Machine Protection Issues for Crab Cavities – SPS test and HL-LHC

M. Zerlauth

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

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

- Short introduction to crab cavities
- Challenges for Machine Protection in view of HL-LHC and crab cavities
  - New ultra fast failures due to crab cavities
- Possible mitigation strategies
- First thoughts on CC tests in the SPS
- Conclusions

HL-LHC baseline parameters

parameter	value
energy [TeV]	7
protons/bunch [10^{11}]	2.2 (~2x nominal)
bunches	2808
bunch spacing	25 ns
rms bunch length [cm]	7.55
β function at IP1, 5 [m]	0.15 (~1/4 nominal)
normalized rms emittance [μm]	3.75
full crossing angle [μrad]	590 (~2x nominal)

Goal of High Luminosity LHC (HL-LHC) as fixed in November 2010

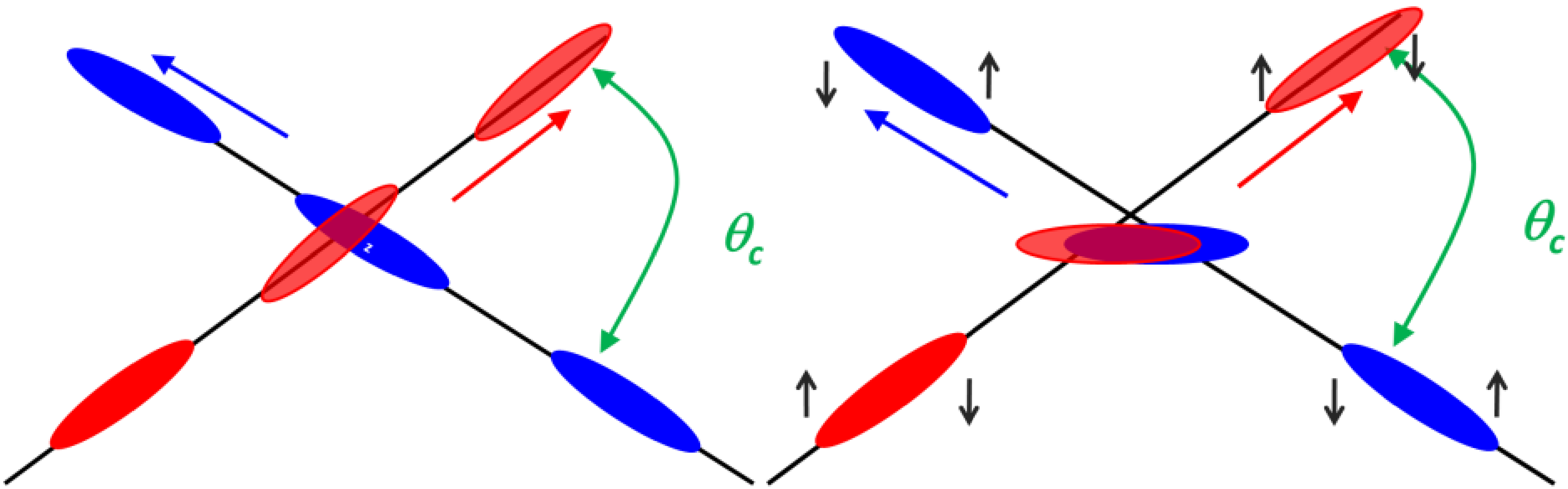
The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of **5×10^{34} $cm^{-2}s^{-1}$ with levelling,** allowing:

An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **3000 fb^{-1}** twelve years after the upgrade.
This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

CC are an essential ingredient to obtain this goal:
First for performance as CC are critical to increase peak lumi!
Secondly as method of levelling
Thirdly to improve the data quality by reducing pile up density

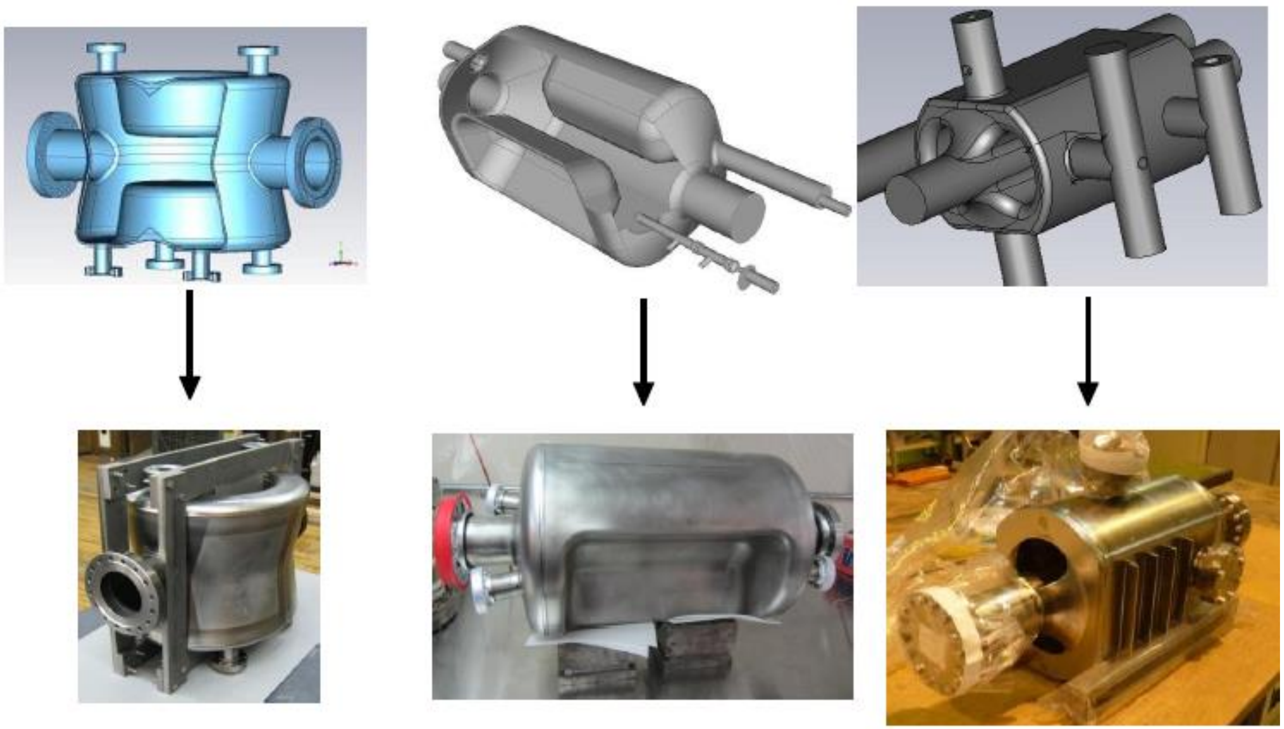
Effect of the crab cavities



- **RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" and then luminosity is maximized**
- ***Crab cavity maximizes the lumi and can be used also for luminosity levelling: if the lumi is too high, initially you don't use it, so lumi is reduced by the geometrical factor. Then they are slowly turned on to compensate the proton burning***

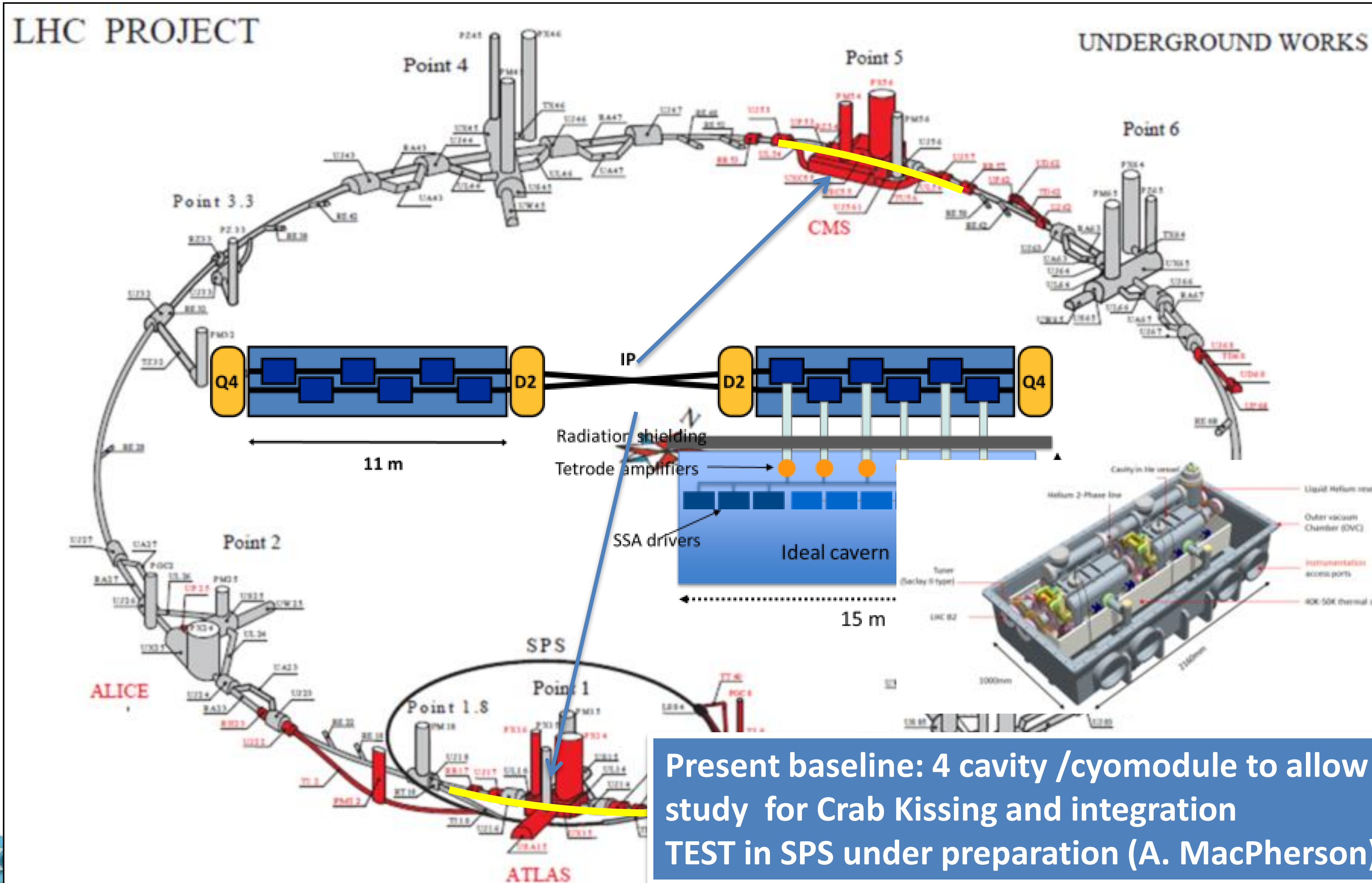
Situation: from drawings to reality…

All Prototypes in Bulk Niobium (2011-12)



LARP-BNL LARP-ODU-JLAB UniLancaster-CI-CERN

Crab Cavities for fast beam rotation



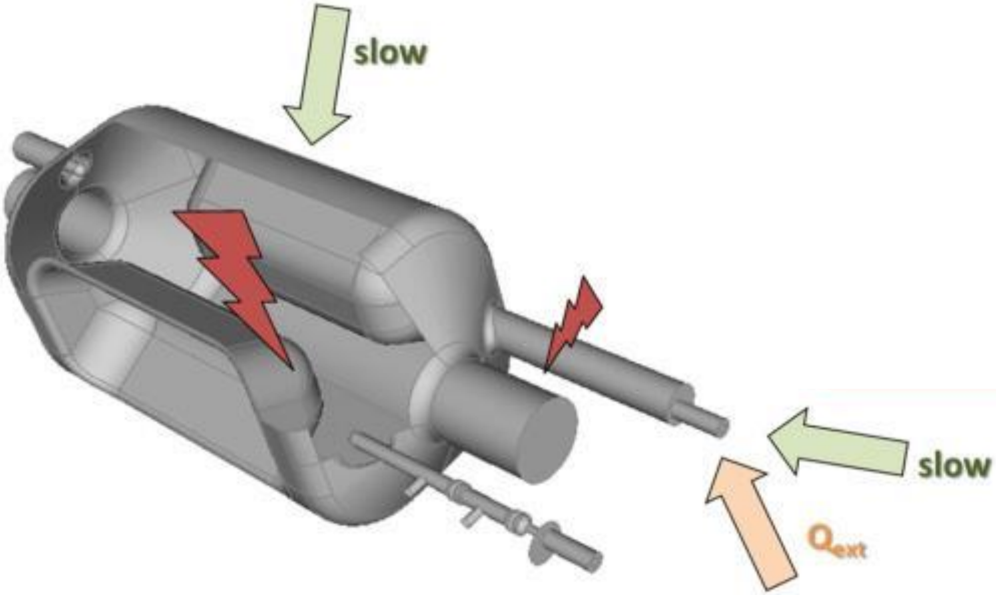
Present baseline: 4 cavity /cyomodule to allow study for Crab Kissing and integration
TEST in SPS under preparation (A. MacPherson)

Failure classifications of crab cavities

Slow/fast (external) failures

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

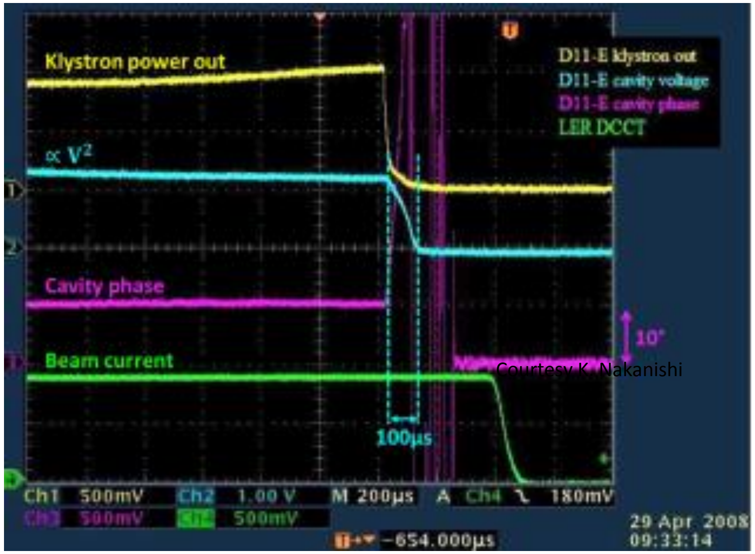
Timescales > 15 ms.

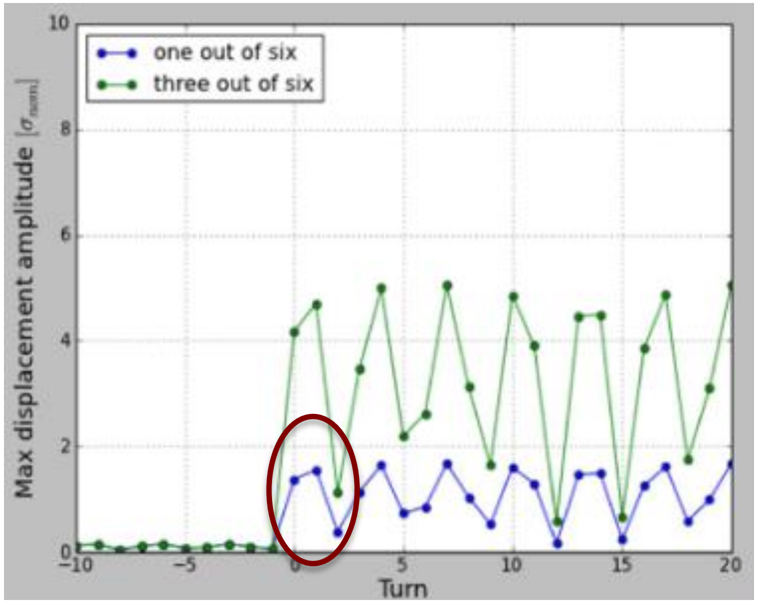


Courtesy: T.Baer

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.

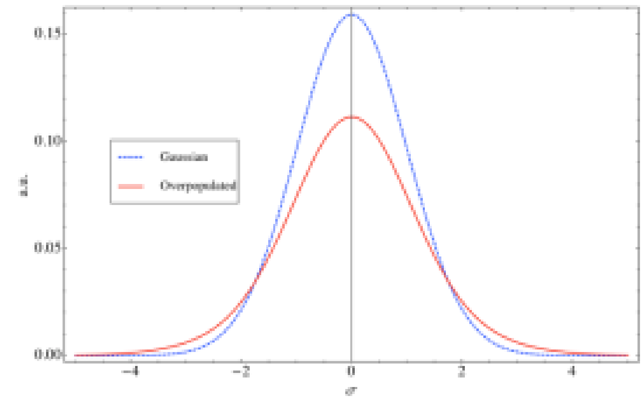


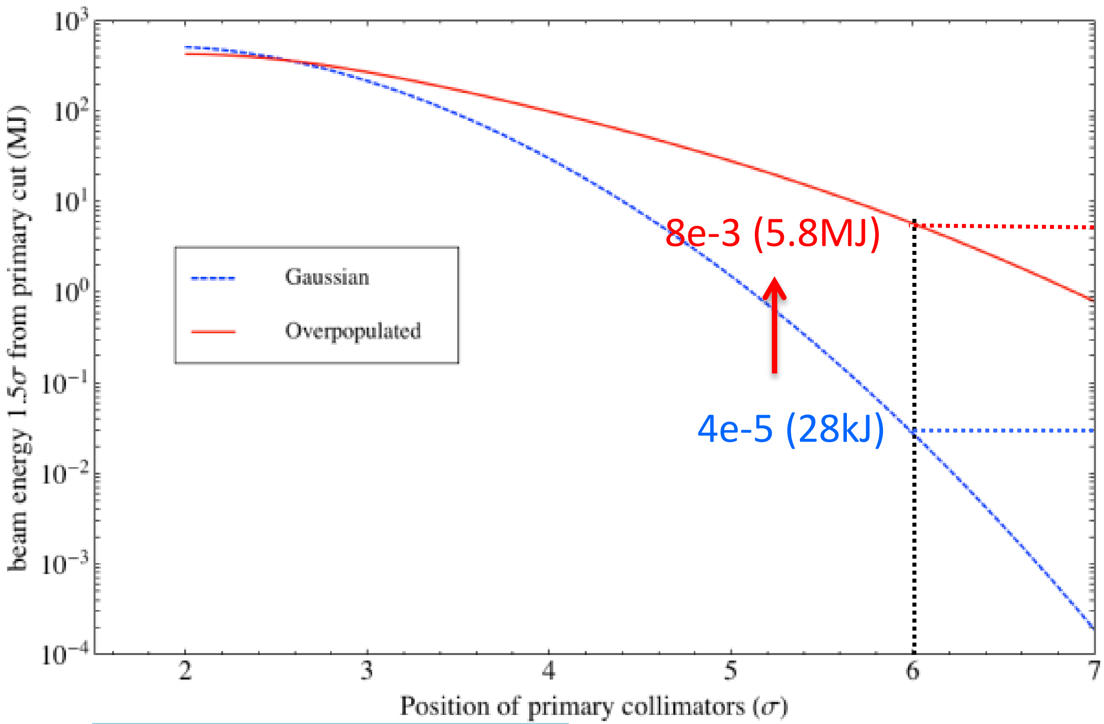


* 3 CCs/IP and beam, 3.3 MV/module, instantaneous drop of in single CC

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

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
  - …

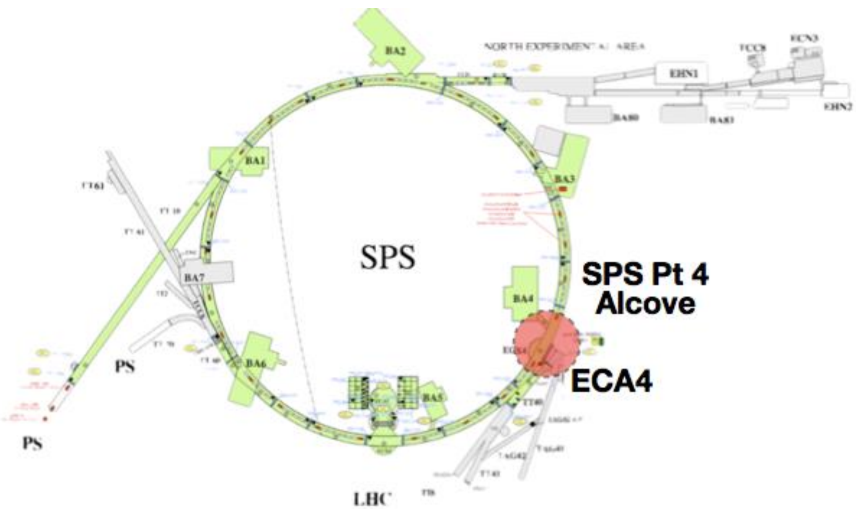
High **reliability** method required.

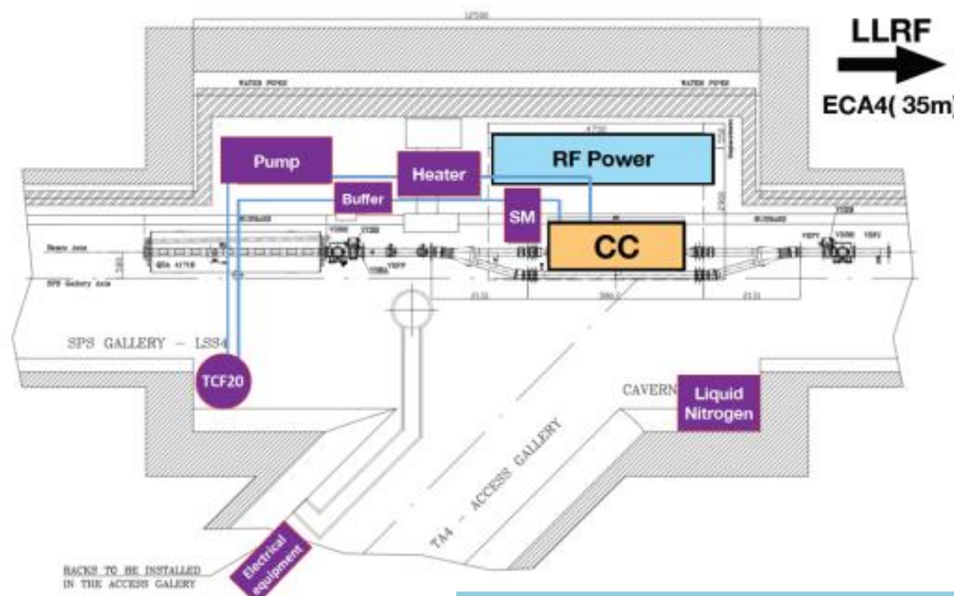
High Luminosity LHC

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?





Courtesy: A.Macpherson

Beam Issues: Compatibility with other SPS user cycles

Horizontal aperture:

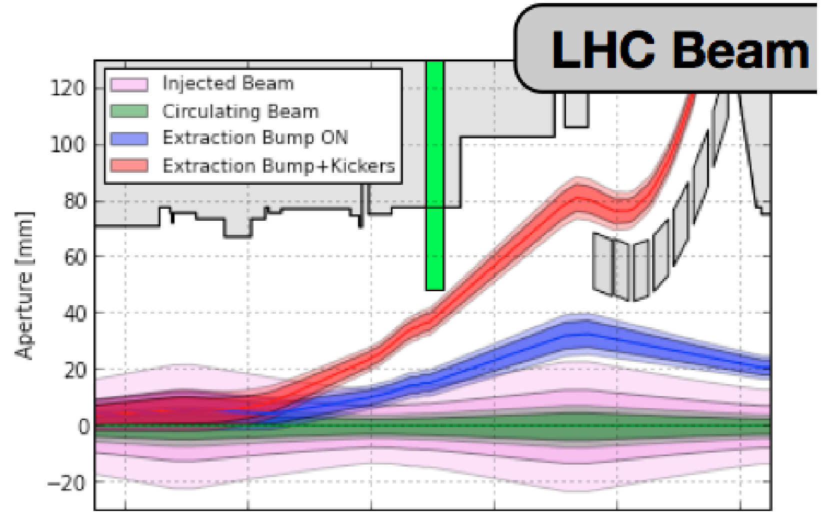
- Crab Cavity = **42mm** (radius)
- Extraction septa = **44.7 mm**
- 35% gain in margin due to βcc

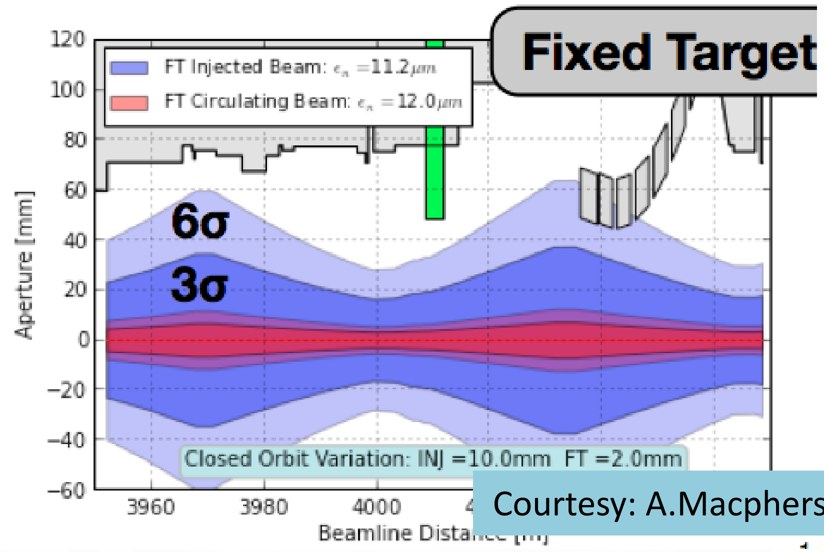
Crab cavities with SPS beams

- **LHC beams: cannot be in when LHC beam extracted**
- **Fixed Target:**
  - **large beams at injection and at slow extraction**
  - Orbit variation at injection >10 mm
  - Orbit drift of up to 6mm in ramp.

Baseline

- **Crabs need dedicated beam time**
  - Compatibility with Fixed Target beam can be checked with an MD ...

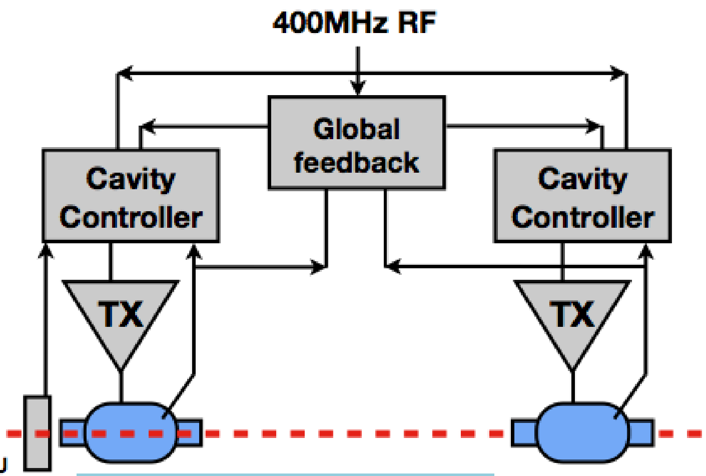


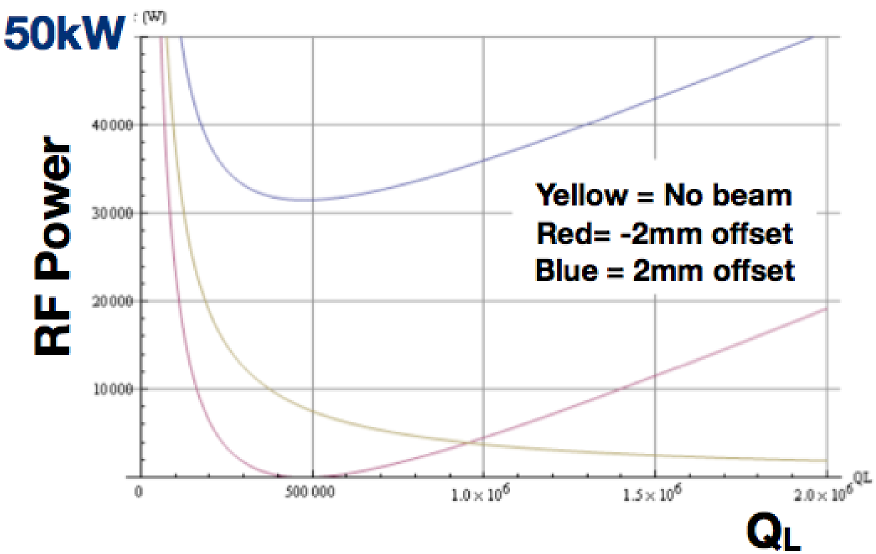


Courtesy: A.Macpherson

Beam issues: Machine protection

- **MPS Possibilities:**
  - 2 crabs per cryomodule => LLRF structure is the same as for the LHC
  - Can test full range of LLRF procedures and MPS mitigations
  - Helium tanks linked by bi-phase line: use isolated quenches for MPS tests
- **SPS MPS Considerations**
  - Closed orbit drift in ramp up to 6mm => complications with cycling beam
  - Correctors at SPS Pt 4 in interlock chain => complicates orbit centering

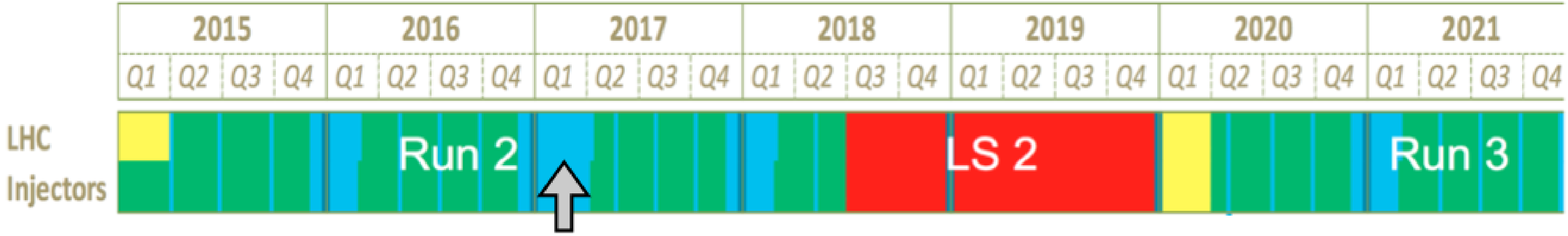




Courtesy: A.Macpherson

Schedule

- **CERNs accelerator schedule**
  - **Constraint:** COLDEX running in 2014/2015



EYETS: 19 wks (end of 2016 run)

Can we be ready to install in Q1 2016? .... challenging

What is a more feasible schedule?

- **End of 2015:** Remove COLDEX from SPS. Install support table + cabling
- **EYETS:** Install 1st Cryomodule: **Test cavity in 2017.**
- **End of 2017:** Exchange cryomodule: **Test 2nd cavity in 2018.**
- **Start of LS2:** Finish SPS beam tests

If we are not ready to install a cryomodule at start 2016 => limited to two cavity types tested in the SPS (unless we can to a fast cryomodule exchange)

20

Courtesy: A.Macpherson

Conclusion

- New ultra-fast failure modes expected due to crab cavities
  - In combination with overpopulated tails this cannot be safely protected by todays LHC MPS architecture
  - 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 -> Profit from SPS tests to do so
- Next: Put in place document with Alick for interlocking strategy

High
Luminosity
LHC

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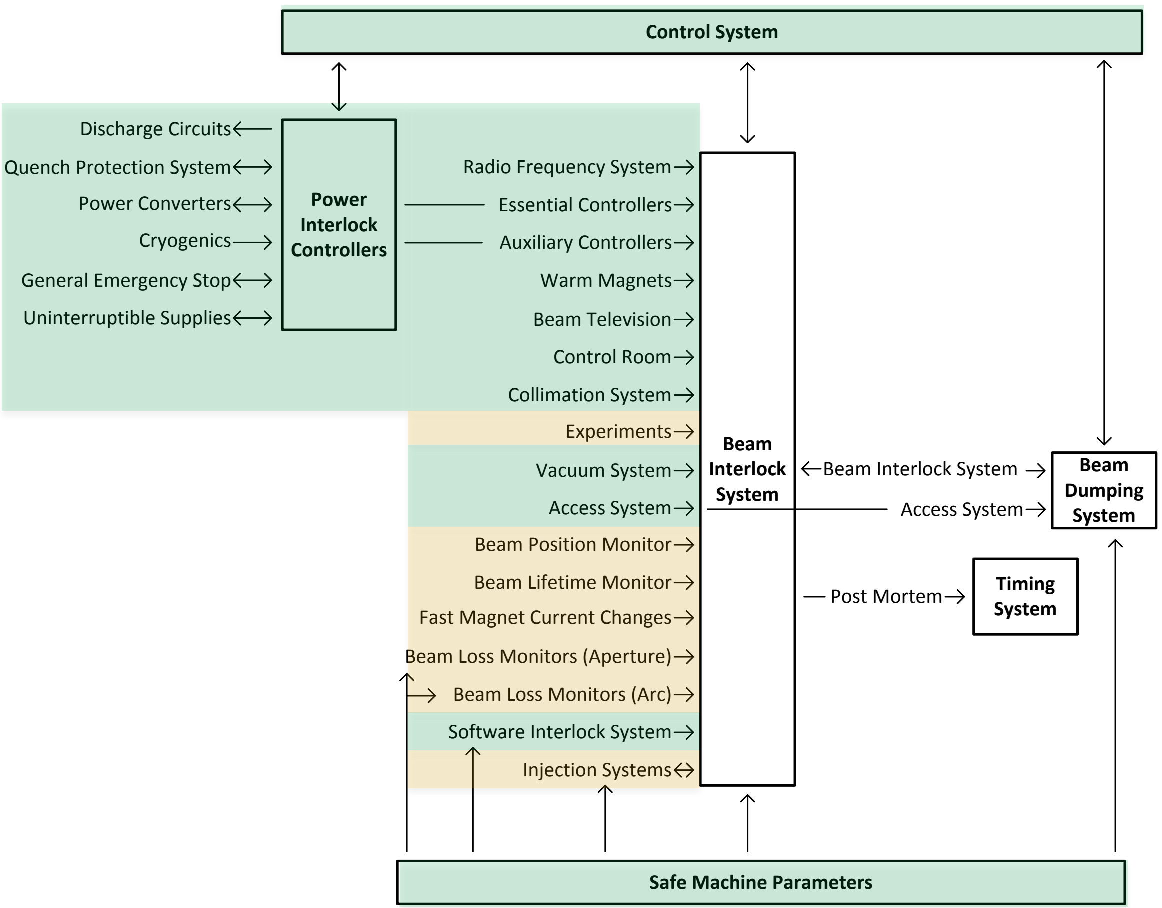
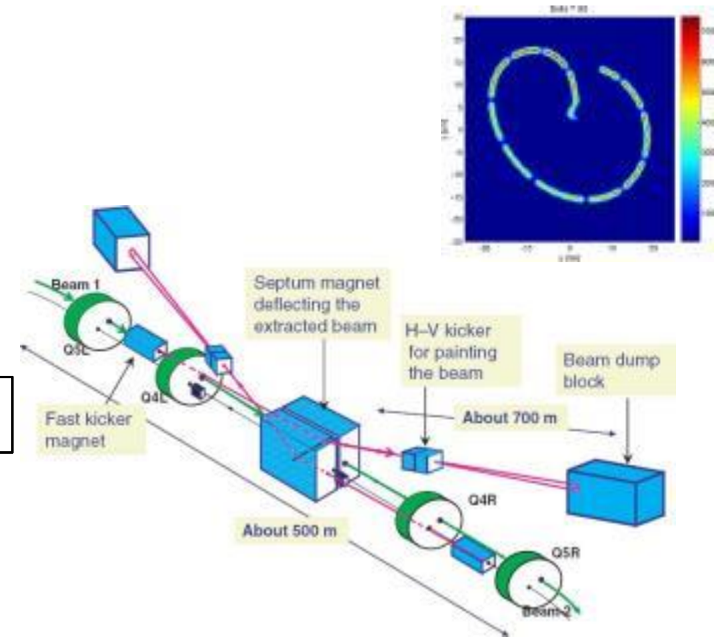
LHC Failure scenarios and their mitigation

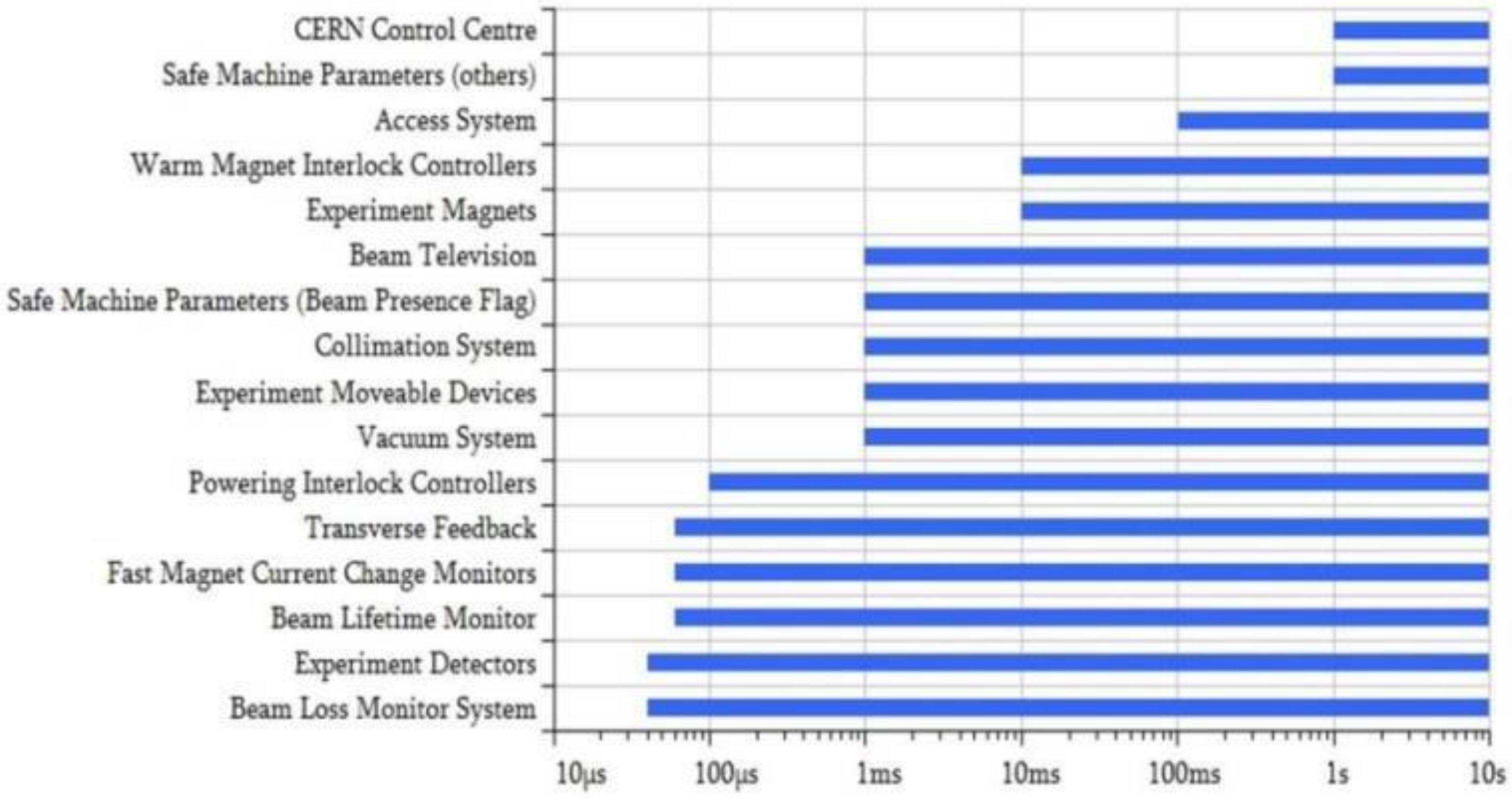
- Three classes of failures considered for LHC protection
  - Ultra Fast failures (single beam passage during e.g. beam transfer, injection,…): passive protection with collimators and absorbers
  - Fast failures (few LHC turns following beam losses, certain fast powering failures,…): active protection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

Machine Protection Architecture



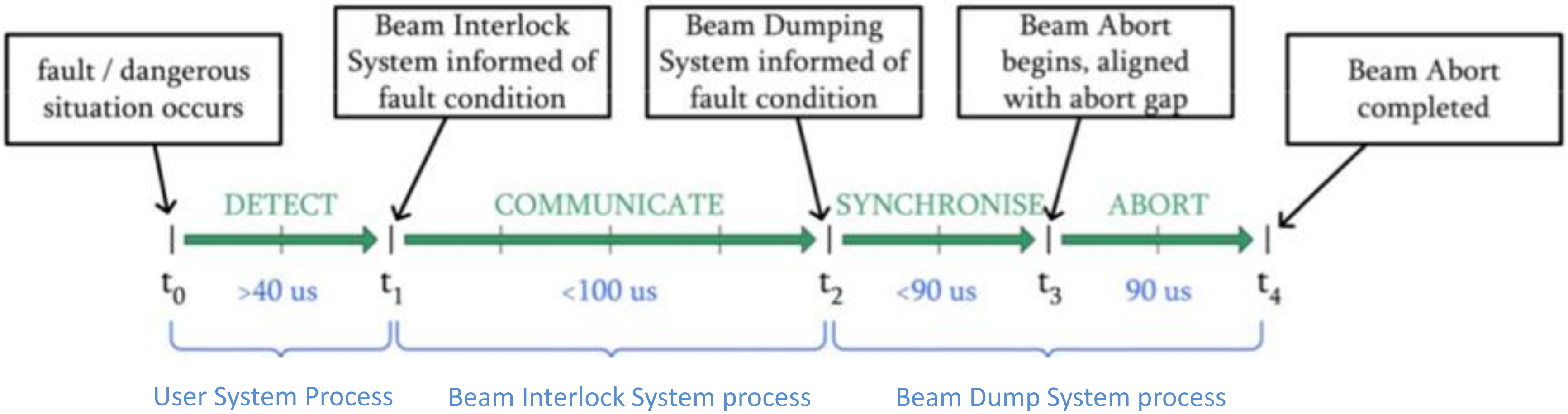


Failure detection time @ LHC today



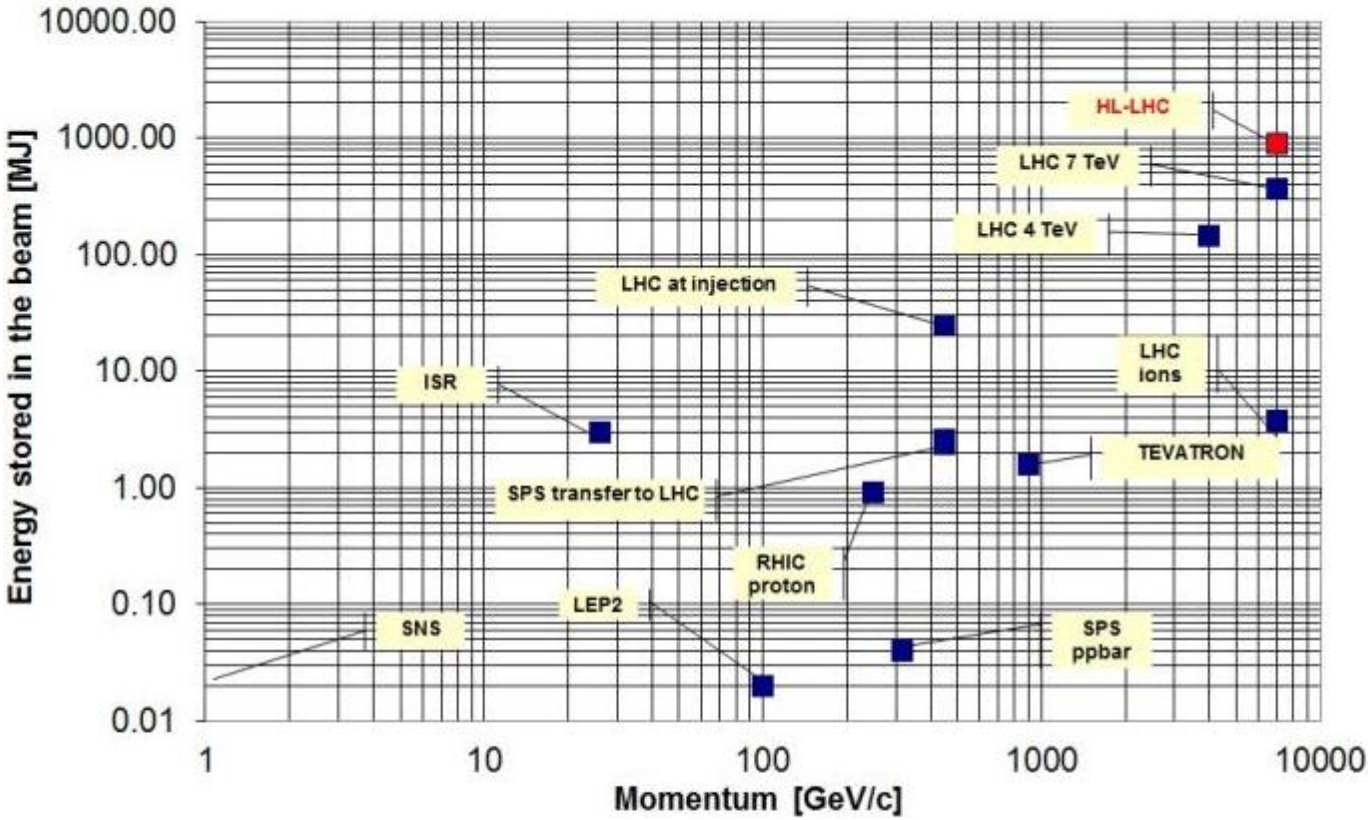
best failure detection time = 40µs = half LHC turn

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.

- **Horizontal aperture:** Crab Cavity = 42mm (radius) Extraction septa = 44.7 mm
- • But 35% gain in margin due to βCC **=> CC in ~shadow of MSE**
- **• To consider: Feasibility an upstream absorber.** (~1.5m space @ BA4)
- **• Crab cavities with SPS beams**
- • **LHC beams: CC** cannot be in when LHC beam extracted
- • **Fixed Target:** beams larger at injection and debunching at slow extraction
- **• To consider: Can CC stay in during SPS Fixed target cycle**
- • Implications to the crab cavity MD request

- Wit bump ON : Problem with beam loaded power in tetrodes, hence crabs cannot be IN with bump ON
- BIS until beam is dumped? 100us?!
- LLRF as mitigator of CC faults -> FMCM?

- Max time is 30 min (done with LHC rampdown to get crab cavities out), should not move faster than 15 min
- Potential loss of 20min to move back IN, tetrode to move on support table (for filaments and tetrode 5 min cooldown)

- What happens in case of bad extractions -> not protected by absorber
- Problem of injected beam from PS (closed orbit variations)
- Flux of luminosity debris in IR1&5 -> How to make this study, maybe possible to use FT halo?
- 2 CC in cryostat, could be used to compensate but also fail simultaneously
- Quenches realistically probably on ms range

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.

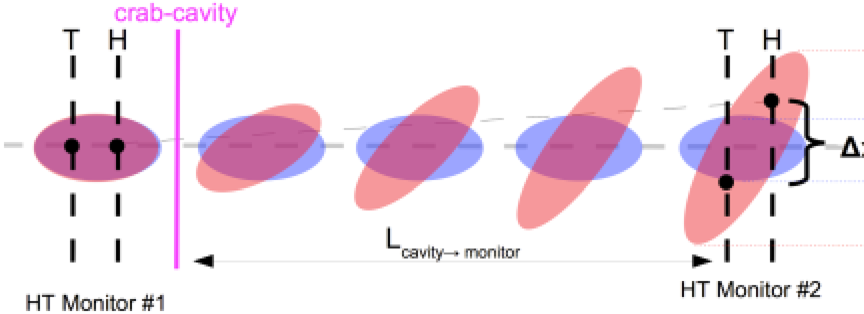
• **Head Tail**

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

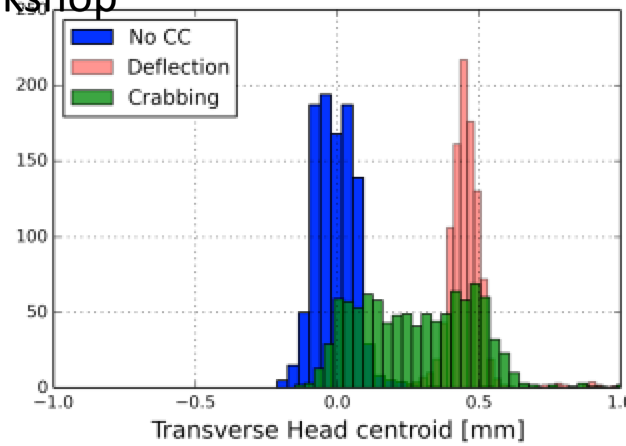
• Observe: transverse beam centroids at SPS HeadTail monitor

• Crabbing Mode: Expect broadening of head-tail centroids

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



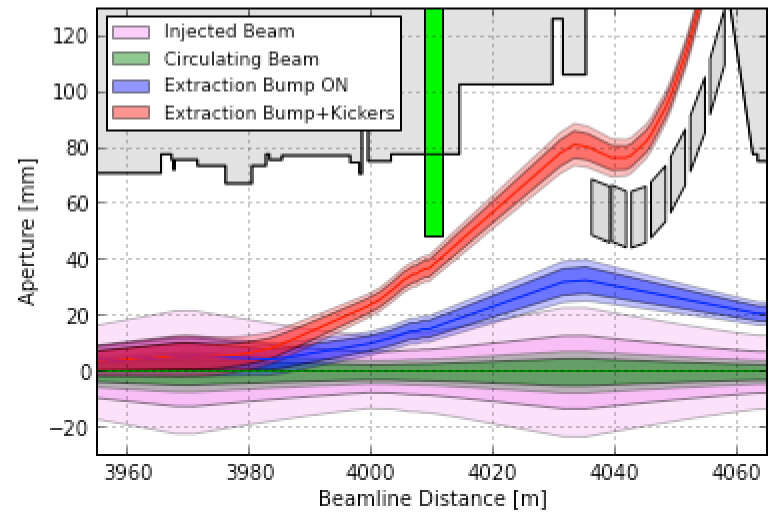
Head Tail: see R. Steinhagen 4th LHC CC workshop

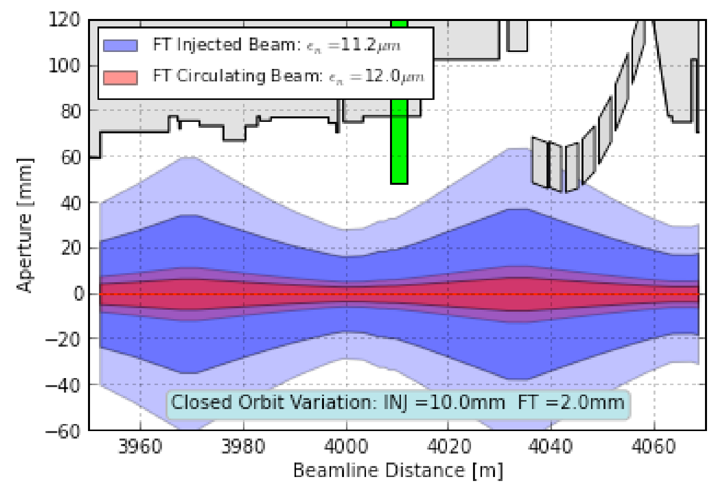


MADX thin track simulations

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

High Luminosity LHC

CCs in the SPS

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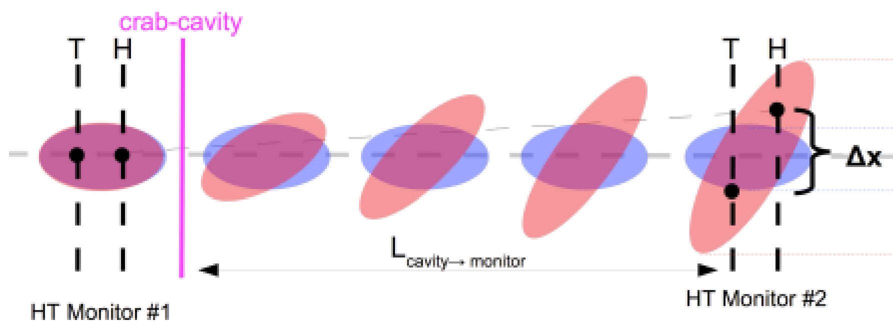

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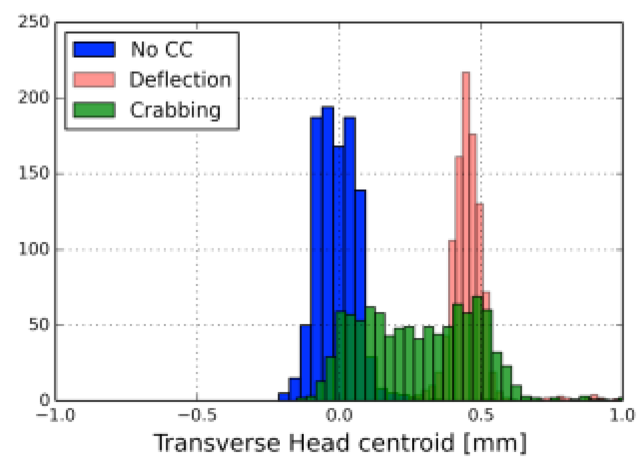
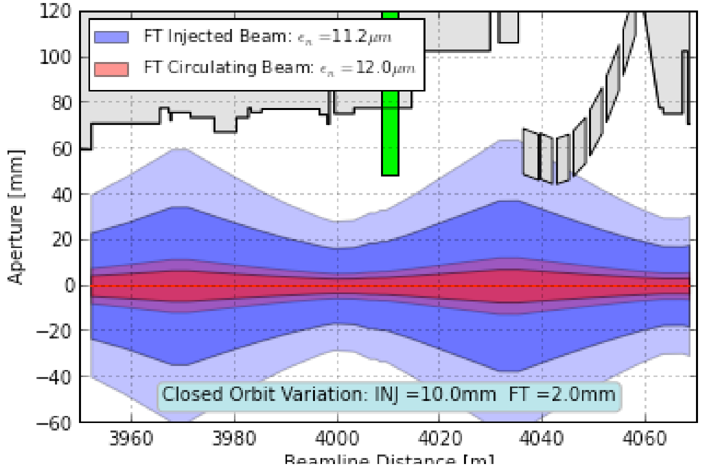
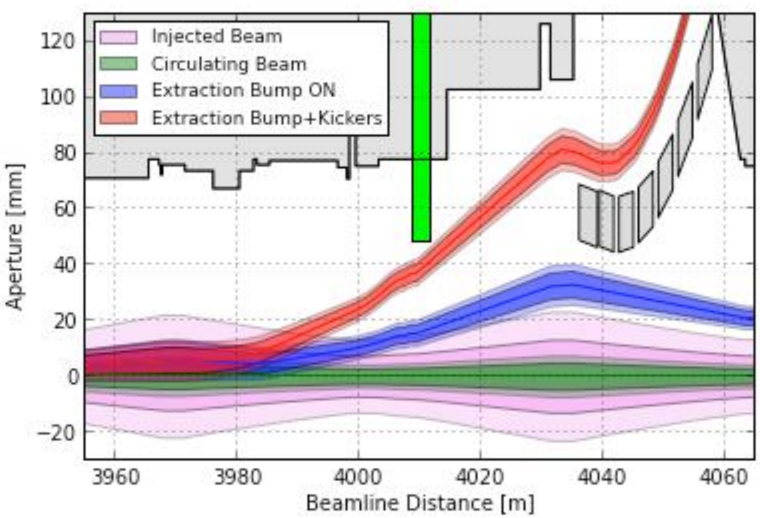
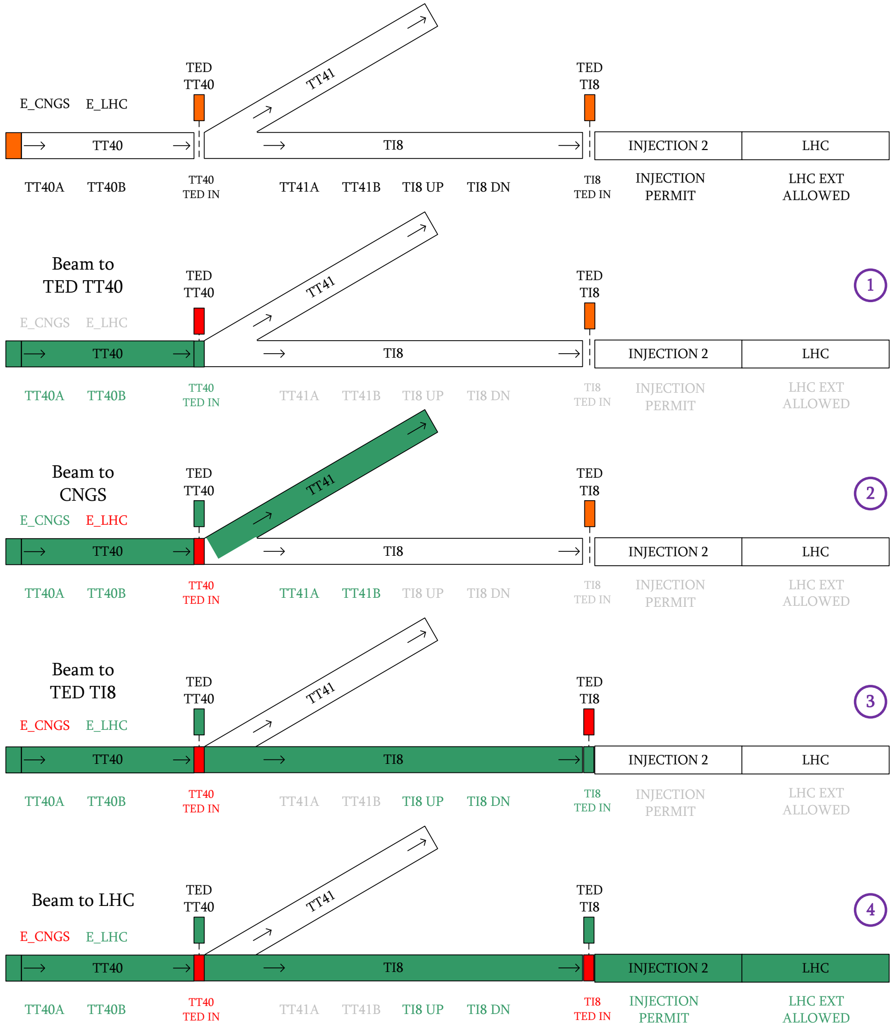


MADX thin track simulations

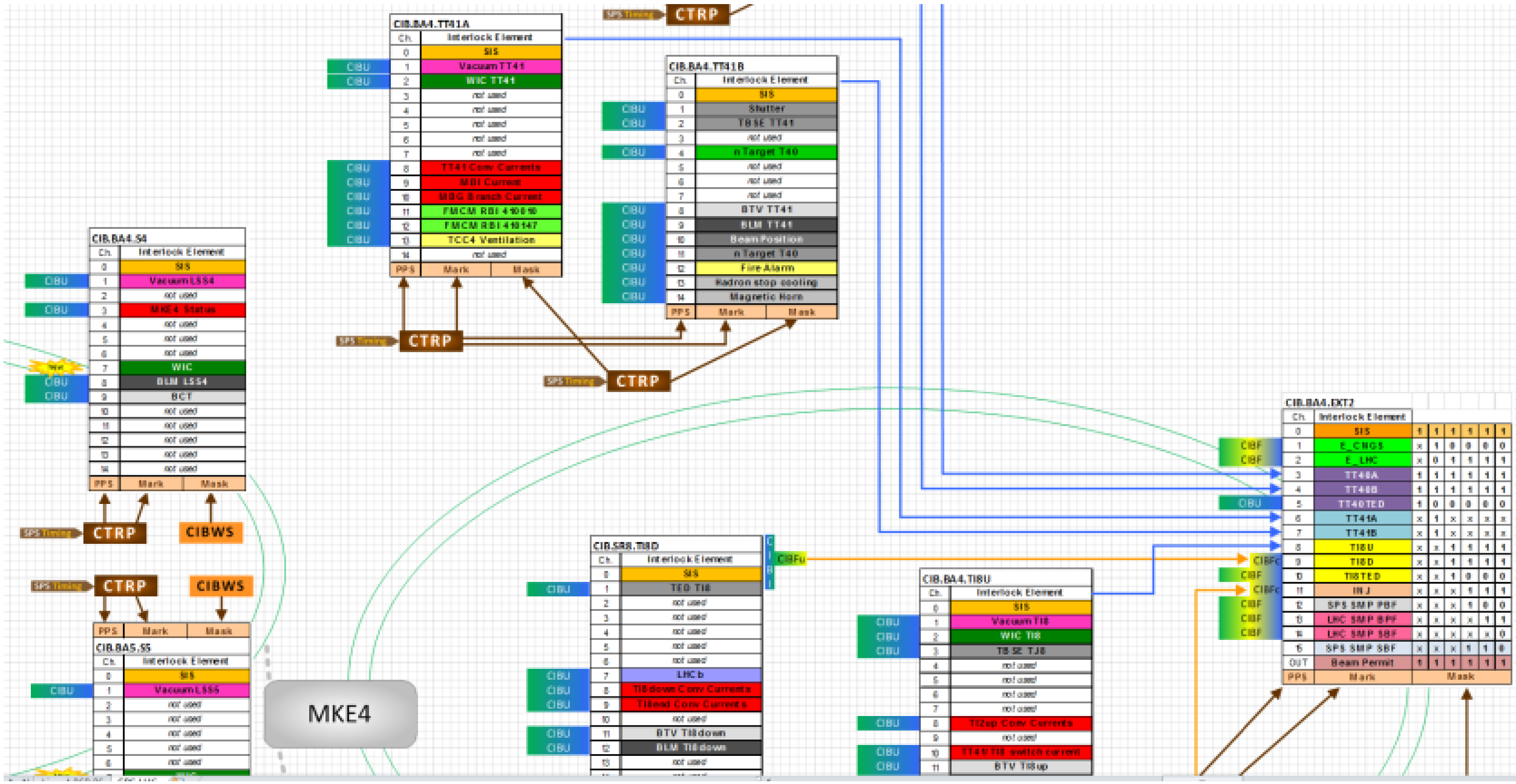
SPS Extraction Interlock







SPS Extraction Interlock - BIS



Beam Interlock System

Example for Beam 2

(Duplicated for Beam 1)