Potential failure scenarios that can lead to very fast orbit changes and machine protection requirements for HL-LHC operation

Daniel Wollmann

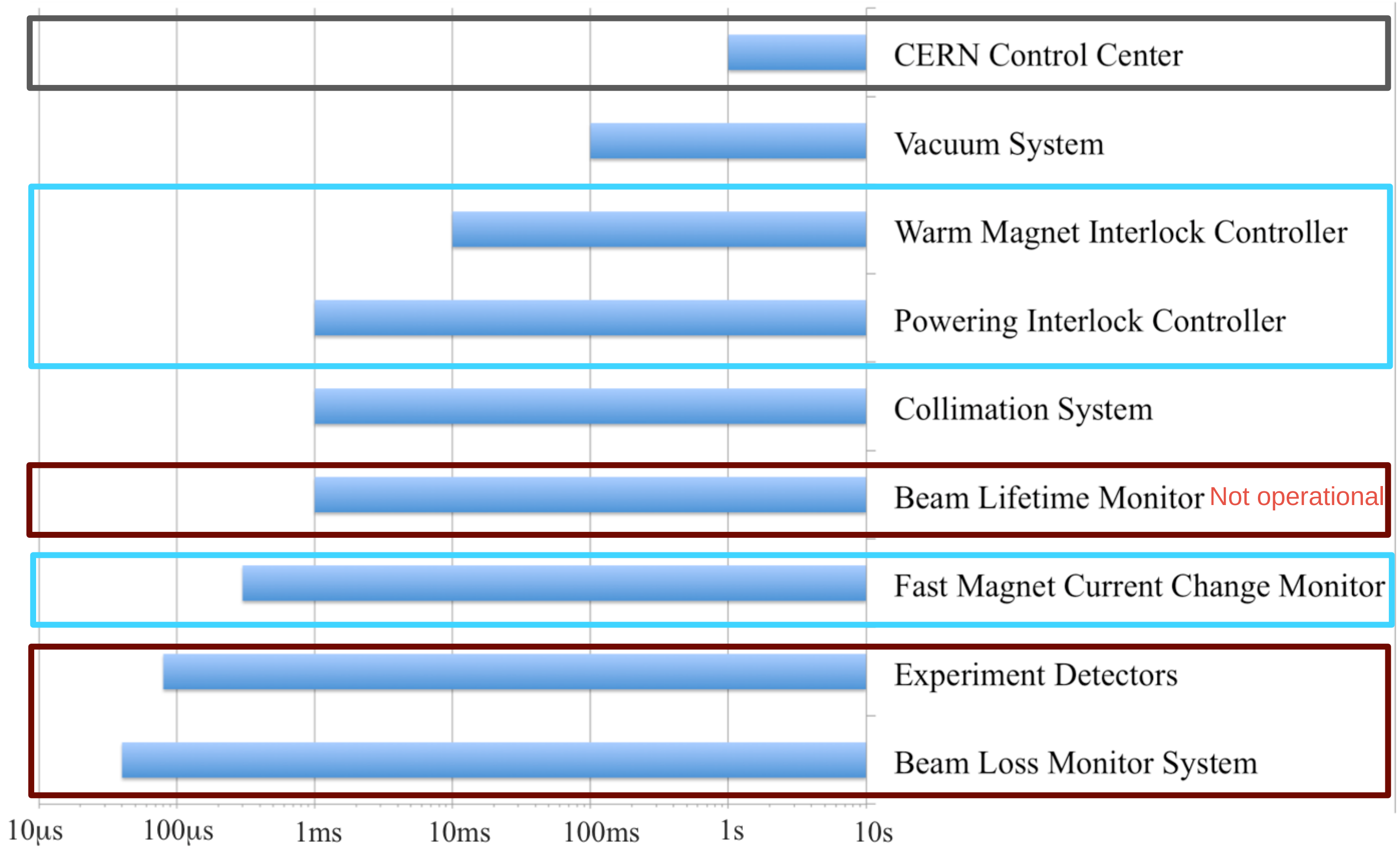
with input from R. Bruce, R. Calaga, R. Jones, S. Redaelli, A. Santamaria, J. Uythoven, M. Valette, M. Zerlauth

Review of the needs of a hollow e-lens for the HL-LHC, 6 - 7 October 2016, CERN

Outline

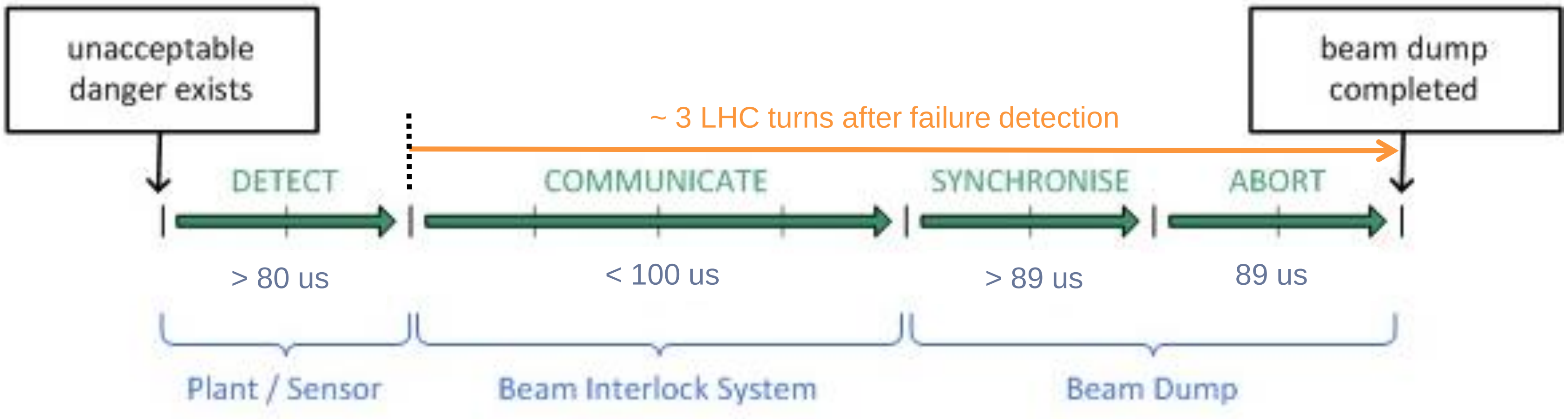
- Machine Protection strategy and reaction time in LHC
  - Detection systems
  - Reaction time of machine protection system
  - Failure classification
- Fast failures in HL-LHC
  - Crab cavity failures
  - Beam-beam kick
  - Firing of quench heaters
- Effects of halo cleaning on machine protection
- Halo monitoring
- Conclusion

Reaction times of major LHC machine protection systems



- Failures leading to beam losses → **BLM system ultimate safety net.**
- Powering failures
- Human intervention

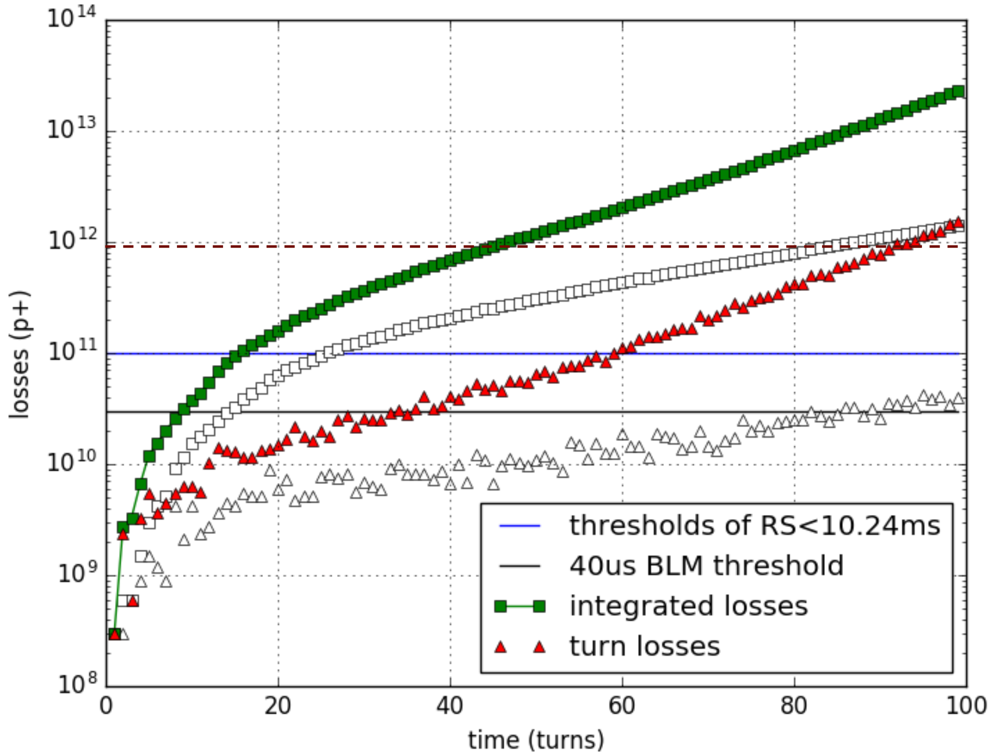
Assumptions for LHC Machine Protection



- **Ultra- Fast failures** (< 3 turns):
  - Beam injection from SPS to LHC.
  - Beam extraction into dump channel.
  - Missing beam-beam kick after dump of one beam.
- **Fast failures** (< few milliseconds):
  - Detected by: BLMs (>40us), FMCM (~100 us), Beam Life Time monitor (~1ms), …
  - Equipment failure with fast effect on orbit: e.g. D1 separation dipole fastest failure with circulating beam.
- **Slow Failures** (> few milliseconds):
  - Instabilities, Magnet quenches, Moving devices, …
  - Multi-fold redundancy (BLM, PC, QPS, RF, …)

Example: D1 powering failure (LHC)

- Critical loss levels reached in collimation region some ten turns after begin of failure.
- Fast Magnet Current change Monitor (FMCM) provides redundancy to BLM system → beams dumped before orbit change detectable.



- Combined failure of D1 circuits in both IP 1 and 5
- Single D1 circuit failure

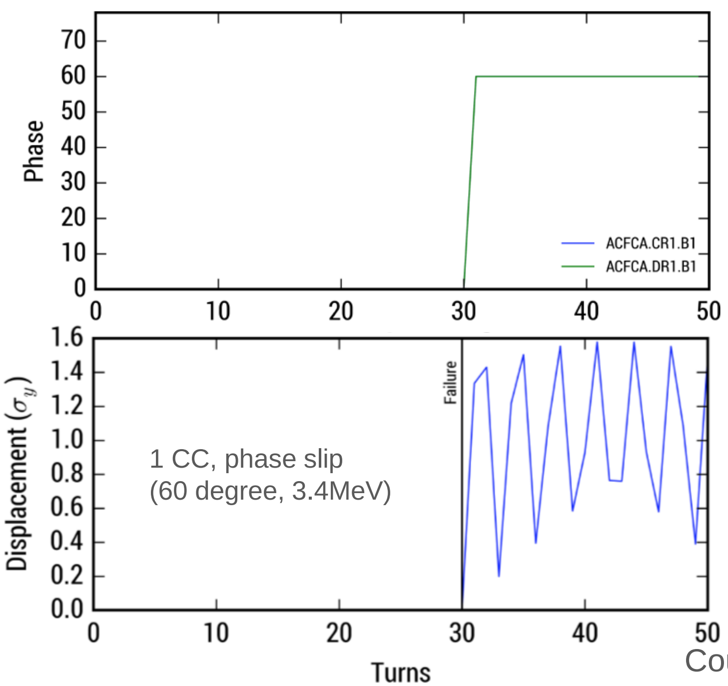
Courtesy M. Valette

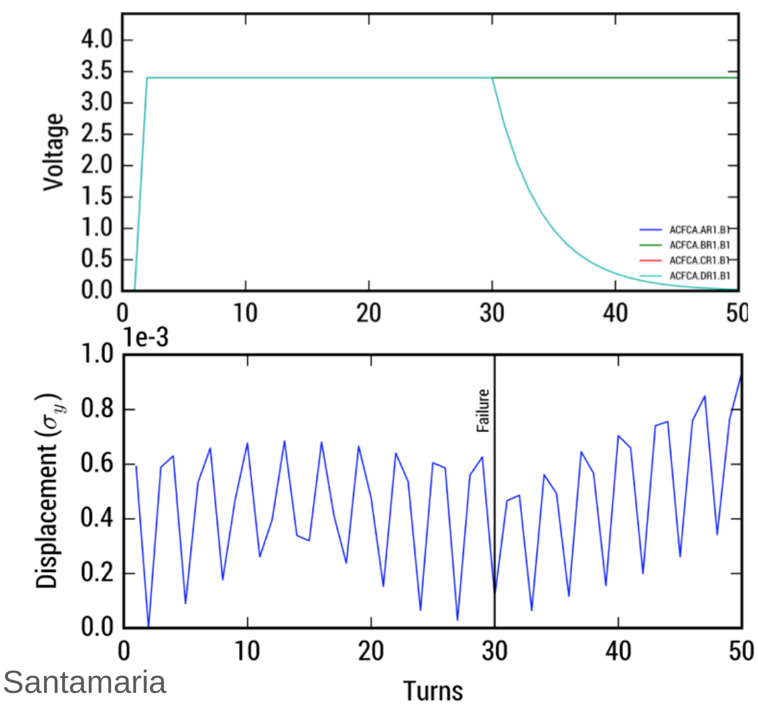
Fast and ultra fast failures for HL-LHC

Failure type	criticality	comment
Injection failures and **Asynchronous** beam dumps	• Upgrade of protection devices under study / foreseen; machine configuration to be chosen to accommodate failures	
Crab Cavity failures	• Single CC failure probably manageable • Combined failures of multiple CC → high risk for damage • Higher operating voltages increase criticality significantly	See more details below
Missing **beam-beam kick**	**Low risk** - depends on halo distribution and collimator gaps	See more details below
Kick due to **quench heater firing** in MB and new HL-LHC magnets	Not critical	See more details below
Discharge of CLIQ (variation of magnet currents by few kA for 100 – 200 ms)	Not critical in case of foreseen connection schemes	To be studied further
Warm **D1 powering failure**	superconducting D1 → mitigated	

Crab cavity failures

- **Modeling improved** in recent years → detailed tracking studies including Collimation system etc. possible with SixTrack.
- Still missing proper modeling of **beam driven CC failures** → work in progress + validation in SPS test.
- **Study cases**:
  - **Phase slip** by 60 degree (wrong operation settings, controller / operator failure) – should be avoided in low-level RF.
  - Exponential **decay of cavity voltage** – no displacement of beam core, criticality to be studied in combination with other failures.

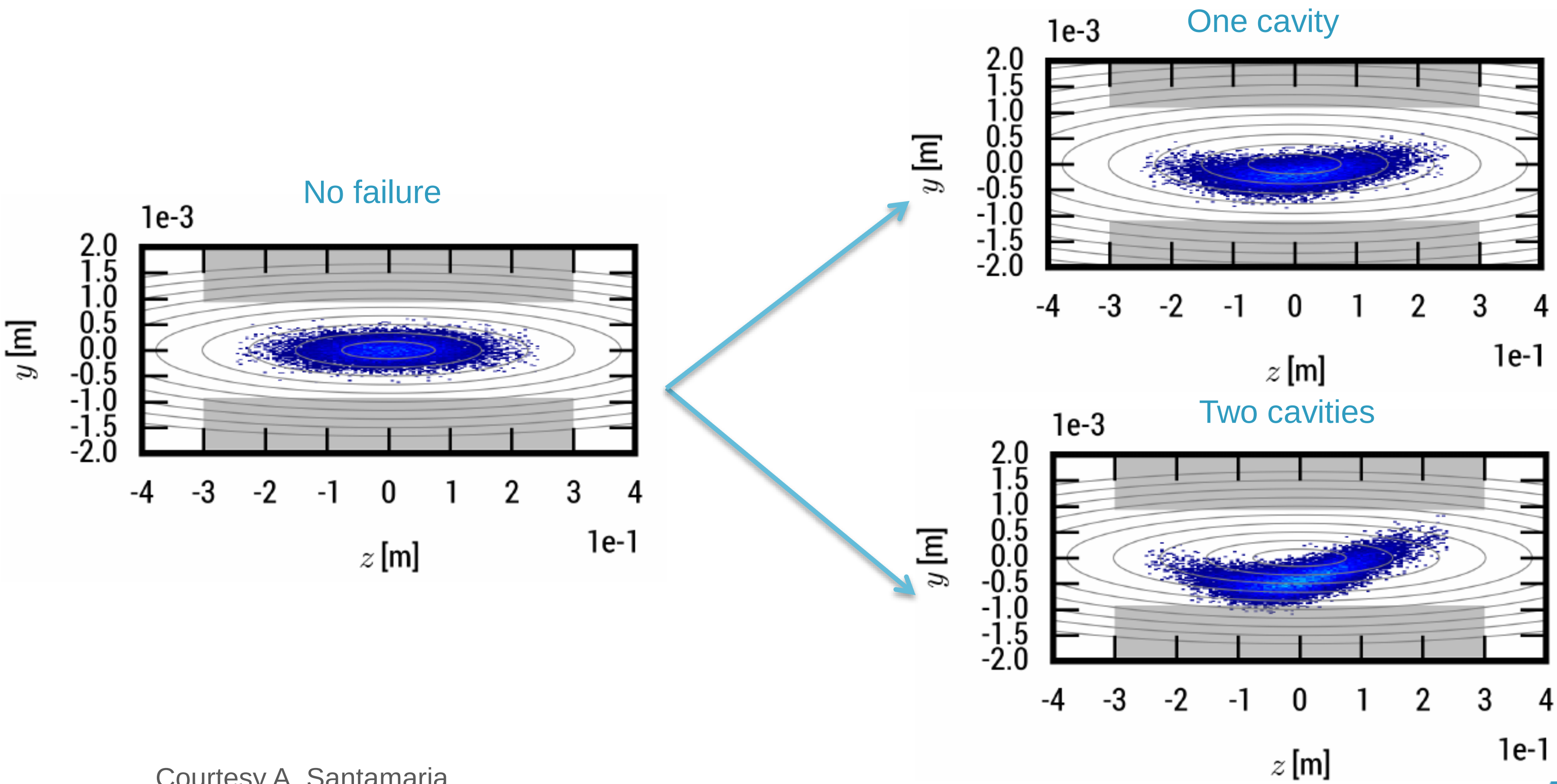




Courtesy A. Santamaria

Crab cavity phase slip - illustration

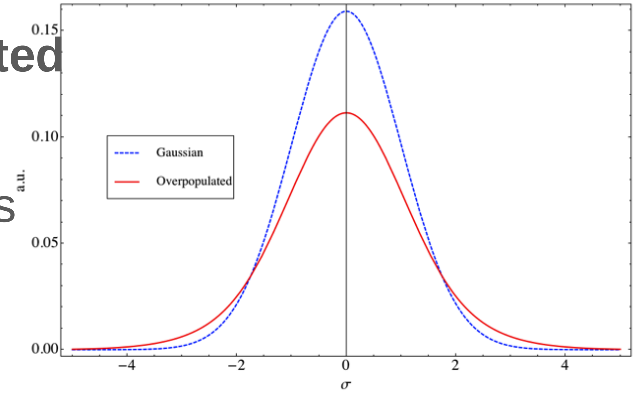
Longitudinal bunch shape at primary collimator in IR7

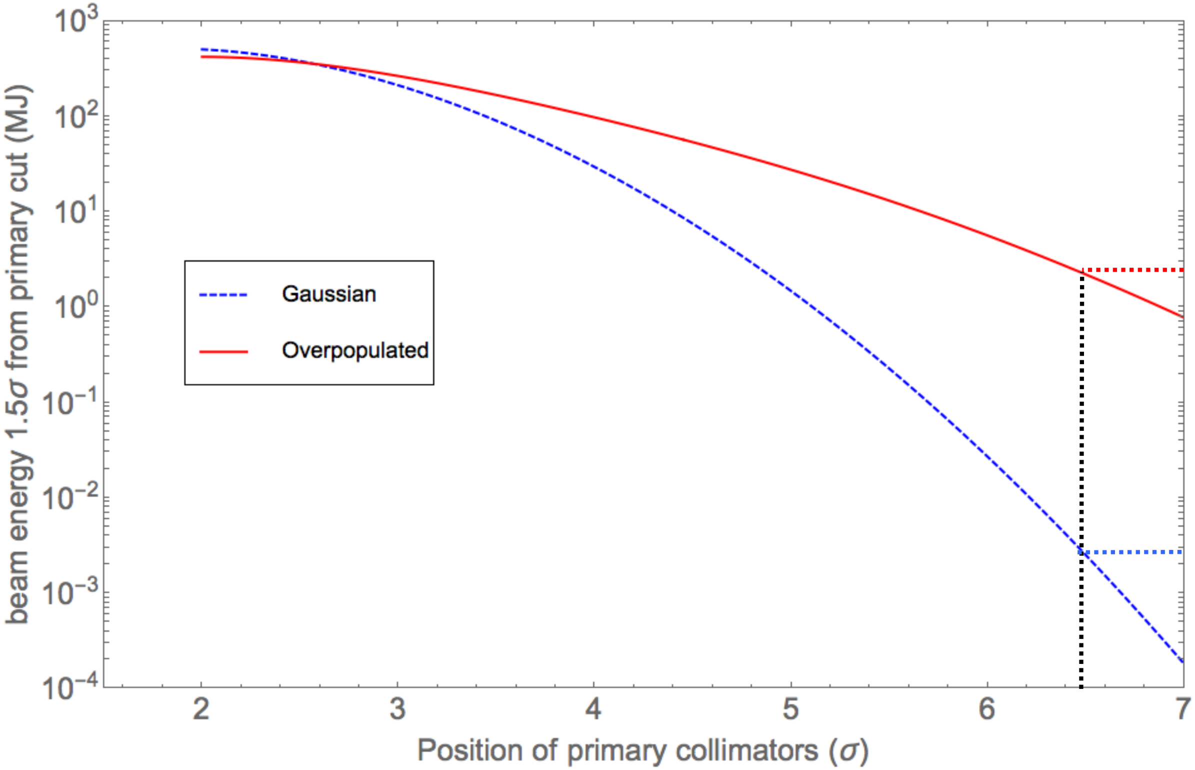


Courtesy A. Santamaria

Energy lost due to 1.5σ beam shift

- Measurement in LHC showed beams with **overpopulated tails** (2% of beam outside 4 σ).
  [F. Burkart, CERN Thesis 2012 046] and Talk by G. Valentino
- Fraction of beam **1.5 σ inside** of the primary collimators (6.5 σ): 3.7×10^{-6} (2.5 kJ) ➔ **3.3×10^{-3} (2.2 MJ).**



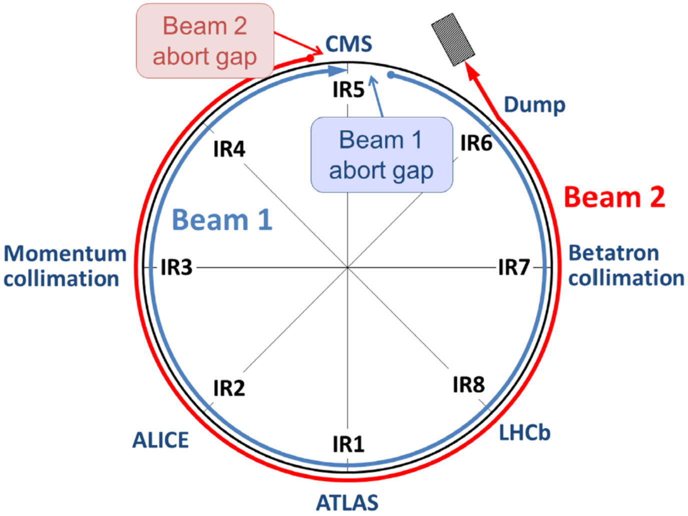


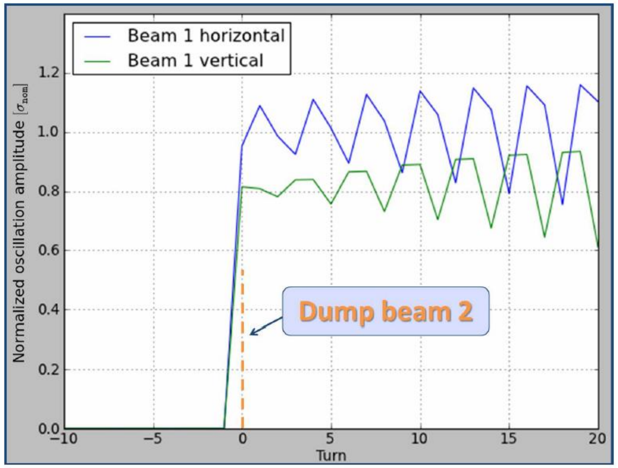
Tracking studies show that **~1/3** of this beam is lost within the first 3 turns.
(See **B.Y. Rendon et al.** *Simulations of Fast Crab Cavity failures in the High Luminosity Large Hadron Collider)*

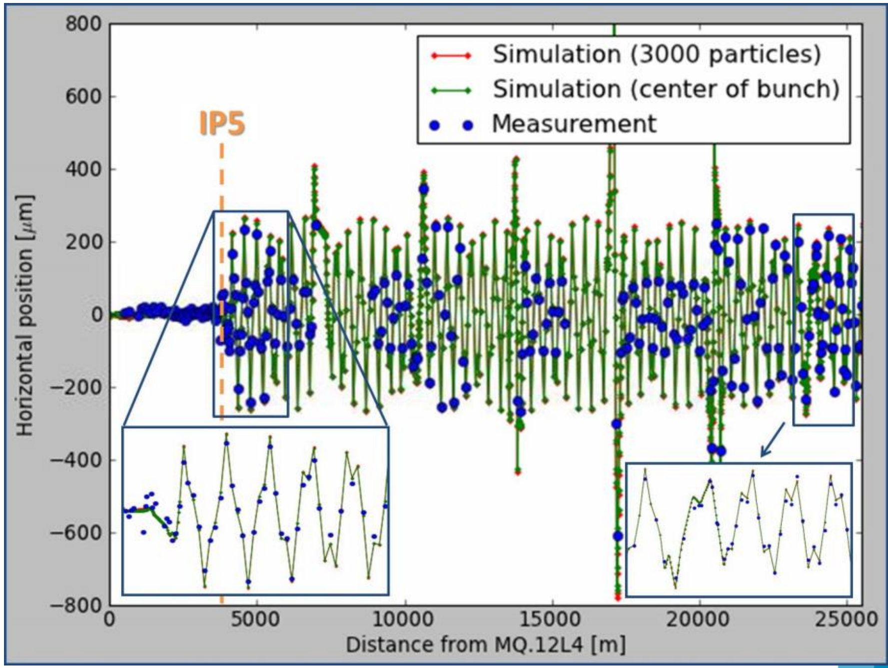
- **> 0.7 MJ** of beam impacting on collimators
- close to damage limit
- halo depletion recommended

Missing beam-beam kick

- Missing long range **beam-beam deflection** after dump of one beam.
- Measured single turn orbit perturbation at 4 TeV: 0.6 σ
- Increase to **0.9 - 1.1 σ for HL-LHC** expected.



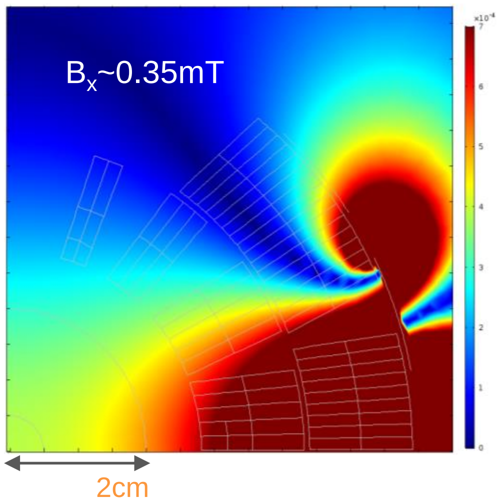


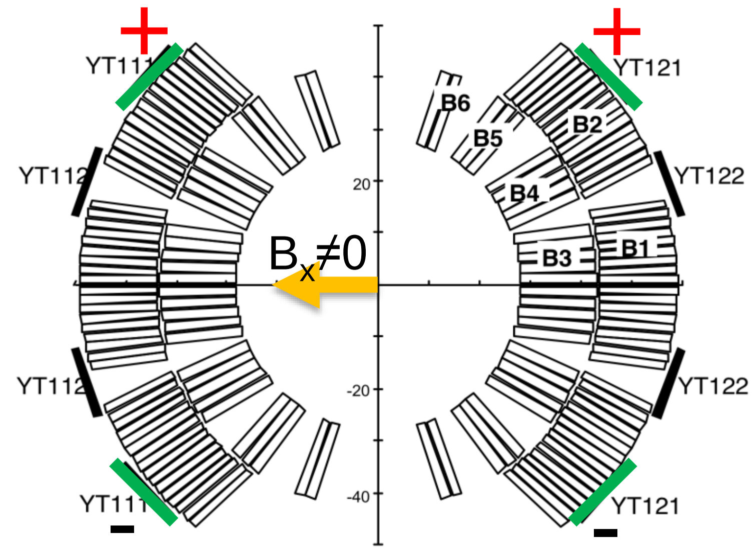


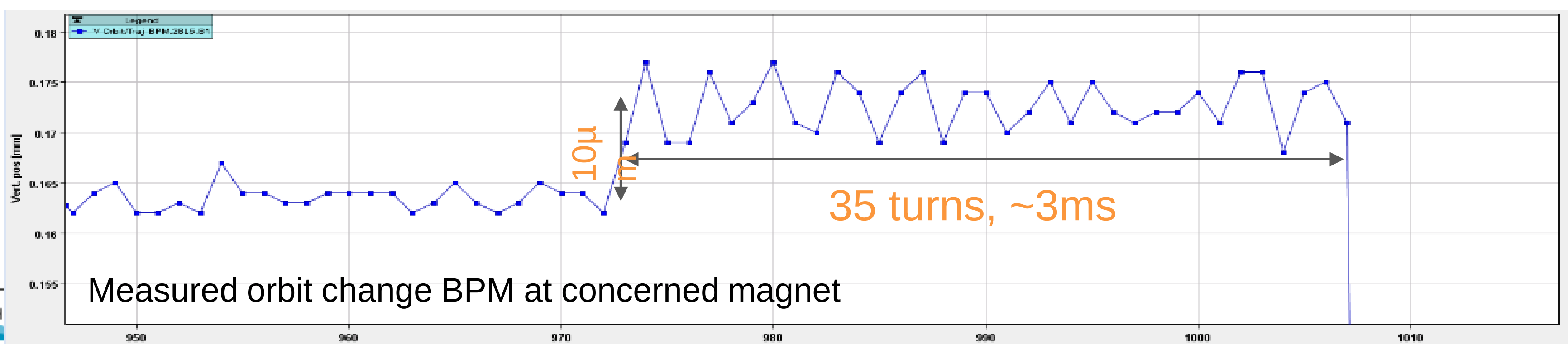
Trajectory perturbation of beam 1 after dump of beam 2, 4TeV, 0.9e11p/b, 84b, 25ns, IP5-xing=68urad, 13.12.2012 08:26:54
Courtesy T. Baer

Quench heater firing with circulating beams

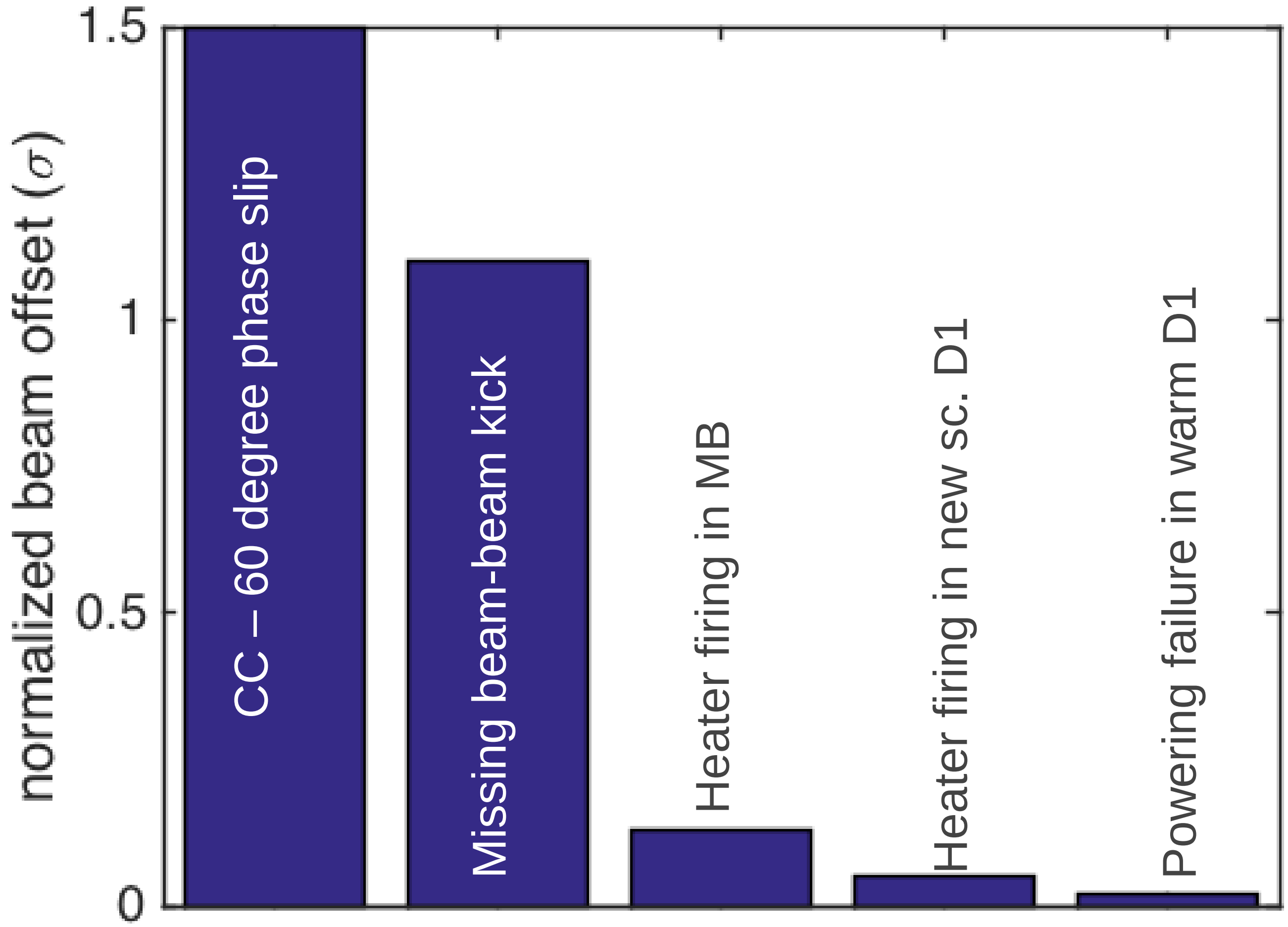
- **Delay up to 5.5 ms** between quench **heater firing and beam dump** can be expected in case of a LHC **main dipole quench**.
- Field from quench heater rises within 20 - 30 us.
- Max expected orbit offsets: 0.13 σ







Normalized offset in first turn after failure



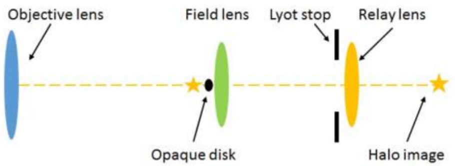
Note: Warm D1 powering failure will lead to increase of beam offset moving beam core into collimators within a few tens of turns → mitigated for HL-LHC

Effects on halo cleaning on machine protection strategy

- Failures of **single crab cavities** can be **mitigated** by partial **depletion** of beam halo.
- Failures of **multiple** crab cavities will cause orbit displacements > 3 σ → halo depletion probably **not sufficient**.
- **Increase** of operational **voltage** of crab cavities increases criticality of failures.
- Beam **halo important *probe*** to detect failures causing dangerous deflections of the circulating beam and dump beam **well before core impacts** collimators.
- Significant **depletion of halo** > 1 σ (?) requires a **review of detection delays** for fast failures.
- **Witness bunches** in combination with bunch-by-bunch beam loss detectors in collimation region could mitigate the effect of halo depletion on failure detection delays → studies started.

Halo Monitoring and Interlocking – some ideas

- If halo depletion is required for machine protection, a **reliable and redundant** monitoring of **halo population is mandatory** → (slow) interlocking.
  - Lyot **coronograph** under development:
    - Design goal **resolution 10^{-6}** of core intensity
    - **Prototype device** installed in LHC aiming at resolution of 10^{-5}-10^{-4}



  - **Gas jet** wire scanner → R&D ongoing by BI + Cockcroft Institute on gas sheet monitors.
  - **Scanning** of halo with **hollow e-lens** in combination with (fast) loss detection in IR7.
  - Halo monitoring via e-beam of hollow e-lens → not possible for LHC.
- Monitoring / **interlocking of losses from witness bunches** with gated fast loss monitors.

Conclusion

- Warm **D1 powering failures mitigated** for HL-LHC
- **Crab cavities** will **potentially** become the source of one of the **most critical failures** for HL-LHC → mitigation by halo depletion possible for single failures.
- Other fast failures still under study, but seem not to become critical with HL-LHC parameters.
- Proper **model for beam induced** crab cavity failures currently missing → work ongoing.
- If halo depletion becomes **baseline** for HL-LHC:
  - **Review of protection strategy** for fast failures
  - Reliable and redundant **halo monitoring** / interlocking needs to be foreseen.

Thanks a lot for your attention.