Experience with LHC Machine Protection

M. Zerlauth CLIC – Machine Protection Workshop June 2012

Acknowledgements: R.Schmidt, J.Wenninger,T.Baer, V.Kain, C.Bracco, R.Assmann,…
for material shown and many more colleagues working on MP

- Risk with Energy and Power
- Design considerations for LHC Machine Protection System
- LHC Machine Protection Architecture + few examples
- LHC operation and machine protection systems
- Injection Protection
- Summary

1v0

- **Risk with Energy and Power**
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Risk with Energy and Power

- Risks come from Energy stored in a system (Joule), and Power when operating a system (Watt)

  “very powerful accelerator” … the power flow needs to be controlled

- An uncontrolled release of the energy or an uncontrolled power flow can lead to unwanted consequences

  Loss of time for operation or damage of equipment

- This is true for all systems, in particular for complex systems such as accelerators

  For the RF system, magnet system (LHC=10GJ) …

  For the beams (LHC=360MJ/beam)

- The LHC is the first accelerator at CERN where machine protection considerations determine daily operation

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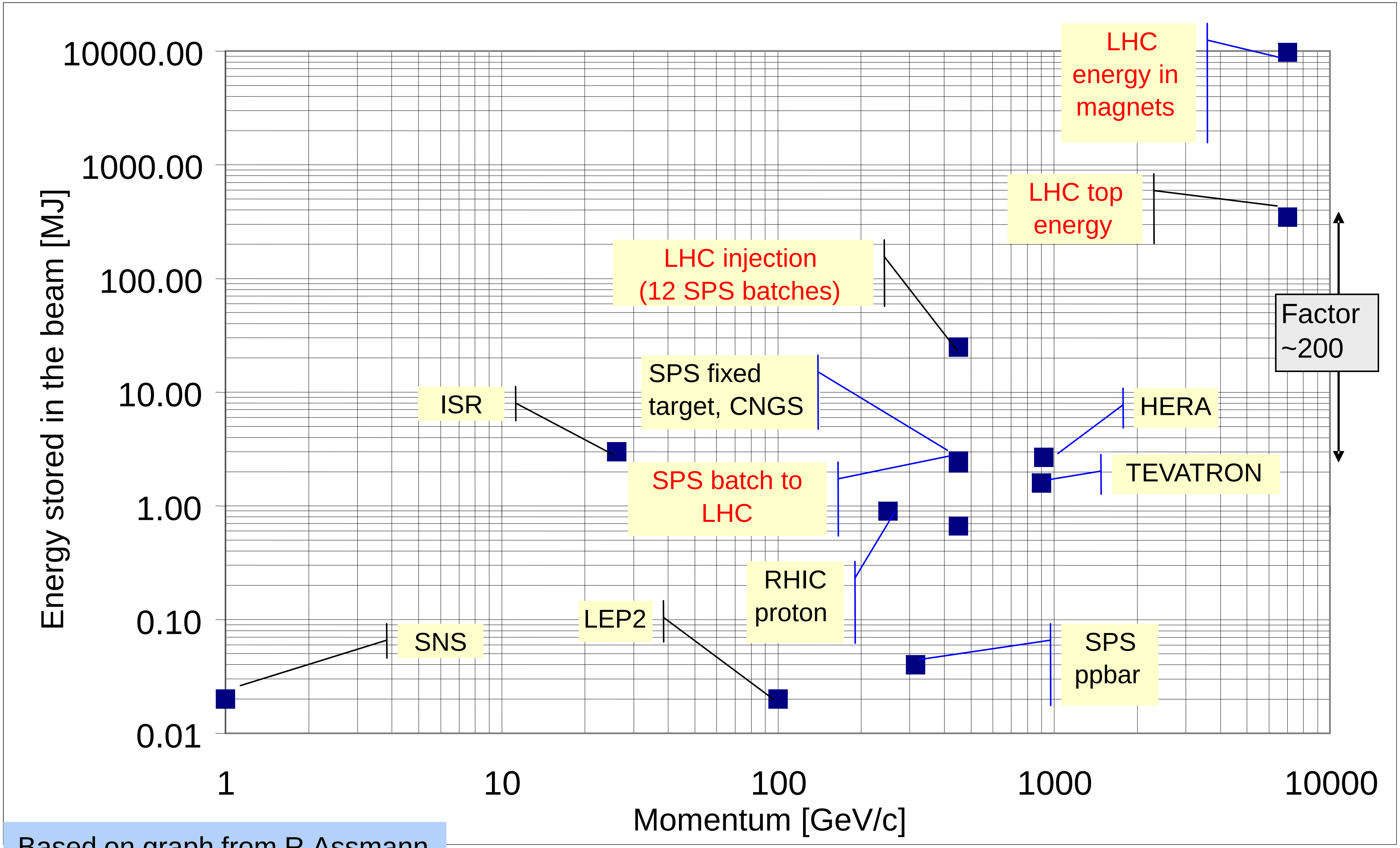
Livingston type plot: Energy stored magnets and beam



Based on graph from R.Assmann

What parameters are relevant?

- Momentum of the particle
- Particle type
  - Activation is mainly an issue for hadron accelerators
- Time structure of beam
- Energy stored in the beam (synchrotrons and storage rings)
  - one MJoule can heat and melt 1.5 kg of copper
  - one MJoule corresponds to the energy stored in 0.25 kg of TNT
- Beam power (linear machines and fast cycling machines)
  - one MW during one second = one MJ
- Beam size
- Beam power / energy density (MJoule/mm^2, MWatt/mm^2) increasingly important for future projects, and increasingly complex machines (such as ILC and CLIC, XFEL,..)

The energy of an 200 m long fast train at 155 km/hour corresponds to the energy of 360 MJoule stored in one LHC beam

Machine protection to be considered for an energy in the beam >> 1 kJ
Very important if energy > 1 MJ

Protection Functions of LHC MPS

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)

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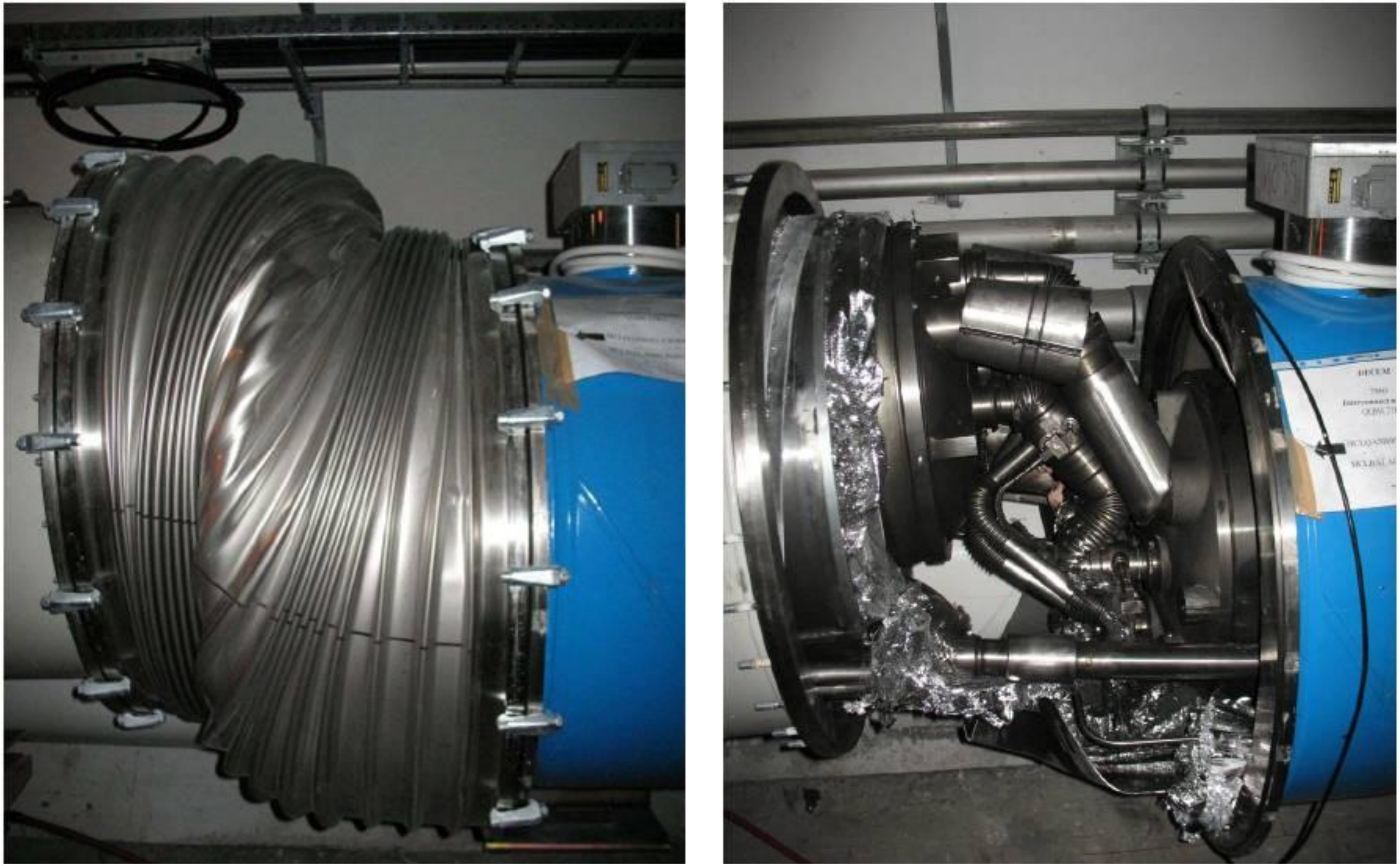
Accidental release of 600 MJoule stored in the LHC dipole magnets (one out of eight sectors, interconnect)



without beam!

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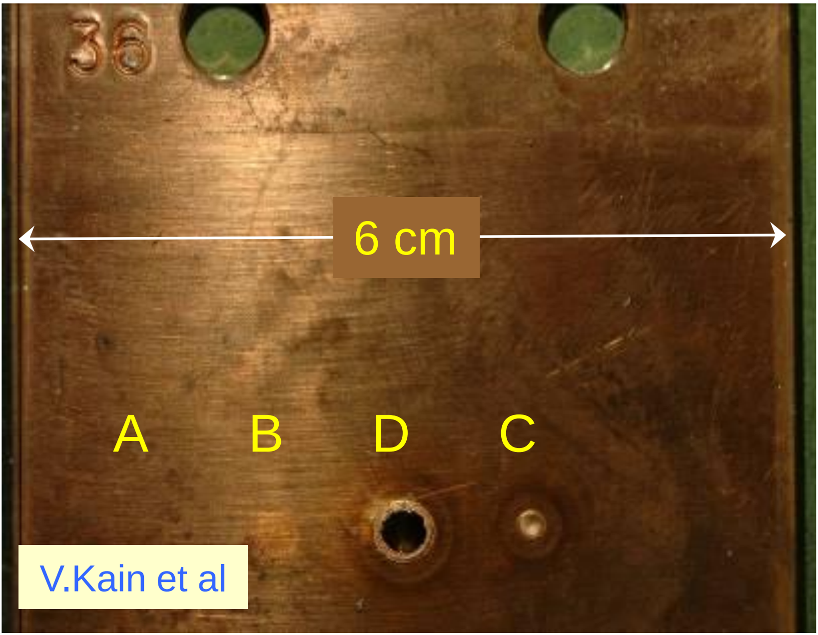
SPS experiment: Beam damage with 450 GeV proton beam

Controlled SPS experiment

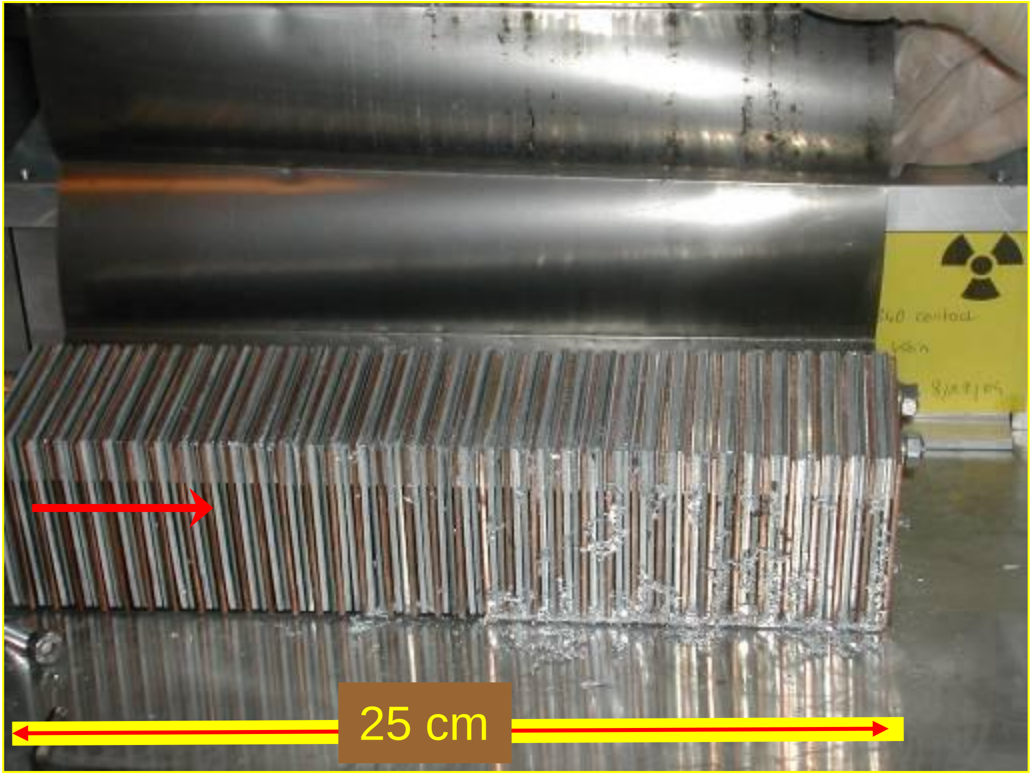
- $8 \cdot 10^{12}$ protons clear damage
- beam size $\sigma_{x/y}$ = 1.1mm/0.6mm

stainless steel no damage

- $2 \cdot 10^{12}$ protons



V.Kain et al



- Damage limit ~200 kJoule
- 0.1 % of the full LHC 7 TeV beams
- factor of ~10 below the energy in a bunch train injected into LHC

- Risk with Energy and Power
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Machine Protection organisational aspects

- The risks during LHC operation are known since a long time
- Systems for protection were designed and included in the first design report (1995)
  - beam dumping system
  - magnet protection system
  - beam loss monitors
- It was realised that an interlock system is required since there is coupling between different systems (~1999)
- The work on a coherent interlock system started in 2000
- The beam and powering interlock systems connect to many accelerator systems, and a forum for discussions and decisions was required
- Birth of the Machine Protection Working Group in 2001, and in the following a Reliability Sub-Working Group to discuss, define and follow-up the required high dependability systems

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Design principles for LHC machine protection 1/2

- Protect the machine
  - highest priority is to avoid damage of the accelerators, requires a very high reliability for detecting failures and stopping operation
- Protect the beam
  - complex protection systems will always reduce the availability of the machine
  - in the design of protection systems: minimise number of “false” interlocks stopping operation
  - trade-off between protection and operation (will we every operate with many 10.000 interlock channels?)
- Provide the evidence
  - if the protection systems stops operation (e.g. dumps the beam or inhibits injection), clear diagnostics should be provided
  - if something goes wrong (near miss or even damage), it should be possible to understand the reason why
  - diagnostics is frequently not taken seriously enough at design phase, resulting in loss of valuable machine time during later operation

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Design principles for LHC machine protection 2/2

- Failsafe design

  detects internal faults

  if protection equipment does not work, stop operation rather than damage equipment
- Critical equipment should be redundant (possibly diverse)
- Critical processes not by software (no operating system)

  no remote changes of most critical parameters
- Demonstrate safety / availability / reliability

  use established methods to analyse critical systems and to predict failure rate
- Managing interlocks (masking during early operation)

  LHC: masking only possible if operating with low intensity / low energy beams
- Design the system with testing in mind

  possibility for remote testing, for example between runs
- Appropriate diagnostics implemented in design stage

  possibility for efficient data analysis following failures

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LHC: Strategy for machine protection

Definition of aperture by collimators	Beam Cleaning System
Early detection of failures for equipment acting on beams generates dump request, possibly before the beam is affected.	Powering Interlocks Fast Magnet Current change Monitors Equipment systems,…
Active monitoring of the beams detects abnormal beam conditions and generates beam dump requests down to a single machine turn.	Beam Loss Monitors Other Beam Monitors
Reliable transmission of beam dump requests to beam dumping system. Active signal required for operation, absence of signal is considered as beam dump request and injection inhibit.	Beam Interlock System
Reliable operation of beam dumping system for dump requests or internal faults, safely extract the beams onto the external dump blocks.	Beam Dumping System
Passive protection by beam absorbers and collimators for specific failure cases.	Beam Absorbers

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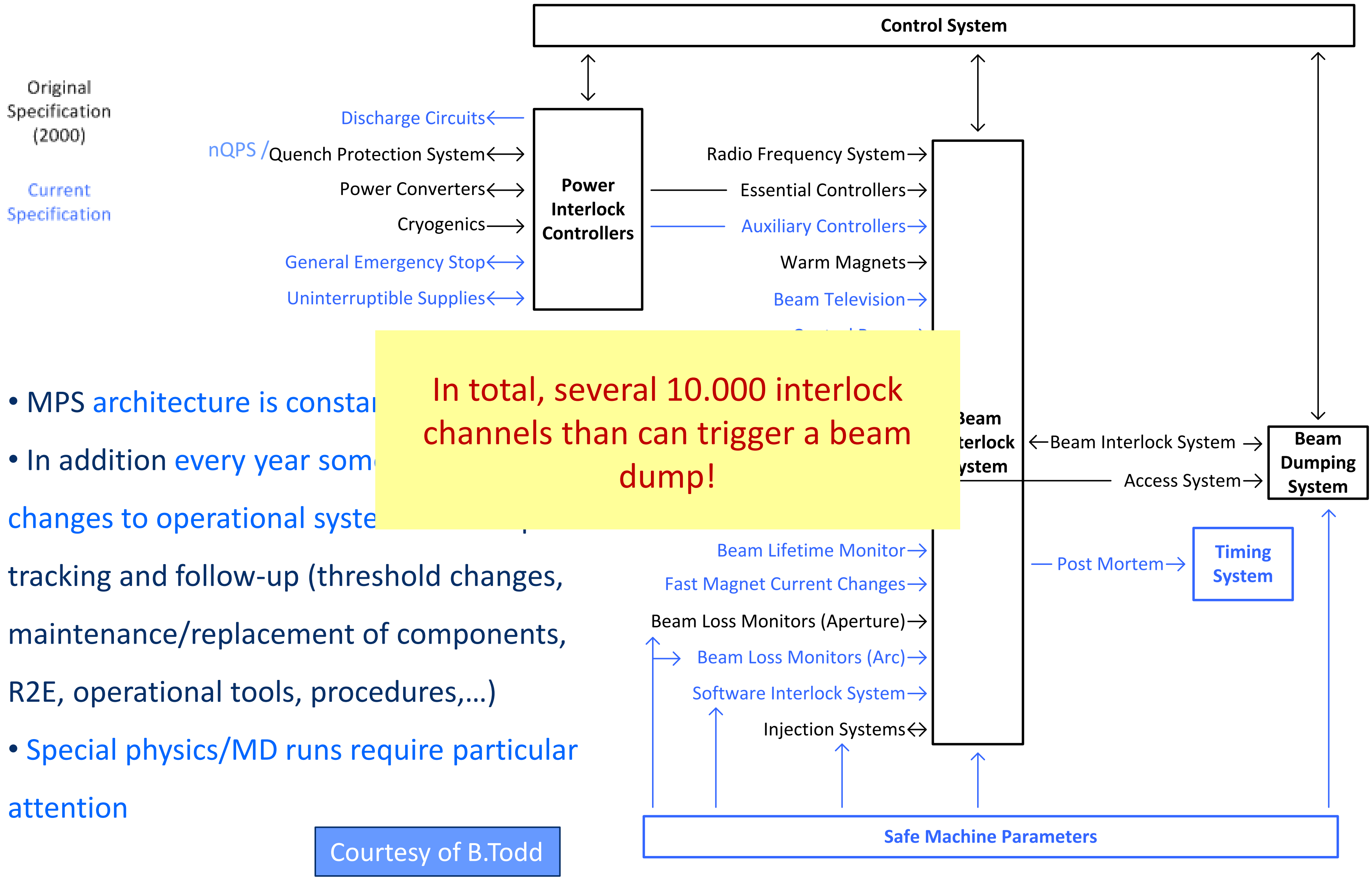
LHC Machine Protection Architecture



In total, several 10.000 interlock channels than can trigger a beam dump!

- MPS architecture is consta
- In addition every year som

changes to operational syste

tracking and follow-up (threshold changes, maintenance/replacement of components, R2E, operational tools, procedures,…)

- Special physics/MD runs require particular attention

Courtesy of B.Todd

Machine Protection and Controls

- **Software Interlock Systems (SIS)** provides additional protection for complex but also less critical conditions
  - The reaction time of those systems will be at the level of a few seconds (much longer than hardware interlock systems)
  - The systems rely entirely on the computer network, databases, etc – clearly not as safe as HW systems!
  - Surveillance of magnet currents to avoid certain failures (local bumps) that would reduce the aperture
- **Sequencer:** program to execute defined procedures
  - Dependable execution of defined and well-tested procedures and operational checks
- **Logging and PM systems**: recording of data – continuous logging and fast recording for transients (beam dump, quench, …)
  - Very important to understand what happened

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Magnet Powering Failures with fast effects on beams

- Incident in TT40 extraction line revealed danger of nc magnets with low time constants

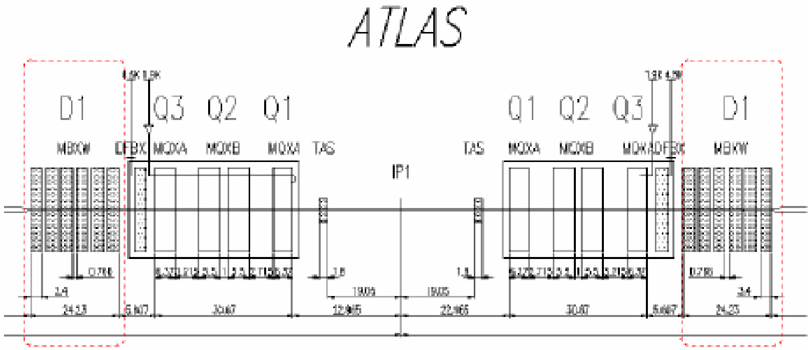
- Powering Failures in normal conducting separation dipoles D1 in IR1 and IR5 found to be fast(est) failure in LHC

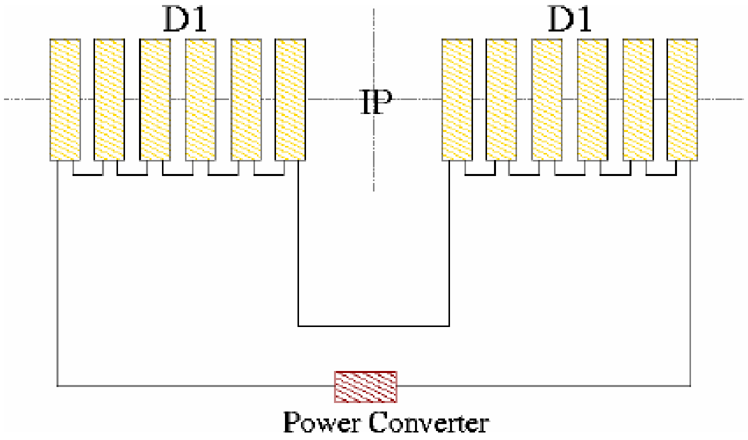
- 12 modules powered in series.

- $\beta_x > 2000\text{m}$

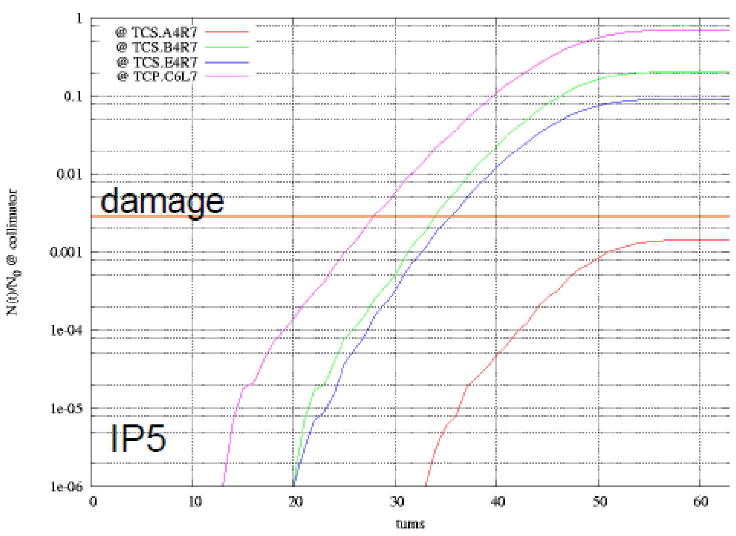
- time constant: $\tau = \frac{L}{R}, \tau = 2.53\text{s}$

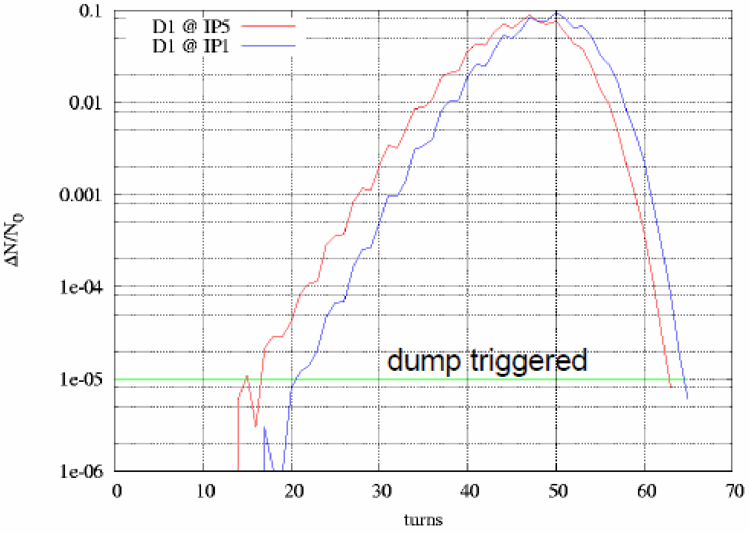
$$B(t) = B_0 \cdot e^{-\frac{t}{\tau}}$$

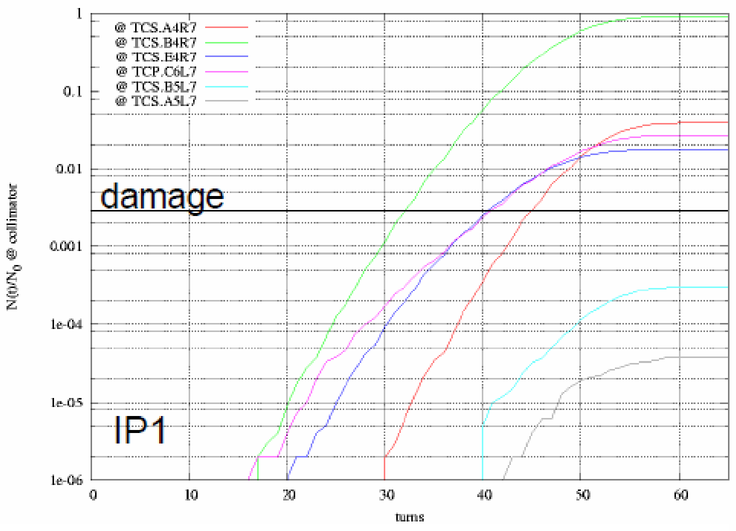


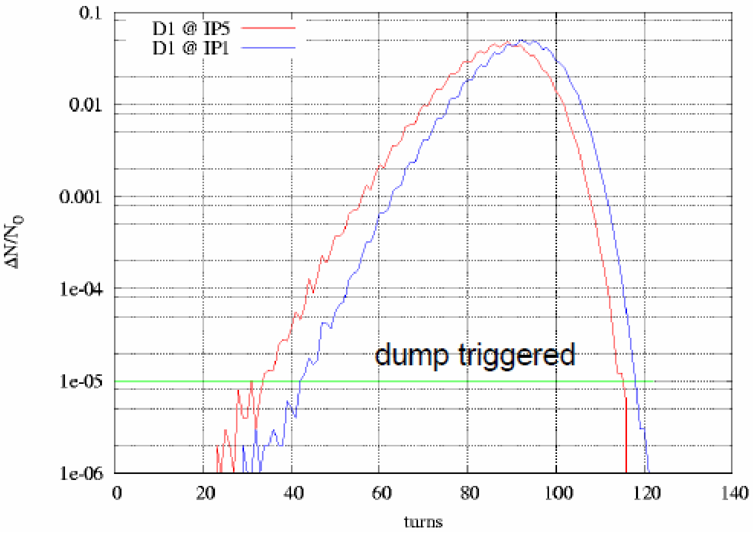


Studies of Fast(est) LHC failure

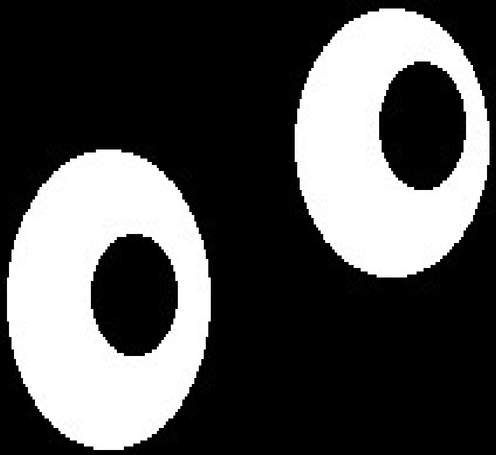








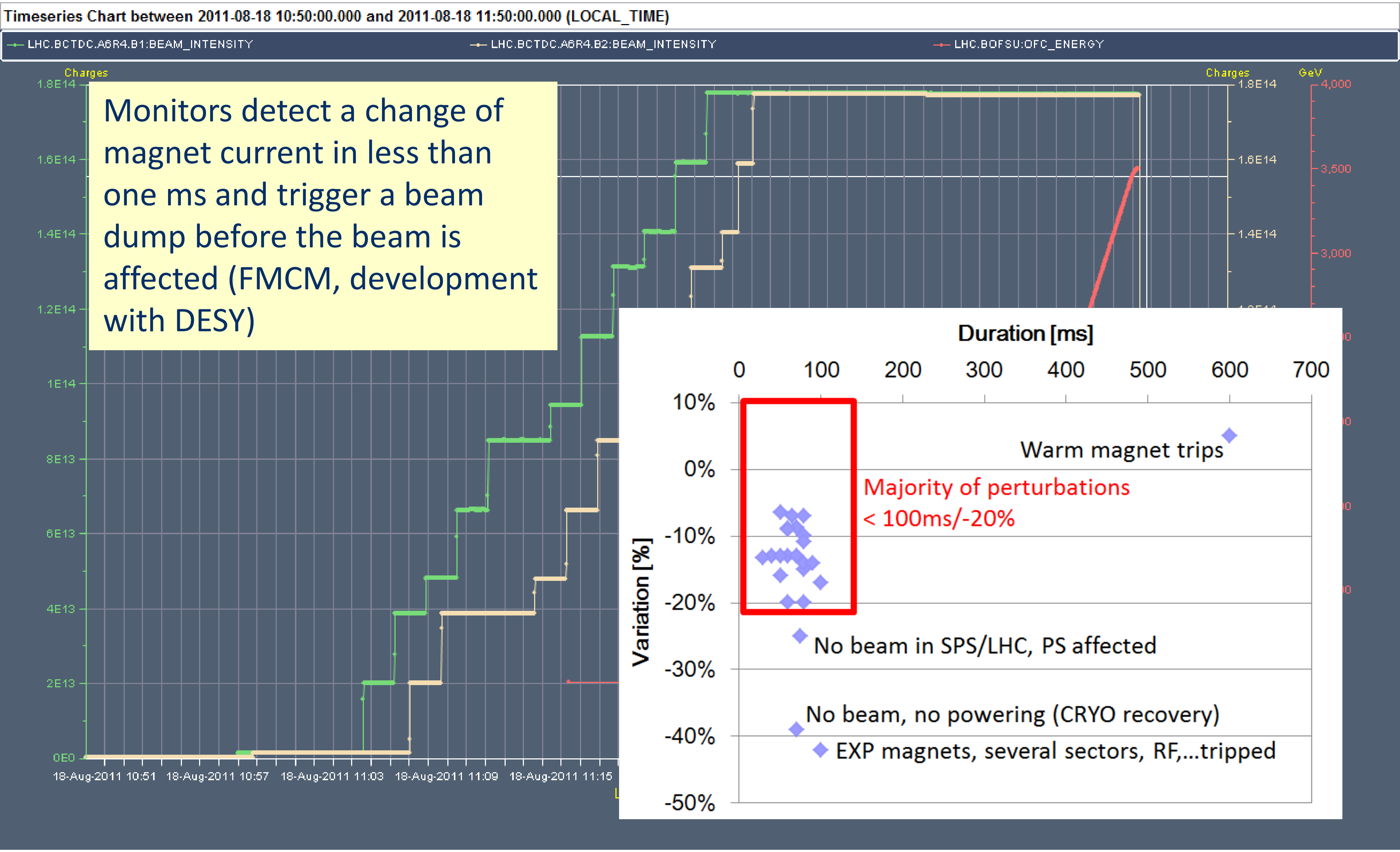
Courtesy of V.Kain



Suddenly the AC distribution for CERN fails – no power for LHC!

Courtesy of R.Schmidt

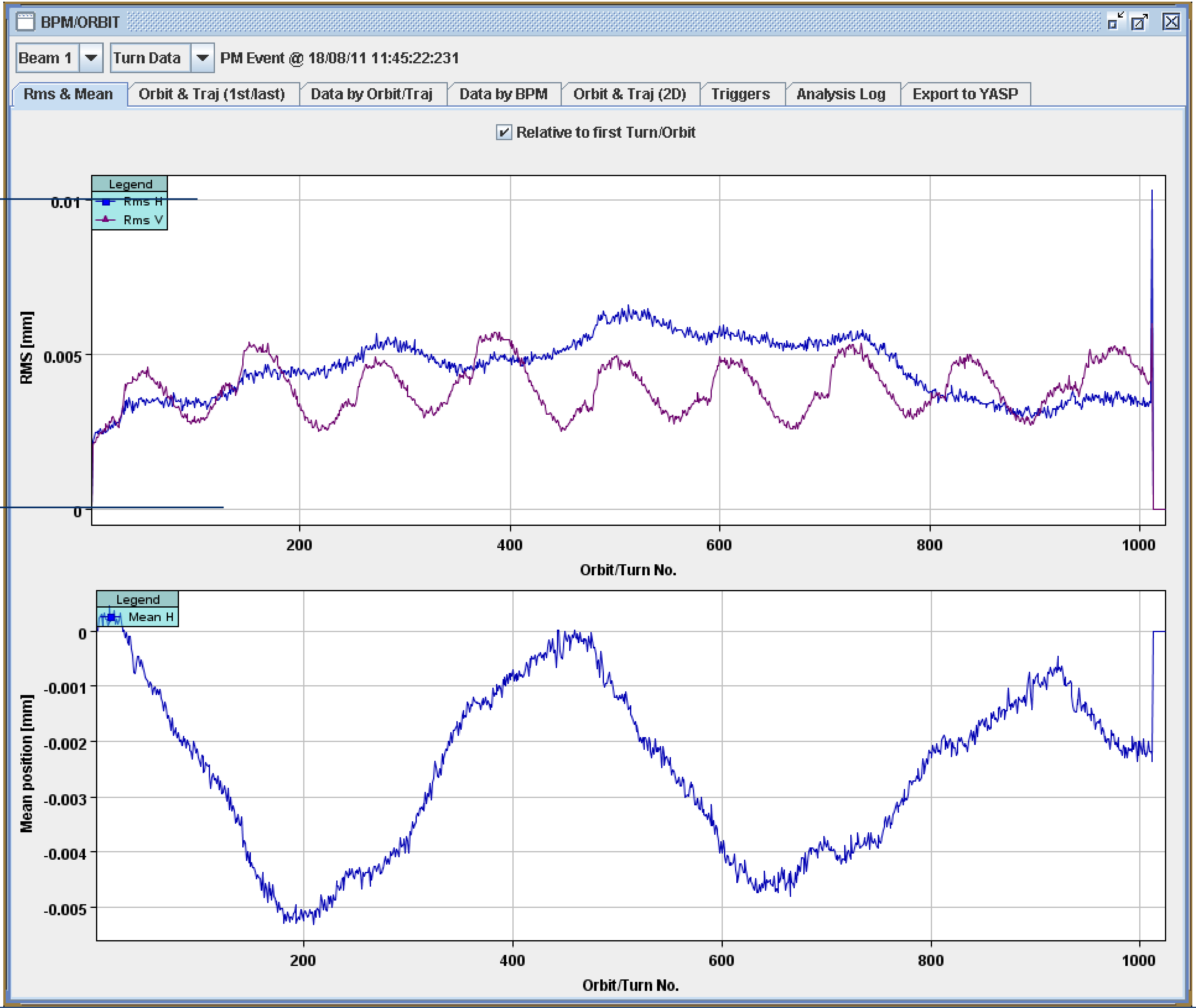
Total power cut at LHC - 18 August 2011, 11:45



Monitors detect a change of magnet current in less than one ms and trigger a beam dump before the beam is affected (FMCM, development with DESY)

Orbit for last 1000 turns before power cut

10 micrometer



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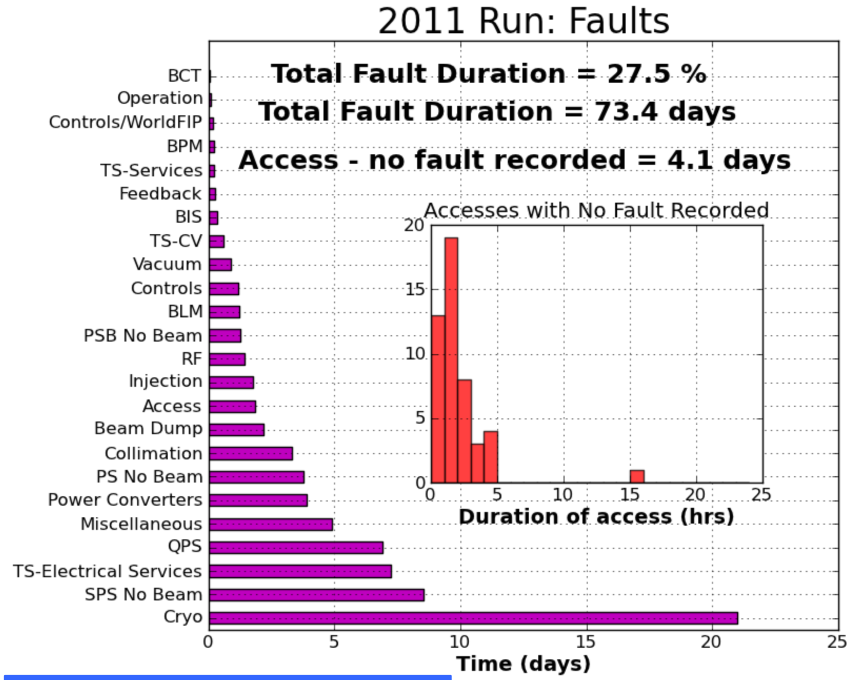
Origin of LHC beam dumps and downtime…

- Complex LHC Magnet powering accounts for large fraction of premature beam dumps (@3.5TeV, 35% (2010) / 46% (2011))
- Downtime after failures often considerably longer than for other systems

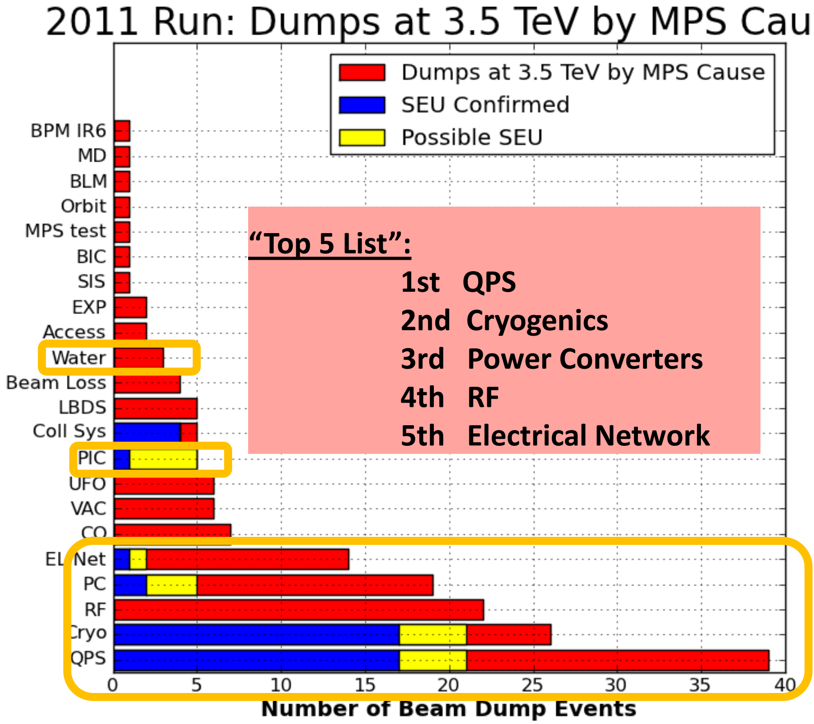


Total Fault Duration = 27.5 %

Total Fault Duration = 73.4 days

Access - no fault recorded = 4.1 days

Courtesy of A.Macpherson



"Top 5 List":

1st QPS
2nd Cryogenics
3rd Power Converters
4th RF
5th Electrical Network

Potential gain:

- ~35 days from magnet powering system in 2011
- With 2011 production rate (~ 0.1 fb^{-1} / day)

Analysis of Protection dumps

1200 beam dumps were cleanly executed during 2011 (-10% wrt to 2010)

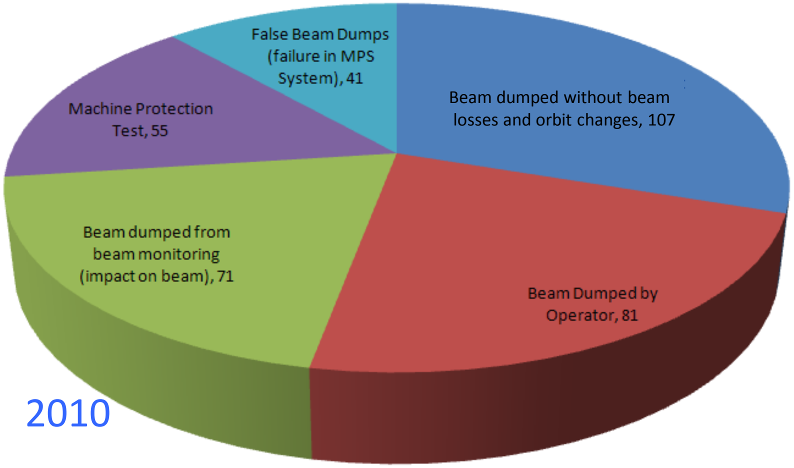
40% more successful ramps to 3.5TeV

~ **Factor of 3 less dumps caused by beam losses, orbit changes,…** -> confirm 2010/11 improvements

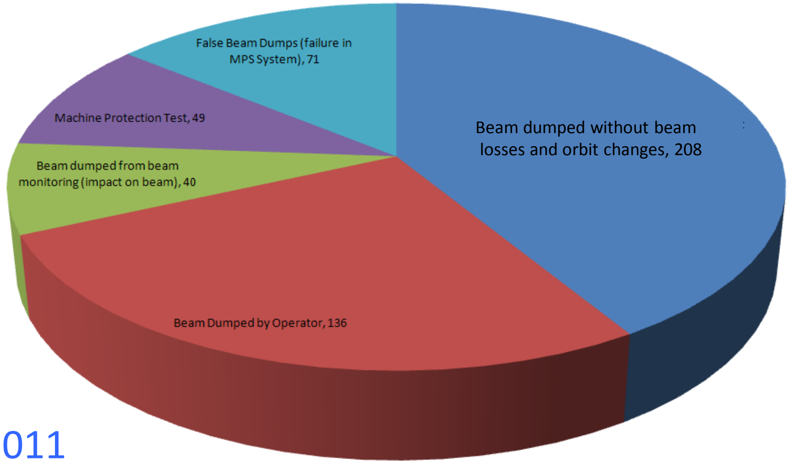
No beam induced quench with circulating beams >100MJ @ 3.5TeV in 2011

No equipment damage observed (apart from kicker erratic causing damage in close by experiment)

MPS response of all dumps from 3.5TeV meticulously analyzed and validated – Initiating system always identified, but sometimes not fully clear why it triggered (‘spurious’ triggers, SEUs,…)



2010



2011

Nota bene: All statistics only counting fills with E > injection

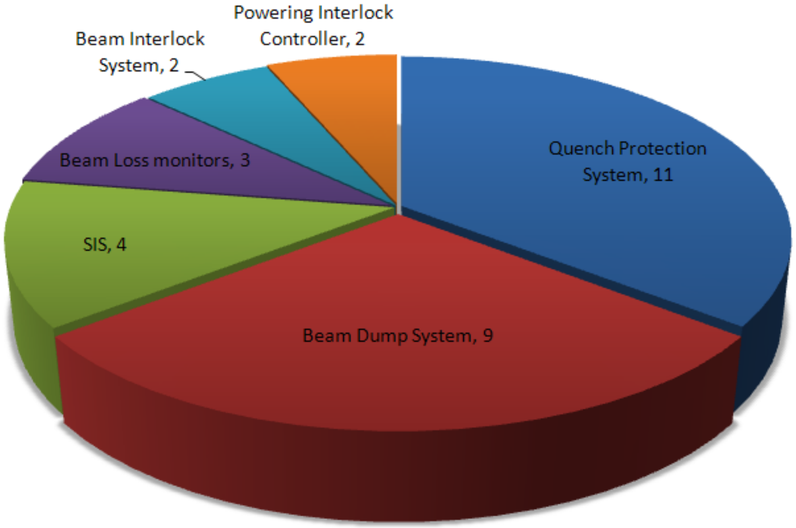
Dependability of MPS backbone

Complexity and high level of safety in MPS systems comes at certain cost, i.e. false positives

False triggers of most MPS backbone systems remained (surprisingly) constant with time

95% of false dumps in 2011 above injection energy (< thresholds,…)

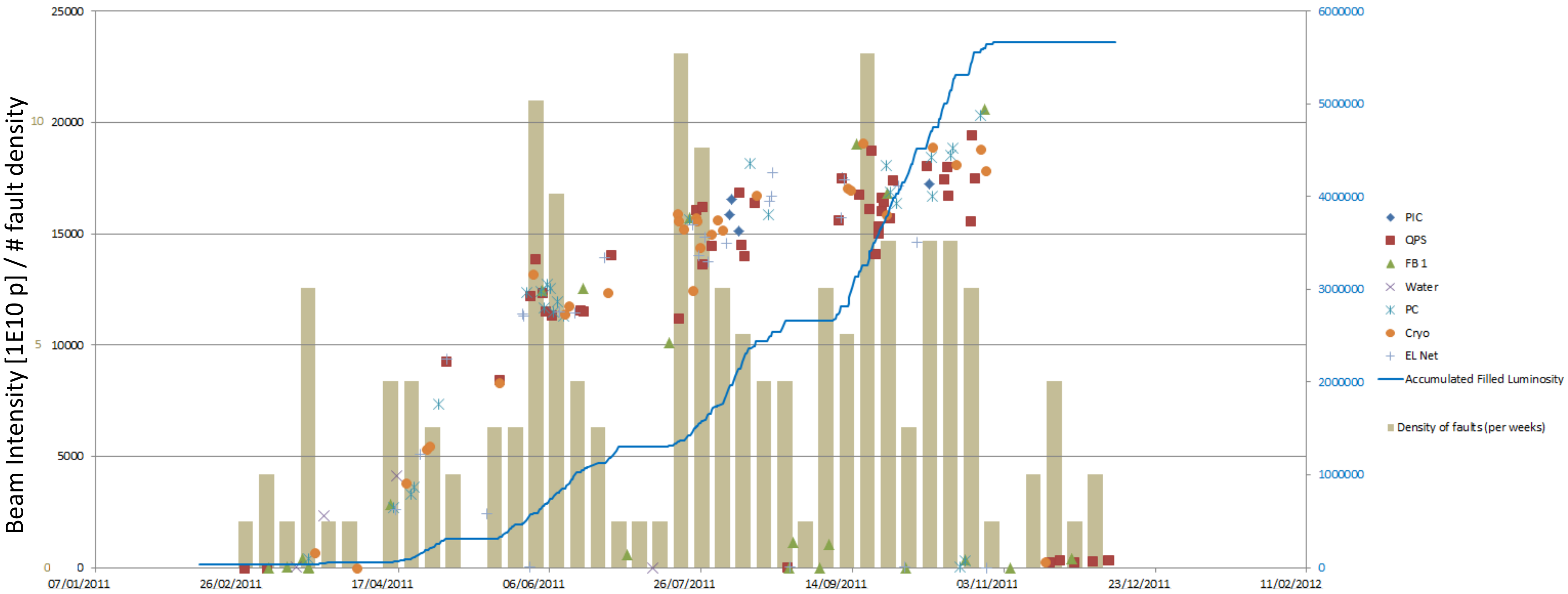
Increase of false positives from QPS (to large extend due to R2E)



2010 : 8% of fills dumped due to MPS

System	Unsafety per year	False dumps/y Average	Std.D.
LBDS[RF]$^{(1)}$	1.8×10^{-7}(2x)	3.8(2x)	+/-1.9
BIC [BT]$^{(2)}$	1.4×10^{-8}	0.5	+/-0.5
BLM [GG]	1.44×10^{-3} (Front-end) 0.06×10^{-3} (Back-end VME)	17	+/-4.0
PIC [MZ]	0.5×10^{-3}	1.5	+/-1.2
QPS[AV]	0.4×10^{-3}	15.8	+/-3.9
MPS	**2.3×10^{-4}** **5.75×10^{-8}/h is SIL3**	**41**$^{(3)}$	**+/-6.0**

Dependence of faults on intensity



- Strong dependence of fault density on beam intensity / integrated luminosity
- Peak of fault density immediately after each technical stop?!
- Much improved availability during early months of 2011 and ion run -> Confirm potential gain of mitigations related to radiation effects on protection electronics

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SPS, transfer lines and LHC

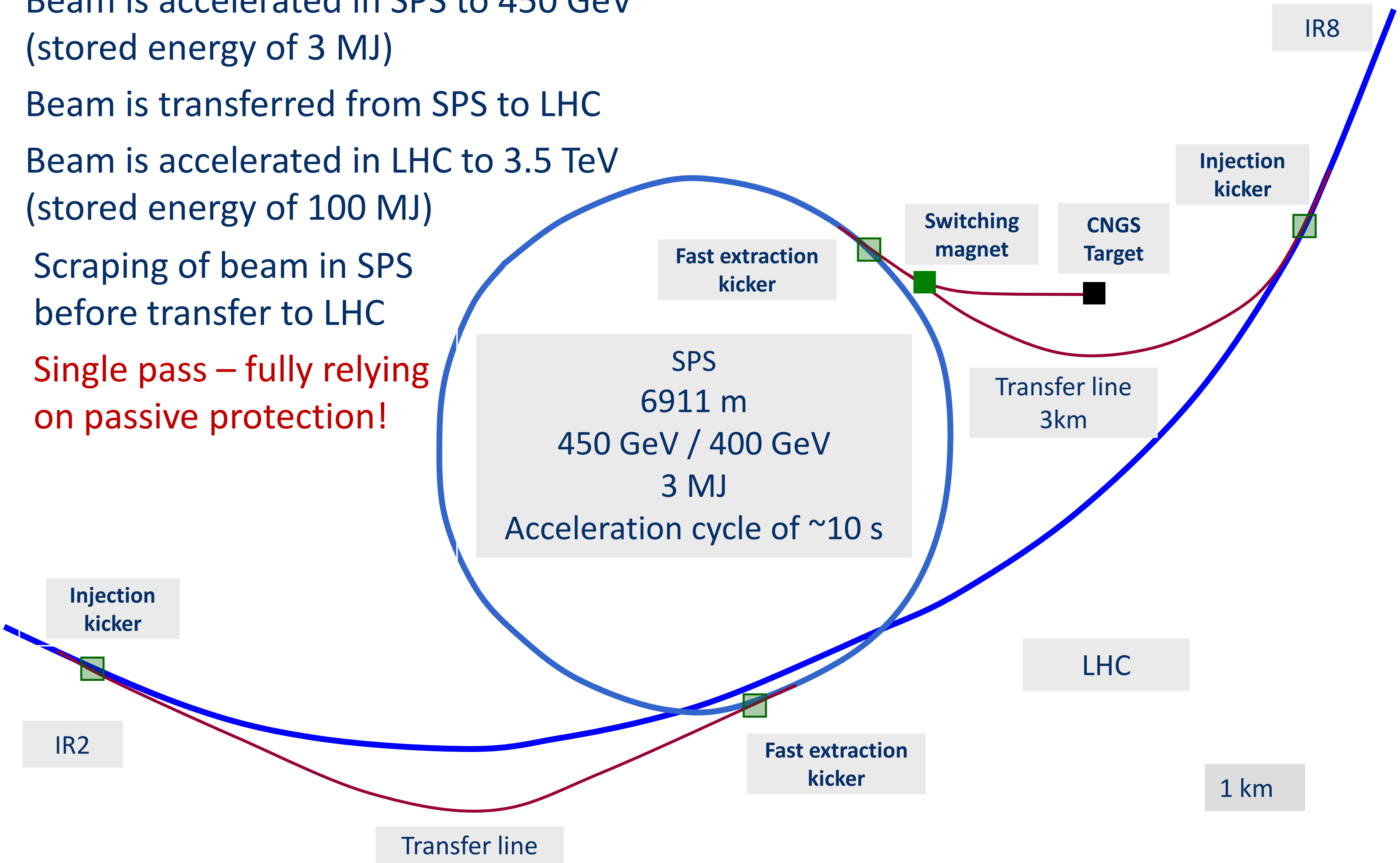
Beam is accelerated in SPS to 450 GeV (stored energy of 3 MJ)

Beam is transferred from SPS to LHC

Beam is accelerated in LHC to 3.5 TeV (stored energy of 100 MJ)

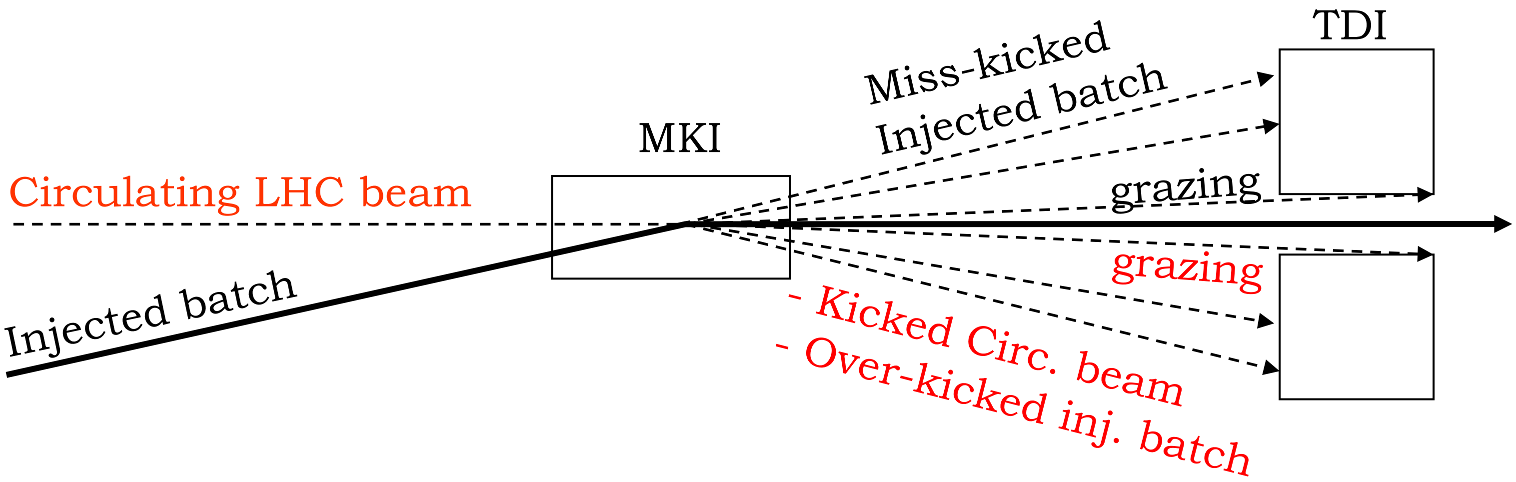
Scraping of beam in SPS before transfer to LHC

Single pass – fully relying on passive protection!

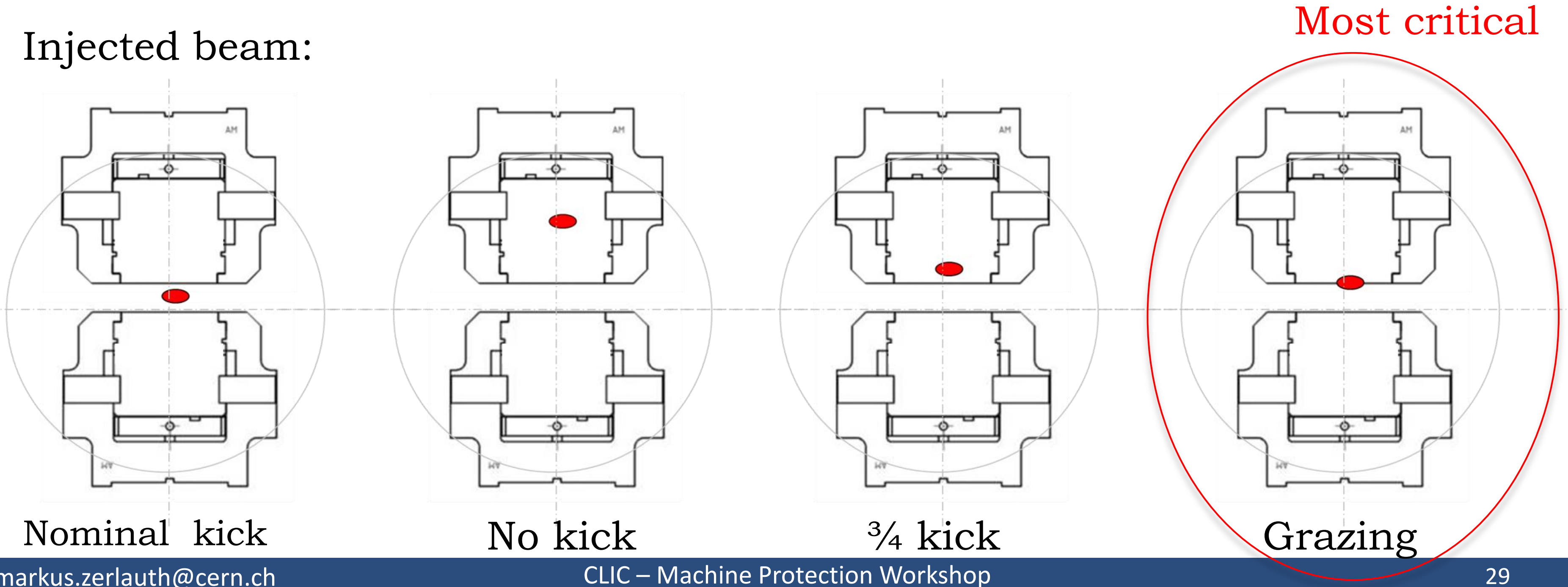


SPS
6911 m
450 GeV / 400 GeV
3 MJ
Acceleration cycle of ~10 s

Injection Scheme



Injected beam:



Nominal kick

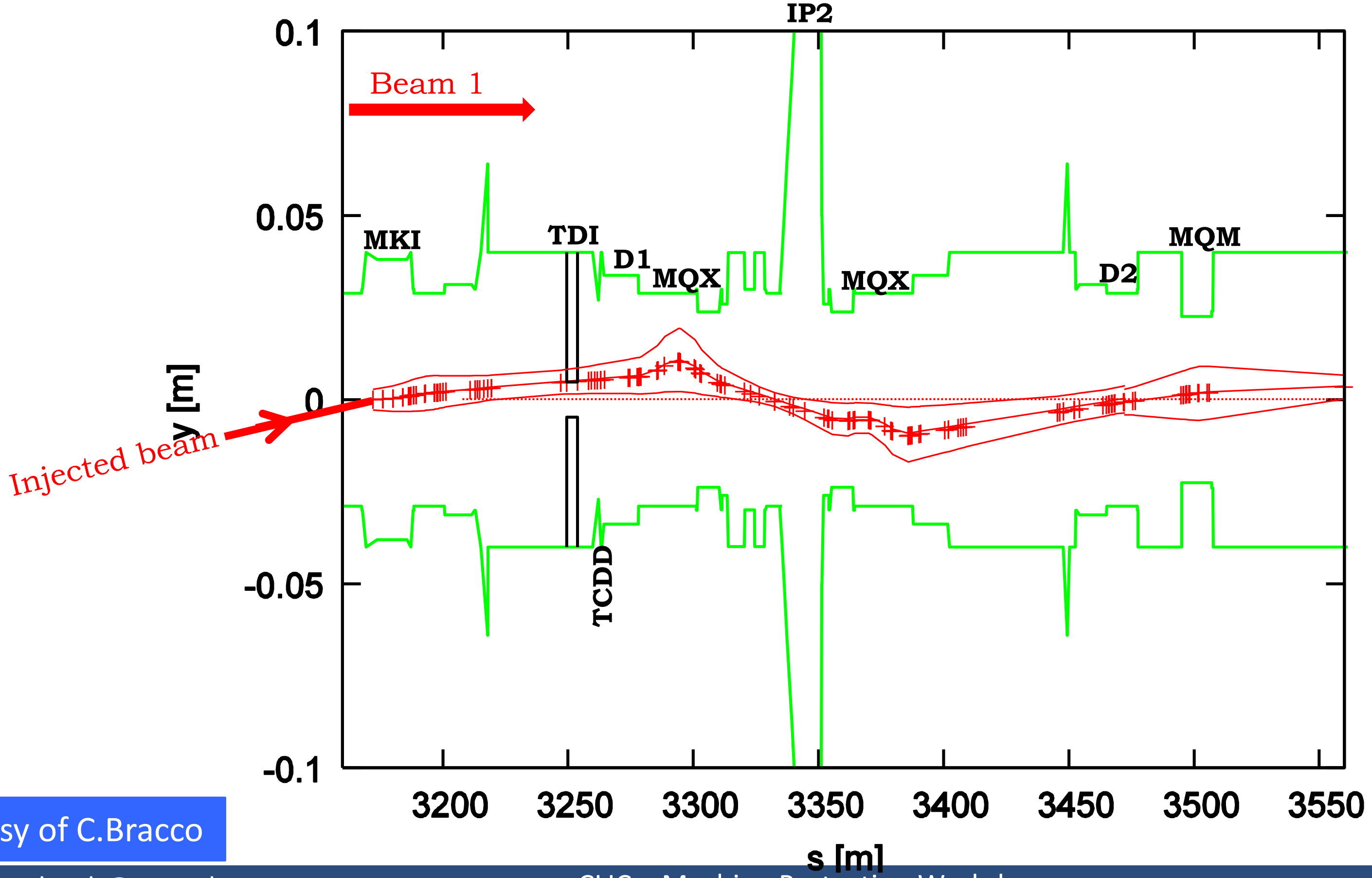
No kick

¾ kick

Grazing

TDI grazing

- Nominal MKI kick = 0.85 mrad
- TDI grazing:
  - Injected beam: 86% kicker strength



Courtesy of C.Bracco

Loss Pattern following kicker erratic

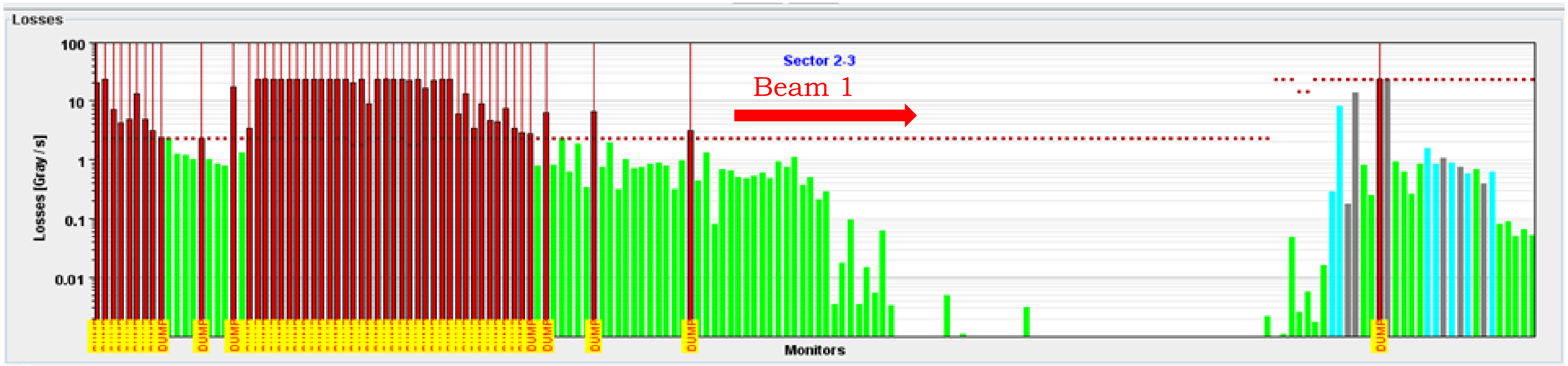
Upstream of IP2

TDI

Losses starting at TDI, no injection loss signature ➔ only circulating beam kicked by MKI

Downstream of IP2

Insertion losses: 3 magnets quenched (D1.L2, MQX.L2, D2.R2)



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Summary 1/2

Machine protection should always start during the design phase of an accelerator

- Particle tracking

  to establish loss distribution with realistic failure modes
- Calculations of the particle shower (FLUKA, GEANT, …)

  energy deposition in materials, activation of materials, accurate 3-d description of accelerator components (and possibly tunnel) required
- Coupling between particle tracking and shower calculations

Machine protection

- is not equal to equipment protection
- requires the understanding of many different type of failures that could lead to beam loss
- requires comprehensive understanding of all aspects of the accelerator (physics, operation, equipment, instrumentation, functional safety)
- touches many aspects of accelerator construction and operation
- includes many systems
- is becoming increasingly important for future projects, with increased beam power / energy density (W/mm^2 or J/mm^2) and complex machines

Summary 2/2

LHC Machine Protection Systems have been working very well during first years of operation, thanks to continuous rigor of operation crews and MPS experts

Ever more failures are captured before effects on beam are seen (no losses or orbit movements)

Still no quenches with circulating beam (with ~ 100MJ per beam and 10mJ for quenching a magnet)

Additional active protection will provide further essential redundancy for next years of running (beam current change monitors, additional SW interlocks…)

Injection protection remains a critical item for machine protection

One has to remain extremely vigilant to maintain level of safety of protection systems while increasing efforts on increasing MPS availability

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Thanks a lot for your attention

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Summary

Machine protection

- is not equipment protection
- includes many systems
- requires the understanding of many different type of failures that could lead to beam loss and possible damage
- requires fairly comprehensive understanding of the accelerator (accelerator physics, operation, equipment, instrumentation, …)
- touches many aspects of accelerator construction and operation
- needs close collaboration between many teams
- is along with the quality of the provided monitoring and diagnostics data a driving factor for efficient operation of complex machines as the LHC

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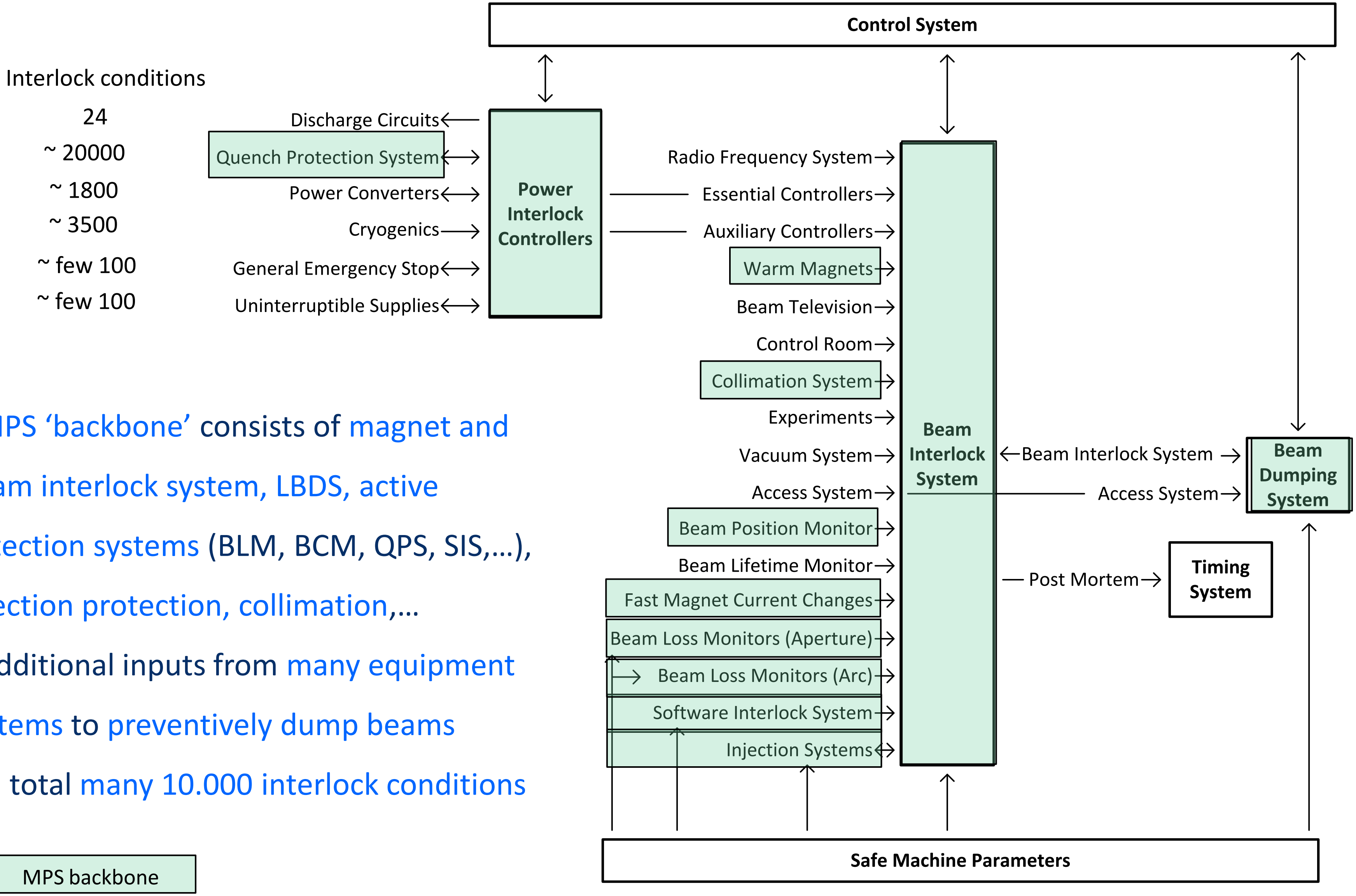
Risks and protection (examples for beam loss)

- Protection is required since there is some risk
- Risk = probability of an accident (in accident per year)
  - consequences (in Euro, downtime, radiation dose to people)
- Probability of an accident (e.g. uncontrolled beam loss)
  - What are the failure modes that lead to beam loss into equipment (there is an practical infinite number of mechanisms to lose the beam)
  - What is the probability for the most likely failure modes?
- Consequences of an uncontrolled beam loss
  - Damage to equipment
  - Downtime of the accelerator for repair (spare parts available?)
  - Activation of material, might lead to downtime since access to equipment is delayed
- The higher the risk, the more protection is required

LHC Machine Protection System (initial design)

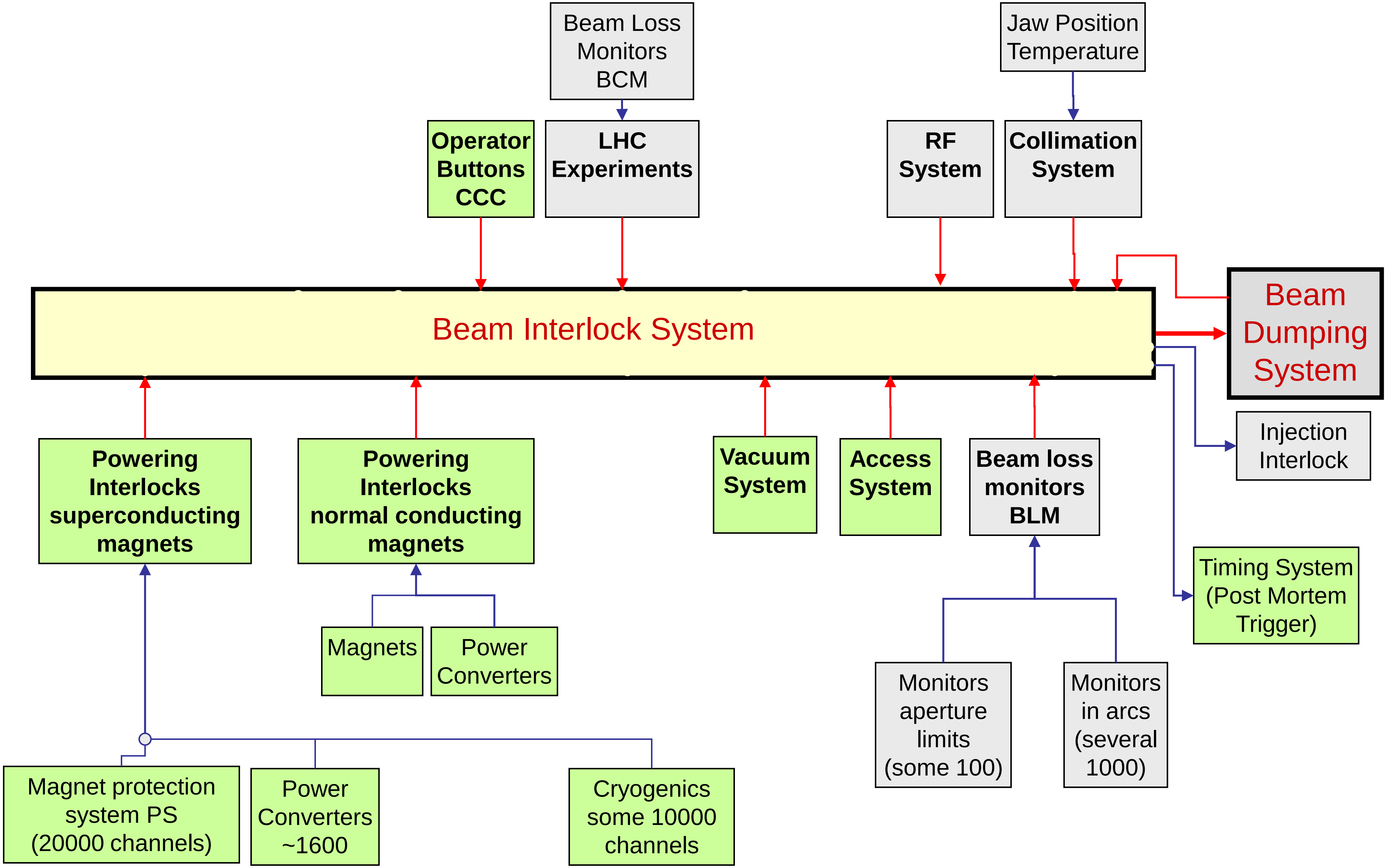


- MPS ‘backbone’ consists of magnet and beam interlock system, LBDS, active detection systems (BLM, BCM, QPS, SIS,…), injection protection, collimation,…
- Additional inputs from many equipment systems to preventively dump beams
- In total many 10.000 interlock conditions

🟩 MPS backbone

Systems detecting failures and Beam Interlocks

(initial design)



Safe deposition of stored energy / power

Energy in the LHC beams

- Beam cleaning with collimators, limiting particle losses around the accelerator
- Beam loss monitors to detect beam losses, and requesting a beam dump when beam losses too high
- Regular and irregular beam extraction discharging beam energy into a specially designed target (beam dump block)
- Stop injection

Energy in the magnets

- After a quench: discharge the magnet energy into the magnet coils (quench heaters)
- Discharge the energy stored in the electrical circuit into resistors (energy extraction)
- Stop power converters
- …….and dump the beam as fast as possible

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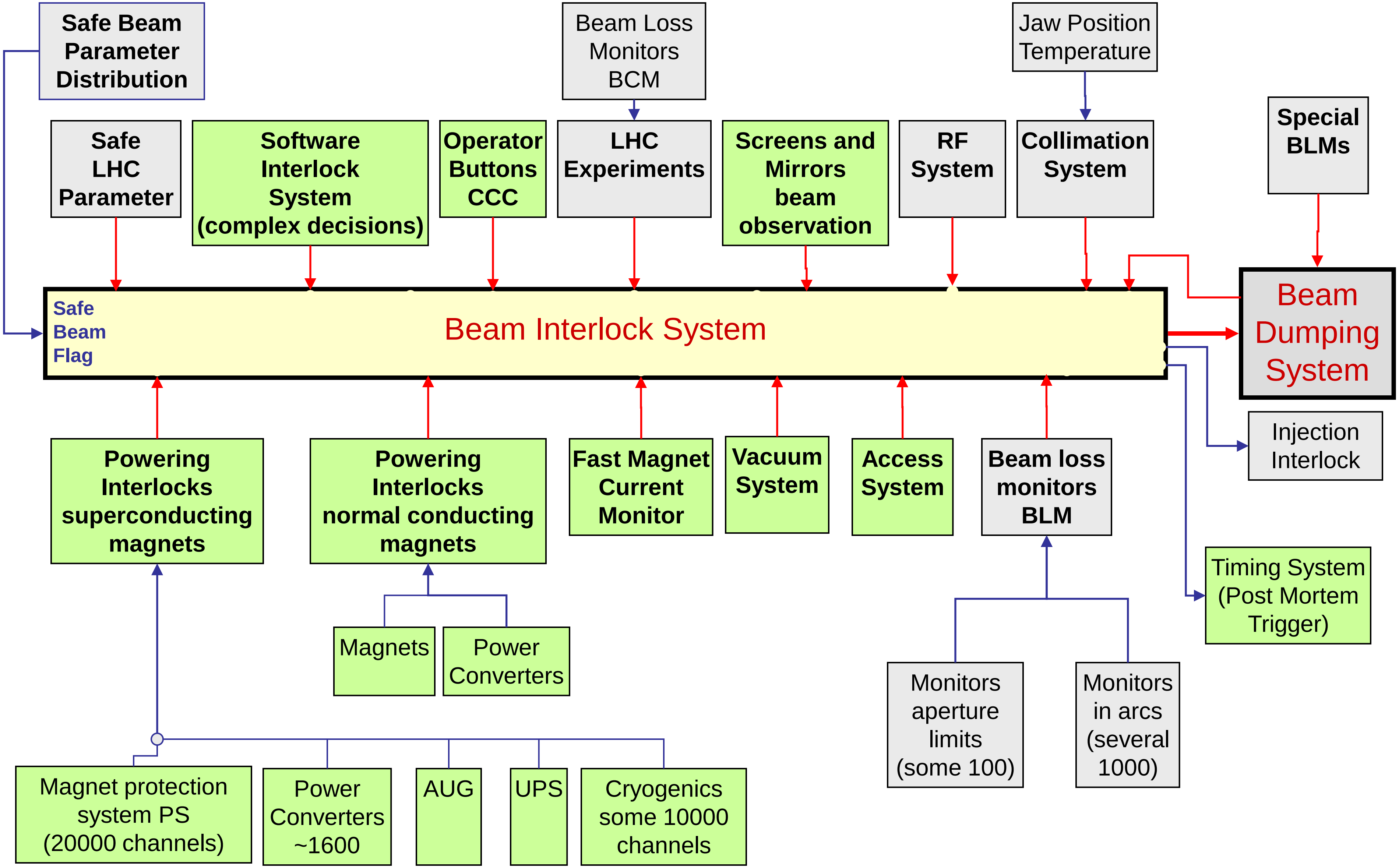
Systems detecting failures and Beam Interlocks

(today)



Beam losses, machine protection and collimation

Continuous beam losses: **Collimation** prevents too high beam losses along the accelerator (beam cleaning)

A collimation system is a (very complex) system installed in an accelerator to capture mostly halo particles

Such system is also called (beam) Cleaning System

Accidental beam losses: **“Machine Protection”** protects equipment from damage, activation and downtime

Machine protection includes a large variety of systems

Regular and irregular operation

Regular operation

Many accelerator systems

Continuous beam losses

collimators for beam cleaning

Collimators for halo scraping

Failures during operation

Beam losses due to failures, timescale from nanoseconds to seconds

Machine protection systems

Collimators

Beam absorbers

Beam losses in accelerators

Particles are lost due to a variety of reasons: beam gas interaction, losses from collisions, losses of the beam halo,…….

- Continuous beam losses are inherent to the operation of accelerators
  - To be taken into account during the design of the accelerator
- Accidental beam losses are due to a multitude of failures mechanisms
- The number of possible failures leading to accidental beam losses is (nearly) infinite

Beam losses and consequences

- Particle losses lead to particle cascades in materials that deposit energy in the material
    - the maximum energy deposition can be deep in the material at the maximum of the hadron / electromagnetic shower

- The energy deposition leads to a temperature increase
    - material can vaporise, melt, deform or lose its mechanical properties
    - risk to damage sensitive equipment for some 10 kJ, risk for damage of any structure for some MJoule (depends on beam size)
    - superconducting magnets or cavities could quench (beam loss of ~mJ to J)

- Equipment becomes activated due to beam losses (acceptable is ~1 W/m, but must be "As Low As Reasonably Achievable" - ALARA)

Energy deposition and temperature increase

- There is no straightforward expression for the energy deposition
- The energy deposition is a function of the particle type, its momentum, and the parameters of the material (atomic number, density, specific heat)
- Programs such as FLUKA, MARS, GEANT and others are being used for the calculation of energy deposition and activation
- Other programs are used to calculate the response of the material (deformation, melting, …) to beam impact (mechanical codes such as ANSYS, hydrodynamic codes such as BIG2, AUTODYN and others)

Question: what is dangerous (stored beam energy, beam power)? When do we need to worry about protection?

DIDT

Beam Current Change Monitor was vital part of MPS systems for e.g. HERA

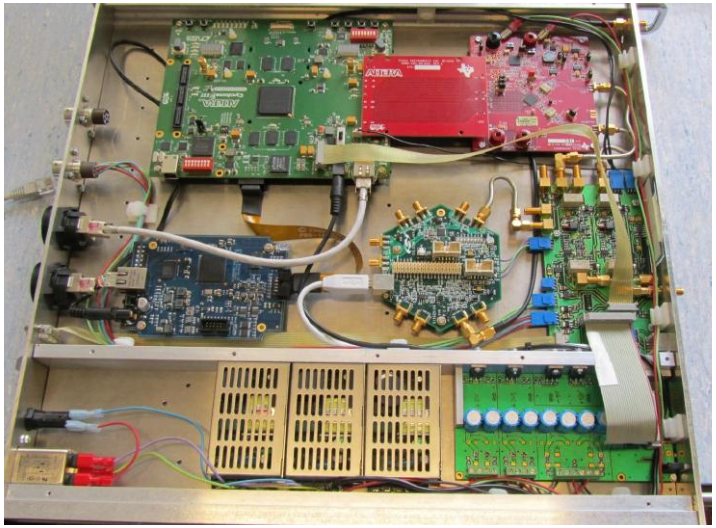
Proposed for use in LHC MPS in 2005 (EDMS Doc. 359172)

With HERA like system, changes of < 0.1% of total beam current could be captured in 10 turns

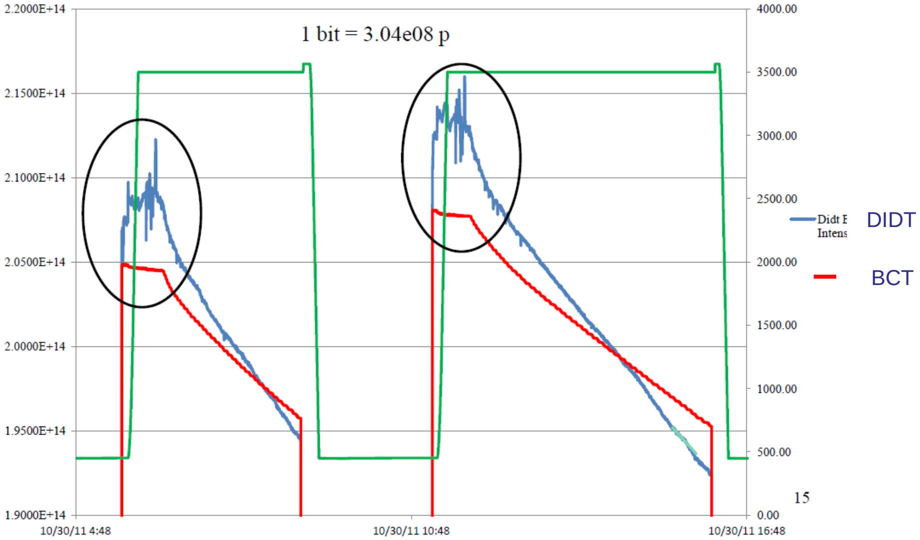
BI started development (with DESY consultancy) mid 2010, for deployment end 2011 + 2012 run

First system installed and data recorded, but showing not understood effects of bunch length,…?

Important to validate and finish soon, as such system adds layer of protection when probing quench/UFO limits with > BLM thresholds



First system now installed in IR4



First measurements during proton runs

Courtesy of M.Pfauwadel, D.Belohrad

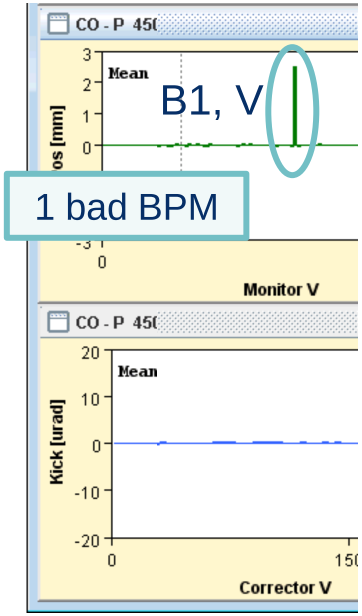
Work ongoing: Novel PC Interlock System

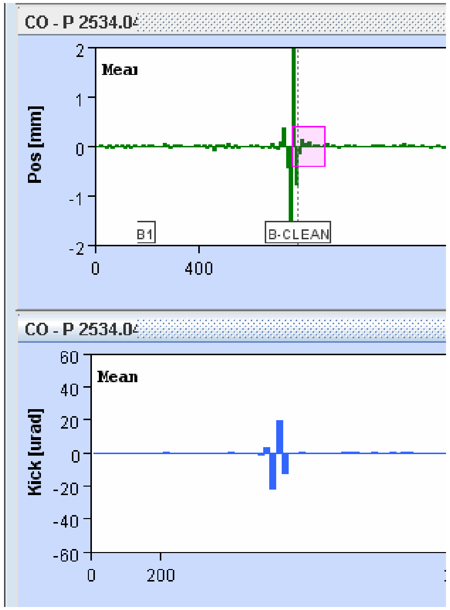
In addition to existing SIS interlocks at injection, ramp, squeeze and SB, new SW interlock system monitoring PC currents to protect against operations- and feedback- failures

Redundant to SIS for arcs, adds protection for LSS 1/2/5/8 due to capability of tracking bump shape amplitude/variations

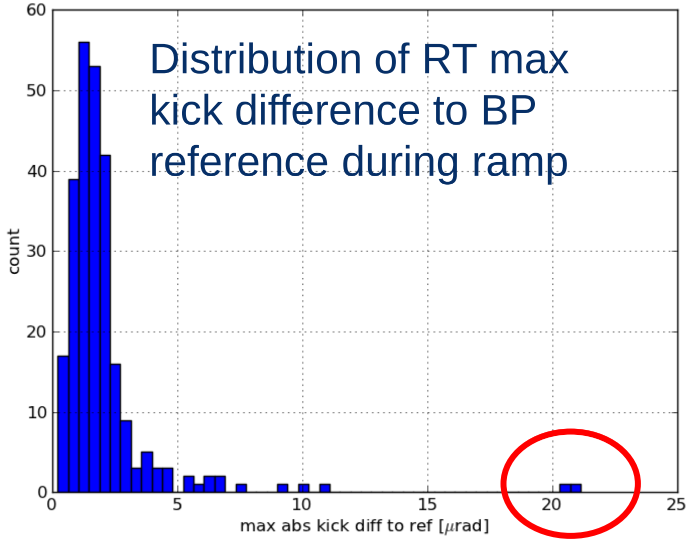
Key interest for all other (non-COD) converters where currently no current tracking is done

Currently under commissioning and testing, after initial experience connection to BIS





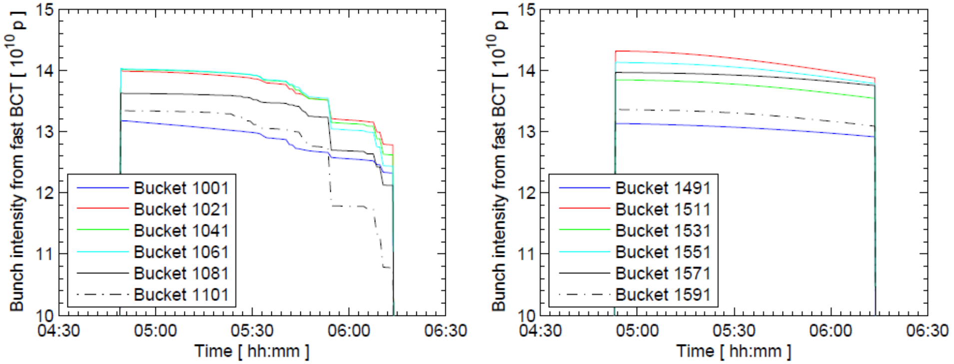
Fill 1717: Bump >2mm during ramp in IR7



Courtesy of K.Fuchsberger

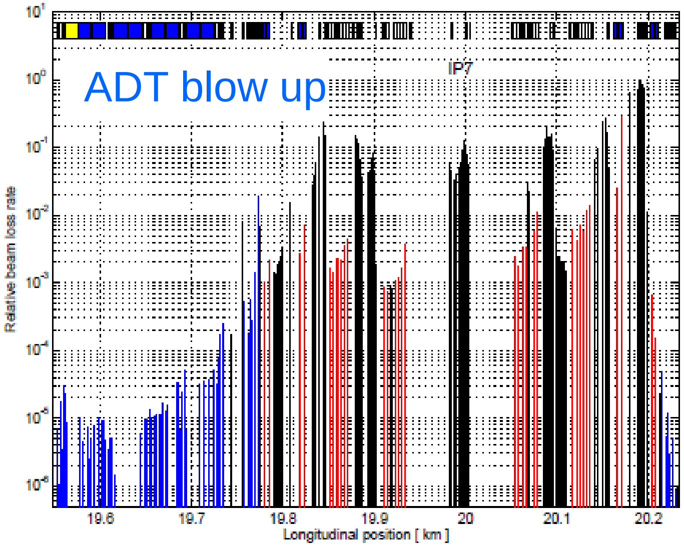
Other improvements for 2012 - ADT

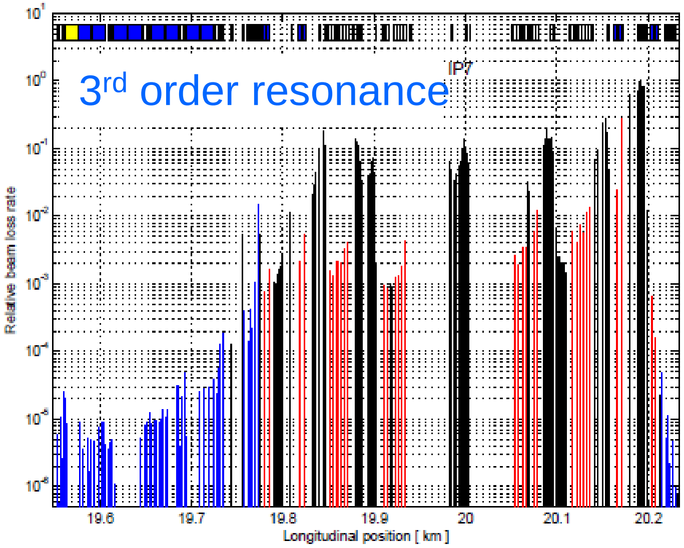
- Considerable work went into finalization and commissioning of transverse damper
- MDs demonstrated selective and very deterministic bunch blow-up
- Allows for abort gap cleaning and increased efficiency when performing loss-maps, quench MDs,…
- System fully operational for both beams, should become default



Blow up of selected bunches during MD (left) and unaffected bunches (right)

Courtesy of W.Hofle





Loss-maps performed with ADT and 3rd order resonance method

Classification of failures affecting the beam

- Type of the failure
  - hardware failure (power converter trip, magnet quench, AC distribution failure such as thunderstorm, object in vacuum chamber, vacuum leak, RF trip, kicker magnet erratic firing, ….)
  - controls failure (wrong data, wrong magnet current function, trigger problem, timing system, feedback failure, ..)
  - operational failure (chromaticity / tune / orbit wrong values, …)
  - beam instability (due to too high beam / bunch current)
- Machine state when failure occurs: operational scenarios
  - Injection (single pass)
  - Stored beam at injection energy, during acceleration and at top energy
  - Extraction (single pass)
- Parameters for the failure
  - time constant for beam loss
  - damage potential
  - probability for the failure

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Protection and the related systems

- Avoid that a specific failure can happen
- Detect failure at hardware level and stop operation
  - monitoring of the hardware
- Detect consequence of failure with instrumentation
- Stop operation
  - stop injection
  - extract beam into beam dump block
  - stop beam by beam absorber / collimator
- Elements in the protection systems
  - hardware monitoring and beam monitoring
  - beam dump (fast kicker magnet and absorber block)
  - collimators and beam absorbers
  - beam interlock systems including the logics and linking different systems

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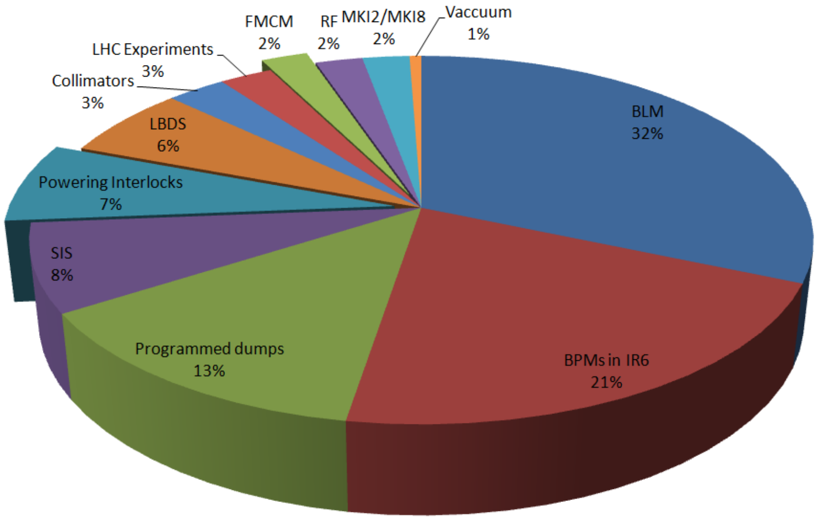
Interlock systems

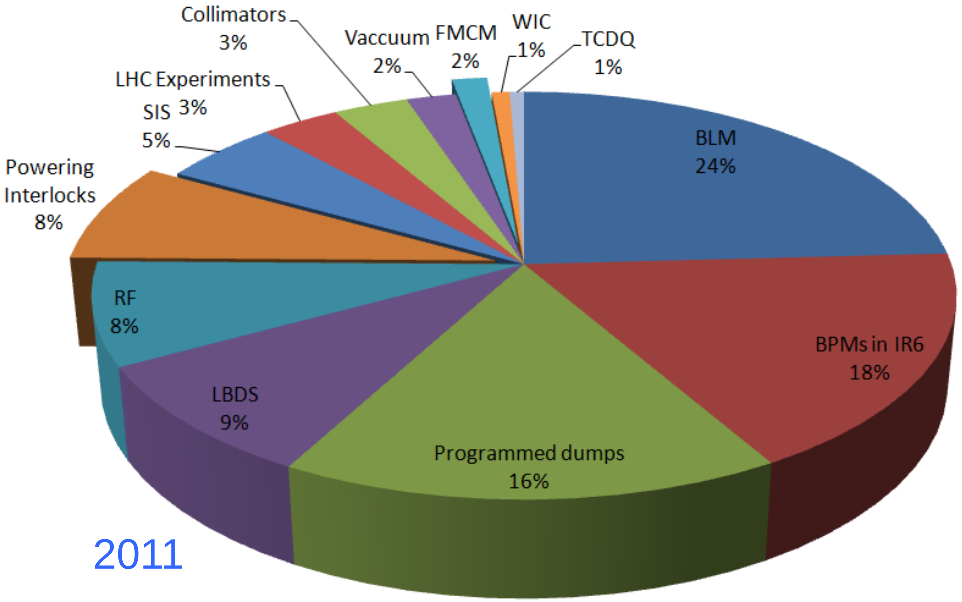
- Define functionality
  what systems are connected
- Define dependability
  what failures cannot be tolerated
- Define time constant
  how fast is the reaction time
- Define hardware, in particular the interfaces
  interfaces: clear definition
  connectors are the weakest link – watch out
- Define testing
  not too late, could have an impact on the design

Energy dependence of faults

Strong energy dependence: While spending ~ twice as much time @ injection, only ~ 10 percent of dumps from magnet powering (little/no SEU problems, higher QPS thresholds,….)



2010



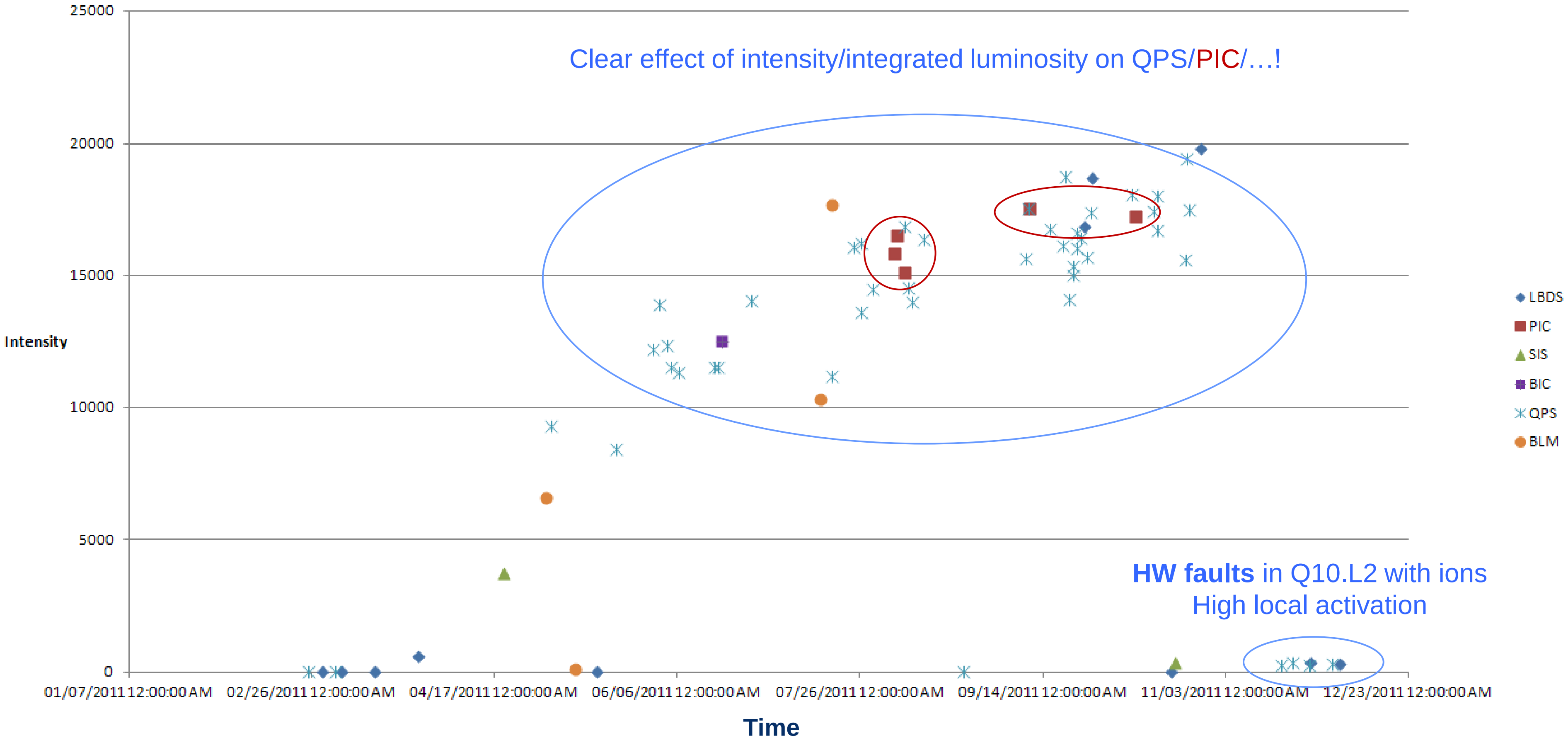
2011

@ injection twice as many dumps wrt to 3.5TeV

@ injection 20% more dumps wrt to 3.5TeV

False Beam Dumps from MPS

Occurrence of false dumps of some systems clearly related to increasing beam intensities



Clear effect of intensity/integrated luminosity on QPS/PIC/…!

HW faults in Q10.L2 with ions
High local activation

“First” MKI2 MS3 Erratic 28/7/2011

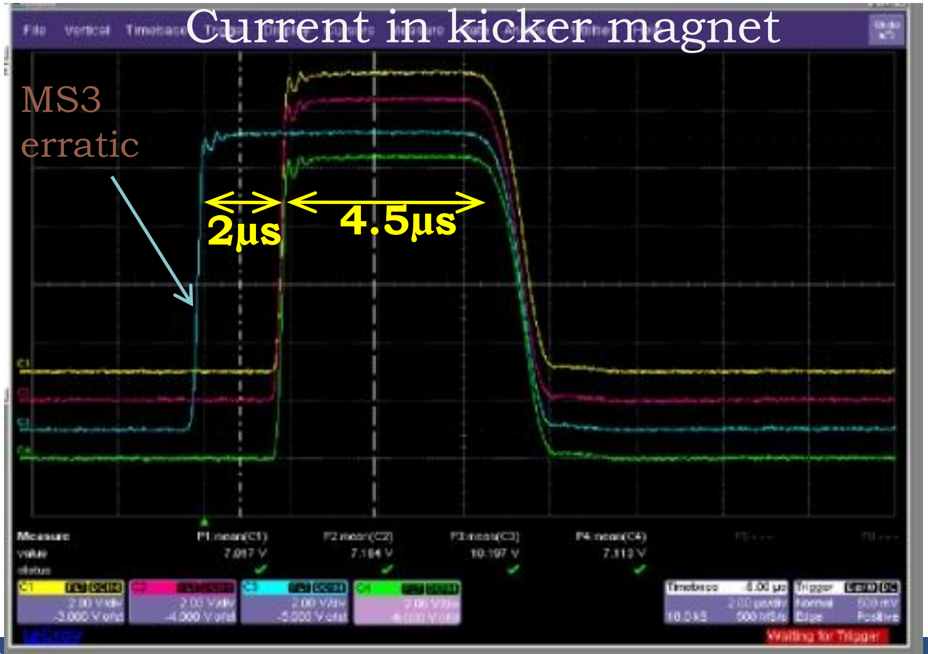
- 16:30:43 erratic turn-on of MKI2 MS3 at **full** PFN voltage;

- Interlocks detected an MS erratic and correctly triggered MS’s and DS’s of system (within 2μs), emptying PFN via both ends.

- Hence **kicker-C** pulsed for **6.5μs** and **3 other kicker magnets pulsed** for up to **4.5μs**, emptying PFNs of energy.

- **Circulating beam was not in IP2** and therefore not disturbed.

- **Batch was extracted from SPS** but saw no kick at MKI2 (current already back to zero in all magnets) and went **straight into the TDI upper jaw.**


Current in kicker magnet