Magnet protection in the LHC

Arjan Verweij, on behalf of the MPE group

One of the mandates of the MPE group: Support LHC operation and maintain state-of-the art technology for magnet circuit protection and interlock systems for the present and future accelerators, magnet test facilities and CERN hosted experiments.

The MPE group consists of 48 staff, 23 fellows and students, and many collaborators.

A large number of these people are involved in the study, detection, and protection of quenches in the LHC.

We are heavily involved in Machine Protection (MPP) and LHC magnet commissioning, operation and performance (HWC, MP3 and COMS).

Our main quench-related activities

1. **Simulation/calculation of quench behavior (propagation, hot spot, current discharge, …) of conductors, magnets, and circuits. (PE section)**
2. Development of quench detection systems, data acquisition, and cold mass diagnostics. (EP section)
3. Development of energy extraction systems, protection diodes, and quench heater discharge units. (EE section)
4. Monitoring and follow-up of the performance of magnet protection systems. (SW and PE sections)
5. Analysis of all quench/trip in the LHC. (PE, EP, EE, SW sections)
6. Study and experiments of beam induced quenches. (mainly PE section, and BE dep.)
7. Study of novel protection systems. (PE section)

Computer codes we are using

Software	Used for	Description
QP3	Conductor	In-house Fortran code, especially developed for electro-thermal calculations of 1D conductors with helium cooling.
Roxie	Coil/magnet	In-house Fortran code, especially developed for field optimization of accelerator magnets.
PSpice	Circuit	Commercial software for the electrical modeling of entire circuits.
COMSOL	Specific parts	Commercial multiphysics modeling and engineering simulation software.

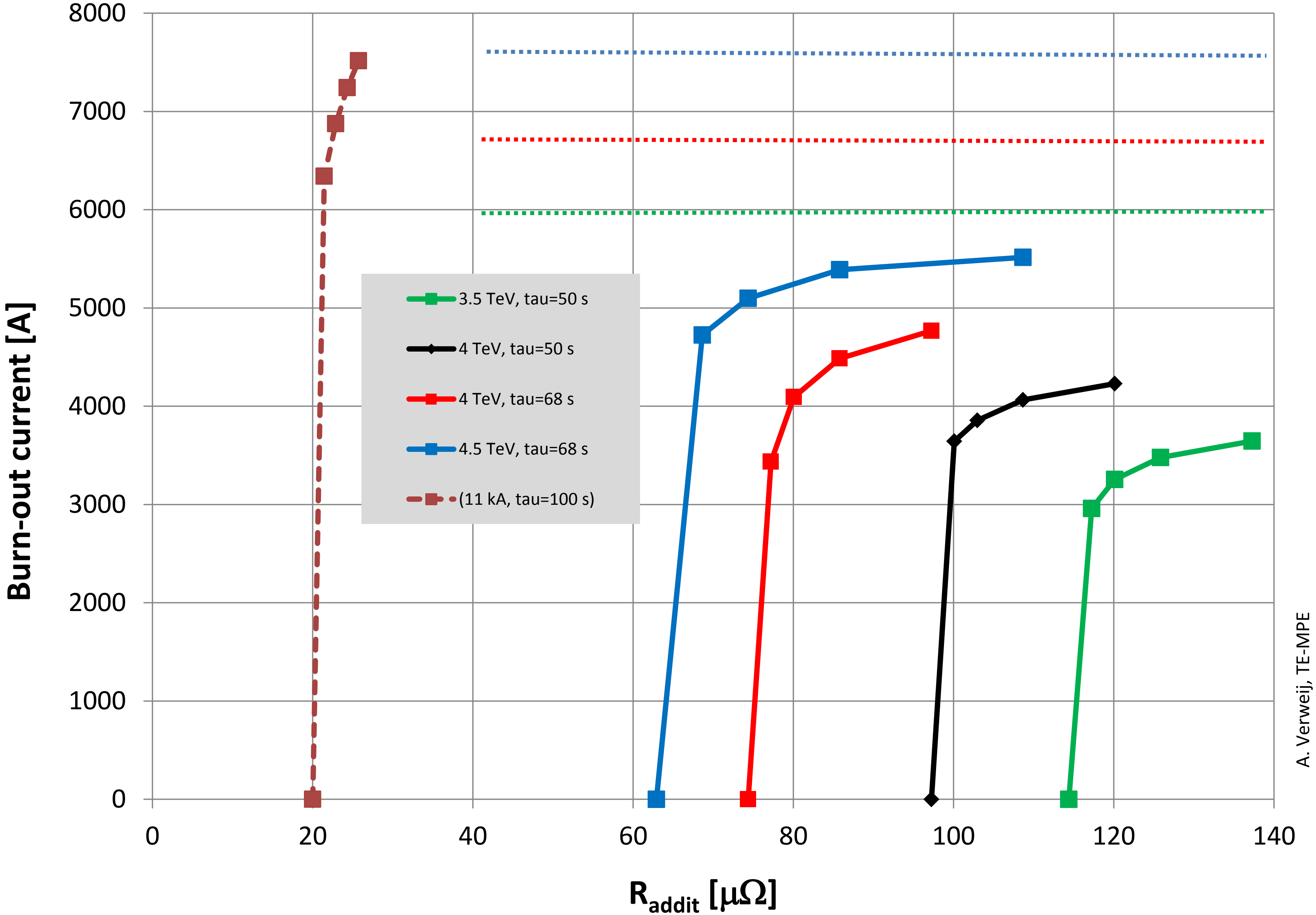
For running these models we keep a database of properties for used materials (copper, various SC, st. st., aluminum, kapton, helium, epoxies, …

Outputs of one code are often used as input for other codes.

A short list of simulations done with QP3

Type of simulation	Circuit / magnet
Hot spot calculations	600 A bus, 600 A magnet, 6 kA bus
Beam Loss Monitor (BLM) threshold study	MQM, MBRB, MB, MQ, MQTLH
QPS threshold study	6 kA MQM & bus
Quench propagation study	MB & MQ magnet, RB and RQ bus, 13 kA pigtail
Bus protection for defective joints	RB & RQ bus
Simulation of the 2008 accident	RB bus
Temperature increase in the interlayer splice	MB
Safe current in case of a defective interpole joint	MB
Safe current for a defective bus joint in LHe and GHe. Joint with and without shunt.	RB and RQ, incl. magnet, bus and diode **See example next slide**
Simulation of experimental tests on joints	Several tests in FRESCA, Q8-Q9 test in SM18
CSCM for 4-5 TeV and & TeV validation, for various types of current cycles	RB and RQ

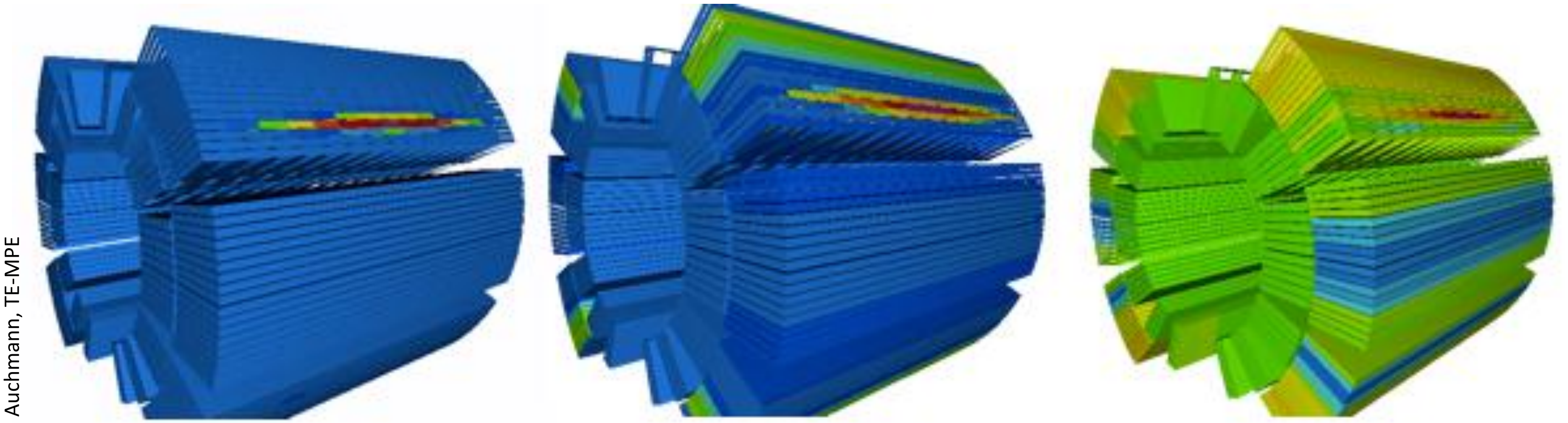
Safe LHC operation current in case of quenching defective 13 kA joint



Roxie

2D and 3D quench simulation of entire coils, including longitudinal and turn-to-turn propagation, heater firing, cooling, and quench back.

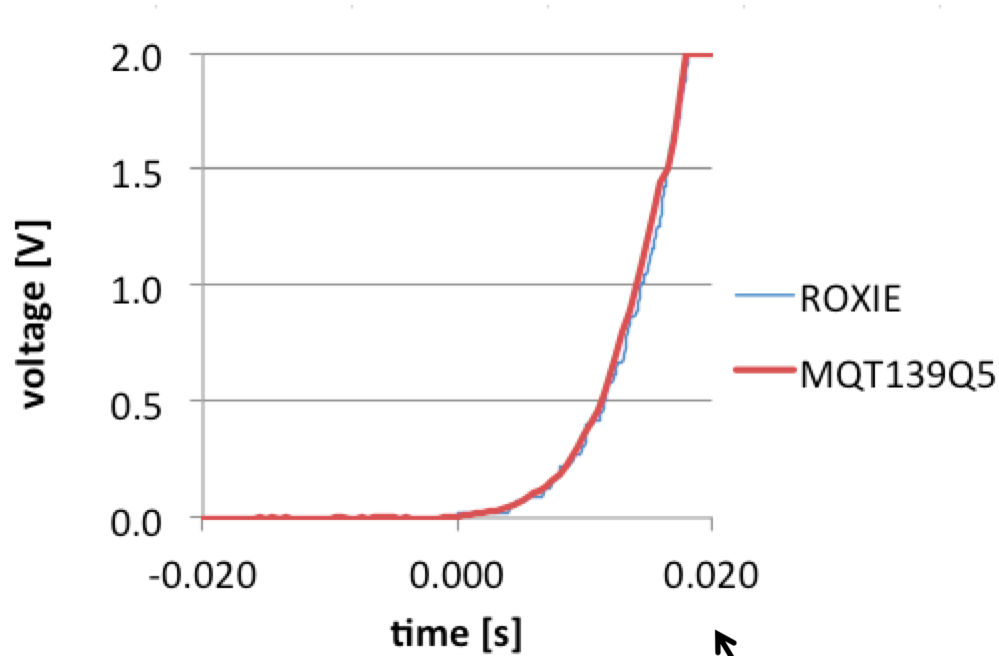
Roxie quench models available and validated for several types of magnets. Similar models of the remaining LHC types of magnet will be made and validated this year.



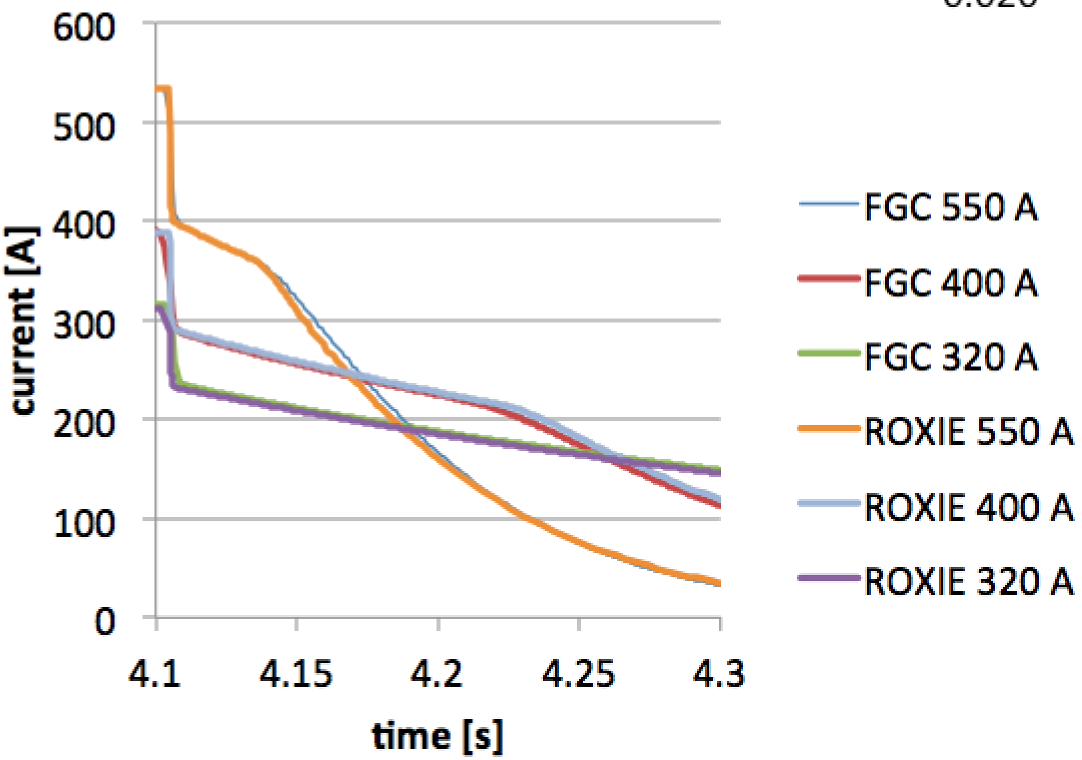
B. Auchmann, TE-MPE

Roxie: excellent agreement between calculated and experimental quench curve, including quench back

Example:
600 A MQT corrector magnet



V(t) for a quench in a single magnet



Current decay during a quench in a series of magnets including quench back.

B. Auchmann, D. Rasmussen, TE-MPE

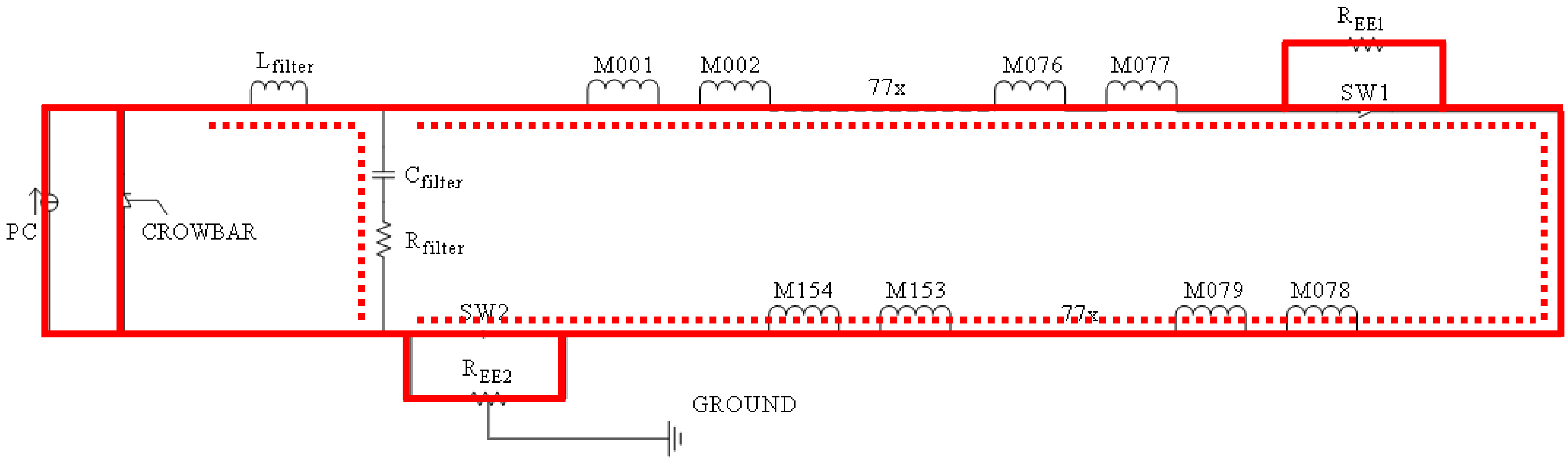
PSpice

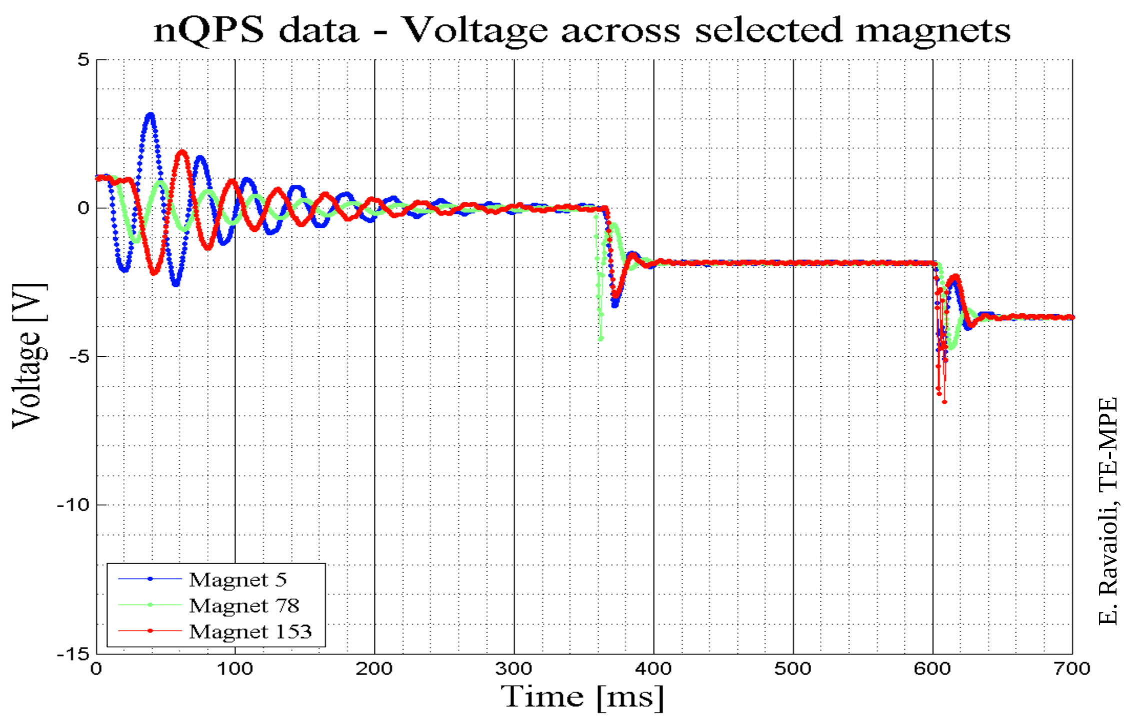
Electrical modeling of entire circuits (up to 1000's of elements), including power converter, current leads, capacities to ground, magnets, switches, energy extraction, crowbar, busbars, warm leads, ...

Effective thermal modeling is included (e.g. resistive built-up of a quenching magnet) with some additional input from Roxie. If needed, a magnet can be discretized in many parts.

Examples:

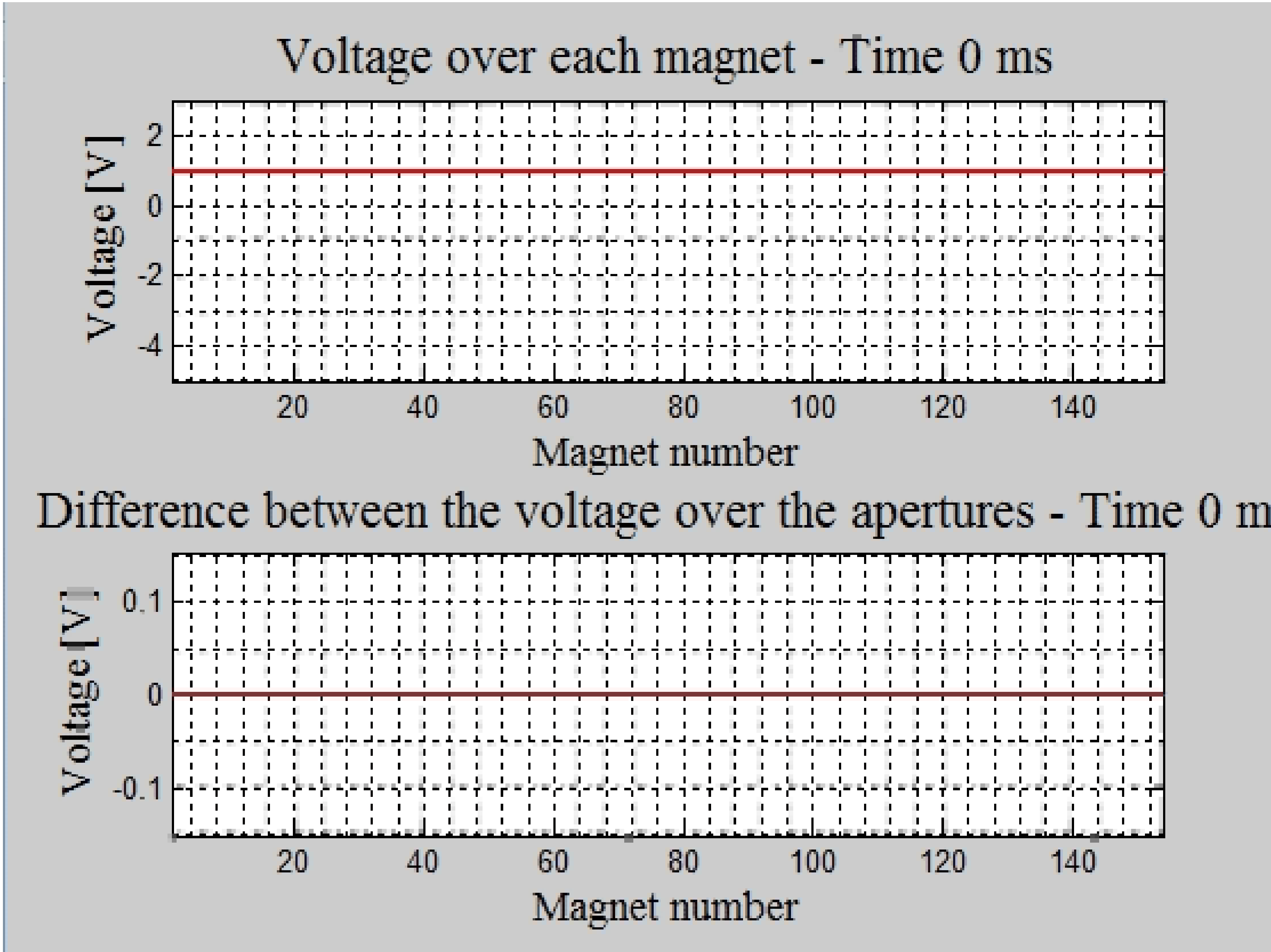
- False triggering of the QPS due to voltage waves.
- Optimisation of energy extraction systems (to limit quench back and/or hot spot and/or false triggering)
- Failure cases (short to ground, damaged parallel resistance, non-opening of a thyristor, inter-turn short, …)





Example:

Voltage waves in the main dipole circuit after a fast power abort.



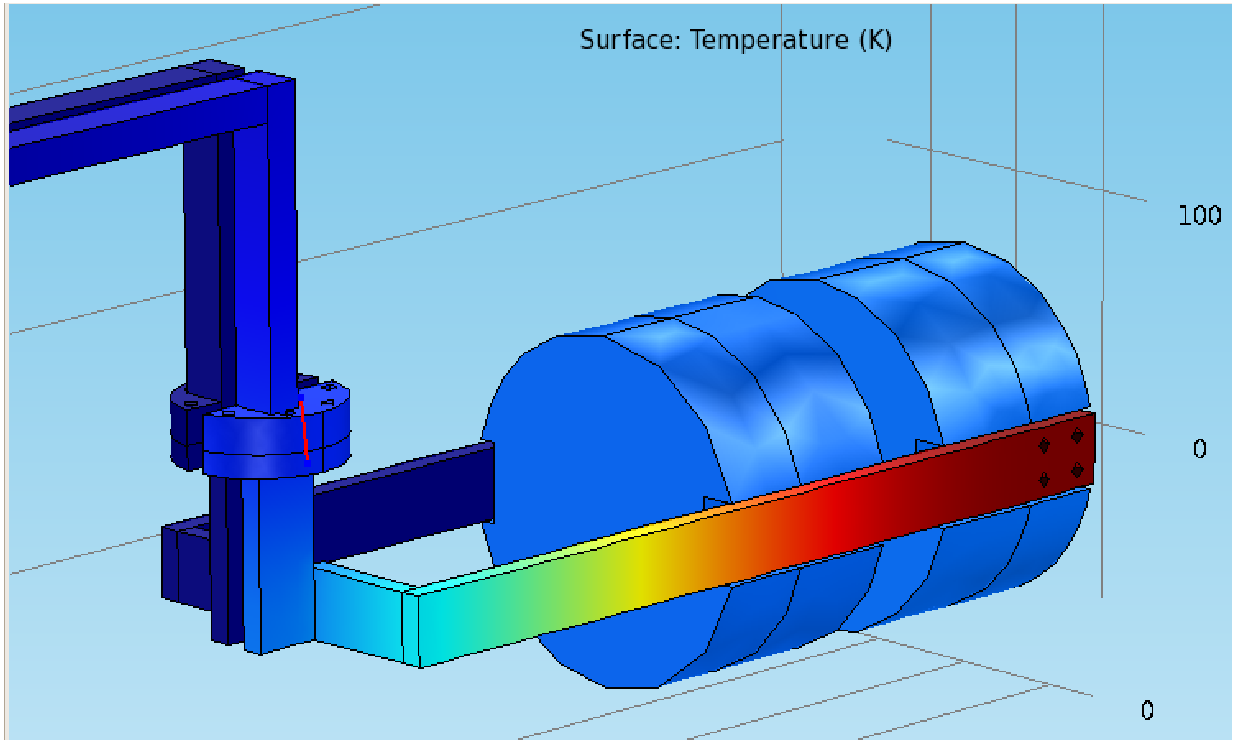
E. Ravaioli, TE-MPE

Multiphysics modeling and engineering simulation software

Thermo-electrical modeling of specific parts of circuits, that require a 3-D approach, such as the shunt on the 13 kA joints, the bolted ‘half-moon’ connection to the diode, ‘praying hands’ 6 kA joints, current leads, etc.

<u>Example:</u>

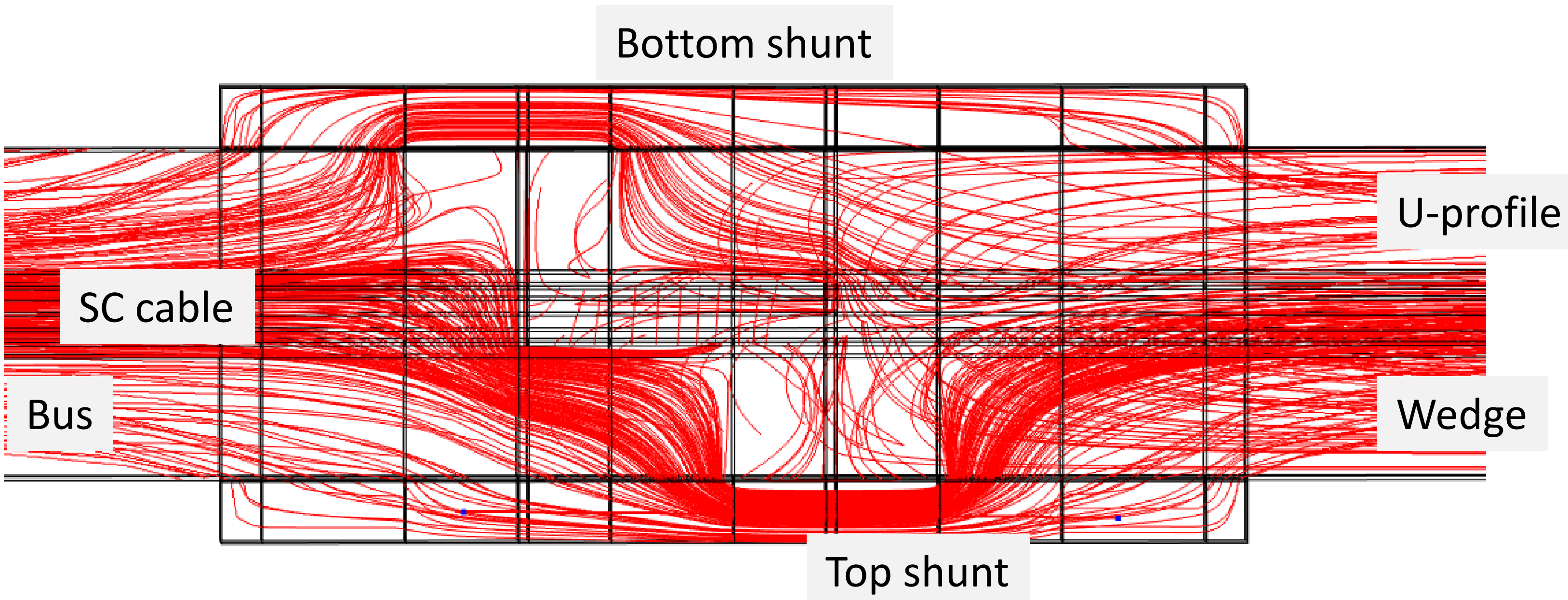
Thermo-electrical modeling of a high resistance between the bus and the heat sink of a cold bypass diode.



D. Molnar, H. Riihimaki, Z. Charifoulline, TE-MPE

Example:

Thermo-electrical modeling of the current redistribution through the shunts on the 13 kA busbar joints.



D. Molnar, Z. Charifoulline, TE-MPE

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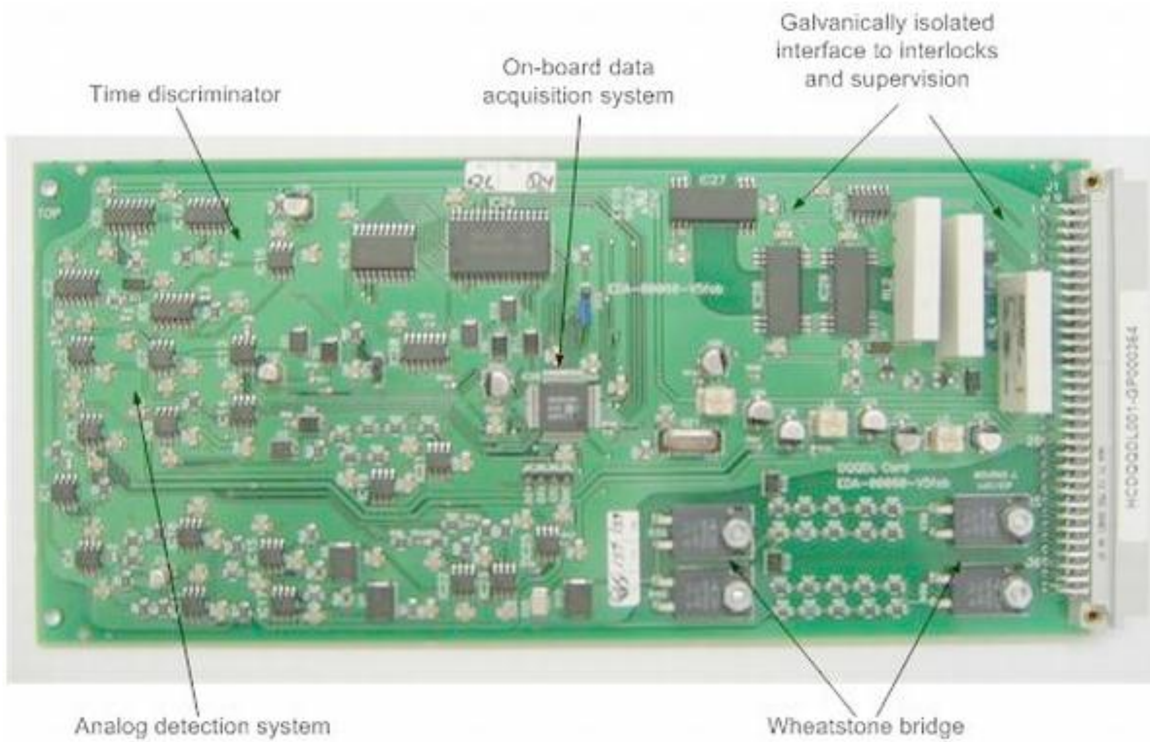
SC circuits in the LHC

	# circuits	# magnets	Stored energy per circuit	Quench detection	Energy extraction
13 kA dipoles	8	1232	1.3 GJ	Yes	Yes
13 kA quads	16	788	24 MJ	Yes	Yes
RQX	8	32	5.4 MJ	Yes	No
IPD's	16	18	0.5-1.1 MJ	Yes	No
IPQ's	76	220	0.2-1.1 MJ	Yes	No
600 A with EE	202	5125	2-150 kJ	Yes	Yes
600 A without EE	192	208	2-52 kJ	Yes	No
80-120 A	300	1516	0.2-16 kJ	No	No
60 A	752	752	11 kJ	No	No
Total	**1569**	**9891**			

Maximum total stored energy in all LHC SC magnet circuits: about 10 GJ

Quench detection systems: presently in the LHC

Type	System	Design	Qty
DQQDL	MB, MQ	Analog bridge; µcontroller for DAQ only	4032
DQQDS	nQPS symmetric quench detection	Digital FPGA based fast detector	1632
DQQDC	HTS current leads	Digital high precision detector	1198
DQQBS	nQPS splice protection	Digital high precision detector	2068
DQQDG	600 A global circuit protection	Digital DSP based fast detector	836
DQQDI	IPQ, IPD global circuit protection	Digital DSP based fast detector	360
DQQDT	IT global circuit protection	Digital DSP based fast detector	48



R. Denz, TE-MPE

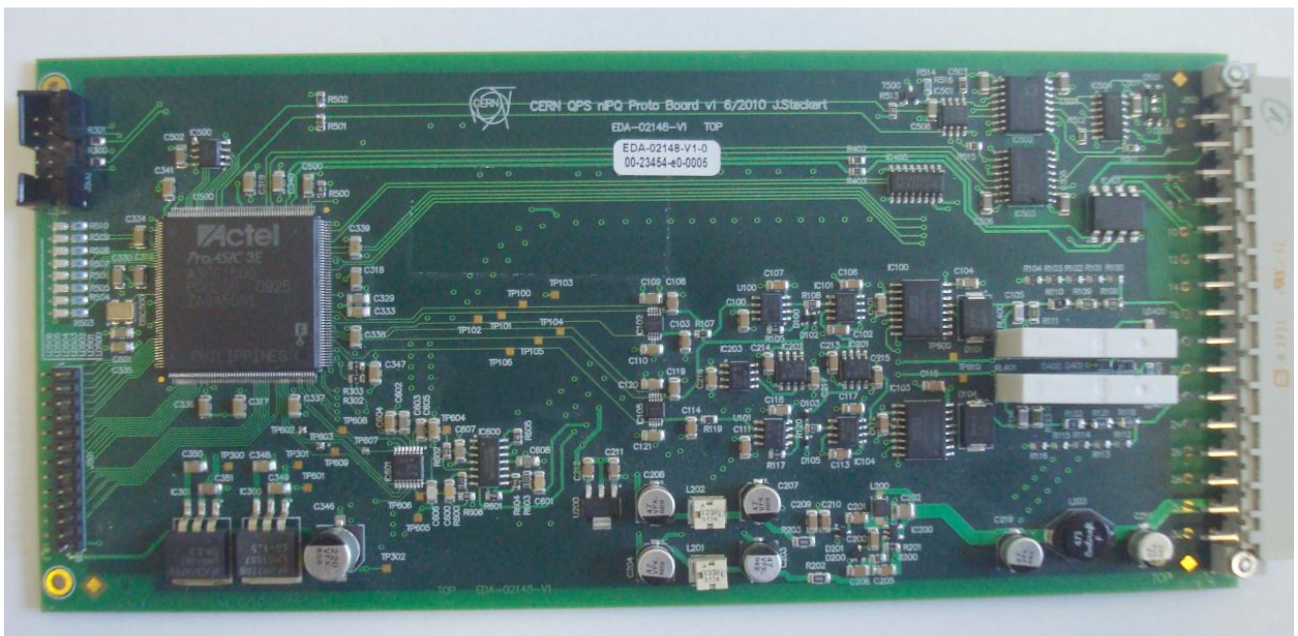
High precision digital detectors

- 24 bit.
- Resolution: ΔU = 1 μV.
- Current
- Thresho
- Two in c board).
- Radiatio some ar
- Real trig

Quench detection systems: next generation

Most of the QPS boards will be replaced/upgraded in the coming years in order to become radiation tolerant, and/or improve firmware, and/or replace obsolete electronics, and/or enhance performace.

Special QPS boards with dedicated firmware will also be installed in SM18 in march 2013 for the Nb3Sn magnet bench.



R. Denz, J. Steckert, TE-MPE

Data acquisition and supervision

The data acquisition systems transmit:

- diagnostic information for the protection systems and the protected equipment (magnets, bus-bars, leads …)
- software interlocks reflecting the functional state of the system

Total: 0.5 TByte/week, going up to 1.5 TByte/week after 2015.

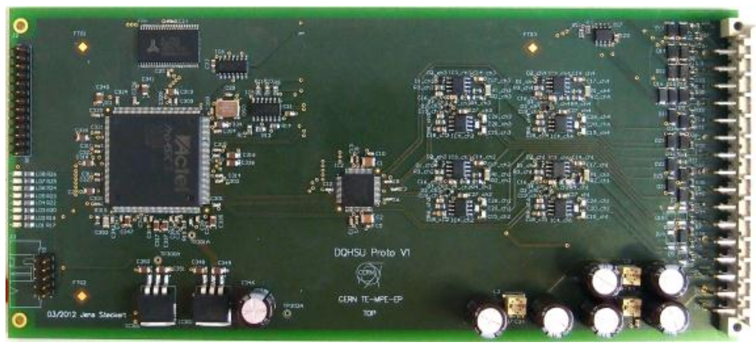
Total: 13722 interlocks

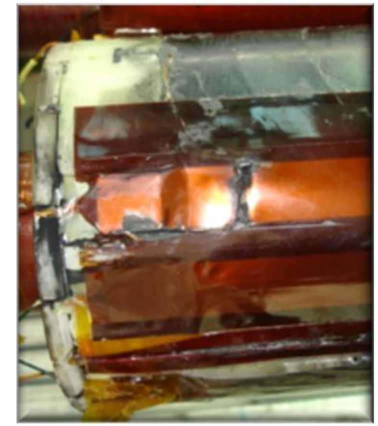
Due to the mere size of the system, reliability, availability and maintainability are a major challenge.

Upgrades during the long shut-down (2013/14)

Implementation of **enhanced quench heater circuit supervision** for LHC main dipoles, supposed to identify potential fault states of the quench heater circuits, which may affect the integrity of the concerned magnet

4928 systems

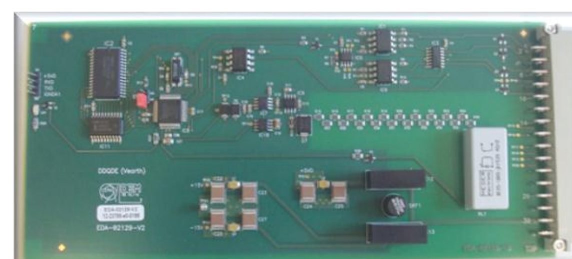




Installation of **earth voltage feelers** for the LHC main circuits.

The system serves for enhanced circuit diagnostics and will monitor the electrical insulation strength of the LHC main circuits especially during fast discharges.

1308 units



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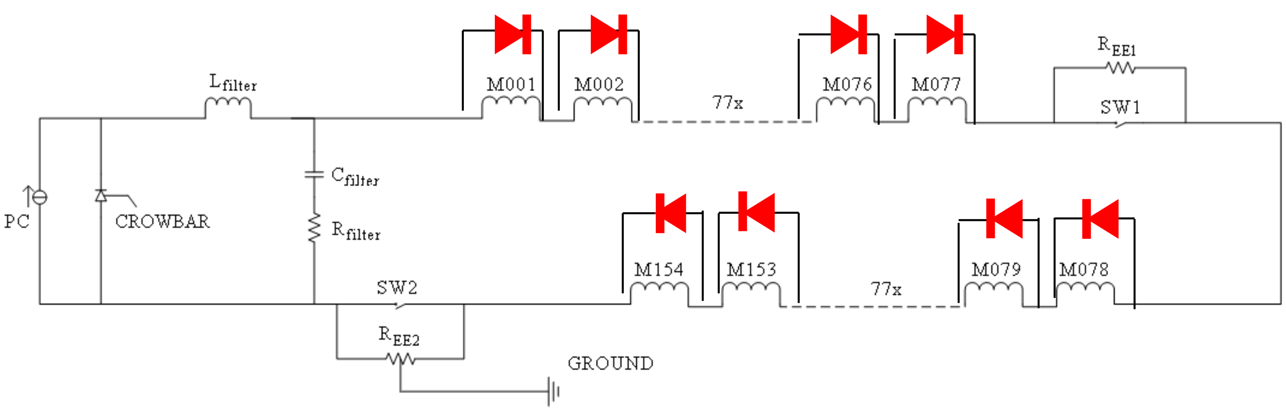
Protection elements

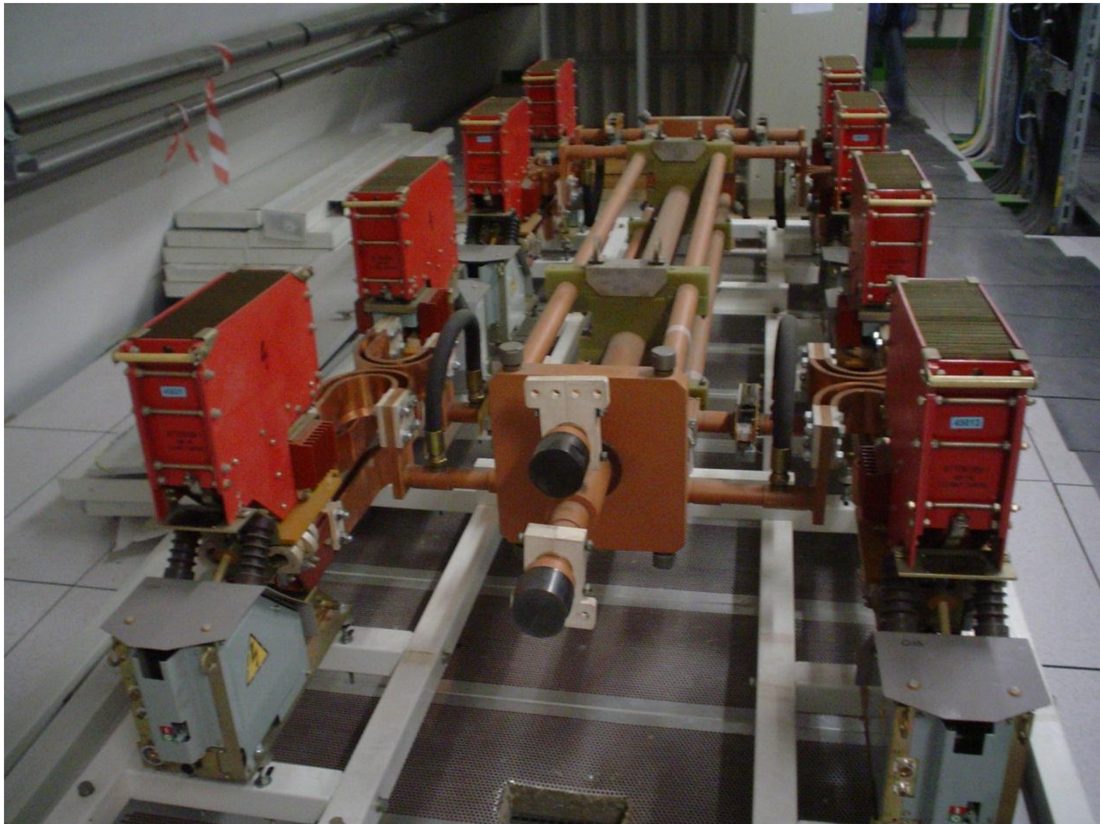
6076 quench heater power supplies.



K. Dahlerup-Petersen, TE-MPE

About 2000 cold 13 kA bypass diodes, to conduct the current in the main 13 kA circuits around a quenched magnet.

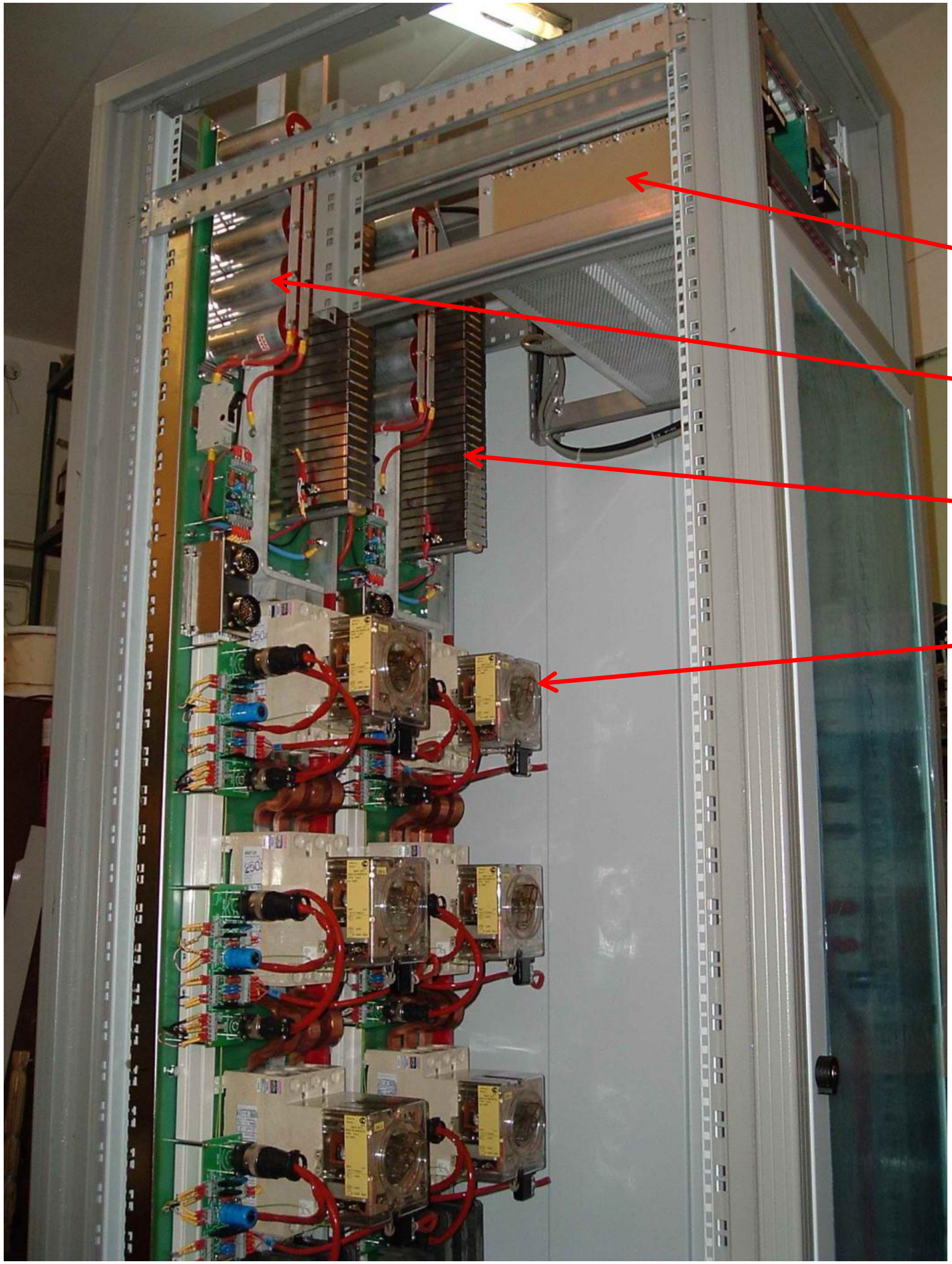
Energy extraction for the 13 kA circuits



K. Dahlerup-Petersen, TE-MPE

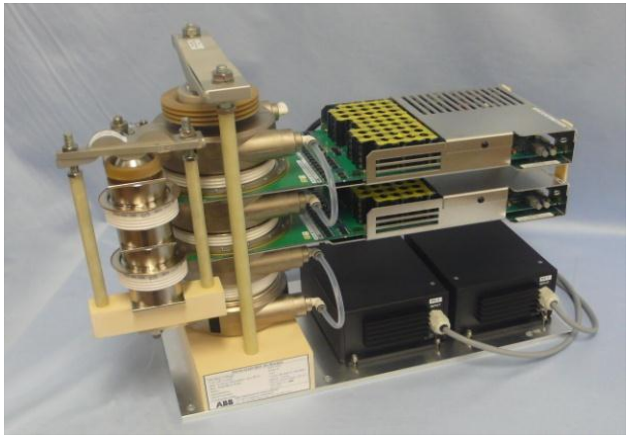
32 systems containing 2x4 switches, and large extraction resistances

202 energy extraction systems for the 600 A circuits



G. Coelingh, TE-MPE

R&D for even better switches



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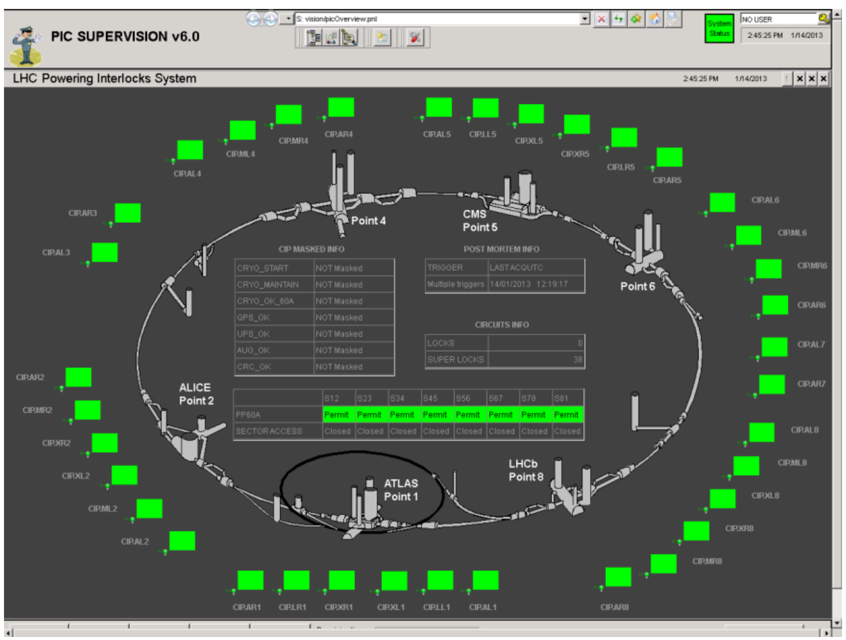
Magnet powering interlock system

Dependable interlocking for magnet powering systems of the LHC.

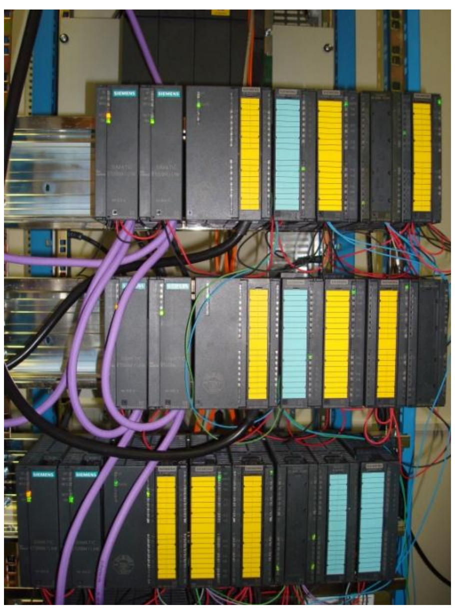
60 installations currently in operation (44 in LHC), further renovation of SPS, Booster, LINAC4, PS during LS1 and LS2.

In conjunction with QPS and power converter system assuring protection of sc and nc magnets.

Preventive shut-down of close-by circuits in case of main magnet quenches (avoiding quench propagation)

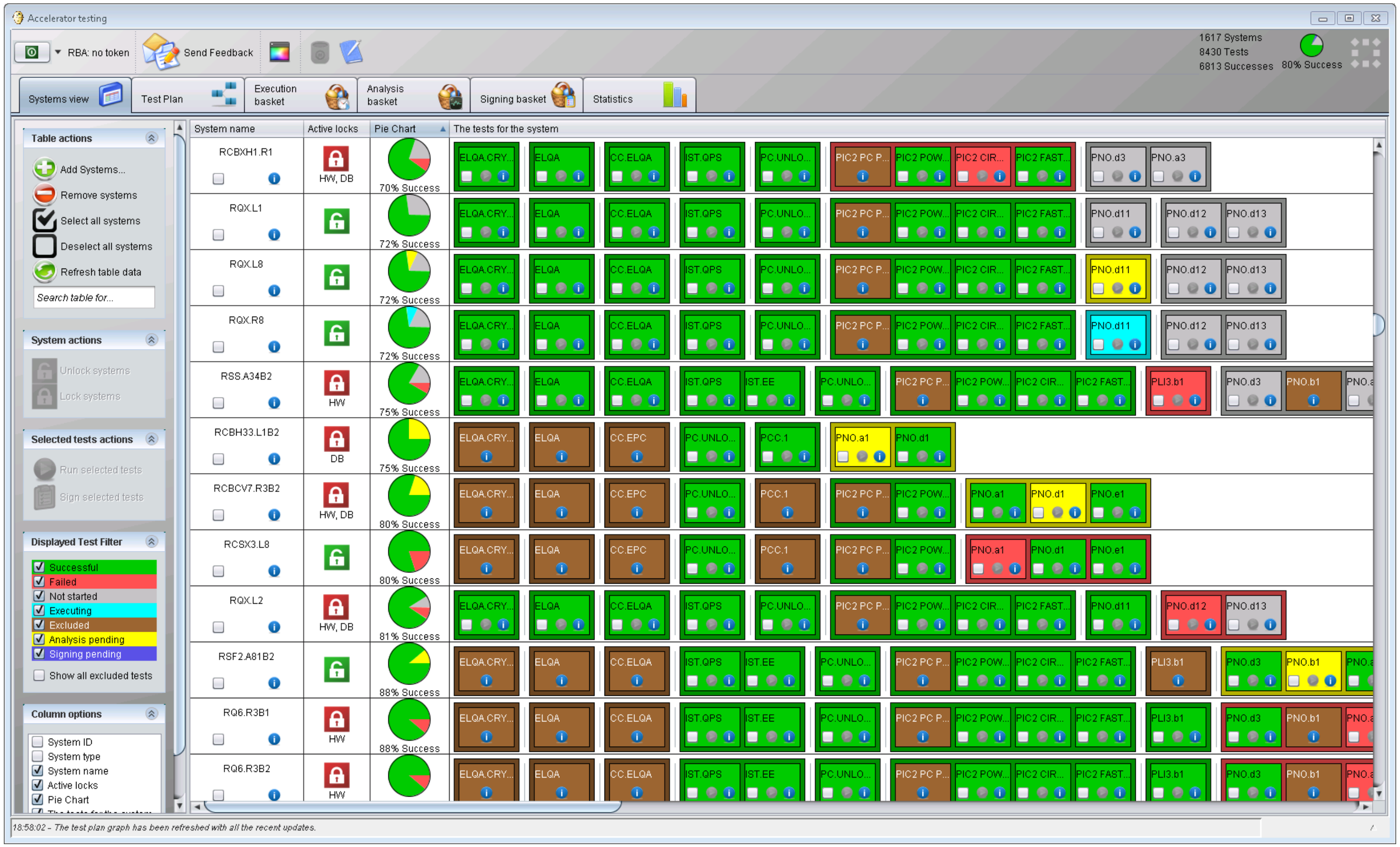


M. Zerlauth, TE-MPE



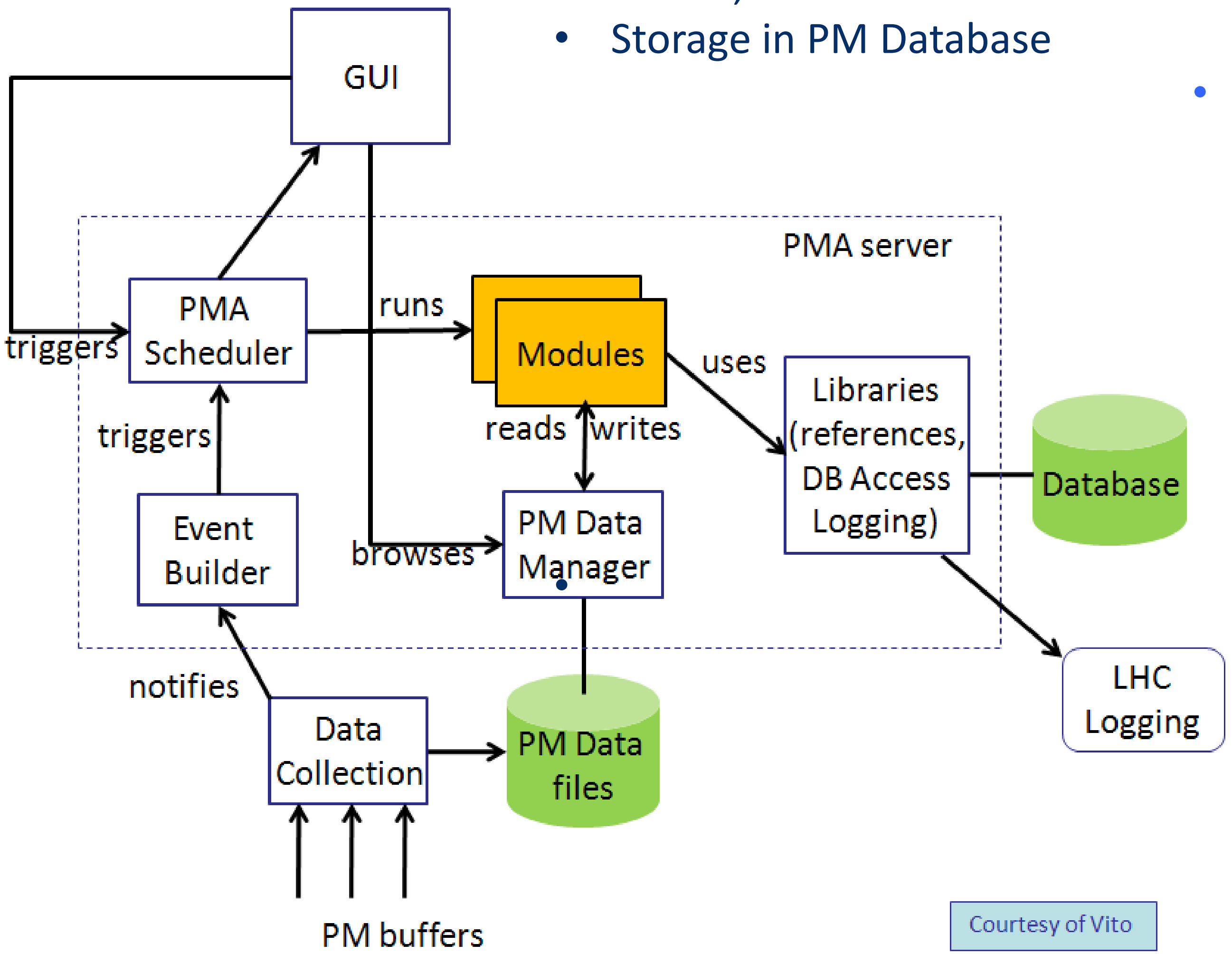
Accelerator test environment

- Software framework for dependable execution, tracking and analysis of commissioning steps (hardware and beam commissioning)
- More and more automated test analysis



Post-mortem system

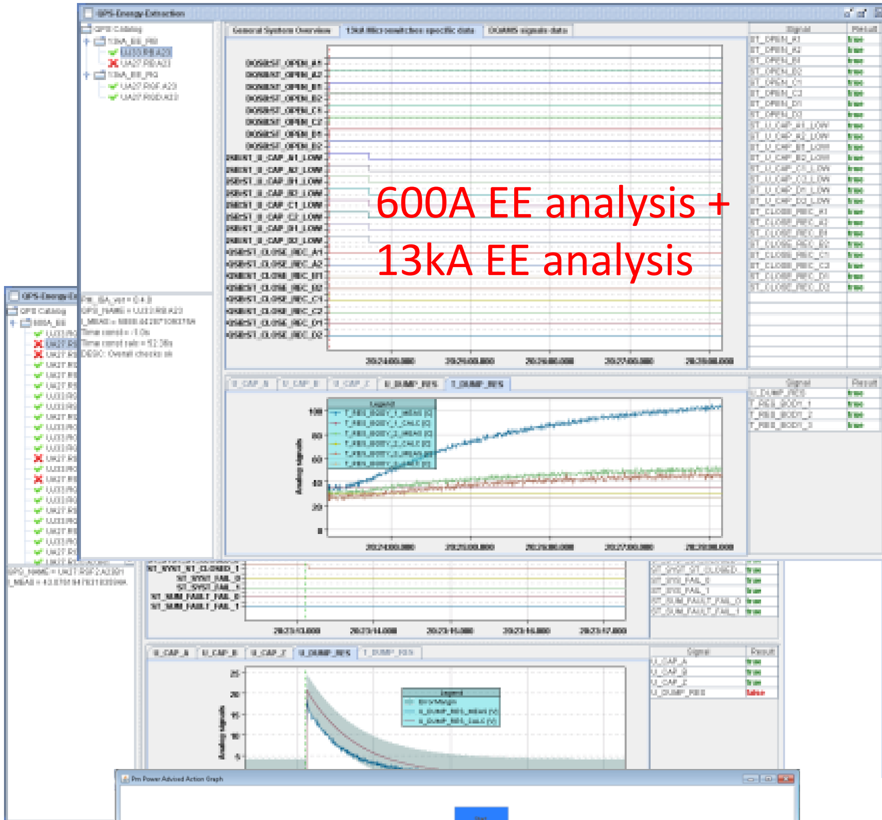
- Highly dependable redundant data collection architecture
- Automatic analysis + classification of ALL powering events, based on set of automatic tools
- Storage in PM Database

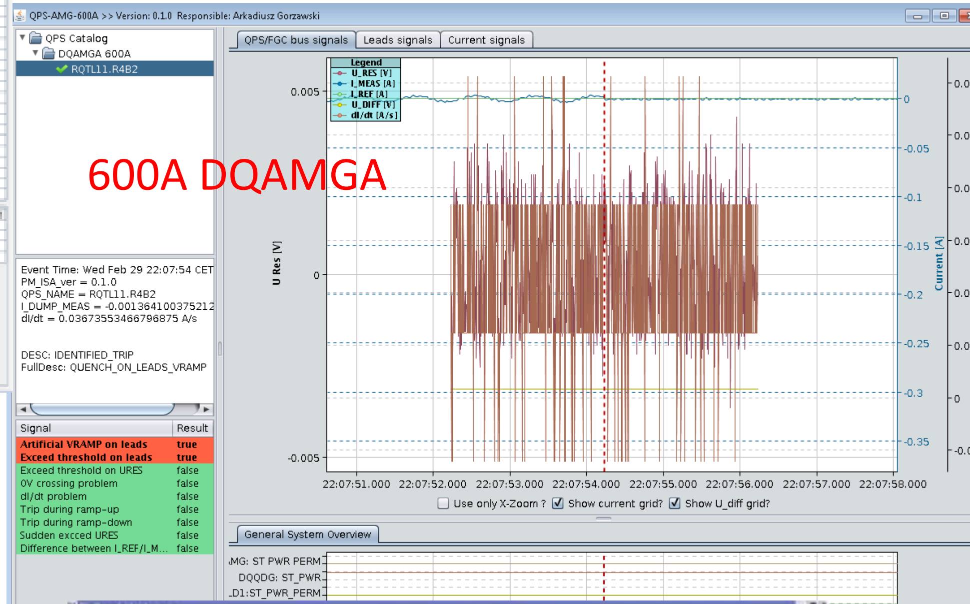


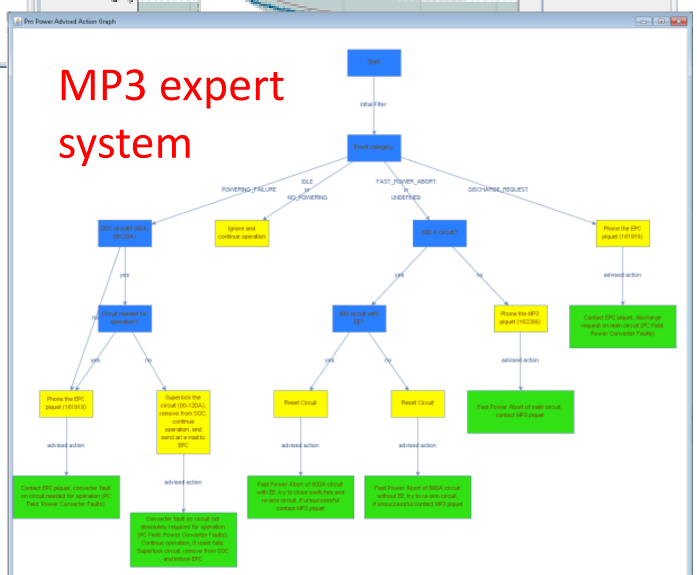
- Automatic identification of powering events of particular interest, triggering advised actions, logbook entries, e-mails, and SMS to inform operators and experts

Courtesy of Vito

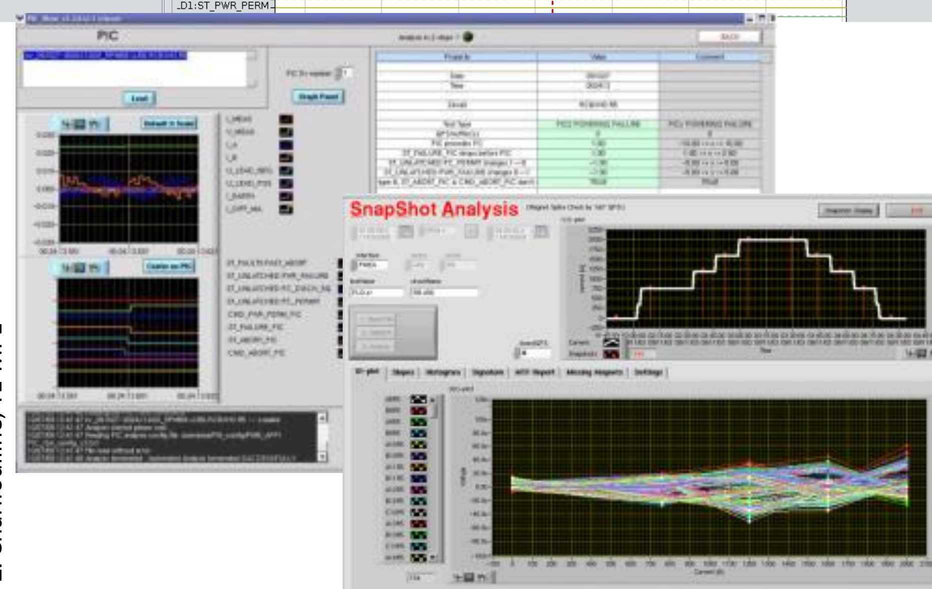
Powering analysis







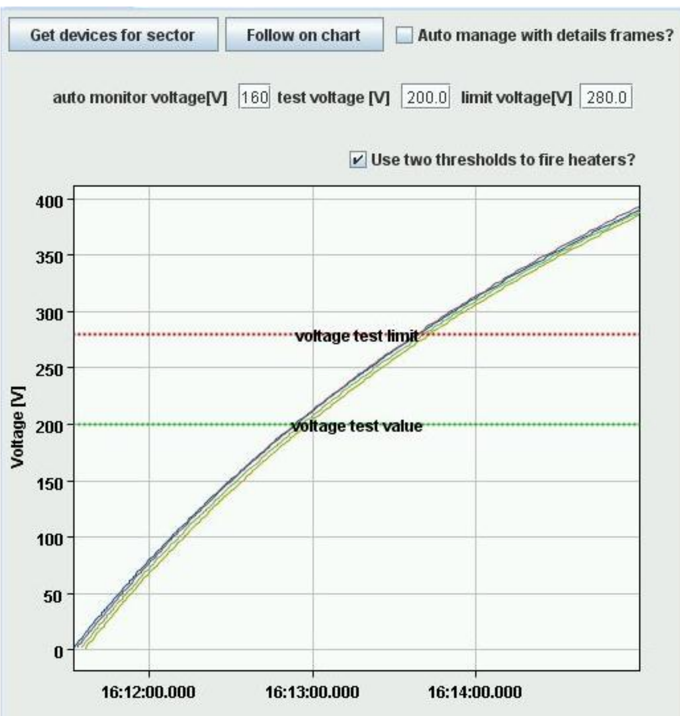
M. Zerlauth, TE-MPE



Z. Charifoulline, TE-MPE

Heater discharge test at low voltage

- Automatic test for over 6000 heater units at safe energy.
- Quench heater energy is reduced to 140 J (in stead of nominal 2.8 kJ), while maintaining a representative discharge curve for analysis.
- Dedicated tool to monitor voltages.



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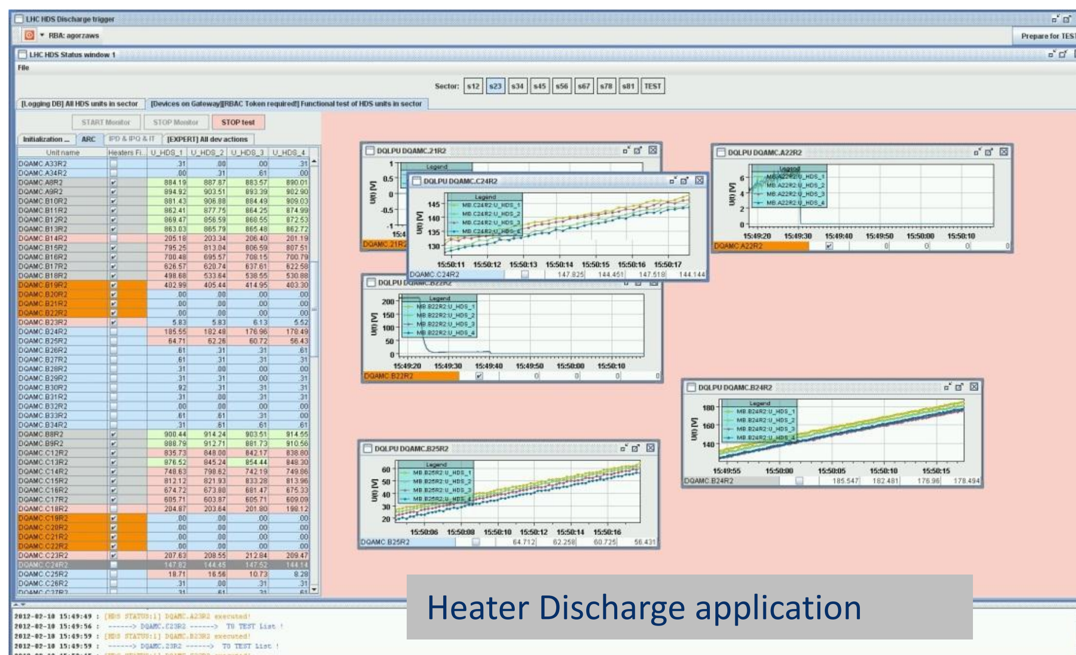

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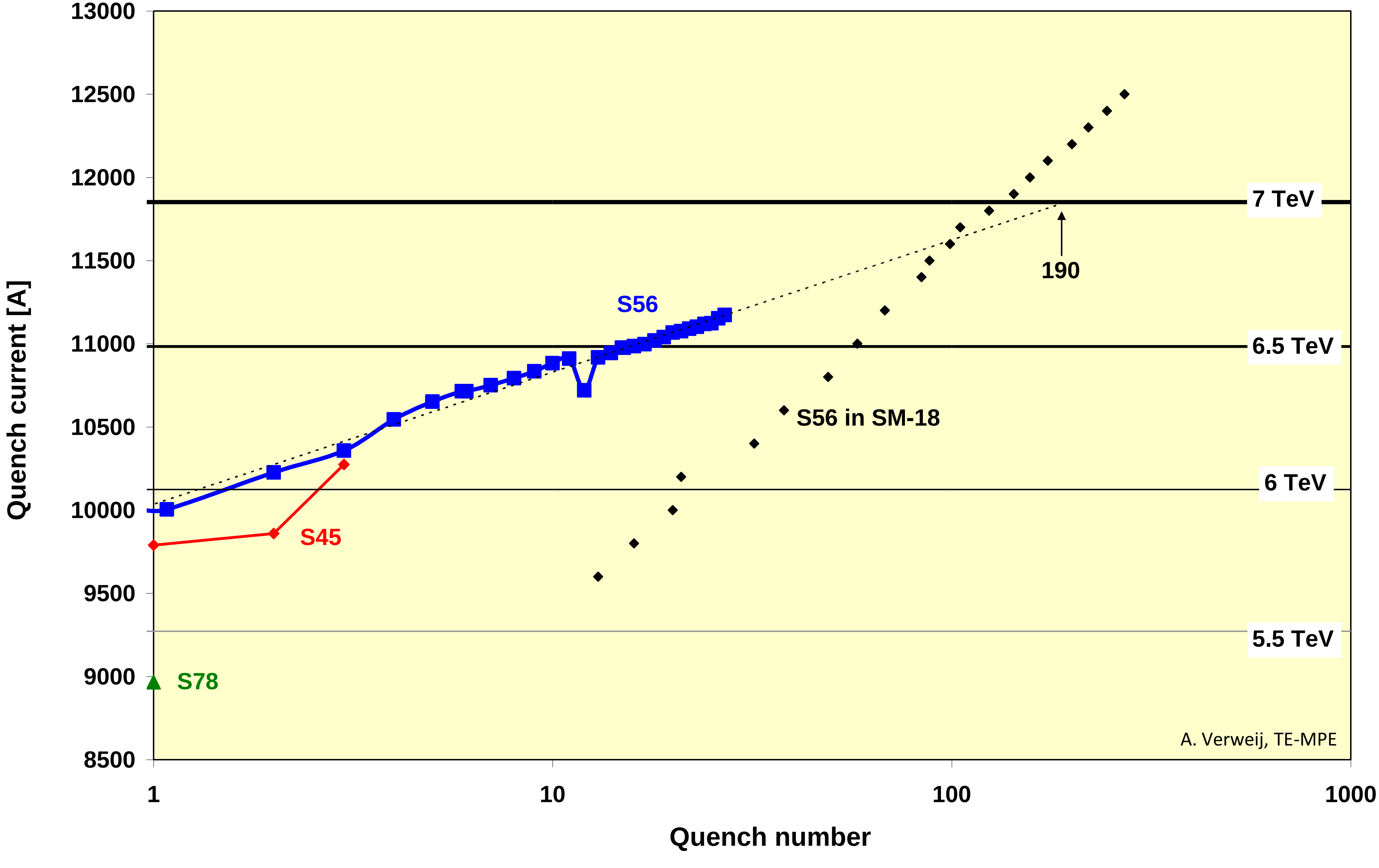
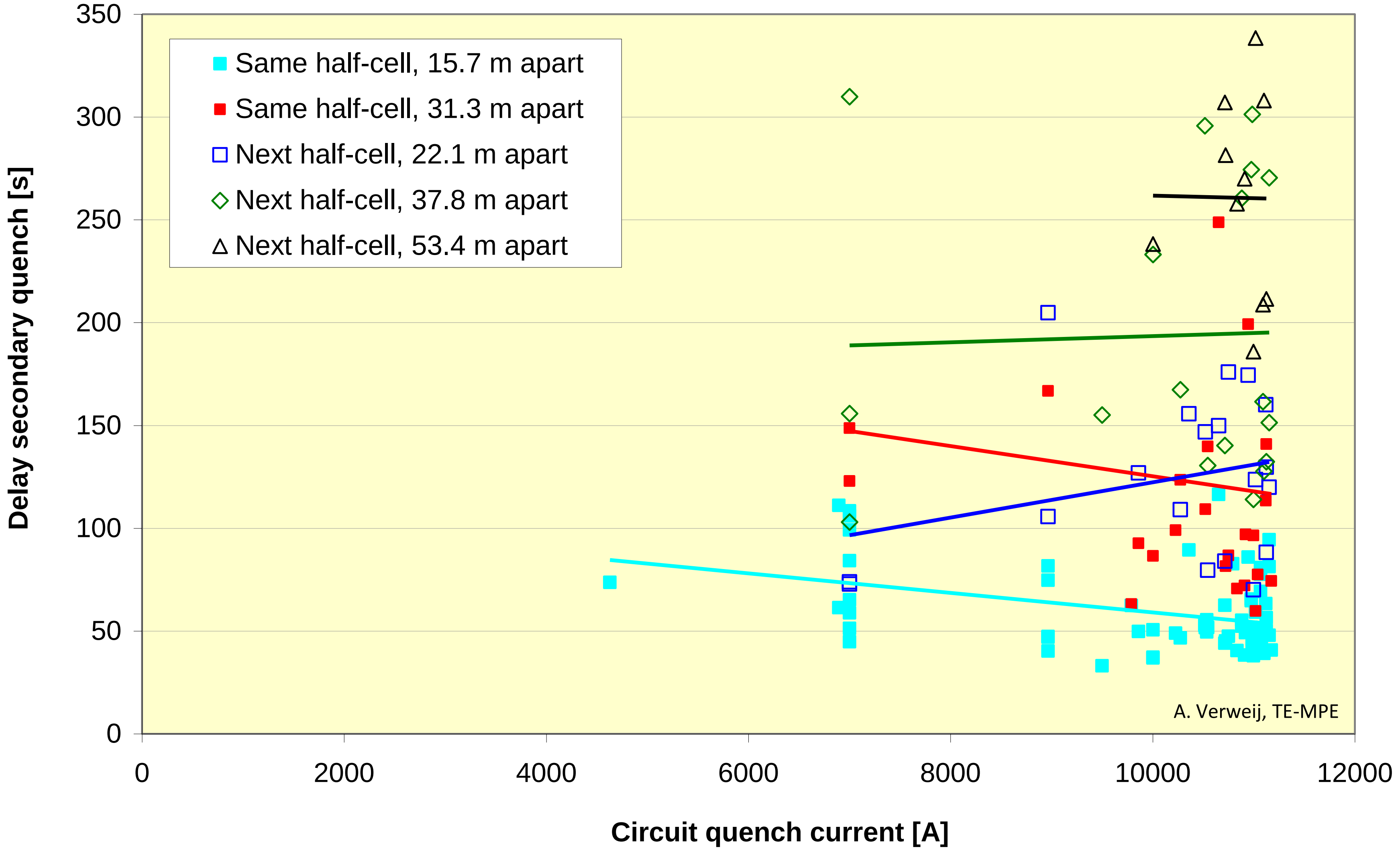
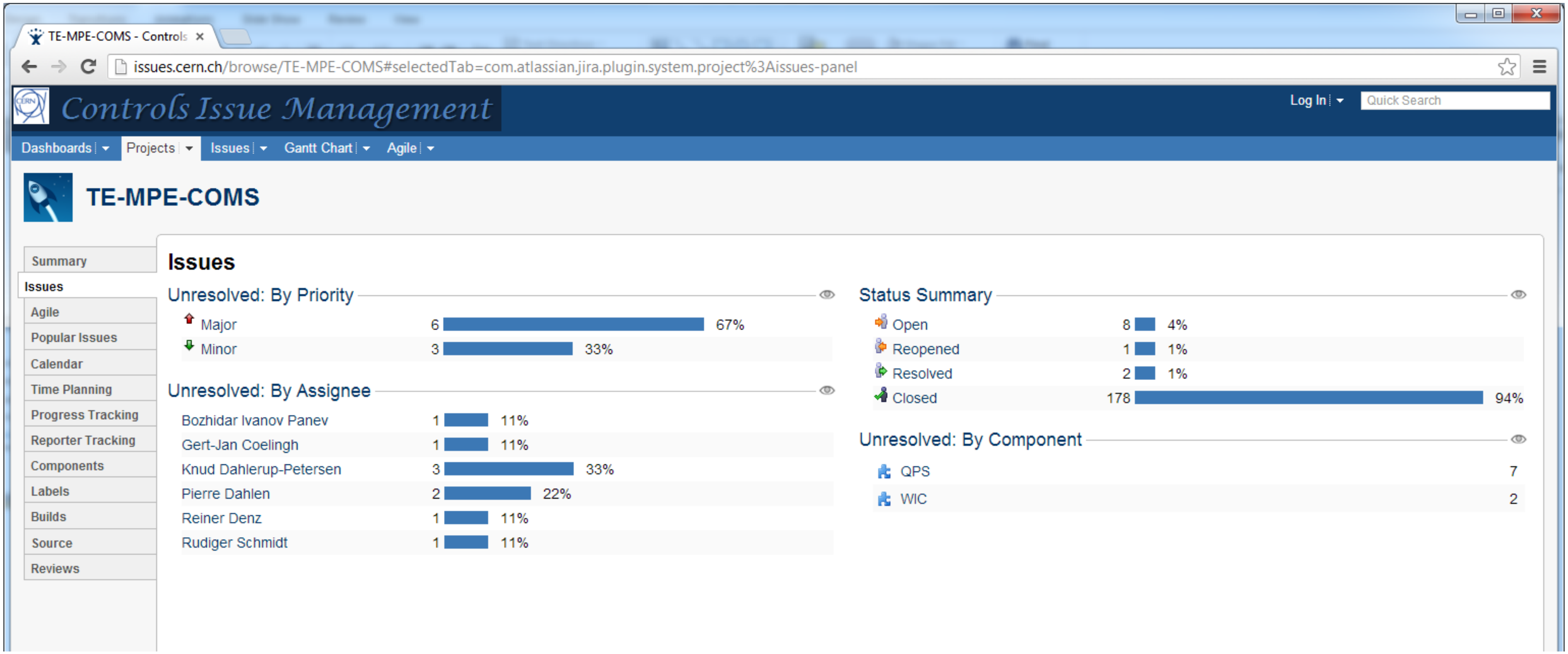
Training of the main dipoles in the LHC in 2008

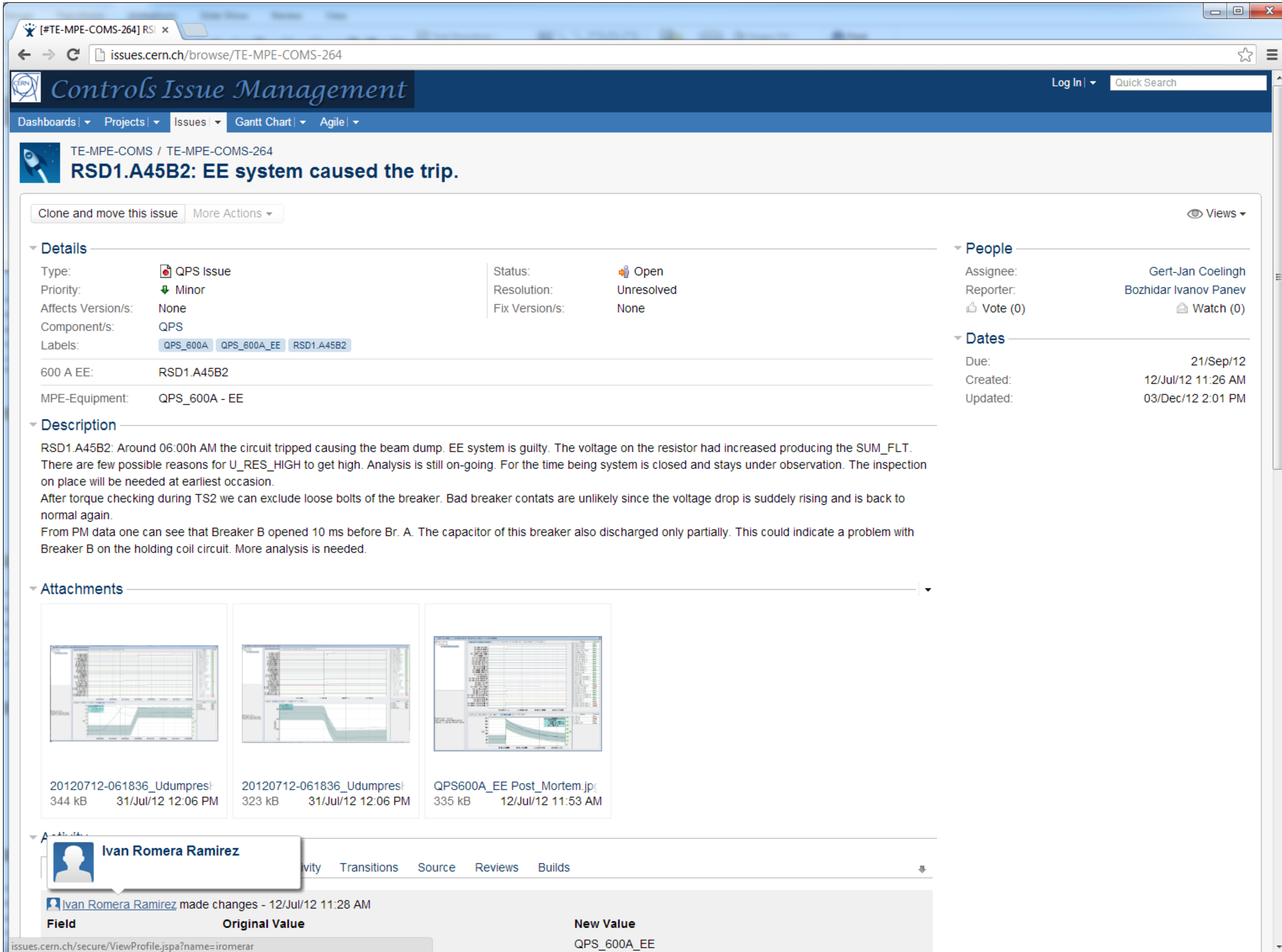


Thermal quench propagation in the LHC main dipole circuit



Follow-up of 100's of issues/year.





[#TE-MPE-COMS-264] RS

issues.cern.ch/browse/TE-MPE-COMS-264

Controls Issue Management

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TE-MPE-COMS / TE-MPE-COMS-264

RSD1.A45B2: EE system caused the trip.

Clone and move this issue | More Actions | Views

Details

Type:	QPS Issue	Status:	Open
Priority:	Minor	Resolution:	Unresolved
Affects Version/s:	None	Fix Version/s:	None
Component/s:	QPS		
Labels:	QPS_600A QPS_600A_EE RSD1.A45B2		
600 A EE:	RSD1.A45B2		
MPE-Equipment:	QPS_600A - EE		

People

Assignee: Gert-Jan Coelingh
Reporter: Bozhidar Ivanov Panev
Vote (0) Watch (0)

Dates

Due: 21/Sep/12
Created: 12/Jul/12 11:26 AM
Updated: 03/Dec/12 2:01 PM

Description

RSD1.A45B2: Around 06:00h AM the circuit tripped causing the beam dump. EE system is guilty. The voltage on the resistor had increased producing the SUM_FLT. There are few possible reasons for U_RES_HIGH to get high. Analysis is still on-going. For the time being system is closed and stays under observation. The inspection on place will be needed at earliest occasion.
After torque checking during TS2 we can exclude loose bolts of the breaker. Bad breaker contats are unlikely since the voltage drop is suddely rising and is back to normal again.
From PM data one can see that Breaker B opened 10 ms before Br. A. The capacitor of this breaker also discharged only partially. This could indicate a problem with Breaker B on the holding coil circuit. More analysis is needed.

Attachments

20120712-061836_Udumpres 344 kB 31/Jul/12 12:06 PM
20120712-061836_Udumpres 323 kB 31/Jul/12 12:06 PM
QPS600A_EE Post_Mortem.jp 335 kB 12/Jul/12 11:53 AM

Activity

Ivan Romera Ramirez

...vity | Transitions | Source | Reviews | Builds

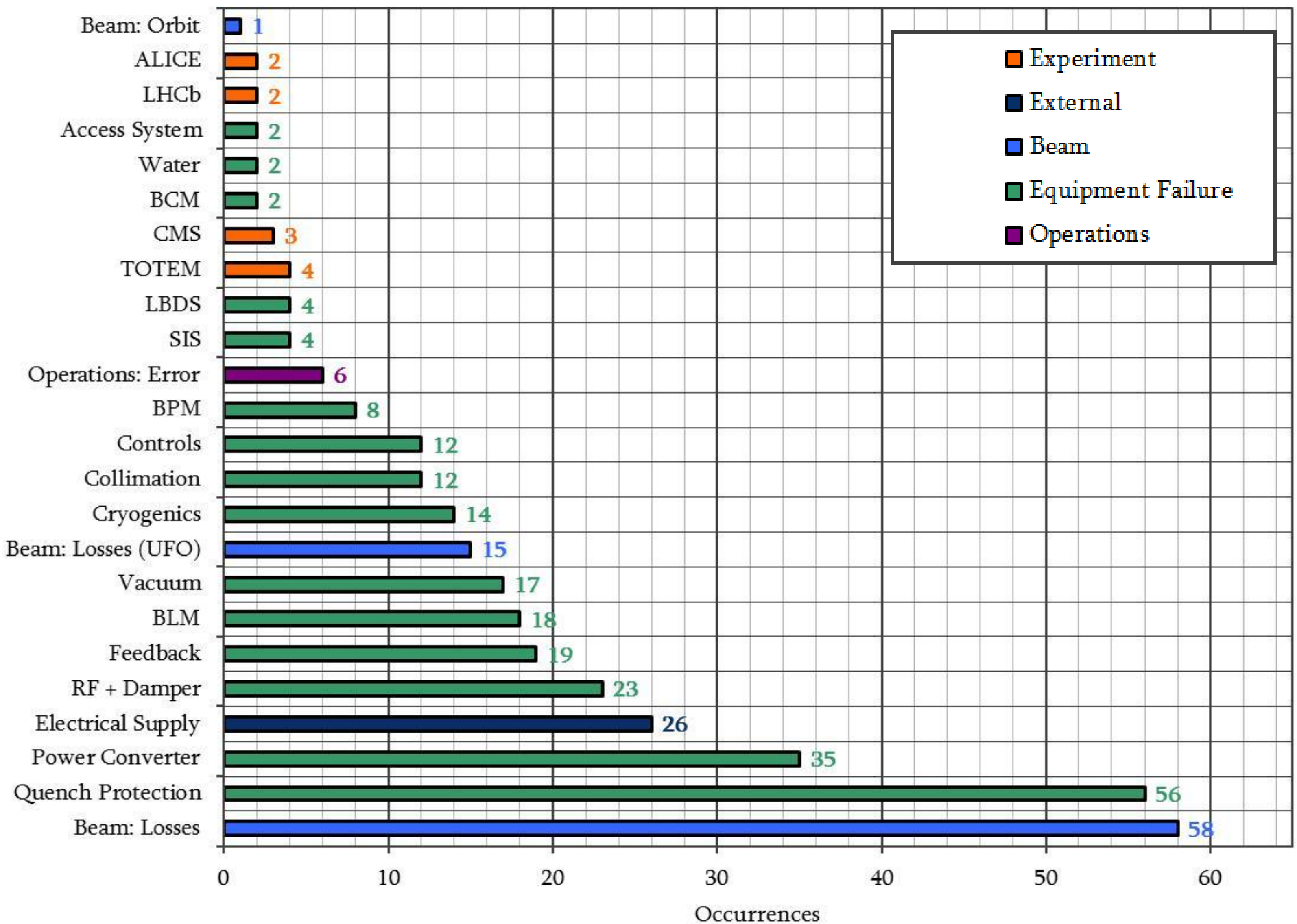
Ivan Romera Ramirez made changes - 12/Jul/12 11:28 AM

Field	Original Value	New Value
		QPS_600A_EE

issues.cern.ch/secure/ViewProfile.jspa?name=iromerar

Cause of protection beam dumps in the LHC in 2012

585 fills: 64 tests, 345 protection dumps, 176 end of fills



D. Wollmann, A. Apollonio, TE-MPE, B. Todd, TE-EPC

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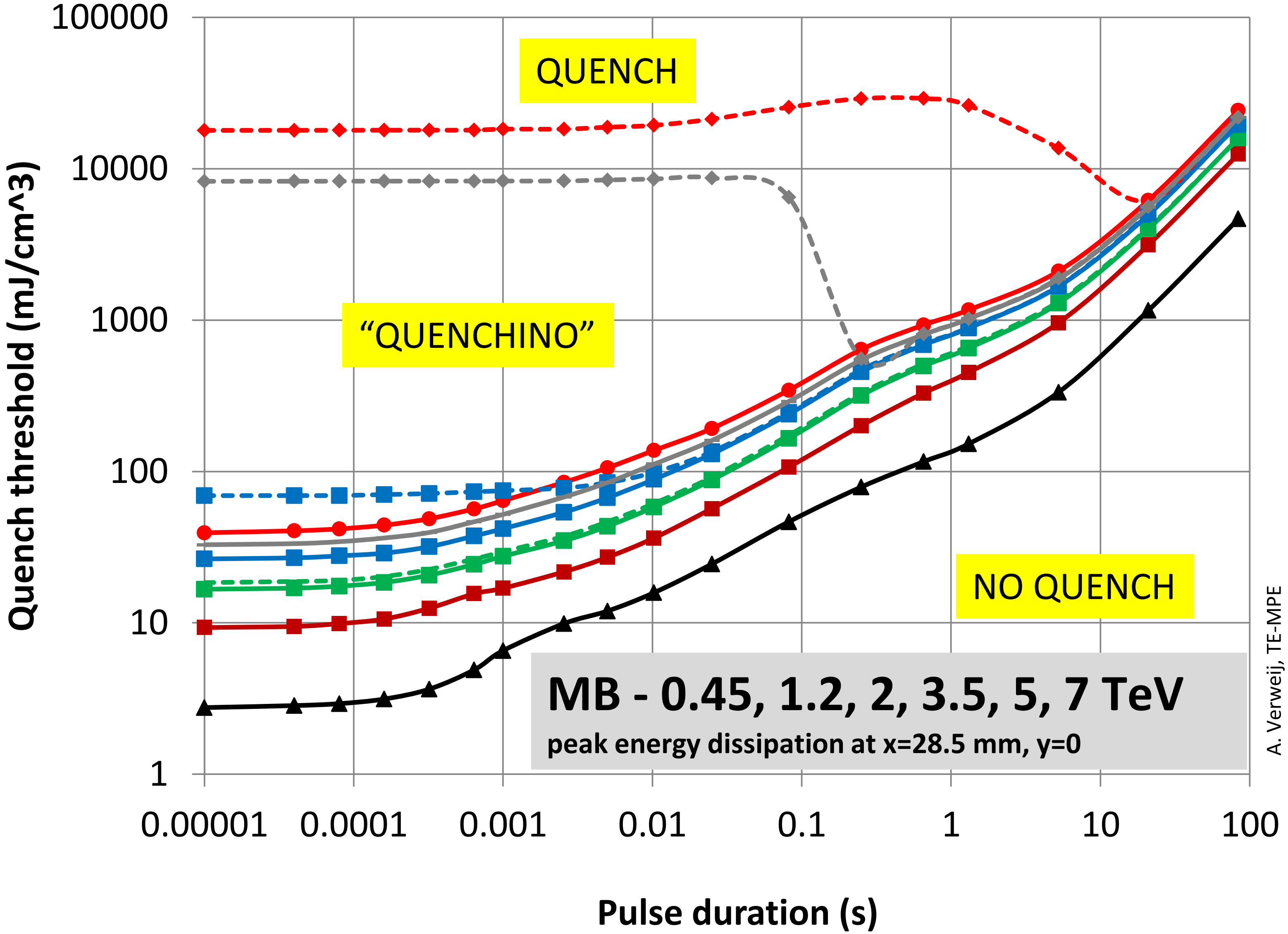
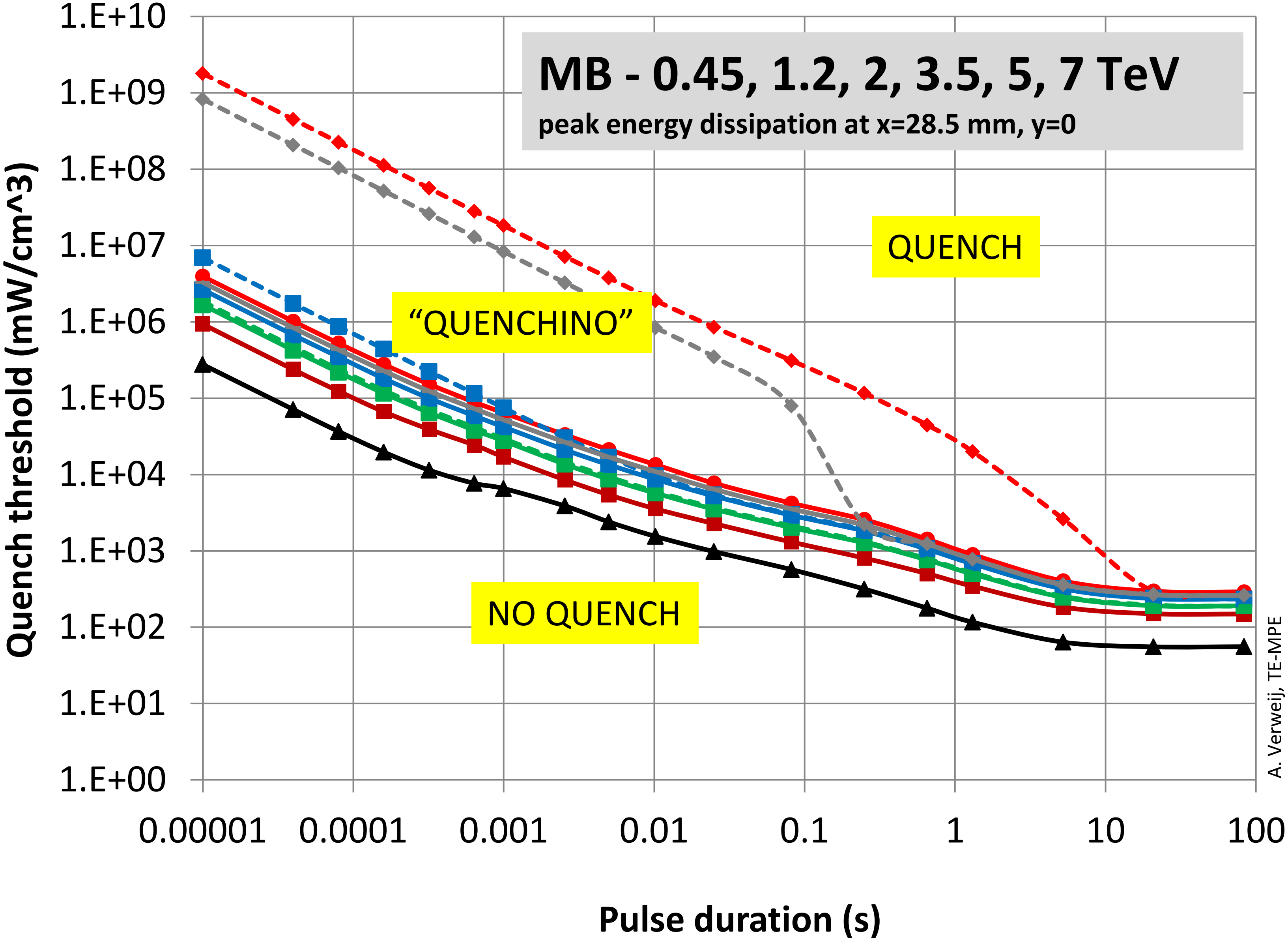
Calculation of beam-induced quench levels in all magnets of the LHC

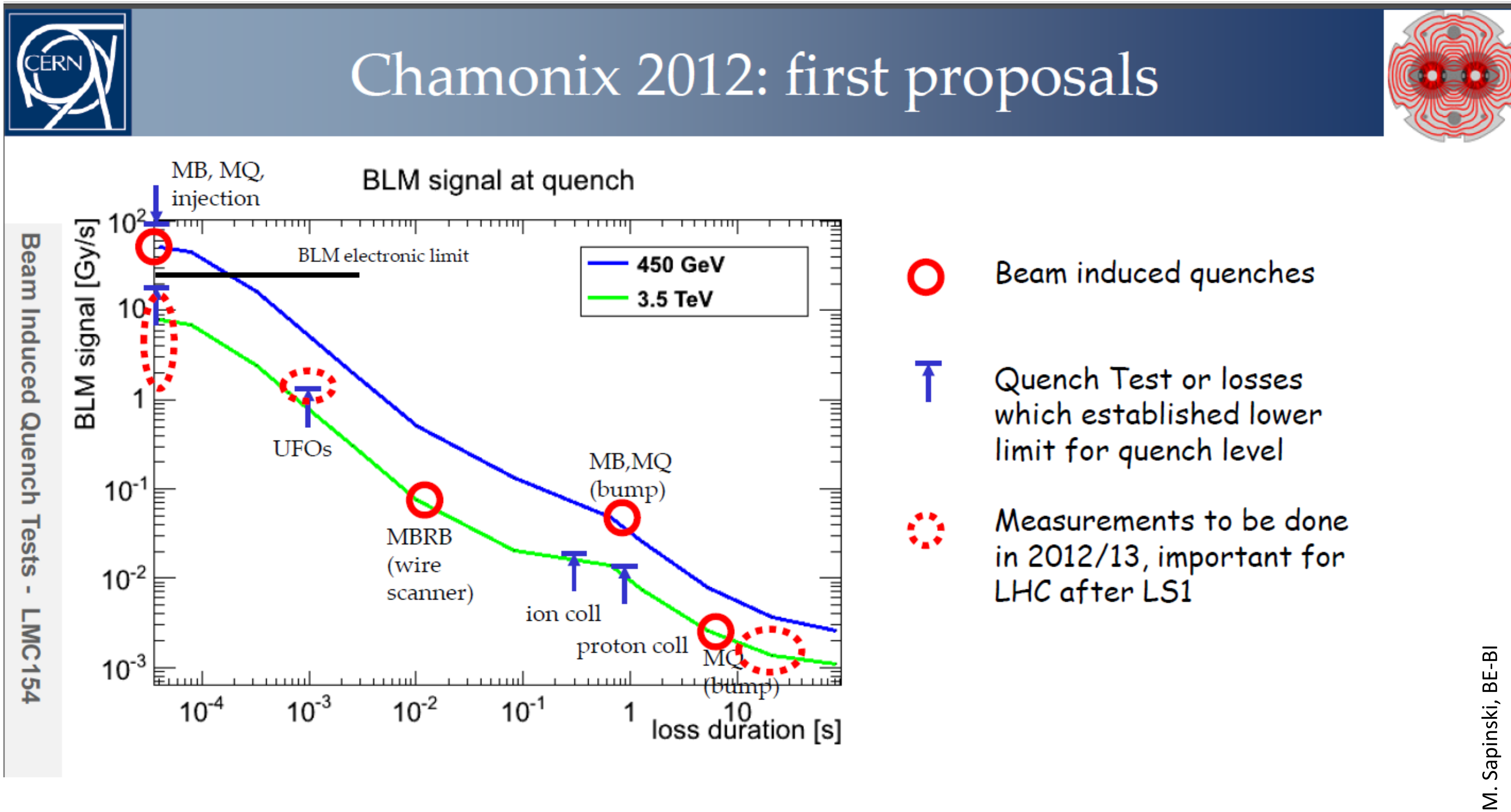


Quenchino: slang for a quench that would have recovered if the quench heaters would not have fired

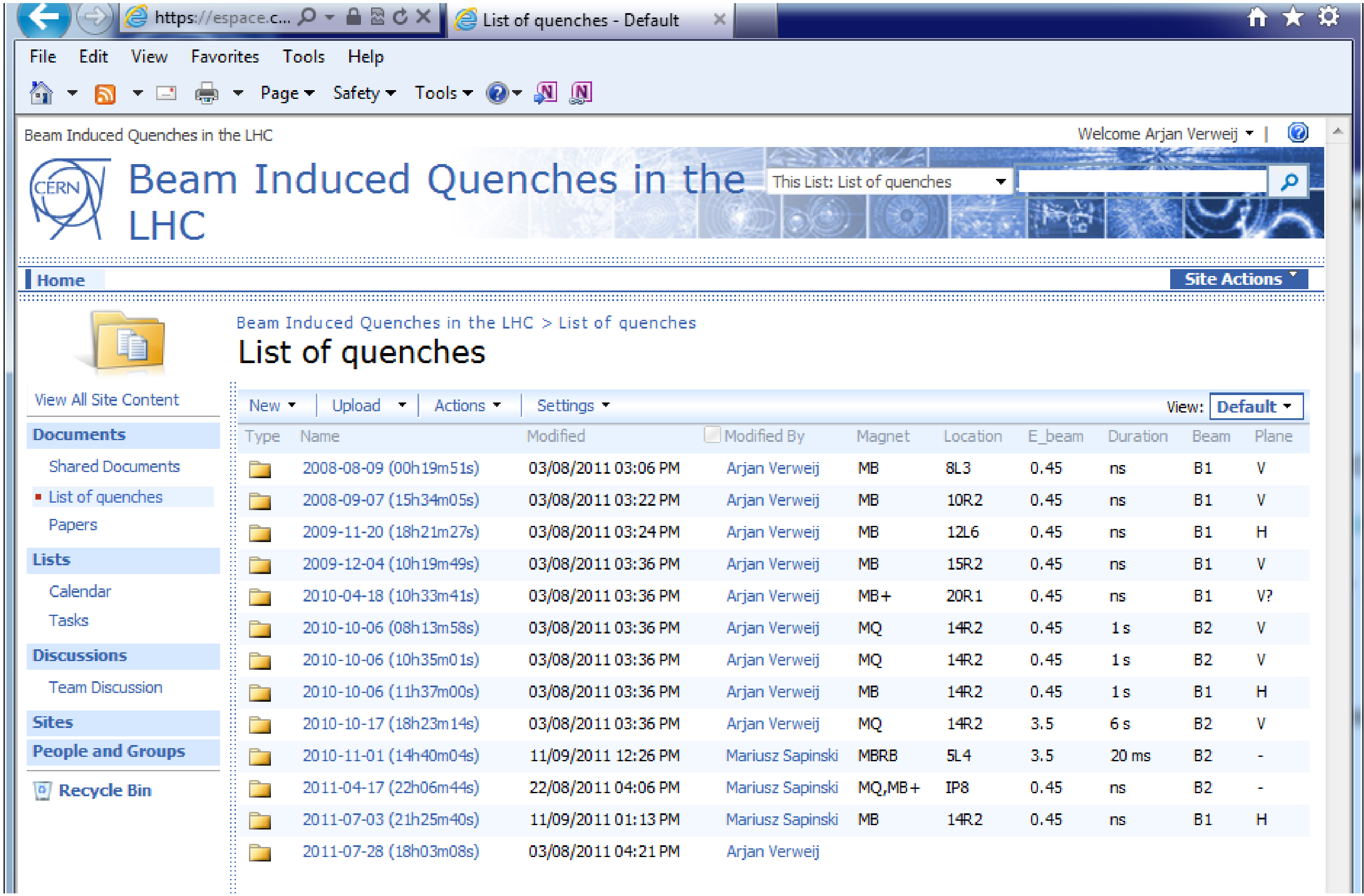
… and in terms of mW/cm³



Proposals for quench tests in the LHC, to better understand beam-induced quench levels



Follow-up of the beam induced quenches in the LHC



Type	Name	Modified	Modified By	Magnet	Location	E_beam	Duration	Beam	Plane
	2008-08-09 (00h19m51s)	03/08/2011 03:06 PM	Arjan Verweij	MB	8L3	0.45	ns	B1	V
	2008-09-07 (15h34m05s)	03/08/2011 03:22 PM	Arjan Verweij	MB	10R2	0.45	ns	B1	V
	2009-11-20 (18h21m27s)	03/08/2011 03:24 PM	Arjan Verweij	MB	12L6	0.45	ns	B1	H
	2009-12-04 (10h19m49s)	03/08/2011 03:36 PM	Arjan Verweij	MB	15R2	0.45	ns	B1	V
	2010-04-18 (10h33m41s)	03/08/2011 03:36 PM	Arjan Verweij	MB+	20R1	0.45	ns	B1	V?
	2010-10-06 (08h13m58s)	03/08/2011 03:36 PM	Arjan Verweij	MQ	14R2	0.45	1 s	B2	V
	2010-10-06 (10h35m01s)	03/08/2011 03:36 PM	Arjan Verweij	MQ	14R2	0.45	1 s	B2	V
	2010-10-06 (11h37m00s)	03/08/2011 03:36 PM	Arjan Verweij	MB	14R2	0.45	1 s	B1	H
	2010-10-17 (18h23m14s)	03/08/2011 03:36 PM	Arjan Verweij	MQ	14R2	3.5	6 s	B2	V
	2010-11-01 (14h40m04s)	11/09/2011 12:26 PM	Mariusz Sapinski	MBRB	5L4	3.5	20 ms	B2	-
	2011-04-17 (22h06m44s)	22/08/2011 04:06 PM	Mariusz Sapinski	MQ,MB+	IP8	0.45	ns	B2	-
	2011-07-03 (21h25m40s)	11/09/2011 01:13 PM	Mariusz Sapinski	MB	14R2	0.45	ns	B1	H
	2011-07-28 (18h03m08s)	03/08/2011 04:21 PM	Arjan Verweij						

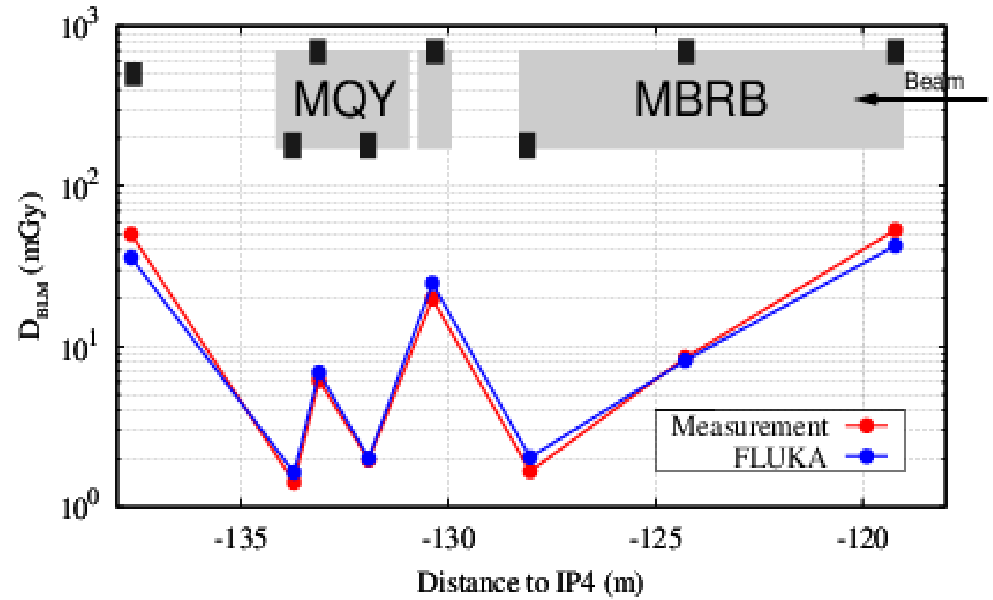
So far no beam induced quenches at 3.5-4 TeV, even with a beam energy of up to 150 MJ.

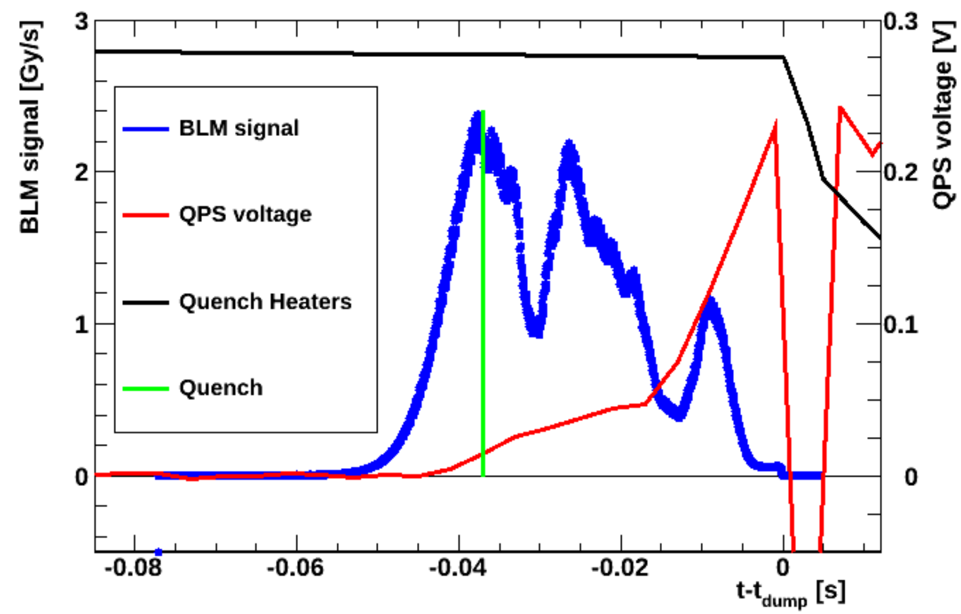
Example:

Quench test on 1/11/2010 on MBRB (4.5 K) to better understand the quench limit for beam losses with a time scale of 1-10 ms.

Correlating measured signals from beam loss monitors and QPS, with calculations using Fluka and QP3.

	energy density [mJ/cm³]	
	FLUKA and experiment	QP3, dry coil, FLUKA radial shape
cable average	11.6	15.6

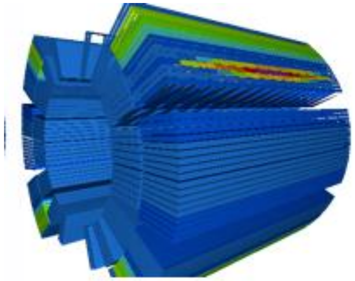




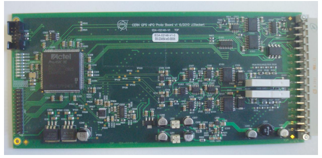
M. Sapinski, A. Priebe, BE-BI, M. Bednarek, TE-MPE, A. Lechner, EN-STI

Conclusion

After having commissioned and operated the magnet circuits in the LHC for 5 years, we have built up in the MPE group an extensive experience in:

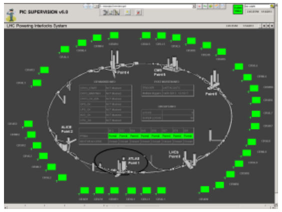


The calculation/simulation of quench phenomena (training quenches, quench back, beam-induced) in SC strands, cables, busbars, coils, and circuits, using 4 different codes/programs. Quench simulations for Nb-Ti, Nb_3Sn and HTS are qualitatively very similar and can be done with the same codes.



(Radiation tolerant) quench detection and interlocking, with current dependent thresholds and L(I) compensation.

Quench protection by means of cold diodes, energy extraction systems (switches and dumps), and quench heater units.



Data acquisition, monitoring, automation, and analysis of powering events.

Conclusion

Detection thresholds in the machine might have to be larger than in a single magnet test, due to electrical transients, mutual coupling, noise pick-up, powering requirements, switch delays, ...

For example:

- Corrector magnets were tested in B4 with U_{thr}=50 mV, 10 ms, but in the machine we have to use thresholds up to 2 V, 190 ms.
- Several main dipoles have thresholds of 200-300 mV, because voltage waves induced by the converter and the switches caused spurious trips for smaller thresholds.

Quench protection should be a key issue when starting the design of an accelerator magnet (setting clear constraints on the Cu/SC ratio and cable size). At this stage one should be somewhat conservative concerning the threshold, in order to leave some margin for operation.