Crab Protection @ LHC

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Outline

MPS @ LHC Overview

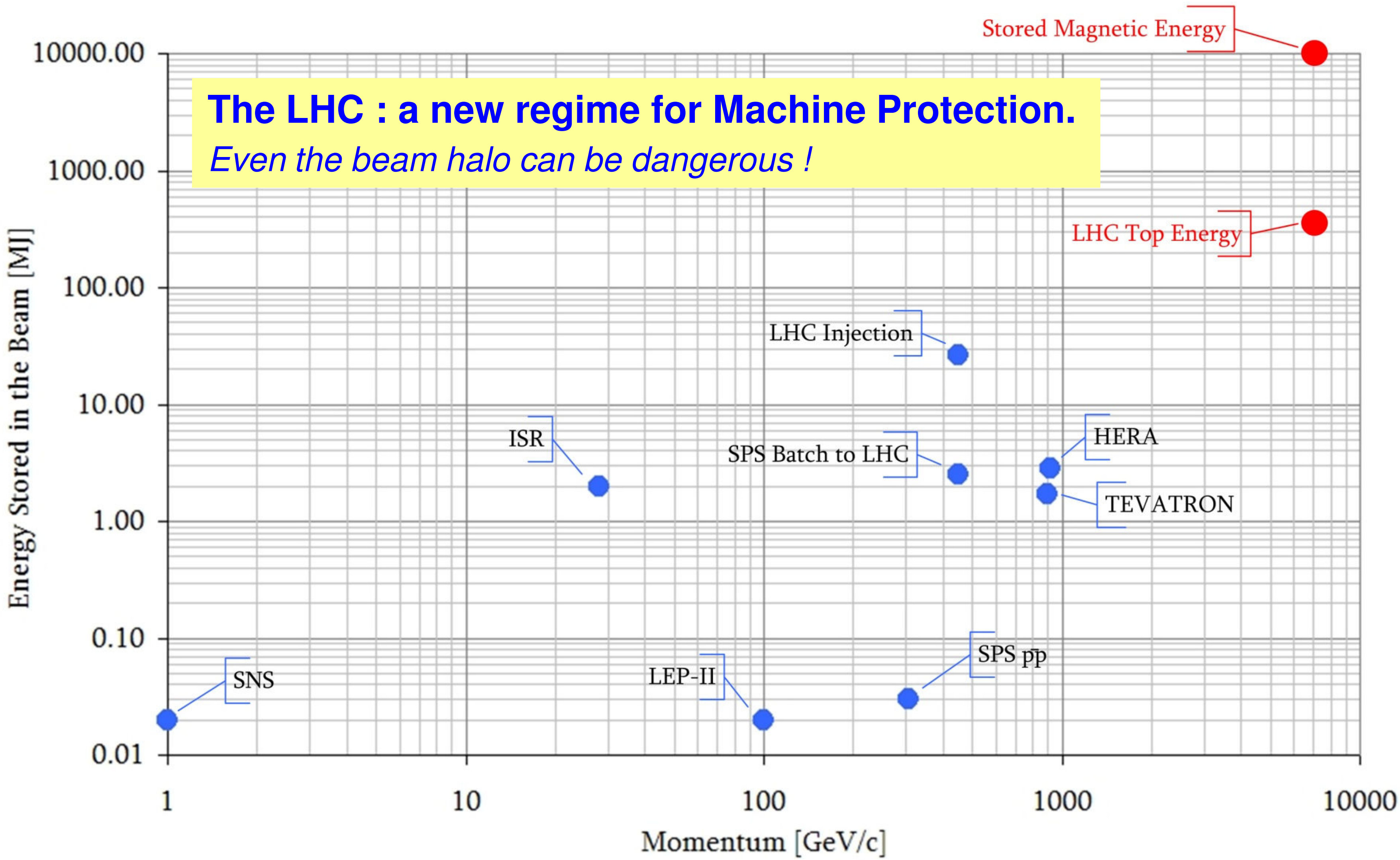
Failures and LHC Protection

Conclusions

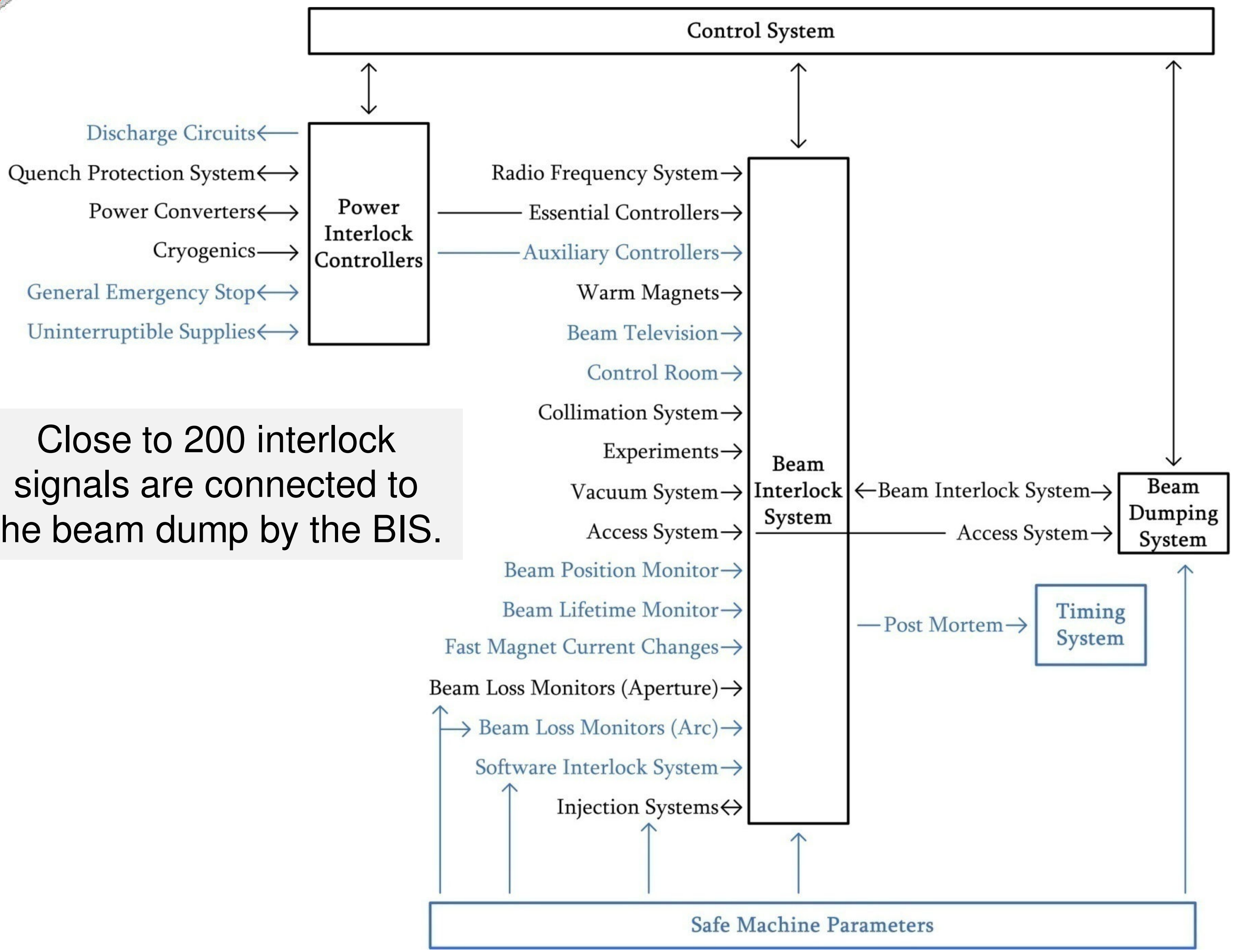
Stored Energies

The LHC : a new regime for Machine Protection.

Even the beam halo can be dangerous !



Beam Interlock System

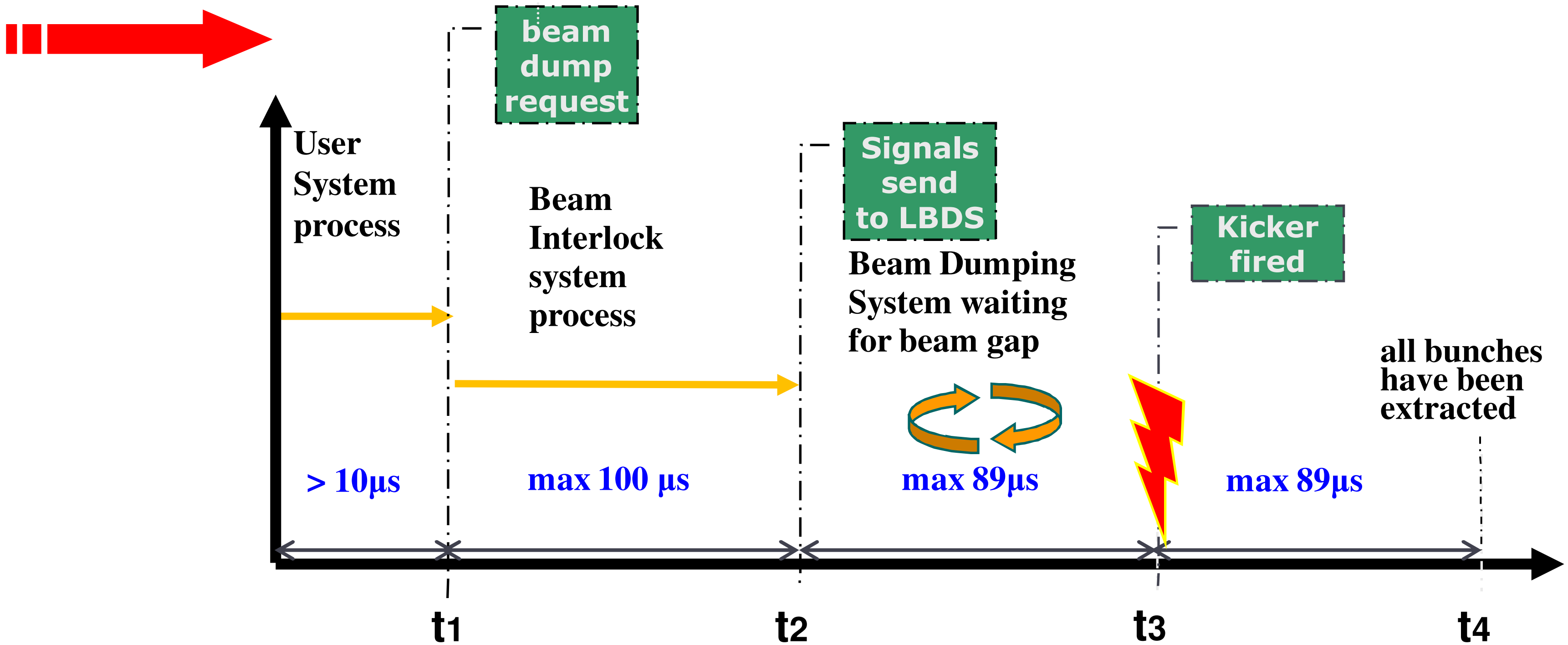


Close to 200 interlock signals are connected to the beam dump by the BIS.

Dump Delays

USER_PERMIT signal changes from *TRUE* to *FALSE*

a failure has been detected…



Achievable response time ranges between 100 µs and 270 µs.

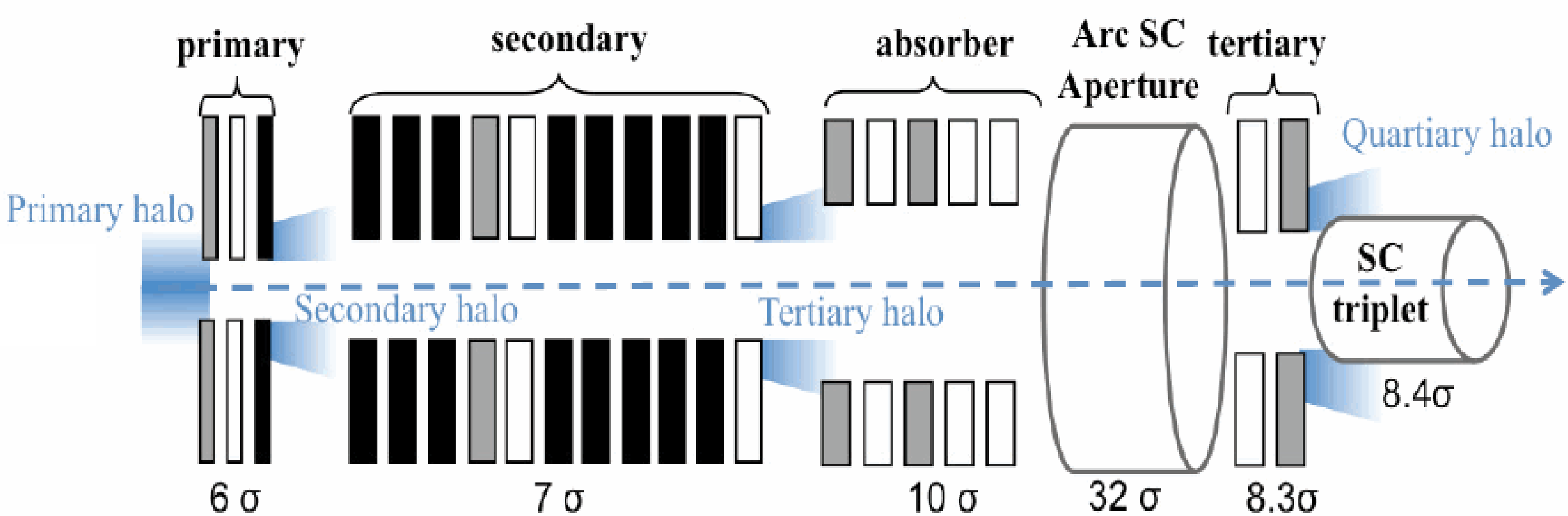
>> Triggering a dump is not the end of the story,

must be able to survive up to another <u>3 turns</u>.

MPS & Collimation

Although the primary design goal of the collimators is beam cleaning, they also play an essential role for MP.

- Collimators define the machine aperture.
- The large majority of failures leads to a primary particle impact at one of the collimators.
  - BLMs downstream of collimators are critical for failure detection.
  - Collimators are robust to survive limited beam impact.



Courtesy C. Bracco

Failure Categories

- Single turn (single-passage) beam loss (ns -µs)
  - Failures of kicker magnets (injection, extraction…).
  - Transfer failures between two accelerators or from an accelerator to a target station.

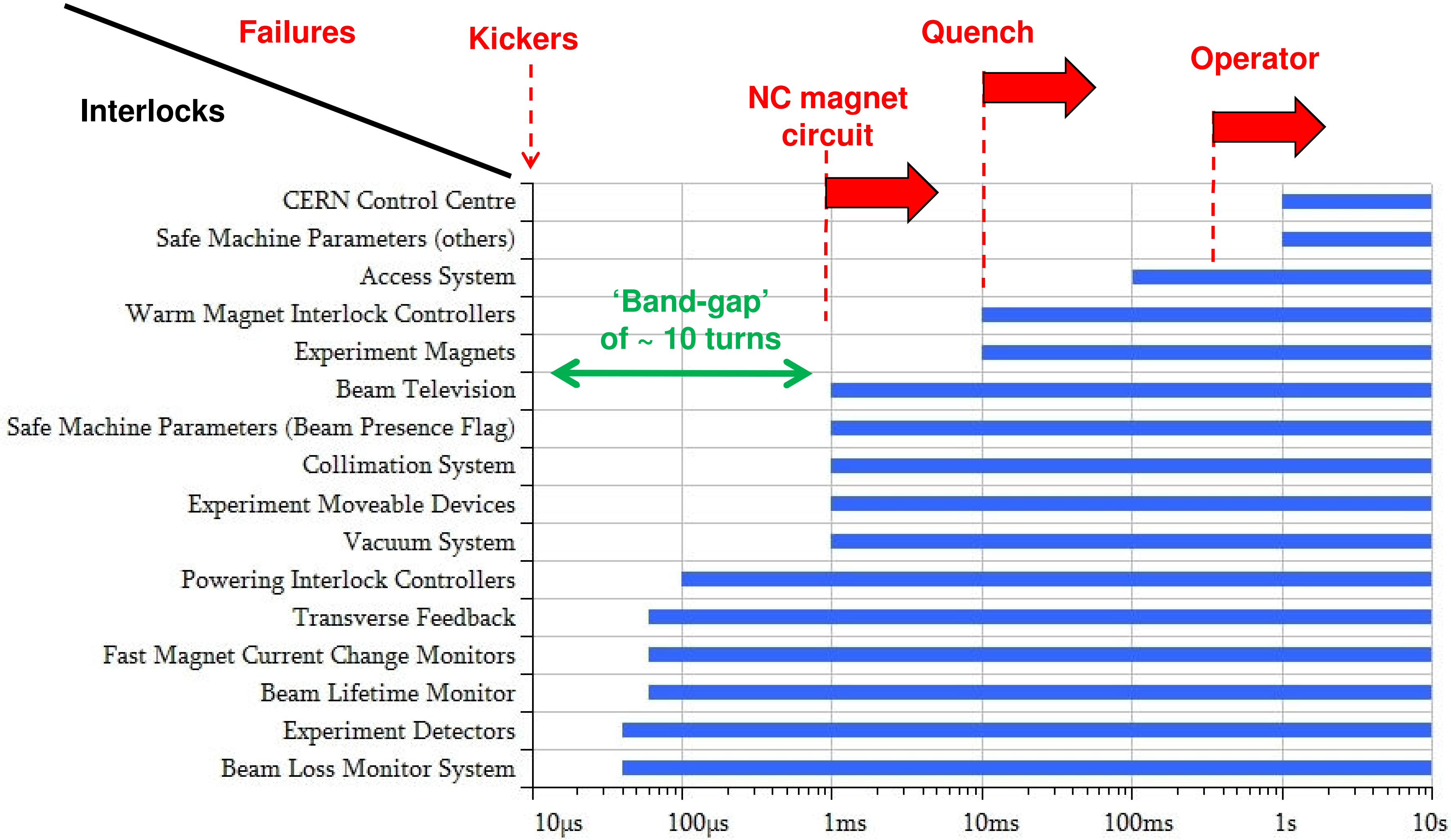
High reliability design

Passive protection

- Very fast beam loss (ms)
  - Multi turn beam losses in circular accelerators.
  - Large variety of possible failures, mostly in the magnet powering system, with a typical time constant of some 10 turns to many seconds
- Fast beam loss (some 10 ms to seconds)
- Slow beam loss (many seconds)

Active protection

Times Scales



Best failure detection time = 40 us = half turn

Protection : Crabs - LHC

Two protection aspects:

- Protection of the LHC against uncontrolled beam loss induced by the Crab schema.
- (Self-) Protection of the cavities.

A proper analysis of the MP aspects would require information on the cavities and simulations that I do not have.

Therefore this is only a first glimpse at the issues – to first order I'm more concerned with protection of the LHC.

Protection of Cavities

- Many issues that I do not know about and that have to be addressed…

- Picked up from some presentations : beam stability requirements of < 0.2 mm and interlocks on power.

  - Interlock based on a BPM with a tolerance of 0.2 mm requires a ‘super-rock-solid’ bunch length and intensity insensitive BPM acquisition.
    - Tricky with the present BPM system. BI to jump in.
    - Very (too?) harsh constraint for operation (IR1 and IR5).

  - Direct interlock on power output would be recommended if feasible.

Protection of the LHC

Two ingredients are needed to analyze failure scenarios induced by the Crab schema:

- The ‘amplitudes’ (beam excursions)
- The time constants

Since there are many open points, this presentation outlines only the most evident issue –thorough follow-up study needed.

Only damage issues are considered, not quenches.

Particle Excursions

- Global crab (test) : $\beta^* = 0.55$ m, $\theta_C = 0.3$ mrad
  - Crab excursions extend over entire ring.
  - Crab excursions must be compatible with collimation.

$$\Delta\hat{x}[\sigma_x] \cong 0.6\,\Delta s[\sigma_s] \;\Longrightarrow\; |\,\Delta\hat{x}_{\max}\,| \cong 1.2\,\sigma_x$$

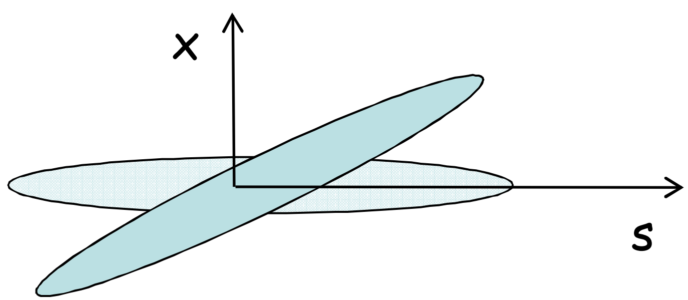
Assuming a full length of $\pm 2\ \sigma_s$

- Local crabs : SLHC-I, $\beta^* = 0.25$ m, $\theta_C = 0.4$ mrad
  - Nominal crab excursions only local around IR1 & IR5.
  - Collimation does not see the crab when cavities are at nominal setting.

$$\Delta\hat{x}[\sigma_x] \cong 1.2\,\Delta s[\sigma_s] \;\Longrightarrow\; |\,\Delta\hat{x}_{\max}\,| \cong 2.5\,\sigma_x$$

Assuming a full length of $\pm 2\ \sigma_s$

Even larger excursions for more extreme θ_c…



Failure Time Constants

Possible failure modes:

- Cavity trips.
- Cavity phase changes or jumps.
- ‘Controlled’ cavity voltage changes.
- …

From a discussion with J. Tückmantel, it seems that the those failures or changes may occur over time scales of **less than 1 LHC turn**.

If confirmed, this could make protection against Crab cavity failures very difficult.

Global Crab Failure Scenarios

With global crab the ‘perturbation’ (which also the desired effect) is present everywhere in the ring:

- A failure (trip, phase…) will redistribute or eliminate the perturbation.
- Particles are not pushed to significantly larger amplitudes around collimators etc, therefore no excessive risk.
- Transitions due to failures may however require to dump to beam.
- Resonant effects when the tunes reach the integer could be an issue (OP error, circuit failures), but most likely the beam loss will be dominated by other effects.

>> At first sight not a major issue,
to be confirmed by a more thorough analysis.

Local Crab Failure Scenarios

With the local crab schema the ‘perturbations’ should be invisible outside IR1 and IR5.

- A failure (trip) of one cavity could push a good part of the last 2-3 sigma of beam halo into the collimators.
- A counter-phased cavity could push a good part of the whole beam (peak excursions of ~5 σ-ish) into the collimators (and maybe other elements), assuming collimators are at 6 sigma.

  Also a risk for the triplets? And the triplet protection?...
- …

If the timescales are confirmed to be around 1 turn, those would be among the worst failures at the LHC – high risk of damage.

Failure Mitigation

Possible counter-measures:

- Very fast (< 1 turn) failure detection for cavity trips.
  - Good but not sufficient !
- Very fast ‘phase change interlock’.
  - Allow only slow phase changes. Sufficient for all cases?
- Cavity response must be ‘slowed down’ to ≥ a few turns (Qext..).
  - First order recommendation: ≥ 6 turns.
- Splitting the system into multiple independent sub-units (cavities), such that single cavity failure is ‘OK’.
  - Space? Impedance? Cost?
  - Watch out for common cause failures of multiple cavities.
- Local absorbers?
- …

The response time is the most critical point, due to dump delay of up to 3 turns.

Conclusion

- The global crab schema seems manageable with the present LHC MPS. To be confirmed.
- The local crab schema may present a considerable risk to the LHC, and in particular for collimators.
  - Combination of very fast time constants and large amplitudes lead to severe failures.
  - Correlation between crab schema luminosity gain and risk.
- Key factor for MP is the time constant: essential to ensure that failures take many turns to develop.
  - Alternative is splitting into many ‘safer’ components.
- Details depend on the upgrade route (β^*, crossing angle…) and must be worked out.
- MP is critical at the LHC: don’t wait until the last second to address MP issues !