Circulating Beam Failures
and the risk for the experiments

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Outline

- Introduction
- Linear perturbations
- Failure scenarios
- Time response of the protection systems
- Simulations and results
- Non simulated scenarios
- Conclusions

Introduction

Irregularities during the operation of LHC are very likely to affect the beam behaviour.

Losses are produced by failures affecting the transverse optics of the beam (increase of the transverse distribution or displacement of the beam transverse position): ***magnet failures***.

Relevant parameters for the protection of the experimets are:

- ***The location of the losses:*** will the beam hit an experimental device in case of failure?
- ***The speed of the losses:*** will the LHC Protection Systems be able to extract the beam on time?

Linear perturbations

For fast failures, only linear effects are responsible of the losses: dipole and quadrupole failures

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

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

Quadrupole: beta beating all around the ring (defocusing) and tune shift

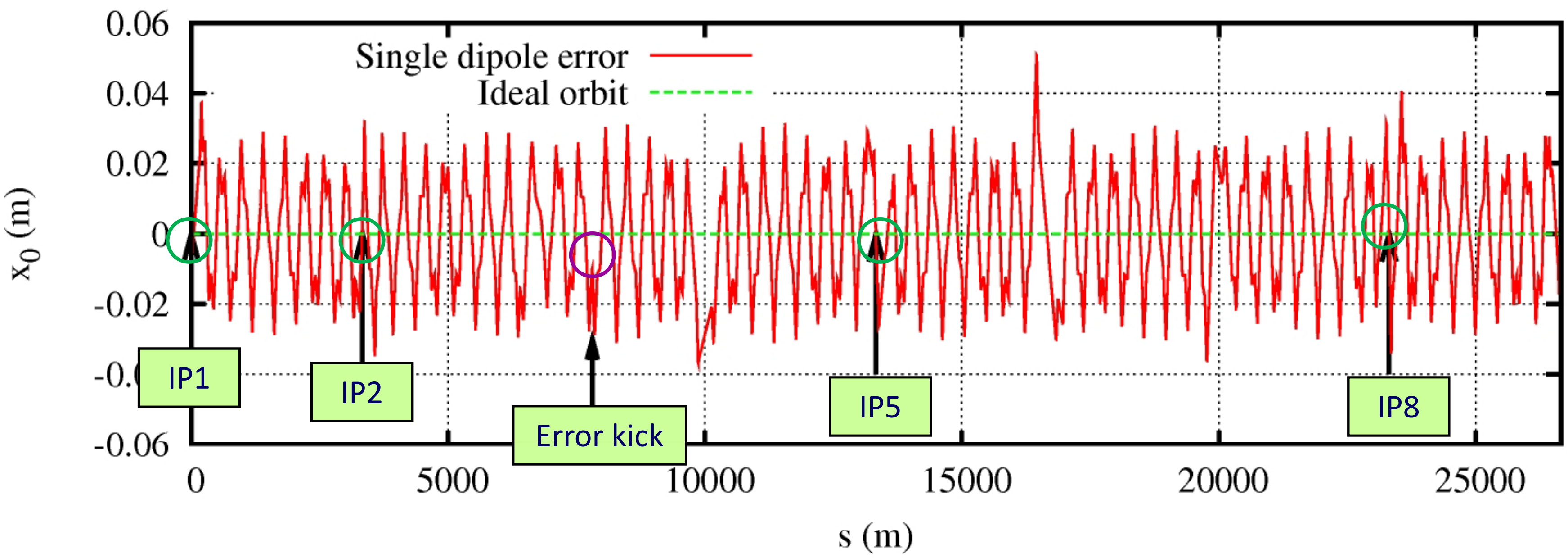
$$\frac{\Delta\beta}{\beta_s} = \frac{\Delta kl}{2\sin(2\pi Q)} \sum_{j=1}^{n} \beta_j \cos(\psi(s) - \psi_j + \pi Q)$$

$$\Delta Q = \frac{\Delta kl}{4\pi} \sum_{j=1}^{n} \beta_j$$

Linear perturbations

The perturbations have an effect in **all** positions in the ring.

Example: single error kick



The local effect is proportional to the betatron amplitude (or its square root) which is much smaller in the IPs than in the collimation sections (10 or 0.55 m compared to about 300 m) -> Good news!

Magnet failures

Magnet failures are characterized by a change in the magnetic field.

The change in the field is assumed proportional to the current in the circuit with the failing magnet (or magnets).

We consider 3 magnet failure scenarios:

- ***Quench:*** only for superconducting magnets
- ***Power converter failure:*** only relevant for normal conducting magnets (high time constants for SC magnets)
- ***Operational failures:*** failures in the control systems or operational mistakes. Cover a large range of possible scenarios.

Losses could also be generated by movable objects going into the beam

Scenario #1: Quench

Quenches are the most expected magnet failure during the operation of LHC

For the simulations, the current decay has been simply modeled by a Gaussian with:

σ_c = 200 ms at 7 TeV

σ_i = 2000 ms at 450 GeV

Failures due to quenches at injection (450 GeV) produce slow losses.

This model is a simple approach, still considered a good estimation.

Scenario #2: PC failure

A Power Converter can deliver a wrong voltage by mistake.

Current decay considered exponential:

- Simple RL model
- Output stage of the PC and other effects shown to have little relevance.

Possible wrong voltages

- ***0V:*** most probable. Produces fast failures only at collision.
- V_{max}***:*** maximum possible voltage difference with respect to the nominal voltage. Produces fast failures at injection.

Scenario #3: Operational failure

Large range of possible failures:

- Operator mistakes
- Failures in the control systems (wrong generation or transmission of control signals, closed orbit feedback control, etc)
- Failures in the BPMs affecting the closed orbit control input

Most of them can be assimilated to the cases studied

- They are slow
- Their effects can be observed in every location of the ring

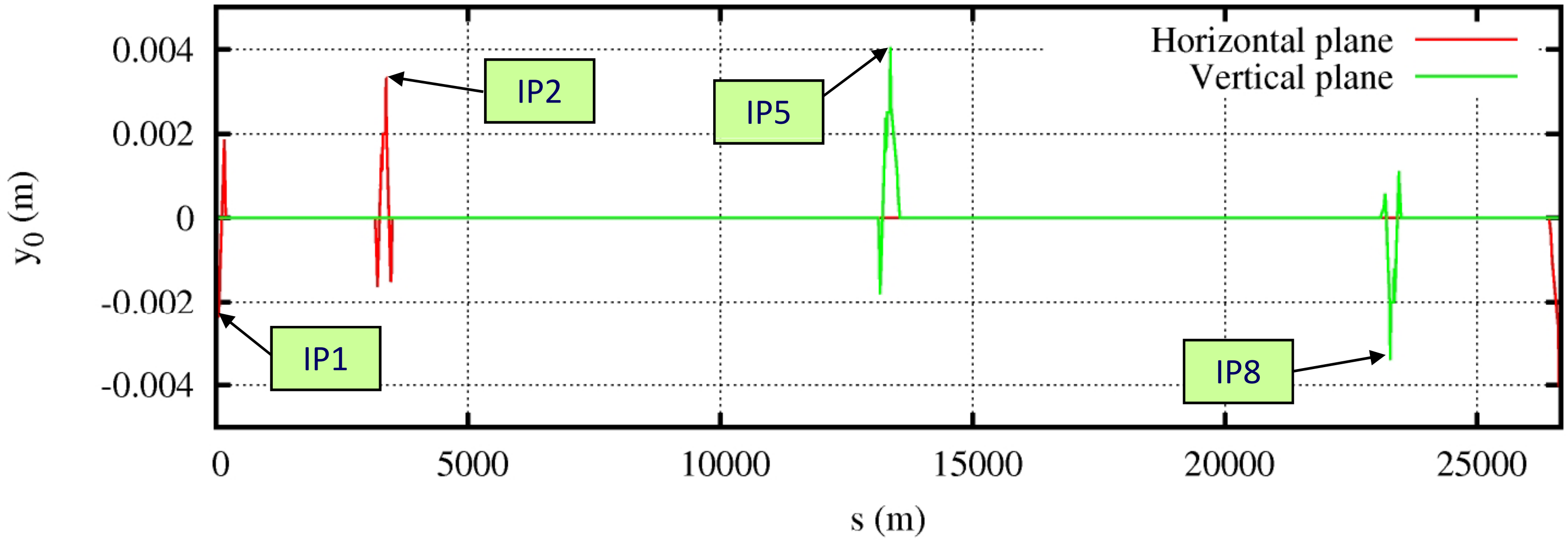
Except …

Closed bumps

Can be generated by wrong settings in the corrector magnets:

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

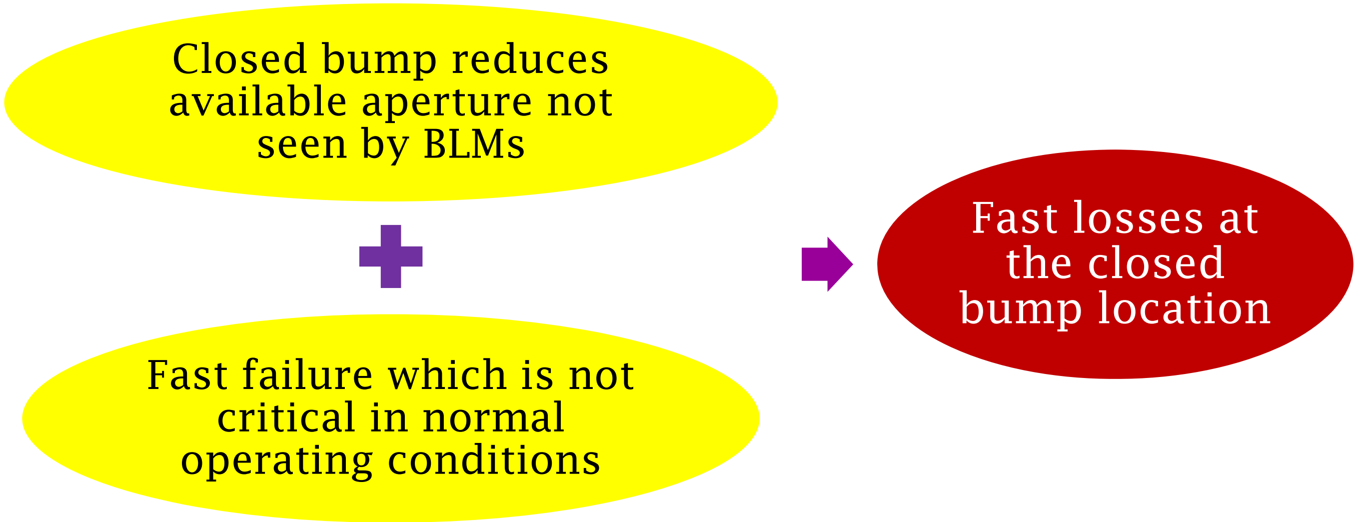
Example: separation closed bumps at injection (not a failure!!)



Uncontrolled closed bumps could affect only experimental areas but they build up slowly: first losses seen by the BLMs and beam extraction before damage threshold

Scenario #3: Closed bumps

Possible critical situation:



Need of two combined failures -> very low probability

Example: possible hit of the VELO (IP8) at injection if it is closed with a separation bump and a failure happens (more on this later)

Scenario #4: Movable object

Some objects (collimators, roman pots, vacuum valves…) could accidentally be moved into the beam pipe during the operation of LHC

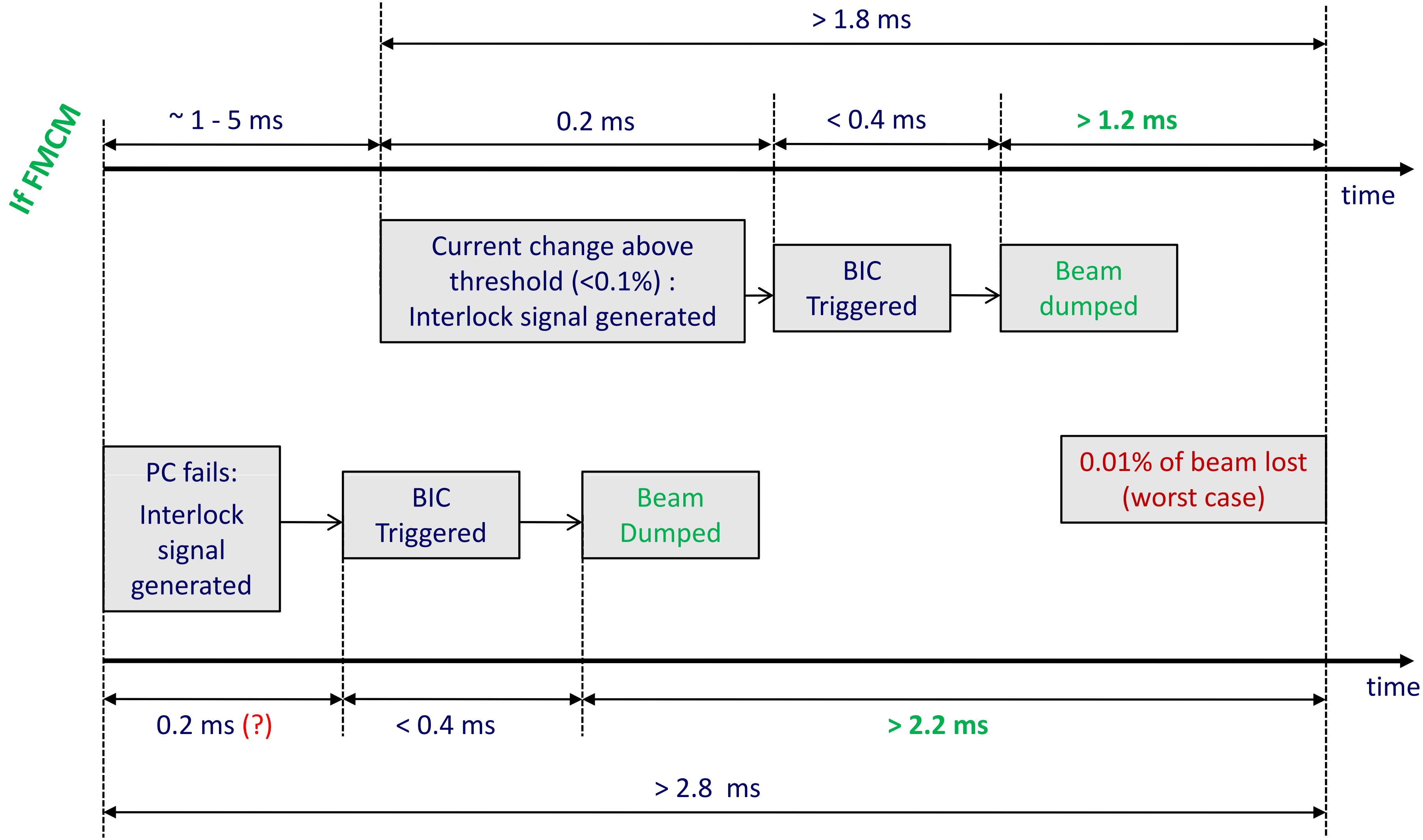
Beam losses due to scattered particles

The mechanical movement is slow compared to the time scale of the previous failure scenarios -> always captured by BLMs

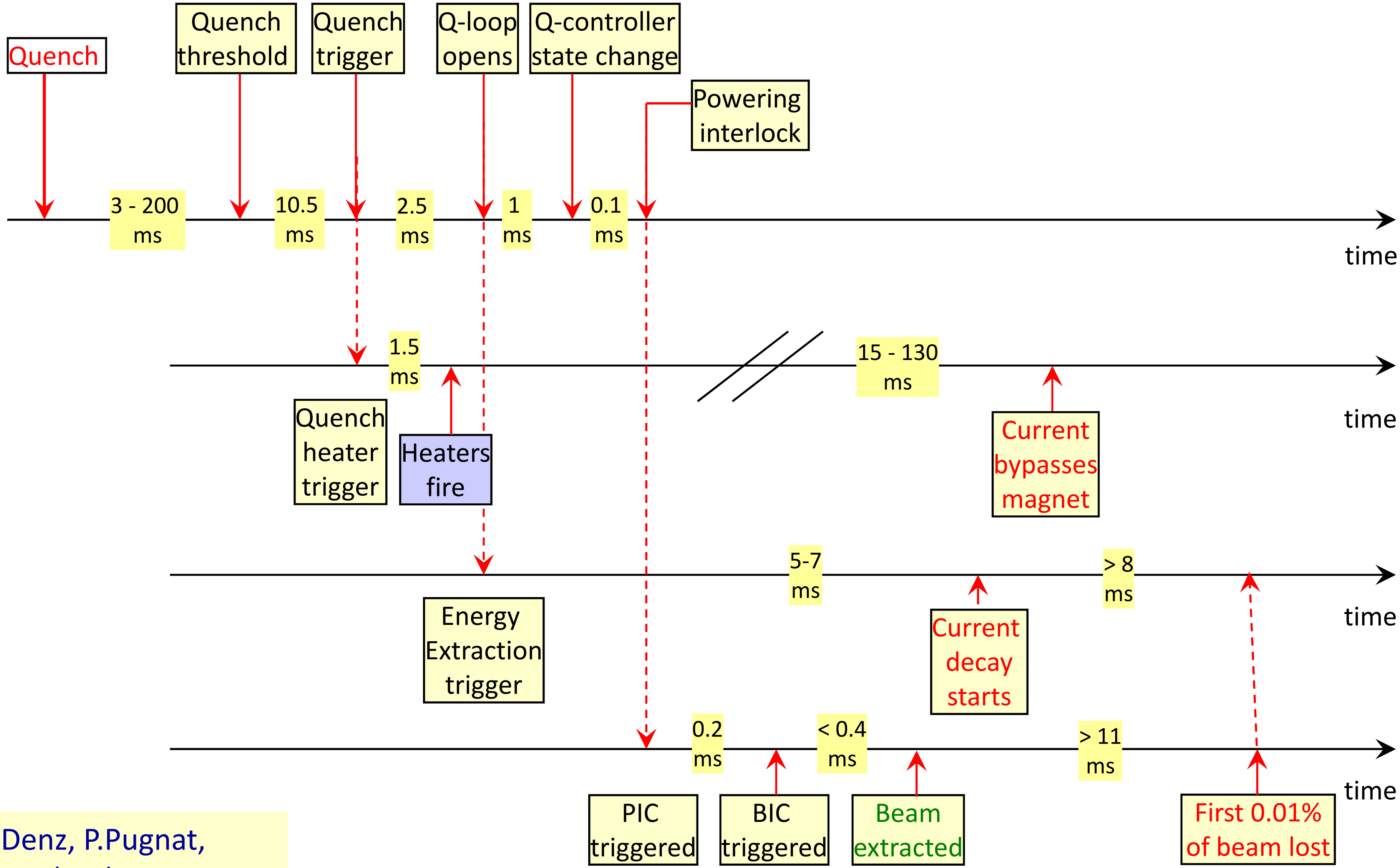
All these objects are interlocked

Response to powering failures

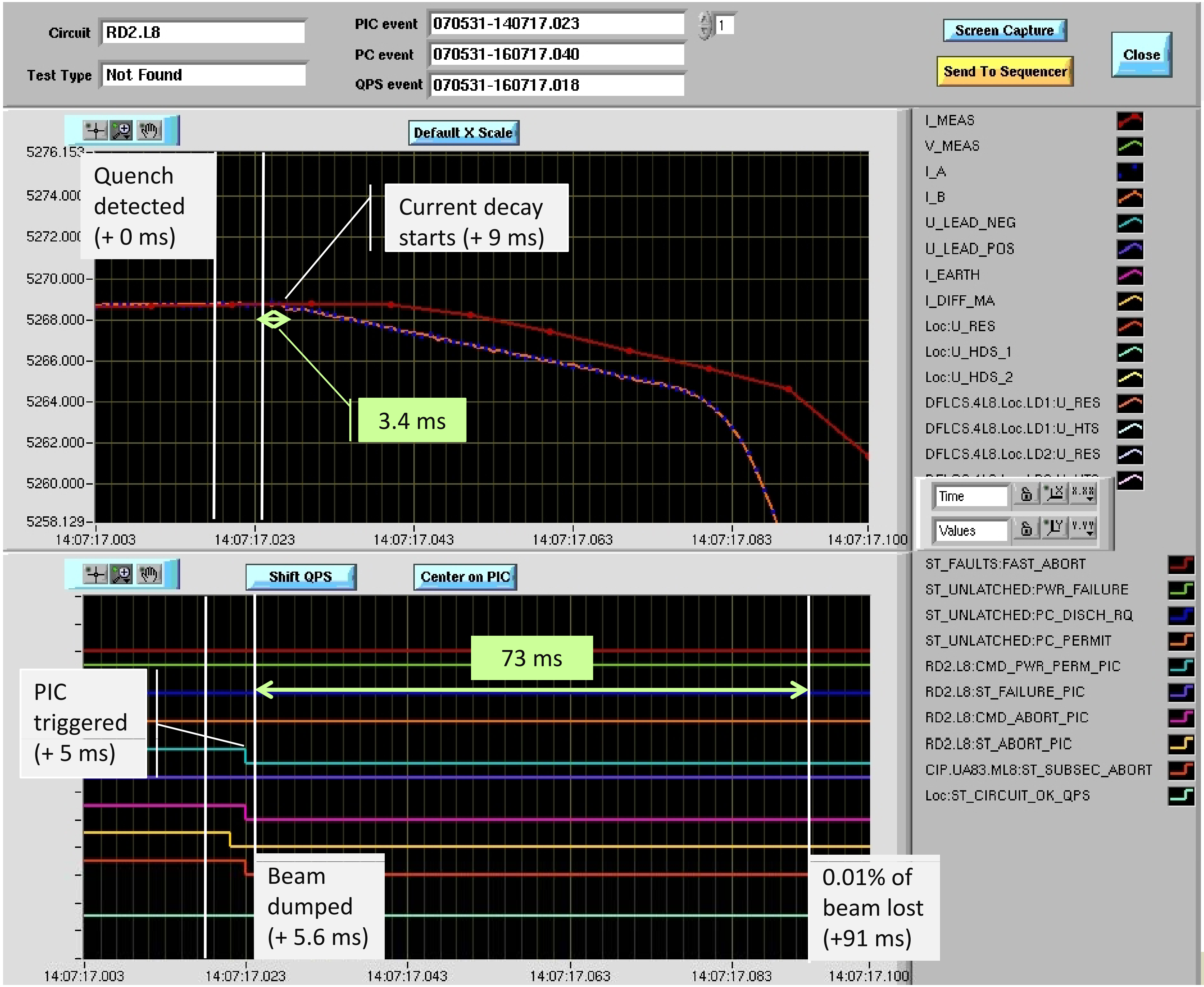
In the warm magnets: Fast Magnet Current change Monitors (FMCMs) added for redundancy at circuits producing fast failures



Response to Quenches



R.Denz, P.Pugnat, M.Zerlauth


Circuit RD2.L8
Test Type Not Found
PIC event 070531-140717.023
PC event 070531-160717.040
QPS event 070531-160717.018
Screen Capture
Send To Sequencer
Close
Default X Scale
Quench detected (+ 0 ms)
Current decay starts (+ 9 ms)
3.4 ms
5276.153
5274.000
5272.000
5270.000
5268.000
5266.000
5264.000
5262.000
5260.000
5258.129
14:07:17.003
14:07:17.023
14:07:17.043
14:07:17.063
14:07:17.083
14:07:17.100
I_MEAS
V_MEAS
I_A
I_B
U_LEAD_NEG
U_LEAD_POS
I_EARTH
I_DIFF_MA
Loc:U_RES
Loc:U_HDS_1
Loc:U_HDS_2
DFLCS.4L8.Loc.LD1:U_RES
DFLCS.4L8.Loc.LD1:U_HTS
DFLCS.4L8.Loc.LD2:U_RES
Time
Values
Shift QPS
Center on PIC
73 ms
PIC triggered (+ 5 ms)
Beam dumped (+ 5.6 ms)
0.01% of beam lost (+91 ms)
ST_FAULTS:FAST_ABORT
ST_UNLATCHED:PWR_FAILURE
ST_UNLATCHED:PC_DISCH_RQ
ST_UNLATCHED:PC_PERMIT
RD2.L8:CMD_PWR_PERM_PIC
RD2.L8:ST_FAILURE_PIC
RD2.L8:CMD_ABORT_PIC
RD2.L8:ST_ABORT_PIC
CIP.UA83.ML8:ST_SUBSEC_ABORT
Loc:ST_CIRCUIT_OK_QPS

Times for Machine Protection

Quench:

- Minimum margin of **11 ms** between beam dump and damage level
- Minimum margin of **3 ms** between beam dumped and current decay (no effect on the beam)

Powering failure:

- Minimum margin of **2.2 ms** between the beam dump and the damage level

Redundancy:

- **BLMs:** For any kind of losses. Should be able to dump the beam within less than **0.4 ms** after losses above threshold detected (minimum possible threshold of ~2 10^{-4} of the beam at 450 GeV and ~2 10^{-7} at 7 TeV)
- **FMCMs:** For fastest failures (warm dipoles an quadrupoles at IR1, IR5, IR3, IR7): BLMs not fast enough. Minimum margin of **1.2 ms** between beam dump and damage level

Simulation parameters

Simulations made for nominal collision and injection optics

Fastest failures (Magnets in the IRs and quenches in the arcs)

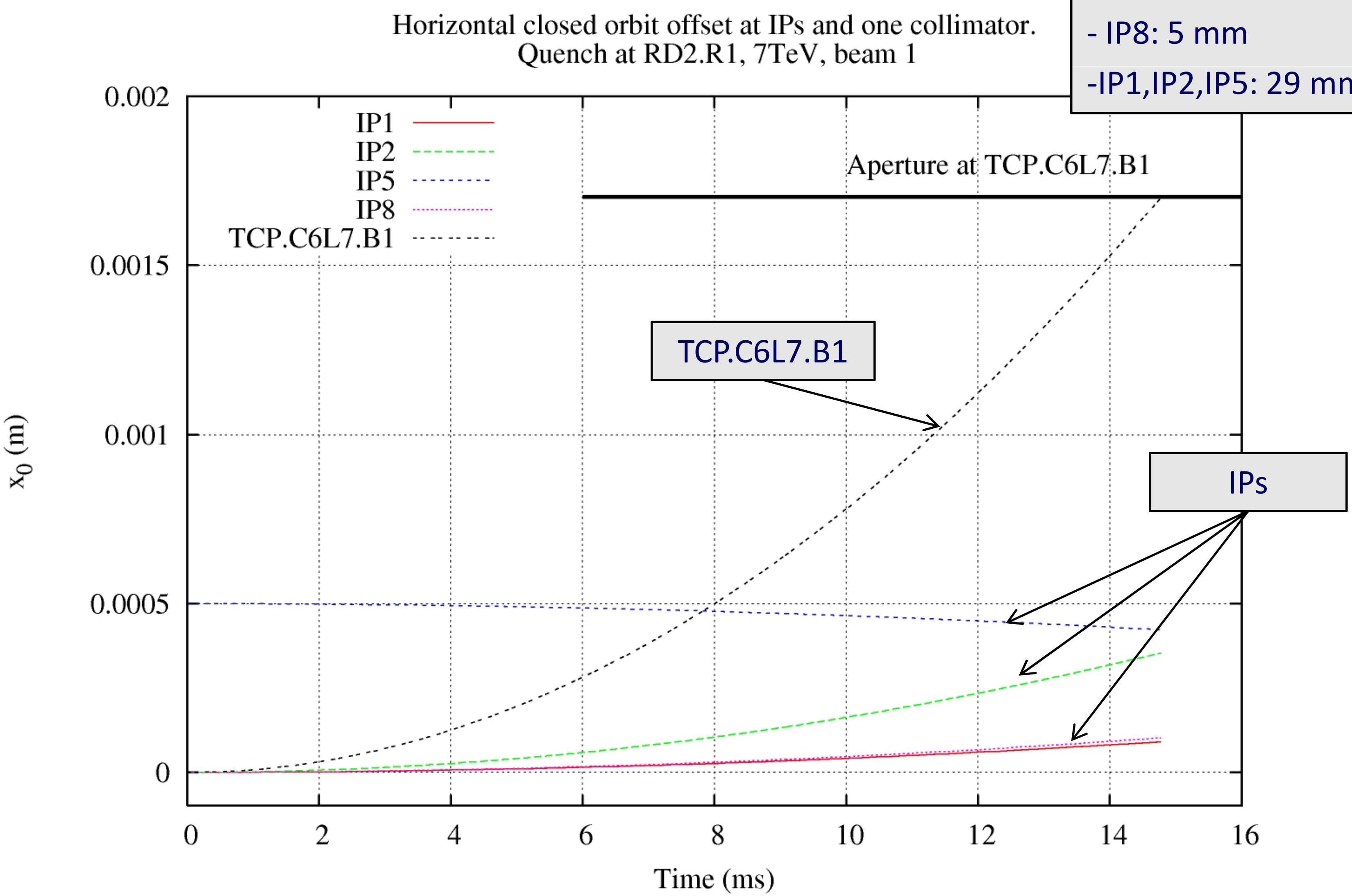
The location of the first impact of the particles is recorded. Scattered particles are not tracked.

	Injection (450 GeV)	*Collision (7 TeV)*
on_sep1	1	0 or 1
on_sep2	1	0 or 1
on_sep5	1	0 or 1
on_sep8	1	0 or 1
on_x1	1	1
on_x2	1	1
on_x5	1	1
on_x8	1	1
on_alice	1	1
on_lhcb	1	1
β^*_1	17 m	0.55 m
β^*_2	10 m	10 m
β^*_5	17 m	0.55 m
β^*_8	10 m	10 m

Results (I)

Example: quench of D2 at IR1, 7 TeV

Apertures:
- Collimator: 1.7 mm
- IP8: 5 mm
- IP1,IP2,IP5: 29 mm



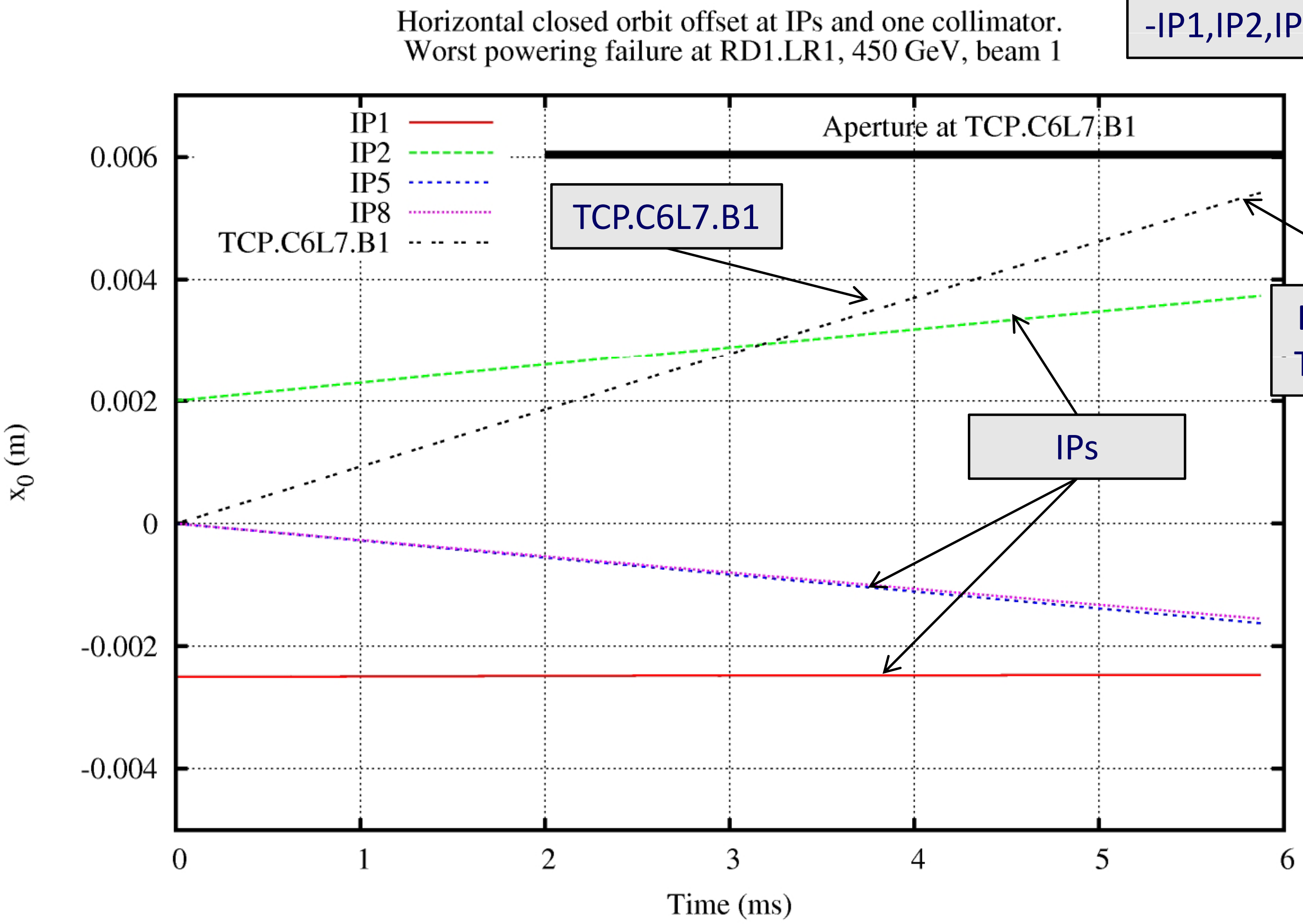
Results (II)

Example: Worst powering failure at D1, IR1. 450 GeV

Apertures:

-Collimator: 6.03 mm

-IP1,IP2,IP5, IP8: 29 mm

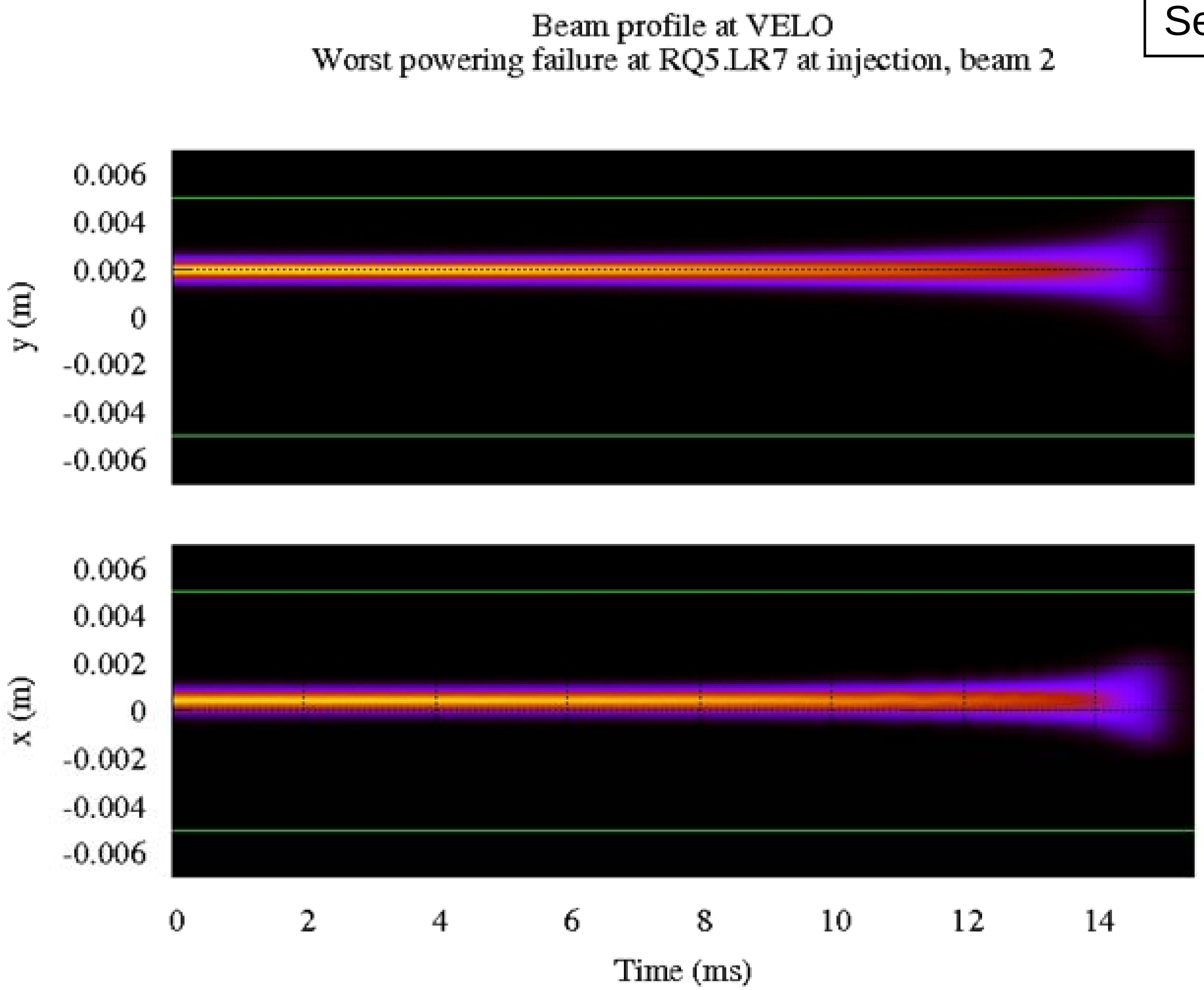


Losses at IP8 (Hypothetical!)

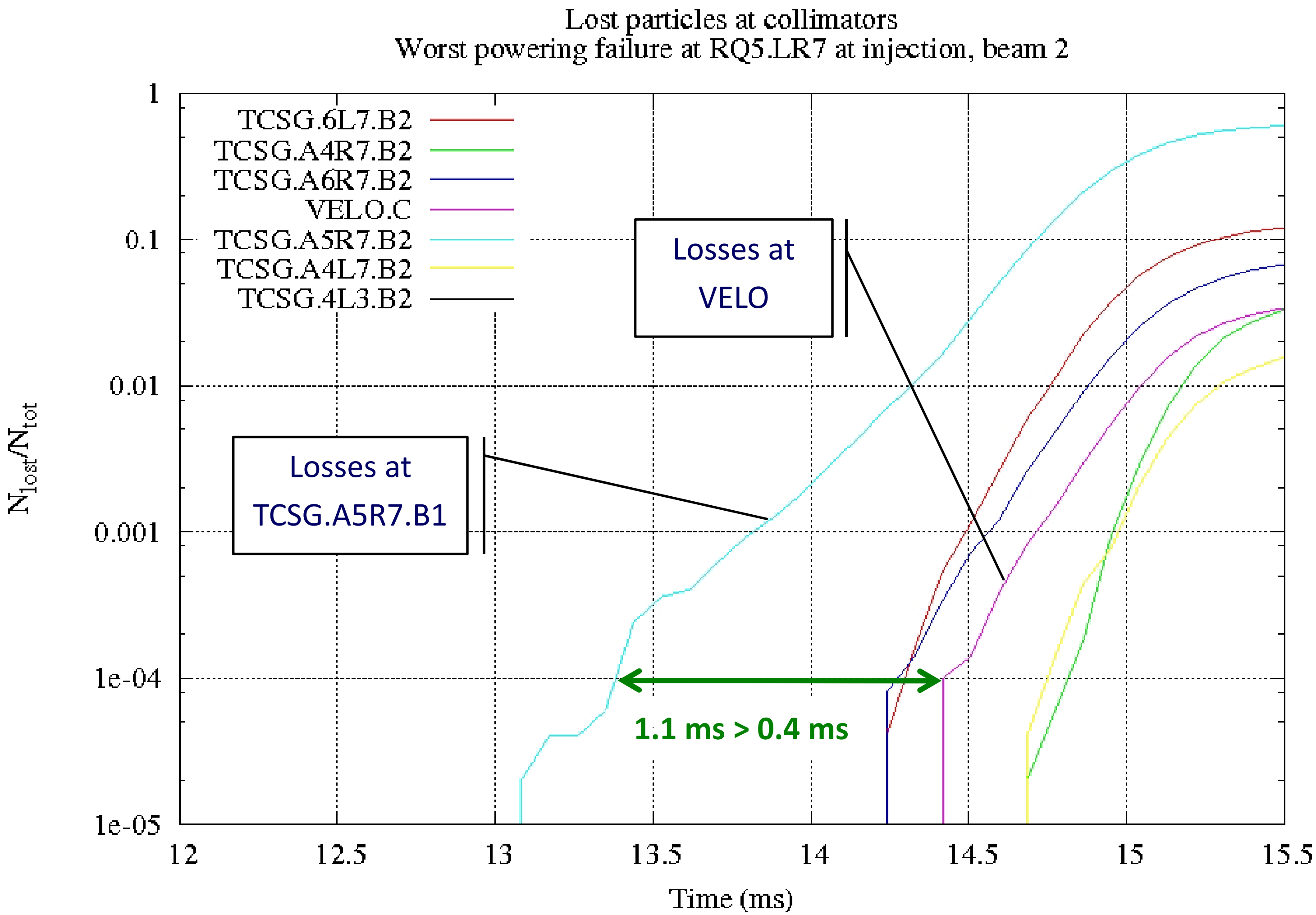
Only case where losses where recorded at an IP.

IP8 with VELO closed, injection (separation bump) + failure

450 GeV
β^* = 10 m
Crossing angle on
Separation bump on



Time constant of losses



Non simulated scenarios

The number of imaginable failures is huge. Priority to

- Failures producing fast losses
- Failures that are more probable
- Failures of possible risk for the experiments

Were not simulated:

- All possible failures of the same kind (phase differences)
- Failures that do not produce significant losses before 50 ms
- All the possible modes of operation

However…

- The worst cases have been considered
- Slower failures are not problematic for the protection systems

Conclusions

Location of failure induced losses

- First impacts always in a collimator for normal operating conditions
- Only an uncontrolled closed bump could lead to losses in the experimental areas
- If the VELO is closed with a separation bump in IP8, some failures could lead to losses in the detector -> **interlock needed**

Speed of the losses

- Fastest failures lead to the total beam lost in less than 10 ms
- Redundancy of the protection systems

Possible issue: unnoticed closed bump + failure