

Machine Protection for the LHC experiments

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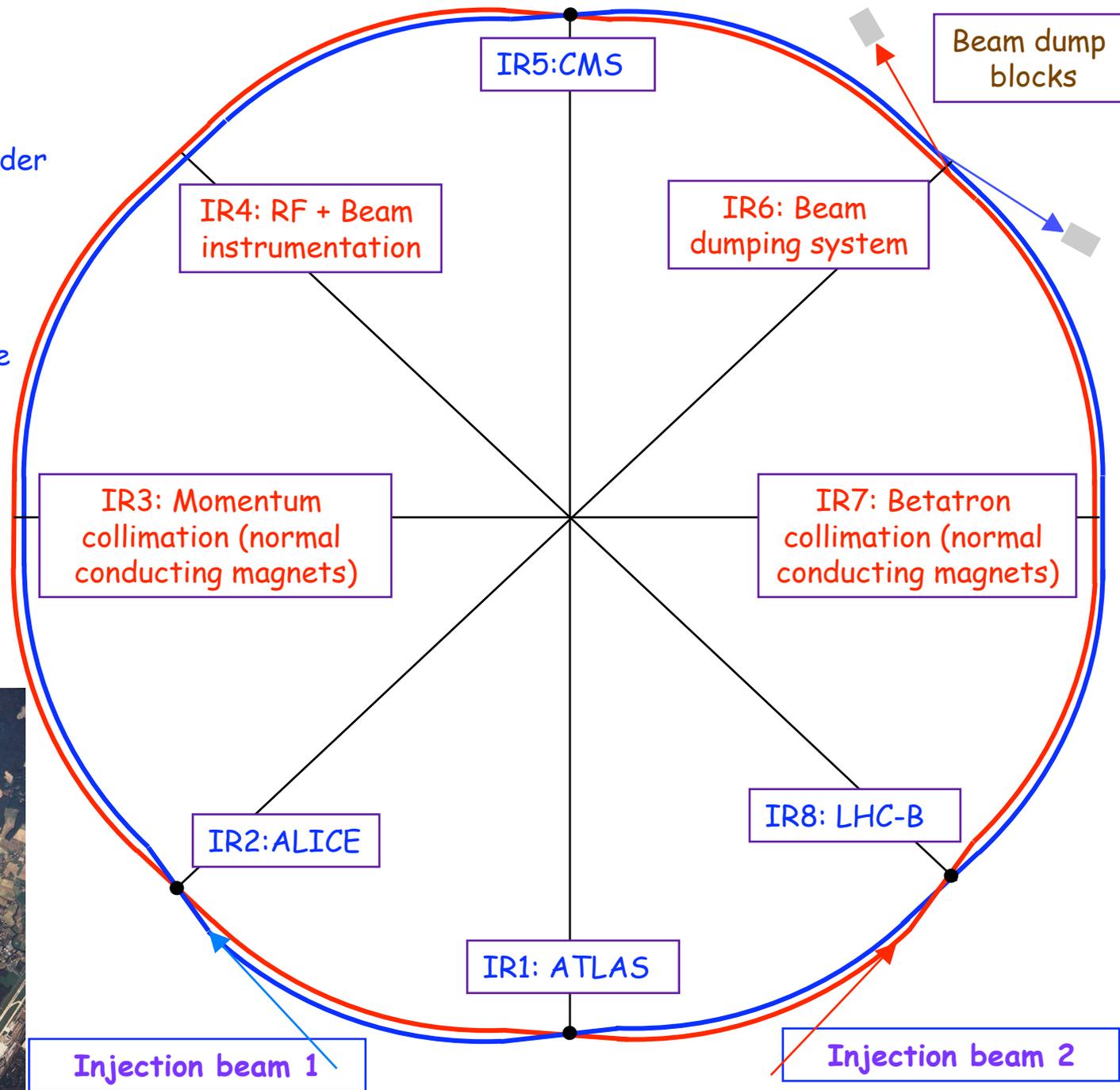
PAC09, Vancouver, 6th May 2009

Introduction
Beam induced damage
Injected beam accidents
Circulating beam accidents
Conclusions

LHC Layout

- 7 TeV p/p and ion/ion collider
- 8 arcs.
- 8 long straight sections (insertions), ~ 700 m long.
- beam 1 : clockwise
- beam 2 : counter-clockwise

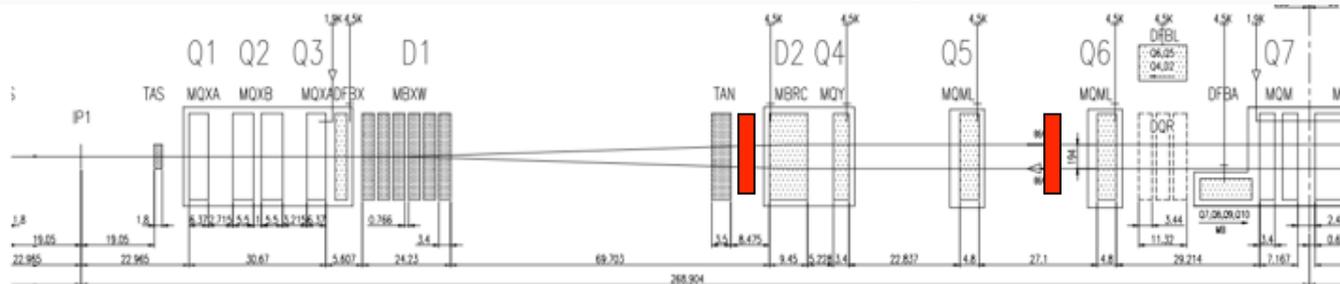
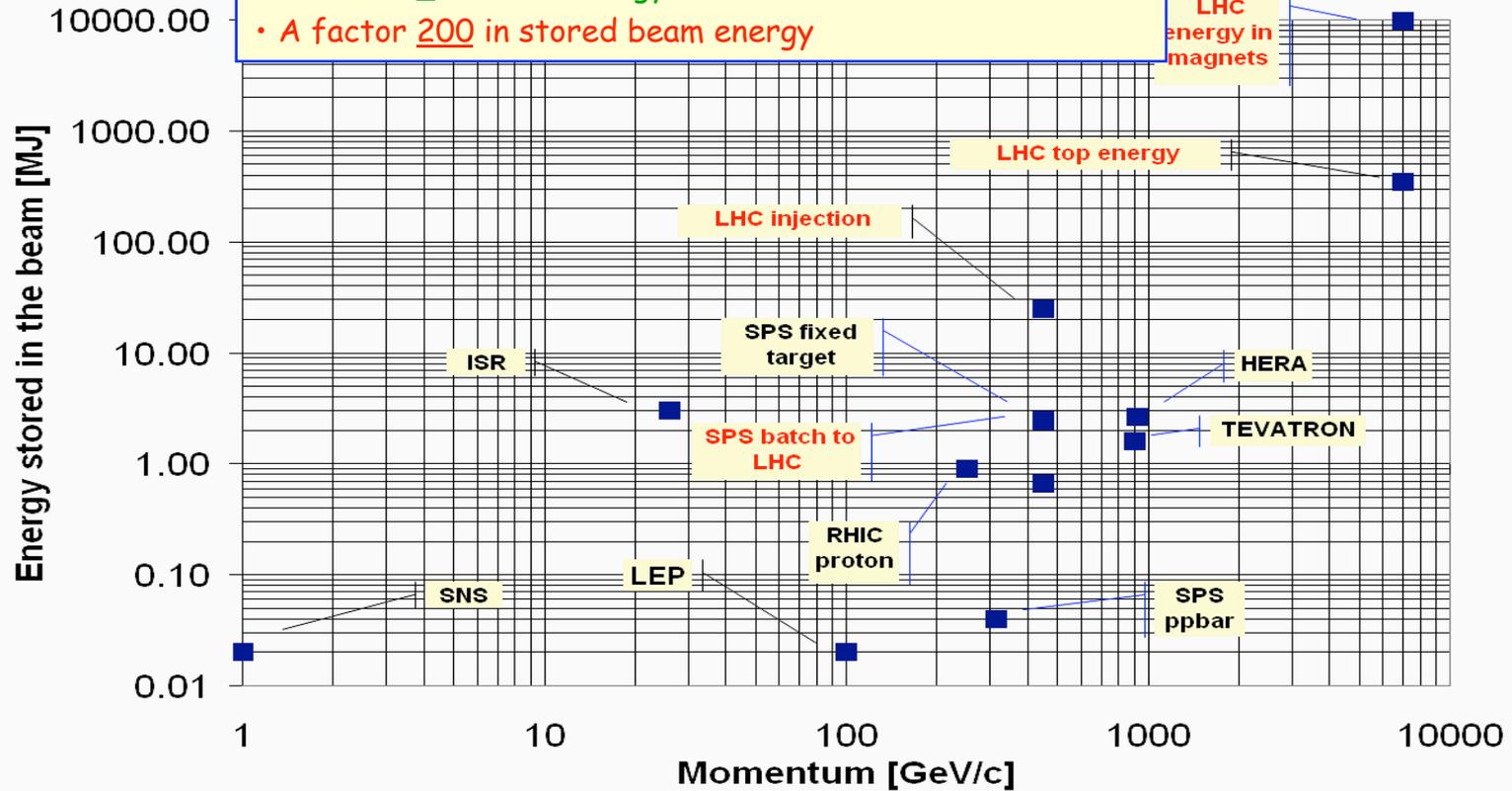
- 4 experimental insertions, including near-beam and moveable detectors



The challenge

Increase at LHC wrt existing accelerators :

- A factor 2 in magnetic field
- A factor 7 in beam energy
- A factor 200 in stored beam energy

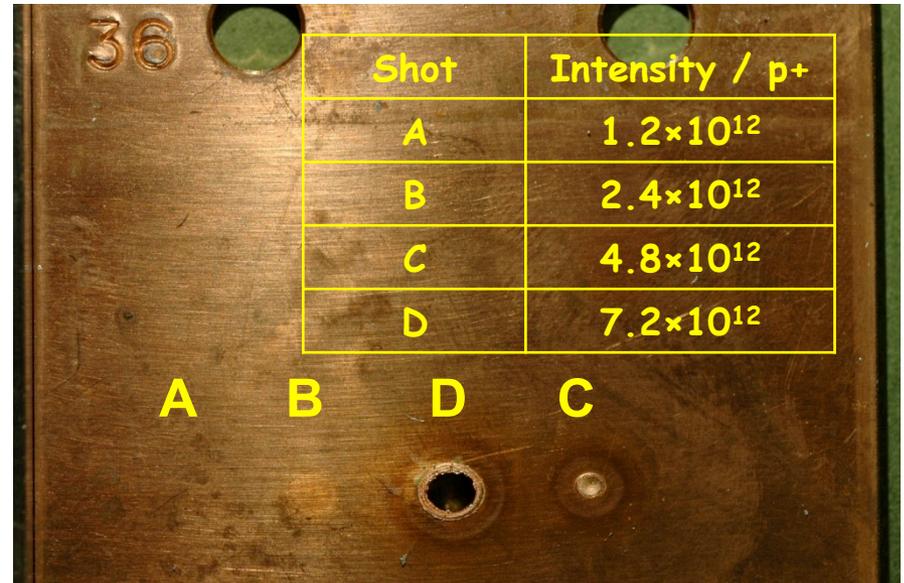


Damage potential of high energy beams

Controlled experiment with 450 GeV beam to benchmark simulations:

- Melting point of Copper is reached for an impact of $\approx 2.5 \times 10^{12}$ p, damage at $\approx 5 \times 10^{12}$ p.
- Stainless steel is not damaged with 7×10^{12} p.
- Results agree with simulation.

Effect of beam impact depends strongly on impact angles, beam size...



Here an example from SPS run in 2008 !

- The effect of an impact on the vacuum chamber of a **400 GeV beam of 3×10^{13} p (2 MJ)**.
- Vacuum chamber to atmospheric pressure, Downtime \sim 3 days.

Slide courtesy of J. Wenninger

Beam accidents can be classified according to the operational situation and the cause of the deviation of the beam from a nominal condition (resulting strike = accident)

The situation can be complicated by aperture restrictions of the experiments

A. On injection

- i. Operational failure of magnet mis-settings at injection
- ii. Mis-kicking of pulsed elements

Inject with 'probe' bunch

B. The circulating (stored) beam

- i. Power converter failure, causing a change in field of the magnets in the relevant circuit.
 - i. This can arise from hardware failure or a controls error
 - ii. Most critical failures for normal conducting magnets
- ii. Quench of a superconducting magnet (with associated quench protection)
- iii. Operation failures e.g. operator-created local bump across an experiment or chromaticity / tune / orbit errors
- iv. Beam instability errors (high beam or bunch current)

C. 'Freak' cases e.g. an object left in the path of the beam, i.e. fully closed collimator

On injection, the most likely failure is a wrongly set magnet, arising from

- A. a mistake by an operator when changing a current
 - B. a error in the generation or communication of a signal in the control system
 - C. An unobserved failure in a dipole, quadrupole or corrector (e.g. final triplet misalignment, giving a kick)
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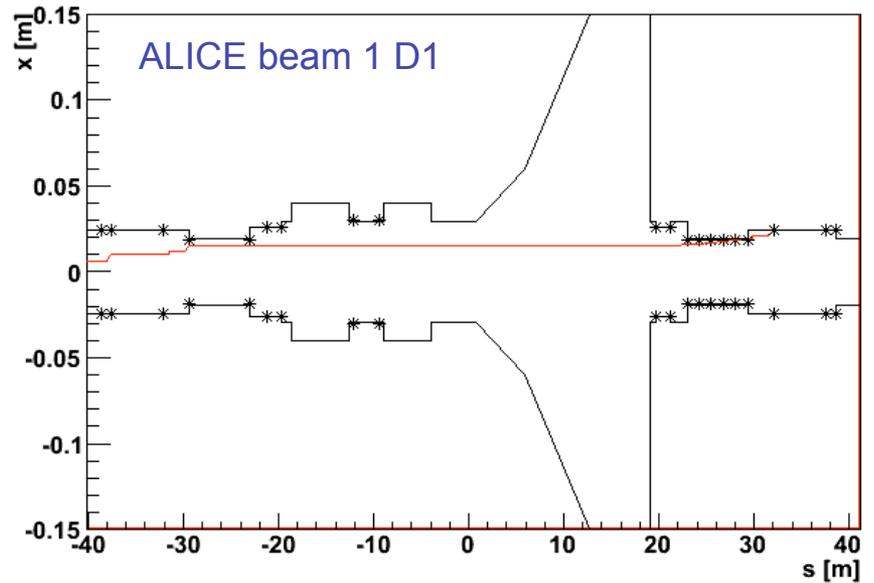
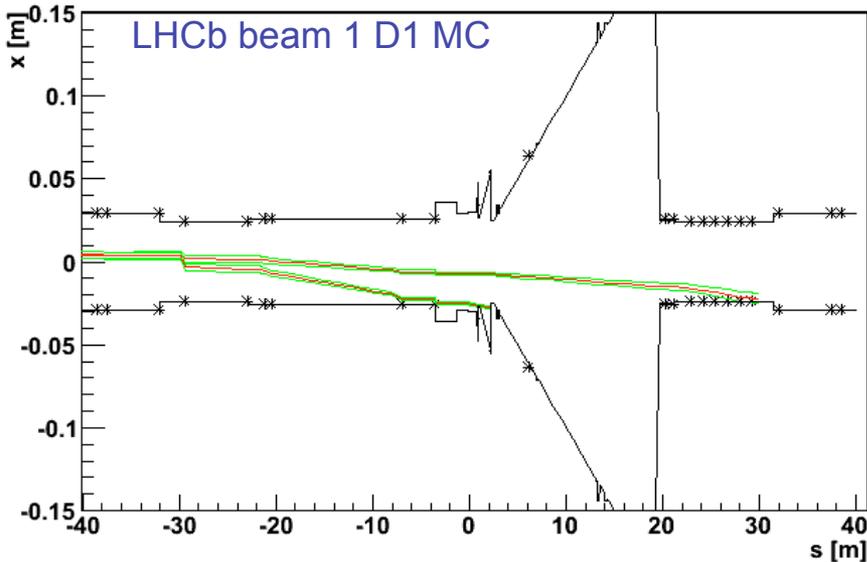
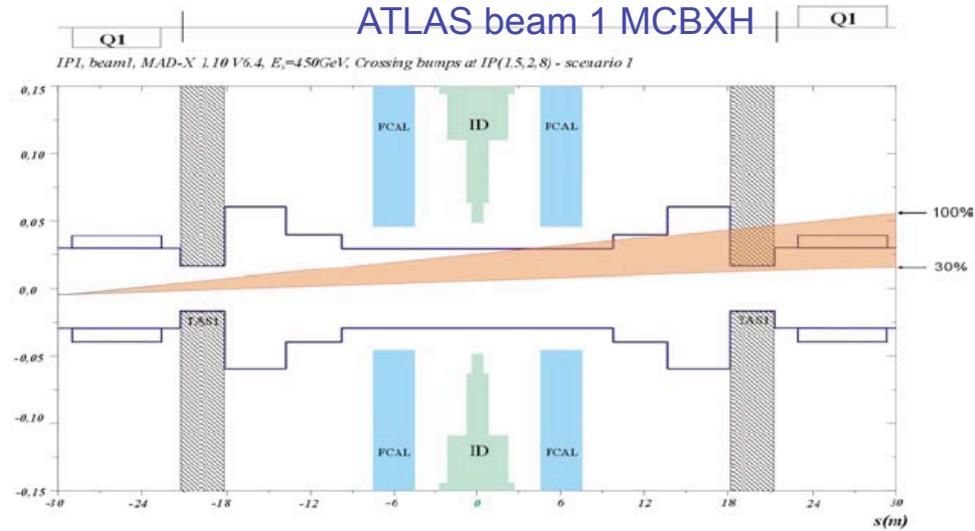
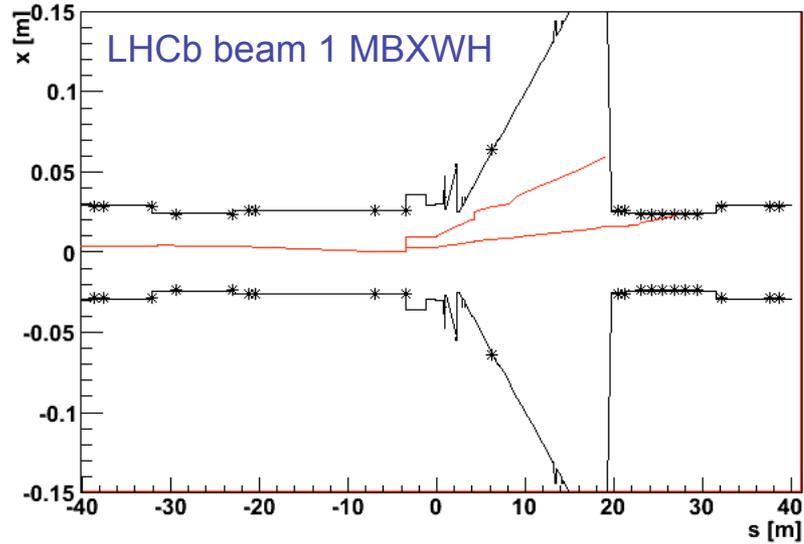
The result is orbit distortion on the first turn, and potential beam strike in the experimental regions (vacuum chamber, magnets, detectors etc) - next slide

The current thresholds for strike can be used to set **current software interlocks**:

1. For the corrector dipoles, 100 μ rad, which is the current injection interlock (tighter later). So the experiments should be okay on injection provided the interlocks are respected.
2. For the separation dipoles, initial interlock is 3% of nominal injection current, which is consistent with computed thresholds (This is also true for a double separation dipole failure at limit of interlocks)
3. Compensation dipoles. It's clear an interlock is needed, and is implemented for the machine restart.

Software interlocks are crucial for protection of experimental regions

Injected beam accidents (LHCb, ATLAS and ALICE beam-strikes)



Circulating beam errors

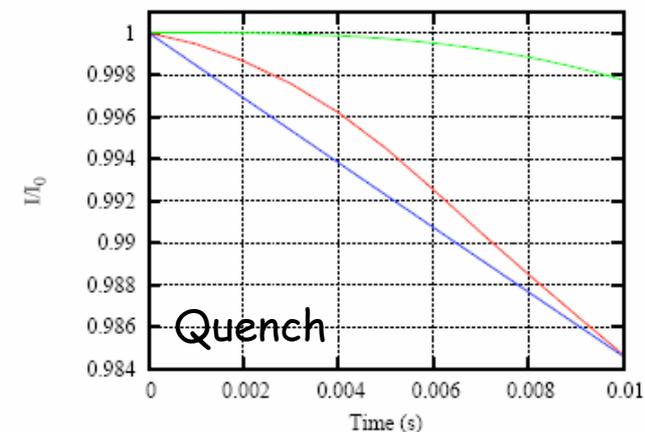
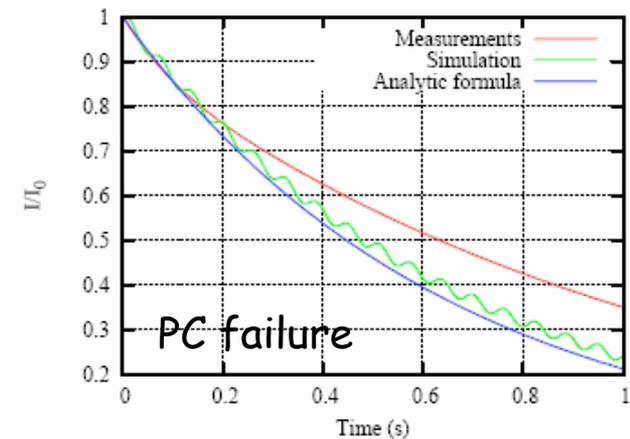
For a circulating (stored) beam, the magnets must already be correctly set to some level if the beam makes a turn, but failures and quenches can occur:

A. A Power Converter can deliver a wrong voltage due to failure or error

1. This can be modelled by a RL circuit, giving exponential change of the currents of all magnets in the circuit (time constant is circuit dependent)
2. Possible wrong voltages are
 - i. From nominal V to zero V
 - ii. From nominal V to maximum V (possible for 450 GeV)

B. A magnet can quench

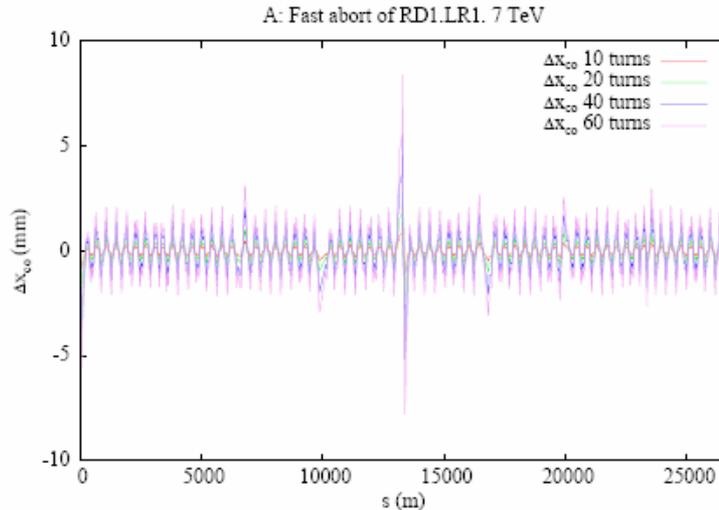
1. The current decay has been modelled by a Gaussian decay (flat-ish at first followed by a drop).
2. The circuit quench protection system operates on all magnets in that family



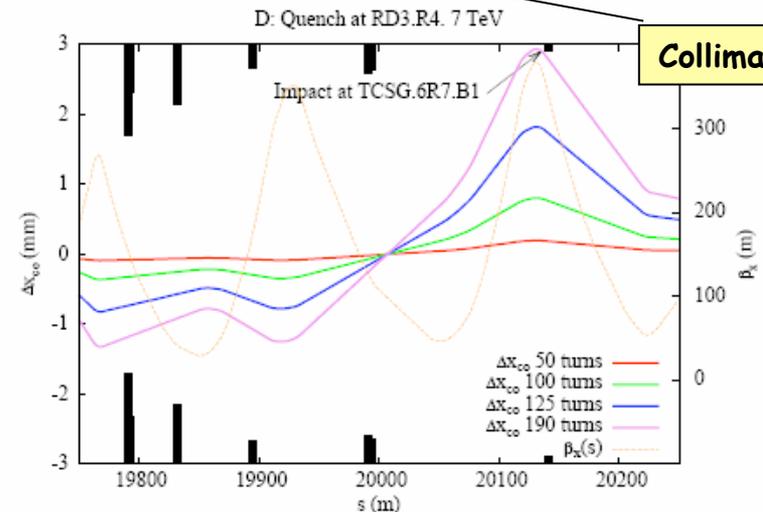
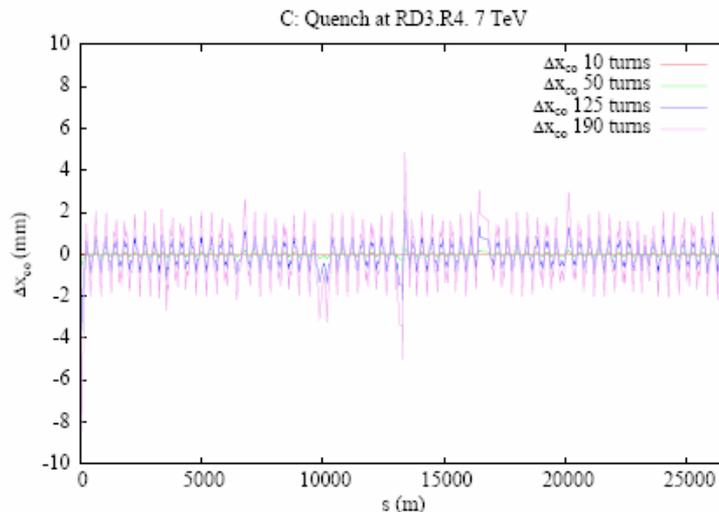
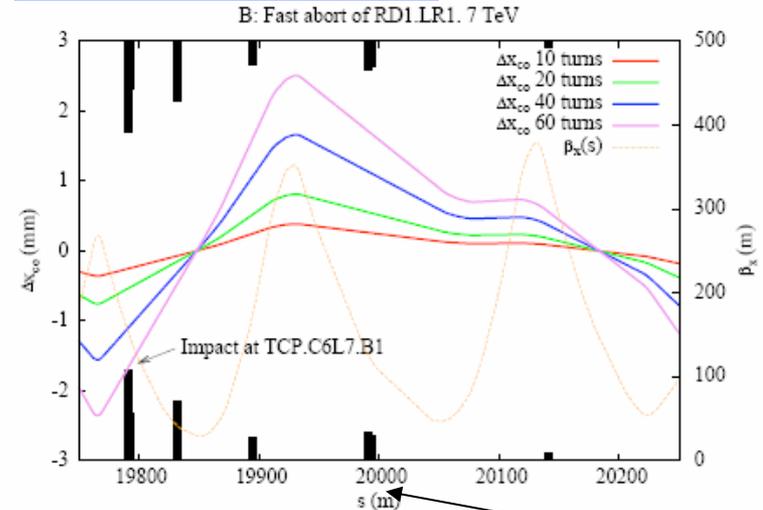
Time-domain dynamics

The evolution of the beam parameters, here beam orbit, is used to evaluate **REACTION** times for internal interlocks and for beam diagnostic systems (beam loss monitors).

Orbit along the ring

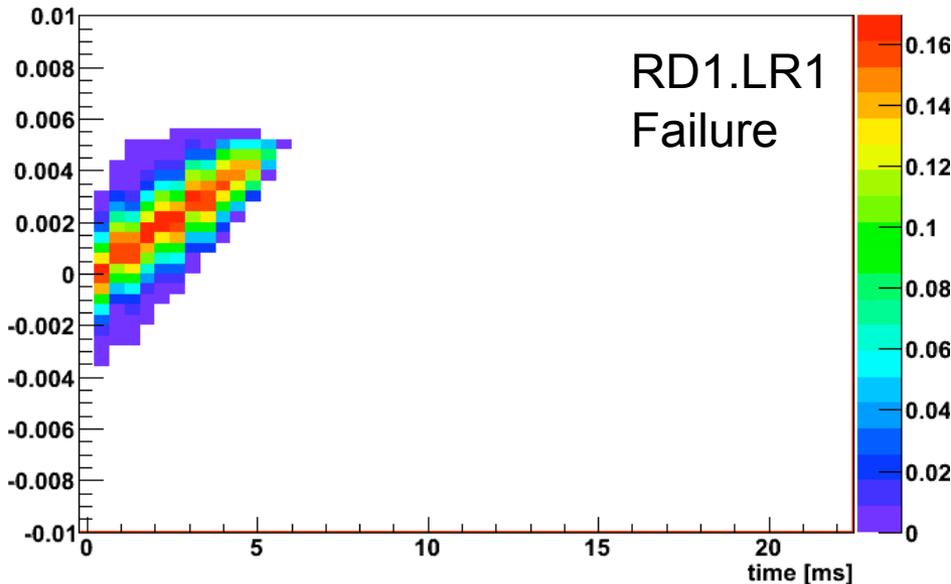


Orbit around collimators

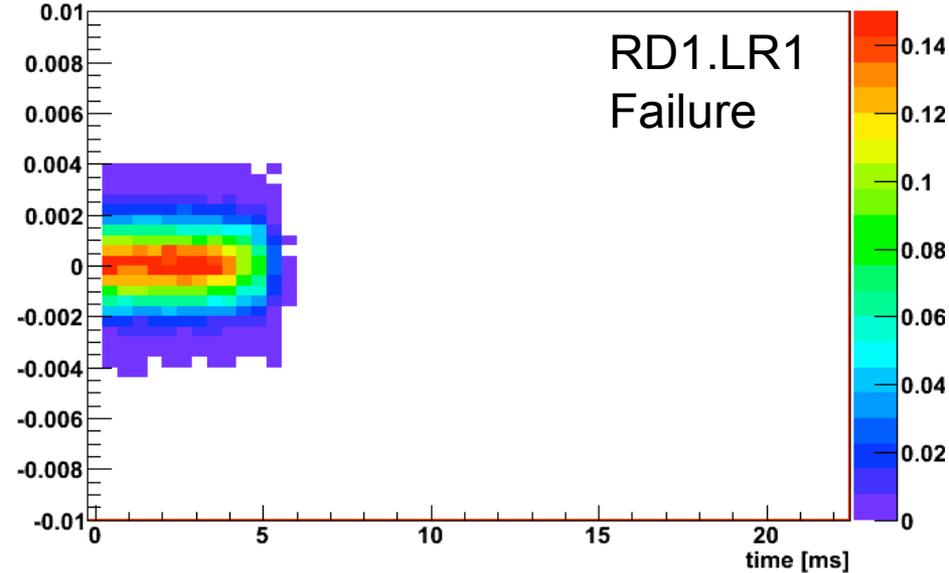


Example: TOTEM 450 GeV collisions: D1 failure in pts 1 (or 5)

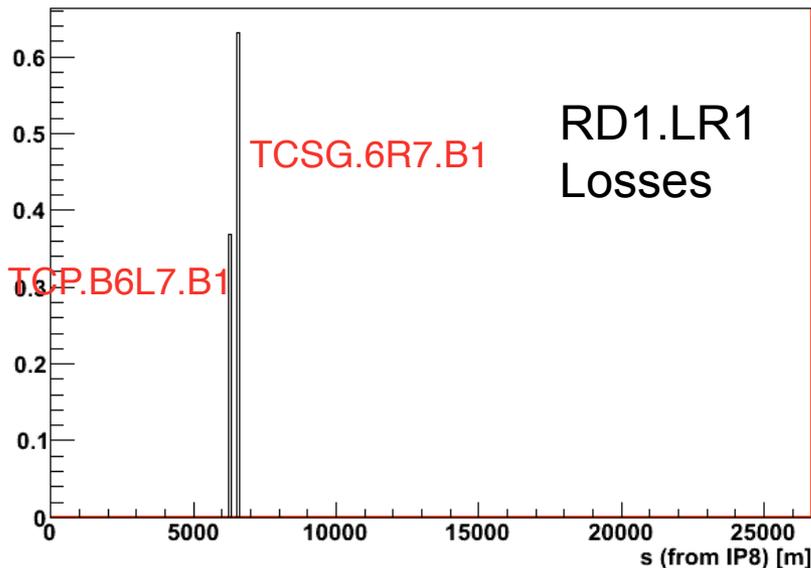
Horizontal proton distribution [m]



Vertical proton distribution [m]



Proton loss fraction



Reconstruct machine reaction to orbit distortion and resulting beam loss

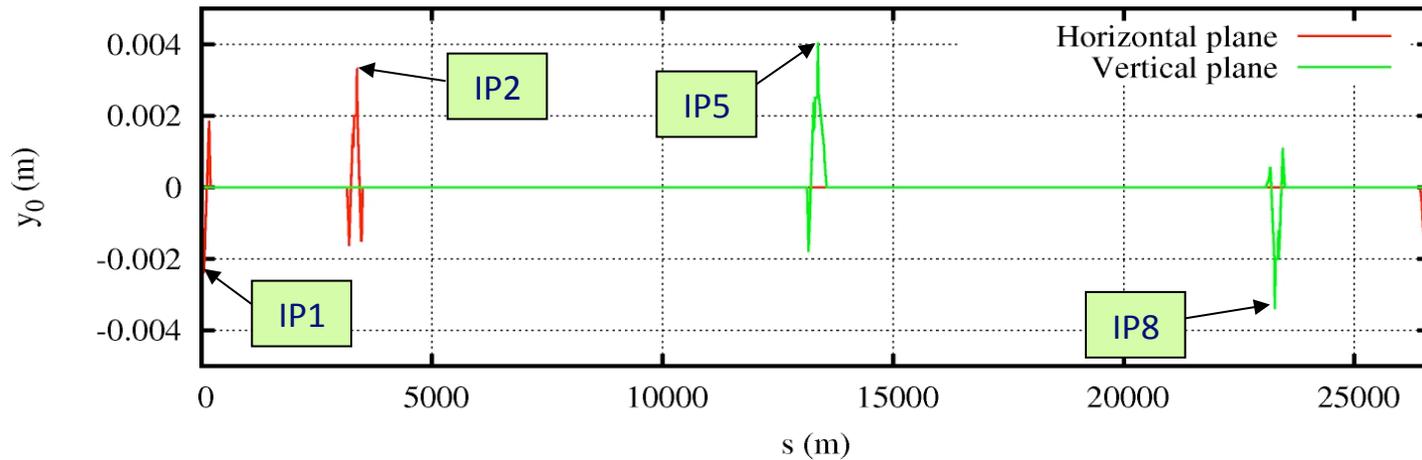
RD1.LR1 failure at 450 GeV. Rising voltage from nominal to top voltage

Orbit distortion occurs within a few turns (few hundred μ s), with loss on the primary and secondary collimators in pt7 after 30 turns. This loss is seen by the BLMs

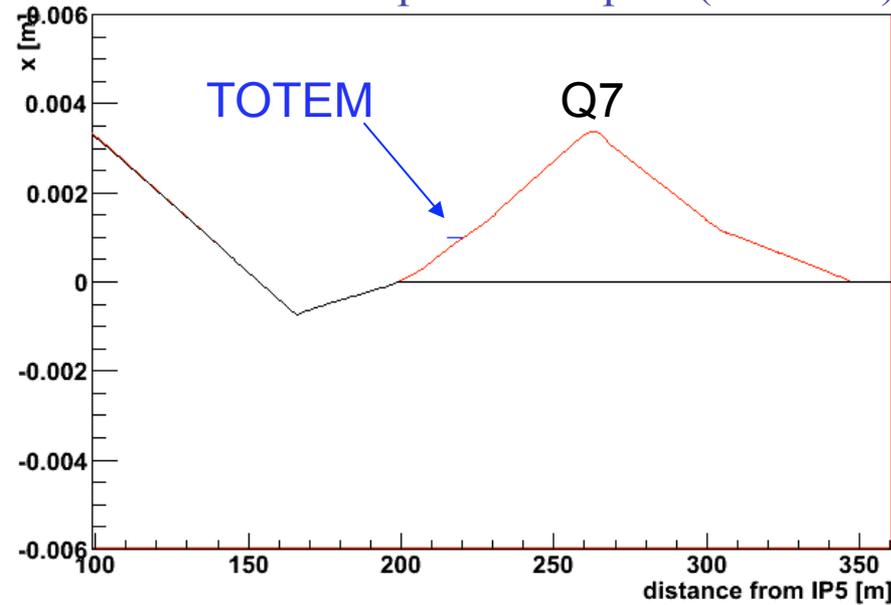
TOTEM does not take beam, but relies on alignment of collimation system (BLMs) and fast machine response time (BLMs/FMCMs)

Local bumps = aperture reduction

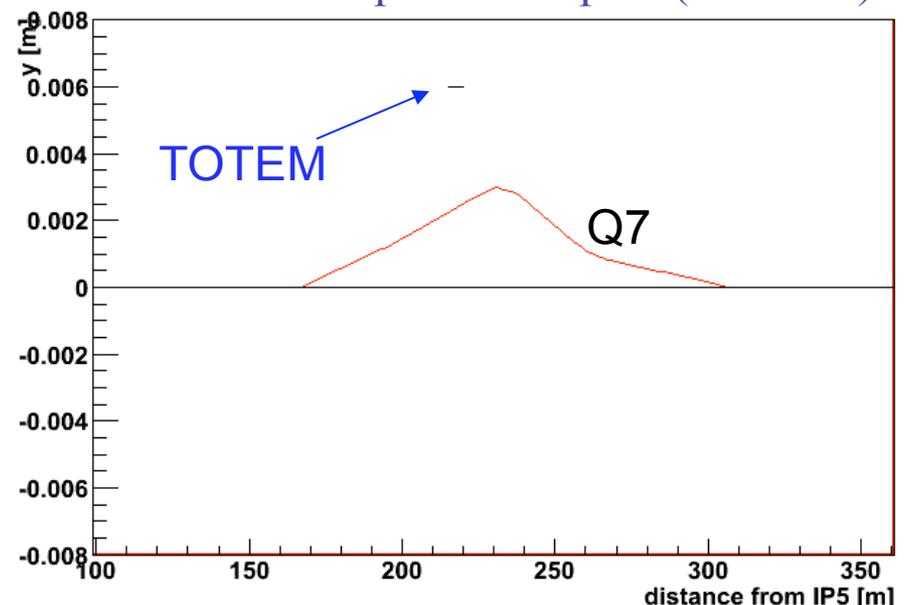
Example of a bump: separation closed bumps at injection:



Nominal orbit ——— Bumped orbit ———
Horizontal bump at 220m pots (**collision**)



TOTEM pots ———
Vertical bump at 220m pots (**collision**)



- Failure cases considered:
 - Quench of final triplet magnets
 - See beta-beat and tune shift
 - MQXA.3R5 is interesting as gives bad phase advance to TOTEM, and is strong ($\tau = 200\text{ms}$)
 - Failure of matching quadrupoles
 - Quench and failure of arc dipoles
 - Failure of separation dipoles
 - In all cases, near beam experiments are in shadow of collimators in points 7 and 3 for both 7 TeV and 450 GeV stored beam
 - BLMs see the loss first (collimators define aperture)
 - BUT rely on the presence and alignment of collimators
 - We need to check early running collimation schemes protect as we'd like
 - BUT rely on the fast response of the beam interlock system
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What about local bumps across the experiments? Dangerous, and the possibilities for detection and interlocking are

A. The corrector magnets around the near-beam detectors could be interlocked, to permit only a small relative change once the orbit is corrected and the moveable detectors flag is enabled.

B. Orbit control software to monitor detector distance to the beam

C. The downstream BLMs may see a signal. Can we use this?

Summary

- ✓ Machine protection for the experiments means doing all we can to protect the delicate experiments and integrate them into the machine protection design and philosophy
 - ✓ For injected beam accidents, the experiments rely on (and to some extent) set the injection interlocks and parameters (including only allowing injection with a probe bunch)
 - ✓ For circulating beam accidents, arising from hardware failure, quenches, operator conditions etc, the near-beam experiments rely on sitting in the shadow of the collimation system and on fast response on machine protection hardware.
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- ✓ Experimental tests of the beam dynamics and system response are planned when we have beam (force a PC wrong voltage)
 - ✓ No time to discuss other issues like asynchronous beam dumps or machine protection related to the upgrades
 - ✓ This is a complex task, and we will be ready to fully protect all the experiments of the LHC.