FMCM sensitivity to mains perturbations - Should and can we do something?

TE/MPE/MI MPP 02nd September 2011

M. Zerlauth

0v1

Protection requirements

FMCM Nr	Converter name	Used in the Transfer Line LHC Insertion	Circuit is ramped using cycle Type	di/dt max [A/s]	Inom max [A]	I max DCCT [A]	Imax Conv.	Precision (+/-) of Imax	Load R mΩ	Load L mH	Umax Conv.	Detection Level (+/-) of Imax	Detection Time ms	Temperature effect on flat top Adiabatic calculation! K/s
1	MST 6177M	TT60	TI2 ~ TI8		7200	7500	7500	1*10-4	3.21	0.039	59	5*10-3	0.1	8.587
2	MSE 6183M	TT60	TI2 ~ TI8		22000	24000	24000	1*10-4	3.59	0.083	80	5*10-3	0.1	14.605
3	MBB 2015M	TI2	TI2 ~ TI8		3690	4400	4400	5*10-5	16	20	160	3*10-3	2.7	0.322
4	MBI 2213M	TI2	TI2 ~ TI8		5150	5400	5400	5*10-5	290	224	1800	3*10-3	2.7	0.184
5	MBIBH 2931M	TI2	TI2 ~ TI8		725	800	810	5*10-5	477	618	450	3*10-3	7.9	0.114
6	MSIB 2952M	TI2	TI2 ~ TI8		950	1000	1620	1*10-4	107	124.6	210	3.5*10-3	3.5	0.149
7	MSE	TT40	CNGS & TI8		22000	24000	24000	1*10-4	3.59	0.083	80	2*10-3	0.1	14.605
8	MBHC 4001M	TT40	CNGS & TI8		900	1000	1000	1*10-4	225	227.4	300	5*10-3	5.1	0.573
9	MBHA 4003M	TT40	CNGS & TI8		1000	1100	1000	1*10-4	184	480	550	1*10-3	5.0	0.073
10	MBI 8160M*	TI8	TI8		5250	5400	5400	5*10-5	528	472	3600	3*10-3	2.7	0.191
11	MBIAH 8783M	TI8	TI8		900	1000	1000	1*10-4	319	840	600	3*10-3	7.9	0.059
12	MSIB 8813M	TI8	TI8		950	1000	1620	1*10-4	102	124.6	210	3.5*10-3	3.5	0.149
13	MBSG 4100M	TI8 / CNGS	CNGS & TI8		3810	4400	6000	1*10-4	57	60	510	1*10-3	4.0	0.458
14	MBG 4101M*	CNGS	CNGS MBG		5100	5400	5400	5*10-5	402	416.1	3600	6*10-4	4.0	0.339
15	RD1.LR1	IR1	LHC	2.02	810	1000	810	1*10-4	854	1740	950	3.5*10-4	0.9	
16	RD1.LR5	IR5	LHC	2.02	810	1000	810	1*10-4	849	1740	950	3.5*10-4	0.9	
17	RMSD.LR6B1	IR6	LHC	8.25	880	1000	1000	1*10-4	529	855	600	5*10-4	1.0	
18	RMSD.LR6B2	IR6	LHC	8.25	880	1000	1000	1*10-4	529	855	600	5*10-4	1.0	
19	RD34.LR3	IR3	LHC	2.25	720	1000	810	1*10-4		2160	950	> 3.5*10-4	> 1.0	
20	RD34.LR7	IR7	LHC	2.25	720	1000	810	1*10-4		1440	950	> 3.5*10-4	> 1.0	

- Today 12 LHC devices and 16 in SPS-LHC transfer lines installed
- Required detection level in the order of 5E-4 of nominal current in <=100µs ->

Very demanding and tight tolerances (worst case, i.e. 7TeV, nominal intensity,…)

Protection requirements (II)

Bending magnets

	Injection (450 GeV)							
			Short circuit		Constant dI/dt		Max ΔV	
	β_{col} [m]	β_{magnet} [m]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]
MBXW	342	89	80.39	34.76	926.16	404.92	**3.24**	**1.41**
MBW (IR3)	342	165	85.05	36.91	527.70	230.71	**2.53**	**1.11**
MBW (IR7)	342	165	110.44	47.75	791.55	346.06	**2.51**	**1.10**
MCBWH	342	354	328.61	113.77	3736.94	1633.79	**7.73**	**3.36**
MCBWV	342	368	321.00	111.91	3665.17	1602.41	**7.58**	**3.30**

	Collision (7 TeV)							
			Short circuit		Constant dI/dt		Max ΔV	
	β_{col} [m]	β_{magnet} [m]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]
MBXW	355	2372	**3.88**	**1.70**	707.56	310.51	**3.88**	**1.70**
MBW (IR3)	355	165	21.36	**9.35**	2081.27	913.34	21.36	**9.35**
MBW (IR7)	355	165	27.59	12.08	3121.91	1370.02	14.99	**6.57**
MCBWH	355	354	62.18	26.16	14738.68	6467.91	20.80	**9.00**
MCBWV	355	368	61.25	25.79	14455.61	6343.68	20.43	**8.84**

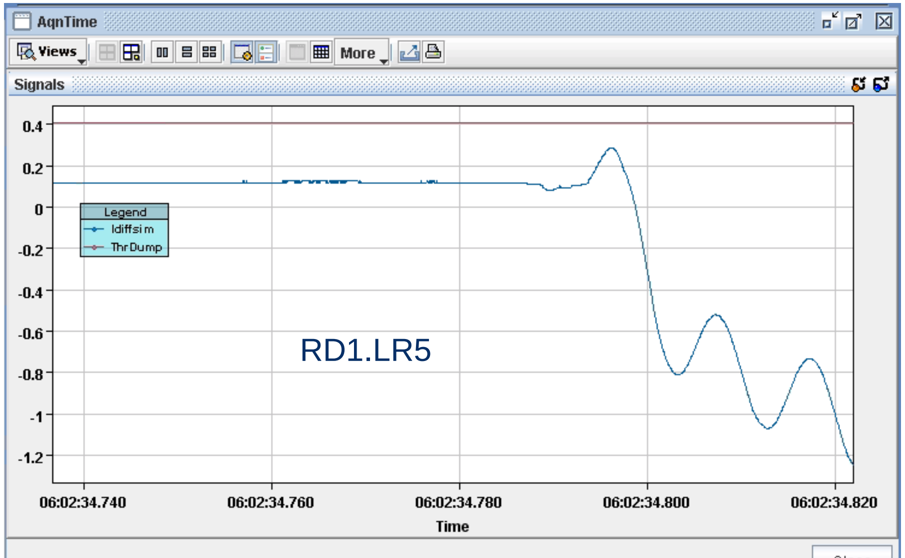
Courtesy of A.Gomez Alonso

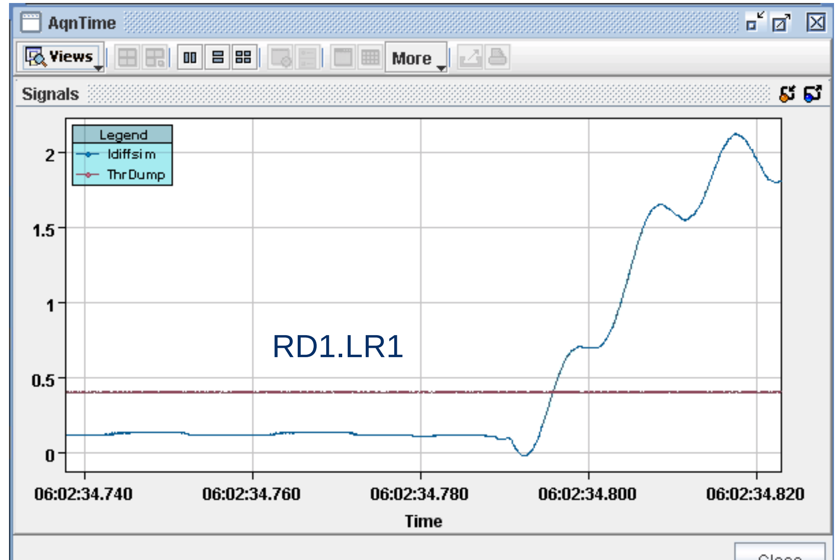
Operational Experience in 2011

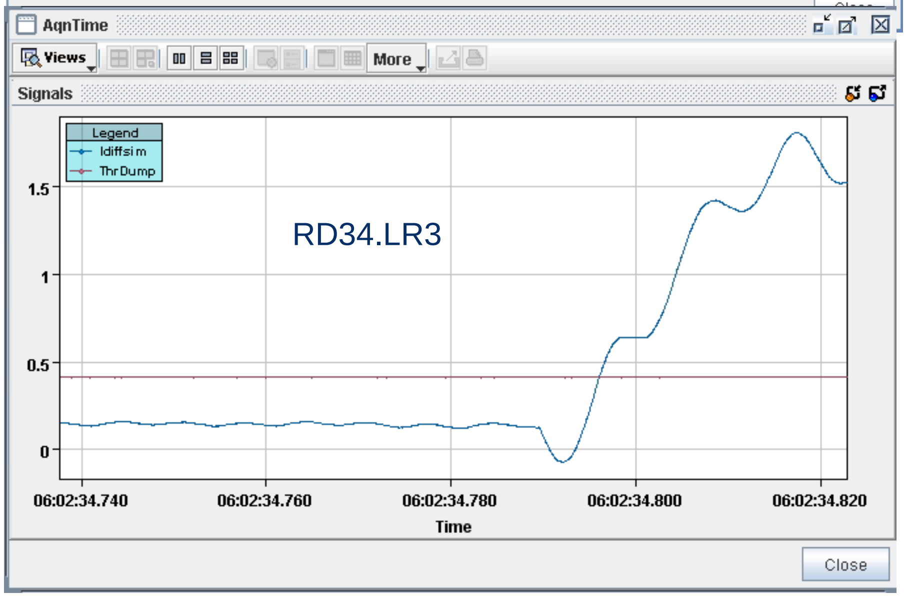
EVENT_TIMESTAMP	ENERGY	INT B1 / B2	Input Channel	Operator Comment
09-JUN-11 05.04.36	3500160	11478/11609	FMCM_RD1.LR5	Site wide electrical glitch (18kV line) caused FMCMs to trigger dump.
30-MAY-11 08.20.41	3500160	21/22	FMCM_RD1.LR5	Another glitch caught by FMCM
30-MAY-11 07.07.01	450120	1/0	FMCM_RD1.LR5	FMCM caught a glitch on the network
28-MAY-11 02.51.11	3500040	11389/11344	FMCM_RD1.LR5	Beam dumped again because of a disturbance caught by the FMCM of RD1.LR5.
28-MAY-11 12.25.29	3500160	11320/11313	FMCM_RD1.LR5	Beam dumped. TI operator confirmed noise on the electrical network.
16-MAY-11 06.40.58	736680	2438/2432	FMCM_RBXWTV.L2	trip of sector 56 and 81 due to electrical perturbation
14-MAY-11 03.56.32	450120	0/0	FMCM_RBXWTV.L2	Spurious AUG in TI2
09-MAY-11 05.40.41	450120	11/10	FMCM_RBXWTV.L2	ring wide electrical glitch seen by the FMCMs...only 1 nominal bunch in .dump OK
29-APR-11 04.43.30	450120	0/0	FMCM_RBXWTV.L2	Power glitch on the 400kV distribution.
29-APR-11 03.23.57	450120	0/0	FMCM_RBXWTV.L2	No beam in the machine. Glitch on the 400 kV.
24-APR-11 06.22.20	3500040	5086/5096	FMCM_RBXWTV.L2	Power glitch on the 400 kV line
16-APR-11 05.15.18	3500040	2626/2678	FMCM_RBXWTV.L2	electrical perturbation
14-MAR-11 07.19.03	3500160	30/31	FMCM_RD1.LR1	Electrical instability tripped warm magnet PCs
11-MAR-11 09.37.40	450120	0/0	FMCM_RMSD-b2	SMP test: switch off of RMSD.LR6B2.
11-MAR-11 09.29.23	450240	0/0	FMCM_RMSD-b1	SMP test: switch off of RMSD.LR6B1
10-MAR-11 12.24.37	3500160	1/2	FMCM_RQ5.LR3	MPS test at 1.5 m with RQ5.LR3 (PC OFF) - OK.
09-MAR-11 09.00.50	3500040	1/1	FMCM_RD34.LR7	EOF test for FMCM by switching OFF RD34.LR7.
03-MAR-11 01.05.01	3500160	2/1	FMCM_RD1.LR5	MPS test on RD1.LR5 at 3.5 TeV and b* 1.5 m.
01-MAR-11 12.01.28	3500160	0/1	FMCM_RD1.LR1	MPS test with OC off on RD1.LR1 at 1.5 m beta*.
27-FEB-11 05.12.06	450120	0/0	FMCM_RBXWTV.L2	Beam dumped when LHCb dipole tripped because of a site wide electrical glitch.
24-FEB-11 02.01.23	450120	12/1	FMCM_RD1.LR5	Electrical glitch in Point 6, but the FMCM of RD1.LR5 triggered

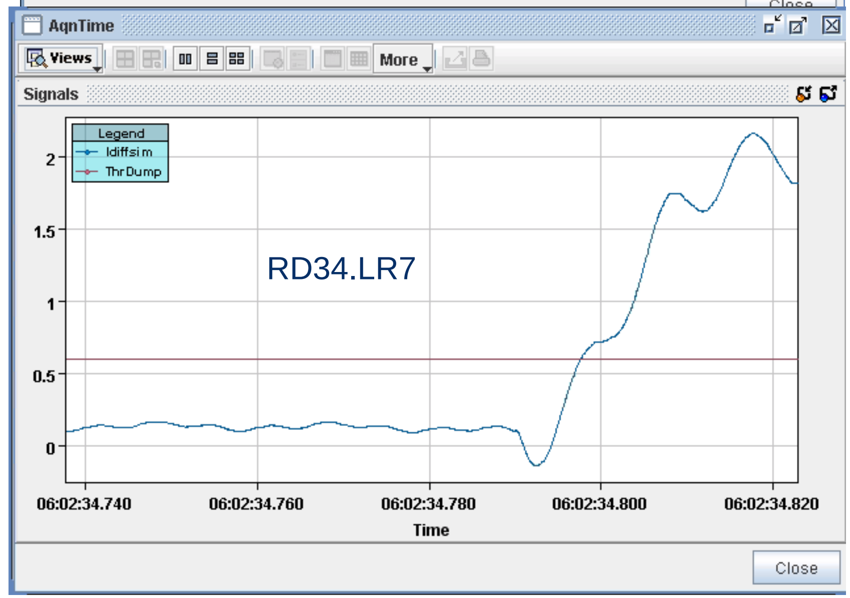
- 15 triggers, 7 @ 3.5TeV, 8 @ injection (6 without beam)
- 1 AUG, 14 electrical perturbations on the 400V/18kV/400kV networks (at least 3 accompanied by equipment trips) + 6 MPS tests

Example – Electrical Glitch 27th of July 2011 @ 06:02

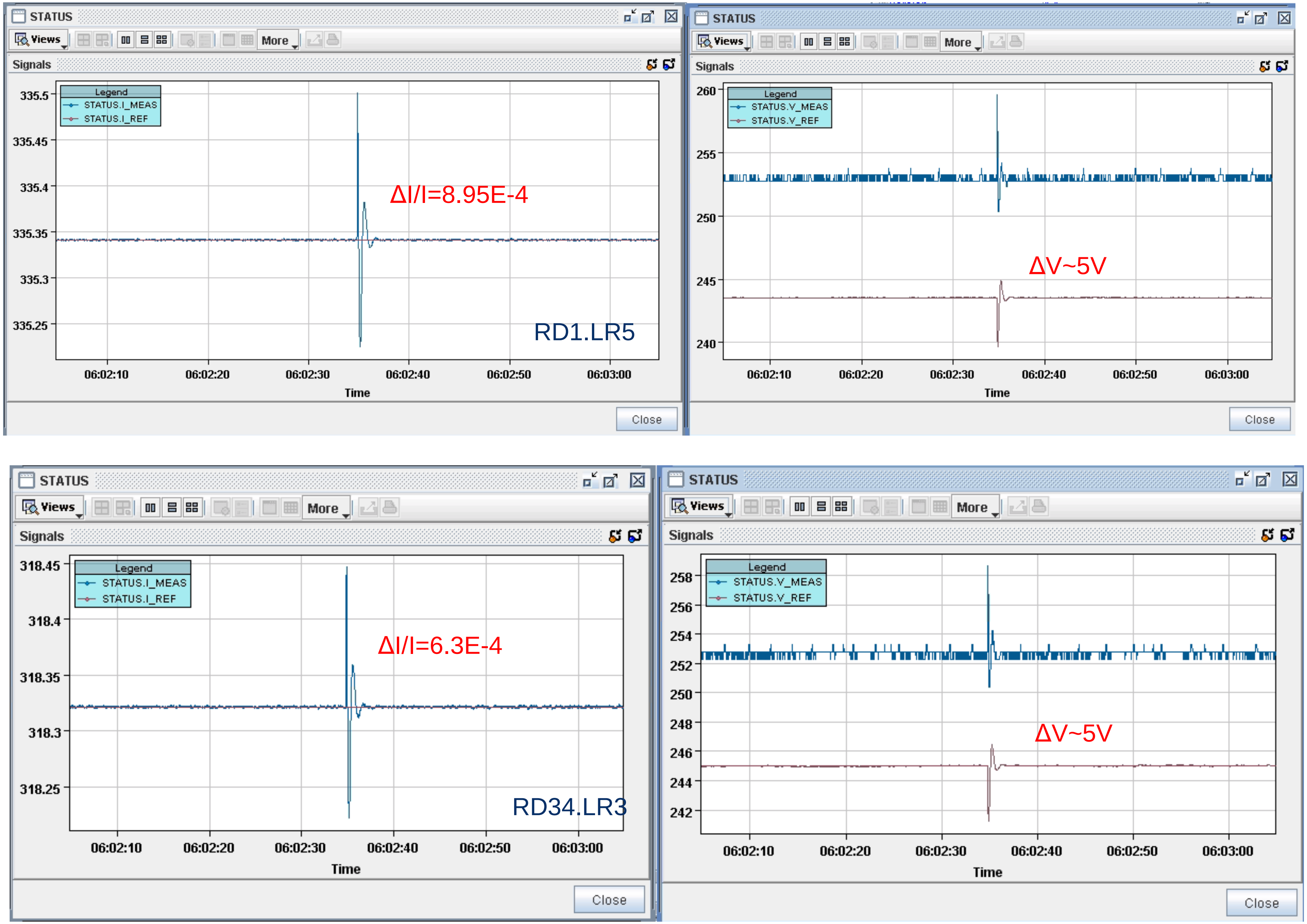








Glitch 27th of July 2011 @ 06:02 – Converter output readings



Are we too sensitive?

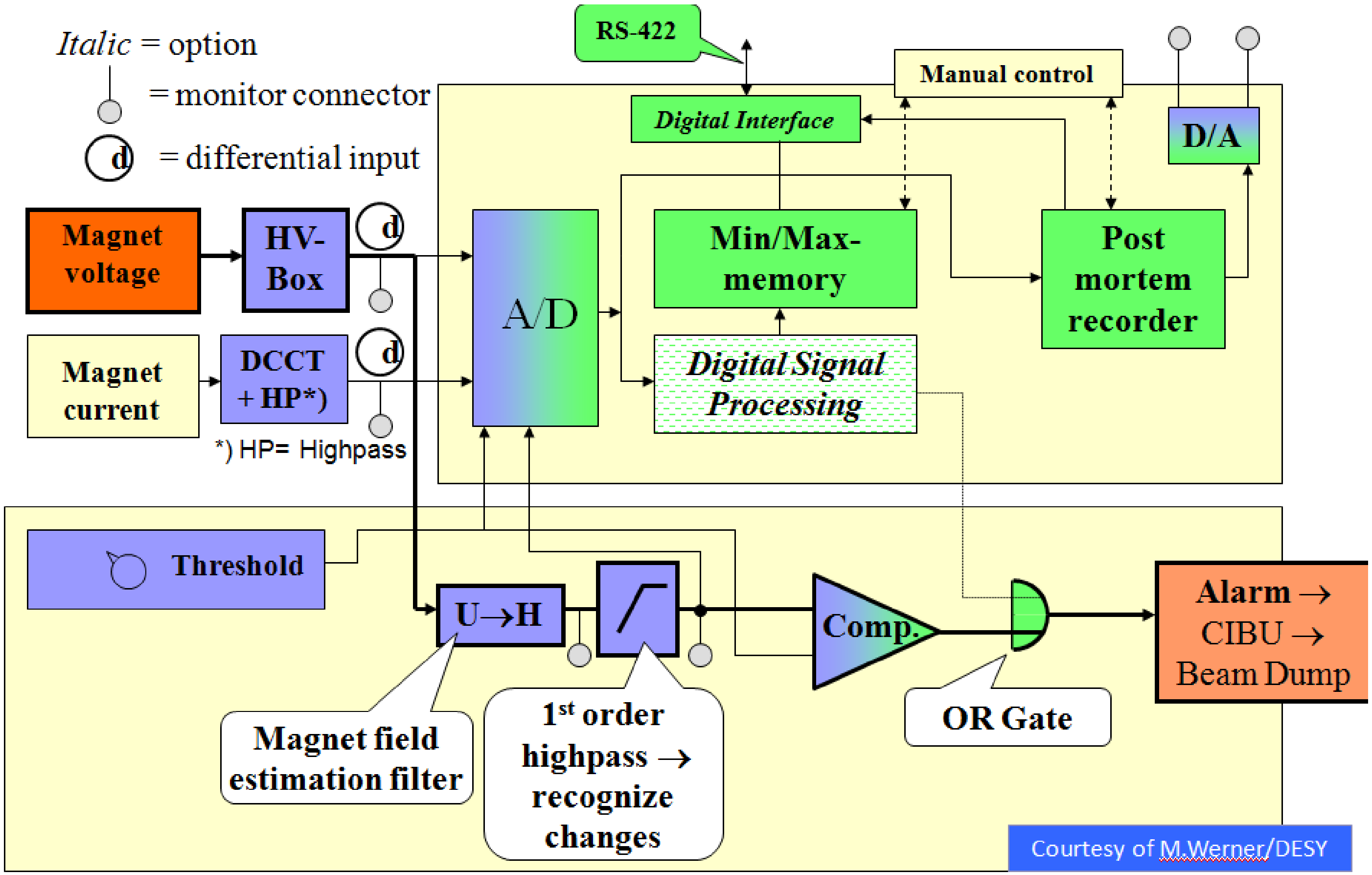
- FMCMs protect against ANY failure, leading to changes of the magnetic field, ie
  - Power converter failures
  - Short circuits in DC part
  - Failures of electrical supply chain (network perturbations, AUG, SVC ...) -> **beware of such common cause failures!**

- All FMCMs currently set to respect (tight) 7TeV thresholds also at injection (for max ΔV scenario)

- Experience shows that often beams are dumped by network perturbation (and consequent triggers of FMCM), without powering equipment physically tripping OFF

Are we more sensitive than required?
Can something be done to (safely) avoid some dumps?

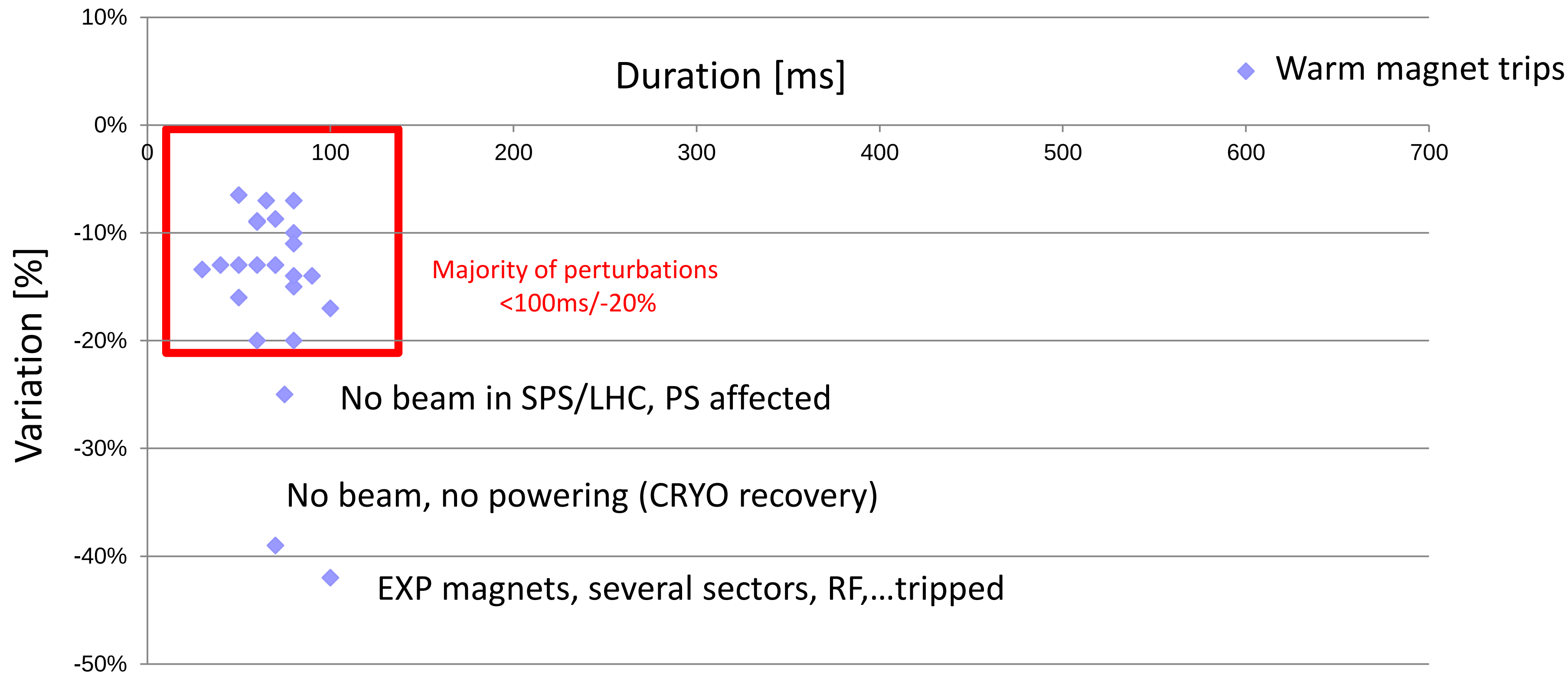
Reminder: FMCM schematics



- Based on Voltage measurement to be fast
- In addition to unfavorable impedance of the circuit (L<<), most nc magnet circuits are powered by a Thyristor Power converter (no intermediate energy storage!)
  - Perturbations are (almost) 1:1 put through

Typical distribution of network perturbations seen by FMCMs

Perturbations mostly traced back to short circuits in 440kV/225kV network, to >90% caused by lightning strikes (Source: EDF)



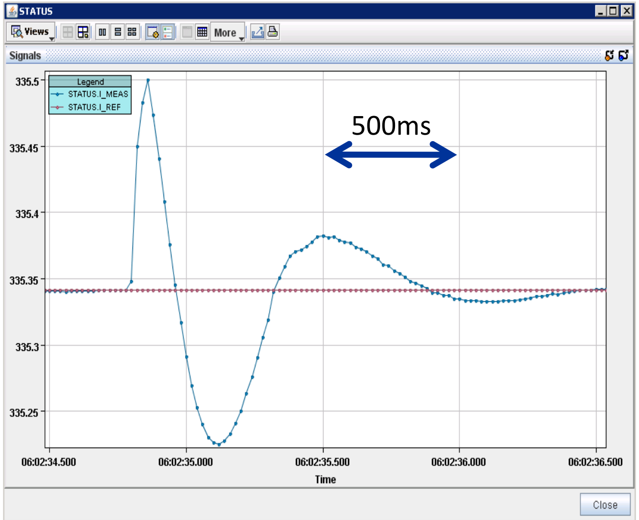
What devices trigger during these perturbations?

- Two basic event families concerning FMCM triggers:
  - Major event (almost all FMCMs trigger, and mostly accompanied by other equipment failures)
    - Favorable to keep tight thresholds -> See major network perturbation 18th of August, AUG event in TI2,…
  - Minor events where ONLY FMCMs trigger, typically RD1s and RD34s (sometimes RBXWT)
    - Area of possible improvements

- Only few possibilities to avoid FMCM triggers
  - Increase thresholds -> within the safe limits (delicate! -> See Slides of T.Baer)
  - Decrease perturbation seen by the magnet chain
    - Improve regulation characteristics of power converter/active filter
    - Change impedance of the magnet circuit
    - Improve converter rejection of perturbations

Reducing the perturbations seen by the magnet?

- Improving regulation characteristics of converter
  - Proofs very difficult for this type of converter, as FMCM triggers already on initial peak, well before regulation loop kicks in
  - EPC looking nevertheless into possibilities



- Adding sc solenoid
  - Very costly solution (>300kEuro per device)
  - Complex integration (CRYO, protection,…)
  - An additional 5 H would only 'damp' the perturbation by a factor of 4

- Improve converter rejection of perturbations
  - Possibility to replace the current thyristor power converter by a switched mode converters
  - Provides complete rejection of minor network perturbations (up to 100ms/-30%)
  - Plug-and play solution, ready for LS1

Conclusion

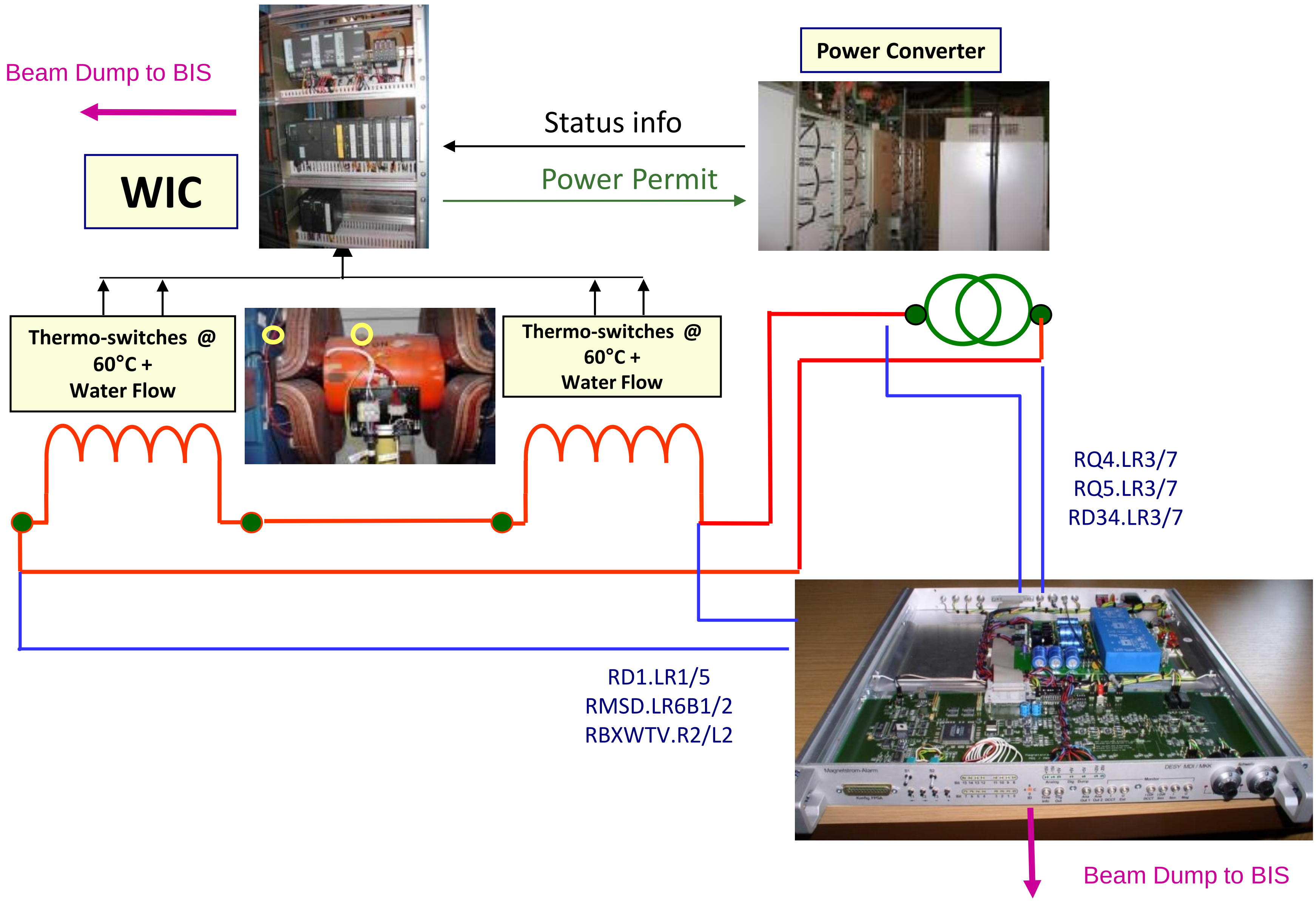
- Tight requirements for detection of current changes result in a certain number of FMCM triggers following network perturbations (often before equipment is affected)
- Choice of thresholds is trade-of between protection & availability
- So far NO unjustified trigger has been observed (apart from 1 component failure on RQ5.LR3)
- Current thresholds are conservative, but (mostly) needed to assure equipment protection
    - 2011 observations and simulations show that an increase of threshold in RBXWT and RD34 by a factor of 2-3 is probably still safe -> Only if validated with pilot beam tests (not for RD1!!)
- Most promising long-term solution for RD1 (and possibly RD34) seems an exchange of power converter

FIN

Introduction of the FMCM

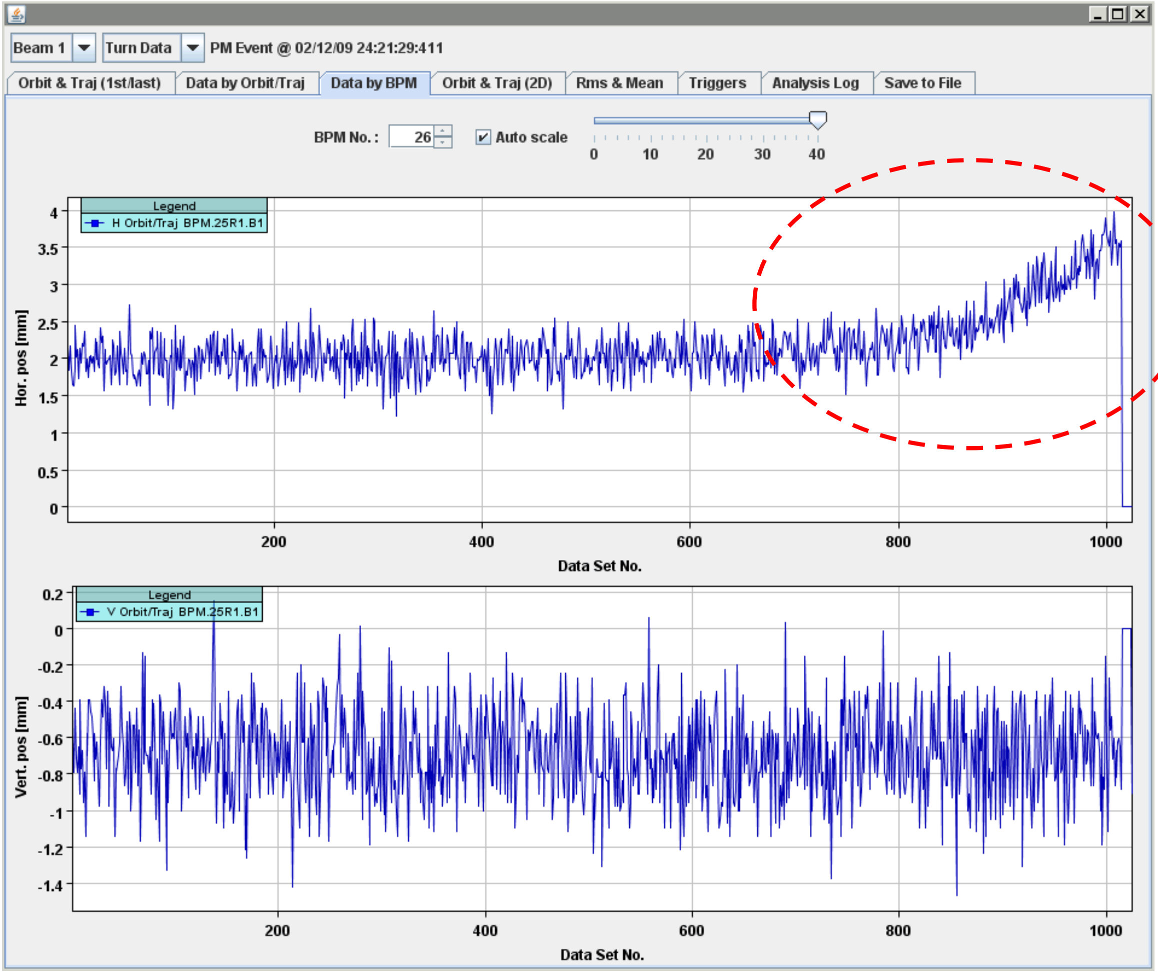
- Failures in the magnet powering system are generally SLOW and beams can be (easily) dumped before starting to extract energy
- Exception are failures in some of the nc magnets, which can generate the loss of 10E-5 * Np after some 10 turns only (MSE, MSI, MSD, D1, MBW, MBXWT...)
- Cannot be caught in time by converter controls or WIC (see as well TL incident in fall 2004)
- Introduced Fast Magnet Current change Monitors (FMCM) as reduncany to COLL+BLM
- Interlock on fast changes of current, no absolute measurement!
- Interlock the beam, but do not stop magnet powering
- Intended to protect against ANY failure in magnet powering, leading to changes of the magnetic field, ie
  - Power converter failures
  - Short circuits in DC part
  - Failures of electrical supply chain (network perturbations, AUG, SVC ...) -> **beware of such common cause failures!**

Protection of nc circuits



FMCM Beam Tests for D1 IR1/5

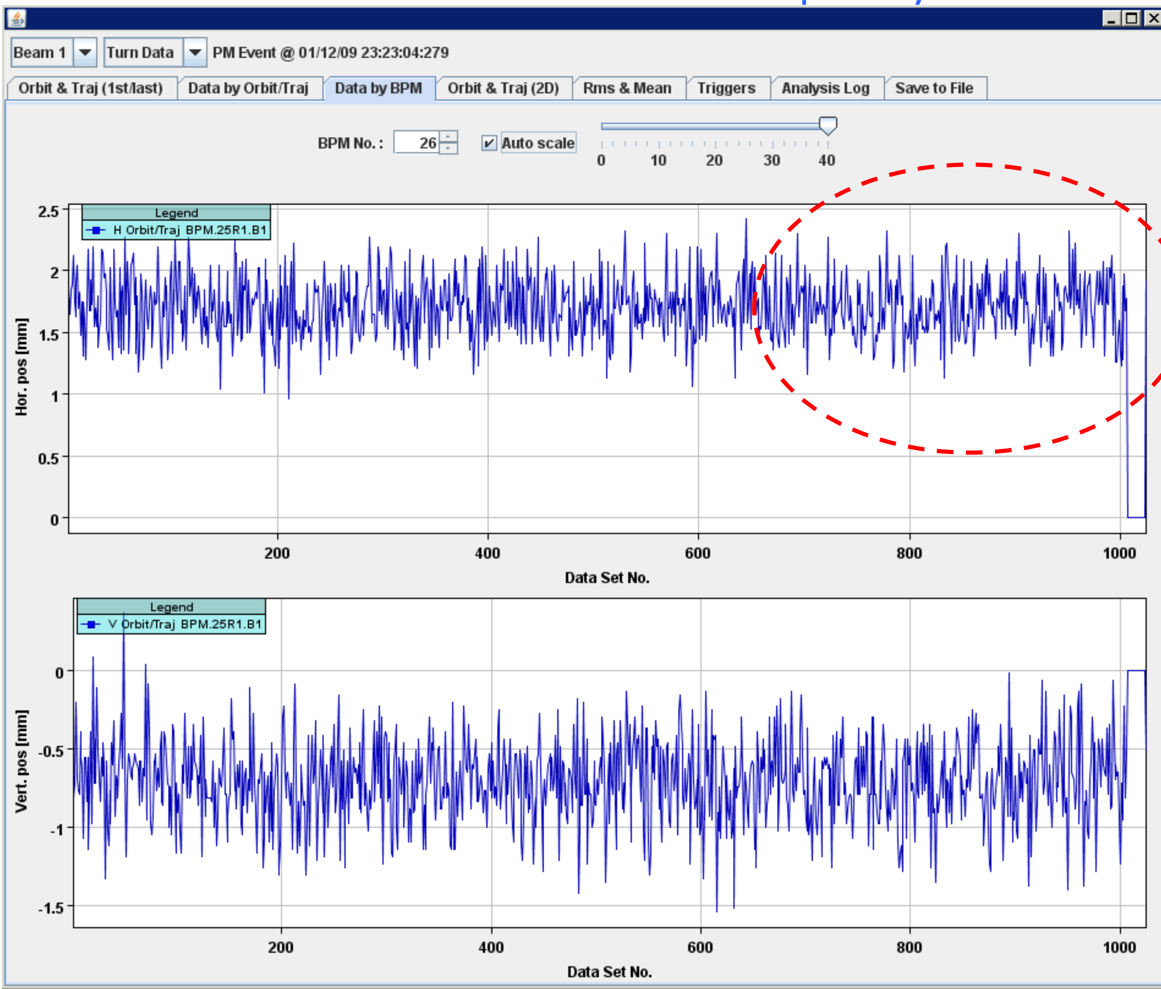
- Low intensity beam test.
- Trajectory evolution after OFF send to RD1.LR1, with FMCM masked
- Beam dumped by BLMs in IR7



- 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

Motivation for FMCM

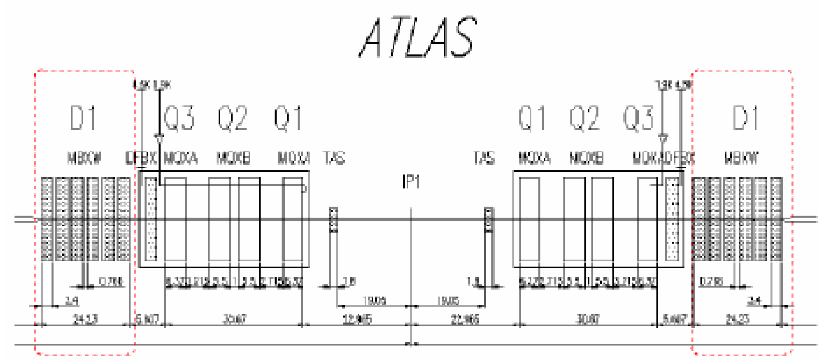
LHC - fastest scenario: trip of D1 @ IP1/IP5

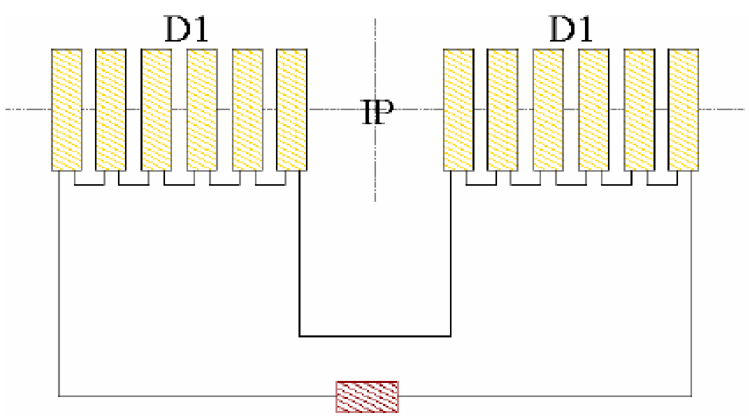
- Separation dipoles **D1** in **IR1** and **IR5**: normal conducting: 12 modules **powered in series**
- **βx > 2000m**
- power converter failure:

$$B(t) = B_0 \cdot e^{-\frac{t}{\tau}}$$

- time constant for D1

$$\tau = \frac{L}{R} \qquad \tau = 2.53s$$

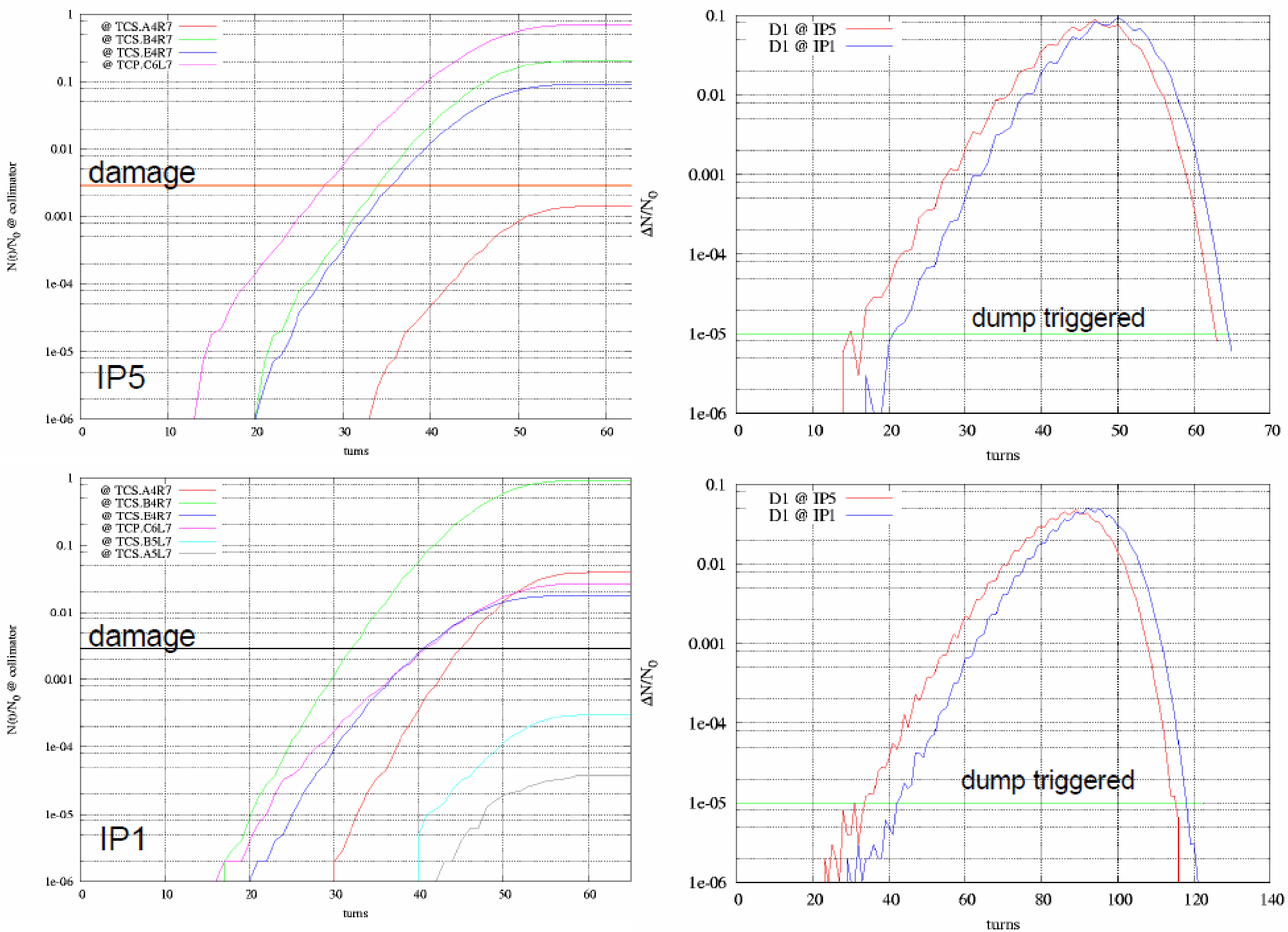




Courtesy of V.Kain

Markus.zerlauth@cern.ch

Studies of Fast(est) LHC failures



Courtesy of V.Kain

Operational Experience in 2010 – 1/2

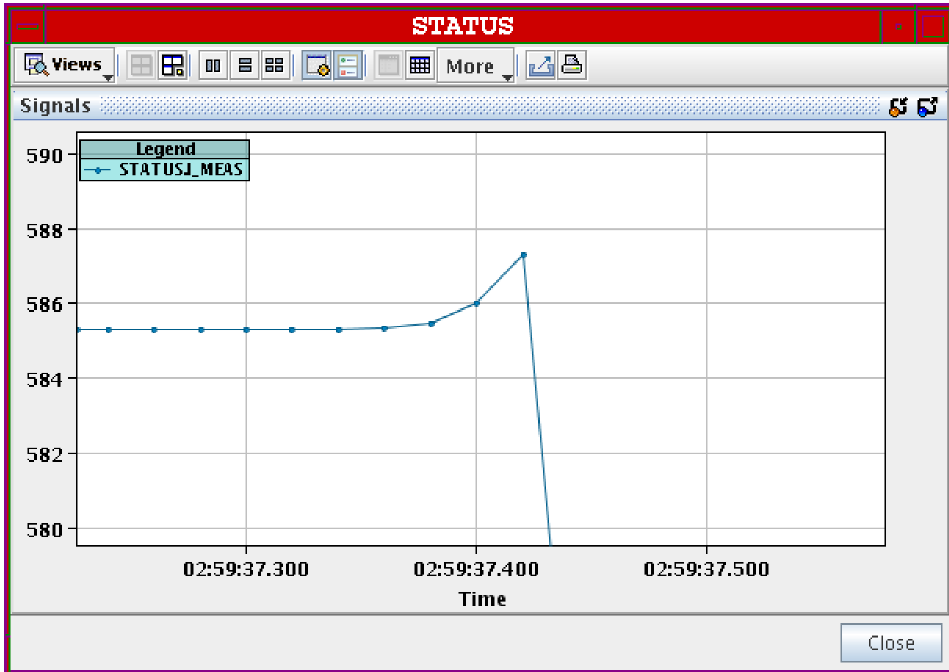
18-MAY-10 05.35.42	3500280	12/12	FMCM_RBXWTV.L2	Glitch on EDF power grid. Few warm magnets lost.
12-MAY-10 06.32.26	450120	0/0	FMCM_RMSD-b1	Power glitch...
10-MAY-10 10.48.44	450120	0/0	FMCM_RMSD-b1	Fast current change due to an electrical perturbation over the network
07-MAY-10 06.15.36	450120	0/0	FMCM_RMSD-b2	B2 dumped by switching MSD OFF. Beam dumped OK
07-MAY-10 06.12.49	450120	0/0	FMCM_RMSD-b1	B1 dumped by switching MSD OFF. Beam dumped OK
02-MAY-10 02.59.37	450240	11/12	FMCM_RBXWTV.L2	Clean dump
01-MAY-10 05.50.32	450120	0/0	FMCM_RMSD-b1	FMCM on MSD pulled the dump but analysis OK
19-APR-10 05.14.30	3500280	1/1	FMCM_RD1.LR1	Perturbation of the electrical network caused problems in the channels of most points.
15-APR-10 05.55.43	3500280	1/0	FMCM_RQ5.LR7	MPS test on RQ5.LR7 (PC off to test reaction of FMCM) - Test passed.
13-APR-10 09.51.26	3500280	1/1	FMCM_RD1.LR5	We switch off RD1.LR5 to study the FMCM
11-APR-10 01.52.11	3500280	1/1	FMCM_RD1.LR1	MP test at top energy. RD1.L1 sent to OFF -> correctly caught by FMCM.
07-APR-10 06.46.58	450120	0/0	FMCM_RMSD-b1	Dump septum current glitch
03-APR-10 07.24.04	3500280	1/2	FMCM_RD1.LR5	Beam dump due to pertbation of on power network
27-MAR-10 02.46.20	450240	0/0	FMCM_RMSD-b2	MPS test on RMSD-b2. Looks good but must be analysed by XPOC team.
22-MAR-10 12.17.13	450240	0/0	FMCM_RD1.LR1	MPS test, sending an OFF command to RD1.LR1. beam dumped as expected, no losses.
10-MAR-10 01.40.24	450240	0/0	FMCM_RQ4.LR3	MPS test on FMCM RQ4.LR3
10-MAR-10 12.52.44	450240	0/0	FMCM_RD34.LR7	MPS test for FMCM on RD34.LR7 (PC off)
10-MAR-10 12.26.07	450240	0/0	FMCM_RD1.LR1	MPS test on RD1.LR1 at 450 GeV

Operational Experience in 2010 – 2/2

EVENT_TIMESTAMP	ENERGY	INT B1 / B2	Input Channel	Operator Comment
26-NOV-10 09.52.35	3500040	90/85	FMCM_RD1.LR5	Perturbation on electrical network. FMCM triggered beam dump.
15-NOV-10 08.44.38	3500160	102/98	FMCM_RD1.LR5	FMCM at point 5 dumped the beams due to an electrical perturbation on the net
15-OCT-10 07.00.12	450120	0/0	FMCM_RBXWTV.L2	electrical perturbation tripped sector 81 without beam in
28-JUL-10 02.58.56	450120	0/0	FMCM_RD34.LR3	LBDS was armed but no beam in the machine - PM when preparing access
17-JUL-10 12.18.49	509040	127/123	FMCM_RBXWTV.L2	Beams dumped because of a glitch on the network-->FMCM
16-JUL-10 01.50.11	450120	38/0	FMCM_RQ5.LR3	FMCM in P5, no "real" electrical problem reported by TI.
16-JUL-10 01.26.34	450240	47/38	FMCM_RQ5.LR3	FMCM in P3. No "real" electrical issue reported by TI.
14-JUL-10 05.02.44	3500280	91/95	FMCM_RD1.LR5	Multiple FMCM triggers on electrical network glitch.
11-JUL-10 04.20.18	450120	9/0	FMCM_RQ5.LR3	Trip of FMCM on RQ5.LR3 due to unstable isolation amplifier.
11-JUL-10 02.57.30	450120	9/0	FMCM_RQ5.LR3	Trip of the FMCM
10-JUL-10 06.26.52	3500280	82/73	FMCM_RD1.LR5	ELectrical glitch on the power network seen by FMCM
10-JUL-10 02.56.06	450240	81/76	FMCM_RMSD-b1	Electrical glitch in P6 seen by the FMCM of the RMSD
04-JUL-10 01.35.44	3500160	56/60	FMCM_RD1.LR5	Electrical perturbation caught by the FMCM
03-JUL-10 08.24.20	450120	9/7	FMCM_RMSD-b1	electrical perturbation on the 18kV seen by FMCM of MSD in point 6
30-JUN-10 03.15.58	450120	0/0	FMCM_RBXWTV.L2	elctrical perturbation due to thunderstorm. several systems affected: collimators
11-JUN-10 02.41.38	450120	2/2	FMCM_RMSD-b1	looks like glitch due to lightning ... dump looks OK
26-MAY-10 09.47.54	3500280	9/8	FMCM_RD1.LR5	dump due to glitch on 18kV lines ... and FMCMs triggered

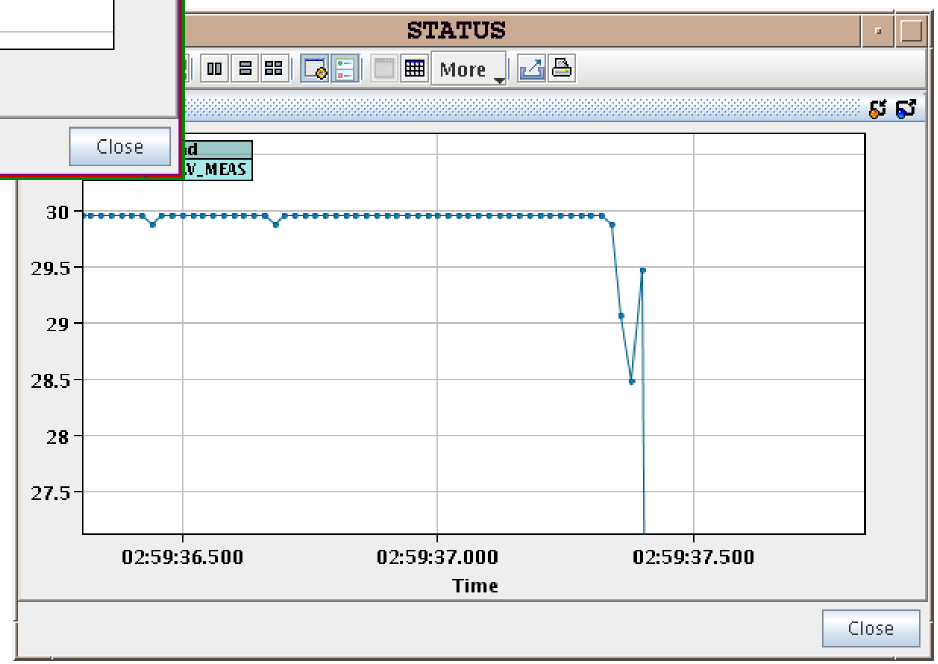
- 24 triggers, 10 @ 3.5TeV, 14 @ injection (7 without beam)
- 1 OP mistake, 4 due to a failing component, 19 electrical perturbations on the 400V/18kV/400kV networks (at least 3 accompanied by equipment trips) + 11 MPS tests

02-MAY-10 02.59.37.127000 AM – RBXWTV.L2 + others



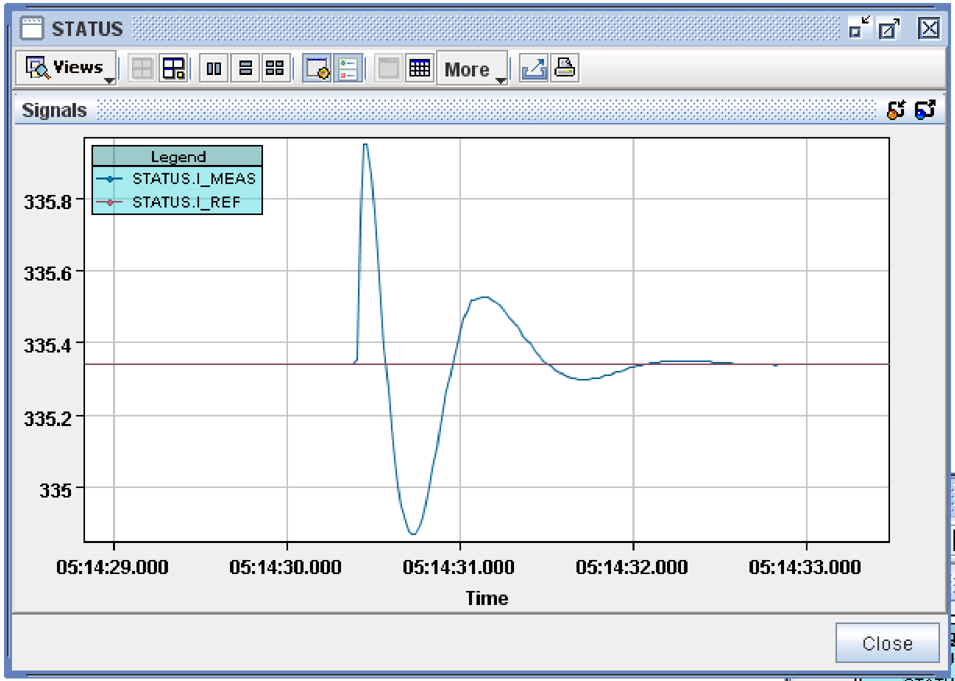
ΔI = 2A
ΔI /I = 3.4 •10E-3

ΔV = 1.5V
ΔV /V = 5 •10E-2



FMCM:
Measured excursion > 1.5
Threshold : 0.6

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

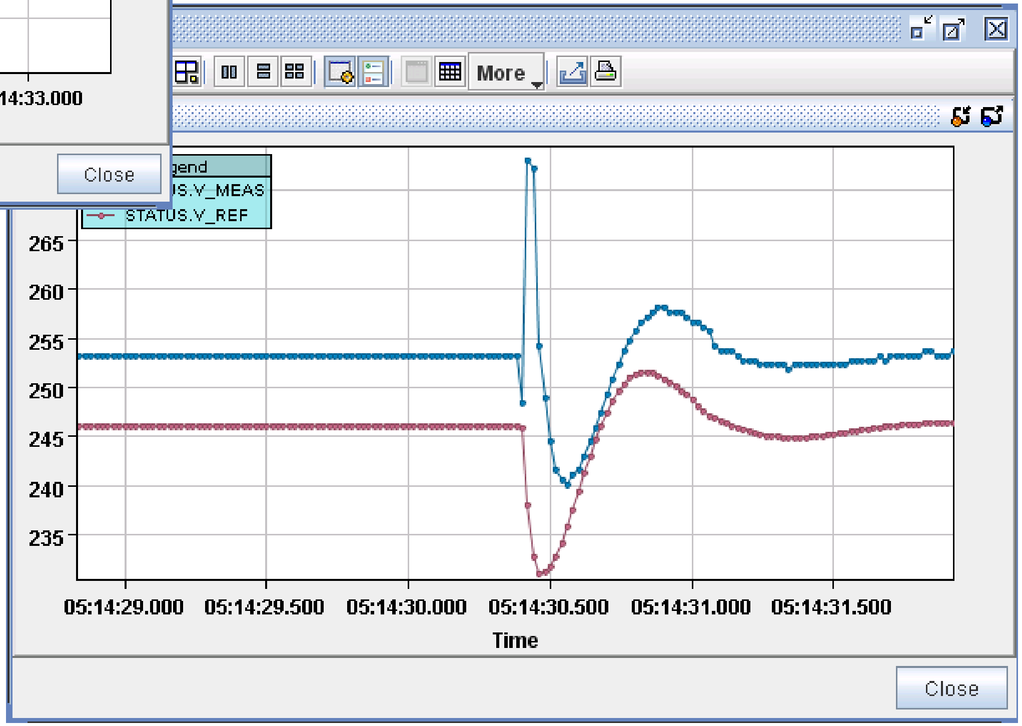


ΔI = 0.7A

ΔI /I = 2 •10E-3

ΔV = 20V

ΔV /V = 8 •10E-2

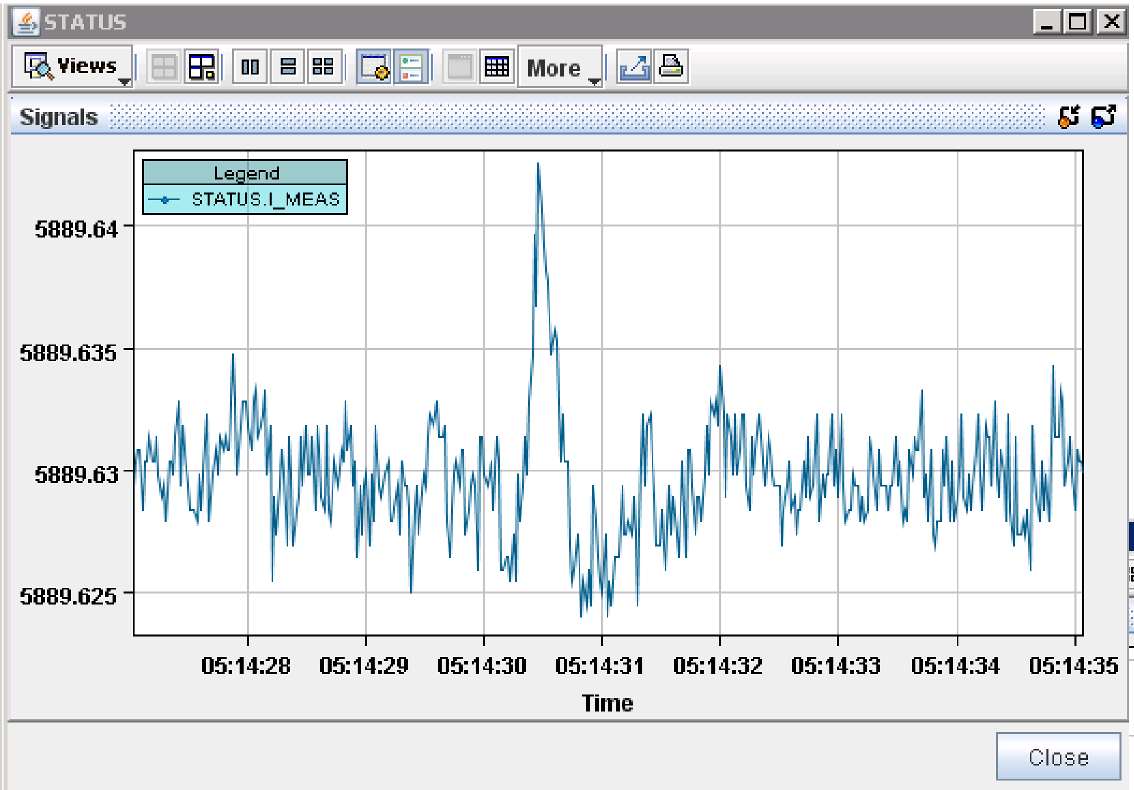


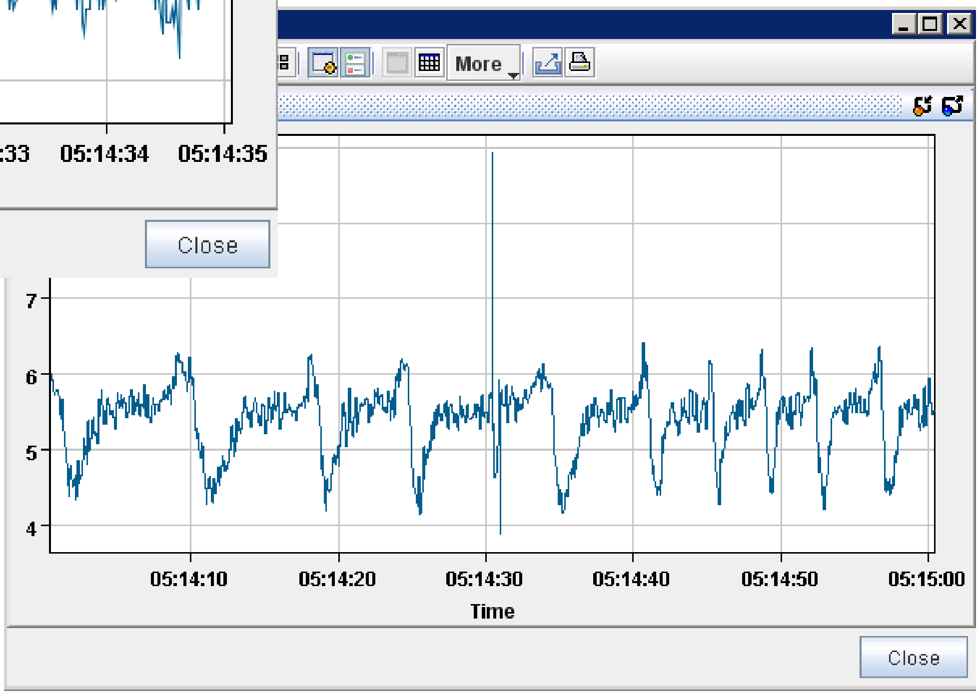
FMCM:

Measured excursion > 8

Threshold : 0.4

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





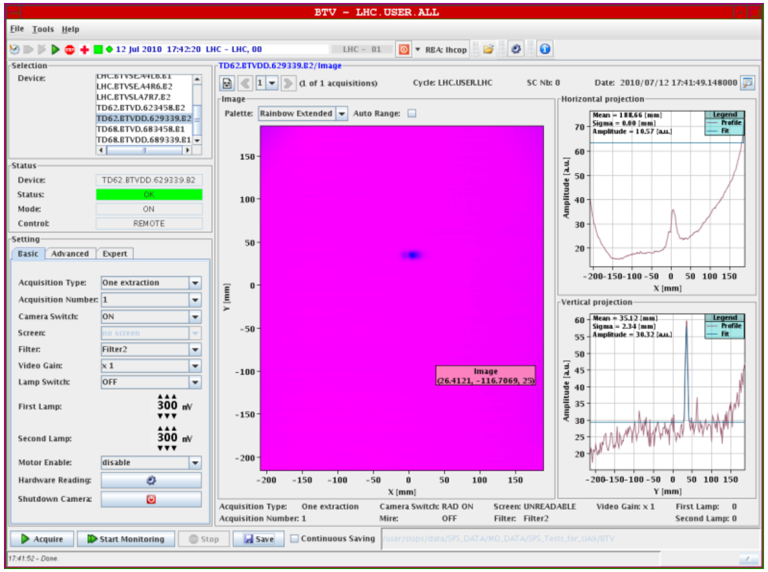
ΔI = 0.018A

ΔI /I = 3 •10E-6

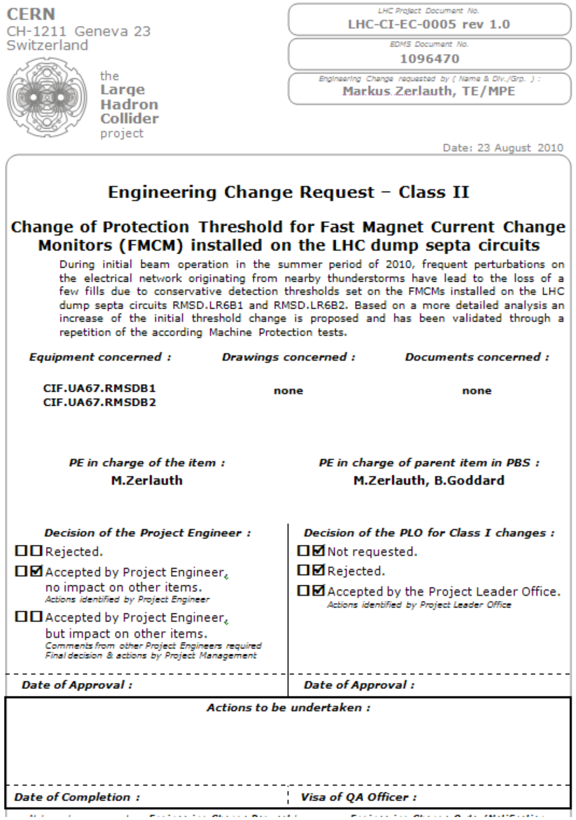
ΔV = 4V

ΔV /V = 8 •10E-1

Adjusting Thresholds on Dump Septas



Device Name	Electrical Circuit	Initial Warning/Dump Thresholds	Modified Warning/Dump Thresholds
CIF.UA67.RMSDB1	RMSD.LR6B1	0.2 / 0.4	0.8 / 1.0
CIF.UA67.RMSDB2	RMSD.LR6B2	0.2 / 0.4	0.8 / 1.0


CERN
CH-1211 Geneva 23
Switzerland

the Large Hadron Collider project

LHC Project Document No. LHC-CI-EC-0005 rev 1.0
EDMS Document No. 1096470
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 : M.Zerlauth

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

Decision of the Project Engineer :
- ☐☐ 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*

Decision of the PLO for Class I changes :
- ☐☑ Not requested.
- ☐☑ Rejected.
- ☐☑ Accepted by the Project Leader Office. *Actions identified by Project Leader Office*

Date of Approval :

Date of Approval :

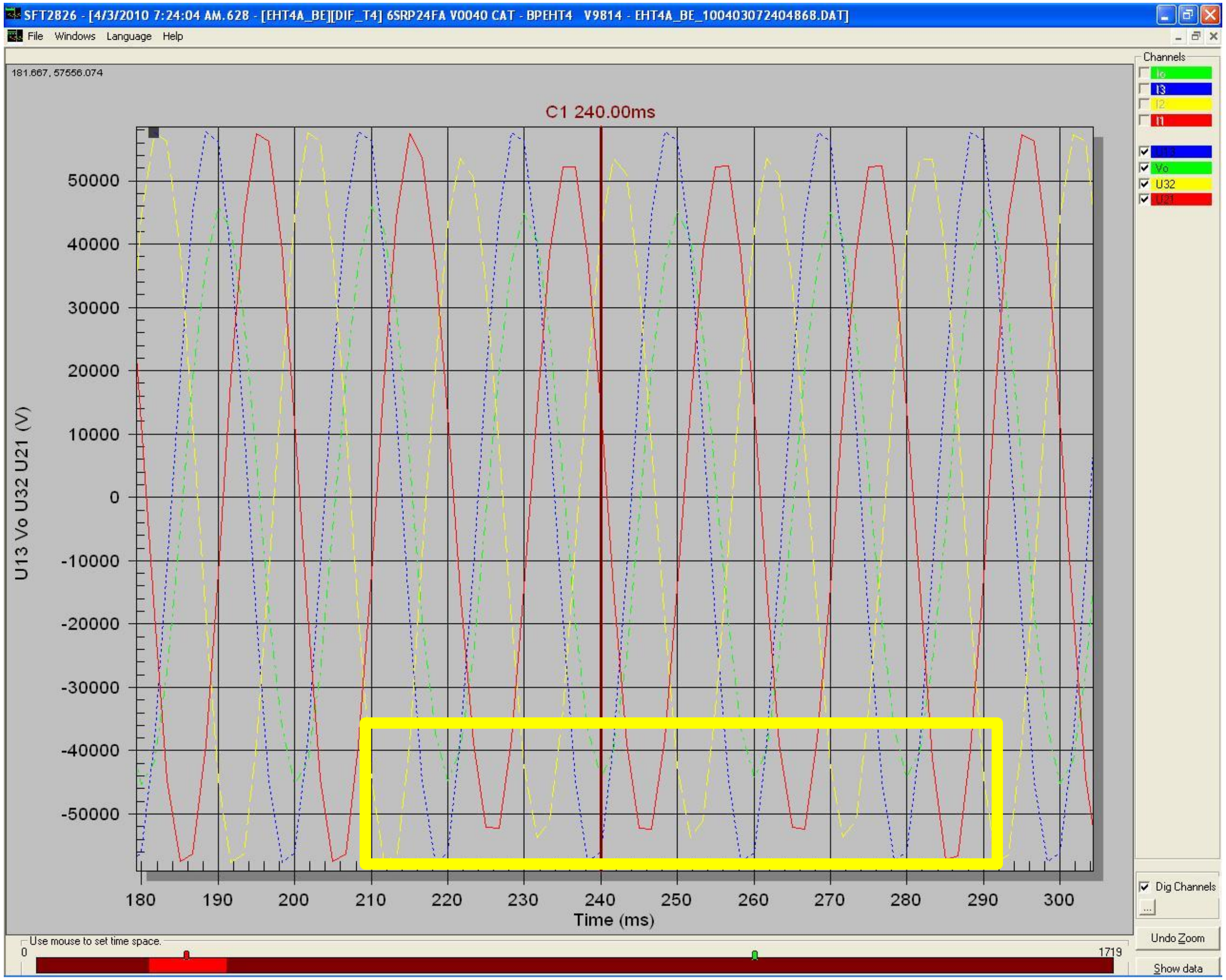
Actions to be undertaken :

Date of Completion :

Visa of QA Officer :

- 2010 experience showed limits @ injection were unnecessarily tight on dump septas in IR6 -> Increased thresholds by a factor of 2.5
- Validation of modifications with standard commissioning procedures + beam tests

03-APR-10 07.24.04.890000 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)

Circuit	Test /device type	Conditions	Current [A]	Measured ΔI/I [1E-4]
RBAWV.R2	ALICE spectrometer magnet intlk	Injection	370	< 1.4
RBLWH.R8	LHCb spectrometer magnet intlk	Injection	364	< 1
RBAWV.R2	ALICE spectrometer PC intlk	Injection	350	42.00
RBLWH.R8	LHCb spectrometer PC intlk	Injection	350	22.00
RBXWTV.L2	FGC fault / FMCM	Injection	40	6.5
RBXWTV.R2	FGC fault / FMCM	Injection	40	6
RBXWTV.L2	FGC fault / FMCM	Nominal	600	0.2
RBXWTV.R2	FGC fault / FMCM	Nominal	600	0.4
RD1.LR1	FGC fault / FMCM	Injection	43.1	3.9
RD1.LR1	FGC fault / FMCM	Nominal	750	0.39
RD1.LR5	FGC fault / FMCM	Injection	43.1	4.4
RD1.LR5	FGC fault / FMCM	Nominal	750	0.32
RQ4.LR3	FGC fault / FMCM	Injection	32.5	7.6
RQ4.LR3	FGC fault / FMCM	Nominal	710	0.42
RQ5.LR3	FGC fault / FMCM	Injection	37	9.5
RQ5.LR3	FGC fault / FMCM	Nominal	710	0.36
RD34.LR3	FGC fault / FMCM	Injection	41	5.4
RD34.LR3	FGC fault / FMCM	Nominal	720	0.17
RQ4.LR7	FGC fault / FMCM	Injection	32.5	0
RQ4.LR7	FGC fault / FMCM	Nominal	710	0.28
RQ5.LR7	FGC fault / FMCM	Injection	38	9.9
RQ5.LR7	FGC fault / FMCM	Nominal	710	0.42
RD34.LR7	FGC fault / FMCM	Injection	41	5.4
RD34.LR7	FGC fault / FMCM	Nominal	720	0.14
RMSD.B1	FGC fault / FMCM	Injection	51.2	5.5
RMSD.B1	FGC fault / FMCM	Nominal	880	0.34
RMSD.B2	FGC fault / FMCM	Injection	51.2	3.4
RMSD.B2	FGC fault / FMCM	Nominal	880	0.34

Results Summary

Magnet	t_{loss}	Type of failure	Mode
MBW (IR7)	1.10	Max ΔV	Injection
MBW (IR3)	1.11	Max ΔV	Injection
MBXW	1.41	Max ΔV	Injection
MCBWV	3.30	Max ΔV	Injection
MCBWH	3.36	Max ΔV	Injection
MQWA	4.09	Constant dI/dt	Injection
MBXWT	5.99	Max ΔV	Collision

Most critical scenarios at injection energies

Worst failure for dipoles: maximum ΔV

Worst failure for quadrupoles: constant dI/dt

Results (II)

Experimental dipoles

	Injection (450 GeV)							
			Short circuit		Constant dI/dt		Max ΔV	
	β_{col} [m]	β_{magnet} [m]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]
MBAW	392	23	Not reached	17845.71	44204.57	19326.21	687.26	294.62
MBWMD	392	19	Not reached	2409.44	26632.68	11643.79	157.38	67.82
MBXWT	392	55	10117.97	625.40	7119.79	3112.77	17.39	**7.57**
MBLW	342	14	28026.42	5446.31	21765.68	9515.94	426.07	184.13
MBXWH	342	11	Not reached	1572.32	32303.82	14123.21	47.34	20.54
MBXWS	342	55	Not reached	Not reached	64241.49	28086.34	30.71	13.25

	Collision (7 TeV)							
			Short circuit		Constant dI/dt		Max ΔV	
	β_{col} [m]	β_{magnet} [m]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]	t for 6σ [ms]	t_{loss} [ms]
MBAW	380	254	1547.89	647.19	52101.23	22778.62	531.94	229.06
MBWMD	380	179	331.94	140.72	34149.32	14930.06	126.68	54.74
MBXWT	380	904	70.37	30.21	6936.90	3032.81	13.74	**5.99**
MBLW	355	40	1567.50	656.45	50803.05	22211.06	616.98	265.25
MBXWH	355	14	657.74	258.02	115920.80	50680.50	135.44	57.94
MBXWS	355	449	201.75	80.65	88525.06	38703.10		

Courtesy of A.Gomez Alonso

Results (III)

Quadrupoles

	Injection (450 GeV)						
		Short circuit		Max ΔV		Constant dI/dt	
	β_{magnet} [m]	t ΔQ [ms]	t_{loss} [ms]	t ΔQ [ms]	t_{loss} [ms]	t ΔQ [ms]	t_{loss} [ms]
MQWA (worst)	383.77	4.71	150.5	0.17	**5.03**	0.14	**4.09**
MQWA (avg)	191.69	9.47	345.6	0.35	10.11	0.29	**8.19**
MQWB (worst)	382.09	60.29	Not reached	1.96	58.42	0.64	18.23
MQWB (avg)	200.69	119.65	Not reached	3.73	115.78	1.21	34.72

	Collision (7TeV)						
		Short circuit		Max ΔV		Constant dI/dt	
	β_{magnet} [m]	t ΔQ [ms]	t_{loss} [ms]	t ΔQ [ms]	t_{loss} [ms]	t ΔQ [ms]	t_{loss} [ms]
MQWA (worst)	391.58	4.62	147.2	1.73	51.52	2.17	62.38
MQWA (avg)	195.72	9.27	336.3	3.47	107.40	4.35	124.81
MQWB (worst)	382.09	60.29	Not reached	20.66	1255.95	9.88	283.65
MQWB (avg)	200.69	119.65	Not reached	39.88	Not reached	18.82	540.04

Courtesy of A.Gomez Alonso

What devices trigger during these perturbations?

Date	FMCM devices triggering during the event
27/2/11 17:12	FMCM_RD1.LR1, FMCM_RD1.LR5, FMCM_RQ5.LR3, FMCM_RQ4.LR3, FMCM_RQ4.LR7, FMCM_RD34.LR3, FMCM_RD34.LR7
10/4/11 6:58	FMCM_RBXWTV.L2, FMCM_RBXWTV.R2, FMCM_RD1.LR1, FMCM_RD1.LR5, FMCM_RD34.LR3, FMCM_RD34.LR7, FMCM_RQ4.LR3, …
29/4/11 15:23	FMCM_RBXWTV.L2, FMCM_RBXWTV.R2, FMCM_RMSD-b2, FMCM_RMSD-b1, FMCM_RD1.LR5, FMCM_RD34.LR3, FMCM_RD1.LR1, …
14/5/11 13:38	FMCM_RBXWTV.L2, FMCM_RD1.LR1, FMCM_RD34.LR3, FMCM_RD34.LR7
22/5/11 9:09	FMCM_RD1.LR5, FMCM_RD1.LR5, FMCM_RD34.LR3, FMCM_RD34.LR7
28/5/11 0:25	FMCM_RD1.LR5, FMCM RD1.LR1, FMCM_RD34.LR3
30/5/11 19:07	FMCM_RD1.LR5, FMCM_RD34.LR3, FMCM_RD34.LR7
30/5/11 20:20	FMCM_RD1.LR5, FMCM_RD34.LR3, FMCM_RD34.LR7
12/7/11 17:06	FMCM_RBXWTV.L2, FMCM_RBXWTV.R2, FMCM_RD1.LR5, FMCM_RD1.LR1, FMCM_RD34.LR3, FMCM_RD34.LR7, FMCM_RQ4.LR3, …
23/7/11 19:07	FMCM_RD1.LR5
25/7/11 5:29	FMCM_RD1.LR5, FMCM_RD1.LR1, FMCM_RD34.LR3, FMCM_RD34.LR7
27/7/11 6:02	FMCM_RBXWTV.L2, FMCM_RBXWTV.R2, FMCM_RD1.LR5, FMCM RD1.LR1, FMCM_RD34.LR3, FMCM_RD34.LR7, FMCM_RQ5.LR3, …
28/7/11 4:38	FMCM_RD1.LR1, FMCM_RD1.LR5, FMCM_RD34.LR3

- Essentially two event families:
  - Major event (almost all FMCMs trigger, and mostly accompanied by other equipment failures)
  - Minor events where ONLY FMCMs trigger, typically RD1s and RD34s (sometimes RBXWT)