Fast Kick Failures

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External Review on LHC Machine Protection

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Fast Kick Failures

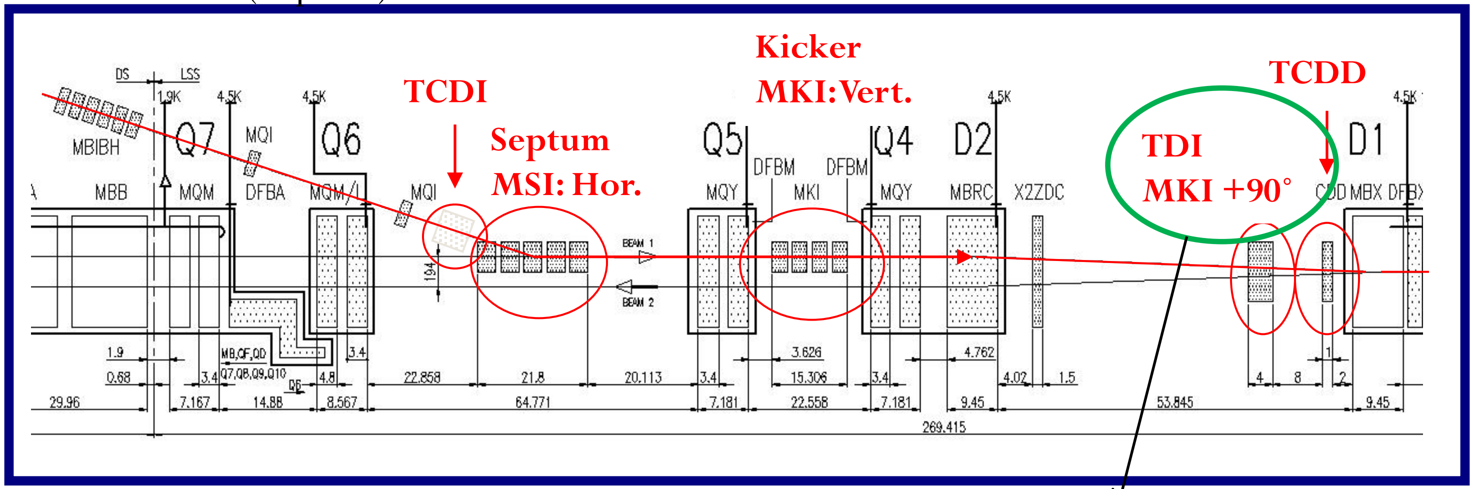
- Fast kick failures are dangerous as there is no 'growth time' of a few turns which allows the beam to be dumped after detection of the failure or beam losses
- Possible causes of fast (kick) failures:
  - Injection System
    - Injection kicker failures
  - Beam Dumping Systems
    - Extraction kicker failures
  - Diagnostic 'kicker' failures
    - Tune kicker
    - Aperture kicker
    - AC-dipole
  - Transverse damper failures

Injection System Kickers MKI

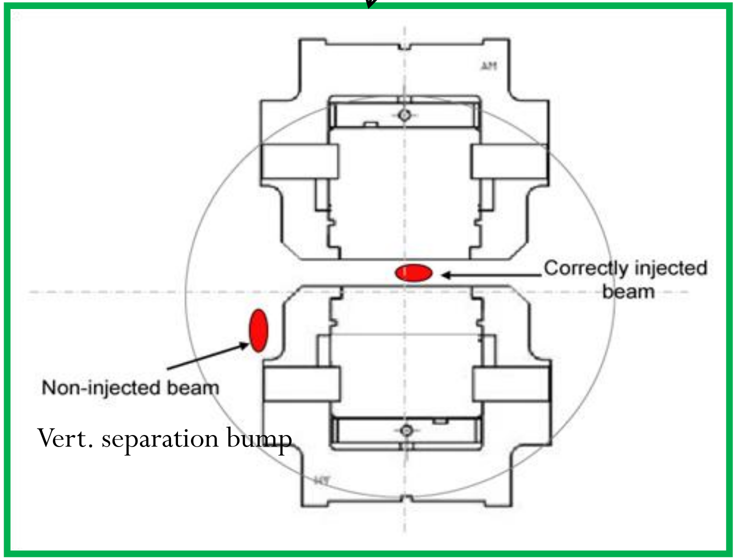
- Travelling Wave Structure, with individual PFNs and ‘classical’ thyratron switches
  - Four injection kickers per beam
  - Errors are: timing, amplitude, missing, erratics.
- Operation is stopped after any detected missing or erratic
- No redundancy in number of kickers
- Machine aperture is protected by two sided injection absorber TDI

Injection Kicker Failures

LEFT OF IP2 (H plane)



- TDI:
  - ~ 4m long, ~ 10 m upstream of D1, additional mask in front of D1 (TCDD)
  - Protects machine against (most) MKI failures
  - Required setting: 6.8 σ (Assuming 7.5 σ machine aperture)
  - TDI has to be at the correct injection settings to protect the aperture!
  - Designed to intercept nominal injection batch of 288 bunches, with TCDD should not quench D1



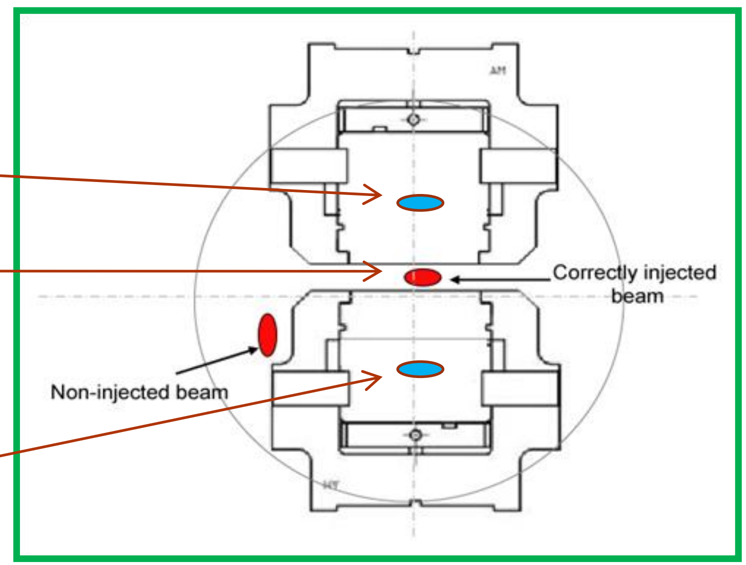
Injection kicker ‘failures’

- Accepted modes – protected by correct positioning of TDI and other absorbers:
  - Missing kick
  - Kicking out stored beam: over injecting on top of pilot
- Procedures – reference files

Injected beam with kicker off

TDI opening ± 6.8 σ

Stored beam being kicked out: over injection



Injection Kicker Failures
Non standard modes

- **Kicker not at correct voltage:** Amplitude problem
  - Injection Beam Energy Tracking System, which checks that the machine energy, calculated by the beam dumping system, is the injection energy of 450 GeV and that the secondary voltage on the PFNs are within pre-defined limits (plus software (SIS), Injection Collimators, Experiments etc.)
- **Kicker erratic:** Amplitude and synchronisation problem
  - Limited to time system is under voltage, 2 – 3 ms before triggering. System switched to standby after injection
  - Expect a few erratics per year .
    Experienced two erratics with beam in the machine in 2010. In total one erratic point 8 and 8 erratics in point 2 of which 6 in the same switch which was replaced last week.
    Most erratics happened during 'Soft Start' of the machine with different kick pulse length…
    - Aging of thyratrons must be detected at an early stage!
  - Erratic of main switch will give a re-trigger of main and dump switches: different kick length and different timing, delay of about 1 μs
  - Erratic of dump switch will trigger all dump switches
- **Kicker missing:** Per system expect about 1 missing kick per year
  - Due to switch missing = ¾ of nominal kick
    - Double triggering system with monitoring, so expect very few missings
    - In 2010 no switch missing occurred
  - Due to system missing (BIS, BETS, AGK, timing. Talk V.Kain)
    - In 2010 had a few per month, none anymore after control system changes a few weeks ago

Injection Kicker Failures
Non standard modes

- **Kicker magnet spark**– kick strength can vary between 75 % and 125 % of nominal kick
  - Nominally 1/operational year per system
  - In 2010 two sparks point 8, during SoftStarts, and one in point 2 during injection with beam
  - SoftStart to reduce breakdown: automatic conditioning of kickers if not pulsed for > 1.5 hours
- **Discharging of ceramic chamber** were experienced in case of large beam losses at injection or when staying a long time with beam at physics
    - Does not affect the magnetic field but could initiate a magnet spark
- **Terminating resistor** breakdown
  - Open circuit or short circuit
  - Will affect amplitude and pulse length
  - Will interlock the system after bad pulse
- **Operational Protection**
  - Delay length and strength settings can only be changed by small amounts. Thresholds on this are set by Management of Critical Settings (MCS)
  - Enable/disable of MKI is not protected at the moment, but in the future should only be possible in 'Expert Mode'
  - Injection Quality Check: each MKI pulse is compared to (tight) references

Injection Kicker Failures
Non standard modes - timing

- Kicker timing error
  - Beam at the wrong position in the machine or kicking out stored beam: TDI
  - Worst timing error is to inject beam in the 3 μs Beam Dump abort gap. This beam could then theoretically be accelerated up to 7 TeV
  - The AGK (Abort Gap Keeper) which is a direct timing link between the beam dumping system and the injection system prevents having any beam injected in the abort gap
- Synchronisation error between kicker magnets – drifts
  - Watched by Injection Quality Check

Effect of all Injection kicker failures: The beam will end up on the TDI, but for small angles the beam can graze the TDI. Additional collimators TCLI and normal collimators in points 3 and 7 are made to intercept this beam

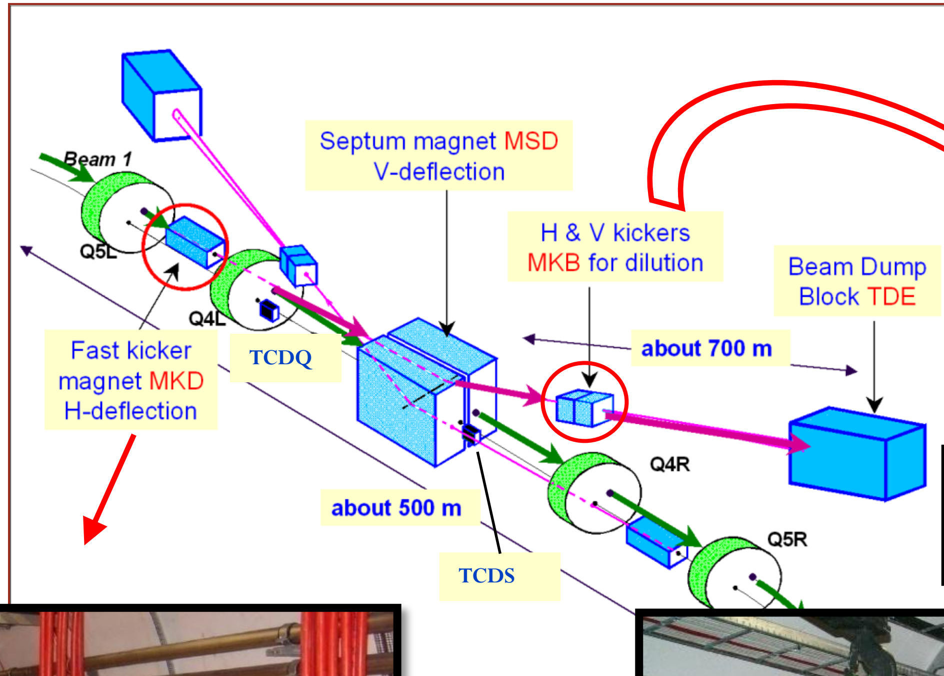
Next talk Verena Kain

- Injection transfer line failures and machine setting
- Operational Experience with the Injection System

LHC Beam Dumping System

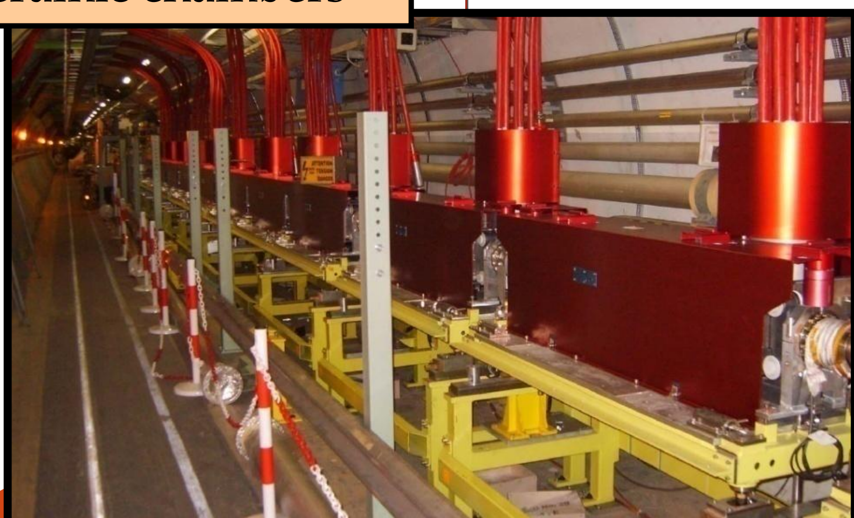
MKD:
2 x 15 Systems

Magnet operates in air with coated ceramic chambers



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

Magnet operates under vacuum



Beam Dumping System

- Extraction kickers MKD and dilution kickers MKB. Extraction septum MSD
- 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 and MSD failure: damage the extraction channel and beam dump block
    - Less critical and not treated here – don't affect the stored beam

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 → *$2.4 \cdot 10^{-6}$ 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, however kick will be slightly different due to different system impedance
  - 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
  - Machine Protection System reliability study: SIL3

Experience from Reliability Run, simulating 10 years of operation: No missings occured!

MKD system Kicking with Wrong Strength

- Probably one of the worst scenario's
- Covered by comprehensive Beam 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
    - Tables are checked against independent data base before each fill
  - Redundant BETS system in the slow control with larger tolerances

Erratic firing of MKD kicker

- Re-triggering system which detects any 'spontaneous' firing of an MKD magnet
- Expect about 1 erratic per year
- MKB erratic will result in a synchronous beam dump
- Within 700 ns at 7 TeV 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 to be sure re-triggering takes place

Experience from Reliability Run: No erratics occurred!
Correct operation of the re-triggering system validated under operational conditions.
After installation of MKD generator cooling: erratics at 5 TeV settings! Not the switch giving erratics, but conduction outside the switch. Isolators being installed in generator

External review of Trigger Synchronisation Unit ongoing

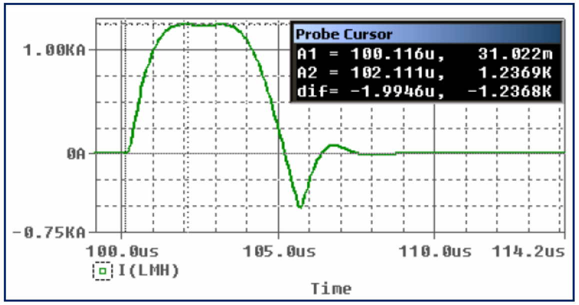
- Presently ongoing
- Preliminary results ok
- Three failures identified which would all lead to an asynchronous beam dump

Talks Brennan Goddard and Chiara Bracco

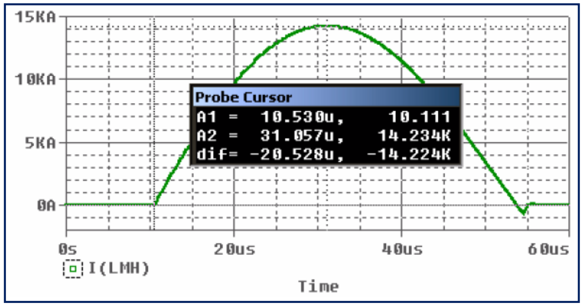
- Operational Experience with the Beam Dumping System
- Energy tracking system (wrong amplitude kicks)
- Post Operational Checks
- Protection against asynchronous dumps

MKQA kicker and AC-Dipole

- Four Systems: 2 planes x 2 beams
- Three generators working on each magnet
  - Tune kicker MKQ, Aperture kicker MKA and AC-dipole
  - By default the system is in Tune Kicker mode and is not interlocked
  - A key is required for each of the four systems to select any other mode than the Tune Kicker.
    - Four key holders have a set of keys, but often set of keys are 'hidden' in the control room
- Tune kicker MKQ: Kick strength limited by system power converter:
  - 0.41 σ at 7 TeV
  - 1.6 σ at 450 GeV
  - About 5 μs pulse length
  - Should not imply any risk



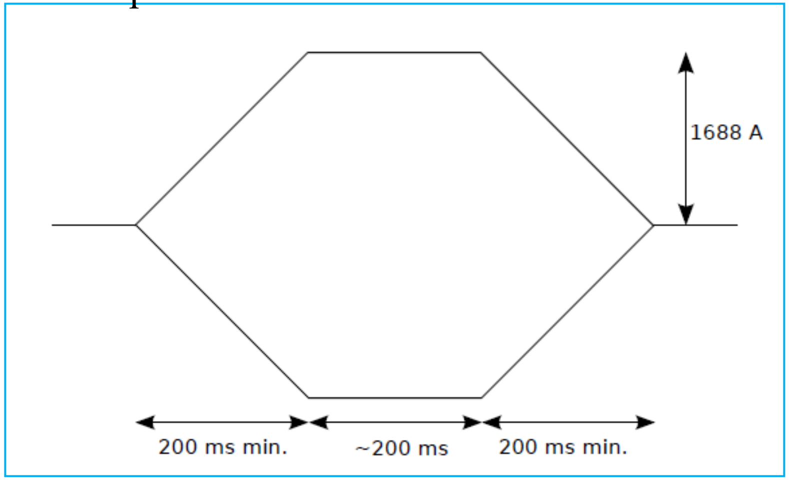
- Aperture kicker MKA: also kick strength limited by system power converter:
  - 1.6 σ at 7 TeV
  - 6.1 σ at 450 GeV
  - Half sine wave of about half the machine
  - Operation potentially dangerous
    - **Can only be operated with 'set-up beam' – MKA is an always active, maskable interlock on the BIC.**

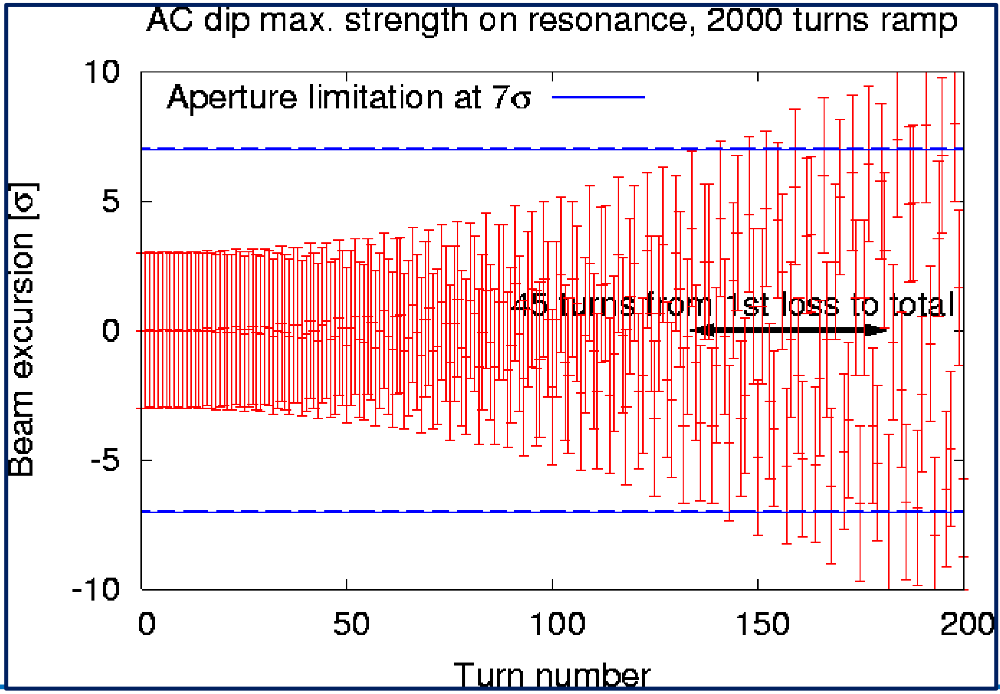


AC-dipole operating **on tune**: beam loss in about 45 turns: ok

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

AC-dipole hardware limitations:





- 45 turns between first losses and total loss of the beam
- If excitation too important: beams lost on collimators and detected by Beam Loss Monitors
- If BLMS trigger beam dump, beam dump within < 3 turns
- **Can only be operated with 'set-up beam' – the AC-dipole is an always active, maskable interlock on the BIC**

Operational Experience with the Diagnostics Kickers

- Always worked according to expectations
  - AC-dipole used regularly for beta-beat measurements
- Not aware of any dangerous situations which could have lead to machine damage

Transverse Damper

- Also used for abort gap cleaning (talk C.Bracco)
- 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

Operational Experience with the transverse damper

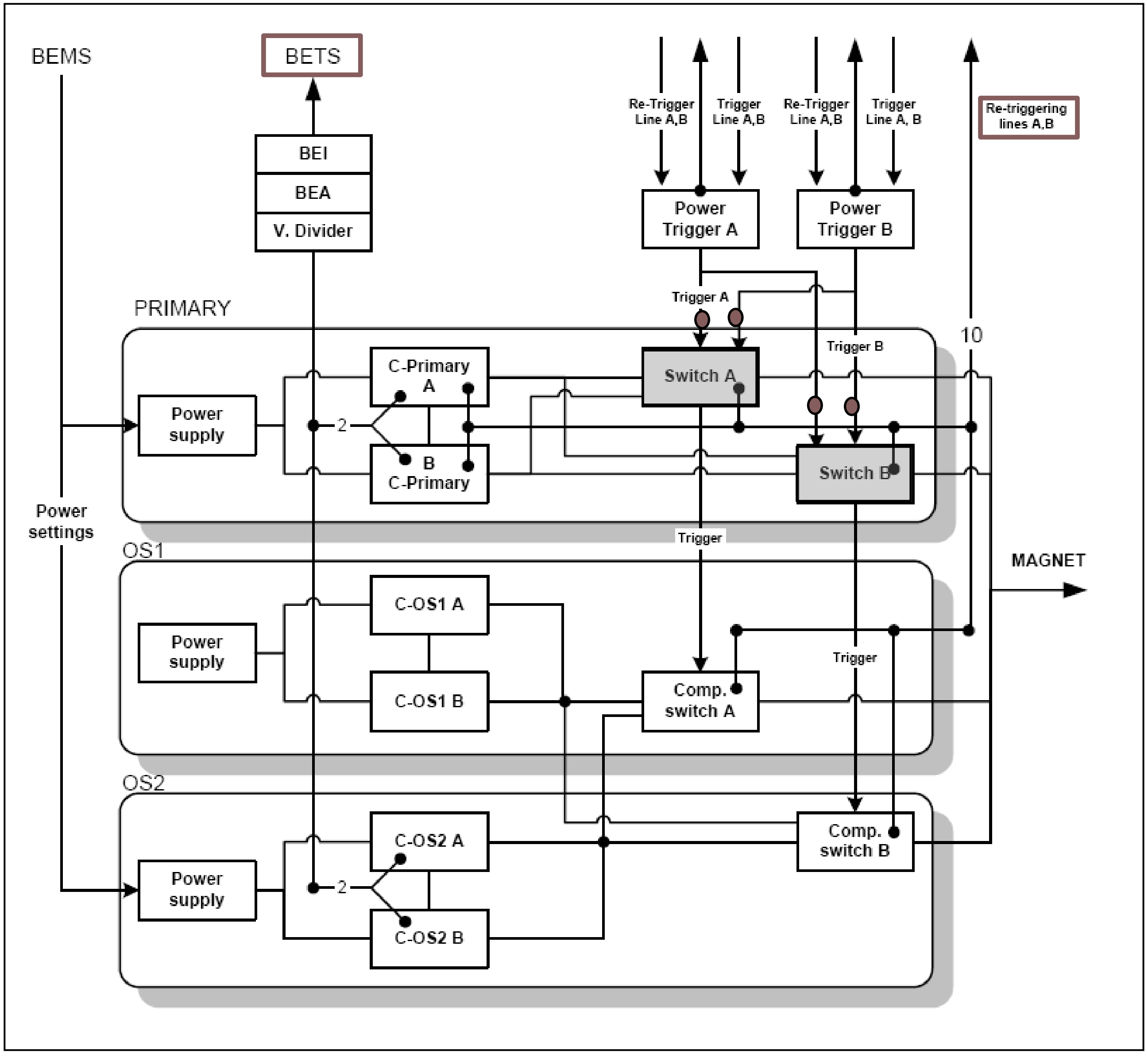
- Lot of hard work on the system by the BE/RF team
- Not aware of any dangerous situations which could have lead to machine damage

Conclusions

- By their nature kickers and other fast acting equipment 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 and injection system
  - Absorbers on both beam dumping and injection system
  - Limitation of power on tune, aperture kicker MKQA and AC-dipole
    - Aperture kicker and AC-dipole can only be used with Set-up Beam
  - AC dipole and Transverse damper (*not really kickers*)
    - Slow enough as to trigger beam dump via Beam Loss Monitors
- No operational experience so far which is scary

Spare Slides

Functional Architecture of 1 MKD Generator



Source of failures (from study)

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

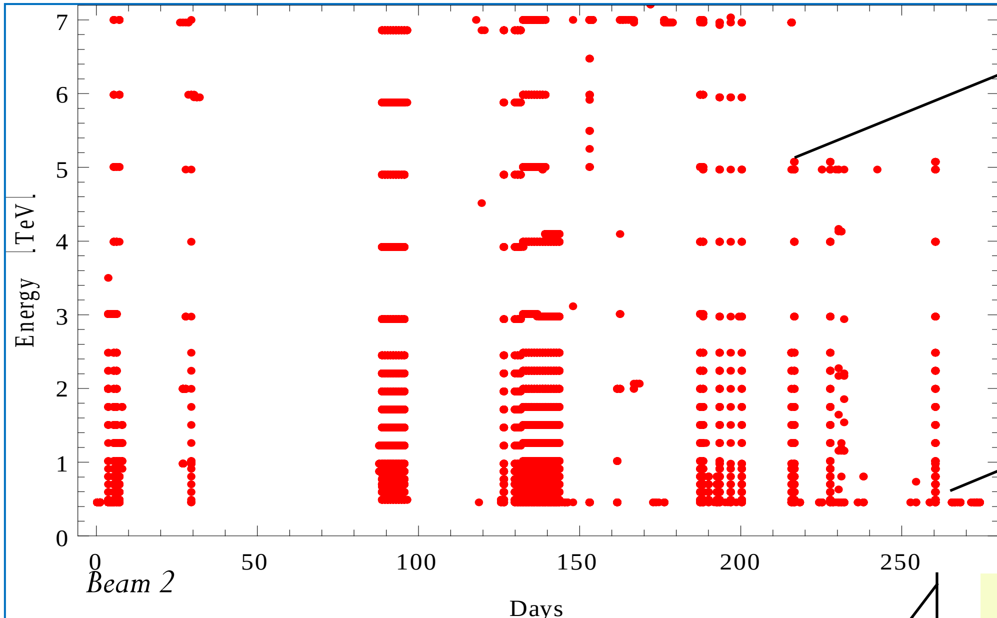
Apportionment of unsafety (=unacceptable failure) to the different components:

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

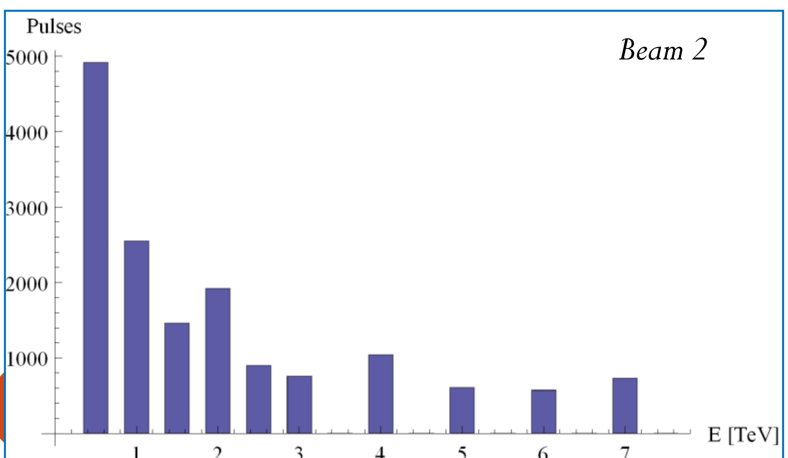
Operational Experience
Reliability Run of the Beam Dumping System



Operation only below 5.5 TeV, due to MKB break down

Operation 'with beam' at injection energy

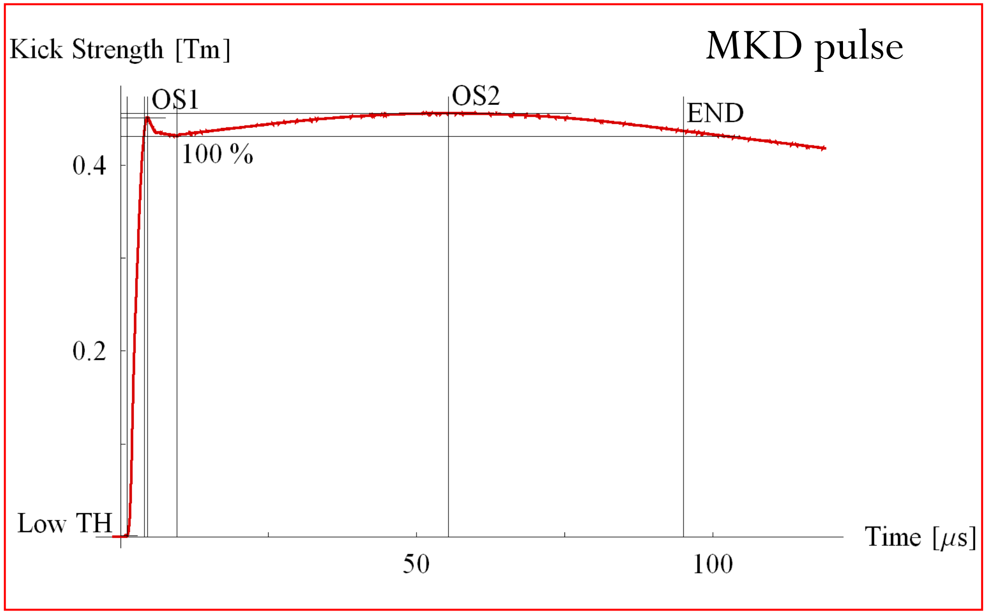
System pulses = 19 magnets



	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 even if redundancy would not be there
- No 'asynchronous' beam dumps were recorded (erratics). No missings.
- However, unexpected MKB breakdown → →