Beam accident scenarios for injected and stored beams, for the experiments

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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 (particularly the moveable detectors of LHCb VELO, TOTEM etc.

There are several classes of beam accident to consider:

A. On injection

i. Operational failure of magnet mis-settings at injection

(kicker and other failures like asynchronous beam dump being studied by B. Goddard et al)

B. The circulating (stored) beam

i. Power converter failure, causing a change in field of the magnets in the relevant circuit. Generally only an issue for short time constant circuits

ii. Quench of a superconducting magnet (with associated quench protection)

iii. Operation failures e.g. operator-created local bump across an experiment

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

A and B have been studied in the last couple of months

Failure scenarios generally mean a change in a magnetic field or a physics obstruction into the beam (aperture restriction)

For example, dipole and quadrupole field changes lead to linear changes in the beam dynamics

Dipole: error kick and closed orbit offset all around the ring

$$\Delta x(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi Q)} \sum_{j=1}^{n} \theta_j \sqrt{\beta_j} \cos\left(\psi(s) - \psi_j + \pi Q\right)$$

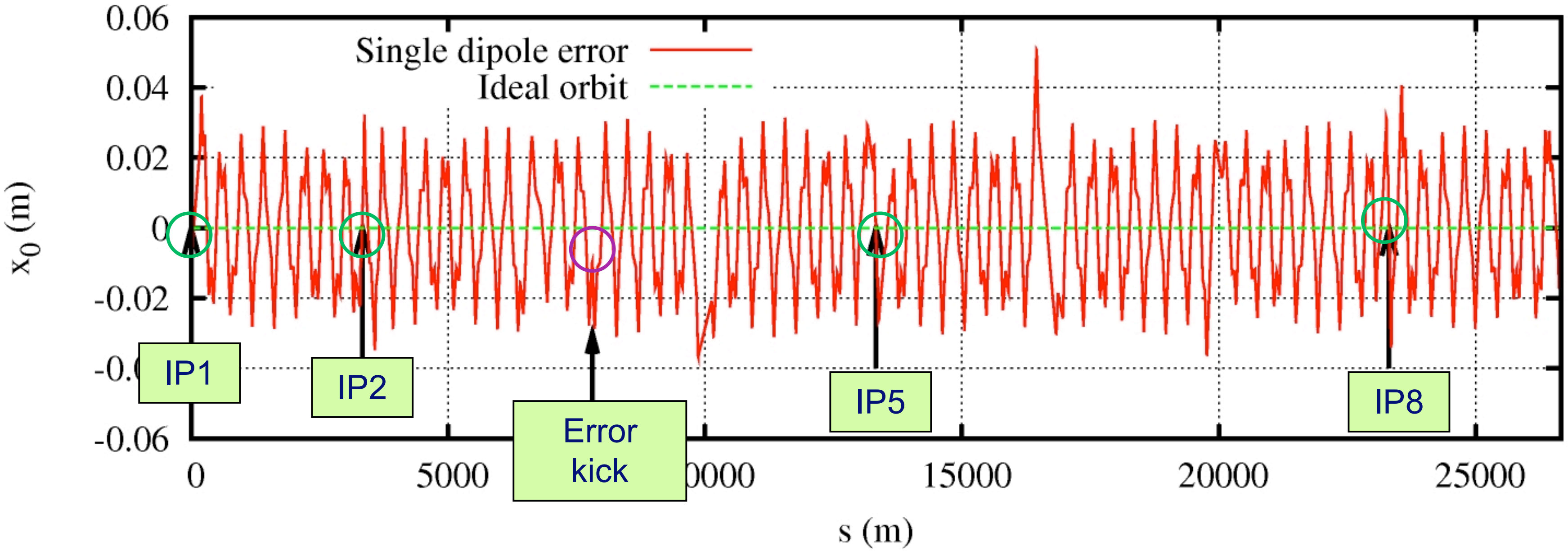
Quadrupole: beta beating all around the ring and tune shift

$$\frac{\Delta\beta}{\beta_s} = \frac{\Delta k l}{2\sin(2\pi Q)} \sum_{j=1}^{n} \beta_j \cos\left(\psi(s) - \psi_j + \pi Q\right)$$

(Hence we can calculate worst-case failures by maximising phase relationships between an experiment and a possible failure)

Sextupole and higher: non-linear effects, inc. chromaticity change and increase in tune spread etc.

The perturbations have an effect in **all** positions in the ring e.g. dipole error



The local effect is proportional to the root of the betatron amplitude which is much smaller in the IPs than in the collimation sections (10’s of metres (or 0.55 m) compared to about several hundred metres)

So a field change in the ring is a potential worry for all experiments which want to operate relatively close to the beam

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

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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)

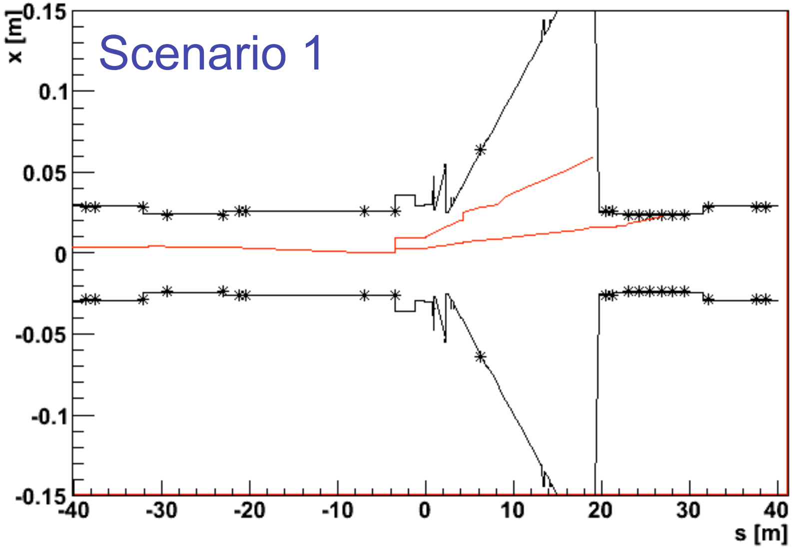
The study has been done previously for point 1, and now for LHCb and ALICE, with interaction region magnet wrong settings of

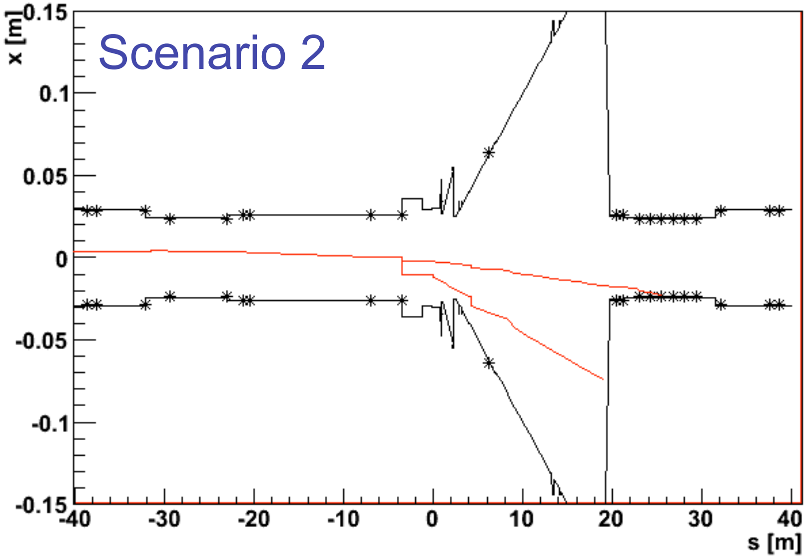
1. MCBXH and MCBXV - strong H and V correctors on final triplet
2. D1 and D2 separation dipoles (potentially very dangerous)
3. MBXWH correction dipole (LHCb)

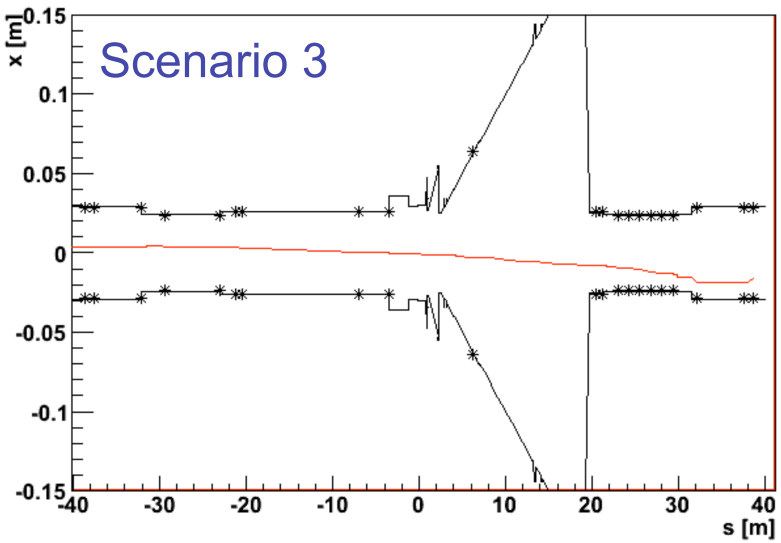
All studies done for nominal optics at injection for beams 1 and 2, with scenarios

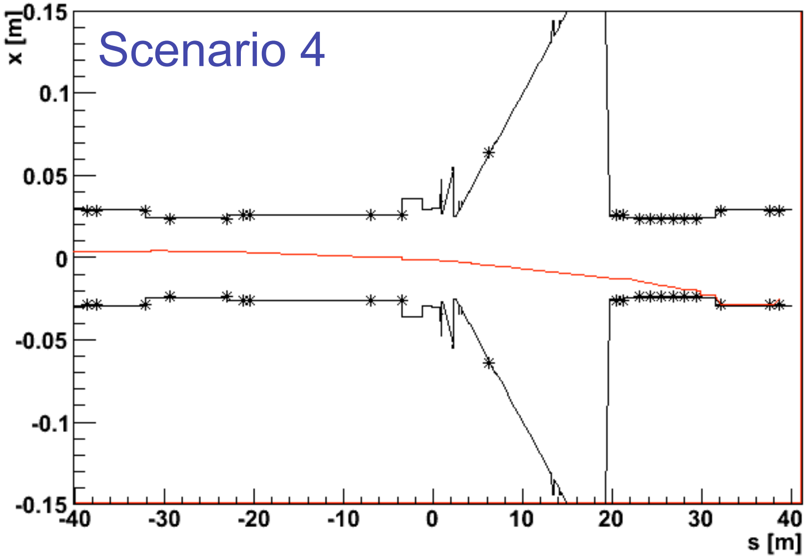
1. Magnet strength from nominal to maximum (factor of 7000/450)
2. Magnet strength from -nominal to -maximum
3. Magnet set to zero current (most likely at start-up)
4. Magnet set to -nominal strength

LHCb MBXWH (beam 1)

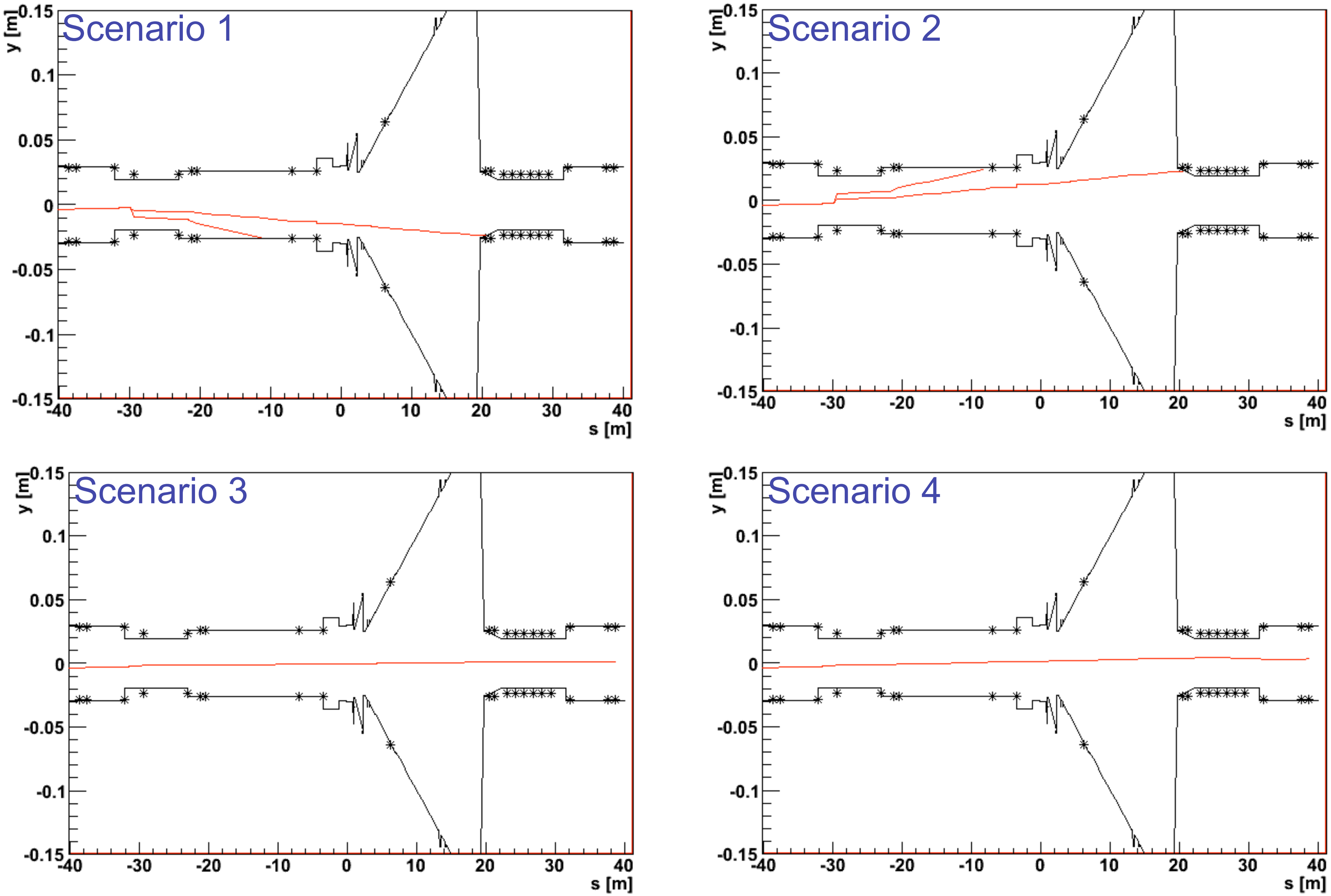




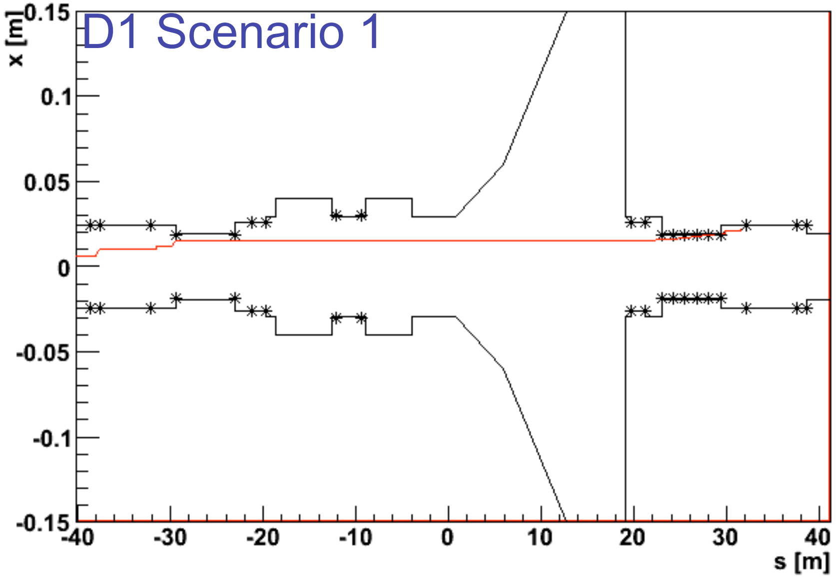


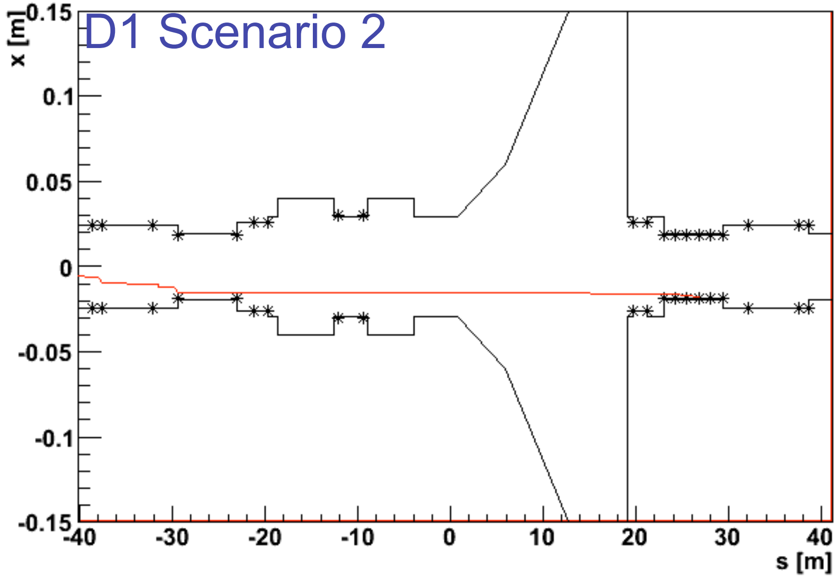


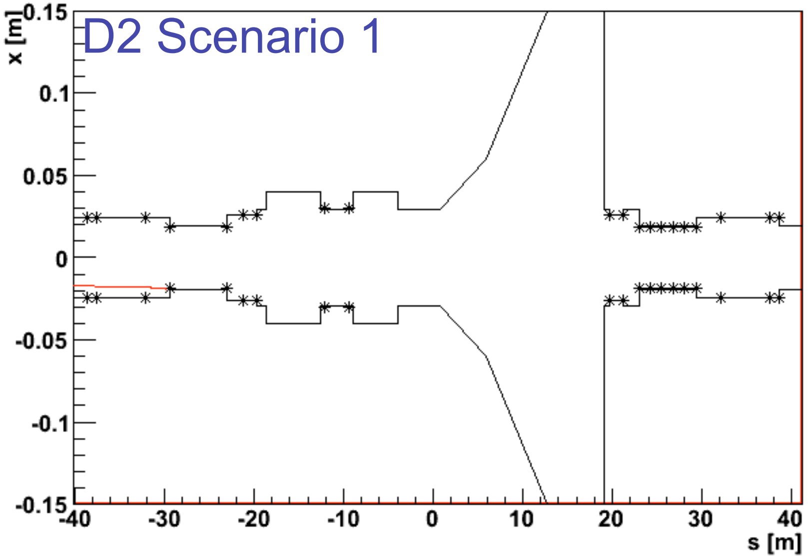
LHCb MBCXV (beam 1)

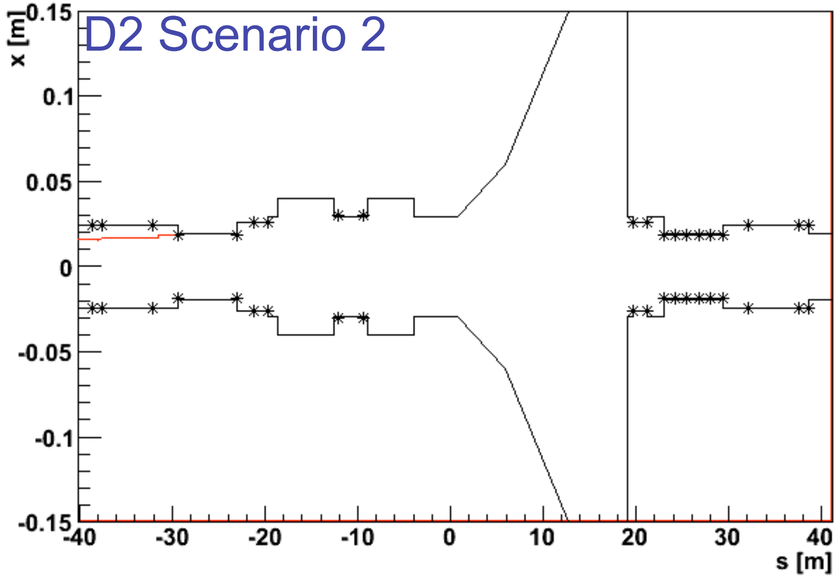


ALICE D1/D2 (beam 1)

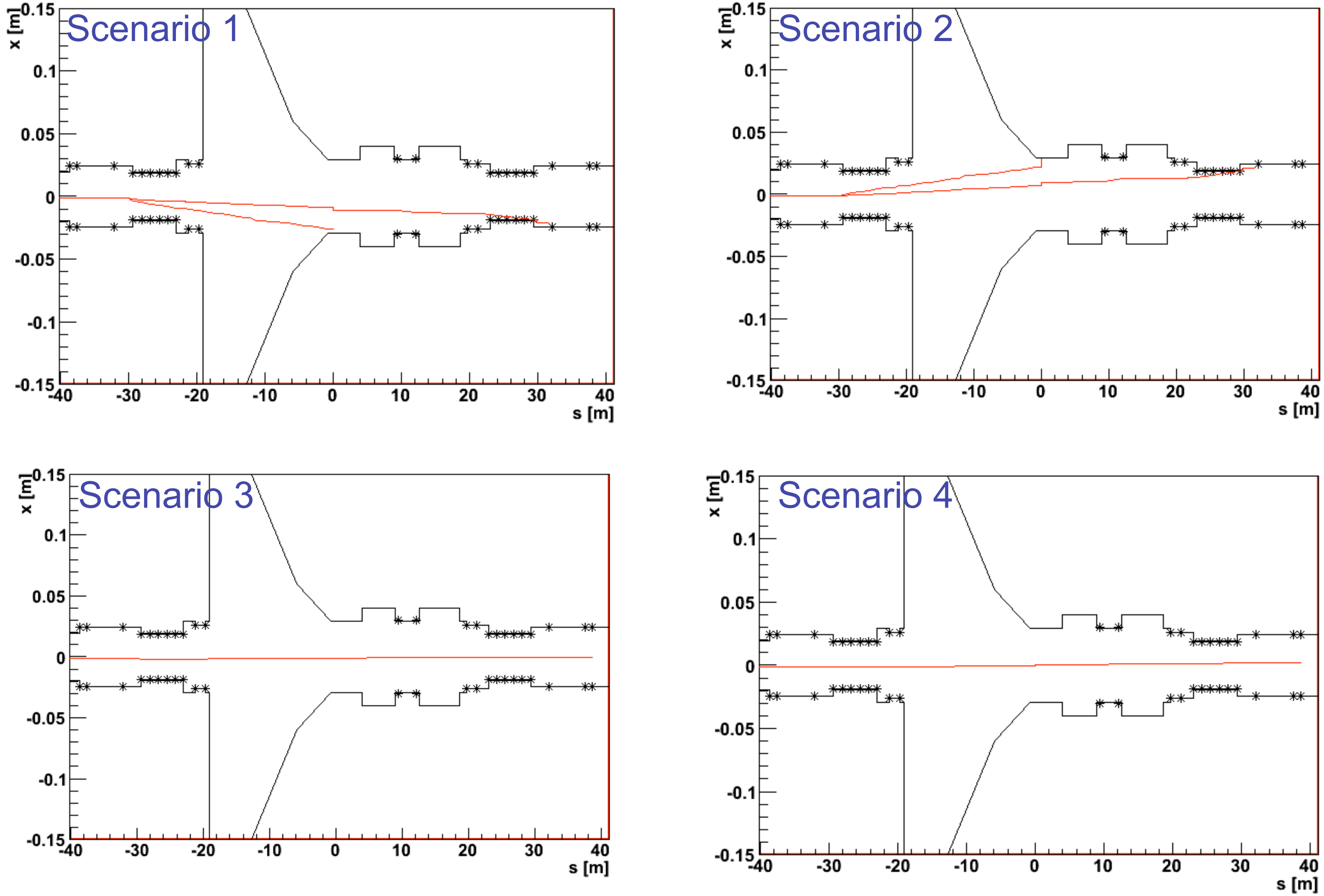








ALICE MBCXH (beam 2)



Thresholds to avoid beam strike (LHCb b1 as example)

Magnet	Nom. angle [μrad]	Max angle [μrad]	Threshold (nom. pol.)	Threshold (rev. pol.)
MBXWH	+181	+2820	35% (987μrad)	-14% (-395μrad)
MCBXH	-5	-1011	35% (-354μrad)	-55% (556μrad)
MCBXV	-48	-1042	30% (-313μrad)	-28% (292μrad)
MBX.4L8	-1533	-23,837	8.5% (-2026μrad)	4.9% (-1168μrad)
MBRC.4L8	+1533	+23,837	8.8% (2098μrad)	4.7% (1120μrad)

Magnet current thresholds can be computed to avoid beam strike on the experiment or the machine at injection.

The thresholds can be related to software interlocks, which are

1. For the corrector dipoles, 100 urad, which is consistent with the computed thresholds. So the experiments should be okay on injection provided the interlocks are respected

2. For the separation dipoles, 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 dipole. It’s clear an interlock is needed.

Software interlocks are crucial for protection of experimental regions

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

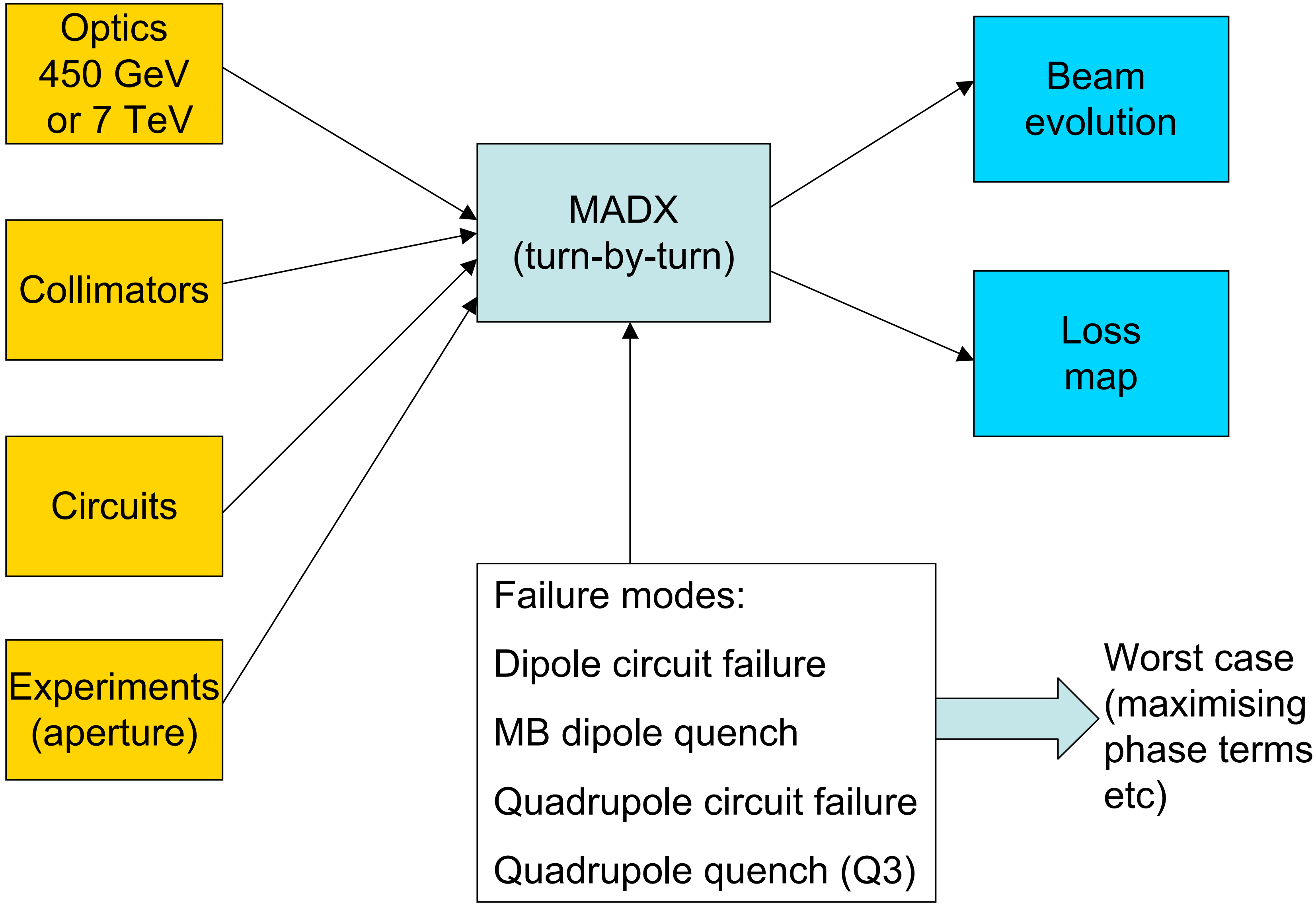
1. This can be modeled by a simple RL circuit, giving exponential decay of the currents of all magnets in the circuit (time constant is circuit dependent)
2. Possible wrong voltages are
   i. From nominal V to zero V
   ii. From nominal V to maximum V (possible for 450 GeV stored beam)

B. A magnet can quench

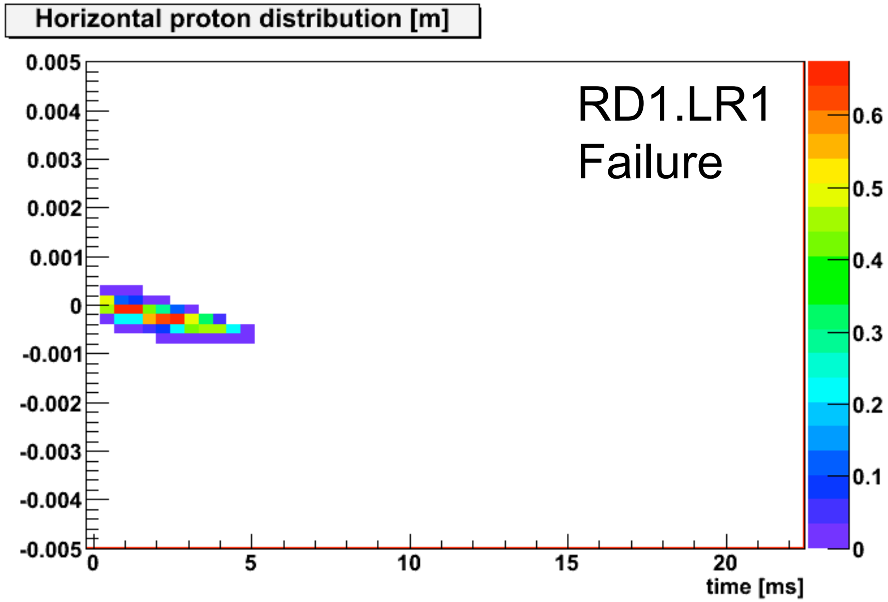
1. The current decay has been simply modeled by a Gaussian decay (flat-ish at first followed by a drop). The circuit quench protection system operates.
2. The quench decay width depends on energy
   i. σ_c = 200 ms at 7 TeV ← Most dangerous
   ii. σ_i = 2000 ms at 450 GeV

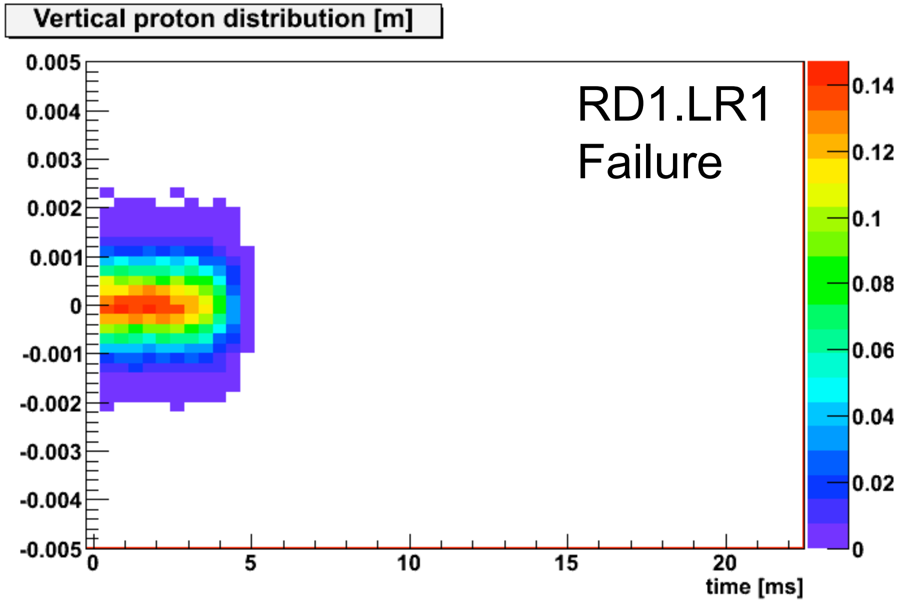
These simple models are okay. Data now exists for field decays under failures and quenches, which can be compared to models and used for simulations.

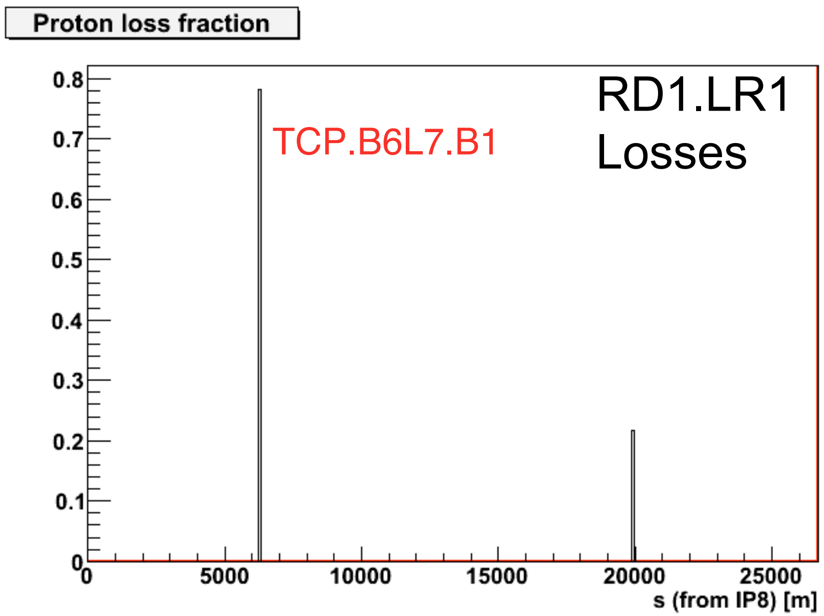
Calculation and failure modes



TOTEM 7 TeV: D1 failure in pts 1 or 5







RD1.LR1 powers D1 on right and left of IP, warm with time constant ~2s.

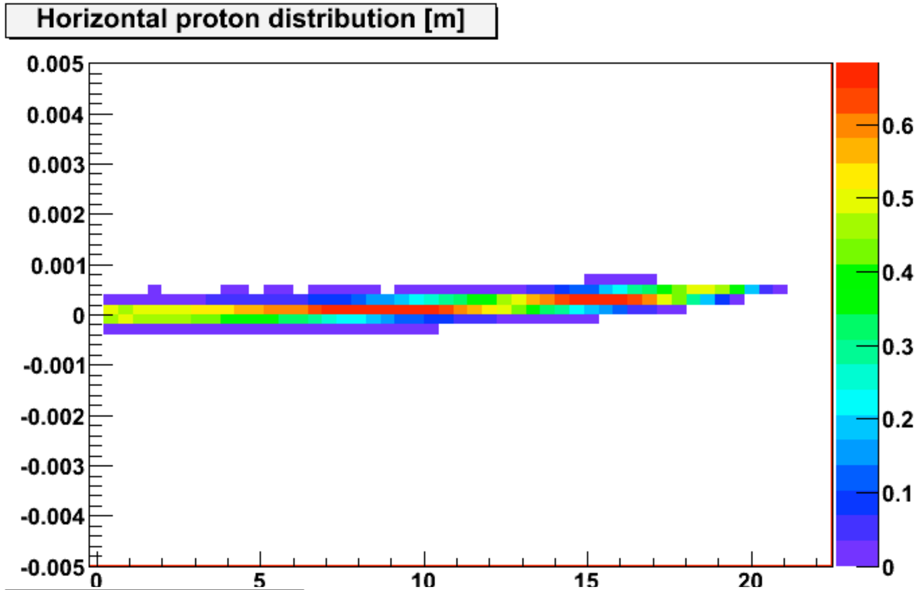
Orbit distortion occurs within a few turns, with loss on the primary collimators in pt7. Detected by fast current monitor on D1

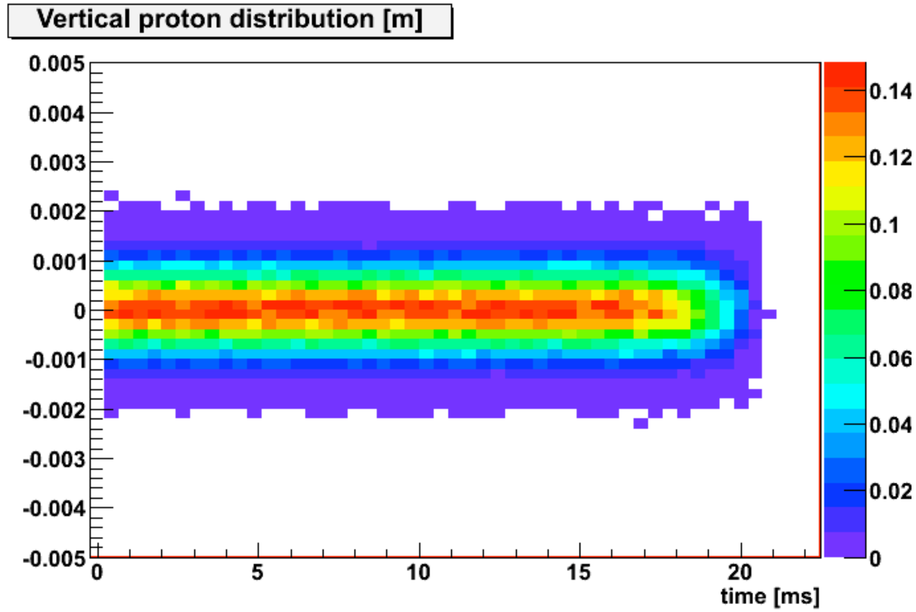
TOTEM does not take beam.

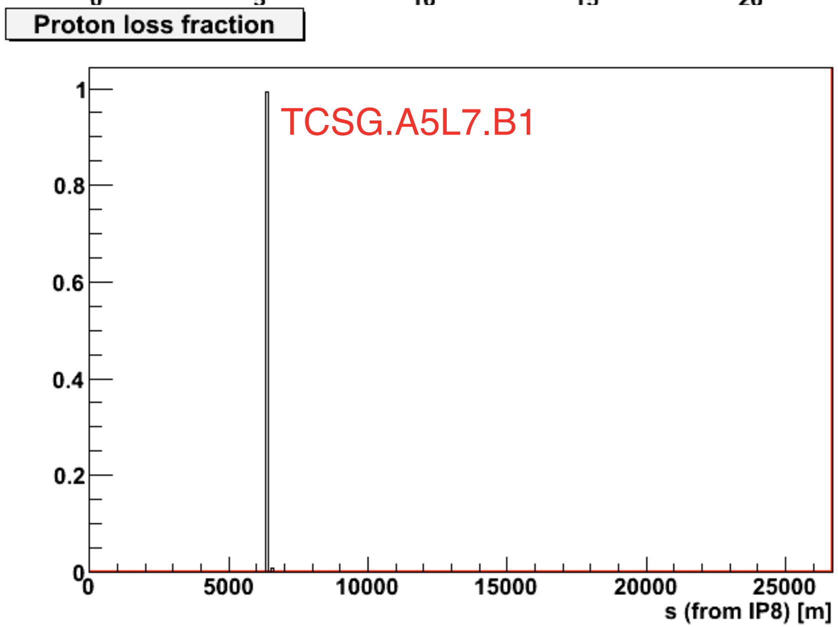
Rescattered protons may play a role, but plenty of collimators in phase with TCP

Similar conclusion for pt5

TOTEM 7 TeV: quench of MB







MB quench in arc, picked to maximise orbit distortion at TOTEM in terms of phase

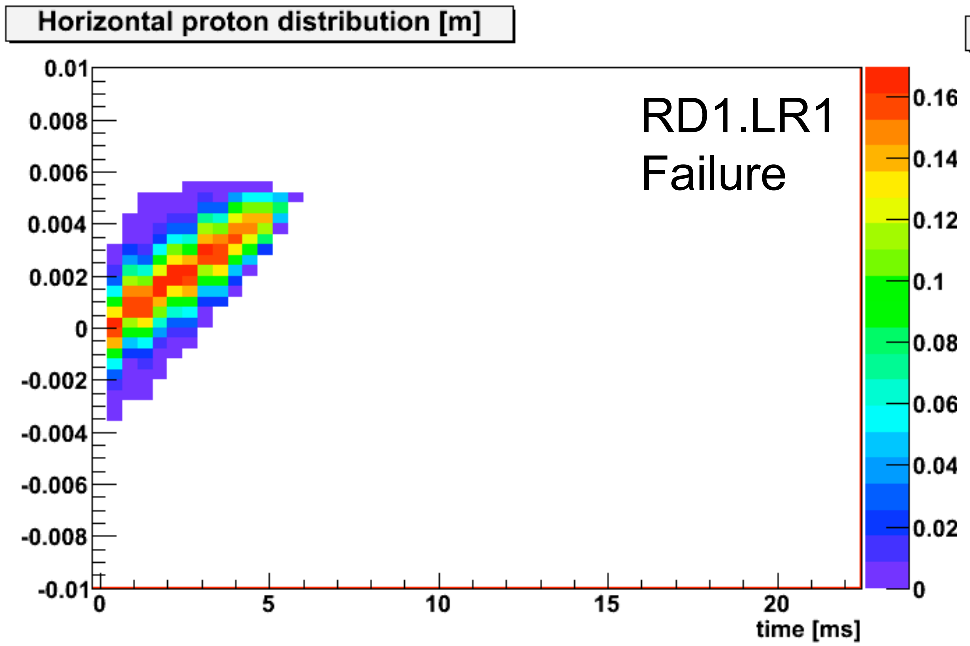
Gaussian decay with width 200ms, and quench protection time constant of 104s

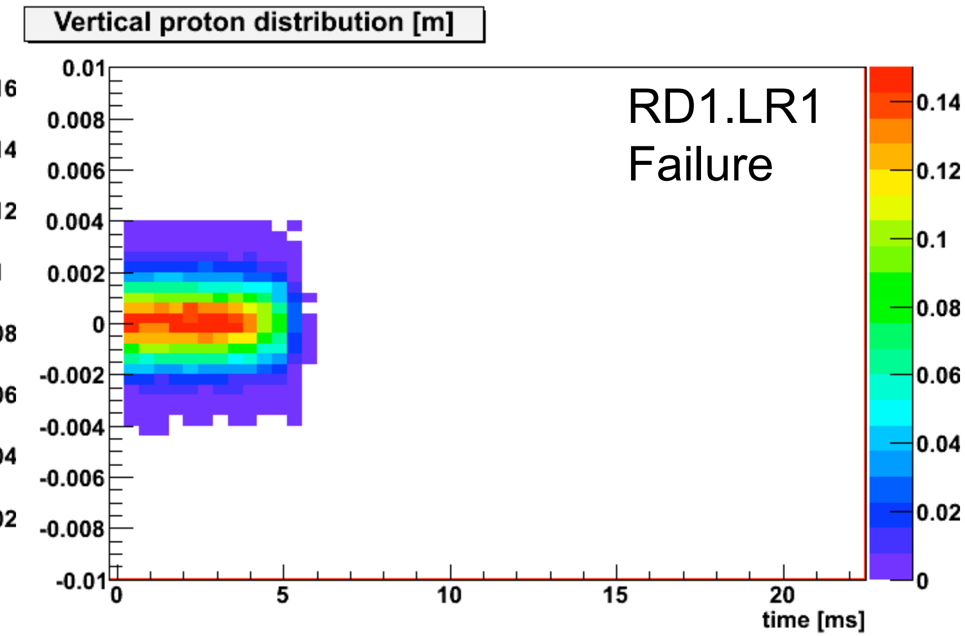
Orbit distortion occurs within 15ms, with loss on a collimator in pt7

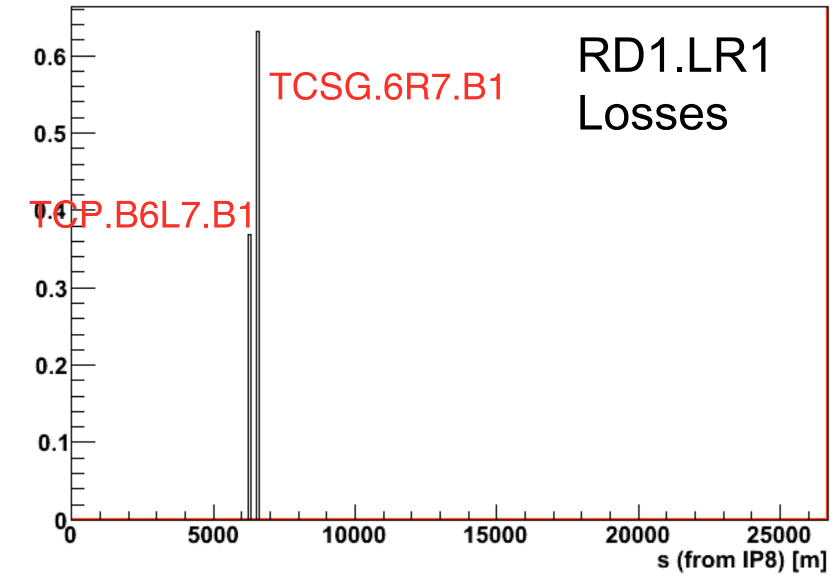
TOTEM does not take beam.

Rescattered protons may play a role, but plenty of collimators in phase with TCP

TOTEM 450 GeV: D1 failure in pts 1 or 5







Worst case at 450 GeV is rising voltage from nominal to top voltage

Orbit distortion occurs within a few turns, with loss on the primary and secondary collimators in pt7. Detected by fast current monitor on D1

TOTEM does not take beam.

Rescattered protons may play a role, but plenty of collimators in phase with TCP

Similar conclusion for pt1

TOTEM accidents for 7 TeV and 450 GeV stored beam

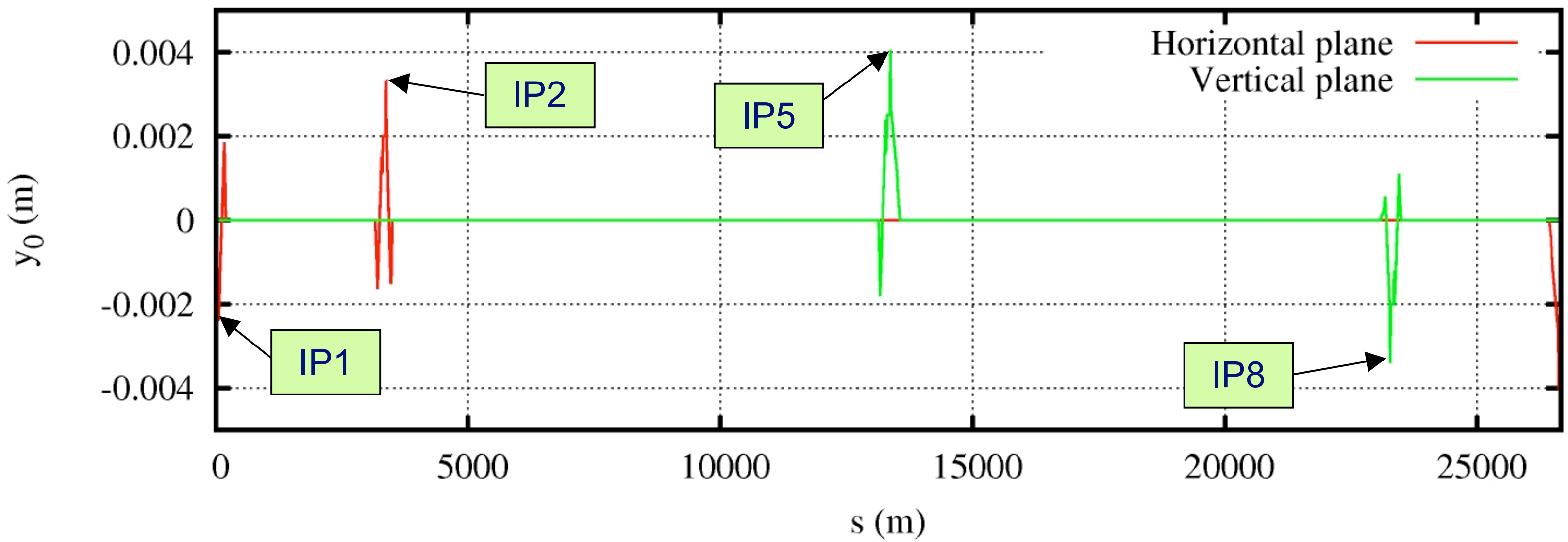
- Other cases considered (includes all key ones)
  - Quench of final triplet Q3 magnet (MQXA.3R5) (beta-beat and tune shift). Again, TOTEM screened by collimators
  - MQXA.3R5 is interesting as gives bad phase advance to TOTEM, and is strong (tau=200ms)
  - Failure of matching quadrupoles
- In all cases, TOTEM pots are in shadow of collimators in points 7 and 3 for both 7 TeV and 450 GeV stored beam
  - TOTEM relies on presence and alignment of collimators
- Collimated protons may rescatter, but unlikely to survive to 10sigma pots (Sixtrack?)
- Studies also done at 450 GeV with inserted VELO (5mm from beam). No danger to near-beam experiments from cases considered (including worst case scenarios)

Local bumps

Can be generated by the corrector magnets

- Playing with the corrector settings
- Failures in the closed orbit control system

Example of a bump: separation closed bumps at injection

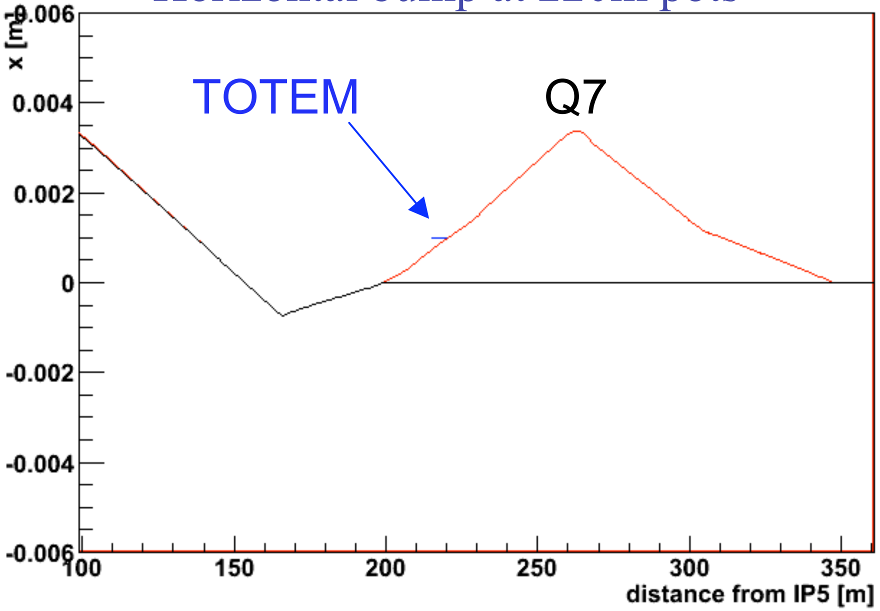


Strength of correctors is around 90 urad, with 30-40 urad used by the global orbit correction. The speed of response is slow (0.5 A/s)

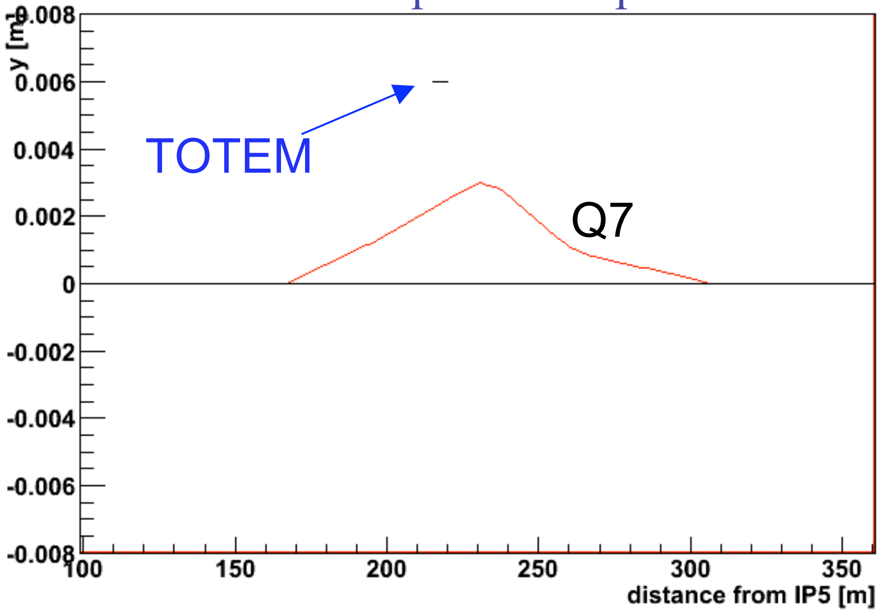
Local bumps across TOTEM

Nominal orbit ——— Bumped orbit ——— TOTEM pots ———

Horizontal bump at 220m pots



Vertical bump at 220m pots



Create enough horizontal distortion at 220m pots with closed 3 magnet bump to send beam into the detectors. The corrector strengths are (bump knob)

MCBCH.5R5 set to 26 urad (it's nominal value is -22 urad)
MCBCH.7R5 set to 41 urad
MCBCH.9R5 set to 31 urad.

The is not enough 'spare' strength in the vertical plane, and it's difficult to make a local bump across the 147m TOTEM pot station

This bump is slow (0.5 A/s), and would need to be detected in BLMs or TOTEM protected by interlocks

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 could monitor the near-beam detector distance to the current beam orbit. Essentially an on-line moveable detector monitor (OM)

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

Low probability failure mode: local bump (not noticed) coupled with fast circulating beam failure e.g. quench. Low probability to occur, but dangerous, and would be mitigated by A, B or C.

Conclusions

- Beam accident scenarios can be dangerous for the experiments, particularly the near-beam moveable ones
- Calculations have been done for
  - Injected beam accidents for LHCb and ALICE
    - LHCb and ALICE at risk from beam strikes, but interaction region magnet current interlocks provide protection
    - Two reports submitted on injection errors
  - Stored beam accidents for TOTEM at 7 TeV and LHCB VELO at 450 GeV
    - TOTEM and VELO in shadow of collimation system for failures and quenches considered, but relies on the correct alignment of the primary and secondary collimators
  - Local bumps for TOTEM
    - TOTEM at risk from local bump, but is a slow risk. Interlocks?
    - A report under preparation (circulating beam, bumps)