Beam Dumping system, operational experience and validation

B.Goddard

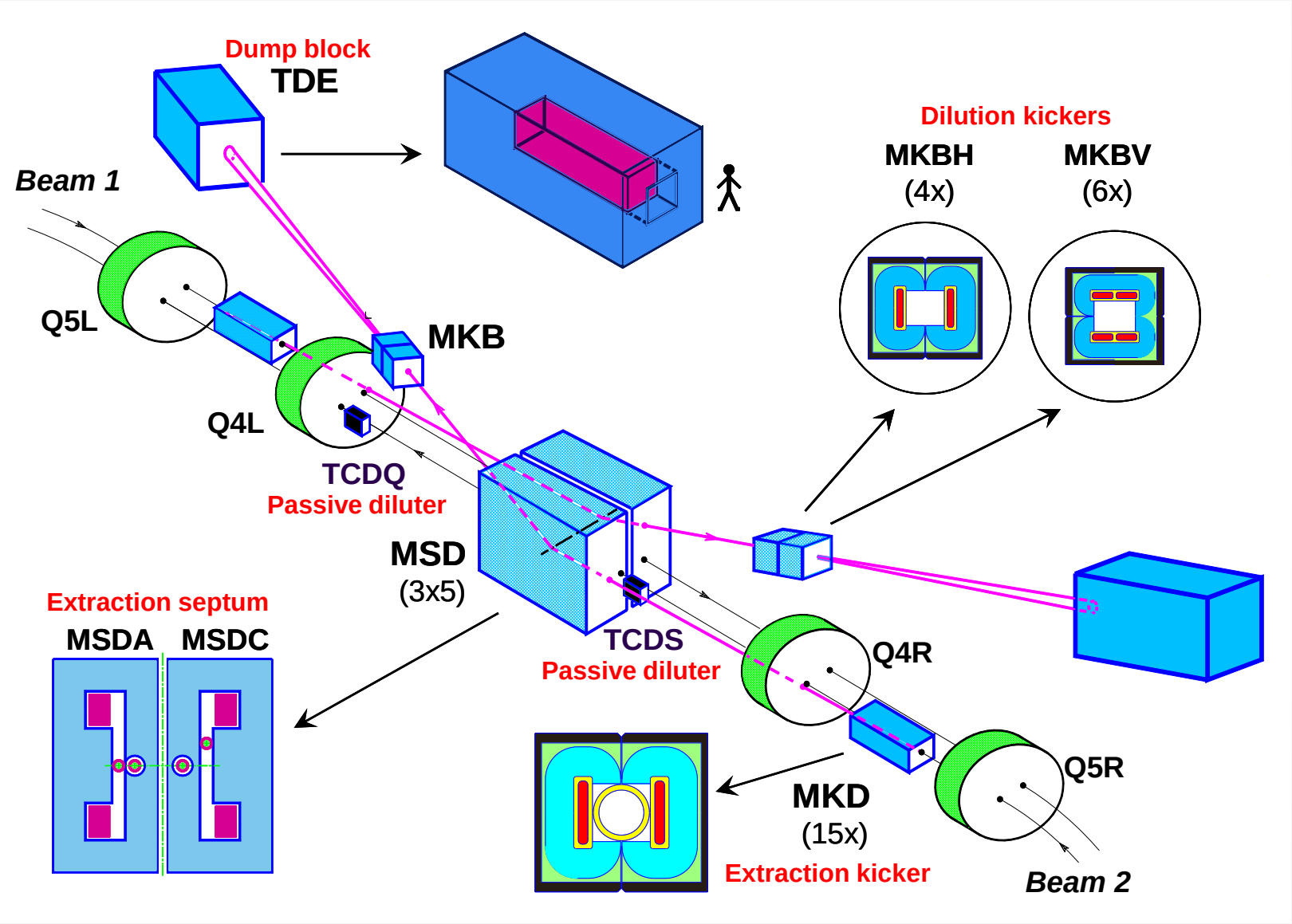
On behalf of the LHC Beam Dump System teams

The major contributions from J.Uythoven, E.Carlier, C.Bracco, W.Bartmann, L.Ducimetière, V.Senaj, V.Mertens and many others are warmly acknowledged

Overview

- Introduction to dump system
- Operational experience
- Reviews and audits
- Outstanding concerns

LHC beam dump overview (and acronyms)



Summary of main parameters

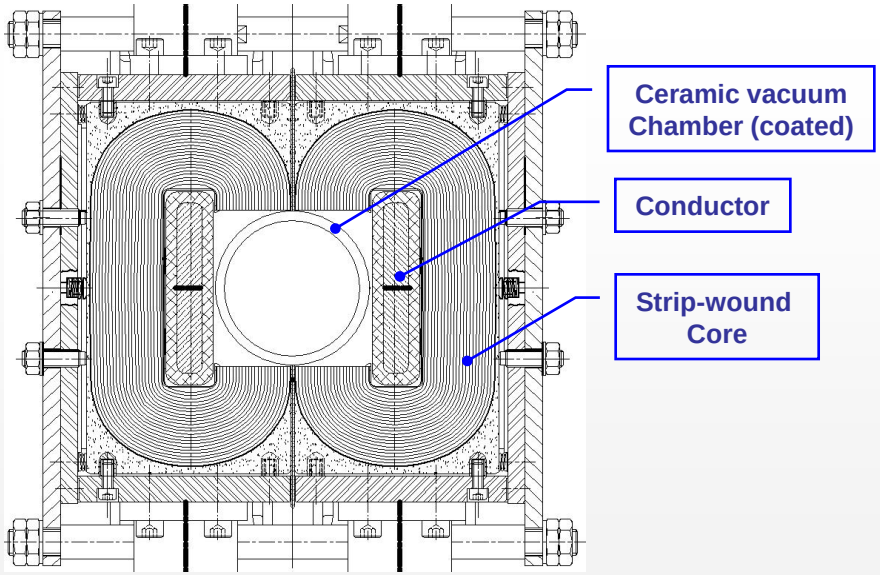
Parameter	Unit	Value	
Extraction kicker (MKD) horizontal deflection	mrad	0.28	
MKD ∫B.dl at 7 TeV	T.m	6.53	***15 magnets of 1.4 m***
Total horizontal deflection (MKD + Q4)	mrad	0.33	
Extraction septum (MSD) vertical deflection	mrad	2.40	
MSD ∫B.dl at 7 TeV	T.m	56.0	***15 magnets of 4.5 m***
Dilution horizontal deflection (MKBH)	mrad	±0.28	***4 magnets of 1.9 m***
Dilution vertical deflection (MKBV)	mrad	±0.28	***6 magnets of 1.3 m***
Total beam line length (start MKD – end TDE)	m	975	
Required particle-free abort gap length	μs	3.0	
System Safety Integrity Level (SIL)		Three	

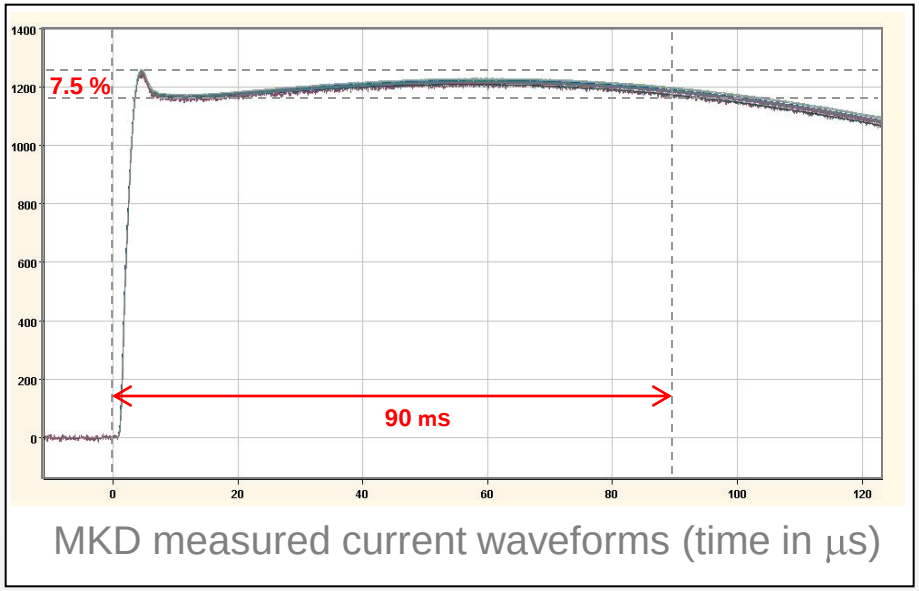
Main subsystems and acronyms

- Extraction kickers MKD
- Extraction septa MSD
- Dilution kickers MKB
- Dump block TDE
- Vacuum lines TD
- Beam instrumentation BPM, BLM, BTV, BCT
- Triggering and synchronisation unit TSU
- Beam energy tracking system BETS
- Slow control and supervision
- Post operational checks IPOC, XPOC
- Protection devices TCDS, TCDQ, TCSG

Extraction kickers MKD

- **Function: deflect beam into extraction septum during abort gap**
  - Rise time of 3.0 μs, pulse length of 90 μs (1 full LHC turn)
  - Fixed deflection angle of 0.28 mrad (for 450 GeV to 7 TeV: 2 to 30 kV)
- **Main components**
  - Kicker magnets (15 per beam)
    - Out of vacuum, strip-wound Fe cores, ceramic chambers, 18 kA single-turn coils
  - Generators (1 per magnet)
    - Capacitor discharge through 2 x 30 kV FHCT solid state switches
  - Transmission lines (8 parallel cables per magnet)

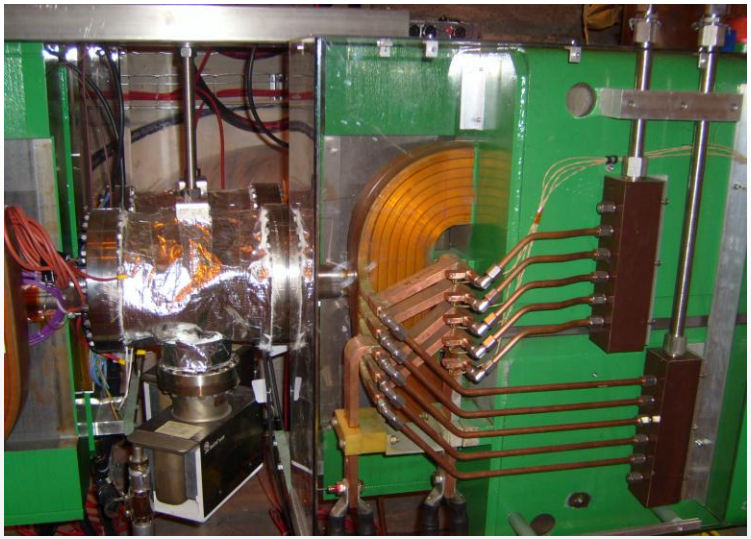


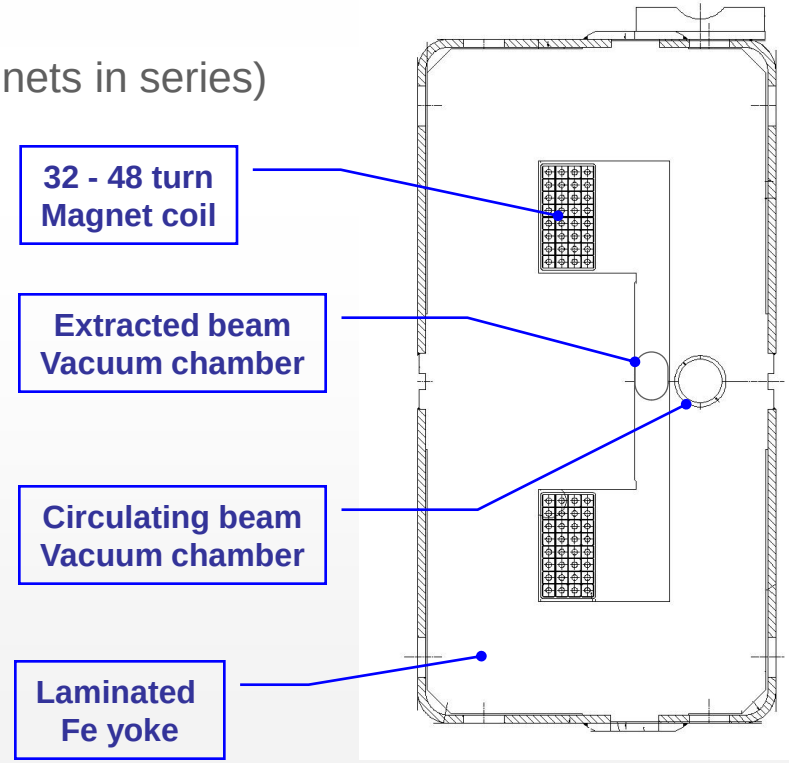


MKD measured current waveforms (time in μs)

Extraction septa MSD

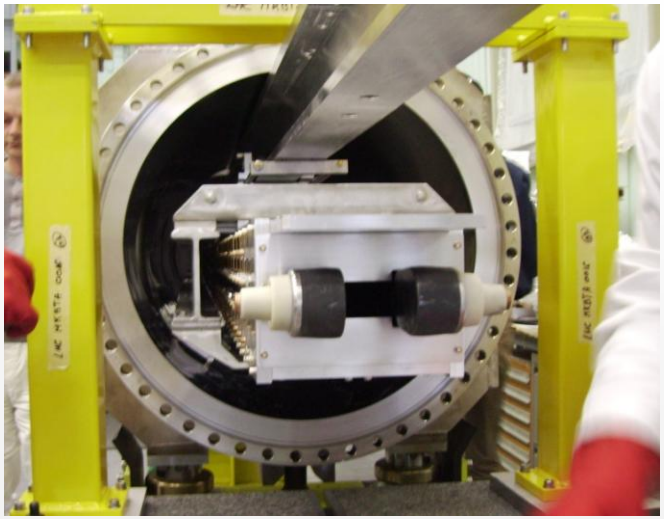
- **Function: deflect extracted beam vertically above the LHC**
  - Fixed deflection angle of 2.4 mrad (for 450 GeV to 7 TeV)
  - Should have no influence on circulating beam
- **Main components**
  - Warm “Lambertson” septum magnets (15 per beam, 5 each of 3 types)
    - Classical multi-turn design with 32-48 turns, 880 A current, water cooled
    - Baked vacuum chambers
  - Power convertor (1 per beam for 15 magnets in series)
    - 600 V Thyristor power convertor

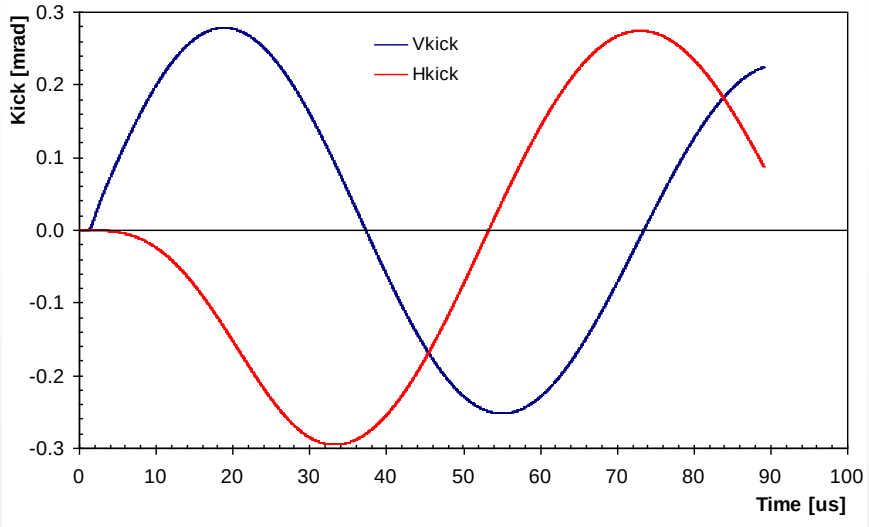




Dilution kickers MKB

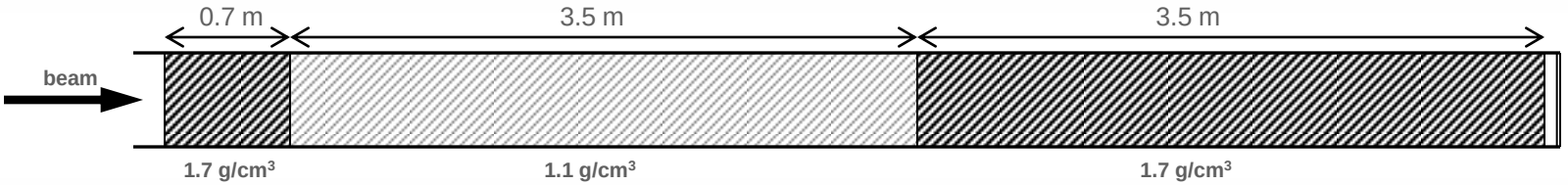
- **Function: sweep beam in Lissajous figure on dump block**
  - Separate horizontal and vertical systems
  - Sine and Cosine-like current shapes over 90 μs (1 full LHC turn)
  - Peak deflection angle of 0.28 mrad (450 GeV to 7 TeV)
- **Main components**
  - Kicker magnets (4 H and 6 V per beam)
    - **In vacuum**, otherwise same technology as MKD
  - Generators (1 per magnet)
    - Single 30 kV FHCT solid state switch (resonant circuit for MKBH to dephase waveform)
  - Transmission lines (10 parallel cables per magnet)

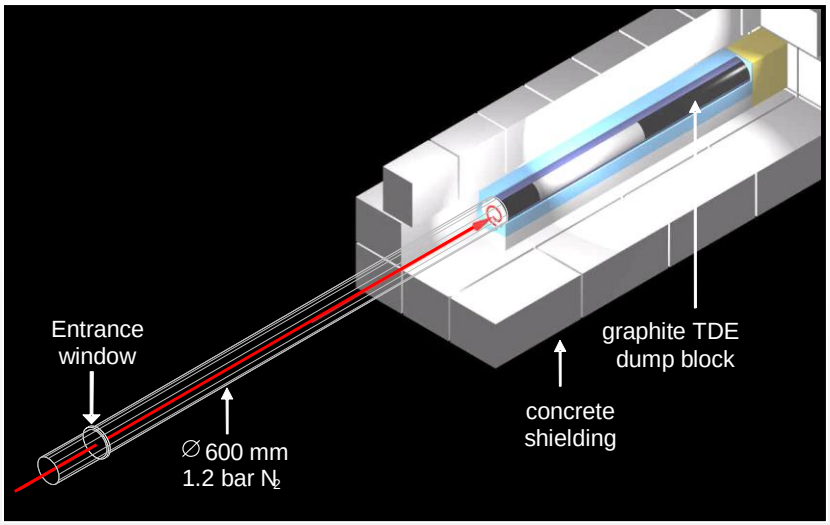




Beam dump blocks TDE

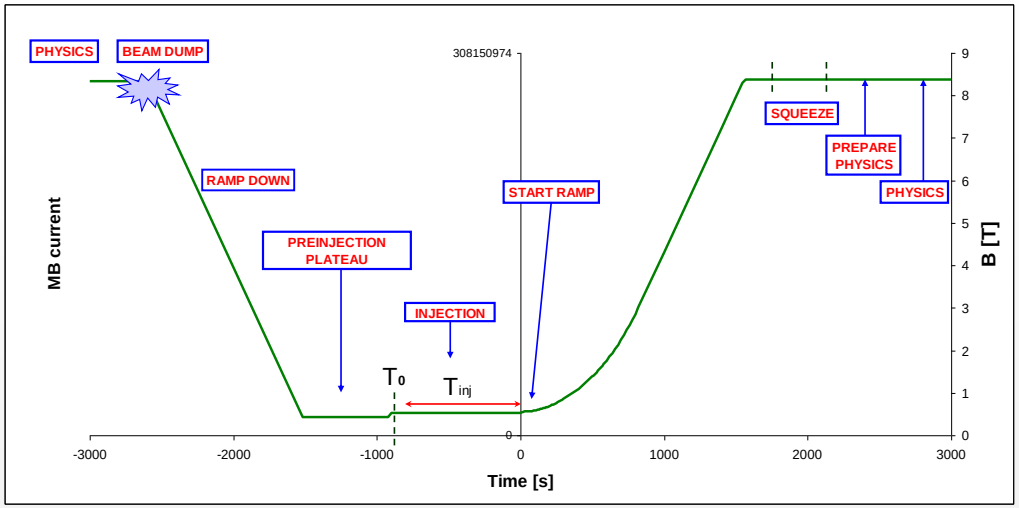
- **Function: safely absorb the full LHC beam energy**
- **Main components**
  - Beam dump core TDE
    - 7.7 m long, 0.7 m ∅ graphite core, with graded density of 1.1/1.7 g/cm^3
    - 12 mm wall, stainless-steel welded pressure vessel, at 1.2 bar of N_2
  - ~1000 tonnes of concrete/steel radiation shielding blocks



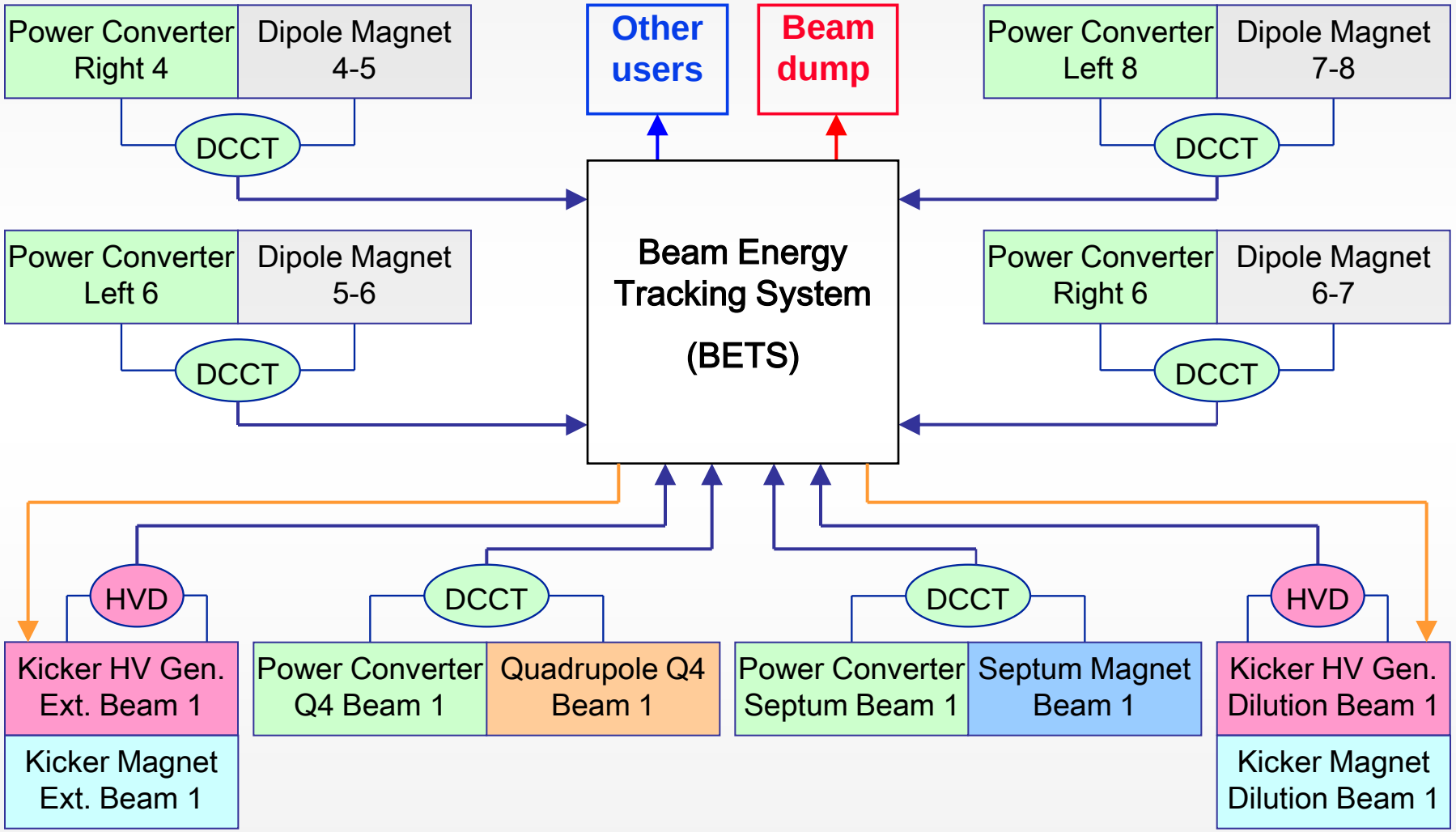


Beam Energy Tracking System BETS

- **Functions: i) provide reference for MKD/B kicker voltages,**
  ii) verify MKD/B voltages, and MSD and Q4 currents
  - Inputs from DCCTs: Main Bend PCs in 4 arcs, MSDs and Q4s in LSS6
  - Inputs from voltage dividers in all MKD and MKB generators
  - Outputs to MKD and MKB generators, and for general LHC SMP energy
- **Main components**
  - Beam energy meter to acquire, transmit and convert DCCT currents into “energy”
  - Generation of references for MKD/MKBs and charging surveillance, using fail-safe SIEMENS SIMATIC S7-F PLCs
  - Redundant tracking of strengths using dedicated HW in LynxOS-VME crate



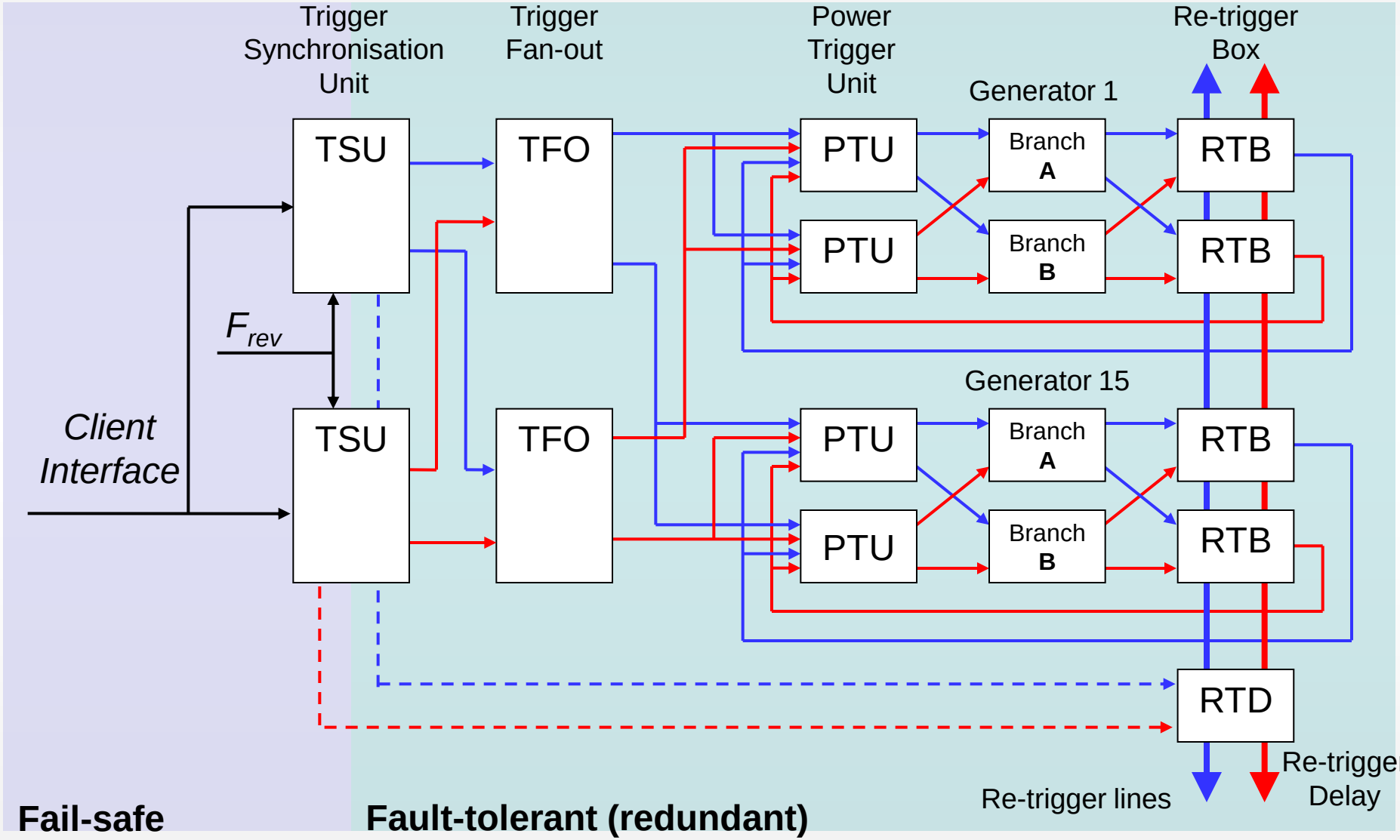
BETS


Power Converter Right 4
Dipole Magnet 4-5
DCCT
Other users
Beam dump
Power Converter Left 8
Dipole Magnet 7-8
DCCT
Power Converter Left 6
Dipole Magnet 5-6
DCCT
Beam Energy Tracking System
(BETS)
Power Converter Right 6
Dipole Magnet 6-7
DCCT
HVD
Kicker HV Gen. Ext. Beam 1
Kicker Magnet Ext. Beam 1
DCCT
Power Converter Q4 Beam 1
Quadrupole Q4 Beam 1
DCCT
Power Converter Septum Beam 1
Septum Magnet Beam 1
HVD
Kicker HV Gen. Dilution Beam 1
Kicker Magnet Dilution Beam 1

MKD/B trigger synchronisation & distribution

- **Function: detect "opening" of beam permit loop or internal fault, generation and distribution of power trigger for MKDs and MKBs synchronised with abort gap**
  - Connected to beam permit loops and RF revolution frequency
  - Other inputs from internal surveillance, access system, "direct" BLMs
- **Main components:**
  - Triggering and Synchronisation unit
    - VME-based, with redundant fail-safe logic (two redundant TSUs)
  - Trigger fan-out and power triggers
    - Redundant pulse transformers, with pre-charged capacitors
  - Retriggering system (in case of spontaneous firing)
    - Re-trigger source sensors in each generator able to trigger all power triggers on the other 14 generators. No synchronisation with the abort gap.
    - More detail in J.Uythoven's talk

Trigger Synchronisation & Distribution

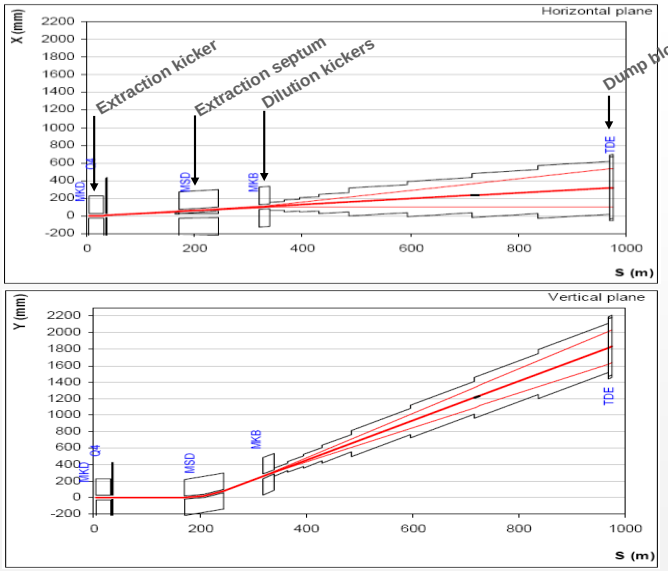


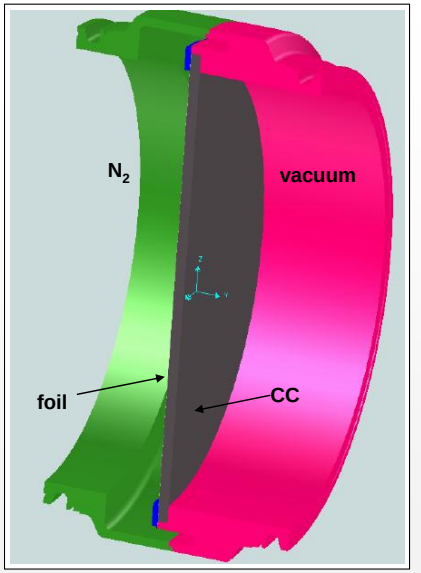
MKD/B state control and surveillance

- **Function: Control equipment state (ON, OFF, STANDBY…), survey FHCT switches, monitor equipment low level status, generate dump request upon fault detection**
- **Main components:**
  - Master PLC (SIMATIC S7-400-F) interfaced through PROFIBUS-DP segment to generator master PLC (SIEMENS S7-300-F master PLC)
  - Safety input and output (S7-300 fail-safe I/O modules) - redundant 4-20 mA current loop sensors for analogue acquisition, with redundant digital I/O sensors/actuators.

Vacuum lines

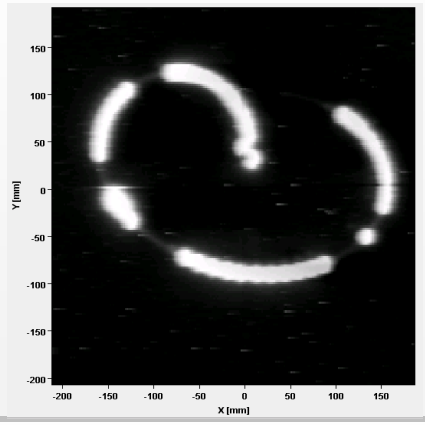
- **Function: connect active components together, and separate beam dump N_2 gas from high vacuum**
  - First part of vacuum lines are baked out to avoid poisoning LHC NEG
- **Main components**
  - Vacuum pipes, bellows, pumps, valves and gauges
    - Reduced aperture differential pumping section between MKB and LHC
  - Entrance window for TDE
    - 15 mm thick, 0.6 m ∅ CFC structural plane, with 0.2 mm steel vacuum barrier foil





Beam instrumentation

- **Beam TV screens (BTVs) for extracted beam**
  - At extraction septum, dilution kickers and dump block (fixed ?600 mm)
- **Beam position monitors (BPMs) for circulating and extracted beam**
  - **Special interlock BPMs near main quads to limit orbit to 4 mm**
  - At main quads and extraction septum for circulating beam orbit
  - At extraction septum and dilution kicker for extracted beam
- **(Fast) Beam current transformers (FBCTs) for extracted beam**
  - Just before dilution kicker (2 for redundancy)
- **Beam loss monitors (BLMs) for circulating and extracted beam**
  - At all extraction / protection elements, dump block and along dump line
  - 2 special units connected directly to dump trigger (not via interlock system)
- **Abort gap monitoring (BRSAs)**

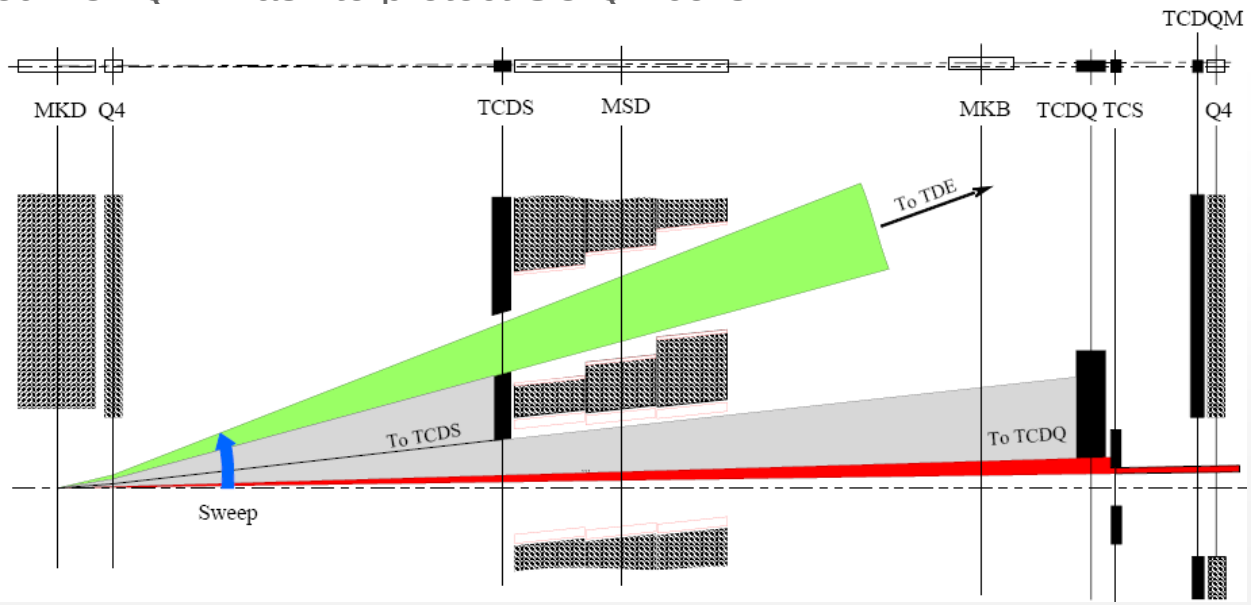


System Powering

- **In case of power cut beam will clearly need to be dumped because most other equipment will stop working**
- **Beam dumping system kickers are on 2 parallel, redundant Uninterruptable Power Supplies (UPS)**
  - Trigger Synchronisation Unit needs power from UPS to start the trigger of the beam dump
  - All other power is stored in capacitors, ready for trigger (energy stored in system)
  - In the event of total power cut AND UPS failure, dump will trigger through retriggering system
- **Tested successfully during commissioning**
  - Still to test: full power off without UPS (combined failure)
- **In operation in 2010, beam always dumped by FMCMs – much more sensitive to general power glitches**

Passive protection devices TCDS/TCS/TCDQ

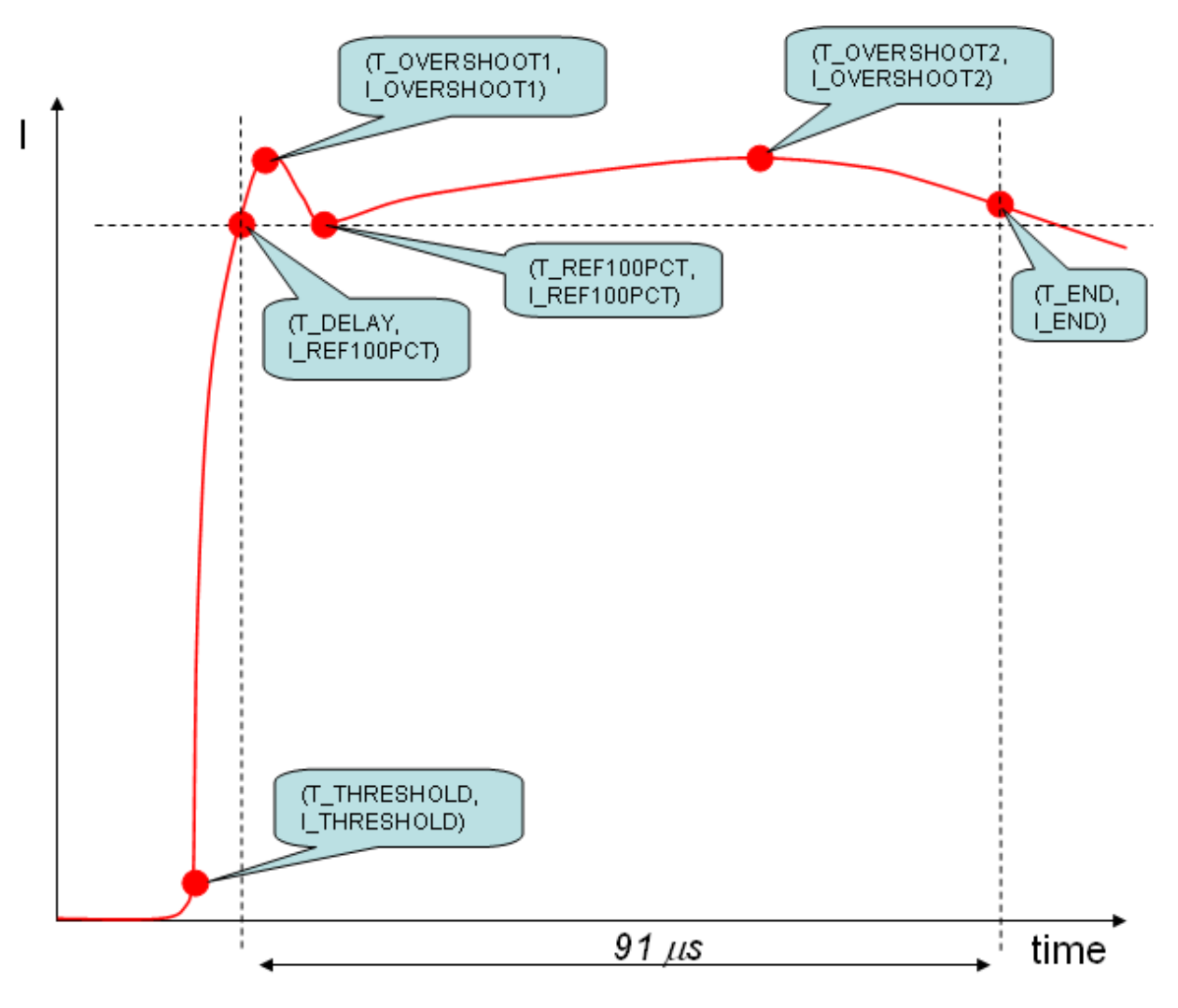
- **Function: dilute/absorb asynchronously swept bunches to prevent damage to downstream components (see talk C.Bracco)**
  - Protection of both local elements (MSDs, Q4) and far-away elements (arc aperture, triplets, collimators)
- **Main components:**
  - Fixed 6 m long TCDS diluter to protect extraction septum MSD
  - Mobile 6 m long TCDQ diluter to protect Q4, arc aperture and triplets
  - Mobile 2 – jawed TCS collimator after TCDQ
  - Fixed TCDQM mask to protect SC Q4 coils



Post operational checking systems

- **Function: check that beam dump operation worked correctly**
  - Important component in reliability of overall system
  - particularly for detecting faults in redundant branches in triggering and generators
  - inputs from sensors in generators, from beam instrumentation and from other logged equipment parameters
  - interfaces with LHC finite state machine control (sequencer), logging, alarms (all via standard LHC high level SW methods)
- **Main components:**
  - generator current waveform acquisition systems (compact PCI crates with digitisers for 2 different types of current transducers)
  - internal Post Operational Checks (IPOC) software running on cPCI FEs to filter, analyse and log data from generators
  - external Post Operational Checks (XPOC) Java software running in LHC control system
- **Extremely important for ensuring system is “good as new” before use**
  - Requires discipline in use – i.e. take seriously

MKD waveform analysis for IPOC and XPOC



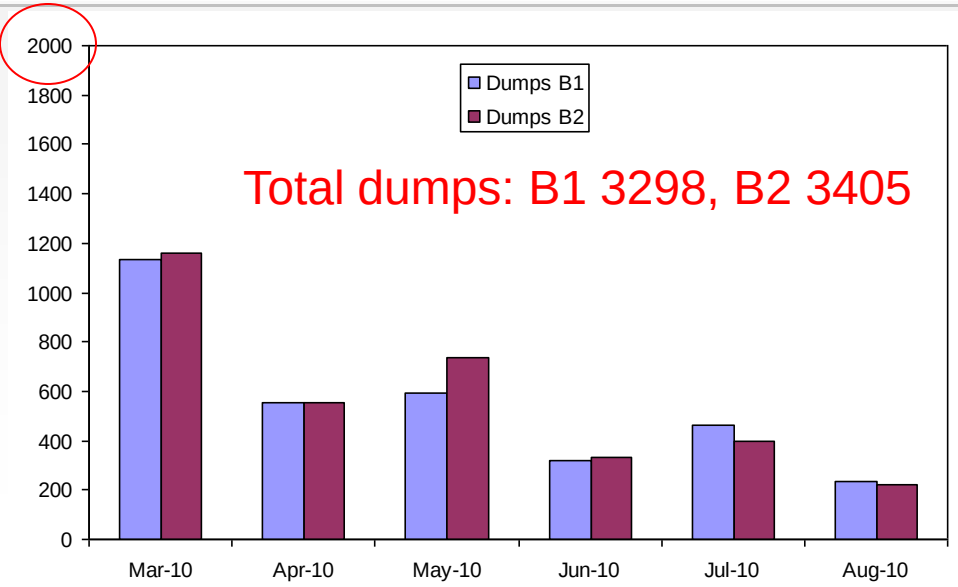
Reliability analyses and failure rates

- **Reliability of full system was analysed (Ph.D. R.Filippini)**
  - Detailed analysis of subsystems
  - ‘Quantitative’ numbers on safety and availability
  - Also partly extended to LHC machine protection system as a whole
- **Safety**
  - Critical subsystems (triggering, energy tracking) looked at in great detail
  - Figures confirm that dump should reach SIL4 as required
    - Dump ‘unsafety’ 4.8×10^{-7} per year of operation
    - Increases to 2×10^{-4} per year without post-mortem diagnostics (hidden failures)
  - Several design choices made using results of reliability analysis
  - Some highlighted areas still to be followed up
    - Redundancy in link from beam permit (interlock) loop
- **Availability**
  - Expected number of false dumps from dump system seems reasonable
    - 8 3 false dumps per year (41 6 from whole MPS)

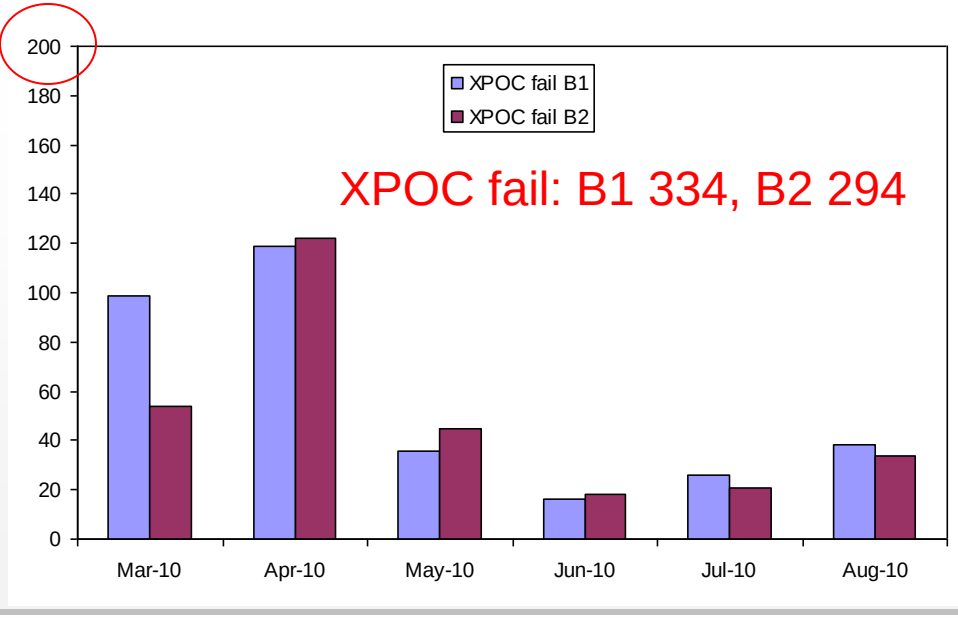
Operational experience

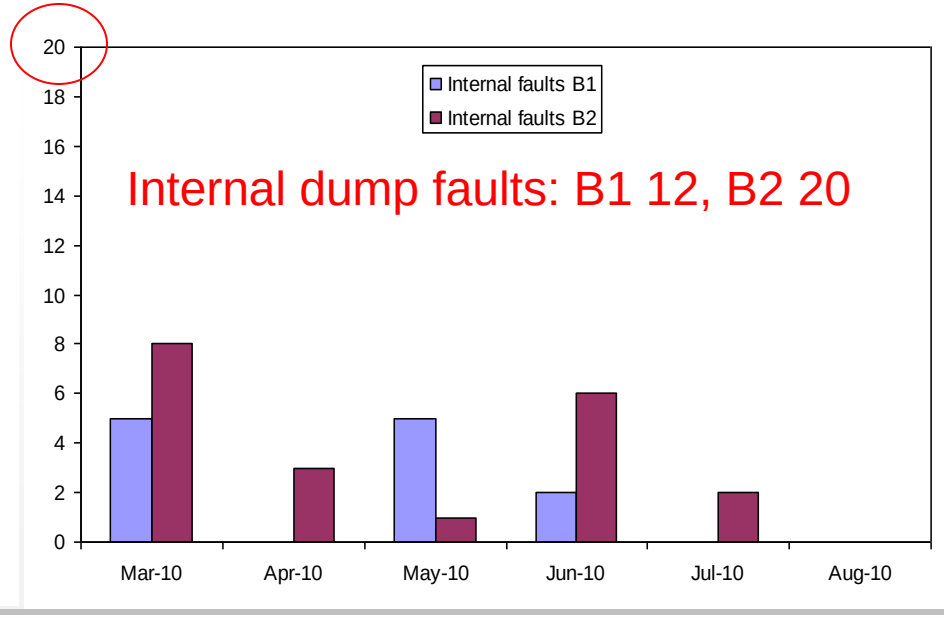
Statistics with beam 1 march to 31 August 2010

Total dumps, XPOC fails and internal faults

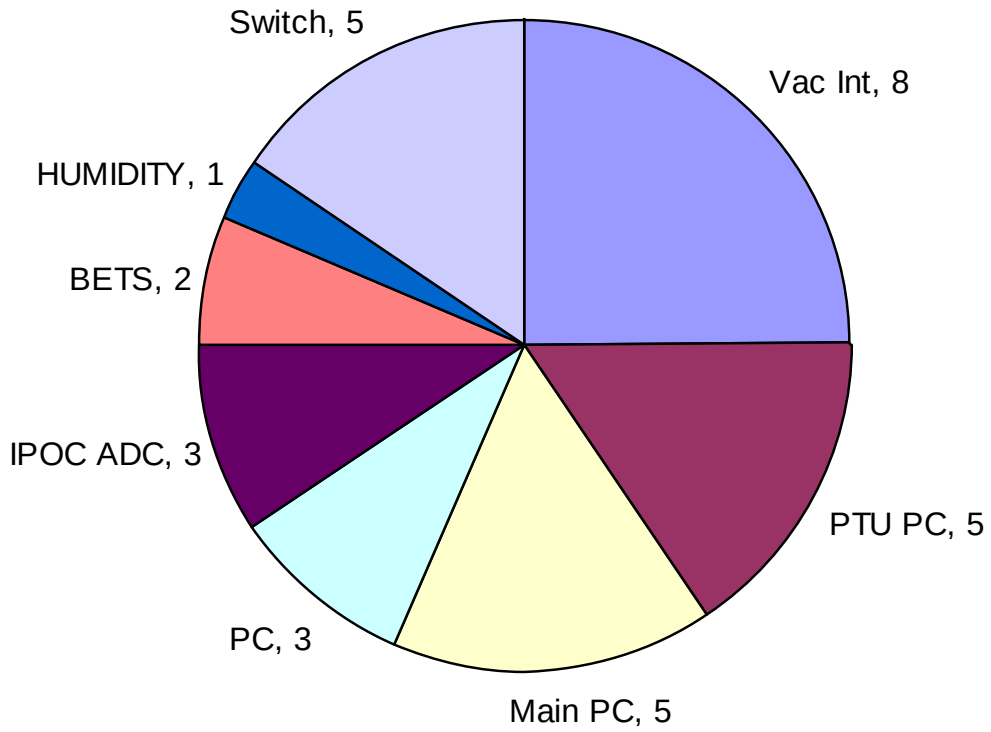


- **Internal fault rate decreasing**
  - 2 internal dump system faults in past 2 months operation
    - One bad vacuum acquisition
    - One switch fault (real, MKB)
- **System is regularly exercised!**



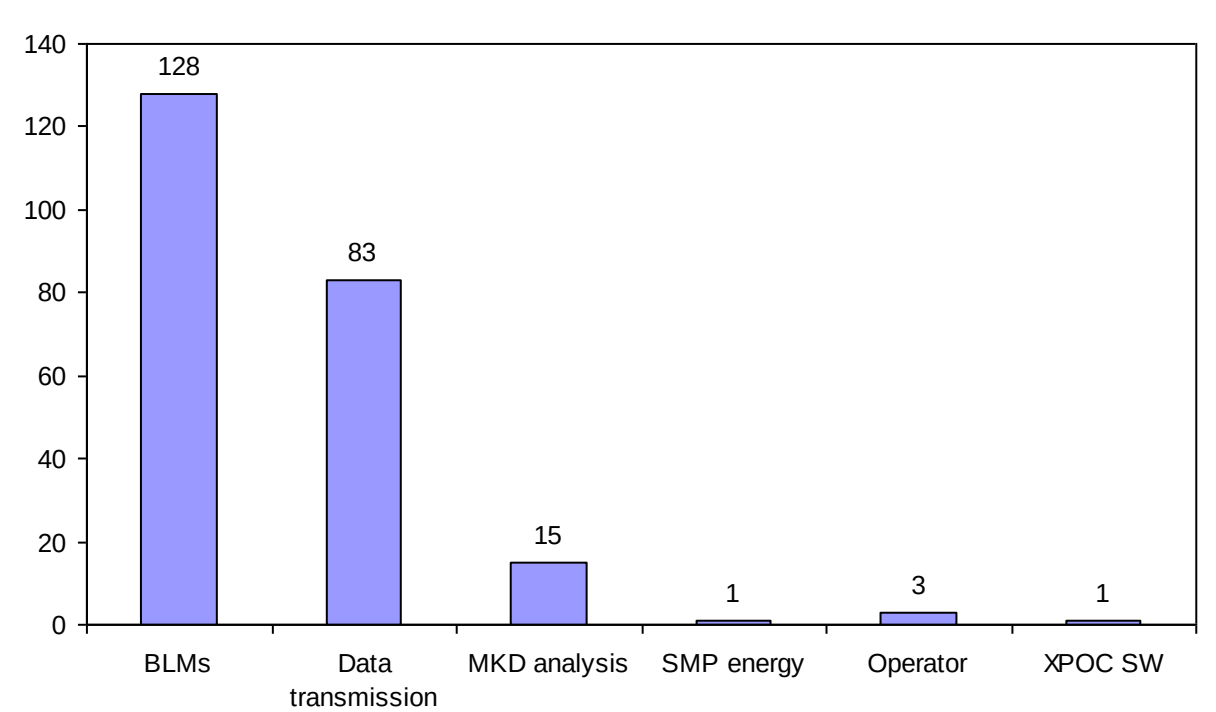


Total of Internal Faults B1 + B2: 32



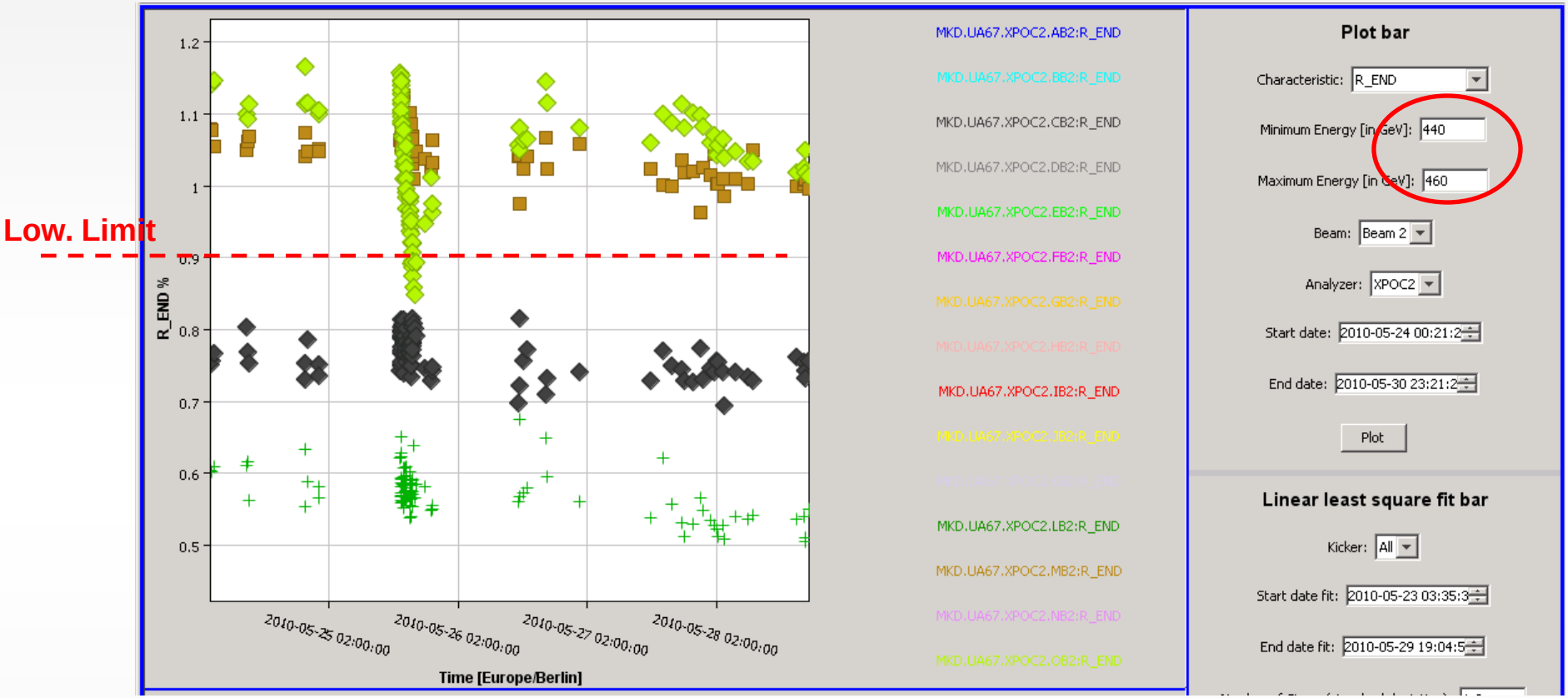
- Vacuum: Vacuum glitches MKB interlock, filtered
- IPOC ADC: cards failing, all cards replaced
- PTU PC: problem Capacitor, all exchanged
- Main PC: Stability problem
- PC: 5 V or 15 V, replaced
- Switch: surveillance problem, switch was ok

231 XPOC fails (excluding 397 tests)



- **Beam losses main cause of failure – uncaptured beam, injection**
  - Thresholds now being updated to improve rate of un-necessary fails
  - Need abort gap cleaning!
- **Data transmission an issue – BCT fixed, BLM fixes in place**
- **Need to be careful not to miss the (few) most critical fails (MKD)**

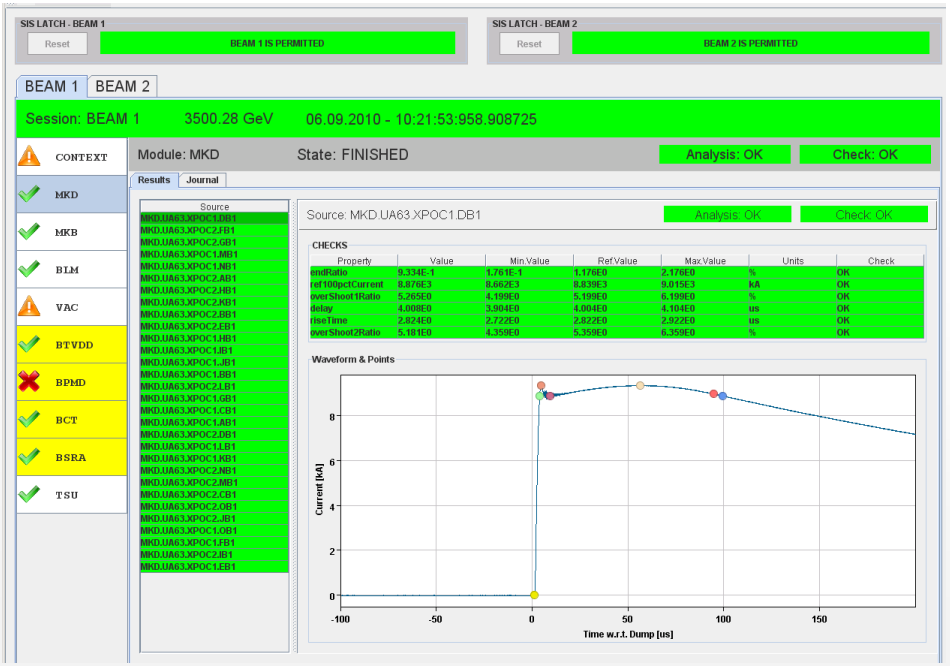
XPOC trend and error leading to generator exchanges



- **To date, (Sub)systems always changed before real failure due to early indication by XPOC:**
  - 5 MKD generators exchanged to date after ‘bad trends’ detected with XPOC.
  - Inspection has shown contact erosion problems
  - Trending tool available; used for offline checks

XPOC development

- **New modules: BTVDD, BPMD, BCT, TSU**
  - New modules help understanding if things go wrong
- **PM GUI being extended with more detailed information**
- **XPOC users GUI being overhauled – new version deployed**
- **Reset by EIC in case of false XPOC due to unbunched beam**
  - Some weakness here – needs better procedure



Operational experience

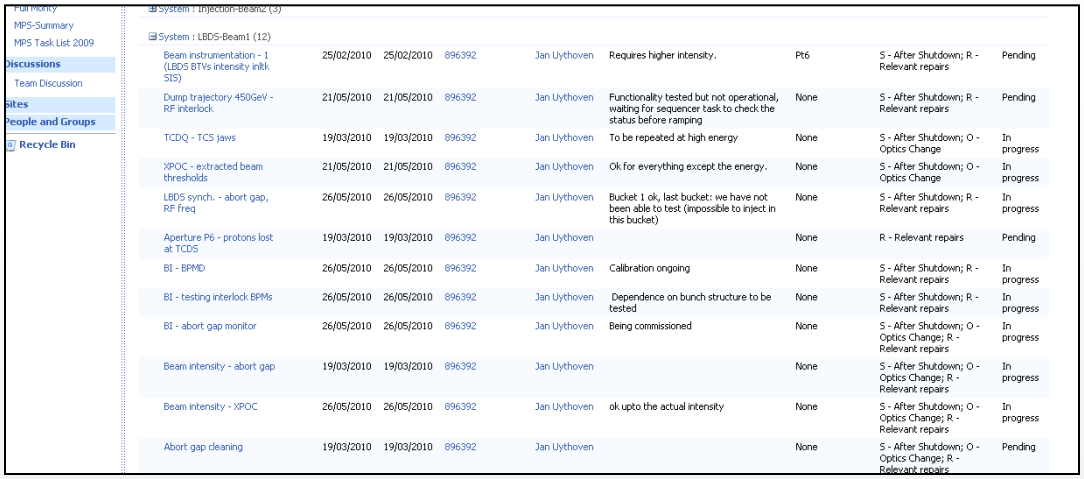
Commissioning steps and results

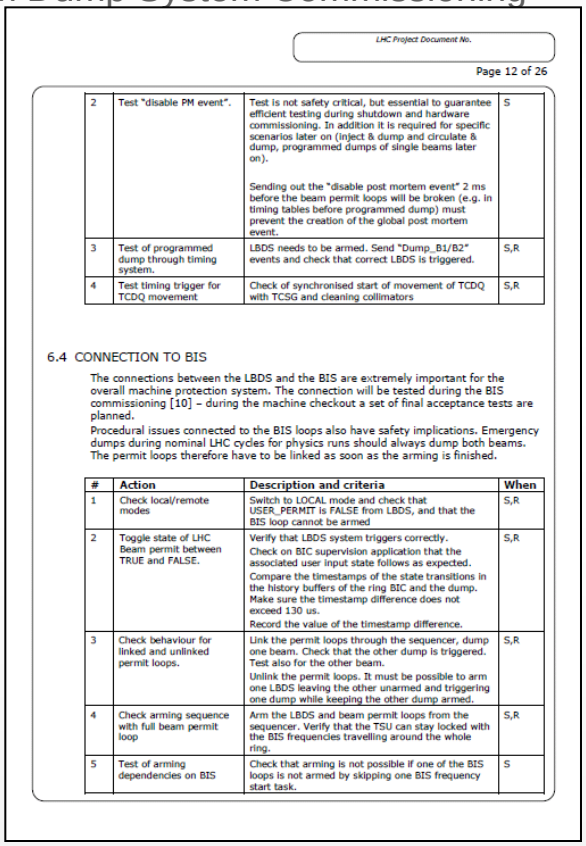
Pre-beam system commissioning and dry runs

- **Beam dump system extensively tested without beam in 2007-2009**
  - Individual system tests made according to documented test procedures
  - Interfaces to other systems commissioned
  - Operated from control room, with extensive dry runs
  - Driven through operational cycle (arm, ramp, inject and dump)
  - 8 month reliability run, accumulated 20’000 pulses (5-10 years of beam operation). Debugged small issues, confirmed reliability analysis assumptions
  - Recommissioning tests after system upgrades (switch cooling system)
  - Tested in extensive dry run pediods by OP group
- **Essential debugging phase – for HW, controls, SW and procedures**

Definition and doc. of commissioning steps

- **Well-defined and well-documented commissioning procedures**
  - LHC-TDE-HCP-0001EDMS: 761461 Hardware commissioning tests for the beam dump system
  - LHC-TDE-TP-0001 EDMS: 761458 Reliability tests for the beam dumping system
  - LHC-OP-MPS-0007 EDMS: 896392 MPS Aspects of the Beam Dump System Commissioning
- **Basis for commissioning plans**
- **Test results tracking system**
  - Tests coded
  - Result tracking patchy – not consistently monitored

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2	Test "disable PM event".	Test is not safety critical, but essential to guarantee efficient testing during shutdown and hardware commissioning. In addition it is required for specific scenarios later on (inject & dump and circulate & dump, programmed dumps of single beams later on). Sending out the "disable post mortem event" 2 ms before the beam permit loops will be broken (e.g. in timing tables before programmed dump) must prevent the creation of the global post mortem event.	S
3	Test of programmed dump through timing system.	LBDS needs to be armed. Send "Dump_B1/B2" events and check that correct LBDS is triggered.	S,R
4	Test timing trigger for TCDQ movement	Check of synchronised start of movement of TCDQ with TCSG and cleaning collimators	S,R

6.4 CONNECTION TO BIS

The connections between the LBDS and the BIS are extremely important for the overall machine protection system. The connection will be tested during the BIS commissioning [10] – during the machine checkout a set of final acceptance tests are planned.

Procedural issues connected to the BIS loops also have safety implications. Emergency dumps during nominal LHC cycles for physics runs should always dump both beams. The permit loops therefore have to be linked as soon as the arming is finished.

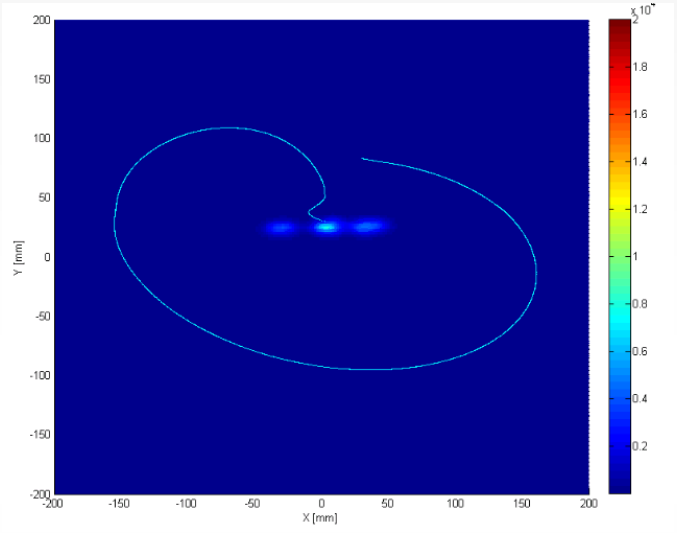
#	Action	Description and criteria	When
1	Check local/remote modes	Switch to LOCAL mode and check that USER_PERMIT is FALSE from LBDS, and that the BIS loop cannot be armed	S,R
2	Toggle state of LHC Beam permit between TRUE and FALSE.	Verify that LBDS system triggers correctly. Check on BIC supervision application that the associated user input state follows as expected. Compare the timestamps of the state transitions in the history buffers of the ring BIC and the dump. Make sure the timestamp difference does not exceed 130 us. Record the value of the timestamp difference.	S,R
3	Check behaviour for linked and unlinked permit loops.	Link the permit loops through the sequencer, dump one beam. Check that the other dump is triggered. Test also for the other beam. Unlink the permit loops. It must be possible to arm one LBDS leaving the other unarmed and triggering one dump while keeping the other dump armed.	S,R
4	Check arming sequence with full beam permit loop	Arm the LBDS and beam permit loops from the sequencer. Verify that the TSU can stay locked with the BIS frequencies travelling around the whole ring.	S,R
5	Test of arming dependencies on BIS	Check that arming is not possible if one of the BIS loops is not armed by skipping one BIS frequency start task.	S

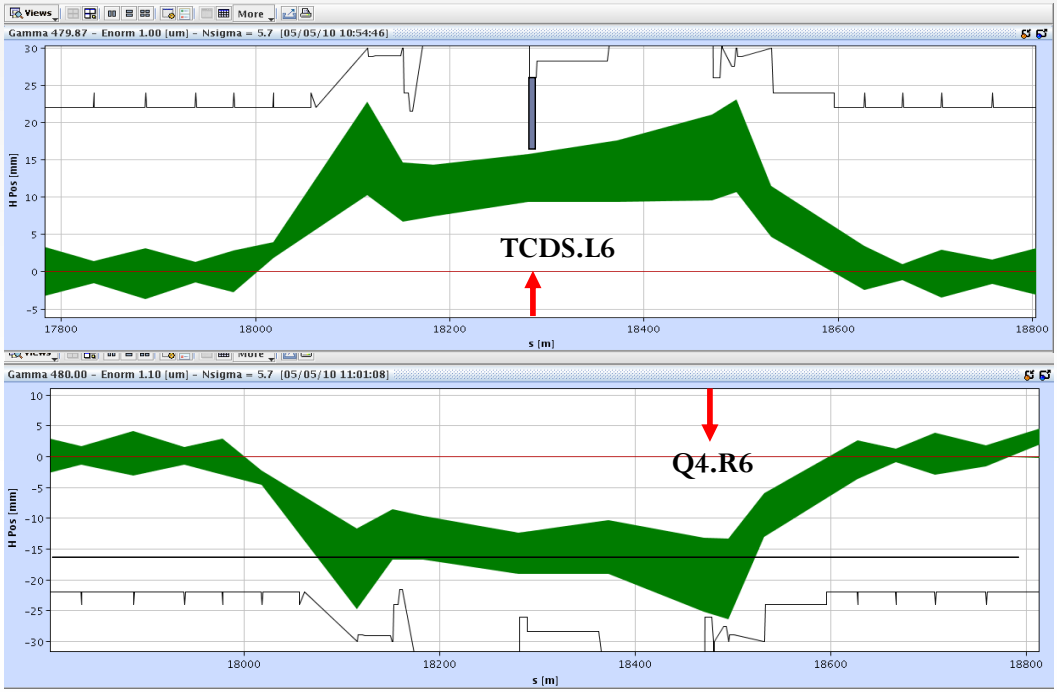
System aperture

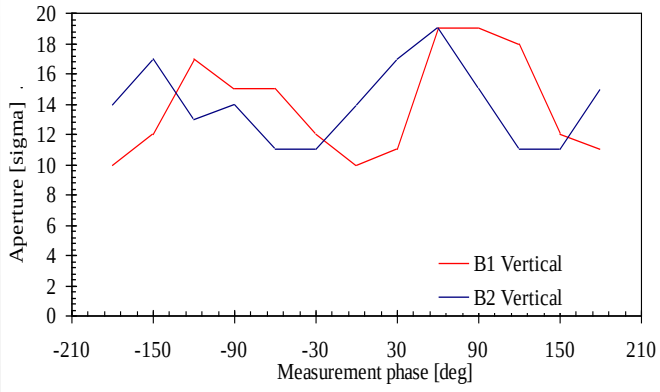
- In general all beams dumped cleanly with low transverse losses, up to 50 bunches per beam and for all energies and emittances
- Dumps from extreme (interlocked) orbits all clean
- Dumps with maximum RF trim all clean
- Dumps with simulated 14/15 MKD kickers all clean
- All related MP tests passed sucessfully

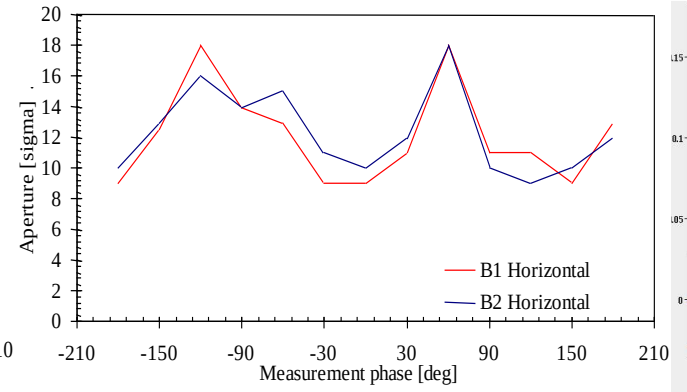
Measured apertures in dump region

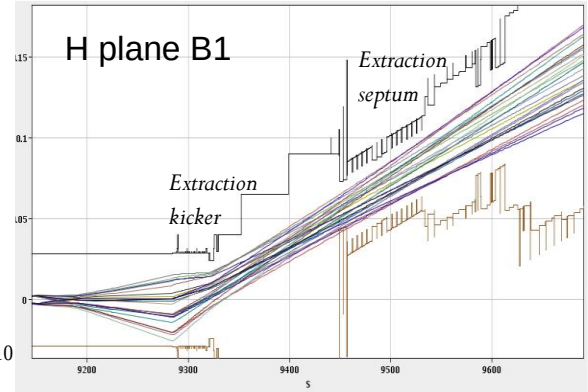
- As expected for circulating and extracted beam





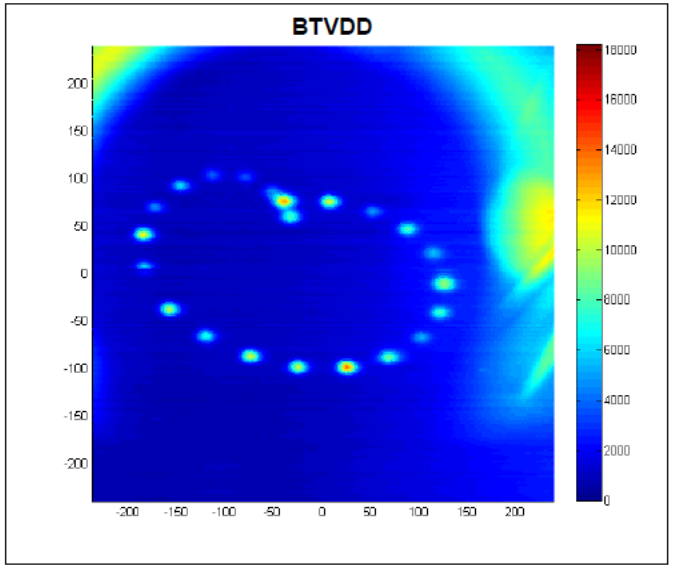


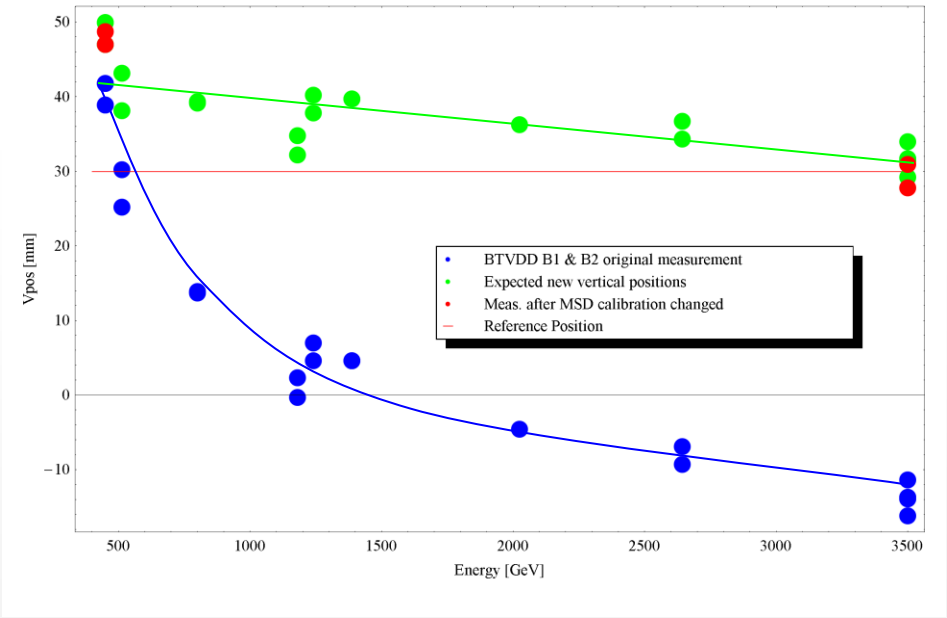


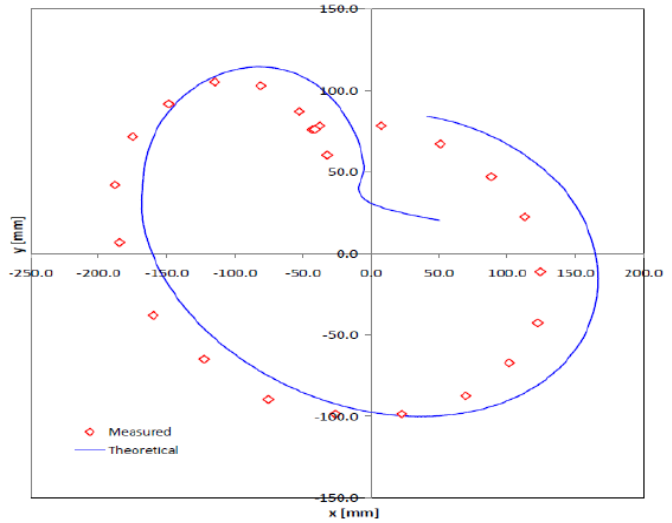


Kicker sweep and energy tracking

- **Sweep is almost perfect**
  - Kicker performance & optics well understood
- **MSD strength error with energy**
  - Corrected transfer function and deployed
  - Now much closer to expectation







Interlocked Beam Instrumentation

- Interlock BPMs – to ensure beam position in tolerance for dump
  - Were setup once in the beginning of the 2010 run.
  - Adjusted after 15th May when lost 2 ramps on BPM interlocks
  - Checked with dump from positions at limit of interlock position and maximum angles
  - Working reliably – may need to tune the algorithm for counting bunches out of tolerance, and should retest with larger numbers of bunches (done only for single bunches and 2 bunches so far)
- Direct Interlocked BLM **(channel not via BIS)**
  - Not tested yet

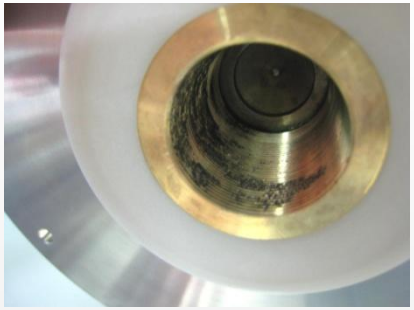
Problems encountered

MKD generator performance / exchange

- **Found GENERAL problem with erosion of contacts – degradation**
  - Performance degradations detected by XPOC
  - Recall and repair program
    - Check all contacts and connections, reassemble with improved procedure (torque etc)
    - Need to make modifications in laboratory
    - Replace 2 spares at each technical stop 2010
    - With 4 spares available in 2011, can replace up to 4 generators at each technical stop
- **MKD switch erratics (2) seen during tests at 7 TeV and 5 TeV…**
  - Reinforces need for the HT holdoff upgrade

Contact erosion series diode stack not sufficiently tightened

Contact erosion on Exit Box
Replaced on 18 out of 30 generators installed



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MKB

- Generators (2008 – 2009)
  - Damaged multi-contact on the multi-chip diode which is in parallel with the GTO stack. Solution: multi-contact replaced by soldering. Done
- Magnets (2008 – 2009)
  - Breakdown on araldite insulators between forward and return path of MKB magnet. Solution: insulators replaced by ceramic ones (MKI type). Done
  - Damaged ground connection of MKB coil. Solution: redesign of the contact and stronger contact tightening. Done
  - Cracks of the MKB coil insulation. Solution: coils ends remoulded with different araldite filler (silica rather than dolomite). Done
- Vacuum pressure false interlock due to noise on signal solved by filtering and voting solution, but still need to find out why noisy signal

Other systems

- **TCDQ movement inversion for one beam**
  - Detected with low intensity beam
  - Procedural error in HW commissioning – **solved**
- **High level SW compatibility between TCDQ and TCSG**
  - Completely different low levels – adds complication. Rationalize?
- **TSU generating a few % of asynchronous dumps**
  - Fault found in internal logic for receiving RF synchro signal – **solved**
- **Problems with acquiring BI data for XPOC**
  - Various issues with BCT, BLMs and servers – **solved**

Reviews and audits

MPS related ‘exercises’

- **External Machine protection system review 11-13th April 2005**
- **External Beam dump system review 28-29th January 2008**
- **External Beam dump system review follow-up 15th June 2009**
- **Internal Beam dump system review 4th May 2010**
- **Internal Machine protection system review 17-18th June 2010**
- **External TSU and FPGA code (external company) - ongoing**
- **MPS system checks with and without beams 2009-2010**
  - Following procedures edms document 896392
  - Progress filled in on the Web
  - Conclusions fed into **Internal** review

External LBDS review follow-up 15th June 2009

- **27 out of 47 recommendations of the initial review of January/February 2008 were implemented at that time**
- **Others implemented 2009.**
- **Remaining concerns:**
  - Potential faulty timing transmission RF
    - **Done**: Now check in place in sequencer
  - FPGA code review and FPGA test bench
    - Code review **on-going** for TSU.
    - Depending on experience will do for other systems (BETS)

Issues from LBDS internal review 4th May 2010

1. F_rev check in sequencer before arming: DONE
2. Formal validation procedures of system after technical stop: DONE
3. Damaged re-trigger resistors (see before): replacement DONE
4. Erosion of contacts: replacement program for next two years ONGOING
   will take long time but trends visible on XPOC
5. BLMs needed to quantify some MP tests already made: DONE
6. Protected sequences and unskippable tasks ONGOING
7. TCDQ software issues for movement DONE
8. TCDQ position settings check can't be done, software precision issue
   DONE
9. Debunched dumps at 450 GeV with 1e11 p^+ & analyse: DONE
10. Set-up TCSG/TCDQ at 450 GeV and 3.5 TeV: DONE
11. Aperture measurements in Point 6: DONE
12. BLM calibration: DONE TCDQ DONE TCT
13. MPS test: system off and RF frequency interlock: DONE
14. Understand why 15 x 1 MKD knob did not cleanly extract: Done

Summary

Beam Dump Performance

- **System performance looks generally solid**
  - No dumps which would have caused damage with unsafe beam
  - No asynchronous dump happened since TSU fix 2009
    - Many dumps with unbunched beam to check performance of protection – see talk of Chiara
    - Expected about two asynch. dumps per year – zero to date with beam
  - All bunch patterns (≤50 bunches) dumped cleanly at 450 GeV and 3.5 TeV
  - Synchronisation extremely stable
  - All failures detected by surveillance or XPOC, requiring expert acknowledge
    - Reset now allowed by EiCs for well-defined circumstances… monitor this
- **System generally well understood**
  - Initial teething troubles diagnosed and fixed
  - MPS checks passed
  - Dump figure as expected
  - Aperture as expected

Outstanding commissioning work

- **Beam validation still needed:**
  - "Direct BLM" trigger check
  - Checks of BPM interlock with larger numbers of bunches, and trains
  - New XPOC modules to fully deploy and test
  - Dump protection (see talk Chiara's talk)
    - Dump protection validation for 3.5 m b* with crossing angles
    - Reducing β*…
  - **Abort gap monitoring and cleaning to commission**
    - Commissioning time needed
    - Decisions still to make on interlocking philosophy
- **System response to full power cut without UPS**
  - Needs reconfiguration of powering – should be done at start of long shutdown

Remaining concerns

- **MKD generator contact erosion**
  - But so far always slow trend caught by XPOC
  - Replacement program started but will go on through 2011
    - Replacement of 2 generators each ~6 weeks – procedures now fully in place
- **MKD corona discharge along switch and erratics above 5 TeV**
  - Solution prototyped and being installed 2010/2011
- **Effect of radiation on switches at high voltages**
  - Big unknown - measurements to be made with test pieces
  - Upgrade of GTO stack design not possible in 2012 shutdown – long term
- **Cooling of MKD generators not sufficient when running for a longer period at 7 TeV beam energy**
  - May need to increase interlock tolerances – needs operational experience
- **Human Factor can be Weakest Link**
  - Sequencer, unskippable tasks etc. have to guarantee hardware settings applied to system, that previous XPOC was ok etc.
  - Procedures: test tracking, access/intervention recovery, generator exchange, resetting XPOC, resetting faults dump equipment, …

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Interdependencies