major challenge



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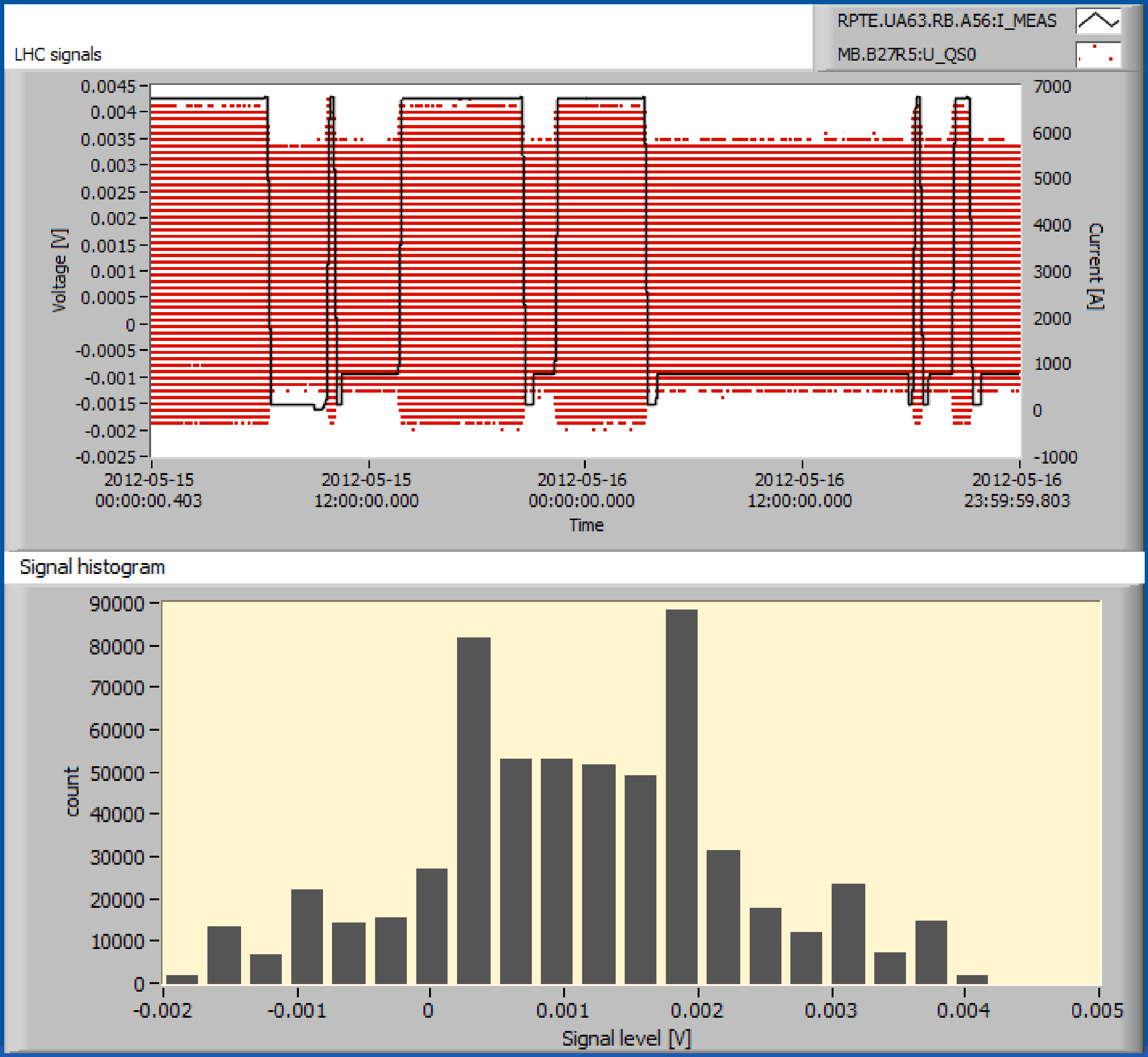
- Performance of the main quench detector types
- Some imitations in real environment Future developments for the quench detection and magnet protection
- Conclusion

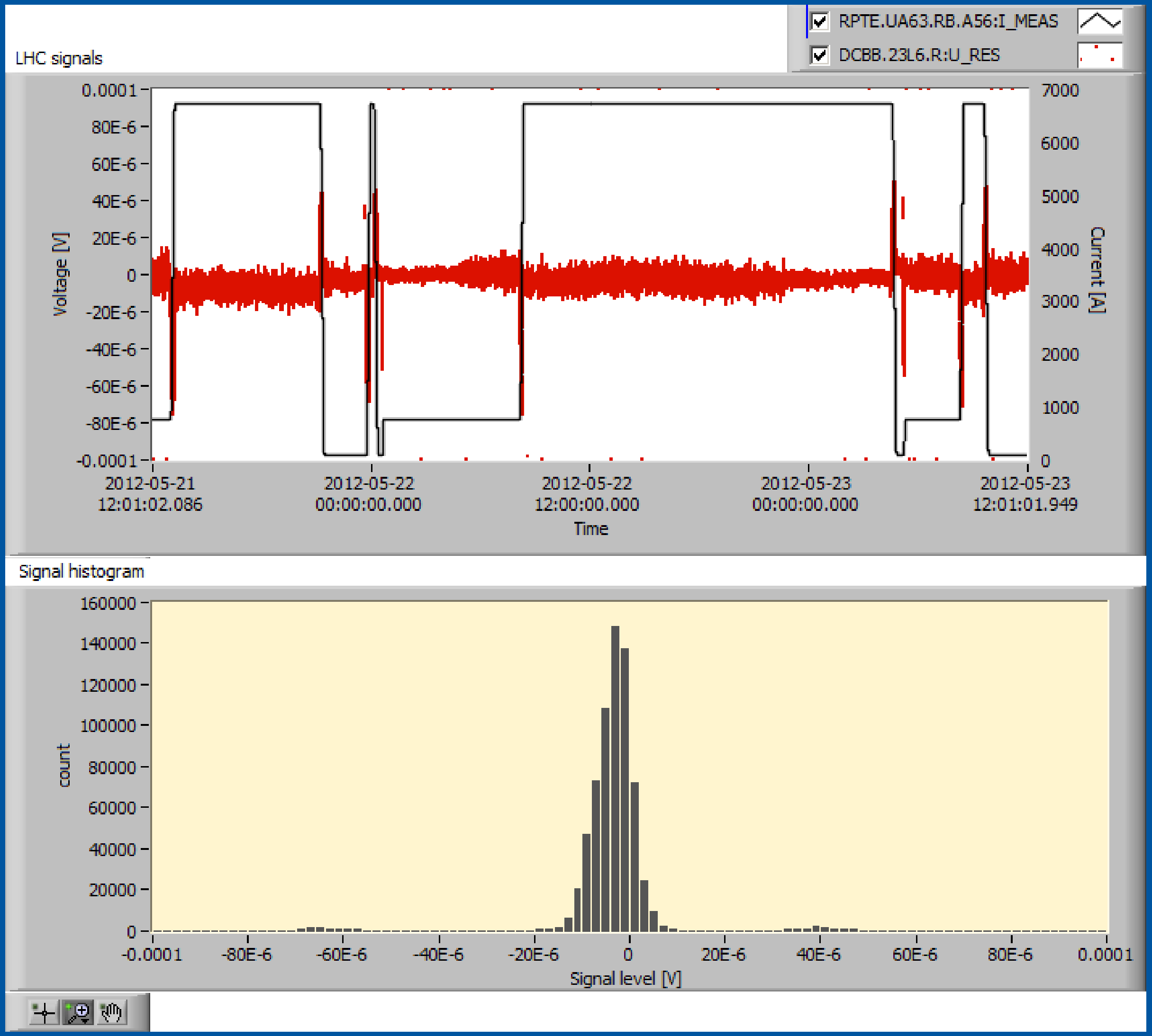
# Performance of local analogue bridge detectors

- **DQAMCMB**
- Main dipole quench protection
- Resolution and range: 122µV@+/-0.25V
-
- Source data
- Logging DB
- Measurement DB
- Signal description
- LHC Power Converter Measured Current
- Analogue output of the bridge (1st comparator)
- Signal name
- RPTE.UA63.RB.A56:I_MEAS
- MB.B27R5:U_QS0
-
- Peak-to-peak Voltage
- 6.227E-3
- RMS voltage
- 1.635E-3
- DC voltage
- 1.129E-3



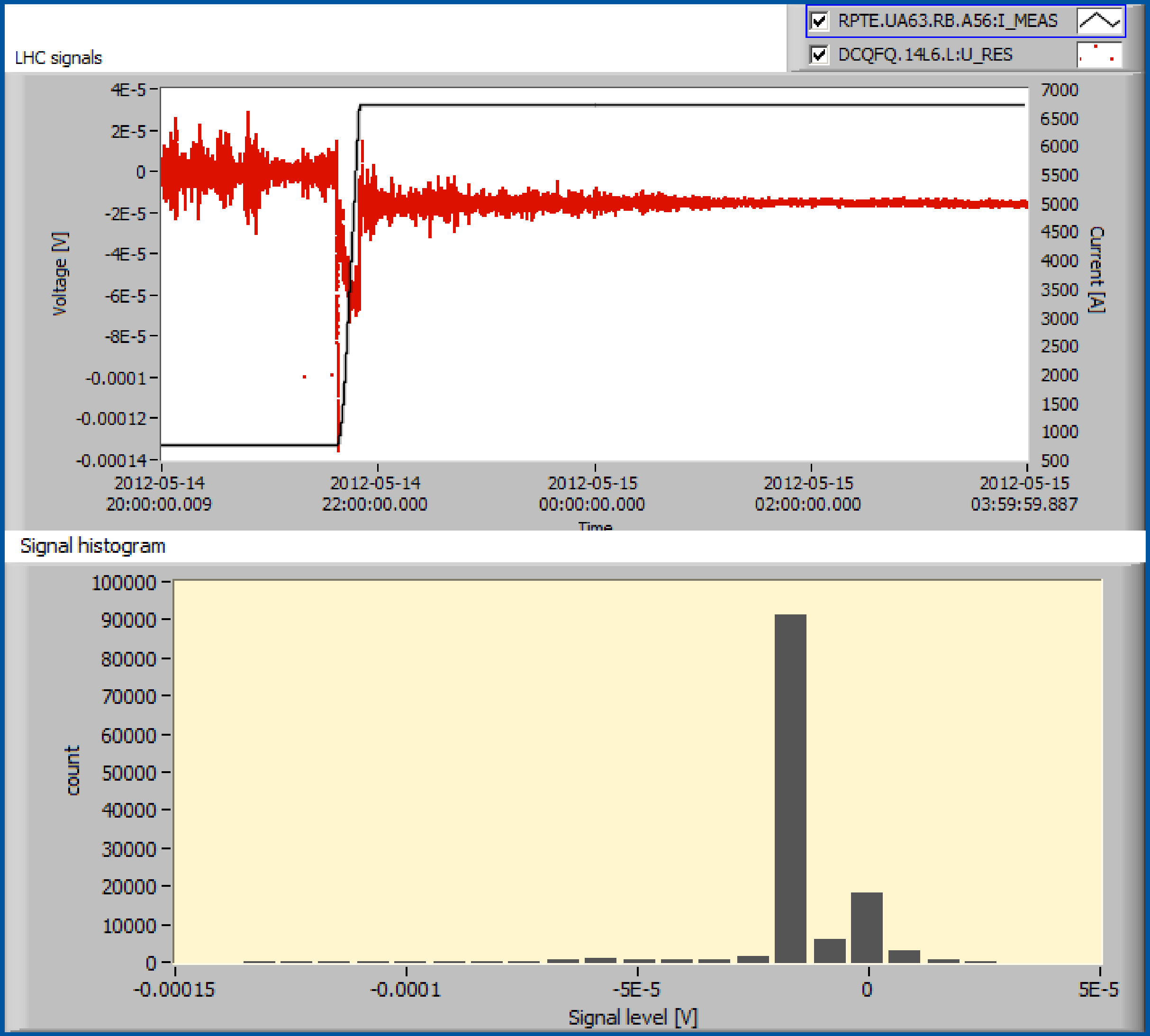
# Performance of digital high precision detectors

- **DQAMGSRB**
- **Main dipole SC bus bar protection**
- Resolution and range: 1.53nV@+/-12.8mV
- 
- Black/Red
- Source data
- Logging DB
- Measurement DB
- Signal description
- LHC Power Converter Measured Current
- Calculated resistive voltage
- Signal name
- RPTE.UA63.RB.A56:I_MEAS
- DCBB.23L6.R:U_RES
- 
- Peak-to-peak Voltage
- 100E-6 – $L_{bus\text{-}bar}$dI/dt during ramping
- 10E-6÷20E-6 – noise night/day
- RMS voltage
- 10.178E-6
- DC voltage
- -3.547E-6



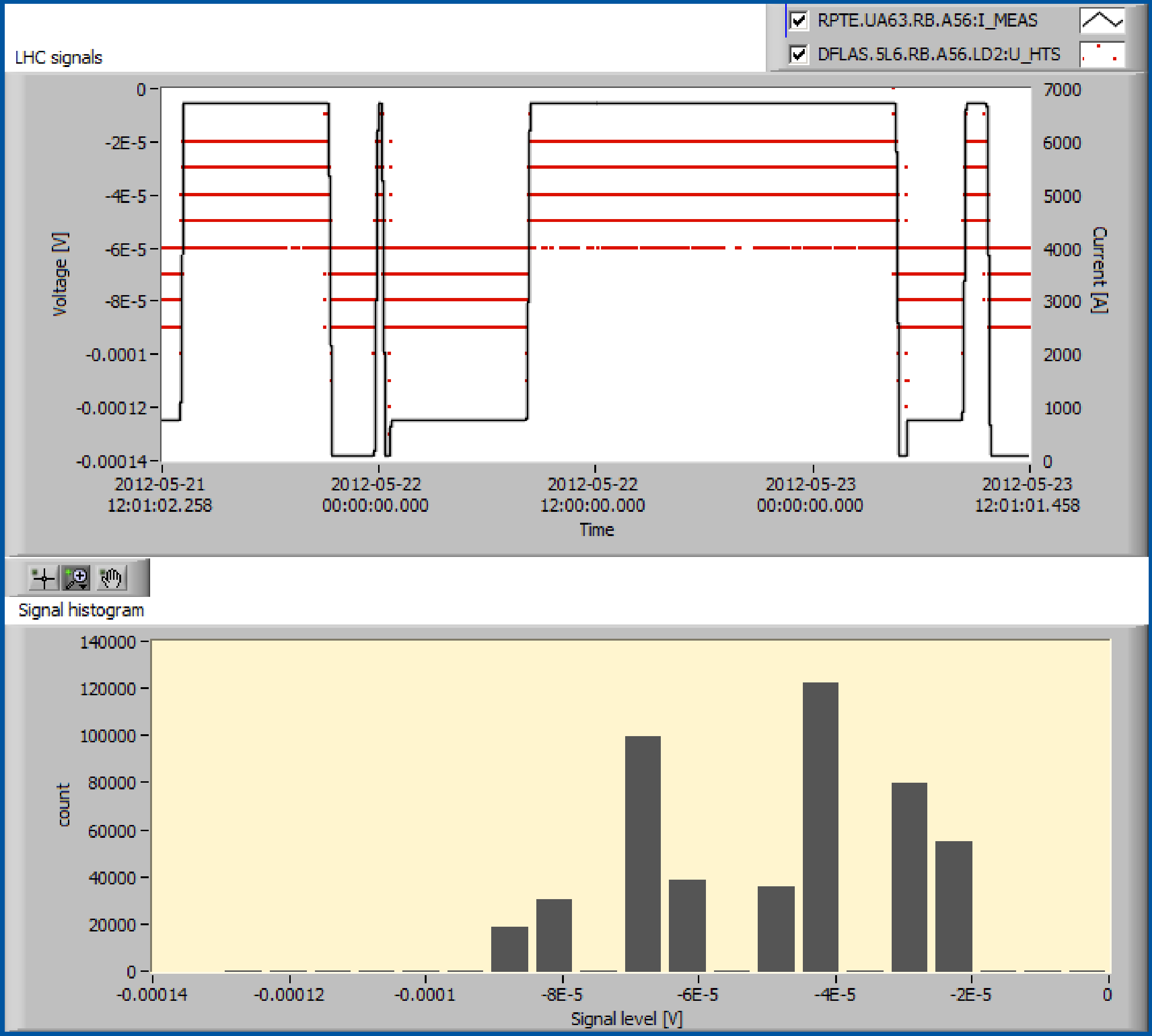
# Performance of digital high precision detectors

- **DQAMGSRQ**
- **Main quadrupole SC bus bar protection**
- Resolution and range: 1.53nV@+/-12.8mV
- 
- Black/Red
- Source data
- Logging DB
- Measurement DB
- Signal description
- LHC Power Converter Measured Current
- Calculated resistive voltage
- Signal name
- RPTE.UA63.RB.A56:I_MEAS
- DCQFQ.14L6.L:U_RES
- 
- Peak-to-peak Voltage
- 164.534E-6
- RMS voltage
- 16.912E-6
- DC voltage
- -13.830E-6



# Performance of digital high precision detectors

- **DQAMGSRB**
- **RB HTS part of current lead**
- Resolution and range: 6.5nV @+/-12.8mV
-
- Black/Red
- Source data
- Logging DB
- Measurement DB
- Signal description
- LHC Power Converter Measured Current
- HTS part current lead
- Signal name
- RPTE.UA63.RB.A56:I_MEAS
- DFLAS.5L6.RB.A56.LD2:U_HTS
-
- Peak-to-peak Voltage
- 130.000E-6
- RMS voltage
- 52.014E-6
- DC voltage
- -48.091E-6



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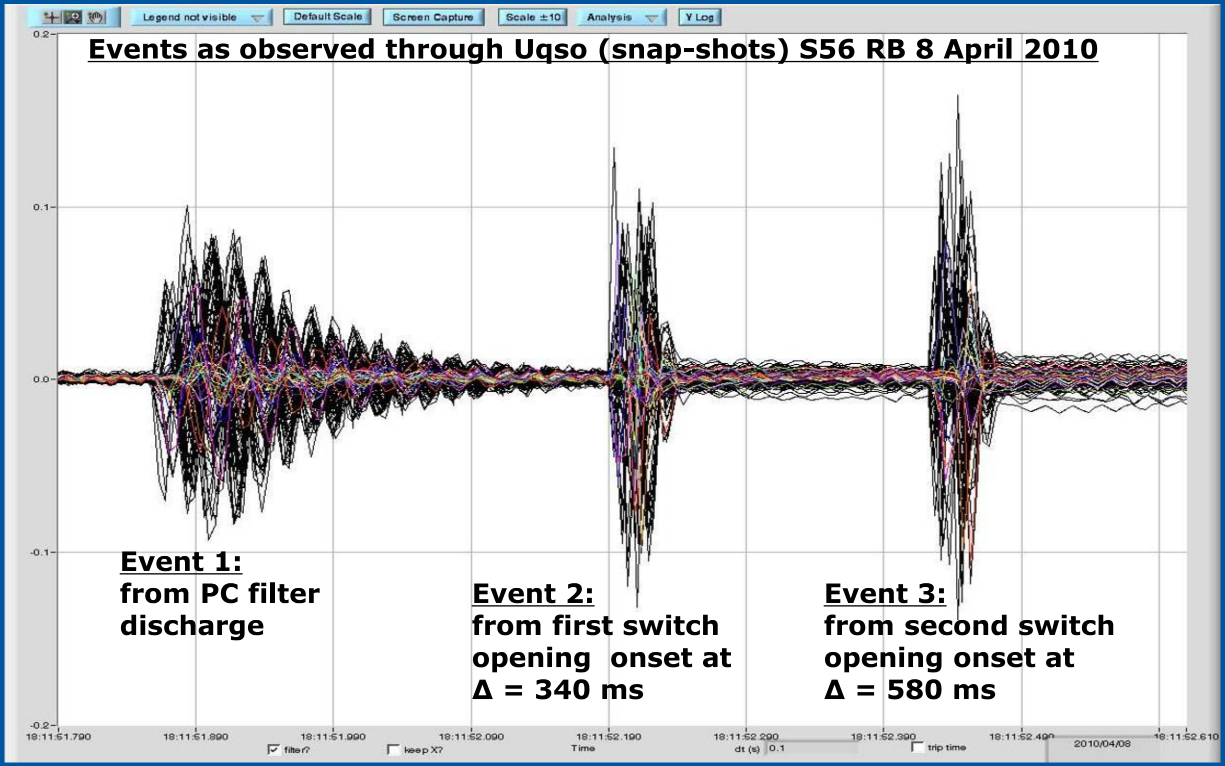
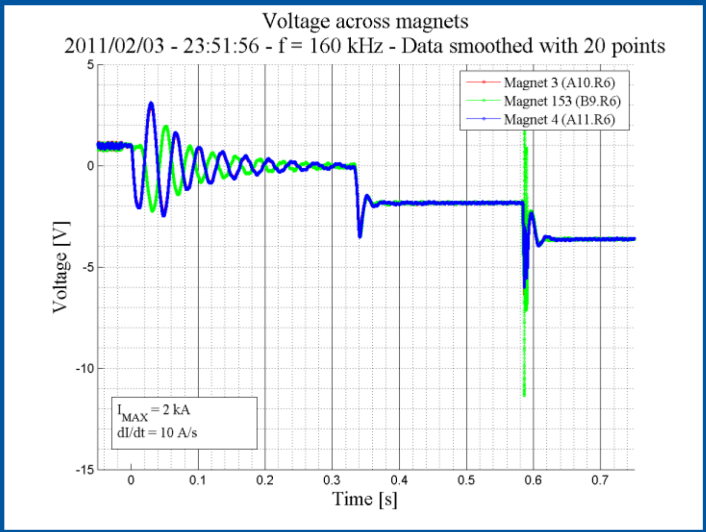
# Example of transient perturbations in circuit powering devices - intrinsic signals seen by the QPS system

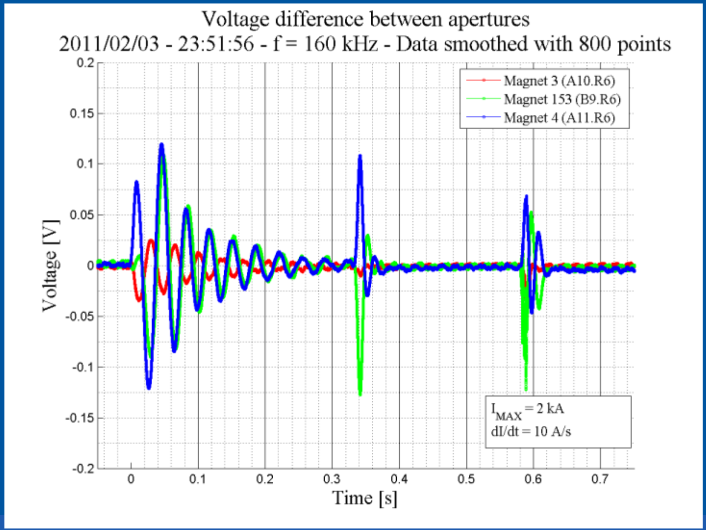



- Delays have been set in the switch opening electronics to separate the 3 events
- Slowing fast transients reduces impact of perturbations: snubber capacitors, more dumping in the converter filter and new crowbar output configuration

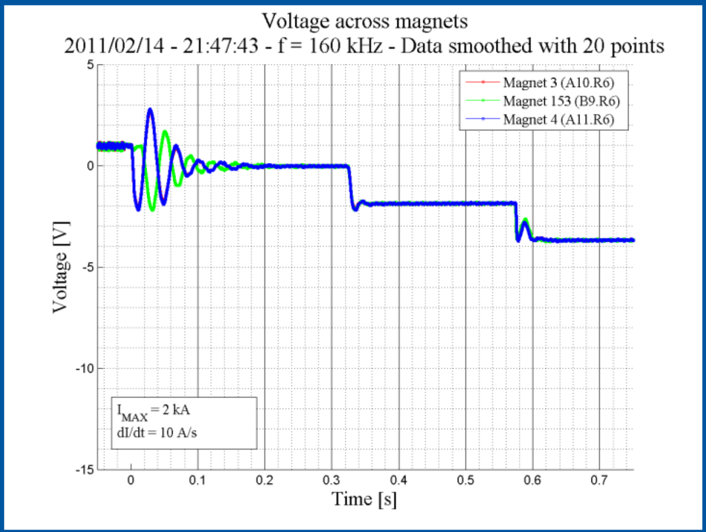
# FPA voltage measurements in Sector 67 – Dipole circuit

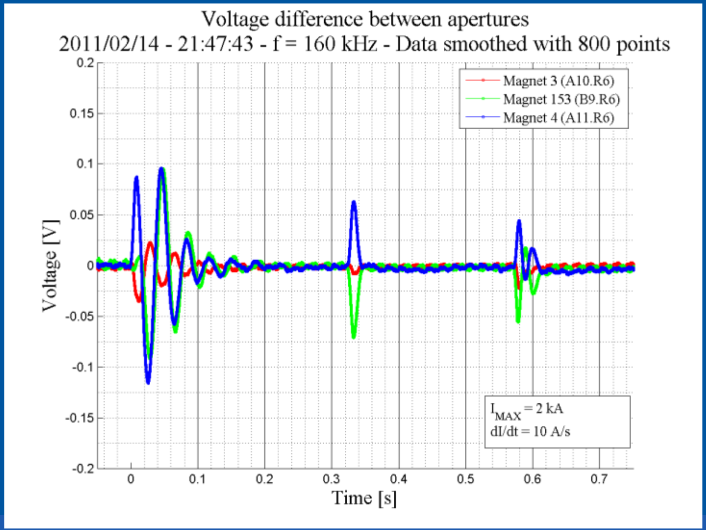
## Before snubbers & additional filter resistors




## After snubbers & additional filter resistors




The snubber capacitors effectively reduce the voltage oscillations across the dipoles caused by the switch opening. (time 0-350 ms)

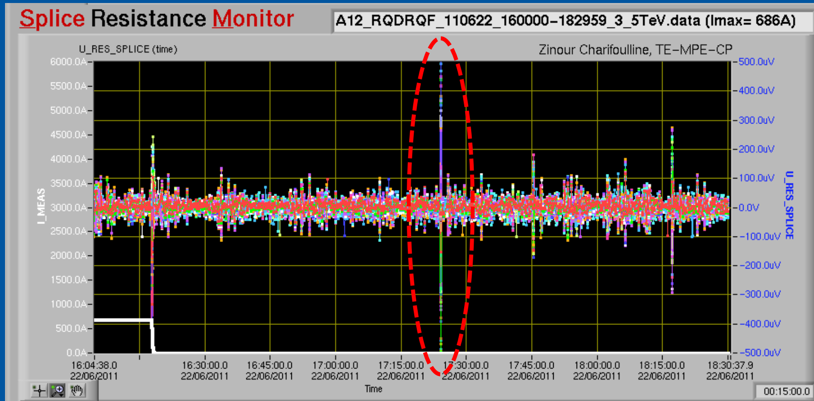
The additional resistors in the power-converter filter damp faster the oscillations due to the power converter ringing. (time 350-600 ms)

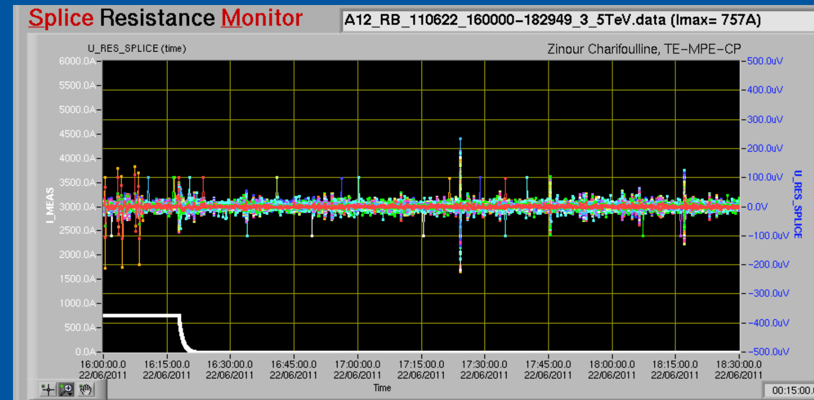
The presence of **unbalanced dipoles**: there are dipoles which are **oversensitive** to any voltage wave propagating through the circuit.

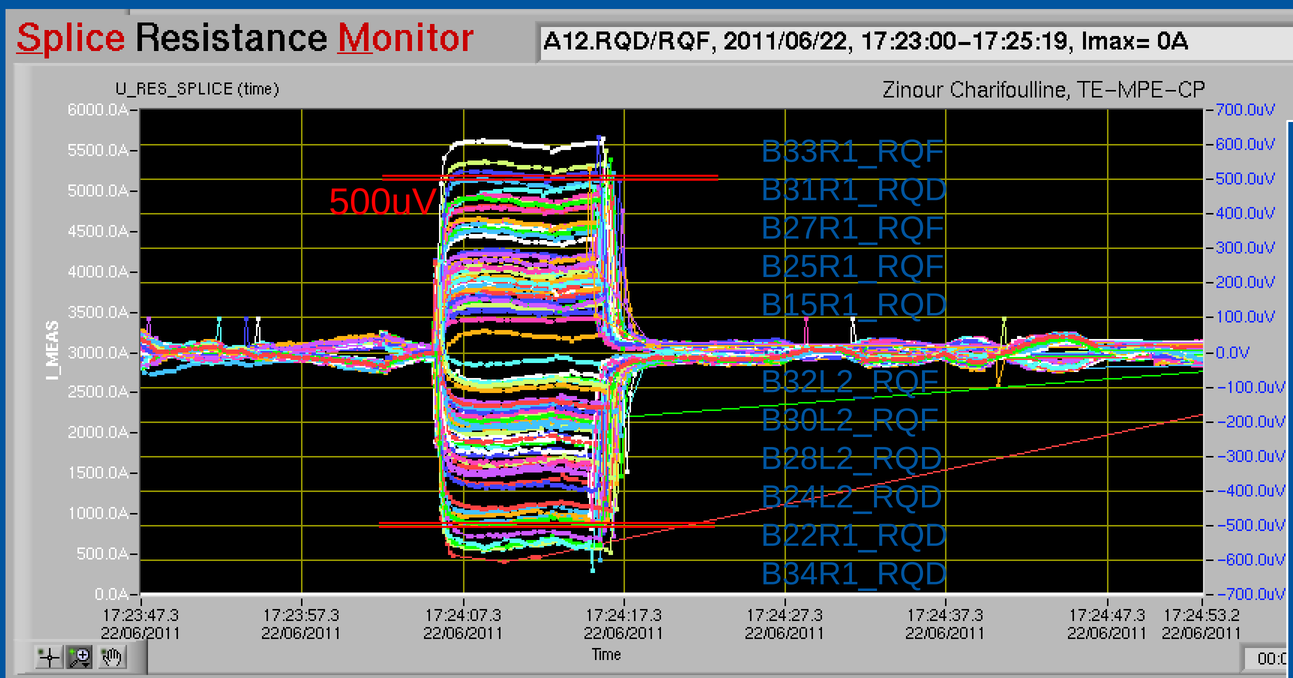
The voltage difference between the apertures of such dipoles is 5-6 times higher than expected.

The phenomenon peaks at 2 kA and it is not limited to the transient after the power converter shut-down.

# Example of a thunderstorm perturbation



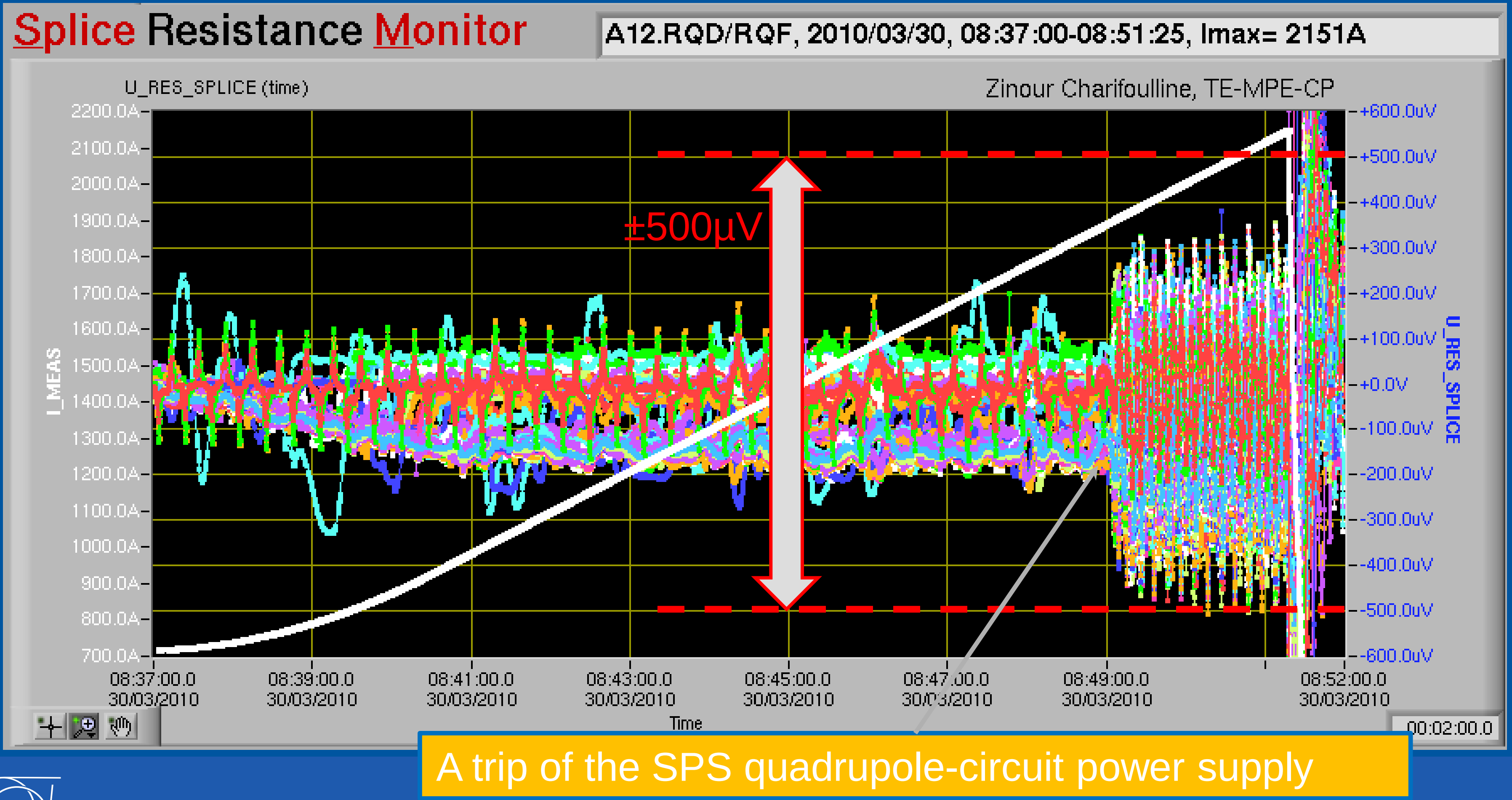

**#22/06/2011 17h24: P1,P2,P4,P5**

- more than 12 channels above 500uV;
- EMC effect is stronger in the middle of the arc;
- EE switches were already open;

Most likely it would trip the circuit.

# The 3.5TeV "Media-Day Trip"

On March 30th 2010 the international media were watching the first 3.5TeV collisions in the LHC. During the first attempt to ramp to collision energy, RQF.A81 tripped 1891 A and RQF.A12 tripped at 2151A about 90sec after sector 81.



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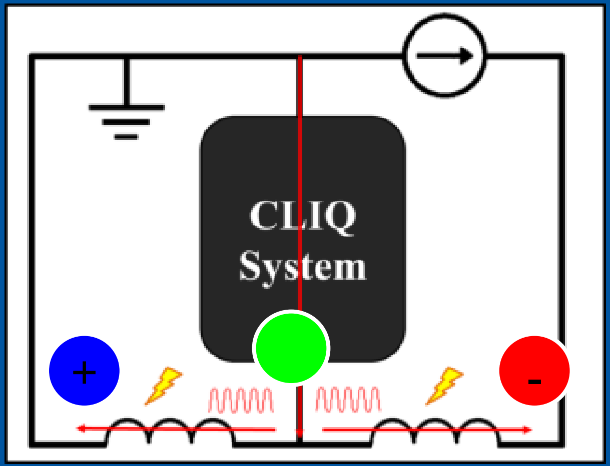
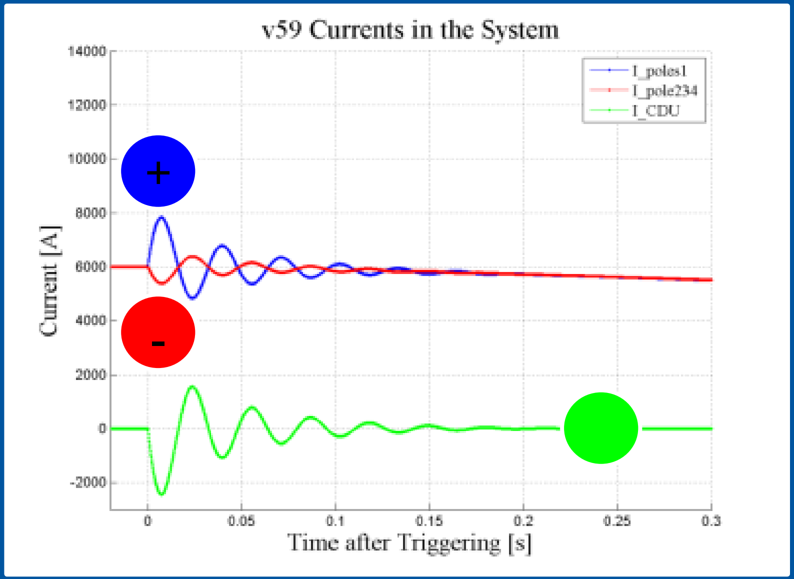
# Fast digital quench detection systems – future developments

- Future developments will profit from the on-going progress in electronics
  - Increasing capabilities of FPGA allow simplified designs using less components
    - FPGA development tool chains are as well improving reducing significantly the time for firmware development and verification
    - Shorter quench evaluation time is feaseable
    - For radiation exposed systems the identification and qualification of suitable ADCs remains a major challenge

# Protection by CLIQ method – Coupling Loss Induced Quench

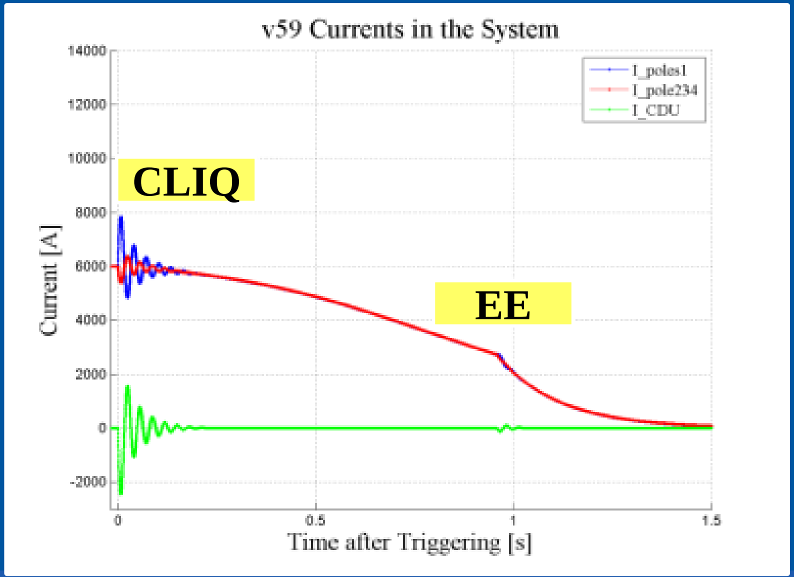



New and very promising quench protection system

Capacitive discharge → Oscillating current in the two sides of a SC magnet → Oscillating magnetic field → Coupling losses → Temperature increase above $T_{CS}$

- Heat deposited directly inside the SC wires (not relying on heat propagation through insulation)
- Stand-alone or hybrid system
- Only requires small conductor attached to the mid-point of a magnet (→ cheap and robust)




Many test performed on model LTS magnets with very good results

# Conclusion

- Detection and protection against quenches in HTS magnets and large scale devices has proven to be a difficult engineering task
  - This is largely due to a very slow normal zone propagation in HTS conductors that leads to formation of localized hotspots while the rest of the conductor remains in the superconducting state

- Modern voltage detection schemes seems to be capable to detect “on time” a normal zone developed within the HTS conductor for large-scale HTS devices, like accelerator magnets, electric power devices and research purpose magnets
  - Challenging limitations in real environment mainly due to EMC

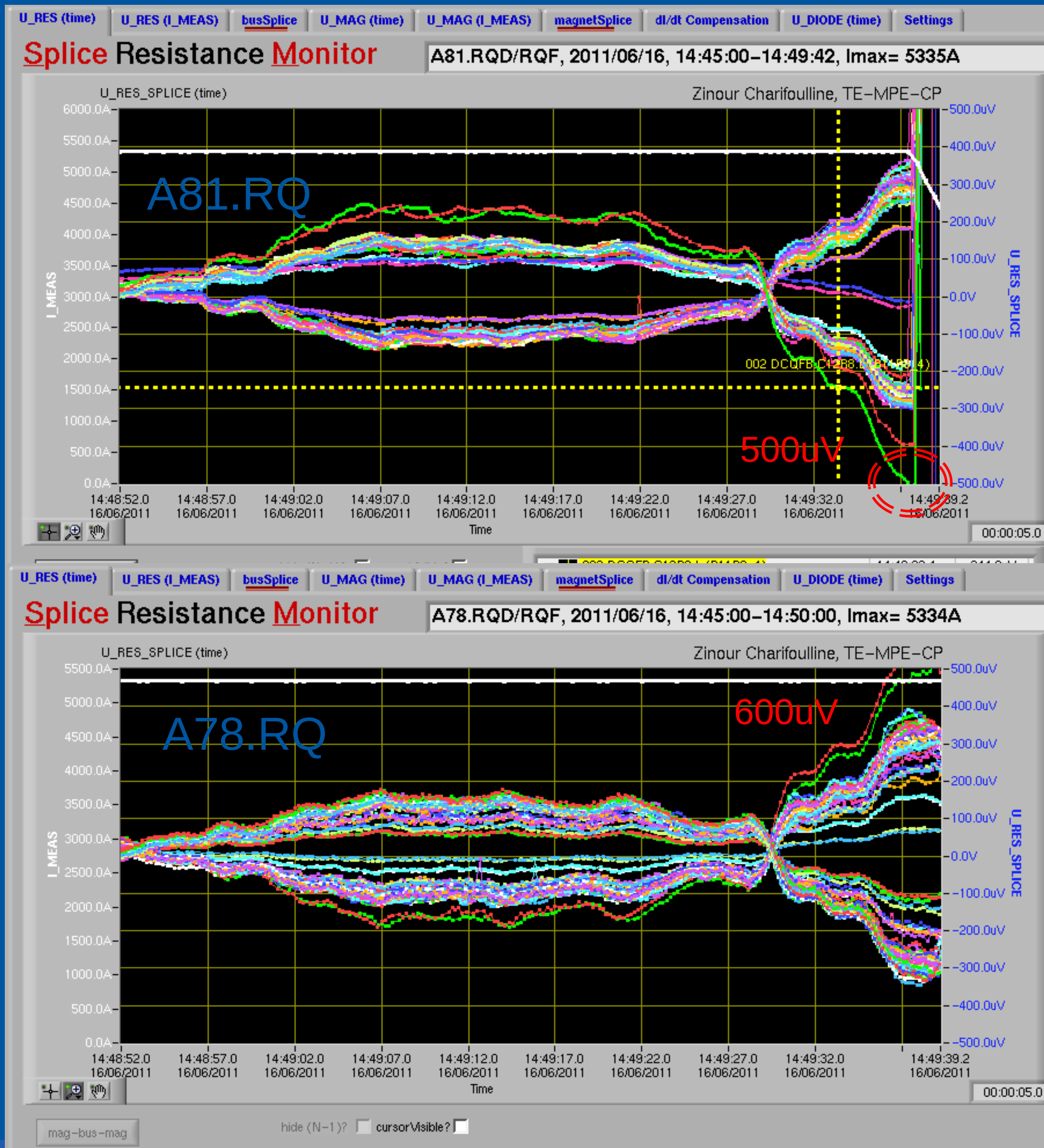
- Alternative methods of quench and hotspot detection for the HTS wires and coils that are based on local magnetic field  sensing and/or local temperature excursions should further be developed as their sensitivity can be superior to the known voltage detection schemes. A unique feature of these methods is their capability to remotely detect instant of quench precursor, even well before a normal zone is developed within the conductor
  - Importance of redundant quench detection in complex HTS magnet systems

# Acknowledgment


- Many thanks to R. Denz, J. Steckert, Z. Charifouline and E. Ravaioli for fruitful discussions and providing materials for this presentation

- The 2014 Kyoto Workshop on HTS Magnet Technology for High Energy Physics – WAMHTS-2

# Unexplained nQPS.BS trip at P8, 16/06/2011




LHCOP 16/06/2011 14:49:
Global Post Mortem Event Confirmation

Dump Classification: Other
Operator / Comment: stefano / Trip of the main quads in S81 - MP3 investigating the source of the trip.

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No information found from SPS&Injection team – ALL OK.

UFO or Tramp AUG?

A81: 98 -> 99