Protection Against Accidental Beam Losses at the LHC

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- Damage levels
- Fast beam losses
- Powering failures
- Interlock system
- Operation crews…

Aims

On the following slides I will :

- present some failure scenarios and time constants.
- present the main protection systems and their capabilities.
- try to show you the impact of operation crews on protection.
- discuss issues around devices that are close to the beam.

The focus is on operation at 7 TeV.

Machine protection system

The role of the machine protection system is to protect all LHC equipment against damage due to the uncontrolled release of energy from

- the magnets — 11 GJ stored energy !
- the beams — 0.36 GJ stored energy / beam

The protection is performed with

- active surveillance systems,
- passive protection devices,
- energy 'dumps':
  - energy extraction (EE) systems for magnets
  - beam dumping systems for the beams

The LHC experiments as a part of the LHC profit directly from the effort to protect accelerator equipment !

Damage by beams

A 450 GeV proton beam was directed on a target in an SPS extraction line in Nov 2004 to verify by experiment the damage limits of materials.

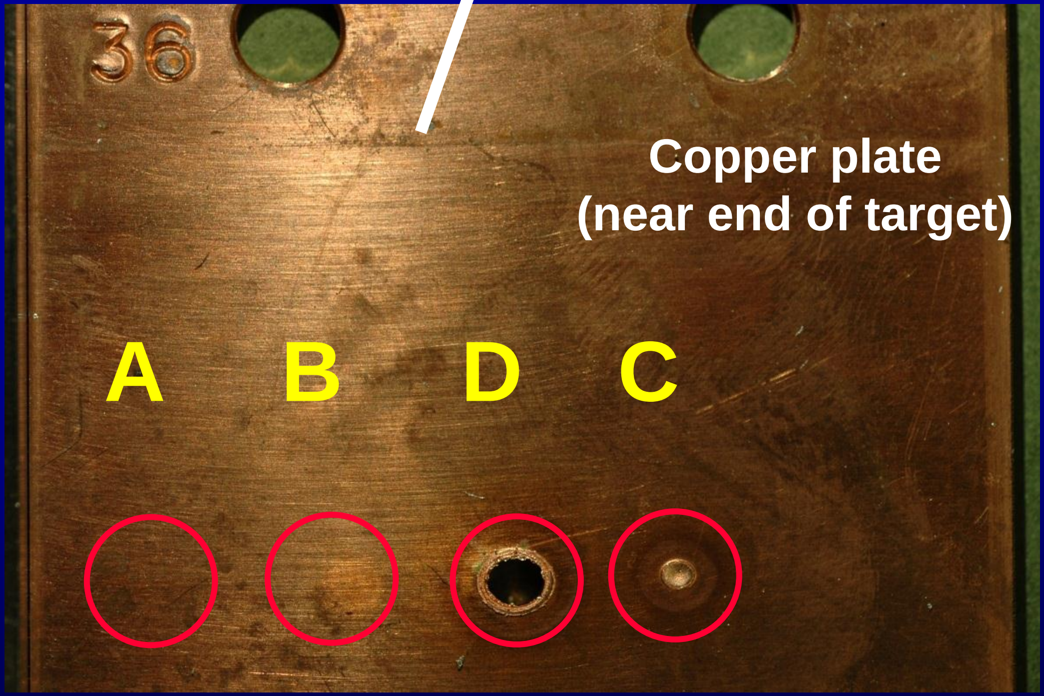
Intensities :

- A : 12 bunches – 1.3×10^{12}
- B : 24 bunches – 2.5×10^{12}
- C : 48 bunches – 5.0×10^{12}
- D : 72 bunches -- 7.5×10^{12}

D $\leftrightarrow$ ¼ nominal LHC injection
$\leftrightarrow$1% of 7 TeV stored energy

A & B are ~ safe.

Stainless steel plates are not damaged, even at int. level D !



Damage & levels for FAST losses

Nominal intensity :

3 $\times 10^{14}$ protons

450 GeV

Validated

- 5 $\times 10^{9}$ protons : pilot bunch, no quench
- 2 $\times 10^{12}$ protons : safe beam limit, below damage level for Cu
- 5 $\times 10^{12}$ protons : ≈ damage level for Cu
- 3 $\times 10^{13}$ protons : nominal injection from SPS (272 bunches) , no damage to graphite collimators

7 TeV

Still to be confirmed !

- 10^{10} protons : ≈ damage level for Cu
- 10^{12} protons : ≈ damage level for collimators

Even the collimators must be protected from massive beam impact !

Time constants for beam losses

time

μs ms … sec min … hours

accidental beam losses

Very slow beam losses (lifetime 0.2 hours or more)

Collimation system limits beam losses around the ring

Very fast beam losses (some turns to some milliseconds)

Fast beam losses (5 ms – several seconds)

Slow beam losses (several seconds – 0.2 hours)

At all times collimators limit the aperture – particles lost on collimators

Hardware surveillance and beam monitoring, failure detection and beam extraction onto the beam dump block

Ultra fast beam losses

- Single turn failures at injection
- Single turn failures at extraction
- Single turn failures with stored beams

Hardware surveillance and passive protection with beam absorbers

Halo growth & beam motion

There are basically 2 type of problems that can affect the beam.

- Halo (tail) growth :
  - The beam size or tail population increase. The flux of large amplitude particle increases. The flux must be intercepted with very high efficiency (better than 99.99% for nominal LHC intensities) by the collimation system to avoid quenches.
- Beam motion :
  - The beam centre of gravity moves away from its reference orbit and may approach the aperture.
  - This is the more dangerous effect, since the beam core may hit accelerator or detector components if it is not intercepted !

Both effects may occur at the same time !

Machine apertures at injection

Mech. aperture of LHC ring defines the scale $a_{ring} \approx 8\sigma$

➔ *tight aperture*

Protection devices protect ring aperture $a_{prot} < a_{ring}$

➔ *protect against injected beam*

Secondary collimators tighter than protection $a_{sec} < a_{prot}$

➔ *limit the amount of halo hitting protection devices*

Primary collimators tighter than secondary $a_{prim} \approx 5\text{-}6\sigma < a_{sec}$

➔ *primary collimators define the aperture bottleneck in the LHC for cleaning of the circulating beam!*

- These conditions must always be fulfilled :
  - ➔ *orbit tolerances are at the level of 0.1-0.5$\sigma \approx$ 100-500 μm.*
  - *! long distance correlations : some objects are separated by kms !*
- The aperture definition includes tolerances for beta-beat (20%), orbit (4 mm), energy offsets, spurious dispersion…

Machine aperture at 7 TeV

Settings at 7 TeV for fully squeezed beams (β^* = 0.55 m IR1/5)

Arc aperture is *large*	$a_{arc} \approx 30\text{-}40\sigma$
Low-beta triplet aperture defines the scale	$a_{triplet} \approx 9\sigma$
Protection devices must protect aperture ➔ *protect against asynchronous beam dump*	$a_{prot} < a_{triplet}$
Secondary collimators tighter than protection ➔ *minimize halo hitting protection devices*	$a_{sec} < a_{prot}$
Primary collimators tighter than secondary ➔ *primary collimators define the aperture!*	$a_{prim} \approx 5\text{-}6\sigma < a_{sec}$

- Operation at nominal intensity requires excellent beam cleaning.
  ➔ *orbit tolerance around collimators is in the range $\sigma/3$ ~ 70 μm.*

Failures & protection systems

To illustrate the machine protection issues and the strategies to protect the machine, I will

- take the example of powering failures,
- discuss the systems involved in protection.

Powering failures

The Magnet powering system will account for a considerable fraction of beam dump requests due to magnet quenches, power converter failures, mains failures, etc..

The most critical failures concern circuits with normal conducting magnets, for example the separation dipoles in the high luminosity interaction regions.

Such powering failures lead to

- Global orbit drifts, speed of up to ≈ 1 mm/ms ≈ 3-4 σ/ms in some locations.

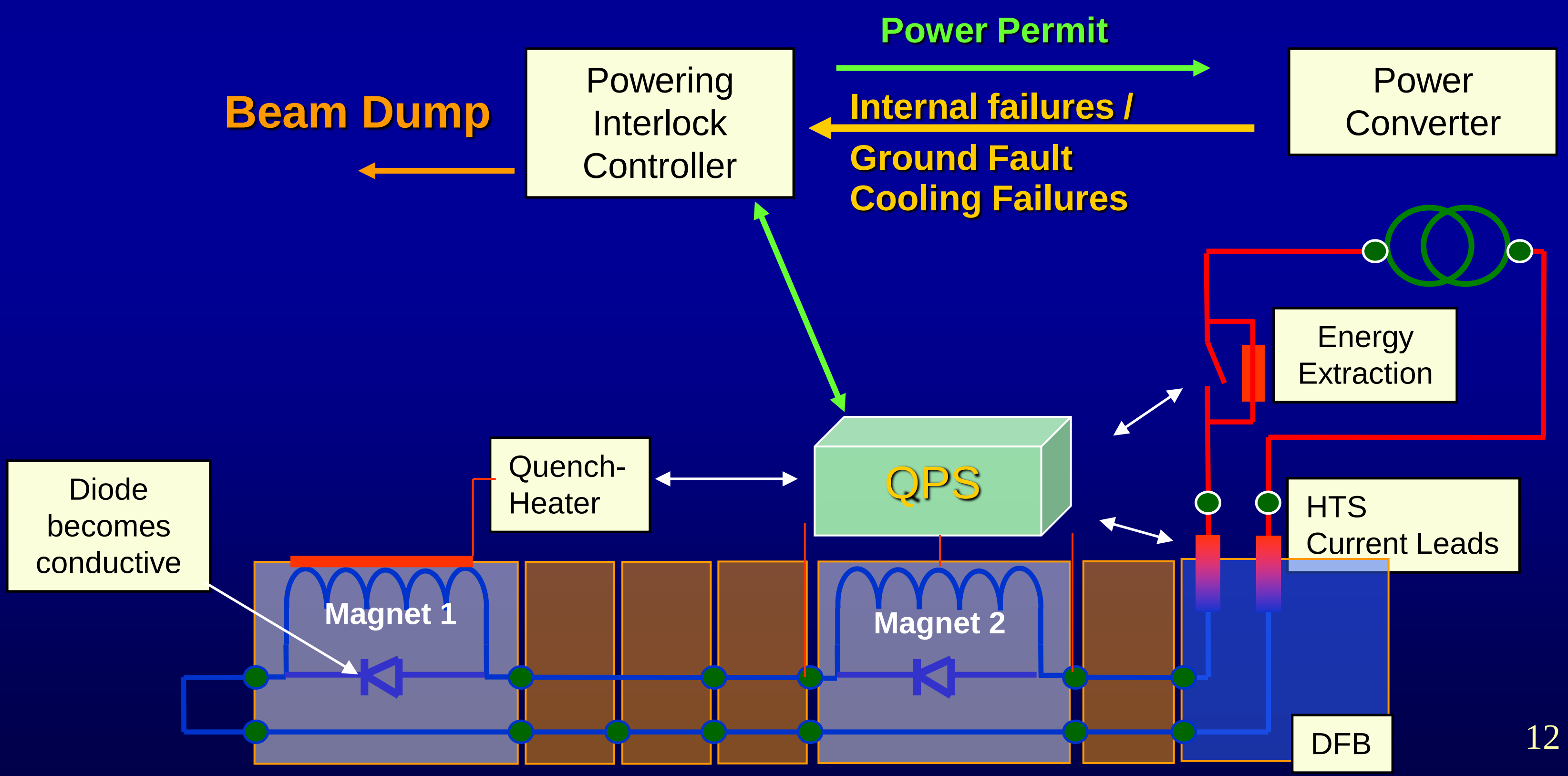
  Orbit drifts maybe detected anywhere around the ring.

- Beam losses when the beams start touching the aperture(s).

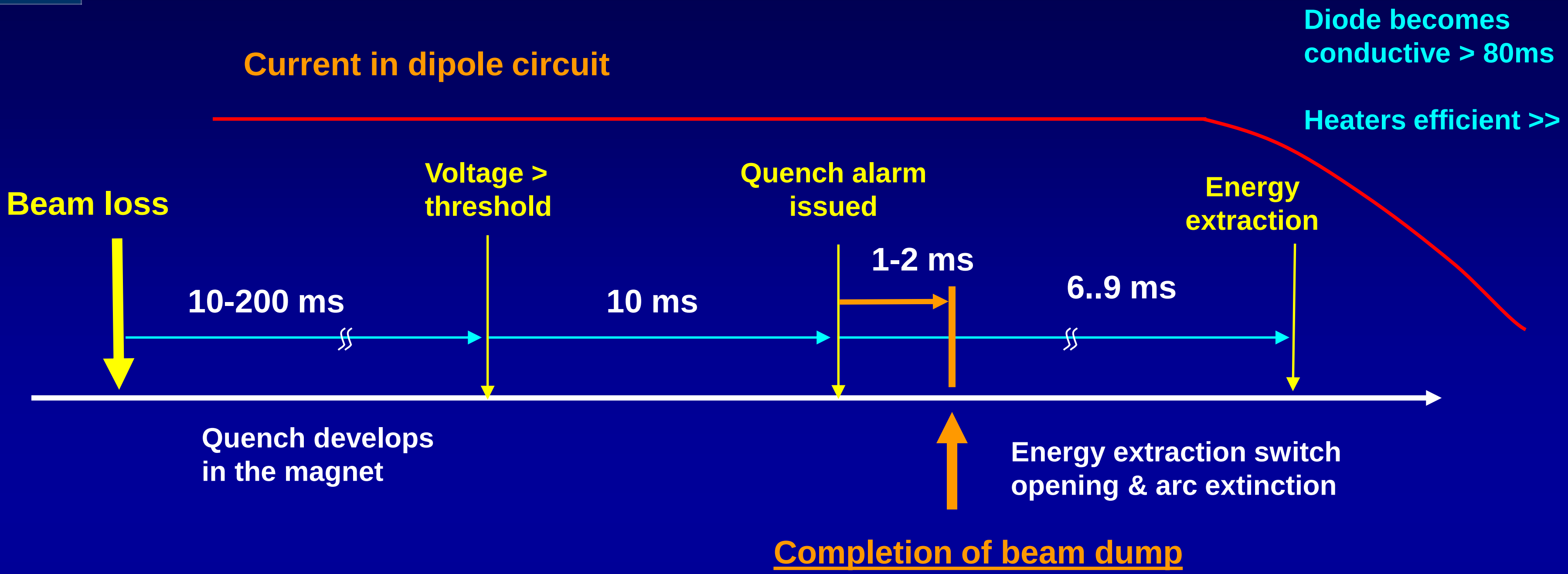
  Since the LHC must always be operated with aperture-defining collimators, losses will almost always appear in the vicinity of the collimators.

Quench of a SC magnet

- Quenching of sc magnet due to e.g. beam losses.
- Quench detection by the QPS (Quench Protection) system.
- Transmission of quench signal, firing of heaters and activation of EE system.
- Current decay only upon complete opening of EE switch, diode will become conductive much later.



Quench protection



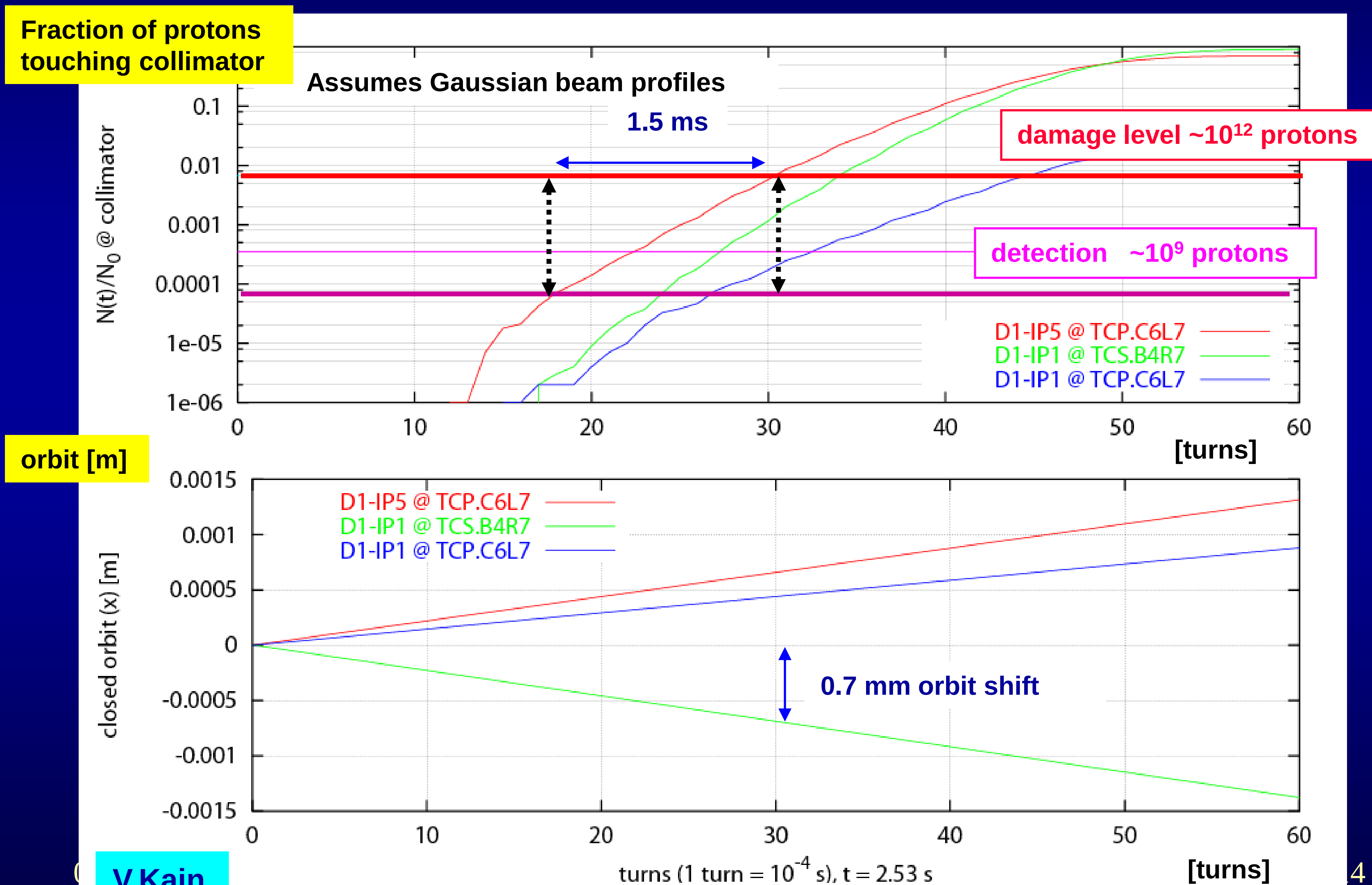
- For slow losses / quenches :
  → the beam will be dumped before the magnetic field is affected !

- For very fast quenches as observed at the Tevatron (few ms) :
  → the field could change before the beam dump is activated by quench protection.
  → we must rely on other protection systems.

One of the fastest mechanism for multi-turn beam losses

Powering failure of a Normal Conducting separation dipole (D1) at 7 TeV.

Damage to collimators possible after ~ 30 turns / 3 ms



V.Kain

Magnet current decay monitoring

- A device that can detect very fast current changes - ~ 0.1% / millisecond - in electrical circuits with short time constants provides efficient protection against powering failures.
- Such a system was developed at DESY for HERA. This device was tested at CERN in March/April 2005. The tests were so successful that we are taking over the DESY device (with small changes).
- We foresee to install ≈30 devices in the LHC and in transfer lines to the LHC.

→ Such a system provides efficient protection against failures of the most critical electrical circuits.

Beam loss monitoring

The Beam Loss Monitoring (BLM) System is our ‘core’ beam monitoring system for protection.

The LHC BLM system :

- Approximately 3600 monitors
- 6 BLMs installed around each quadrupole
- 1 BLM near each of the ~ 240 collimator jaws
- Response times :
  - 1 turn (89 μs) for critical locations (collimators, low-beta,..)
  - 2.5 ms (25 turns) at other locations

In case of a powering failure with global perturbations,

- BLMs at aperture limiting collimators see the loss first.

  Critical condition: the collimators must really define the aperture !
- BLM reaction time depends on the shape of the halo and thresholds

  Halo is sensitive to machine details (non-linearity, beam-beam…)

  Operational thresholds are critical for quench and damage prevention

Beam position interlocking/1

4 interlock Beam Position Monitors (BPMs) will be installed per beam/ring :

- Grouped in 2 redundant pairs, installed in IR6 around the beam dump septa.
- Phase advance between BPM pairs is 90° to cover all beam oscillation phases.
- Large betatron function of β=600 m (LHC ARC ~ 200 m) → sensitivity

  Oscillation amplitudes $\propto \sqrt{\beta}$
- There are 2 distinct interlocks :
  - Interlock on fast position changes with respect to the reference orbit :
    - **Thresholds of ~ 1 mm in 1-50 ms (1 mm ↔ 2σ at 7 TeV)**
  - Interlock on position with respect to the reference orbit :
    - **Thresholds of ± 3.6 mm (± 7σ at 7 TeV)**
    - **Main aim of this interlock is the protection of the dump channel.**
  - Reaction time ~ 1 turn – configurable.

Beam position interlocking/2

The BPM interlock system provides independent interlocking wrt BLMs :

→ No dependence on collimator positions or halo distributions.

→ The reaction times are adequate to protect collimators against beam loss caused by fast powering failures.

→ Limits the maximum amplitude of global orbit changes.

Powering failures summary

Protection systems for ANY powering failure :

- Beam loss monitoring.

  At collimators : reaction after beam movements of few σ.

- Beam position interlocking.

  Reaction after max. of 7σ beam movement (2σ for fast movements) @ 7 TeV.

Additional systems for

→ super-conducting magnets (not for orbit correctors) :

- Quench protection system.

  Likely to be the first system to react for slow losses.

→ very fast normal-conducting circuits :

- Fast current surveillance systems.

Other failures…

Besides powering failures we also have :

- Failures of the transverse feedback system → beam becomes unstable.
- Failure of the RF system → beam de-bunches and looses energy.
- …

→ can be ‘intercepted’ using the same devices as discussed before (BLM & BPMs), because sooner or later, the beam moves or blows up !

Machine operation

Even during 'stable beams', the machine is not stable in the sense that nothing changes:

- Ground motion is shifting the beam orbits, leading the complete separation of the colliding beams after few hours → continuous orbit steering.
- Decreasing intensity may require re-tuning of some parameters.
- Equipment failures may lead to beam dump or poor conditions (low lifetime, backgrounds…).
- …

Beam tuning may be done manually or by feedbacks (orbit).

Do they represent additional risks ?

Machine operation crews /1

The majority of beam tunings (also during stable beams !) concern:

- tunes (quadrupoles) → (in-)stability, halo, lifetime
- chromaticity (sextupoles) → (in-)stability, halo, lifetime
- octupoles & high multipoles → (in-)stability, halo, lifetime
- orbit → beam movement

A parameter change can do good or harm, depending on

- amplitude & sign,
- initial setting,
- beam condition (collisions or not, intensity, bunch pattern….).

One cannot classify those actions in categories 'safe' and 'unsafe' actions, because they will always belong to both categories !!!

→ it is not possible to decide a priori that some are allowed during stable beams and others not !

Machine operation crews /2

What parameters to change, by how much and when to obtain a ***positive effect*** is largely guided by practical (and past) beam experience. It :

- evolves with time (also a lot of trial and error),
- depends on the beam itself (intensity),
- depends on the optics (β*).

The speed at which such actions may be applied to the beam is limited by the available voltage of the power converter and circuit parameters (L & R) :

- The speed is NEVER faster than a failure case, but rather (<<) slower.
- The speed & amplitude of changes can easily be limited at the level of the control system (based on experience).
- Operator actions are no special issue for machine protection system, it is just another potential ‘failure’.

Machine operation crews /3

In our (machine op) learning curve, we will ‘accidentally’ :

- produce backgrounds, quenches and radiation,
- degrade the luminosity,
- loose many beams,
- etc…

This is our learning process !

Unavoidable !

Sorry for that !

The ramp and in particular the beta-squeeze are the most critical phases for us, but they are not happening during stable beams.

Note that on the long term the b-squeeze in IR8 that is foreseen to happen during a fill must become ~ transparent, or it may well be abandoned …

In any case : the machine protection system must be capable of handling the beam intensity that is in the LHC for all failure cases !

Unstable beams mode

When conditions degrade suddenly during stable beams, we may have to act very rapidly to restore conditions and/or save the beam.

- If beam conditions are too poor, the beam will be dumped by the protection system.
- But if the beam is just slightly degraded, we cannot afford to wait for minutes until movable devices are fully OUT of beam before acting.

We now propose that under such conditions :

- We change mode to unstable beams.
- This mode change signals all experiments to move out of beam and switch off.
- While movable devices move out and increase their distance to the beams, we start appropriate recovery procedures.

This gives us more chances to save beams and may also be safer for you, since we may prevent a real failure (ex. quench) by taking appropriate action on time !

Movable devices

Roman pots and VELO are clearly special as far as the distance to the beam is concerned (in stable beams) :

- 10-20σ for RPs — just behind the collimators.
- 70σ for VELO (β^* = 10 m, r = 5 mm) — behind the arc aperture !

Is there an additional risk for such devices (during stable beams) ?

Orbit bumps

A potential additional risk may arise from local orbit bumps :

- The beam is displaced locally (perturbation is limited to some hundreds of metres) using orbit correctors.

  → not seen at collimators and at position interlock BPMs.

- The speed at which the beam may be displaced is ~ 1σ / s at 7 TeV.
- Amplitudes are limited by :
  - Power converter currents.
  - Collimators around insertions (tertiary collimators).

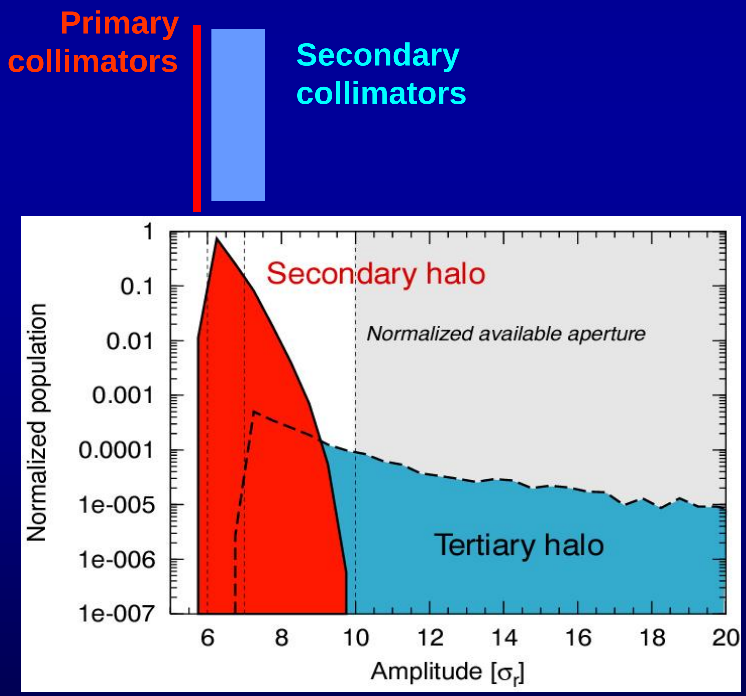
CMS and ATLAS are too far out (vac. chamber is too large) to be within reach of the beam with such local bumps.

Is it possible to 'bump' the beam into the roman pots or into VELO ?

Bumps @ RPs

For some of the roman pots the answer is a clear YES !

- It is possible to move the beam towards some RPs at ~ 1σ / s, i.e. the maximum reaction time is 10 seconds (RPs @ 10σ).
- When the beam reaches a distance of ~ 6-8σ, the RP will see a huge background increase since it starts intercepting the secondary collimator halo → alarm bell !!



→ Must be able to generate a beam dump request based on background rates on the timescale of 0.1-1.0 s.

→ Fast BLMs near or downstream of the RPs are likely to trigger on the large losses with a reaction time of ~ 2.5 ms or less.

Simulations (or practical experience) are needed here !

Bumps @ VELO /1

For VELO the answer is : very difficult and unlikely, but possible !

- The distance to the beam is *'large'*

  → our normal separation bump & crossing angle bumps cannot reach VELO.

- In the horizontal plane the crossing angle essentially prevents a large movement without hitting the triplets or tertiary collimators.

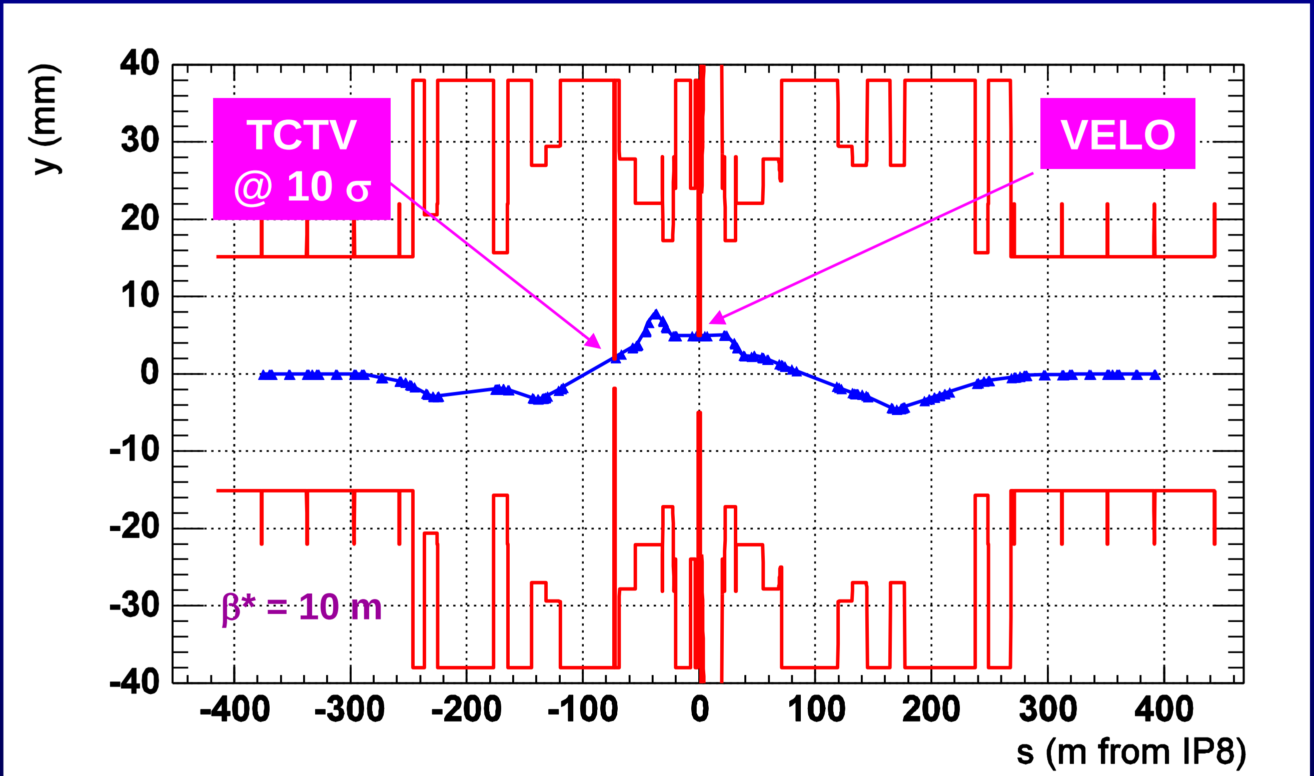
- In the vertical plane, the tertiary collimator limits the movement, but there is a set of orbit corrector settings that can almost make it to VELO (for β^* 10 m).

As an exercise I tried using all possible tricks to generate a local bump that brings the beam to the edge of VELO at 5 mm from the nominal beam axis….

Bump @ VELO /2

It is actually possible to build a vertical bump of 5 mm @ VELO, for β* = 10m.

- Corrector strengths are large but with sufficient margin (60-70% of max).
- The only object that intercepts the beam is the tertiary collimator TCTV.L8B1.

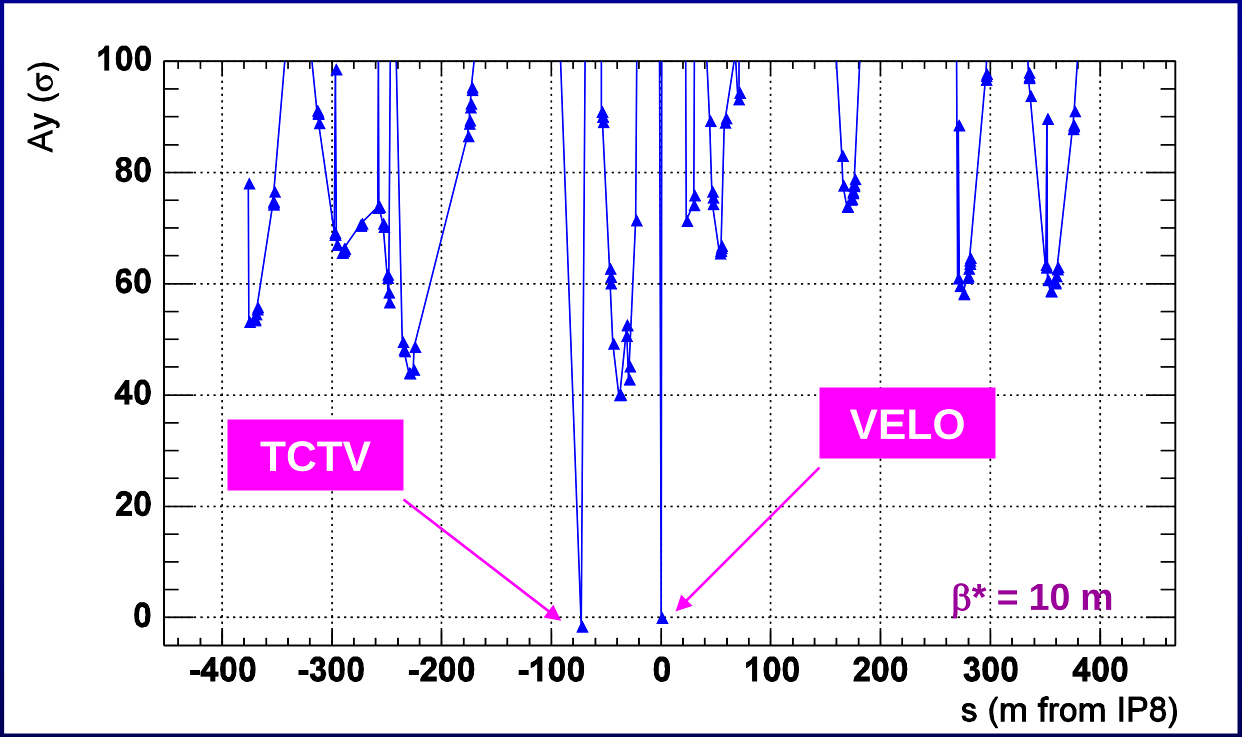


Red : vertical aperture
Blue : bumped orbit

Bump @ VELO /3

A closer look shows that the TCTV, if positioned @ 10σ, would intercept the beam before it reaches VELO.

- The TCVT would touch the beam when it is ~ 2σ away from VELO.

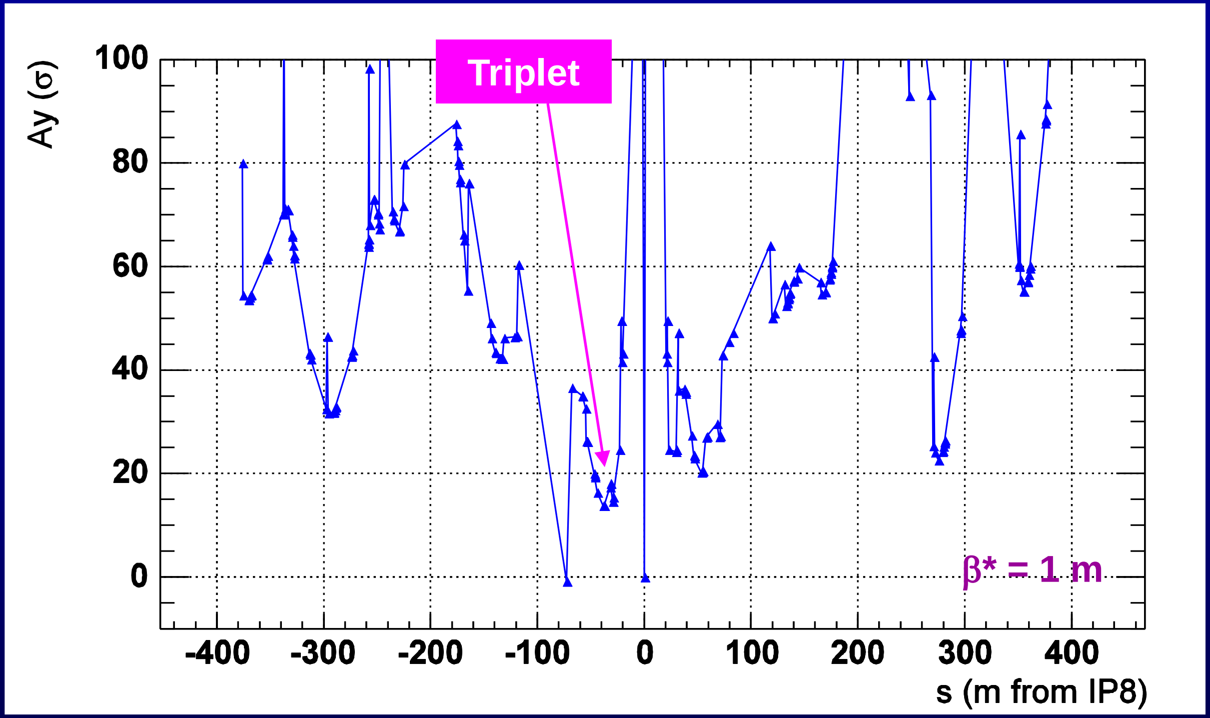


The plot shows the ~ aperture with the orbit bump around IR8 (in r.m.s. beam size).

The aperture is -2σ at the TCTV, indicating that the bump cannot be applied fully without intercepting the TCTV.

Bump @ VELO / 4

For a β* of 1 m, one can again build a bump, but apertures start to become tighter, and the strength of the correctors approach their maximal values.



Note that for this aperture evaluation, only a misalignment of 2 mm has been taken into account. In reality the triplet apertures may be smaller, but not sufficiently to protect VELO.

Bump @ VELO /5

It must be noted that :

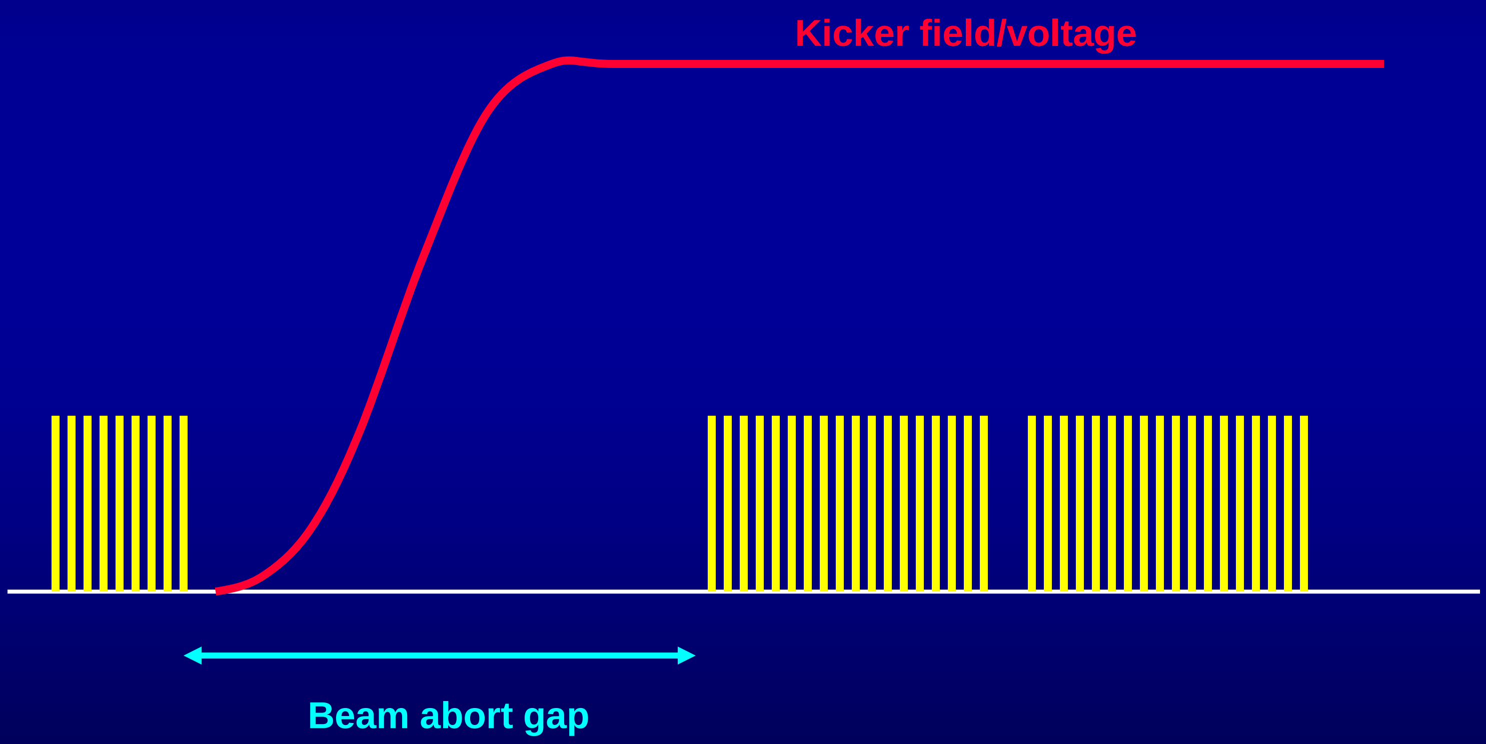
- This is a very complicated orbit bump, that is <u>not USED and not NEEDED</u> in operation, where we only have to move the beams around by say ~ 100-500 μm.
- The beam would approach VELO at ~ 1 σ/second.
- Concerning background increase and protection, the situation is similar to the case of the RPs :
  - When the beam reaches a distance of ~ 6-8σ → huge background increase.
  - Need a reaction (dump request) within 0.1 to 1 second.

Simple measures can be implemented to prevent moving the beams by excessive amounts with such kinds of bumps :

- The maximum strength changes of correctors can easily be limited in stable beams since only small changes are required for beam stabilization.
- The strength changes can easily be surveyed at 1 Hz by a software interlock.
- …

Beam dump

The LHC bunch structure contains a 3 μs long particle free beam abort gap to allow the LHC dump kickers to raise their field to the correct strength for extraction.



Beam dump

If

- the abort gap contains beam,

or

- the synchronisation of the kicker with the abort gap is not correct,

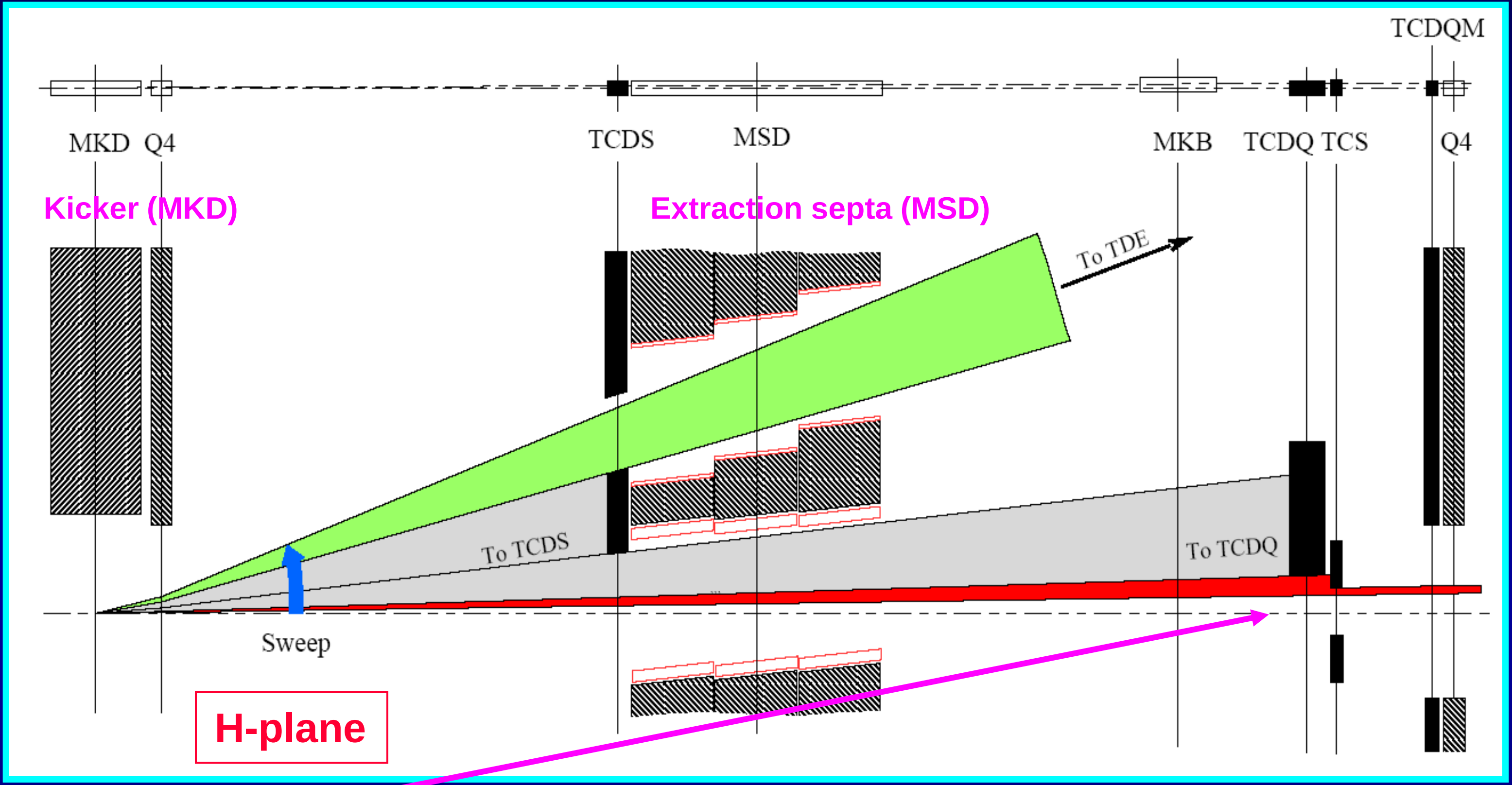
or

- one of the kickers pre-fires (spontaneously), [expected rate ~ 1 / year]

then particles will be swept over all amplitudes due to the rising kicker voltage.
The last case arises because the kickers are always charged and ready to fire !

How do we protect ourselves against such failures ?

Dump sweep protection



The TCDQ absorber downstream of the dump kickers will be positioned to protect machine elements / apertures from the dump sweep. The TCDQ will be positioned at to shadow the apertures (not the collimators !) → distance of ≈8-10σ during most operational phases.

Dump sweep risks

VELO :

- The distance to the beam is ~ *70* σ

→ *protected by TCDQ, arc aperture, tertiary collimators (TCTs)*

Roman pots :

- The distance to the beams may be as low as ~ 10σ .

→ *position of the TCDQ is critical.*

CMS, ATLAS :

- The triplet aperture is the limit with ~9σ.

→ *protected by TCDQ & TCTs.*

Without TCDQ/TCTs some beam hits the triplets…

Summary /1

- The machine protection system is designed to protect ALL LHC equipment, including of course the detectors against damage due to un-controlled release of energy from the magnets or the beam.

- The system is designed to cope with the worse failures, whether they occur in stable beams or not.

- The actions of operators, even in stable beams, will never be as fast and dangerous as the worst equipment (mostly powering) failures.

- An interlock signal to dump the beam in case of abrupt (and dangerous) increases of background, as proposed in the specification on experiments interlocking, is recommended to complement the machine interlock systems, in particular for the devices that move close to the beams.

Summary /2

- Being so close to the beam, roman pots can easily by approached using controlled local orbit distortions (bumps) - need appropriate interlock signal on rates… to request a beam dump.
- VELO cannot be easily approached with the beam even in data taking position, even though it is theoretically possible. Simple preventive measures can be implemented to minimize any remaining risk.