Magnet Powering System

Markus Zerlauth

MPS External Review

September 2010

- Magnet powering and Protection
- Commissioning of Powering Protection Systems
- Failures captured by powering protection
- Electrical perturbations vs powering protection
- What could put protection safety @ risk ?

- **Magnet powering and Protection**
- Commissioning of Powering Protection Systems
- Failures captured by powering protection
- Electrical perturbations vs powering protection
- What could put protection safety @ risk ?

LHC magnet powering

LHC is to a large extent a super-conducting machine

1232 main dipole magnets, ~ 400 main quadrupole magnets + > 8000 corrector magnets powered in 1600 electrical circuits

140 nc magnets powered in 44 electrical circuits mostly in cleaning insertions and close to high luminosity experiments

… to get 7 TeV operation…
LHC needs 8.3 Tesla dipole fields with circumference of 27 kms

… to get 8.3 Tesla …
LHC needs super-conducting magnets <2 K (-271 C)
with an operational current of ≈13kA
cooled in super fluid helium
maintained in a vacuum
in vicinity of high energy particle beams

1 ppm

A magnet will QUENCH with milliJoule deposited energy

Protection Functions

Beam Protection: Beam Energy (360 MJ) ⟶ Beam Dump

100x energy of TEVATRON

0.000005% of beam lost into a magnet = quench

0.005% beam lost into magnet = damage

Failure in protection – complete loss of LHC is possible

Powering Protection: Magnet Energy (9 GJ) ⟶ Emergency Discharge

10-20x energy per magnet of TEVATRON

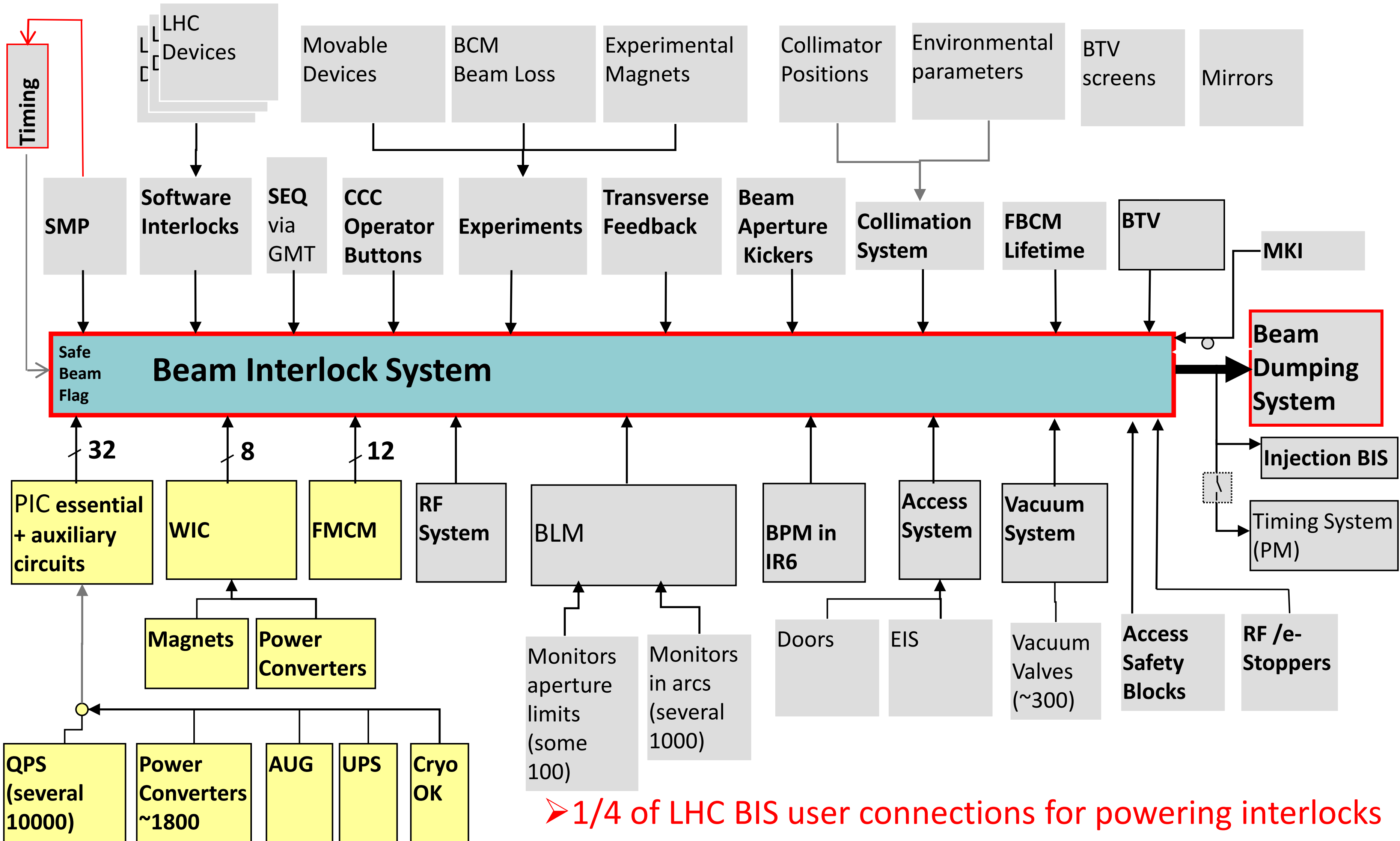
magnet quenched = hours downtime

many magnets quenched = days downtime

magnet damaged = $1 million, months downtime

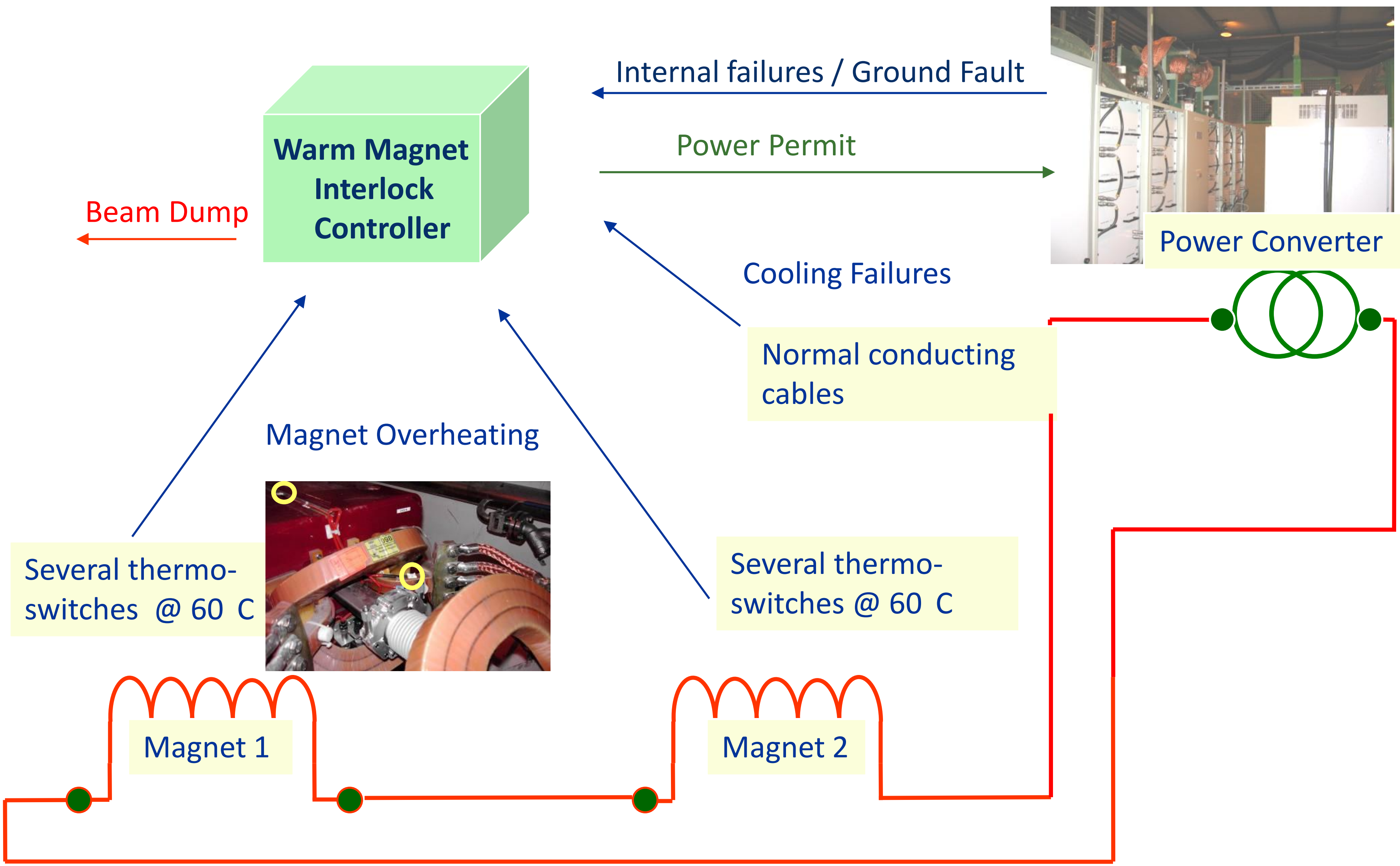
many magnets damaged = many millions, many months downtime (few spares)

Powering Interlocks vs Beam Interlock

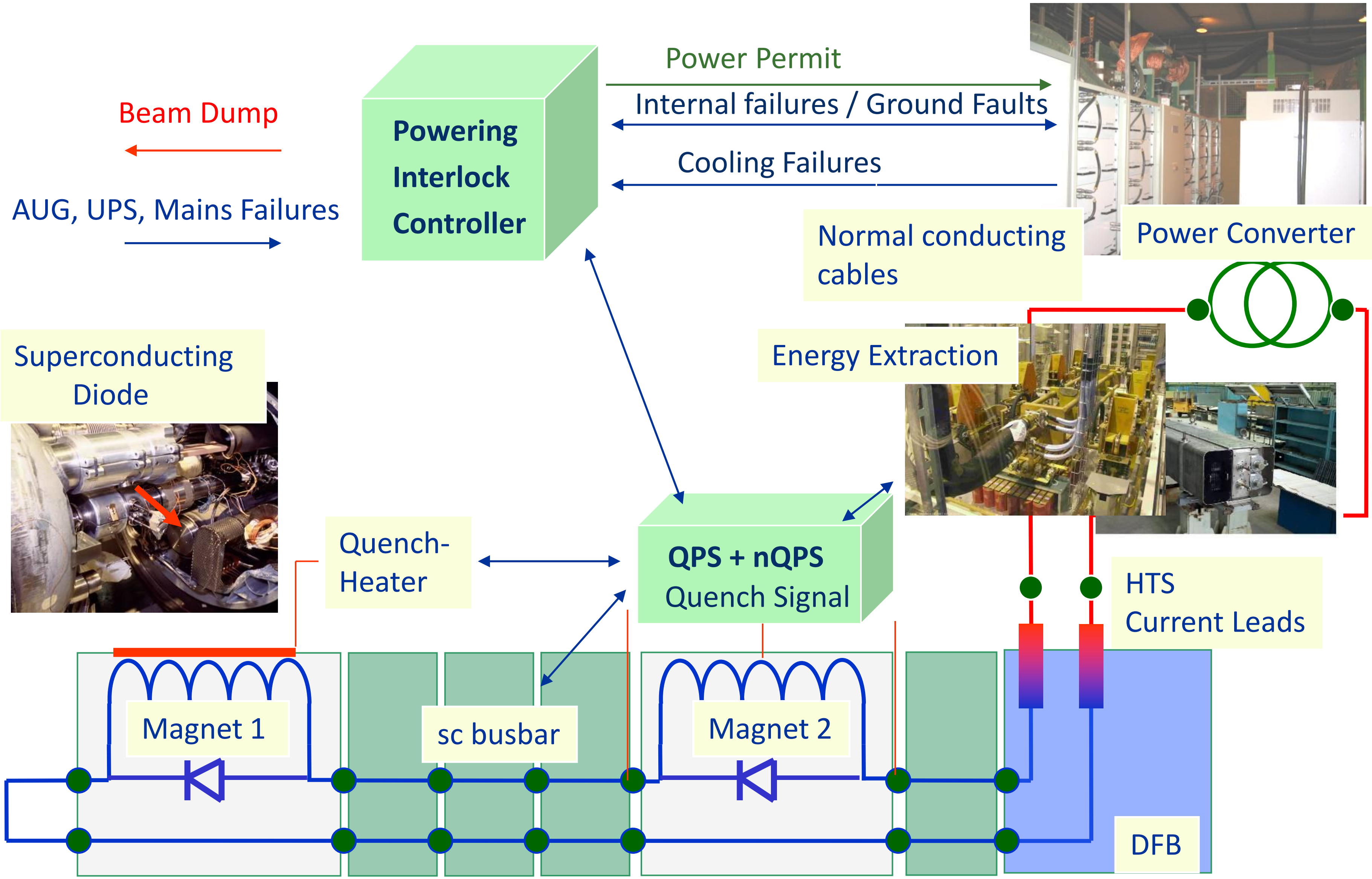


- 1/4 of LHC BIS user connections for powering interlocks, collecting a large inventory of interlock channels

Protection of normal conducting magnets / circuits



Protection of superconducting magnets / circuits



Key facts for Powering Interlock Systems

Both powering interlock systems use of industrial electronics (SIEMENS PLCs with remote I/O modules)

Distributed systems corresponding to machine sectorization (36 controllers for sc magnets, 8 controllers for nc magnets)

All critical signals are transmitted using HW links (Fail safe signal transmission, built in redundancy)

Additional start-up interlocks via SW channels

All circuit related systems OK = Power Permit, else dump beams and activate Energy extraction (if any)

Reaction times ~ 1 ms for sc circuit protection and 100ms for nc circuit protection

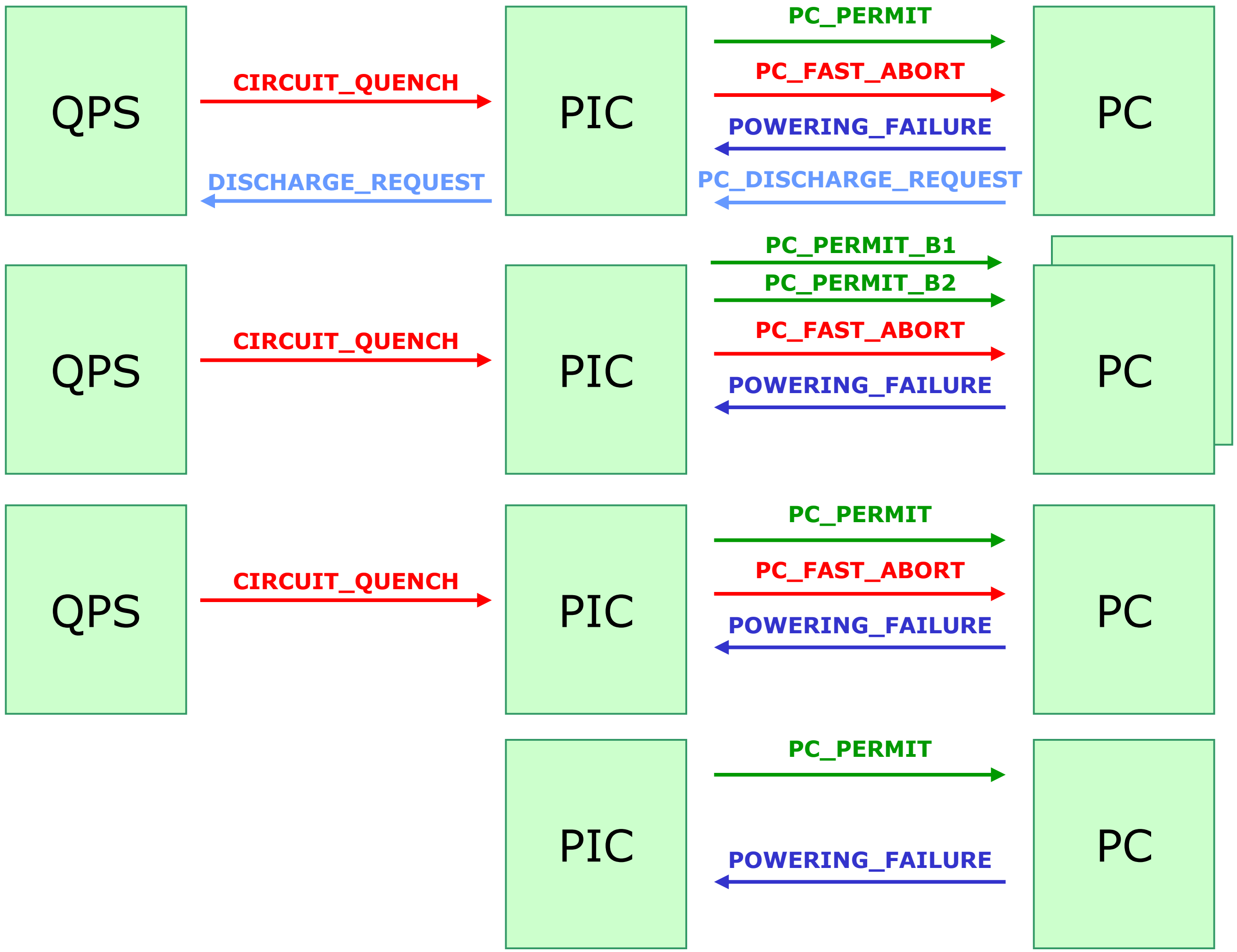
Interlock Types + HW signals

13kA main + IT

Individually powered quadrupoles (IRs)

600A EE, 600A no EE, 600A no EE crowbar + Individually powered dipoles

80-120A correctors



60A dipole orbit correctors

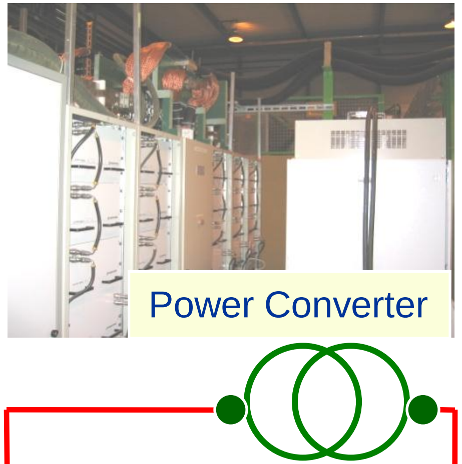
NO HW interlocks, but SW PERMIT via timing system, surveillance through SIS

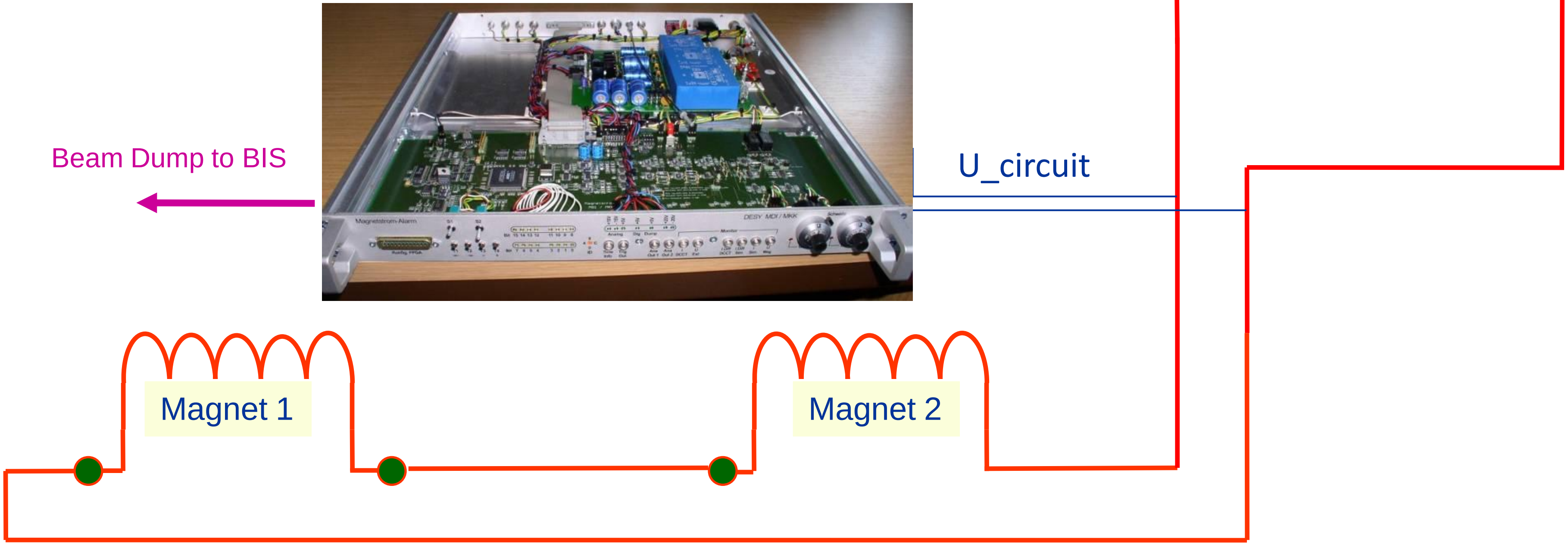
Fast Magnet Current Change Monitors

Fast Magnet Current Change Monitors are (strictly speaking) not interlocking powering equipment

Installed on nc magnets with << natural τ (injection/extraction septas, D1 magnets in IR1/IR5, …) and large impact on beam in case of powering failures

DESY invention which has been ported with great success to LHC and SPS-LHC transfer lines



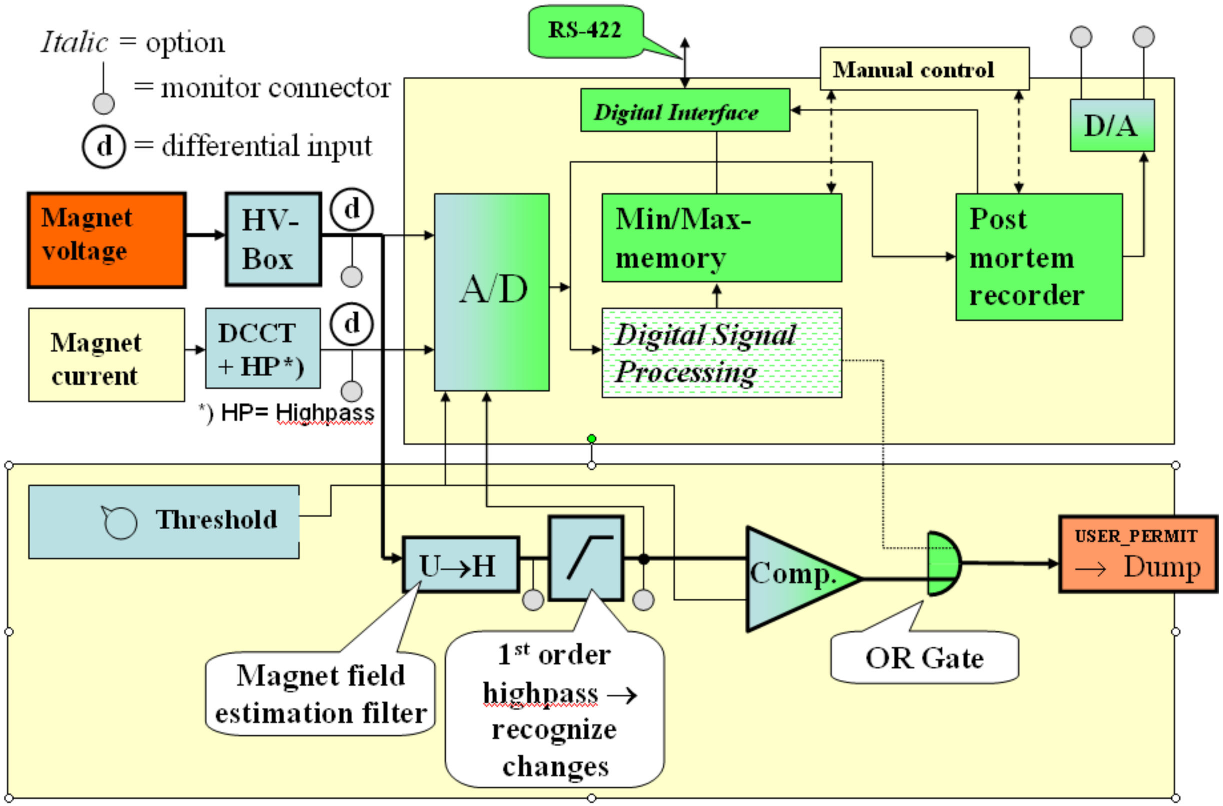


Fast Magnet Current Change Monitors

Precise current measurements are slow (require integration time)

Use voltage drop over the magnet(s) / circuit to calculate changes of magnetic field

Achieving detection of (relative) changes of 10E-4 within 50us as complement to (slower) absolute current surveillance by power converter



- Magnet powering and Protection
- **Commissioning of Powering Protection Systems**
- Failures captured by powering protection
- Electrical perturbations vs powering protection
- What could put safety @ risk ?

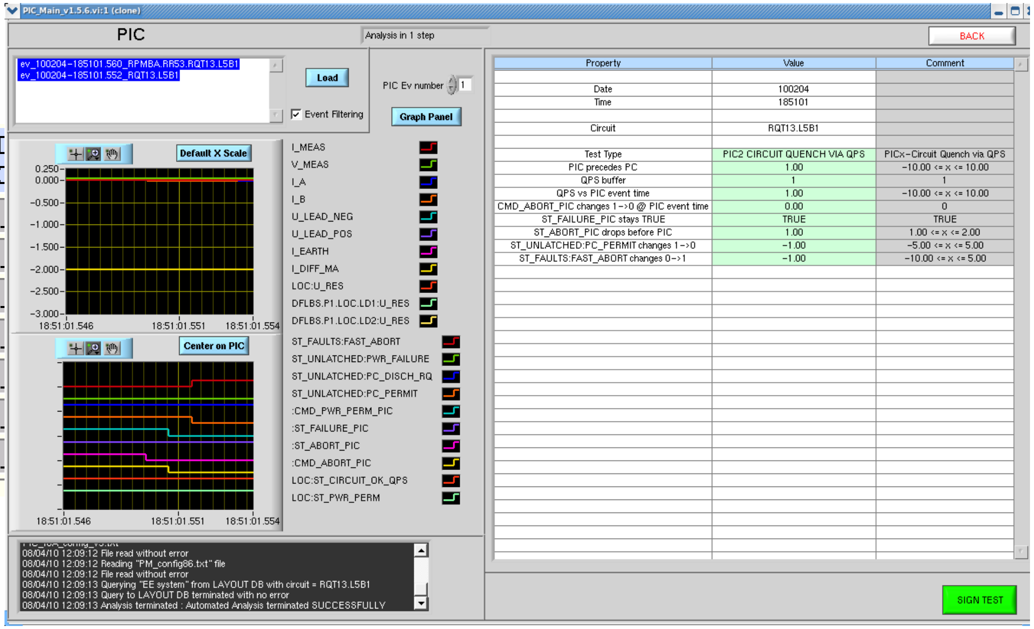
Commissioning powering protection

Commissioning of powering protection systems is done to a large extend BEFORE beam operation (mostly at zero current in circuits)

Dedicated HW commissioning campaign (several campaigns, 1st started in 2006), during which powering protection between main systems (QPS, power converters, CRYO) is validated to 100% (every channel is exercised and validated)

Few thousands of tests for powering protection, execution and analysis /documentation almost fully automated

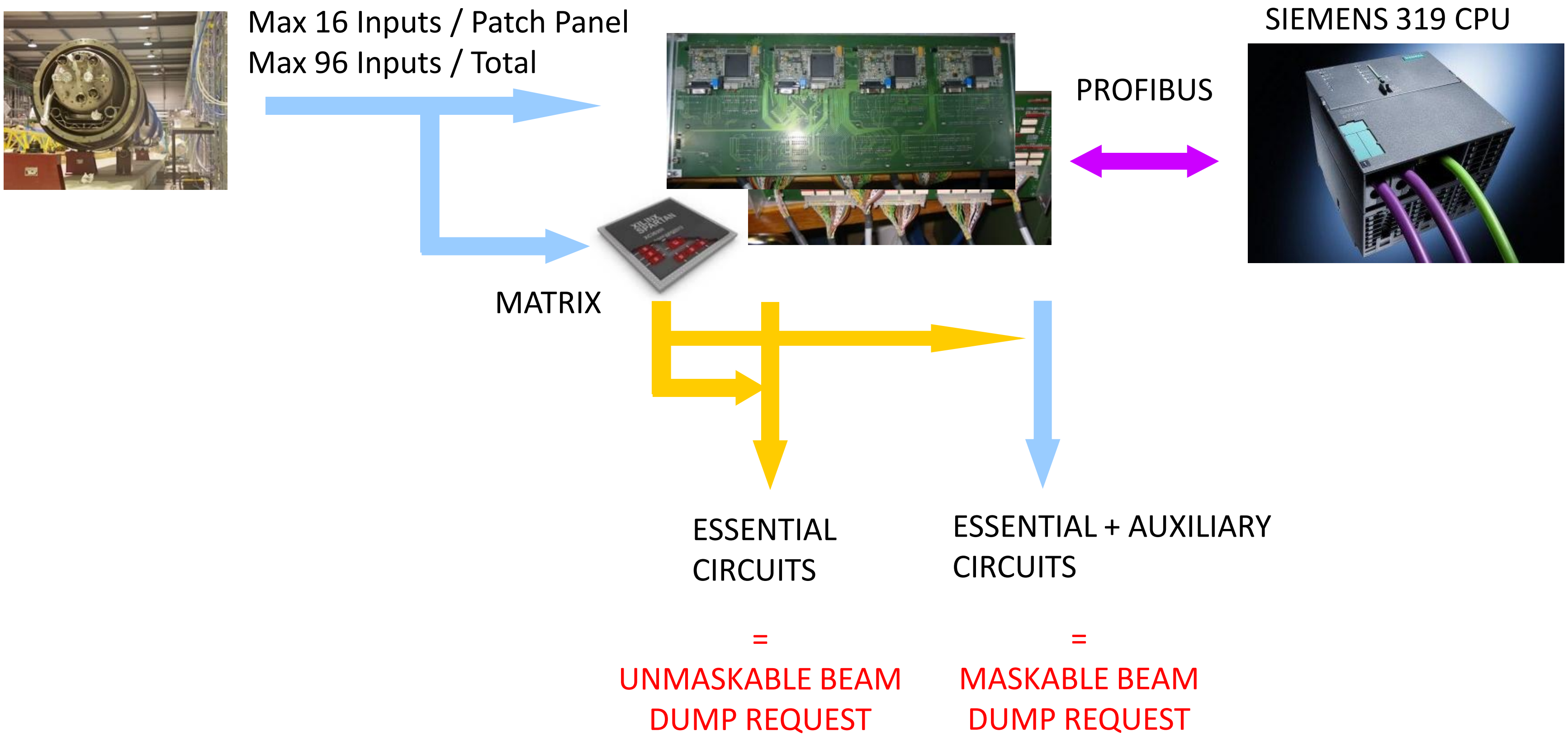
CIRCUIT NAME	LAST PASSED TEST	TESTS EXEC	LAST EXEC	SUC	UNI EX
RCBXH1.R1	24 HOUR HEAT RUN	0 / 11 (0%)	_	_	_
RCBXH2.R1	24 HOUR HEAT RUN	0 / 11 (0%)	_	_	_
RCBXH3.R1	24 HOUR HEAT RUN	0 / 11 (0%)	_	_	_
RCBXV1.R1	24 HOUR HEAT RUN	0 / 11 (0%)	_	_	_
RCBXV2.R1	24 HOUR HEAT RUN	0 / 11 (0%)	_	_	_
RCBXV3.R1	24 HOUR HEAT RUN	0 / 11 (0%)	_	_	_
RQSX3.R1	24 HOUR HEAT RUN	0 / 12 (0%)	_	_	_



Typical test plan and automated analysis for 600A circuit

Automated tests for links to BIS – 1/2

- Whether a sc circuit failure will trigger a (maskable/unmaskable) beam dump request is configurable (for flexibility during initial operation)
- Redundant, independent paths trough PLC and CPLD/Boolean Processor



Automated tests for links to BIS – 2/2

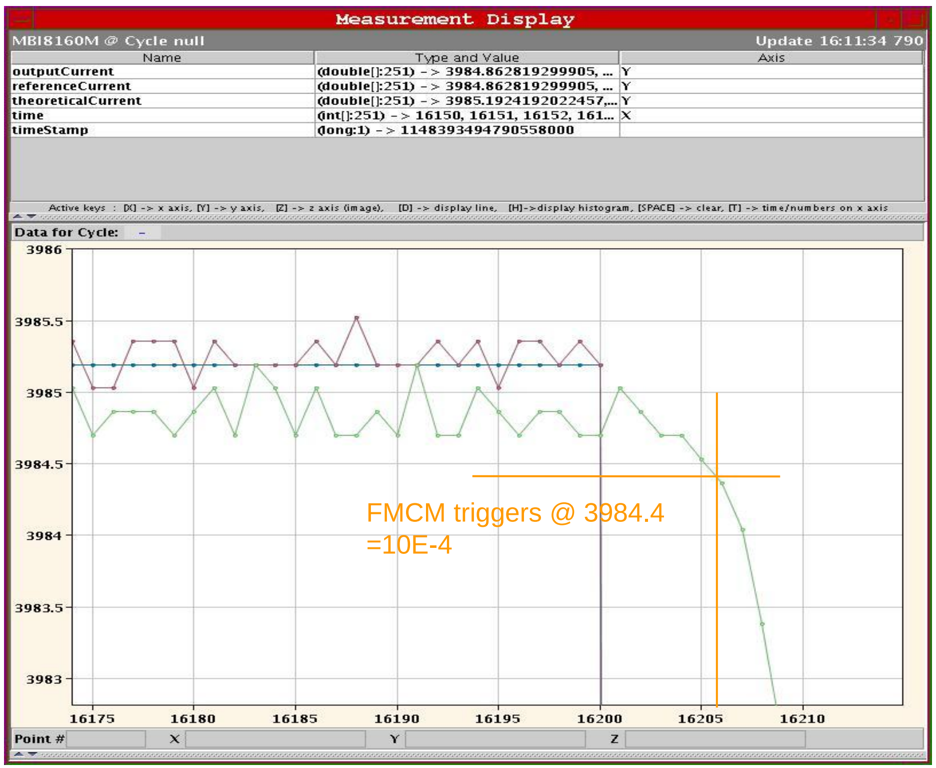
- As final MPS test of powering interlock system, ‚beam dump' configuration is validated with automated test sequence
- Test sequence provokes PC fault and verifies correct & redundant propagation of interlock signals until the Beam Interlock System
- Configuration currently active for 2010 run:
  - Unmaskable & maskable BIS input: RB, RQD, RQF, RQX, RD1-4, RQ4-RQ10, all nc magnets
  - maskable BIS input: RCS, RQT%, RSD%, RSF%, RCBXH/V and RCB%
  - no impact on the beam: RCD, RCO, ROD, ROF, RQS, RSS (and RCBCHS5.L8B1, RCBXH3.L5 and RCBYV5.L4B2 which all have NCs and are locked) + 60A DOC

  Note: Maskable inputs will become automatically unmasked when SBF = FALSE
- ‚Relaxed' configuration shown very useful to increase machine availability during ealry operation (reduction of required powering infrastructure)
  - Few occasions where circuits not included in current config tripped during beam operation without any impact on beam

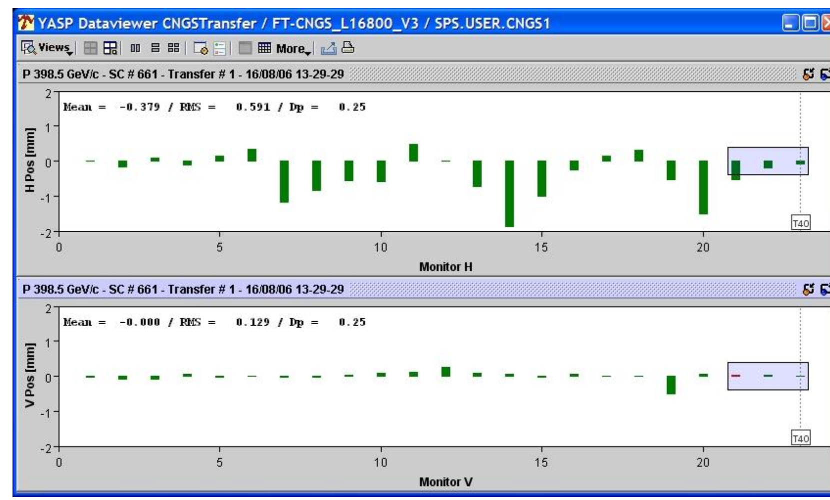
Commissioning FMCMs

Initial setup / commissioning of Fast magnet Current Change Monitors can be done BEFORE beam operation (validation of current change detected after PC OFF)

Confirmation of threshold is done with (low intensity) beam test @ injection and 3.5 TeV



Converter current + FMCM trigger vs. time



H & V orbit deviation in the TT41 line

- Magnet powering and Protection
- Commissioning of Powering Protection Systems
- **Failures captured by powering protection**
- Electrical perturbations vs powering protection
- What could put safety @ risk ?

Failures captured by Powering Interlocks…

- 46 dumps from magnet powering during ramp or at 3.5 TeV (many more if considering injection as well)

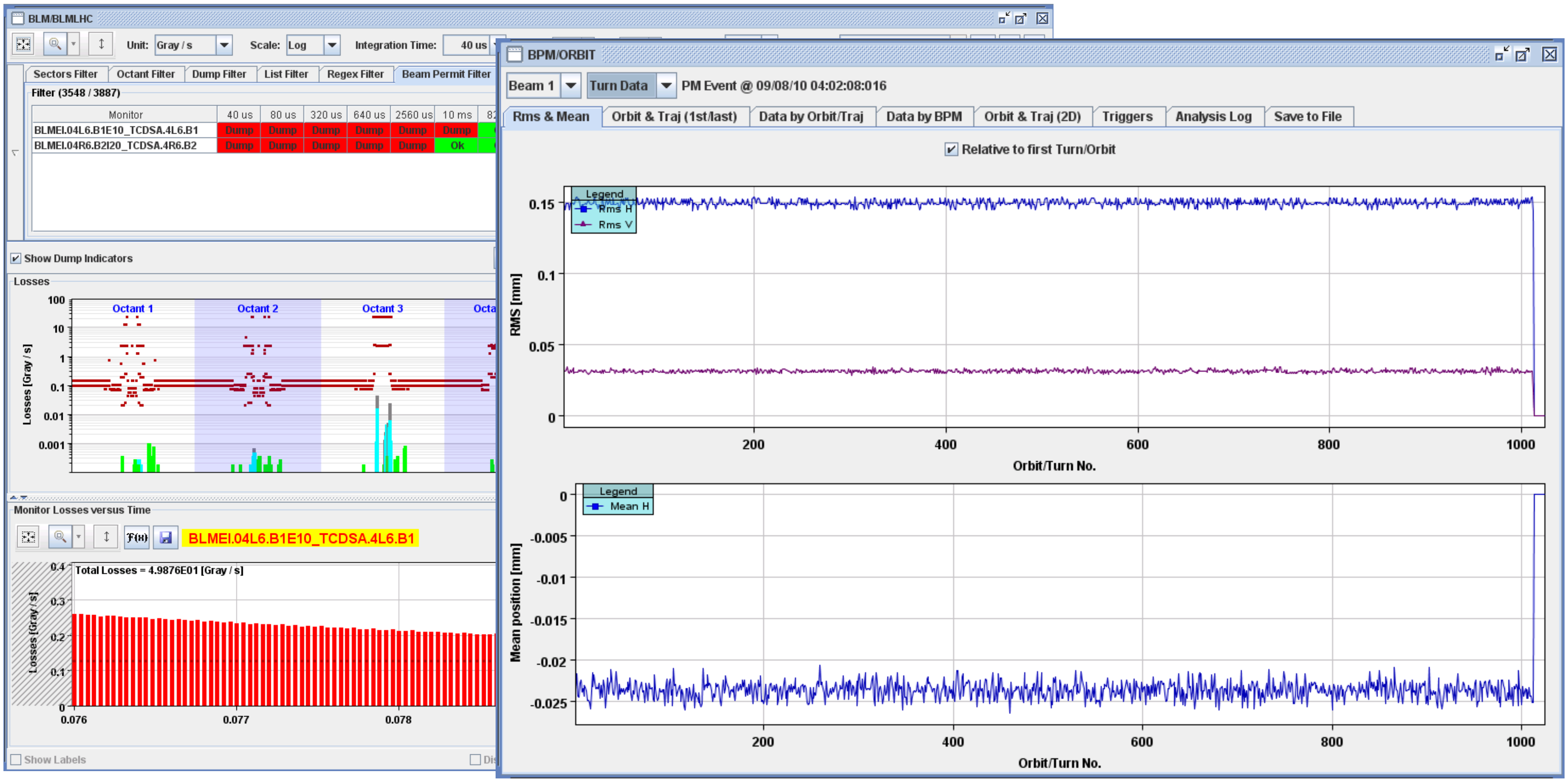
– Individual power converter + cooling failures (14)	PIC / WIC / FMCM
– Tune feedback vs QPS/PC (9)	PIC
– Cryogenics (7)	PIC
– Electrical perturbations / thunderstorms (7)	FMCM / PIC (QPS)
– Quench protection System (6)	PIC
– Operational mistakes / wrong functions… (4)	PIC
– Controls Problems (4)	PIC
– False MPS dump by QPS (1)	PIC
– False MPS dump by Powering Interlock Controller (1)	PIC

- Not yet seen (above injection): UPS failures and Emergency Stop (= simultaneous abort of 2 sectors), overheating of nc magnets

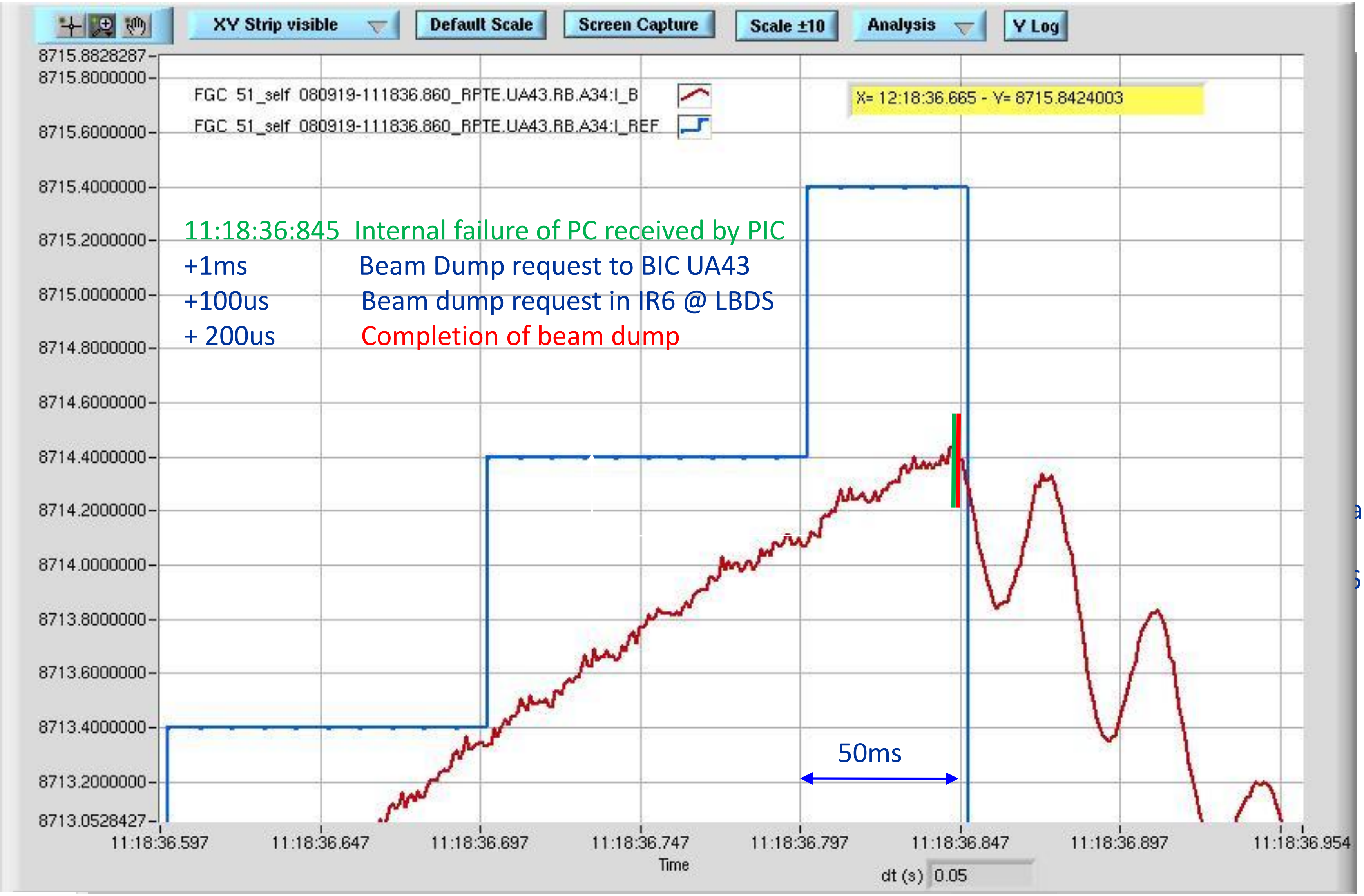
Trip of complete sector @ 3.5TeV

Worst case failure for magnet powering is simultaneous loss of complete sector(s), ie >> circuits. Worst seen so far = 2 full sectors (after thunderstorm).

Example of event on 09-AUG-10 04.02.08.016000 AM , stable beams at 3.5TeV, intensity 2E12, loss of complete sector 67 following false QPS trip (internal power supplies)

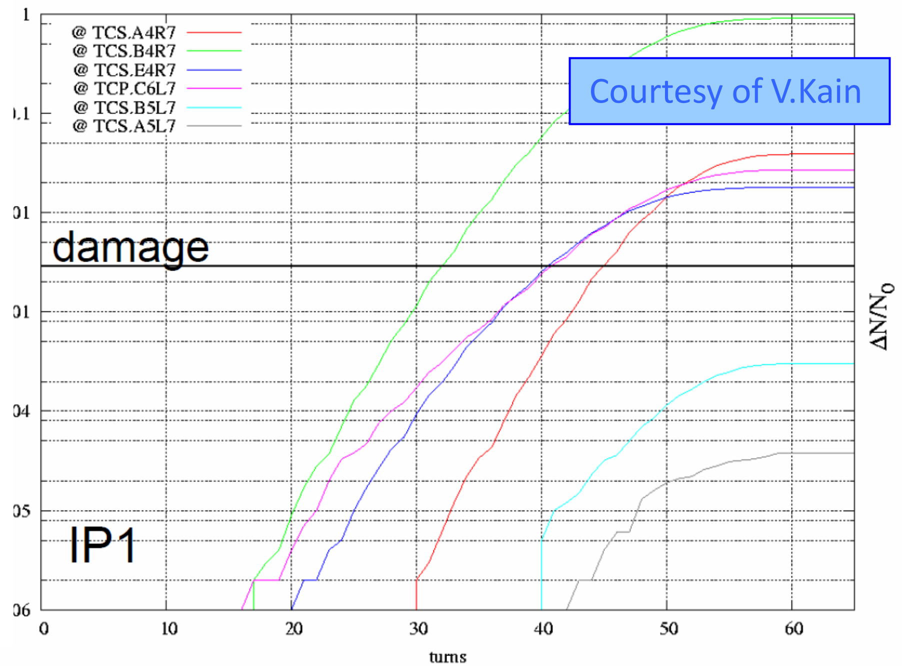


What would have happened with beam on 19th Sep 08 ?



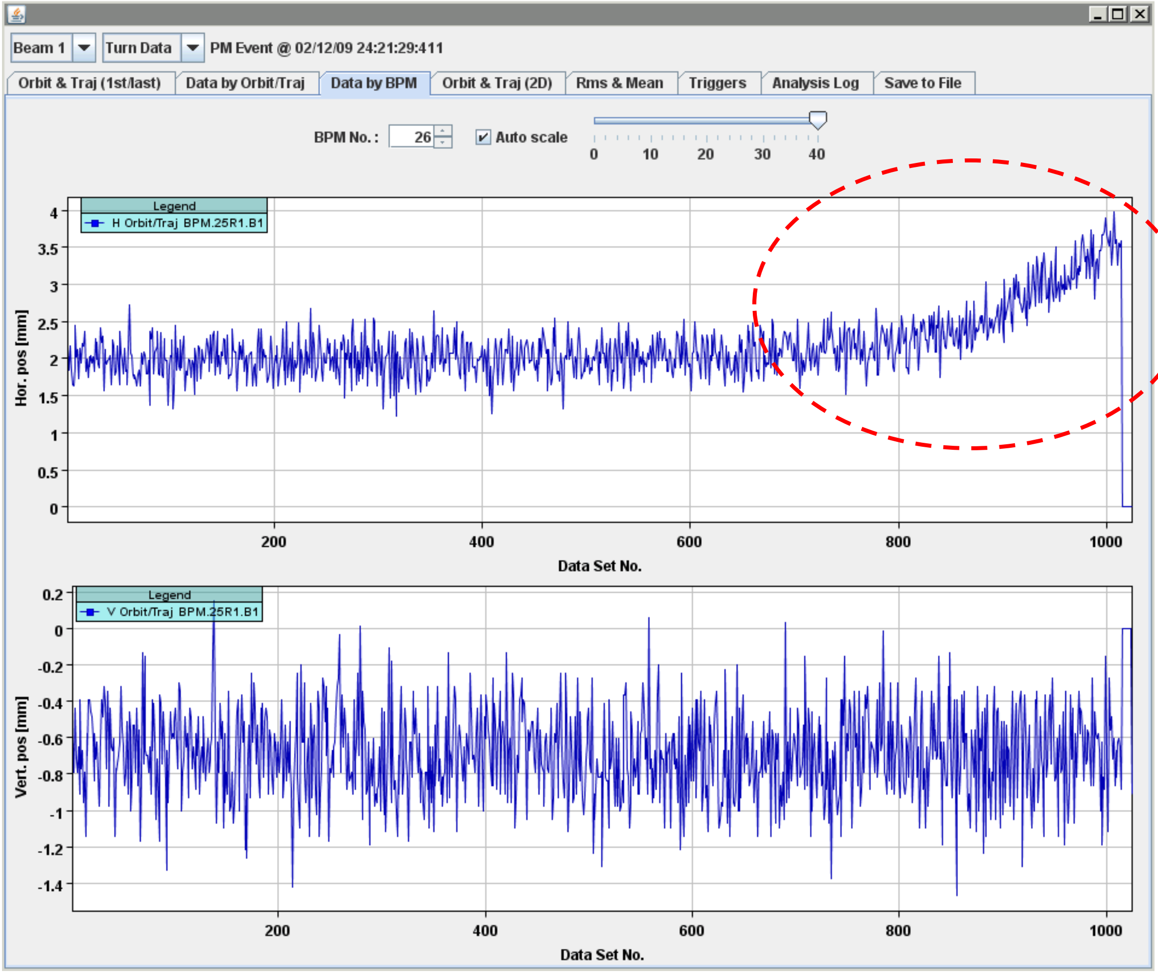
Powering Failures so far…

- Failures in the magnet powering system are generally SLOW and beams can be (easily) dumped before starting to extract energy
- Experience so far confirms that reaction+transmission times (of few ms) for beam dump request out of powering protection are adequat
- None of the dumps so far shows significant losses or orbit changes
- Very good availability, no critical component failure in >4 years
- Exception are failures in some of the nc magnets, which can generate the loss of 10E-5 * Np after some 10 turns only (MSE, MSI, MSD, D1, MBW, MBXWT…)
- Cannot be caught in time by converter controls or WIC
  (see as well TL incident in fall 2004)
- Introduced FMCMs as reduncany to COLL+BLM



FMCM Beam Tests for D1 IR1/5

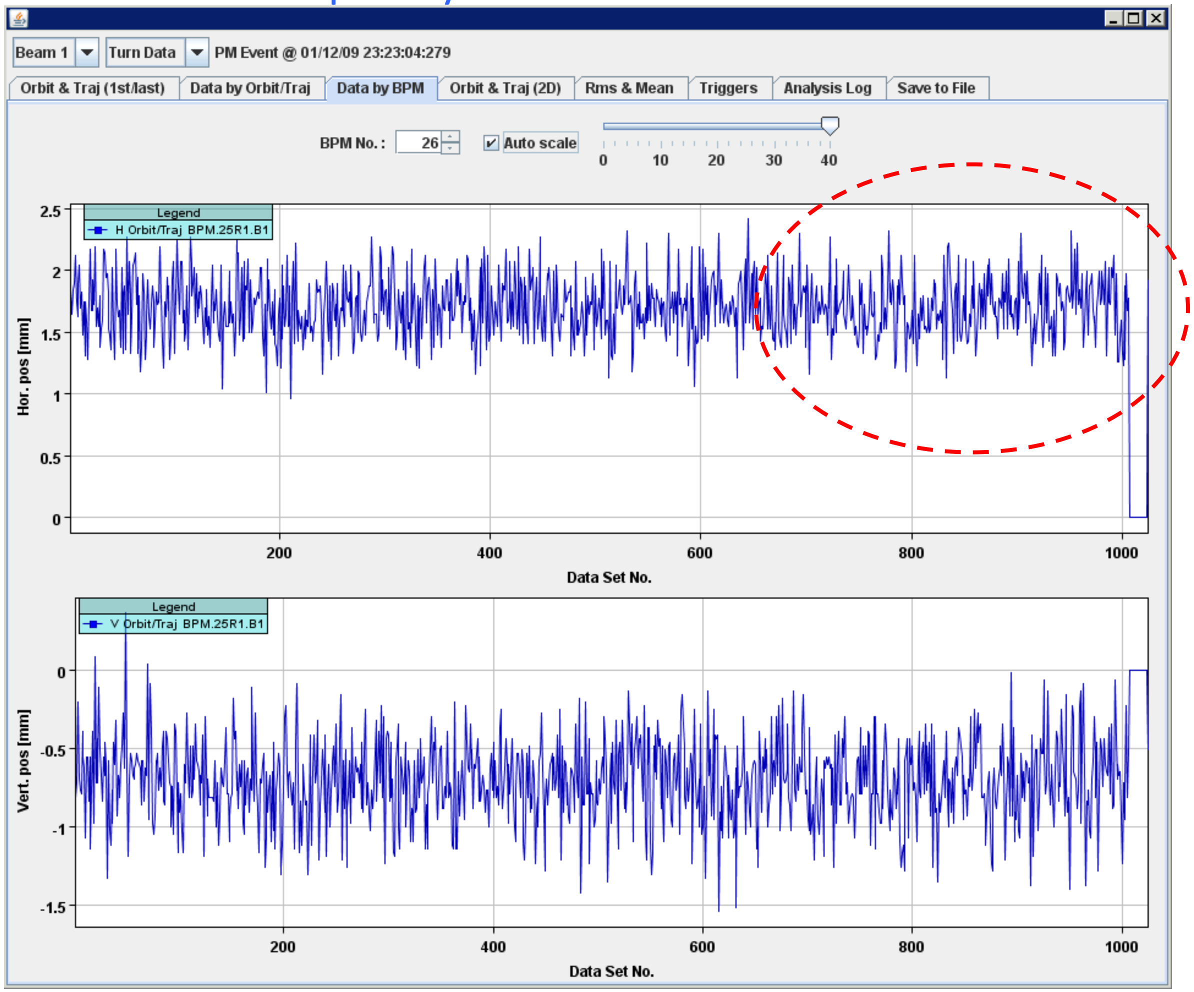
- Low intensity beam test.
- Trajectory evolution after OFF send to RD1.LR1, with FMCM masked
- Beam dumped by BLMs in IR7



- Trajectory over 1000 turns at a BPM
- Position change of ~1.5 mm over last 250 turns

FMCM Beam Tests for D1 IR1/5

- Low intensity beam test
- Trajectory evolution after OFF send to RD1.LR1, with FMCM active
- Beam dumped by FMCM



- Trajectory over 1000 turns at a the same BPM
- No position change visible within resolution

>> The redundant protection is working

- Magnet powering and Protection
- Commissioning of Powering Protection Systems
- Failures captured by powering protection
- **Electrical perturbations vs powering protection**
- What could put safety @ risk ?

FMCMs and mains disturbances

- Beams dumped upon >10 occasions by FMCM following network perturbations, 7 of which happened AFTER the start of the ramp

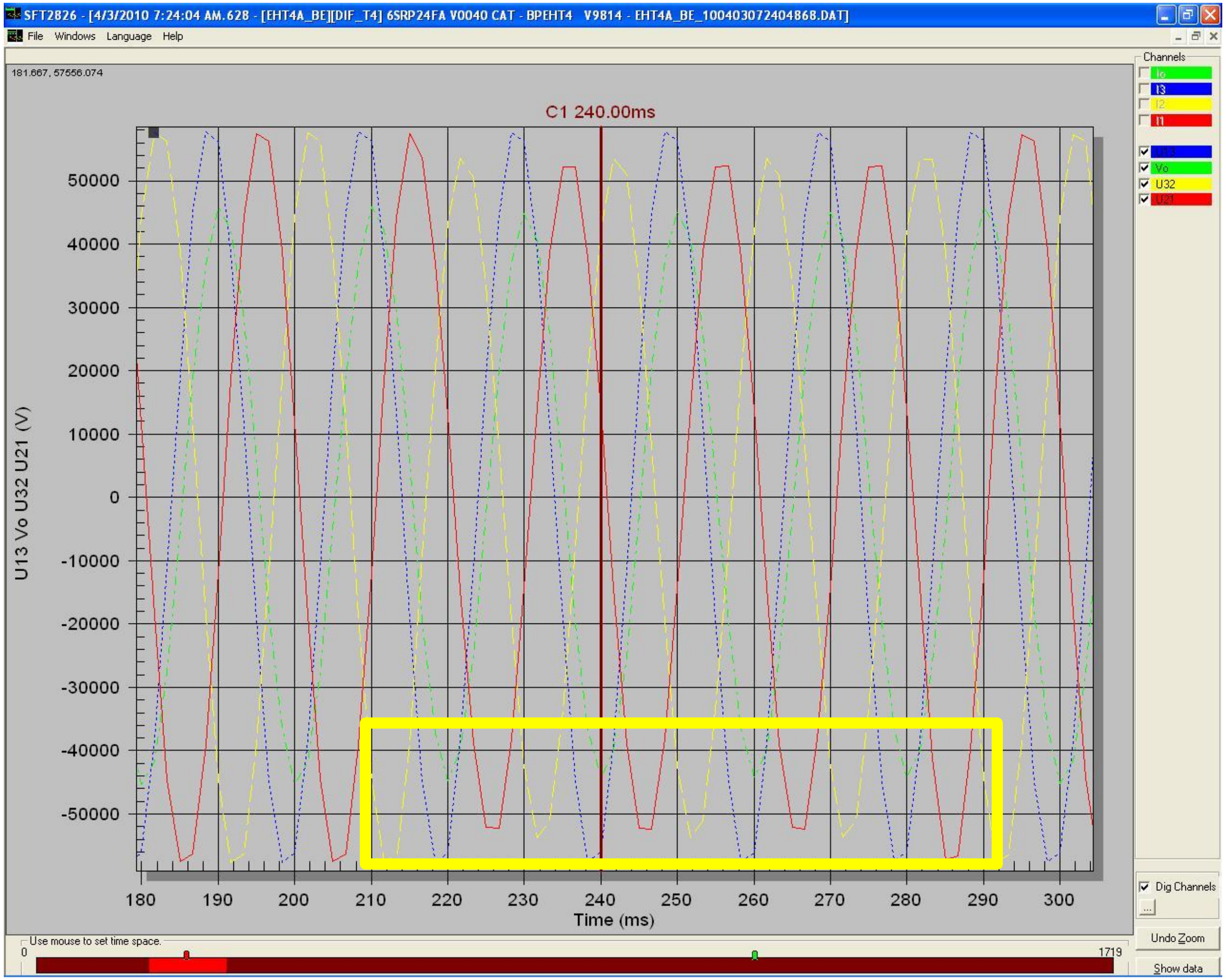
- Network perturbations were mostly traced down to external sources (thunderstorms, etc…)

- All trips happened at flat top (either injection or 3.5TeV) and did mostly not result in self-trips of power converters (apart from 2 events, one of which tripped both RD1s, RD34s and the ALICE and LHCb dipoles, LHC Coll and RF equipment)

- All triggers were correct, as current changes exceeded specified values

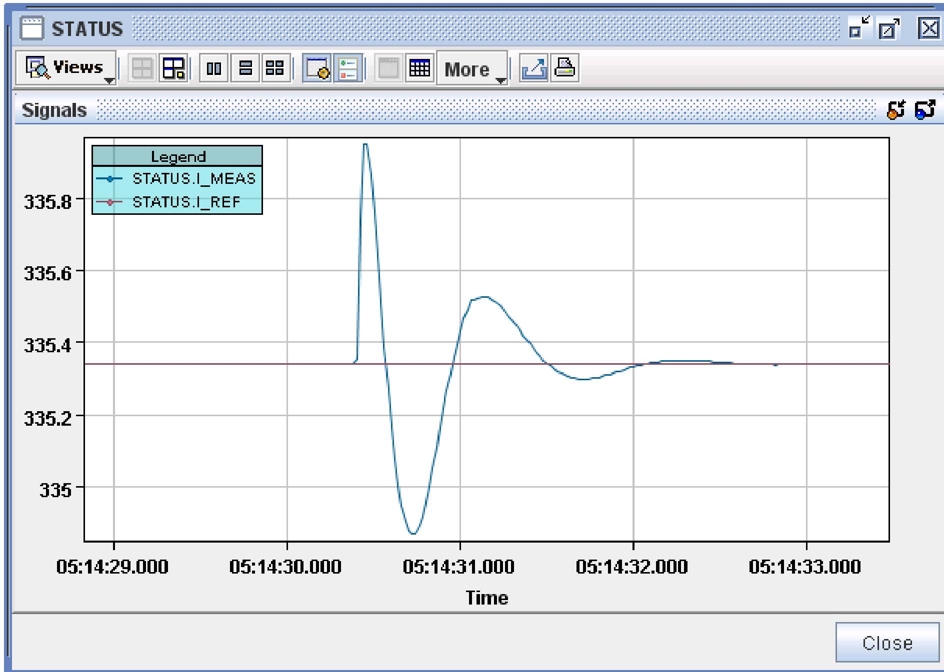
- Mains perturbations seen in all circuits, but current intensities and setup do not yet induce considerable beam movements or losses, but might look well different later (and if happens e.g. during ramping)

03-APR-10 07.24.04 AM – Fault in 400kV S phase -40kV , 30ms



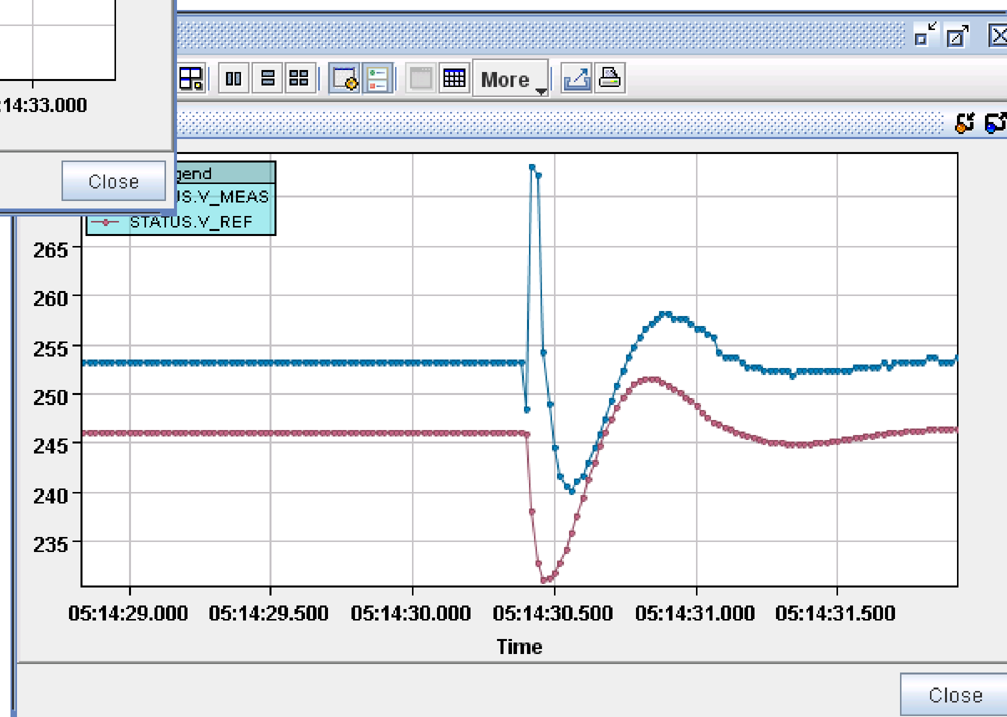
Courtesy of D.Arnoult
Typical perturbation originating in 400kV (2 phases, V dip of ~15% for some 60ms)

19-APR-10 05.14.30.396000 AM – Trip of RD1s in IR1 an IR5



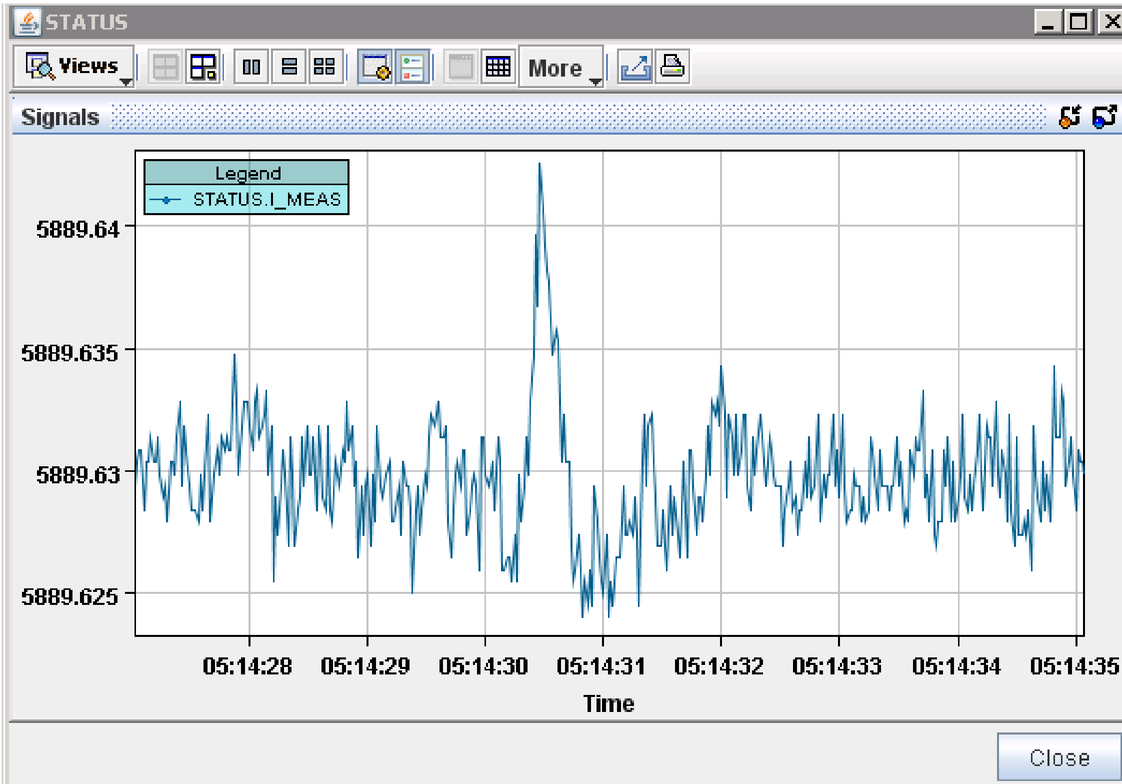
ΔI = 0.7A
ΔI /I = 2 •10E-3

ΔV = 20V
ΔV /V = 8 •10E-2



FMCM:
Measured excursion > 8
Threshold : 0.4

19-APR-10 05.14.30.396000 AM – Perturbation on RB.A12

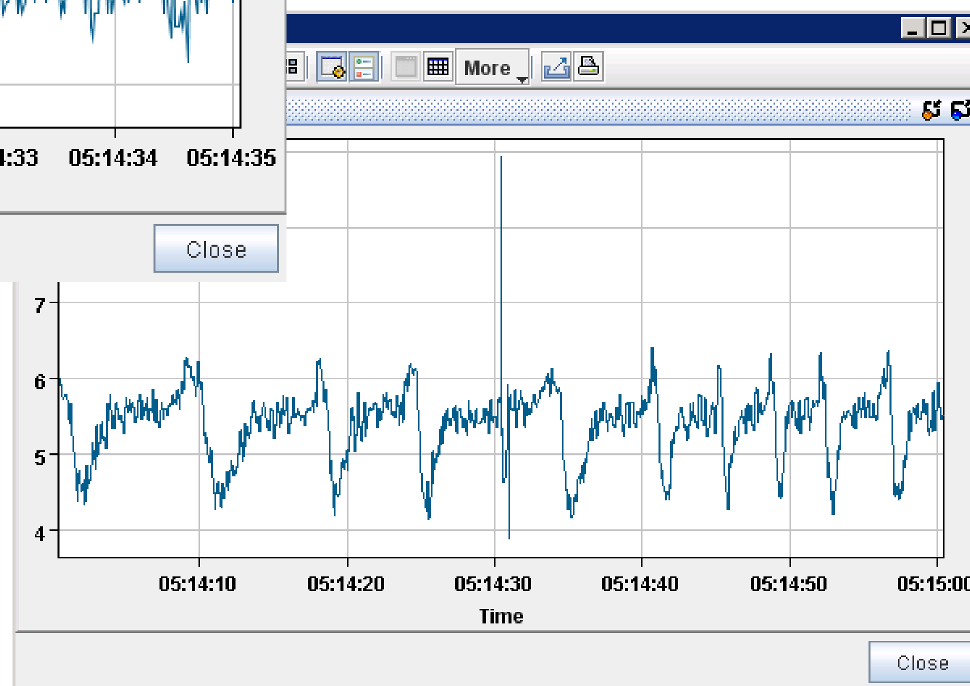


ΔI = 0.018A

ΔI /I = 3 •10E-6

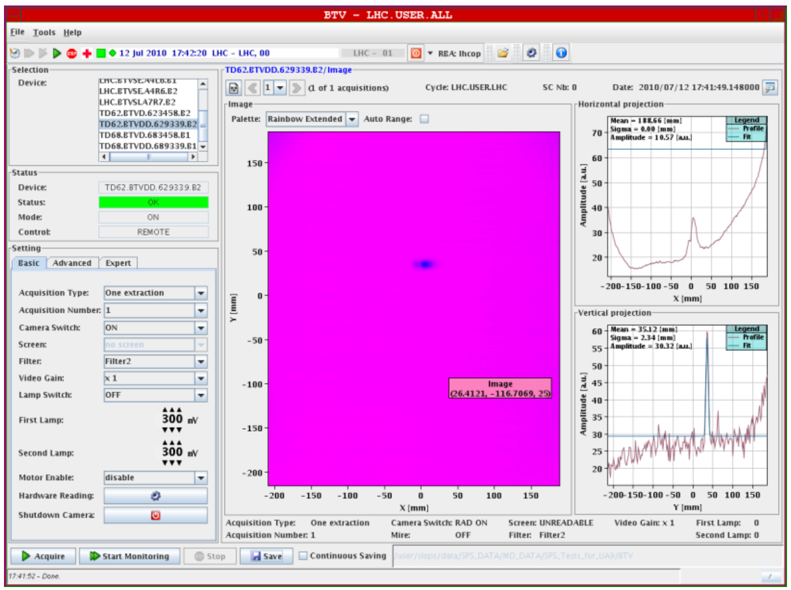
ΔV = 4V

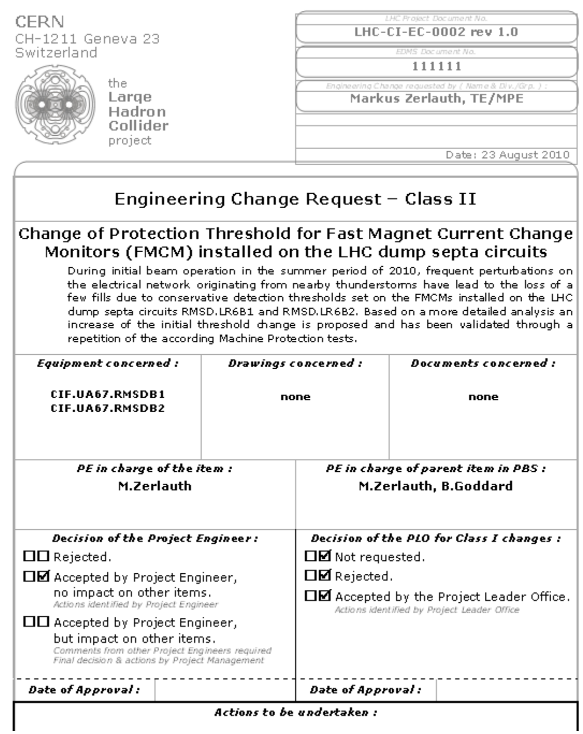
ΔV /V = 8 •10E-1



Dump septa magnets

- Dump septum magnets showed to be particularly sensitive to network perturbations at injection level
- 7 dumps of beams during summer months at injection during filling process following rathe minor network perturbations
- Initially conservative thresholds relaxed by a factor of 2 to increase availability (whilst fully maintaining required safety)





CERN
CH-1211 Geneva 23
Switzerland

the Large Hadron Collider project

LHC Project Document No.
LHC-CI-EC-0002 rev 1.0
EDMS Document No.
111111
Engineering Change requested by (Name & Div./Grp.) :
Markus Zerlauth, TE/MPE

Date: 23 August 2010

Engineering Change Request – Class II

Change of Protection Threshold for Fast Magnet Current Change Monitors (FMCM) installed on the LHC dump septa circuits

During initial beam operation in the summer period of 2010, frequent perturbations on the electrical network originating from nearby thunderstorms have lead to the loss of a few fills due to conservative detection thresholds set on the FMCMs installed on the LHC dump septa circuits RMSD.LR6B1 and RMSD.LR6B2. Based on a more detailed analysis an increase of the initial threshold change is proposed and has been validated through a repetition of the according Machine Protection tests.

Equipment concerned :	*Drawings concerned :*	*Documents concerned :*
CIF.UA67.RMSDB1 CIF.UA67.RMSDB2	none	none

PE in charge of the item :	*PE in charge of parent item in PBS :*
M.Zerlauth	M.Zerlauth, B.Goddard

Decision of the Project Engineer :	*Decision of the PLO for Class I changes :*
☐☐ Rejected. ☐☑ Accepted by Project Engineer, no impact on other items. *Actions identified by Project Engineer* ☐☐ Accepted by Project Engineer, but impact on other items. *Comments from other Project Engineers required. Final decision & actions by Project Management*	☐☑ Not requested. ☐☑ Rejected. ☐☑ Accepted by the Project Leader Office. *Actions identified by Project Leader Office*
Date of Approval :	*Date of Approval :*

Actions to be undertaken :

Repetition of MPS checks + ECR for documentation

- Magnet powering and Protection
- Commissioning of Powering Protection Systems
- Failures captured by powering protection
- Electrical perturbations vs powering protection
- **What could put safety @ risk ?**

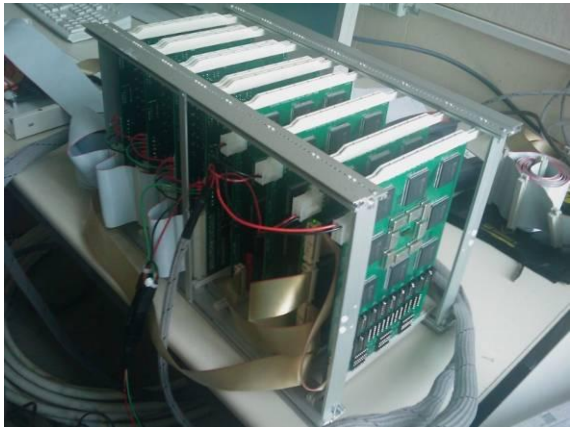
Dependability vs Interventions/Maintenance

- Current good experience is based on a very thorough hardware commissioning campaign, where all protection related features of installed HW have been tested and validated for operation
- During technical stops, interventions, etc... we exchange, upgrade, fix (powering) protection related equipment without systematically requalifying the equipment and protection functionalities (after exchange of power modules, QPS cards, etc..)
- Currently missing clear tracability of changes to protection related systems or clear guidelines/documentation for revalidation of equipment

- Post operational checks for PIC and FMCM included in Post Mortem analysis
- Automated interlock tests exist (as used during HWC) and could/should be integrated into LHC operation on a regular bases (after interventions and e.g. on monthly basis)

Radiation to Electronics

- Recent simulations suggest that radiation might become an (availability) issue in some of the underground areas (e.g. industrial components of the PIC and WIC PLCs are known to be sensitive)
- Upon one occasion experienced a memory curruption in one of our PLCs which resulted in a false dump from the PIC during an end of fill test @ 3.5 TeV
  - No correlation to losses/radiation could be established...
  - Fail safe logic + full redundancy for beam dump requests will maintain safety
- New R2E studies propose relocation of some PLCs
  - UJ56, UJ14, UJ16: Relocation of interlock equipment already prepared
  - US85: WIC to be relocated to UA83 (in progress , before end 2010)
  - TI8: WIC to be relocated upstream of collimator (in progress, before end 2010)
- In-house electronics has been shown to be adaequat for expected radiation levels (e.g. in RRs). Dedicated CNGS rad test for XC95144 (will start investigation of rad tolerant version)



Related recommendations from 2005 Review

- Major worry about Configuration Management in protection systems
  - By design interlock systems do NOT rely for their basic protection functionality on SW and/or configuration data, but direct HW links (including FPGAs)
  - Configuration data exists for higher level protection functions (using SW repositories, versioning, CRCs + run-time verifications)

- Sufficiently quick response time of power converter in case of internal failures ?
  - Experience shows that all power converter faults (MCB faults, water, ….) are caught before current is ramping down and losses occur

- Power converters causing most of problems during the startup of other machines, due to initial period of infant mortality of high power components
  - Could be minimized through extensive operation of the power converters before beam operations

Conclusions

- Very good experience with powering interlock systems, already > 4 years of operation (starting with initial HWC for PIC+WIC, CNGS tests for FMCM)
  - Dependable and fast (no critical component failure in > 4 years)
  - Providing required redundancy to BLM system (avoid beam loss / orbit changes for all observed failure cases)
- Few adjustments to FMCM thresholds have been done following operational experience in 2010 to improve machine availability
- Should implement more rigorous approach for IPOCs and automated test sequences, ie execution on a regular basis
- Need to define clear maintenance/ intervention procedures and eventually define tests needed for revalidation
- R2E developments are being followed up but not a (major) concern

THANKS FOR YOUR ATTENTION