Machine Protection Issues

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Acknowledgments: T. Baer, A.Macpherson,B.Y. Rendon, R. Schmidt, J. Wenninger, D.Wollmann

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

- LHC Machine Protection System today
- Challenges for Machine Protection in view of HL-LHC and crab cavities
  - New ultra fast failures due to crab cavities
- Possible mitigation strategies
- Conclusions

LHC Failure scenarios and their mitigation

- Three classes of failures considered for LHC protection
  - Ultra Fast failures (single beam passage during e.g. beam transfer, injection,…): passive protection with collimators and absorbers
  - Fast failures (few LHC turns following beam losses, certain fast powering failures,…): active protection with BLMs and dedicated protection systems
  - ‘Slow’ failures (powering failures, feedback, RF,..): Protection through equipment monitoring, …

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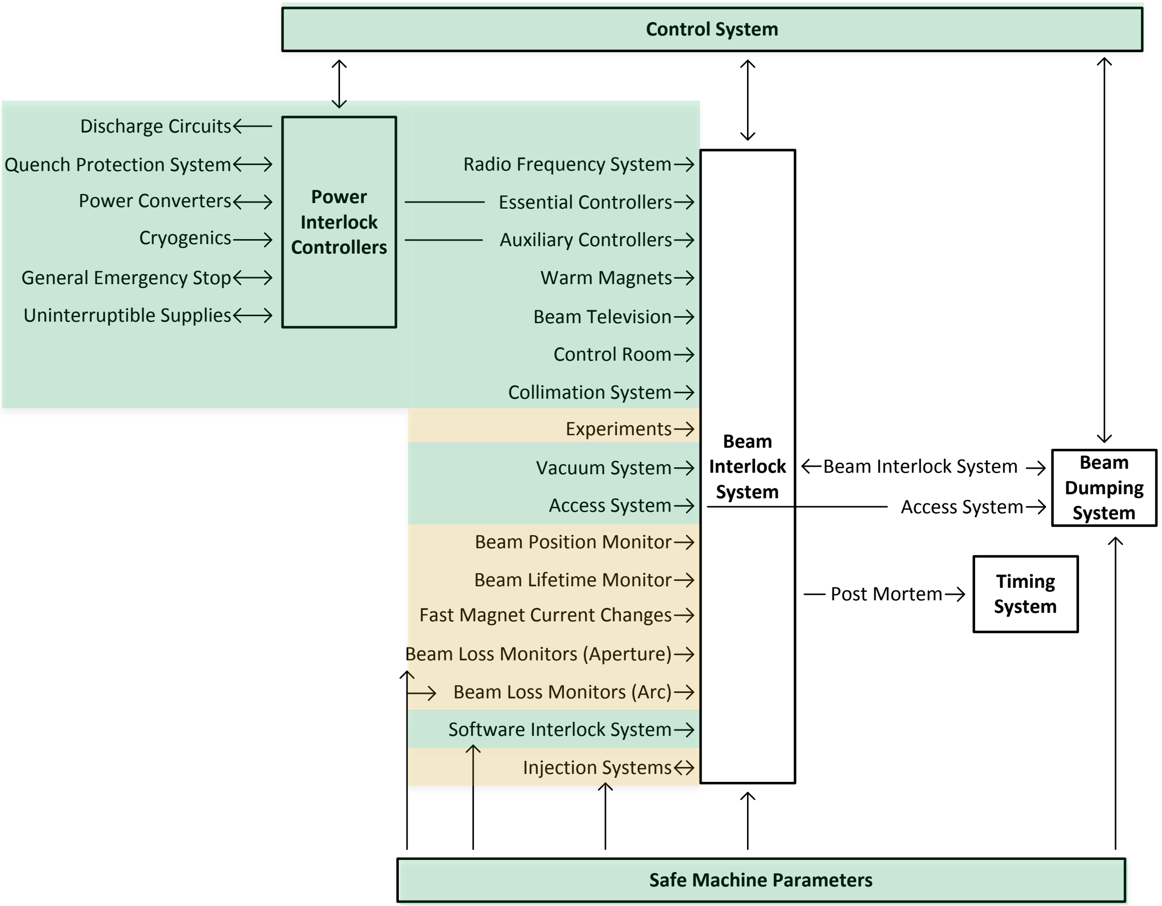
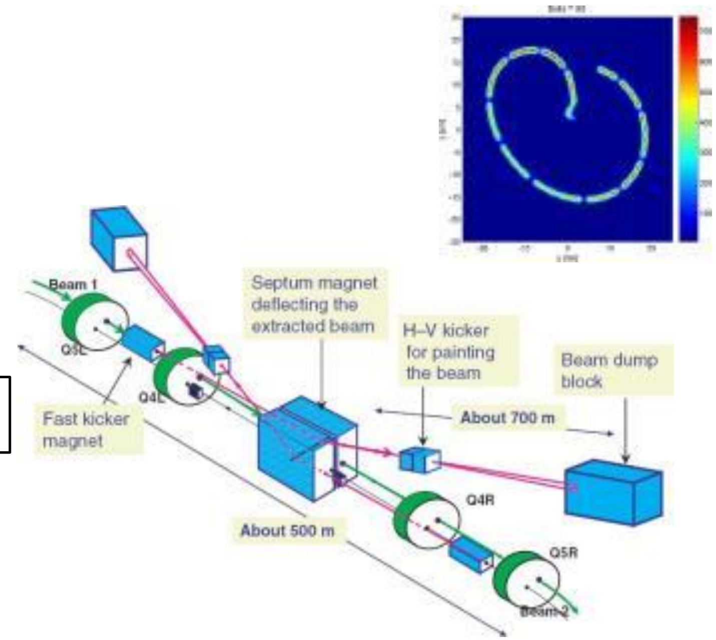
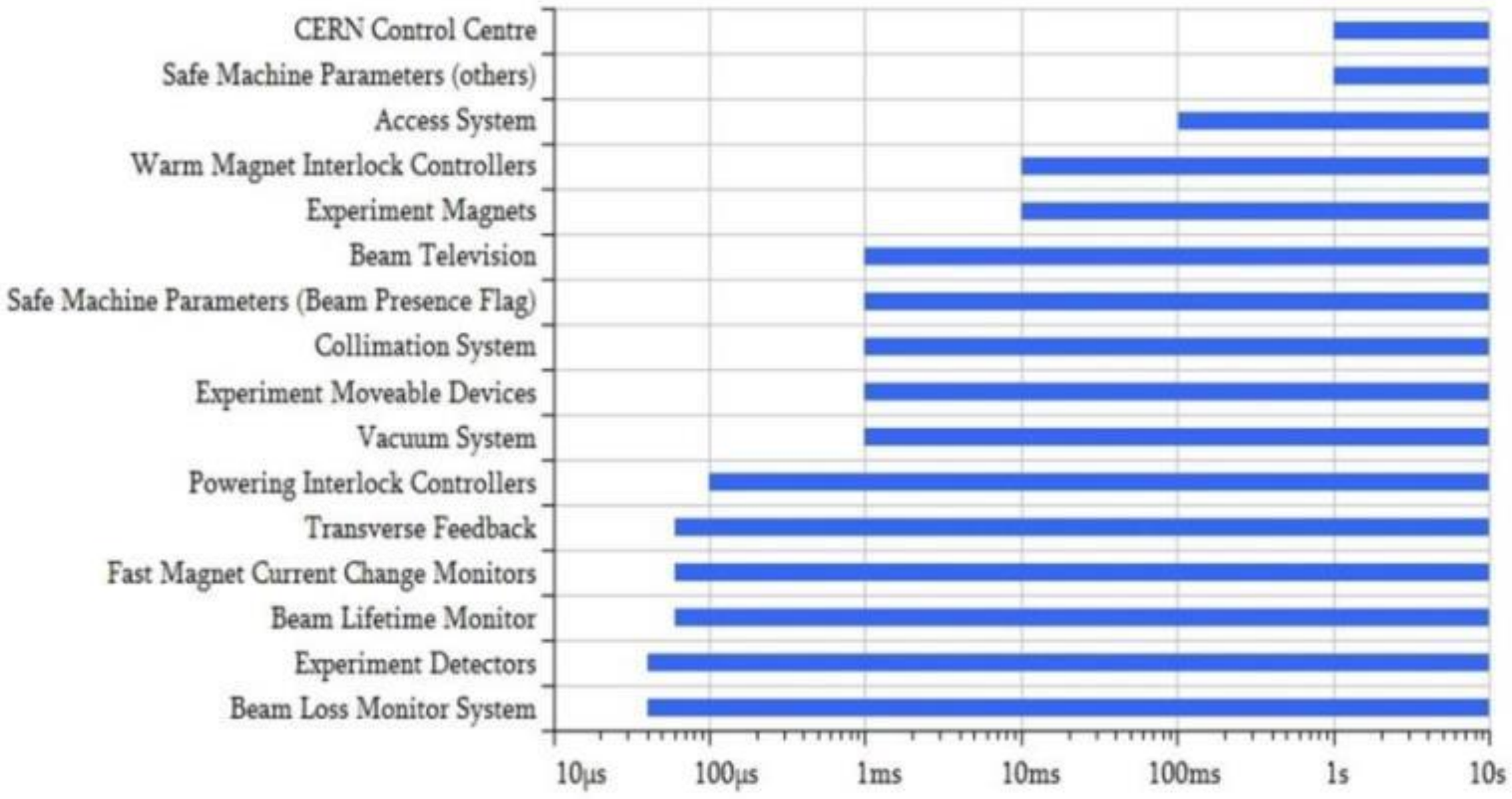
Machine Protection Architecture



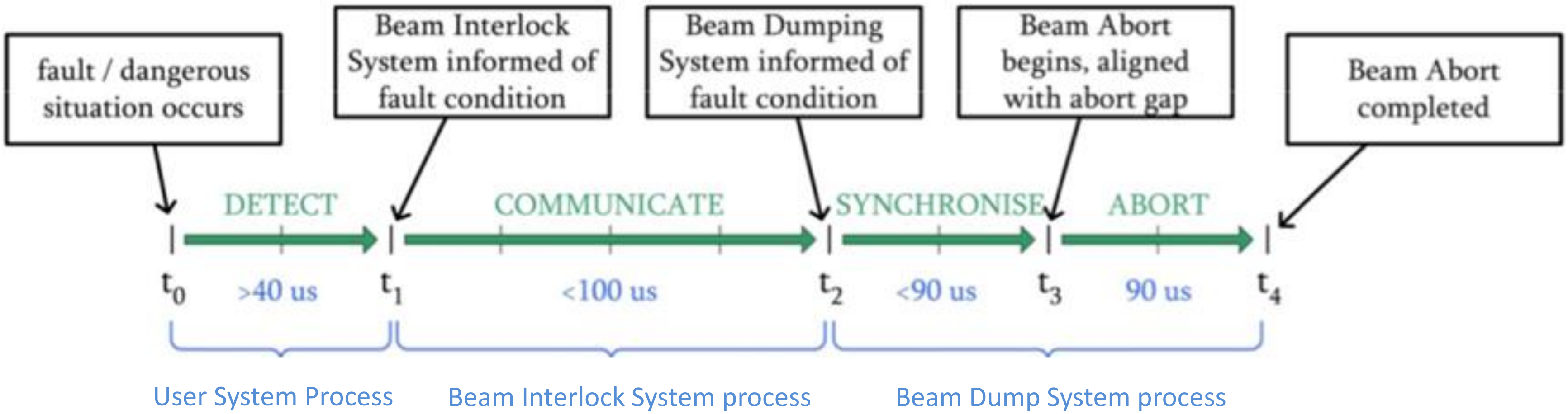


Failure detection time @ LHC today



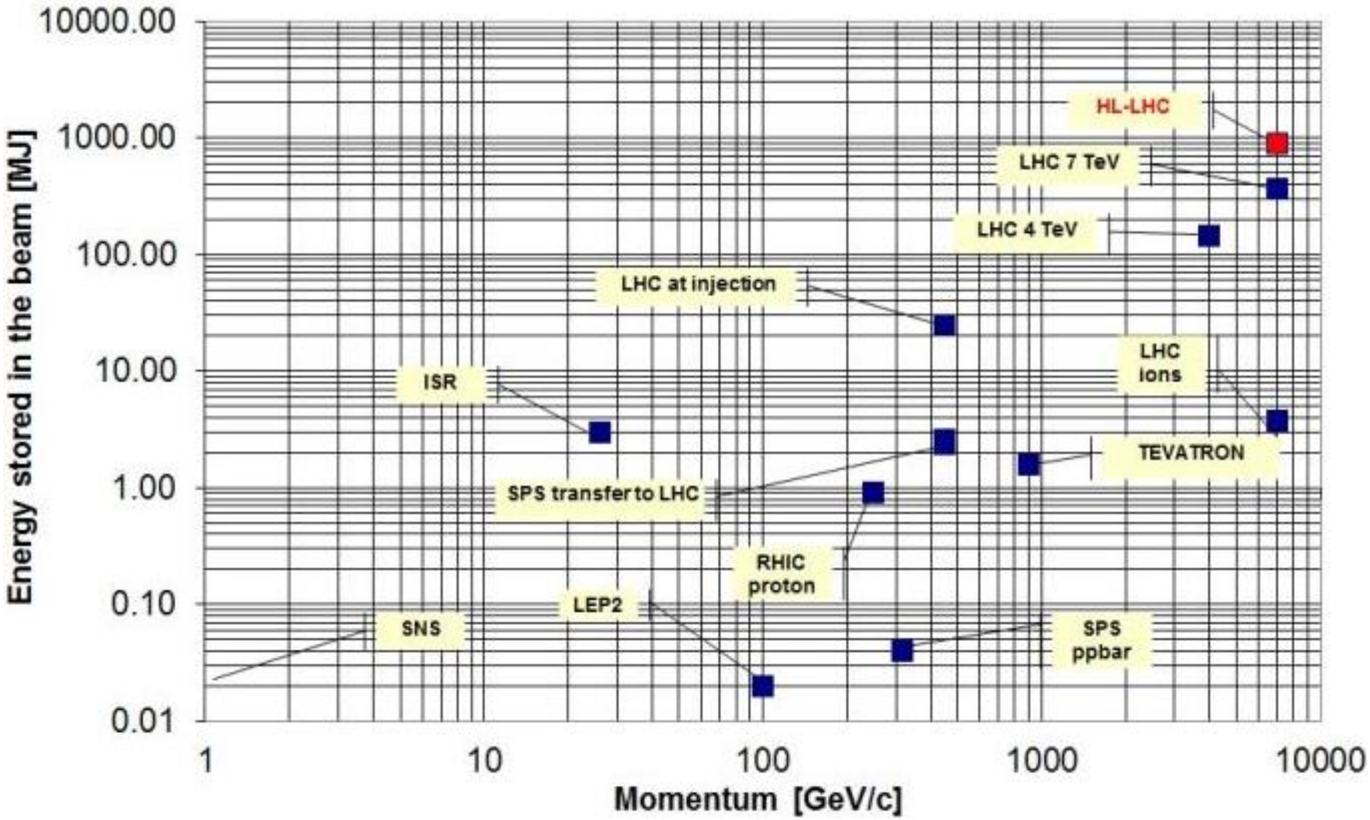
best failure detection time = 40µs = half LHC turn

Machine Protection Response time



- Current MPS architecture cannot protect against failures where damage potential is reached within <= 3 turns
- Todays fastest failure is powering failure of nc separation dipole D1 (>10 turns before damage)

Protection Challenges 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.

- 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.

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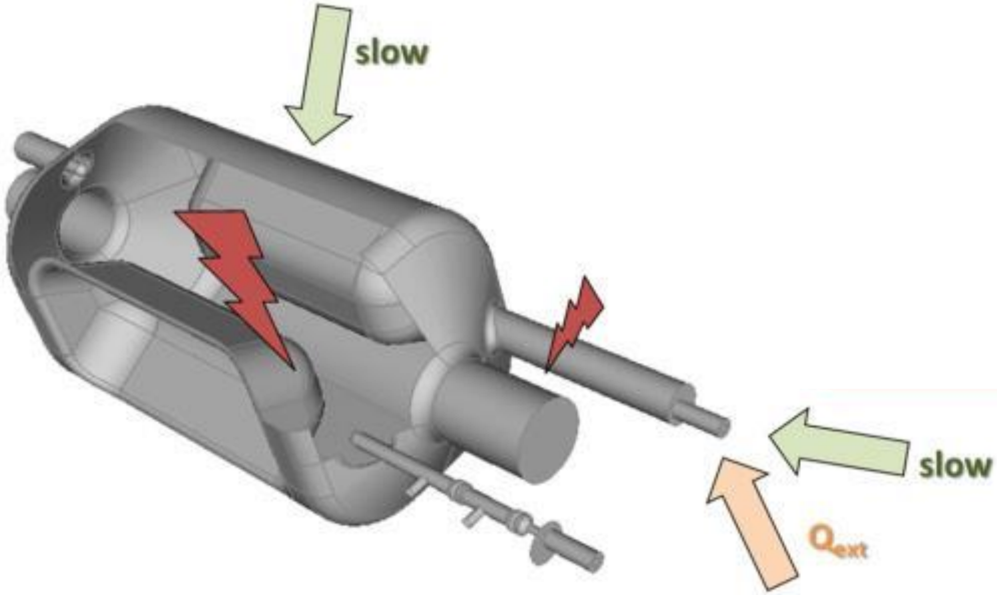
Failure classifications of crab cavities

Slow/fast (external) failures

- Power cut
- Cryogenic failures
- Mechanical changes (tuner problem)
- …

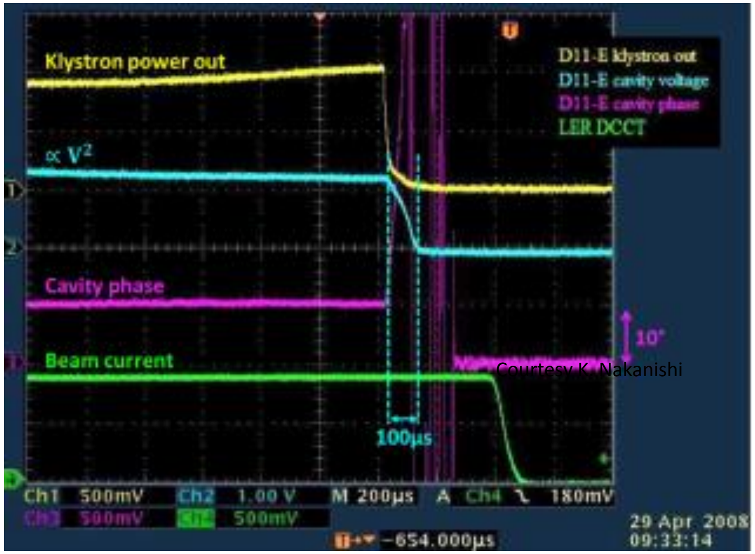
Timescales > 15 ms.

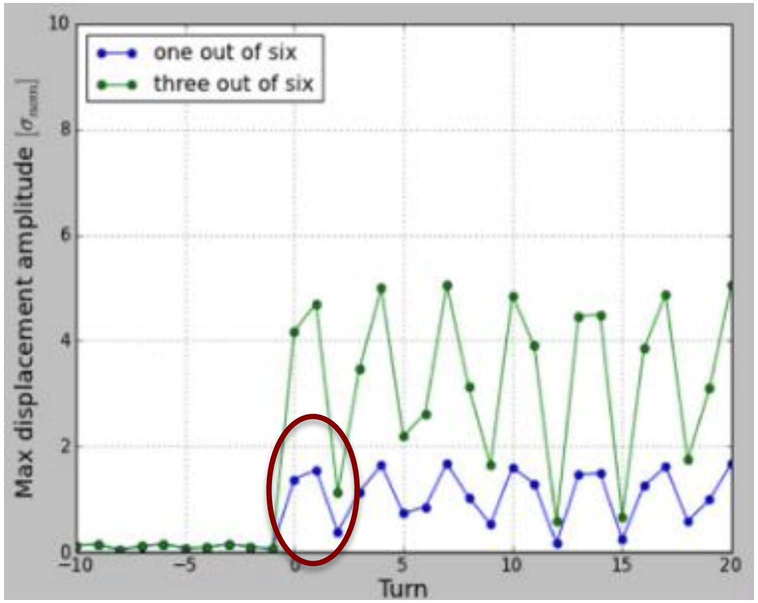


Courtesy: T.Baer

New ultra fast failures due to Crab Cavities

- Little experience with ultra-fast CC failures - KEKB case suggests possibility of single-turn failures (true magnet quench?!)
- (Worst case) tracking simulations predict orbit distortion of 1.5σ* within the first turn (1.7σ after 3 turns)
- Orbit distortion modulated by β-tron tune.

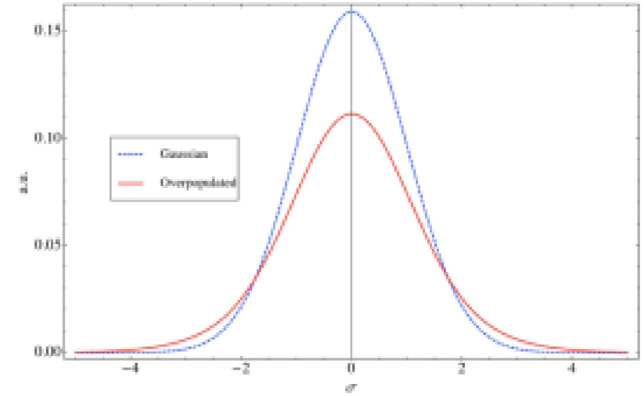


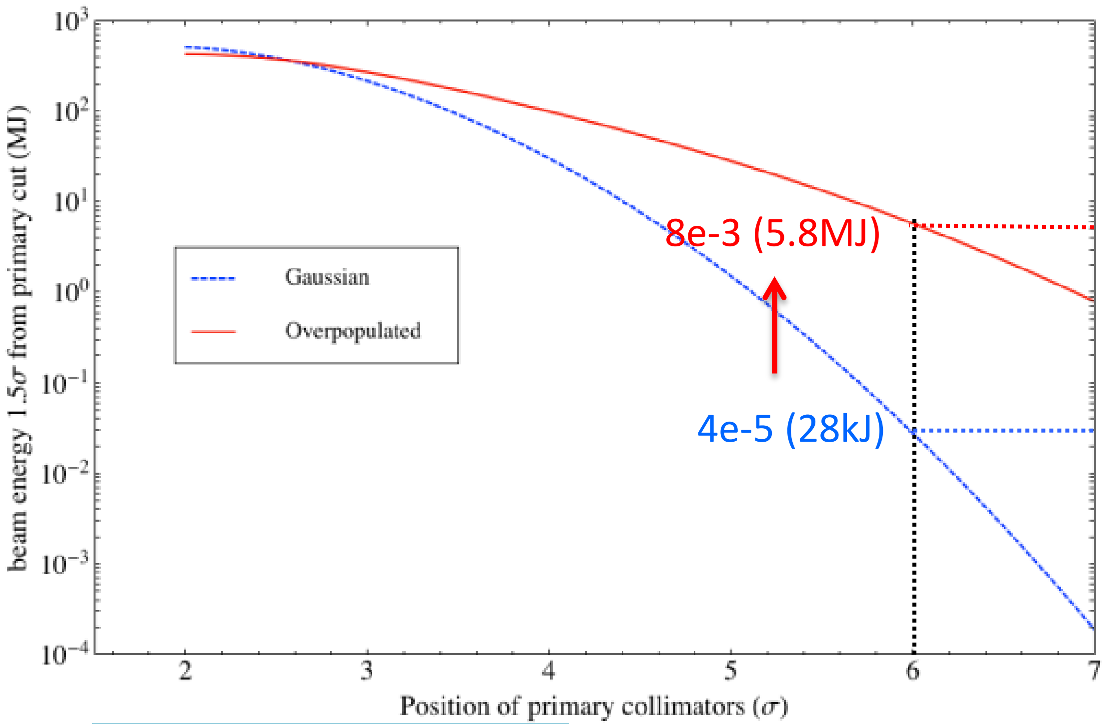


* 3 CCs/IP and beam, 3.3 MV/module, instantaneous drop of in single CC

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]





- Tracking studies show that ~1/3 of this beam is lost within the first 3 turns (see previous talk)
- Potentially > 2MJ of beam impacting on collimators ➔ above (current) damage limit

Courtesy: D.Wollmann

Possible mitigation strategies 1/2

- 'Passive' protection through more and weaker crab cavities per side of IP → New crab-kissing schemes may need 4 CC with max 6.6 MV → **double** kick expected.
- Avoid correlated failures (mechanical/cryo/electrical separation) → Integration?!
- Compensation with fast LLRF control → See next talk.
- Partial depletion of transverse beam tails (1.5σ outside of primary collimators) → **Reduced detection time budget** and redundancy in BLMs (depends on halo).
  - Hollow electron-lens, tune modulation, excitation of halo particles with AC dipole,... → Effectiveness in LHC to be proven

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Possible mitigation strategies 2/2

- Improvement of MPS architecture
  - Direct dump links from CCs to IR6
  - Accept (more) asynchronous dumps with risk of local damage
  - Additional disposable absorbers
  - More abort gaps?!

→ All come with potential decrease of safety/availability

- Investigate use of fast failure detection mechanisms as redundancy to LLRF
  - RF field monitor probe
  - Diamond beam loss detectors
  - Head-tail monitors
  - Power transmission through input coupler
  - …

→ High **reliability** method required.

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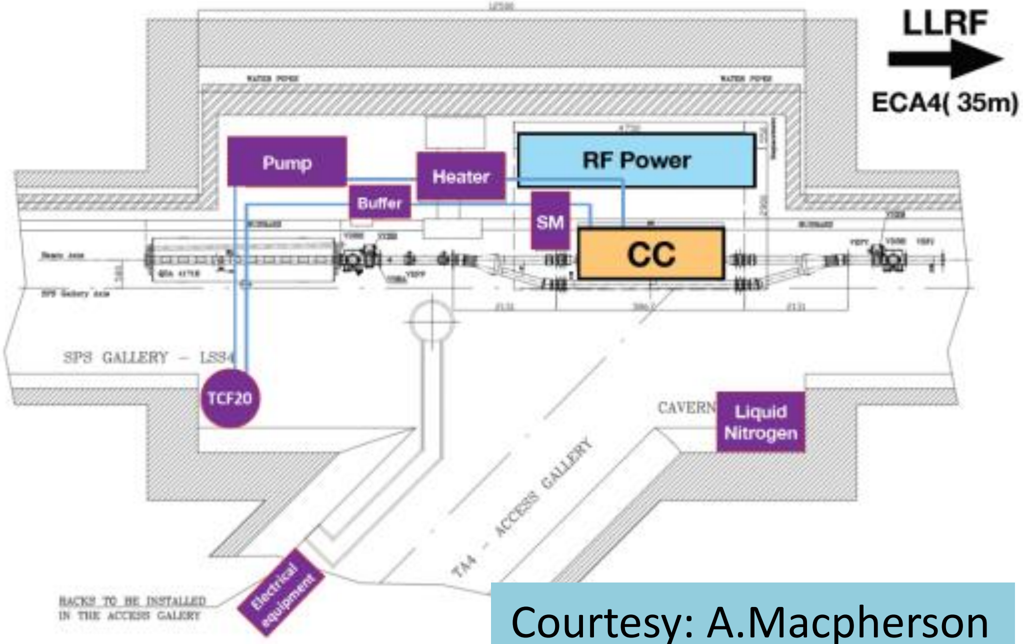
Towards integration of CCs in MPS

- Determine realistic worst-case failure scenarios and time-scales of (chosen) crab-cavity design during SM18 and SPS tests

- SPS test as first occasion to validate (new) failure detection mechanisms

- Measure transverse beam tails with 25ns (2015)

- Revisit damage studies with above input and final optics to derive protection requirements



Courtesy: A.Macpherson

Conclusion

- Multi-fold redundancy for detection of critical failures has proven vital for safe LHC operation during run1.
- New ultra-fast failure modes expected due to crab cavities
  - In combination with overpopulated tails this cannot be safely protected today
  - Mitigation methods (halo depletion) may have knock on effect for detection of other failures via beam losses
- (Urgently) need experimental confirmation of CC's worst case failure scenarios for development of functional requirements to machine protection backbone
  - Active protection will require complex combination of LLRF, redundant failure detection, halo depletion + interlocking -> Detrimental to dependability of overall system & performance!

High
Luminosity
LHC

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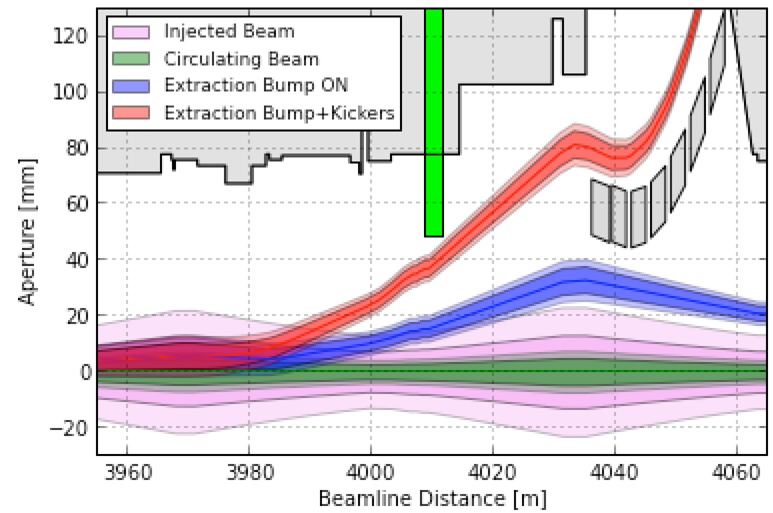
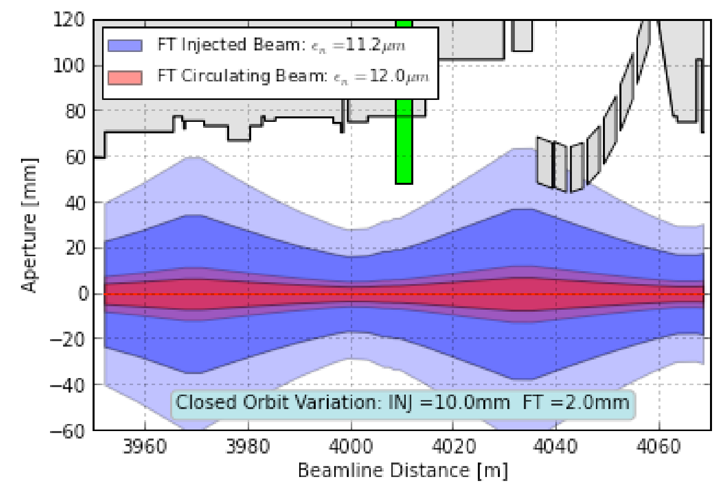
Machine Protection during SPS test

- To avoid LHC extraction (firing of kicker) CC out position must be interlocked with TT40 extraction
- Beam position vs beam loaded power (extraction bump, orbit oscillations after injection,…)
  - Interlocking in SIS only at end of cycle
  - Requires CC internal protection (+ current measurement on correctors?) connected to SPS BIS
- Detailed loss studies as for LHC





Courtesy: A.Macpherson

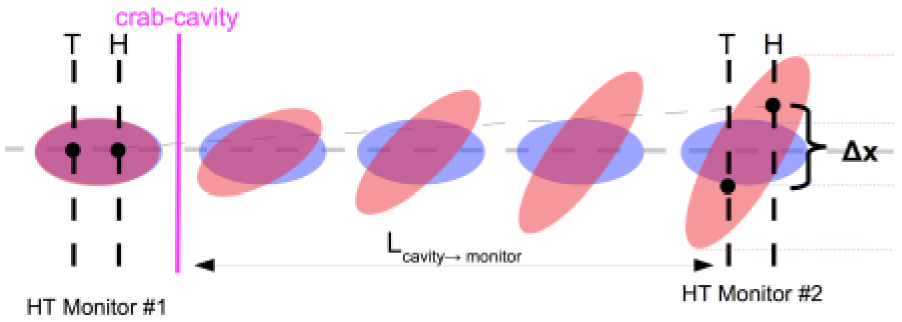
CCs in the SPS

Closed Orbit

• LHC beam: 450 GeV, Cavity Voltage: 3 MV

• Observe: Closed orbit transverse position at 90o phase advance from CC

• Global scheme in deflecting mode: ~1mm offset, no amplitude growth.



Head Tail: see R. Steinhagen 4th LHC CC workshop

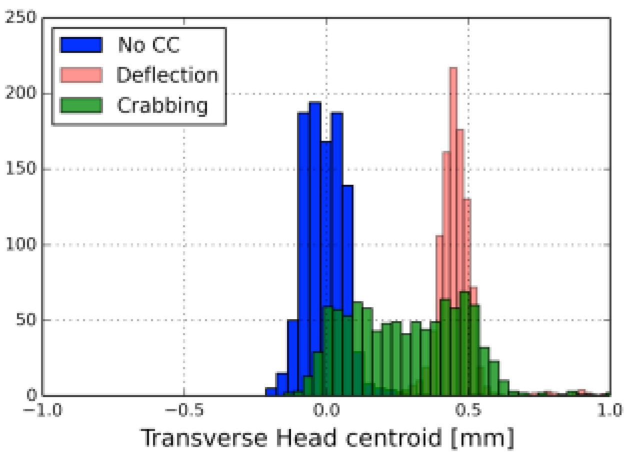
• **Head Tail**

• LHC beam: 450 GeV, Cavity Voltage: 3 MV.

• Observe: transverse beam centroids at SPS HeadTail monitor

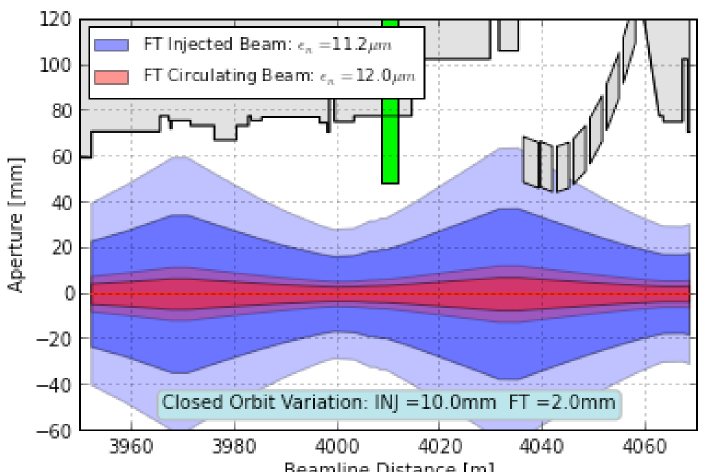
• Crabbing Mode: Expect broadening of head-tail centroids

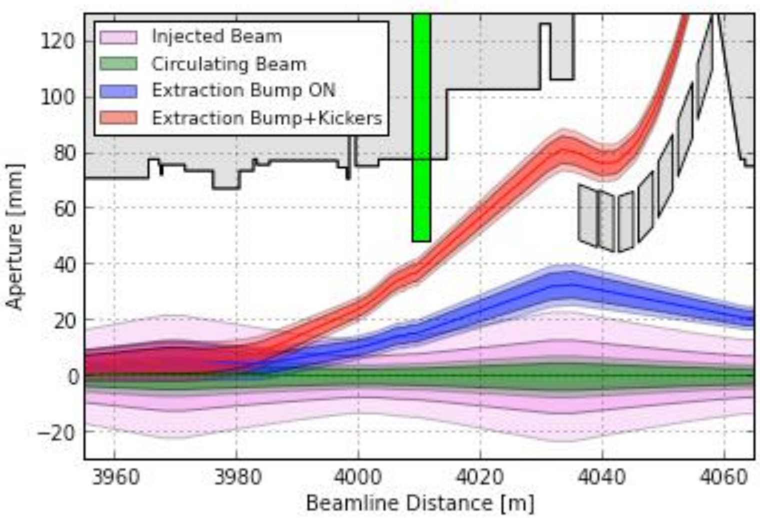
• Deflecting Mode: No significant change in head-tail centroids

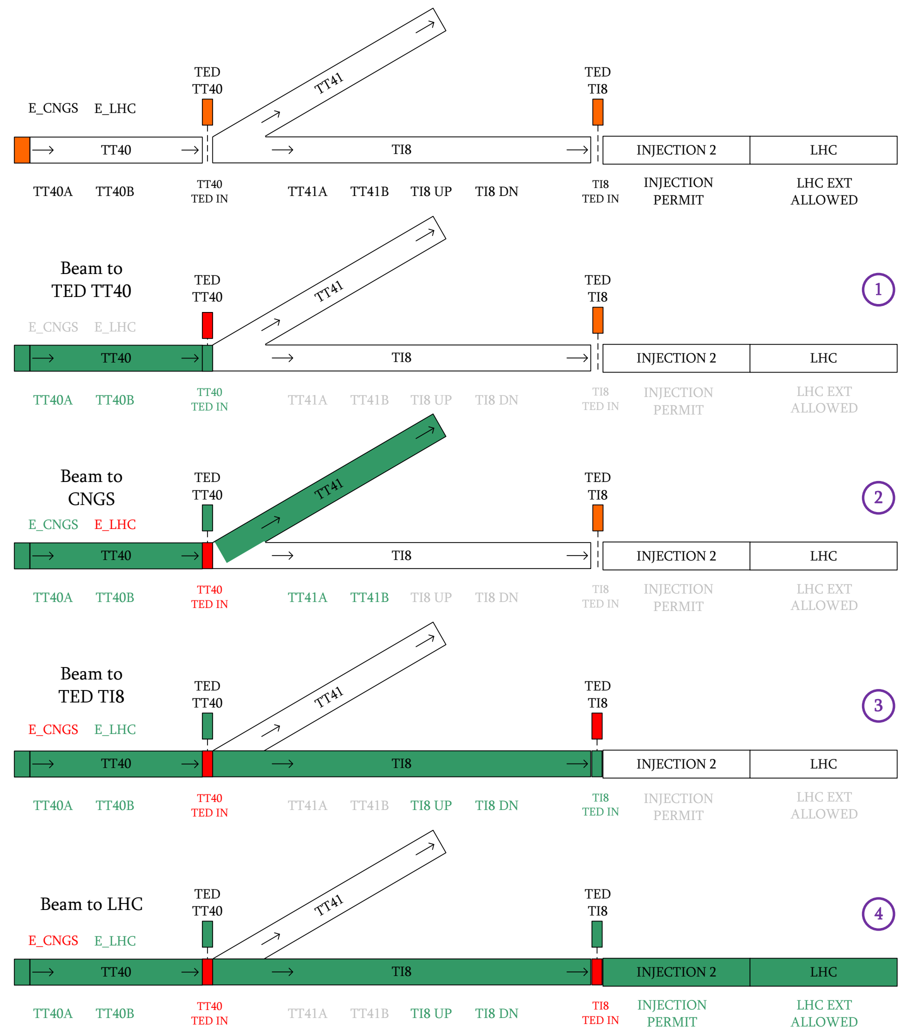


MADX thin track simulations

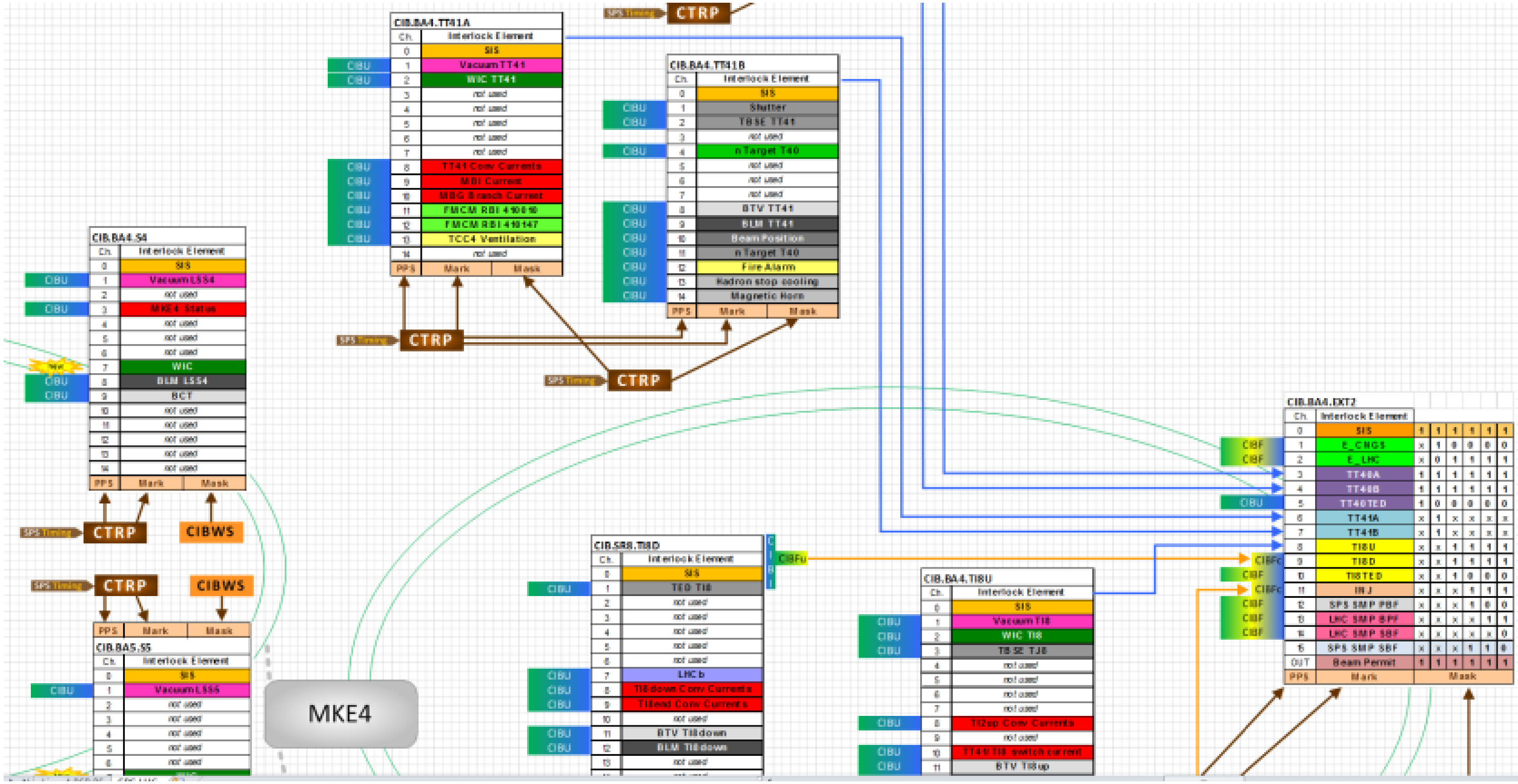
SPS Extraction Interlock







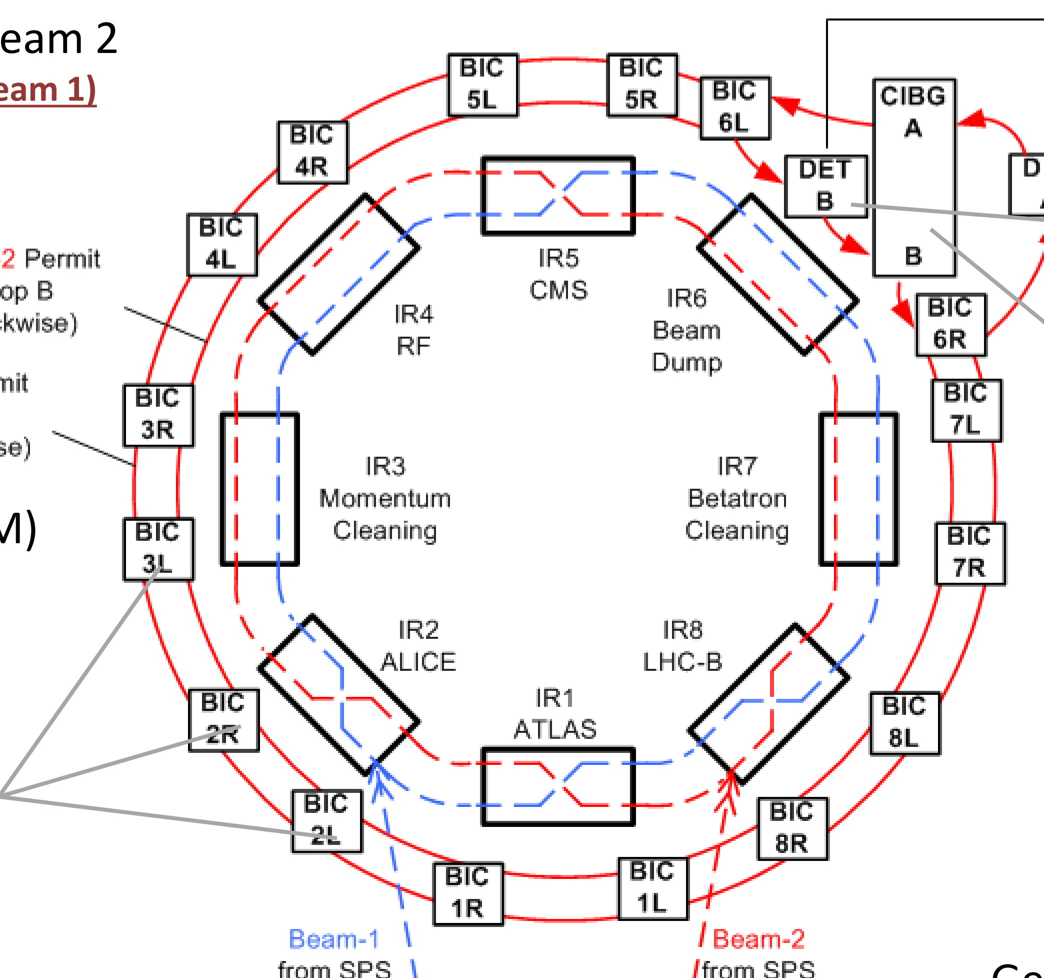
SPS Extraction Interlock - BIS



Beam Interlock System

Example for Beam 2

(Duplicated for Beam 1)



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