LHC Risk Review: Kicker Magnet Reliability

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Thanks to Brennan Goddard, Etienne Carlier, Wolfgang Höfle, Verena Kain and Volker Mertens

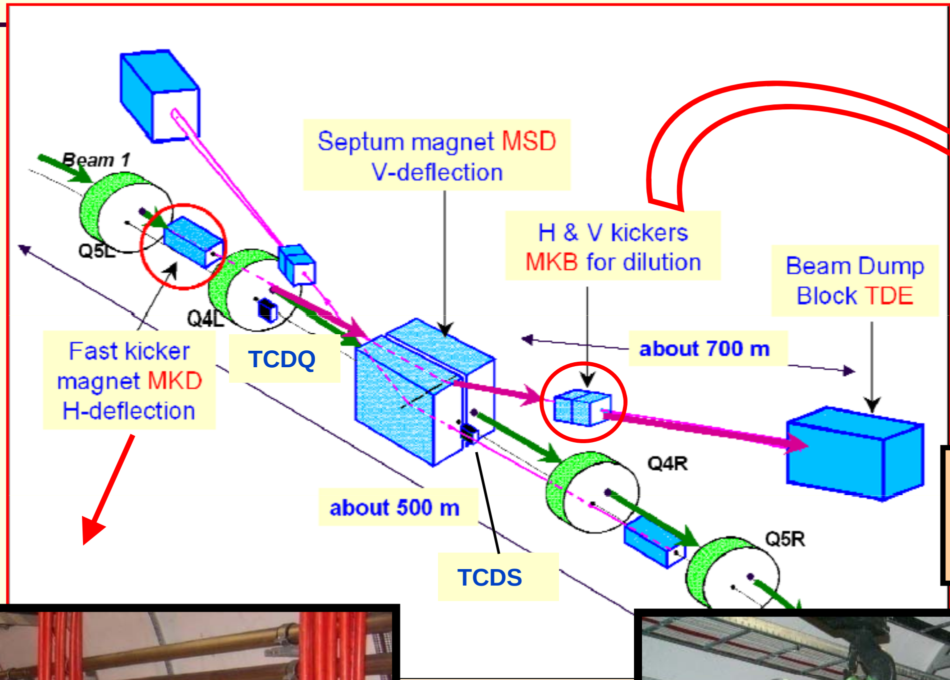
Scope

- Different kicker systems
  - Beam Dumping System
    - Extraction Kickers
    - Dilution Kickers
  - Injection Kickers
  - Kickers for Tune and Aperture measurement
  - AC-Dipole
  - Feedback Kickers (Transverse Damper)
- Discussing
  - Expected failure behavior and likelihood
    - From theory and from experience
  - Measures taken
- Conclusions

Studies / Reviews of Kickers and especially the Beam Dumping System

- LHC review on Machine Protection and Interlocks
  - External, April 2005
- PhD thesis on Beam Dumping System Dependability
  - CERN-THESIS-2006-054
- Beam Dumping System Review
  - Internal, January 2008
  - Mainly on controls aspects – not HV aspects
- Planned review on Beam Dumping System Trigger Synchronisation Unit (TSU)
  - External company: wk 17 – wk 33

LHC Beam Dumping System



MKD:
2 x 15 Systems

Magnet operates in air with coated ceramic chambers

MKBH: 2 x 4 (2)
MKBV: 2 x 6 (2)

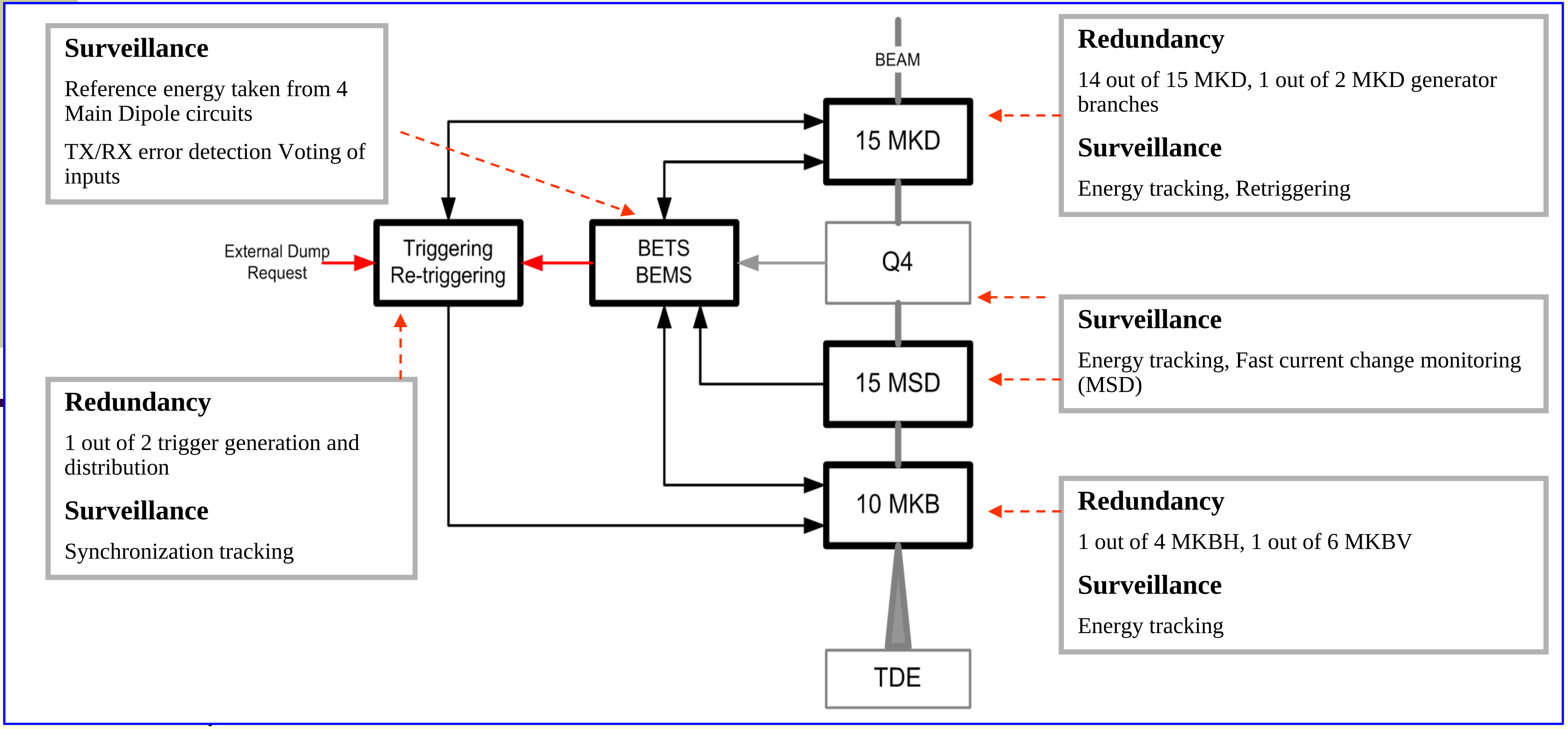
Magnet operates under vacuum

Beam Dumping System

- Extraction kickers MKD and dilution kickers MKB
- Critical because:
  - Important damage could occur as these system have the potential to deflect the full intensity beam up to 'any angle'
  - MKD failure: can damage the arc / LHC
    - Most critical for the LHC
  - MKB failure: damage the extraction channel and beam dump block
    - Talk B.Goddard Friday on consequence of dilution failure

Beam Dumping System

- System safety is based on:
  - Built in redundancy
  - Continuous surveillance
  - Post Operational Checks (IPOC/XPOC)

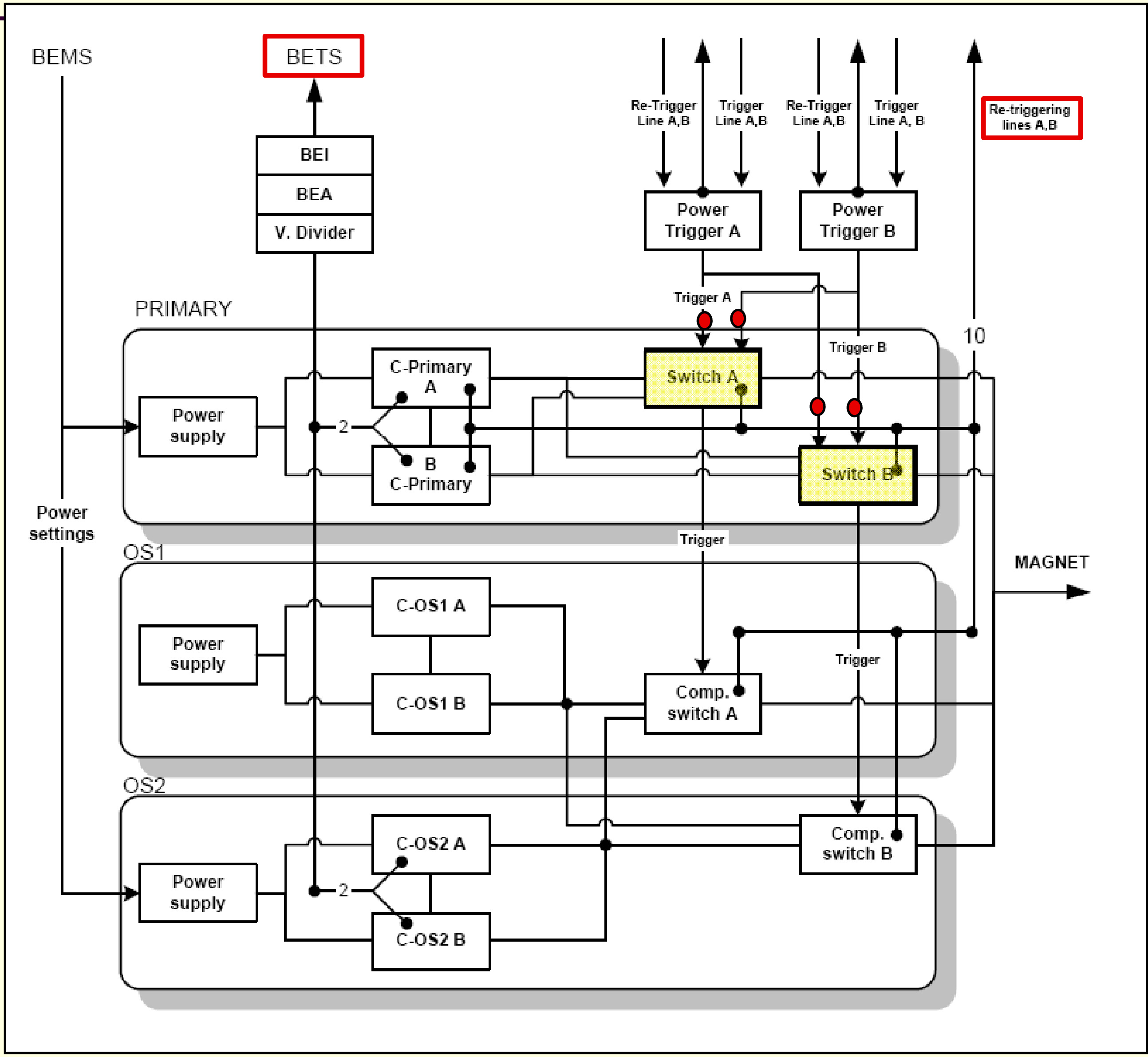


MKD System NOT firing

- One kicker not firing is covered by
  - System redundancy: can dump correctly with 14/15 MKD systems
- It is very unlikely that one, or even more unlikely more than one, kicker will not fire because of:
  - Choice of switch type:
    - The GTO Thyristor switch stack consists of 10 discs
    - Adjusted manufacturer failure rate for 1 disc *$\rightarrow 2.4 \cdot 10^{-6}$ failures per hour for 1 switch*
  - Redundancy within each kicker generator
    - Each generator has two solid state switches in parallel, which can each take the full current
  - Redundancy in triggering system
- Complete system not firing due to no trigger from Beam Interlock System not treated here
  - Fault external to beam dumping system
  - But studied elsewhere: SIL3

Experience from Reliability Run: No missings occured!
Details later

Functional Architecture of 1 MKD Generator



MKD system Kicking with Wrong Strength

- Probably one of the worst scenario's
- Covered by comprehensive Energy Tracking System (BETS)
  - Energy is calculated from the main dipole currents in the four 'adjacent' octants
  - Large redundancy in generation of energy reference and in verification of kicker strength while being ready for the next dump
  - Kicker settings and Energy Interlock values both hardcoded in the Front Ends, using separate tables
    - No remote access to these tables

Erratic firing of MKD kicker

- Re-triggering system which detects any ‘spontaneous’ firing of an MKD or MKB kicker magnet
- Within 700 ns all switches will be fired asynchronously
  - During this delay and the 3 μs rise time of the MKD kickers, the bunches swept over the aperture will be intercepted by the TCDQ and TCDS absorbers.
- Again redundant signal paths

Experience from Reliability Run: No erratics occurred! Details later

Power Cut

- In this case the 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)
- UPS required:
  - Trigger Synchronisation Unit needs power from UPS to start the trigger of the beam dump
  - All other power is stored in capacitors, ready to be ‘released’ at the moment of trigger
- Already tested in 2008 – generates dump – more extensive diagnostics on sychronisation for further tests planned in 2009

Safety Study

- Ph.D. thesis Roberto Filippini (CERN-THESIS-2006-054)
  - FMECA analysis
    - More than 2100 failure modes at component levels
      - Components failure rates from standard literature (Military Handbook)
    - Arranged into 21 System Failure modes
  - Operational Scenarios with State Transition Diagram for each Mission = 1 LHC fill
  - State Transition Diagram for Sequence of Missions and checks

Likelihood for any unacceptable failure

Case studied	Unsafety/year	False dumps/year
Default scenario	2.41×10^{-7} (> SIL4)	4.06
No redundant power triggers	2.34×10^{-6} (SIL4)	3.02
No redundant triggering sys.	4.68×10^{-4} (SIL2)	4.02
14 MKD	0.011 (SIL1)	3.89
No BETS	0.059 (< SIL1)	3.40
No RTS	0.32 (< SIL1)	4.06

All these systems are obligatory !

Source of failures (from study)

Case studied	Unsafety/year	False dumps/year
Default scenario	2.41×10^{-7} (> SIL4)	4.06

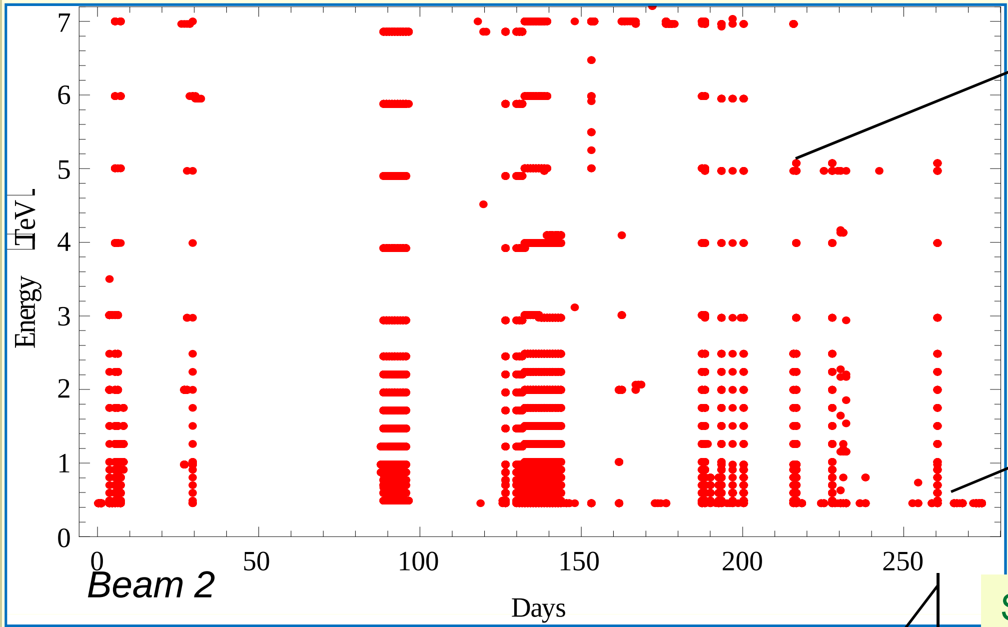
Apportionment of unsafety (=unacceptable failure) to the different components:

System	Total%
MKD	74.8
MSD	18.6
MKB	6.1
BEMS	0.27
Triggering	0.23

MKD is the most complicated system and contributes most to the unsafety.

The MKB dilution failures contribute 6 % to the unacceptable failures (presentation B.Goddard Friday)

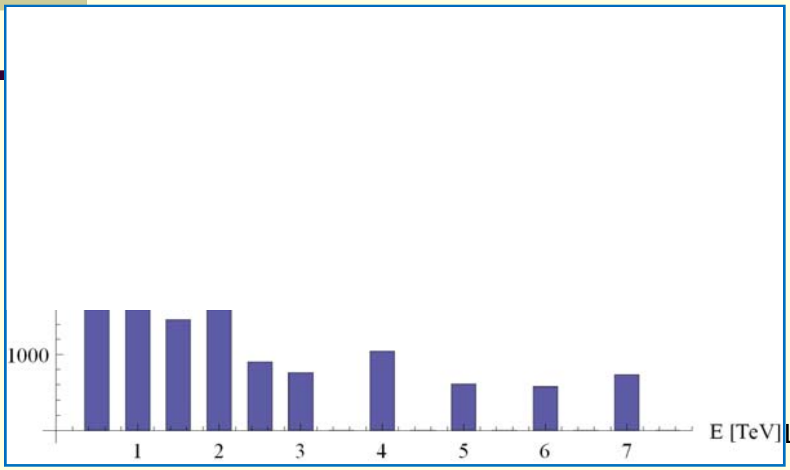
Operational Experience
Reliability Run of the Beam Dumping System



Operation only below 5.5 TeV, due to MKB break down

Operation 'with beam' at injection energy

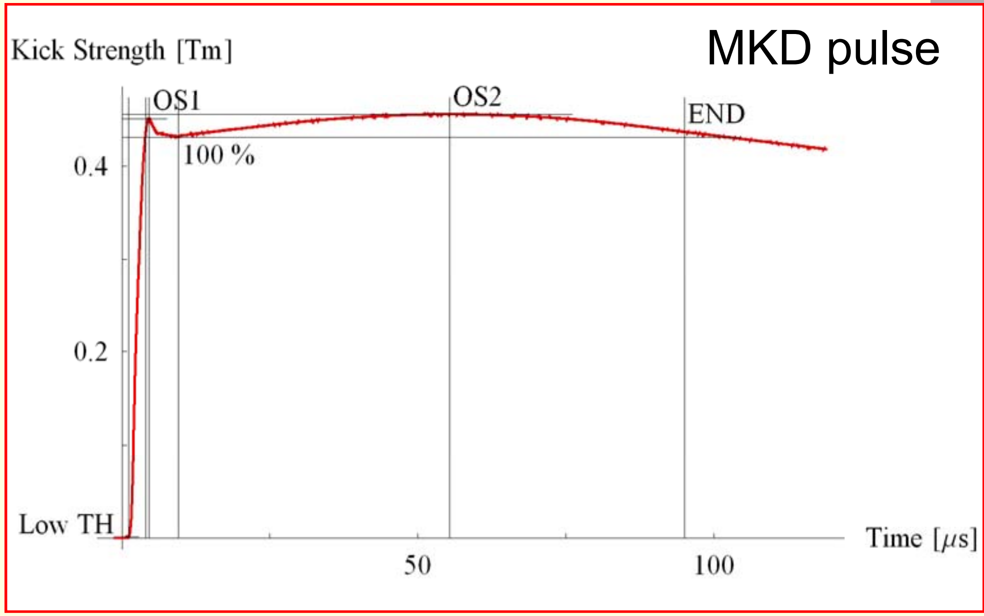
System pulses = 19 magnets



	Beam 1	Beam 2
# Pulses	23'534	15'469
Time considered	10.5 months	9.1 months
Continuous running (p <13 h)	2.7 months	1.7 months

Data from 8/11/07 to 19/09/08

Reliability Run: Internal and External Post Operational Checks (IPOC / XPOC)



- **741'057** Magnet Pulses Analysed with IPOC and XPOC Systems
  - > 10 years of operation
- Some hardware problems discovered →
- No critical failures on the MKD system which would have resulted in a non-acceptable beam dump <u>even if redundancy would not be there</u>
- No 'asynchronous' beam dumps were recorded (erratics). No missings.
- However, unexpected MKB breakdown → →

MKD Issues Discovered

- Four switch failures due to short circuit on one of the GTO discs
  - Within limits of reliability calculation assumptions
  - Would not have given an unacceptable beam dump but internal dump request resulting in synchronous dump
- Problem with voltage distribution of GTO stacks: internal dump request
  - All checked and redistributed for 2009
  - Only affected availability, not safety
- Re-soldering of trigger contacts on GTO stack

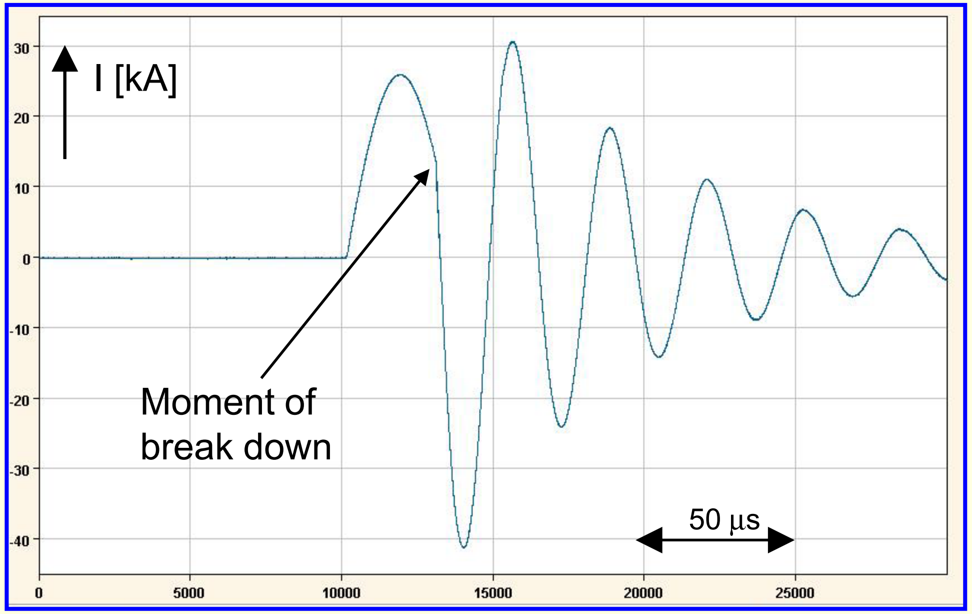
All failures were detected by diagnostics, IPOC/XPOC !

MKB failures

- Unexpected common mode failure on the MKB system. Flashovers in 3 out of 4 magnets simultaneously after operation under bad vacuum: stopped operation above 5 TeV. Measures taken:
  - Additional vacuum interlock
  - HV insulators, identified as weak point, being changed for 2009
  - Reduced conductance between adjacent MKB tanks by smaller aperture interconnects

MKB generator design similar to MKD, but with less redundancy within generator

Measured MKB wave form

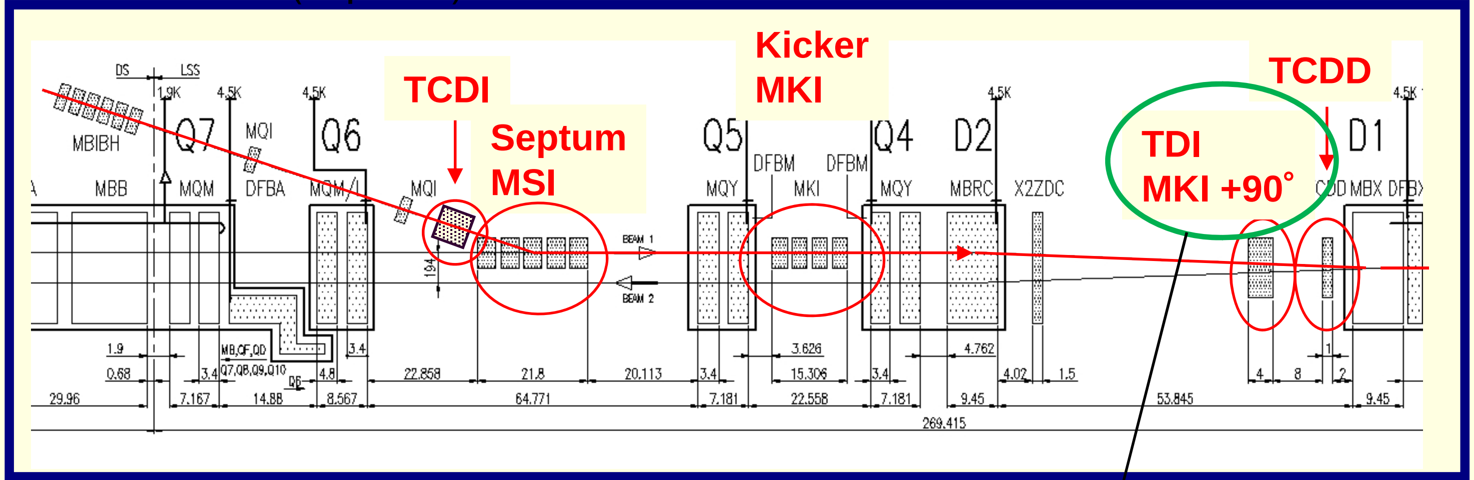


Injection System Kickers MKI

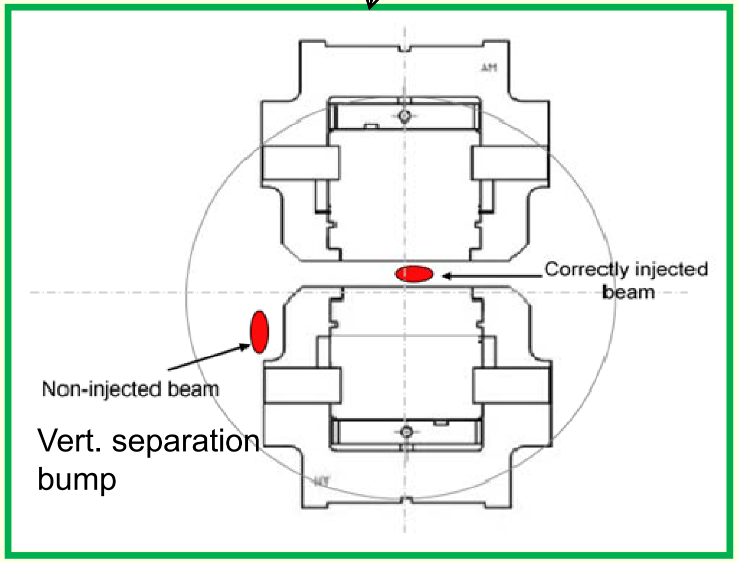
- Travelling Wave Structure, with PFNs and 'classical' thyratron switches
  - Per system experienced / expect about 1 missing kick per year
  - Expect / experienced a few erratics per year
    - Limited charging time of 2 – 3 ms before triggering
    - System switched off after injection
- Operation is stopped after any missing or erratic
- No redundancy in number of kickers
- Machine aperture protected by two sided injection absorber TDI →

Injection Absorber TDI

LEFT OF IP2 (H plane)



- TDI:
  - ~ 4m long, ~ 10 m upstream of D1, additional mask in front of D1 (TCDD)
  - Protects machine against MKI failures
  - Required setting: 6.8 σ (Assuming 7.5 σ machine aperture)



Experience 2008

- Some MKI magnet breakdowns occurred (nominally: 1/operational year)
  - One magnet had shown a breakdown, probably by over-voltage during lab conditioning due to a calibration error
  - Indications of MKI flashovers triggered by beam loss during aperture studies
  - Results in larger kick (short circuit) or smaller kick (emptied PFN): system kick strength can vary between 75 % and 125 % of nominal for a part of the pulse: beam onto TDI / TCDD
    - For small errors beam can graze the TDI: additional collimators TCLI and normal collimators in point 3 and 7.
- Measures
  - SoftStart of the injection kickers if not pulsed for more than 1 hour. Automatic ramp up to nominal operational voltage before beam
  - Installation of additional Beam Loss Monitors at the MKI to monitor beam losses: improve understanding and later possibly interlock
  - For 2009: injection quality check which includes an automatic analysis all MKI pulses and compare to references (similar as for beam dumping system)
- Main protection is the TDI / TCDD

Transverse Damper

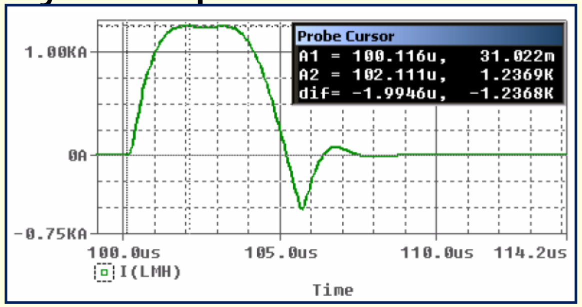
BE/RF

- Also used for abort gap cleaning
- Worst possible failure scenario:
  - Full strength, at injection energy at wrong phase resulting in coherent excitation
  - Results in 1 σ growth after 4 turns
- With collimators set-up correctly will loose the beam on the collimators
  - Beam Loss Monitors at collimators should see this as soon as losses are significant and trigger beam dump request
  - Reaction time of beam dump < 3 turns: beam should be dumped before any losses which can damage equipment
- If collimators not set-up correctly: BLMs are positioned to have a machine wide coverage and will dump before damage

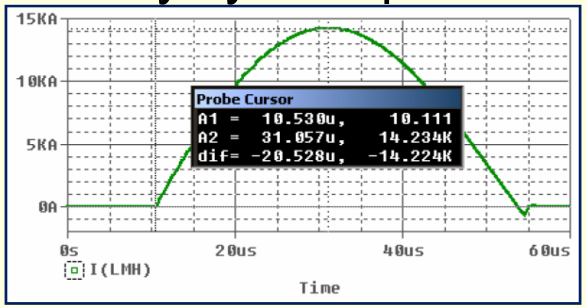
See also W. Höfle, review on Machine Protection and Interlocks, April 2005

MKQA kicker and AC-Dipole

- Four Systems: 2 planes x 2 beams
- Three generators working on each magnet
- Tune kicker MKQ: Kick strength limited by system power converter:
  - 0.41 σ at 7 TeV
  - 1.6 σ at 450 GeV
  - Should not imply any risk



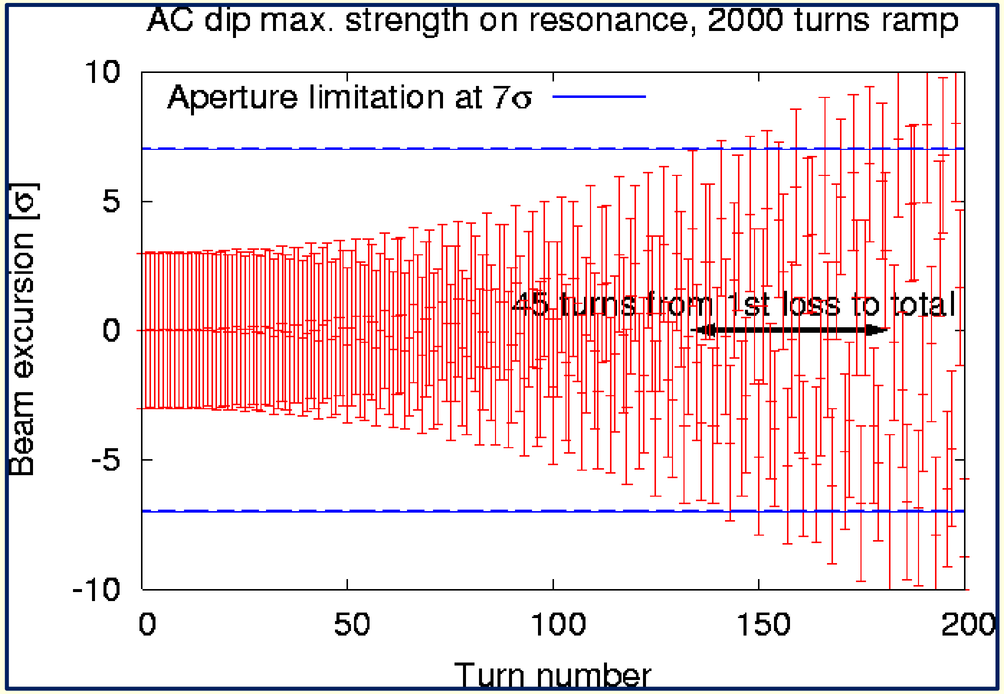
- Aperture kicker MKA: also kick strength limited by system power converter:
  - 1.6 σ at 7 TeV
  - 6.1 σ at 450 GeV
  - Operation potentially dangerous
    - Can only be operated with 'safe beam' – MKA has a maskable interlock on the BIC which is always active
    - Physical key required to switch between MKQ –MKA – AC-dipole



AC-dipole operating **on tune**: beam loss in about 45 turns: ok

BE/CO

Operation on tune, injection energy, nominal strength (normally gives 7 σ for δ = 0.025), ramp up of kick strength over 200 ms = 2000 turns



- If excitation too important: beams lost on collimators and detected by Beam Loss Monitors
- If BLMS trigger beam dump, beam dump within < 3 turns
- Only to be used with safe beam. See also LTC meeting 6 June 2007

Conclusions

- By their nature kickers are a good candidate for possibly causing important damage to the LHC
- Great care has been taken to avoid this
  - Redundancy and surveillance of the beam dumping system
  - Absorbers on both beam dumping and injection system
  - Limitation of power on tune and aperture kicker MKQA
  - AC dipole and Transverse damper (*not really kickers*)
    - Also limited power
    - Slow enough as to trigger beam dump via Beam Loss Monitors
- Requires thorough commissioning of the fully connected system for Machine Protection
  - Systematic and rigorous tests with formal approval before beam current or beam energy can significantly be increased
  - Awareness is present: keep time for it on the schedule !