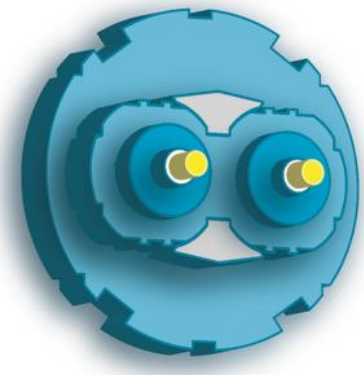


High Luminosity LHC

Machine Protection and Required Availability in view of the HL-LHC goals

D. Wollmann

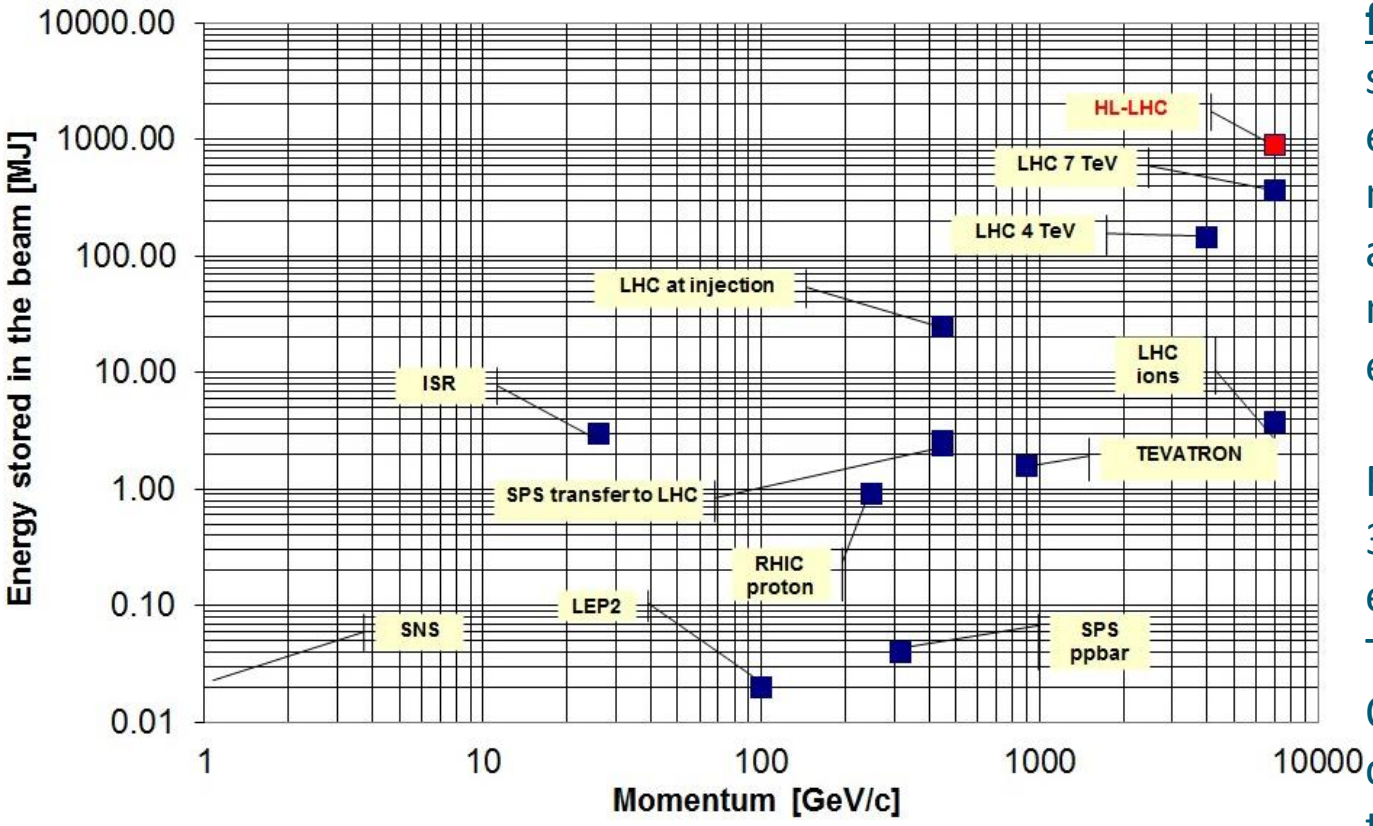
Acknowledgments: A. Apollonio, T. Baer, B.Y. Rendon, R. Schmidt, J. Wenninger, M. Zerlauth

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Outline

- Challenges for MP in HL-LHC.
- MP strategy for ultra fast, fast and slow failures.
- New ultra fast failures due to crab cavities:
  - Expected energy lost in aperture and possible mitigations.
- Availability models for HL-LHC integrated luminosity.
  - Impact of UFO and SEU rates.
  - Impact of failure rate and fault time.

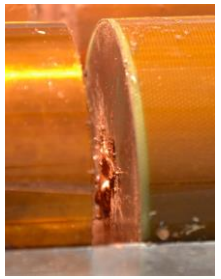
Challenges of MP for HL-LHC



HL-LHC will have a **factor two** more stored beam energy than the nominal LHC and about a **factor five** more than experienced so far.

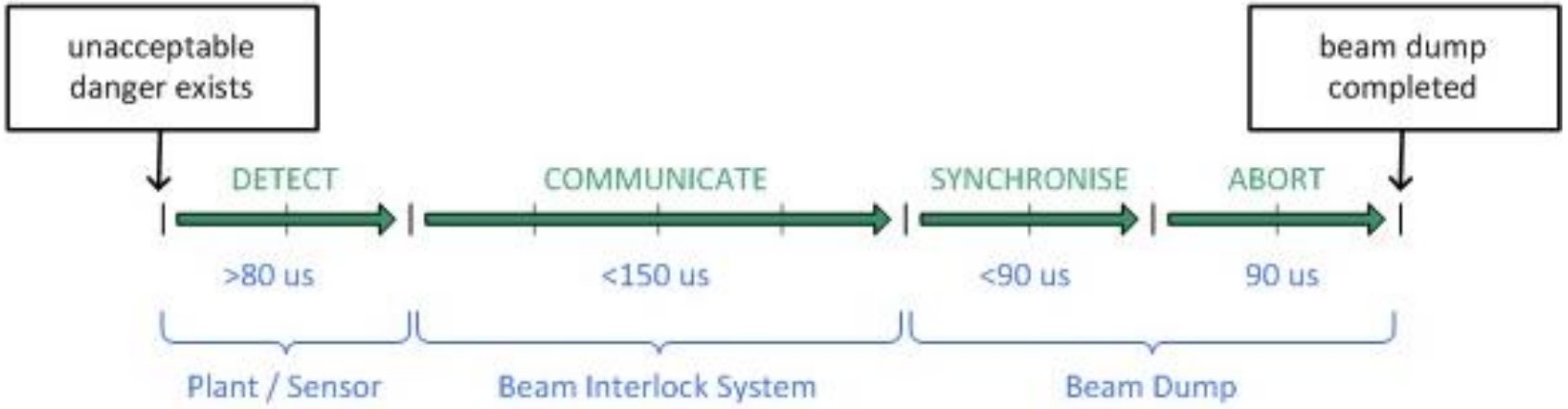
Reminder:
360MJ are equivalent to 90kg TNT

Or can **penetrate** through a **20m** long **copper** block.



- **Re-visit damage** studies in view of HL-LHC **beam parameters.**
- **New failure scenarios**: due to proposed **optics changes** and new equipment e.g. **crab cavities**.
- **Trade-off** between **protection** and machine **availability** due to tighter margins (energy ↑, intensity ↑, quench limits↓).

Assumptions for LHC MP systems

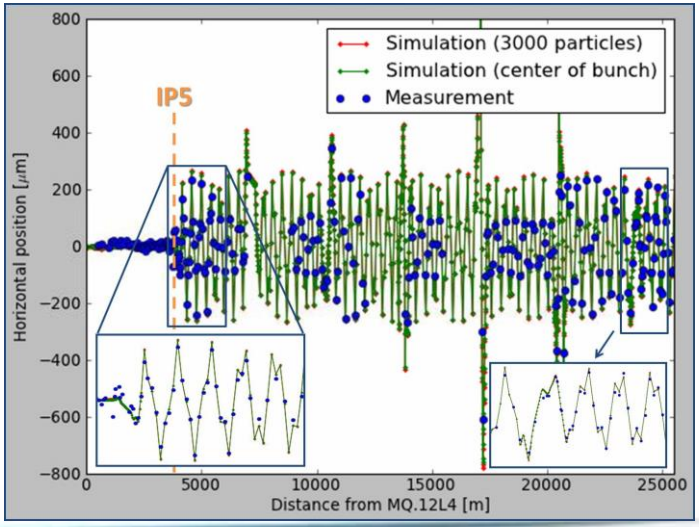


- **Ultra- Fast failures (< 3 turns)**:
  - Beam injection from SPS to LHC.
  - Beam extraction into dump channel.
  - Missing beam-beam kick after dump of one beam.

→ **Upgrade** or replacement of **passive protection** devices (TDI, TCDQ, Collimators etc.) [WP5, WP10, WP14, …]

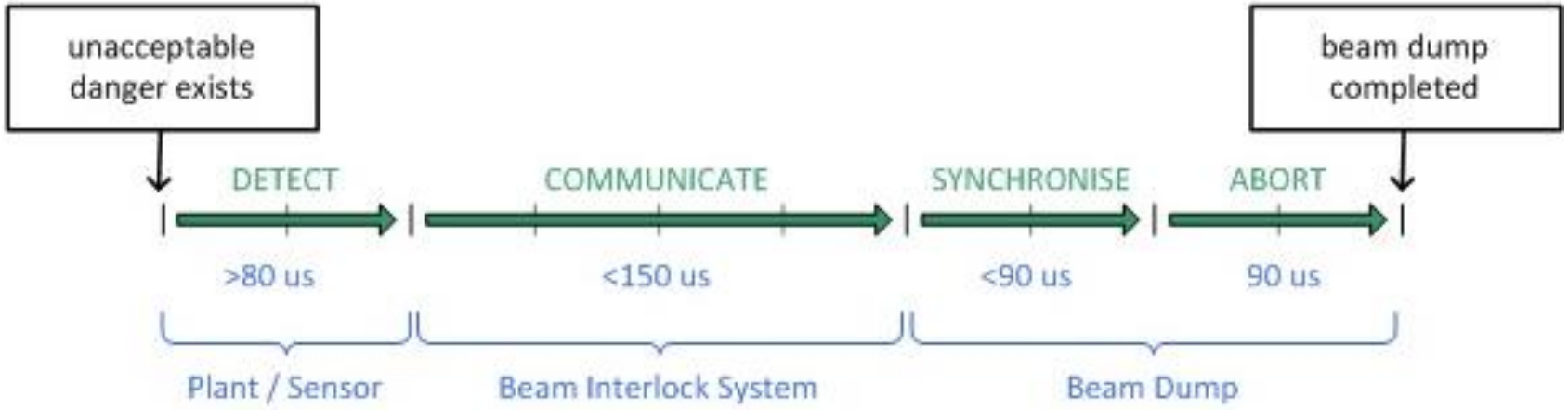
↓

0.6σ single turn orbit perturbation **measured** @4TeV ➔ increase to **0.9-1.1σ expected** for HL-LHC

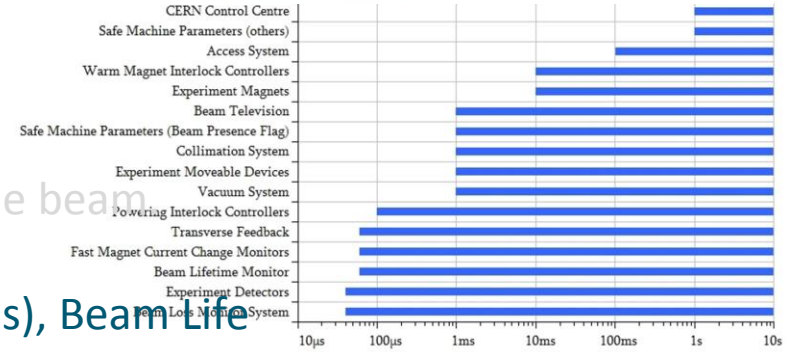


Trajectory perturbation of beam 1 after dump of beam 2, 4TeV, 0.9e11p/b, 84b, 25ns, IP5-xing=68urad, 13.12.2012 08:26:54
Courtesy T. Baer

Assumptions for LHC MP systems

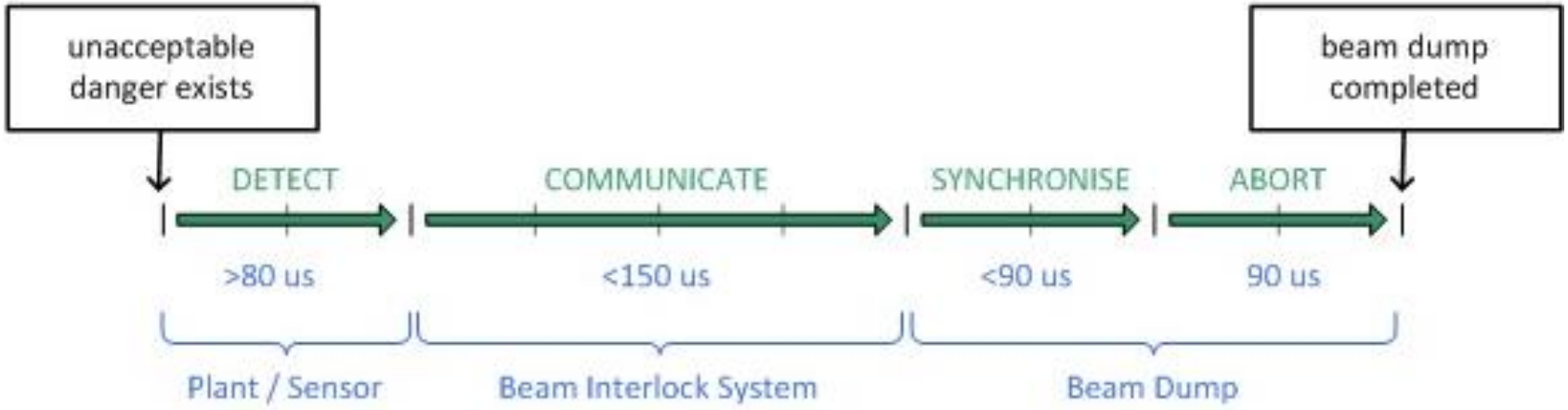


- Ultra- Fast failures (< 3 turns):
  - Beam injection from SPS to LHC.
  - Beam extraction into dump channel.
  - Missing beam-beam kick after dump of one beam.
- **Fast failures (< few milliseconds)**:
  - Detected by: BLMs (>40us), FMCM (~100us), Beam Life Time monitor (~200-300us), …
  - Equipment failure with **fast effect on orbit**: e.g. **D1** separation dipole (IP1/5) fastest failure with circulating beam.
  - **UFOs**.



Reaction time sufficient for HL-LHC optics (25% faster failure) even without replacing D1 by superconducting magnet.

Assumptions for LHC MP systems

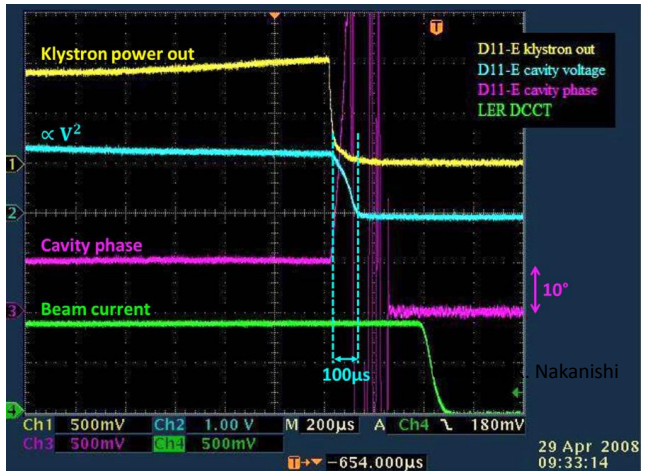


- Ultra- Fast failures (< 3 turns):
  - Beam injection from SPS to LHC.
  - Beam extraction into dump channel.
  - Missing beam-beam kick after dump of one beam.
- Fast failures (< few milliseconds):
  - Detected by: BLMs (>40us), FMCM (~100 us), Beam Life Time monitor (~100µs), …
  - Equipment failure 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, …)

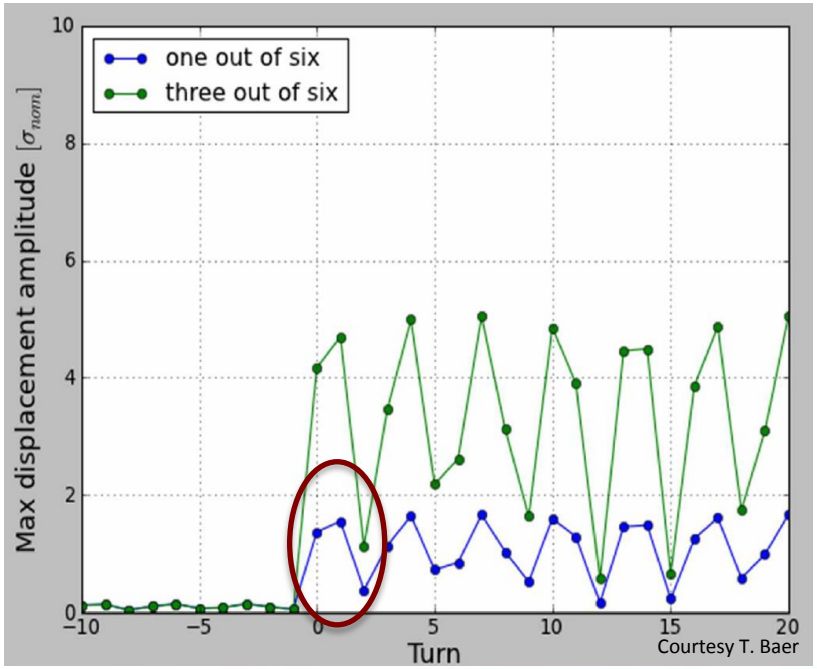
Not expected to have significant impact on MP considerations for HL-LHC, **BUT** likely to become an **increasing challenge** for **Machine Availability**!
➔ Later in this talk!

New ultra fast failures due to Crab Cavities

- 3 CCs per side of IP1/5.
- 3.3MV pro module.
- Voltage decay within **100μs** and large oscillations observed in KEKB.

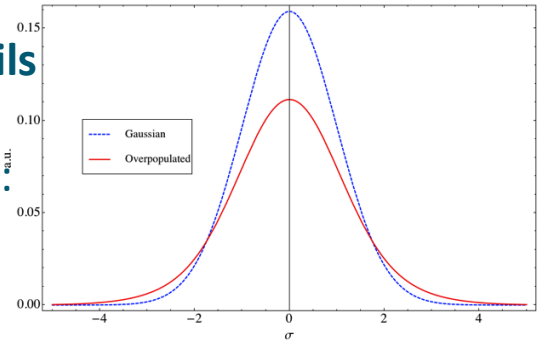


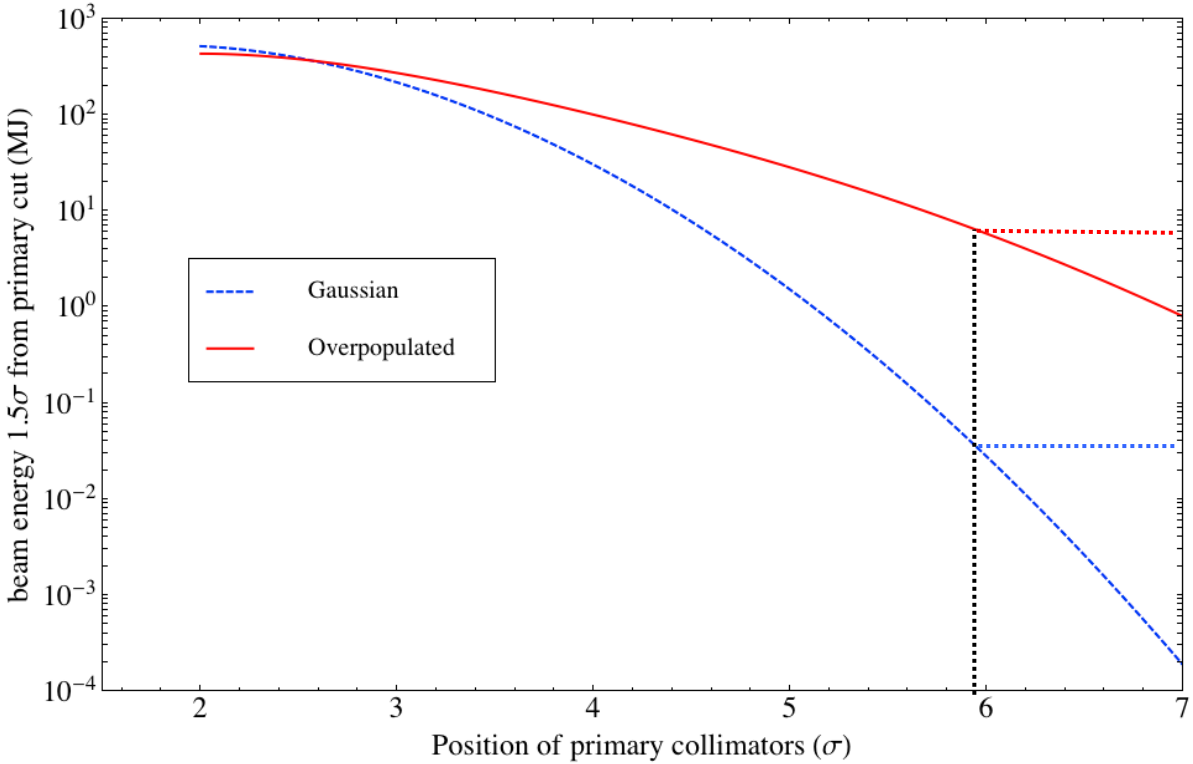
- Tracking simulations predict **orbit distortion of 1.5σ** within the **first turn** after the instantaneous drop of the deflecting **voltage in a single CC**.
- Orbit distortion **modulated by β-tron tune**.



Expected energy lost due to 1.5σ beam shift

- Measurement in LHC showed beams with **overpopulated tails** (2% of beam outside 4σ). [F. Burkart, CERN Thesis 2012 046]
- Fraction of beam **1.5σ inside** of the primary collimators (6σ): 4e-5 (28kJ) ➔ **8e-3 (5.8MJ).**





- Tracking studies show that **~1/3** of this beam is lost within the first 3 turns.

➔ **See B.Y. Rendon's talk (Wed)**

- Thus, **2MJ** of beam impacting on collimators ➔ above damage limit.

Possible mitigation strategies

- **More and weaker** (less voltage) crab cavities per side of IP.
- Very **fast LLRF** control.
- Partial **depletion of halo** (1.5s outside of primary collimators): Hollow electron-lens, tune modulation, excitation of halo particles with AC dipole, … .
- Monitoring and **interlocking** of halo population.

New schemes may need 4 CC with max 6.6 MV ➔ **double** kick expected.

Reduced detection time budget and redundancy in BLMs (depends on halo).

High **reliability** method required.

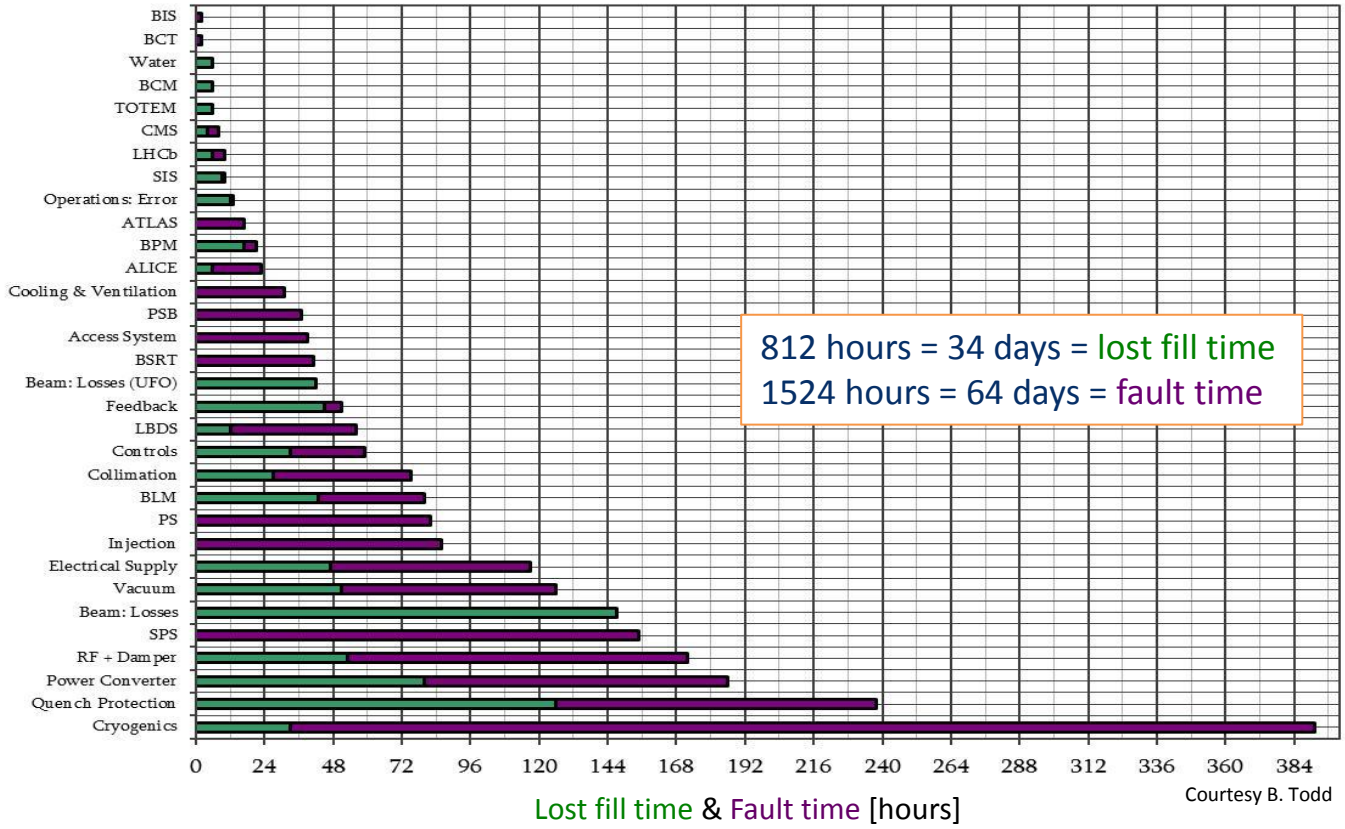
- **Tests of crab cavities** in SM18 and the SPS ongoing or in preparation ➔ confirm **worst case** voltage and phase **failures** (incl. time scales).
- **Efficiency** of hollow e-lens or alternative methods in LHC has to be shown.

Outline

- Challenges for MP in HL-LHC.
- MP strategy for ultra fast, fast and slow failures.
- New ultra fast failures due to crab cavities:
  - Expected energy lost in aperture and possible mitigations.
- Availability models for HL-LHC integrated luminosity.
  - Impact of UFO and SEU rates.
  - Impact of failure rate and fault time.

Availability Model for HL-LHC

- **Monte-Carlo Model** based on 2012 **LHC availability**.
- Estimate the expected **integrated luminosity of HL-LHC**.
- Identify the impact of **UFO-rate, SEU-rate, BLM thresholds, machine failure rate and average fault time** on the yearly integrated luminosity.

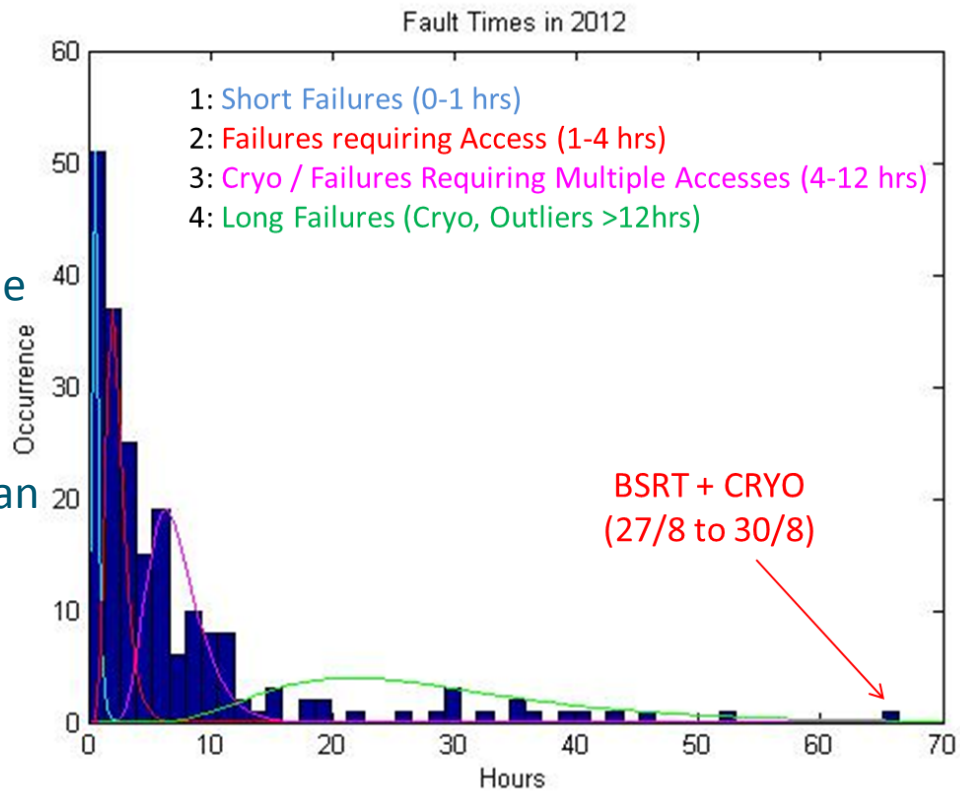


Courtesy B. Todd

Note: Interdependencies of faults have not been taken in account here.

Model Assumptions

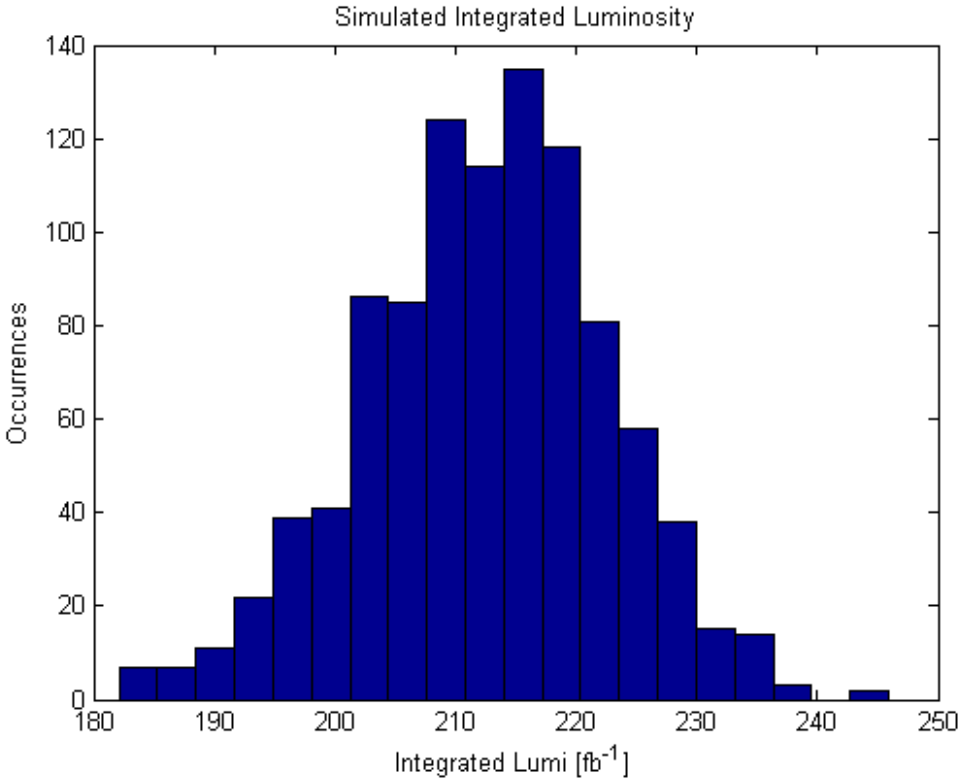
- 160 days of operation
- 2.19x10^{35} [$cm^{-2}s^{-1}$] virtual peak luminosity (Full HL)
- Levelling at 5x10^{34} [$cm^{-2}s^{-1}$]
- 4.5 h average luminosity lifetime
- 6.2 h average turnaround time
- 4 logn distributions for the fault time
- 2 stable beams time distributions:
  - EOF: gauss(mean 9.6 h)
  - EMERGENCY DUMPS: exp(mean 4.6h)
- Simulated 1000 years of operation.



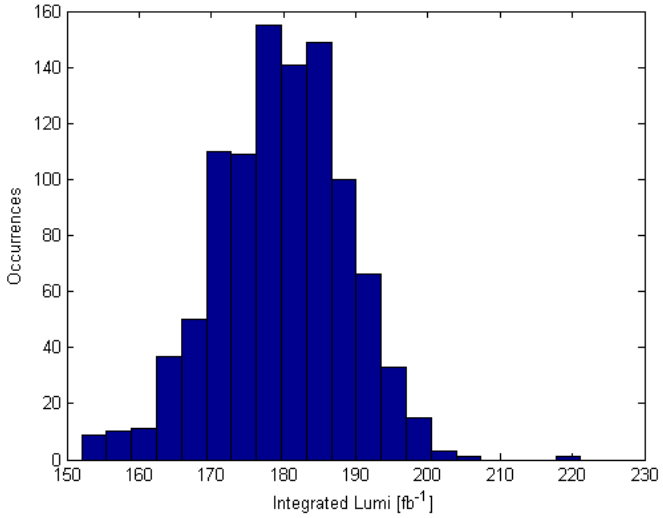
For further details contact: Andrea.Apollonio@cern.ch

Monte-Carlo Results

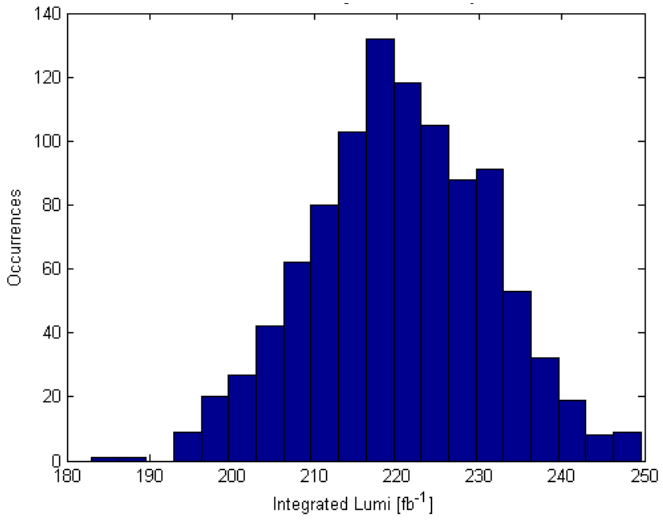
As 2012,
turnaround time 5.5h ➔ 6.2h
Avg: 213 [fb^{-1}] (*reference*)



100 UFO dumps due to 7TeV
Avg: 179 [fb^{-1}] (*-15%*)



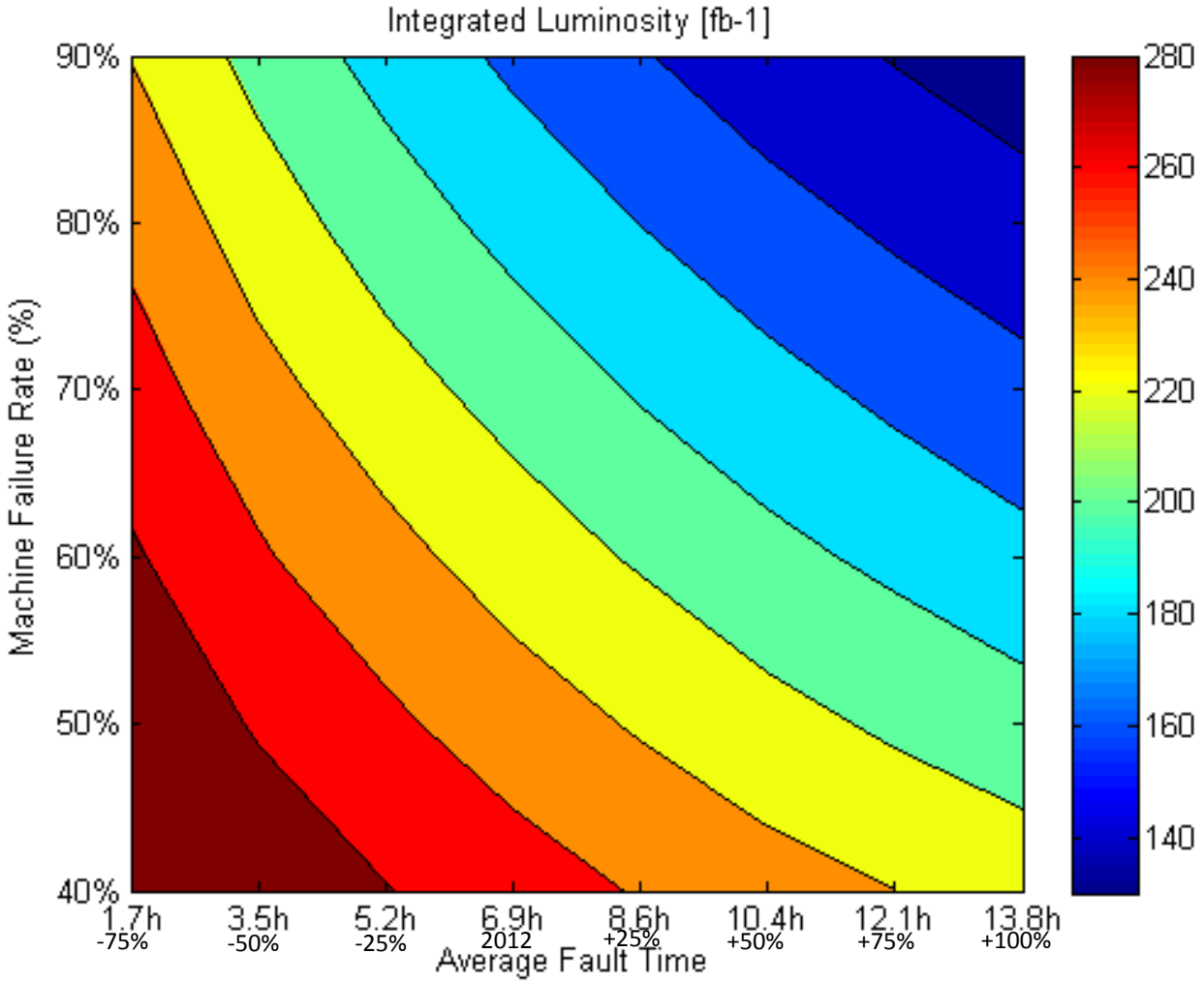
SEU mitigation (50 ➔ 20)
Avg: 220.5 [fb^{-1}] (*+3%*)



Impact of UFOs and SEUs on HL-LHC performance

Failure Scenario/ Mitigation	Assumption	Simulated impact on Integrated Luminosity
1. 2012 Fault distributions	-	213 [fb^{-1}] (*reference*)
2. UFOs (6.5/7TeV)	100 UFO dumps	179.5 [fb^{-1}] (*-15%*)
3. UFOs + Beam Induced Quenches	Factor 3 higher BLM thresholds, 33 UFOs, 3 Beam Induced Quenches	203 [fb^{-1}] (*-5%*)
4. SEU mitigations	20 SEU dumps	220.5 [fb^{-1}] (*+3%*)
5. SEU increase due to higher energy	60 SEU dumps (+50% wrt 2012)	206 [fb^{-1}] (*-3%*)
6. Combined impact of scenarios 3 and 4	-	208.5 [fb^{-1}] (*-2%*)

Sensitivity analysis: Machine Failure Rate and Average Fault Time



Machine Failure Rate = # of Fills to SB with Failures / Total # of Fills to SB

Conclusion

- Multi-fold **redundancy** for failure detection has worked **successful**ly during LHC run1.
- Increased stored beam energy requires a **re-visit of failure scenarios** for HL-LHC beam parameters.
- Upgrade or replacement of **passive protection devices** in preparation / underway.
- **New fast failure** mode expected due to crab cavities
  - In combination with **overpopulated tails** this could be fatal.
  - Mitigation methods (halo depletion) may have knock on **effect** for detection of **other failures** via beam losses: **reduce time budget**.
- Trade-off **protection and availability**: BLM thresholds↑, UFO dumps↓, Beam induced quenches↑, integrated Luminosity↑
- Reduction of average **fault time** and Machine **Failure Rate** is key factor to reach HL-LHC goals for integrated luminosity.

Outlook

- Development of functional requirements for **machine protection backbone** (take into account new equipment and failure modes).
- QPS for **new triplet** magnets (Nb3Sn) and **sc links**.
- Final definition of HL-LHC **beam parameter envelope** necessary to allow for a sufficient design of MP systems and devices.
- Measurement of **beam distribution at 6.5 / 7TeV.**
- Experimental **confirmation of CC's** worst case **failure scenarios.**
- **Study** effect of **depleted halo** on **detection of** other **failures** via BLMs.
- Study **damage limits and potential** due to HL-LHC **beam impact** on accelerator equipment (e.g. new TCDQ).
- Case study for an **LHC System Availability Tracking** (LSAT) tool underway ➔ improve input **data quality** for availability predictions.

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.