Machine Protection & LHC Beam Operation

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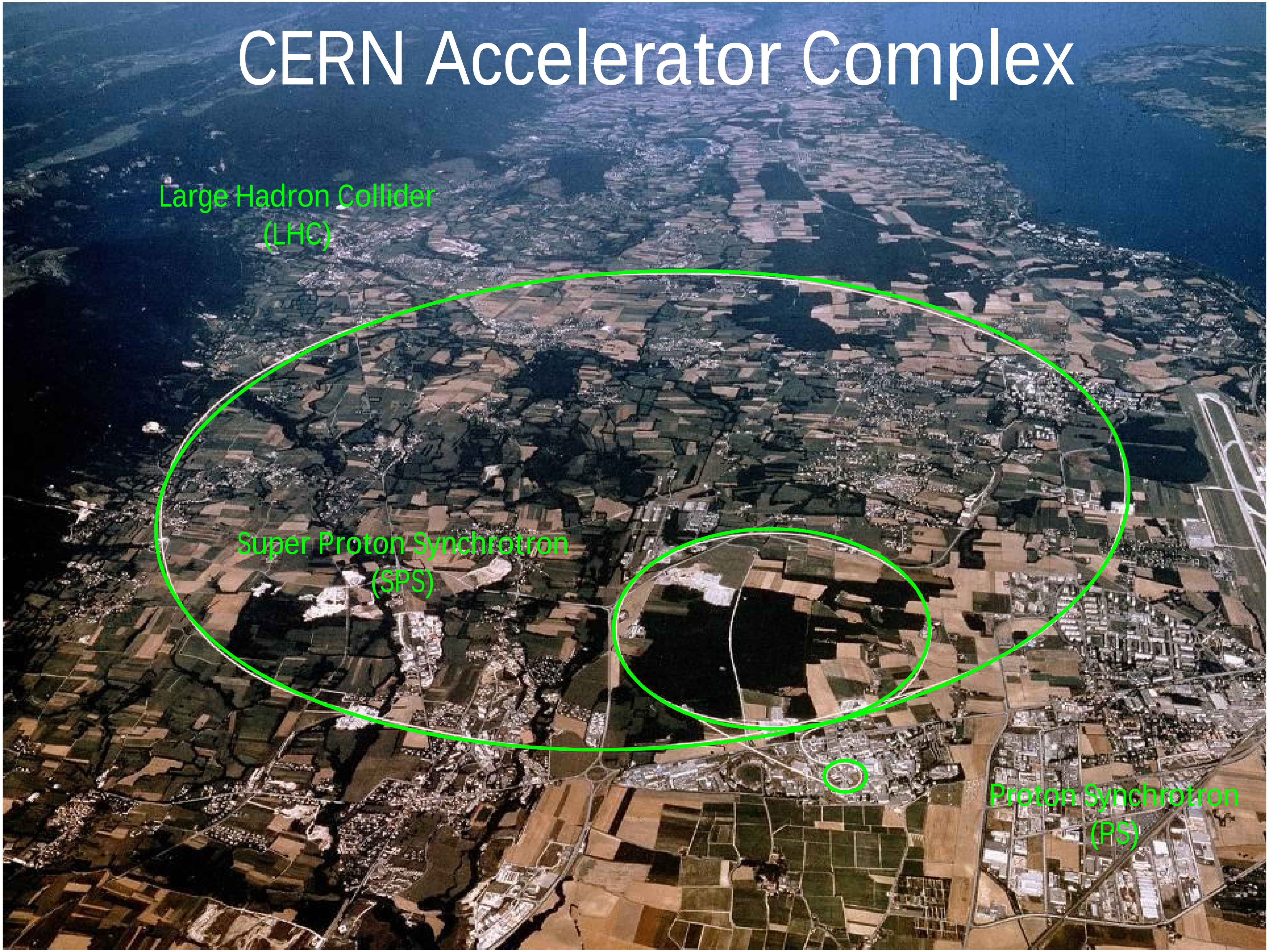
WAO 2012

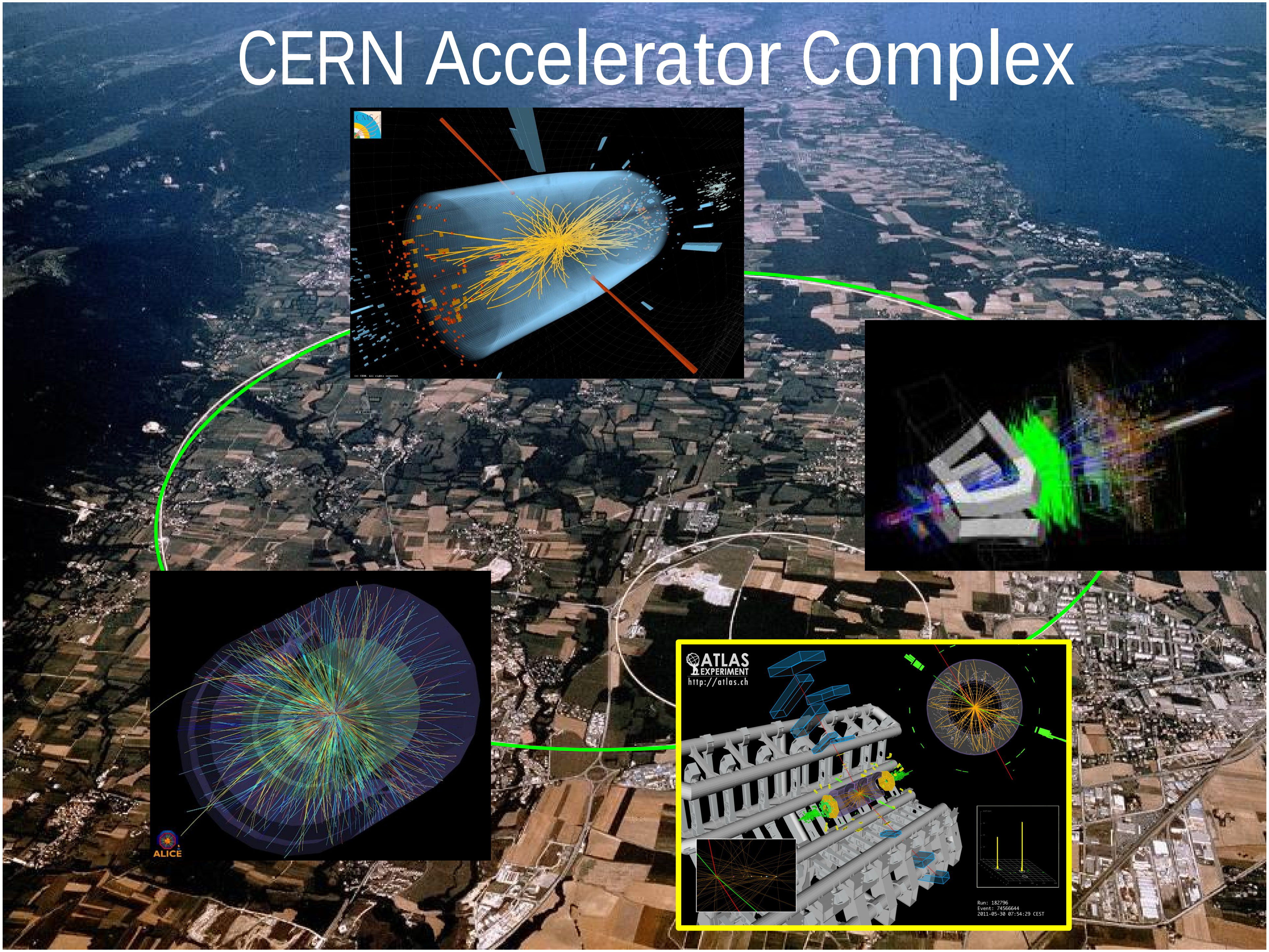
Outline

1. Introduction
2. LHC beam is a dangerous beam
3. LHC Beam Operation /Machine protection
4. Conclusions

CERN Accelerator Complex



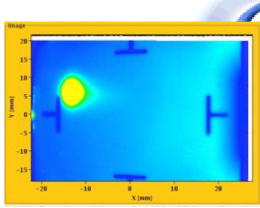
CERN Accelerator Complex

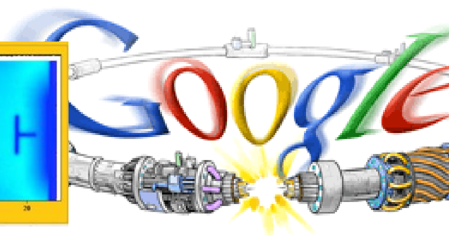


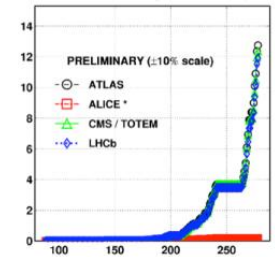
LHC timeline

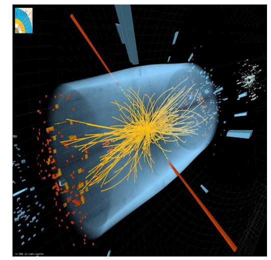
- LHC milestones

4 TeV









August 2008
First Injection

September, 10 2008
Both beams circulating

November 29, 2009
Beams back

October 14, 2010
248 bunches

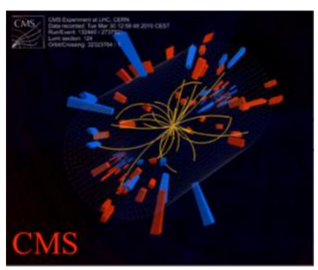
November, 2011
Higgs candidates

February, 2012
highest energy

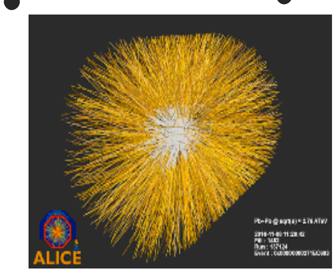
2008 | 2009 | 2010 | 2011 | 2012

September, 19 2008
Incident

March 30, 2010
First collisions at 3.5 TeV

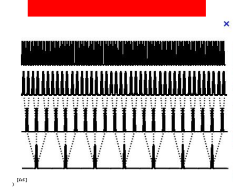


November 2010
Ion run



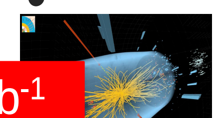
June, 28 2011
1380 bunches

1380

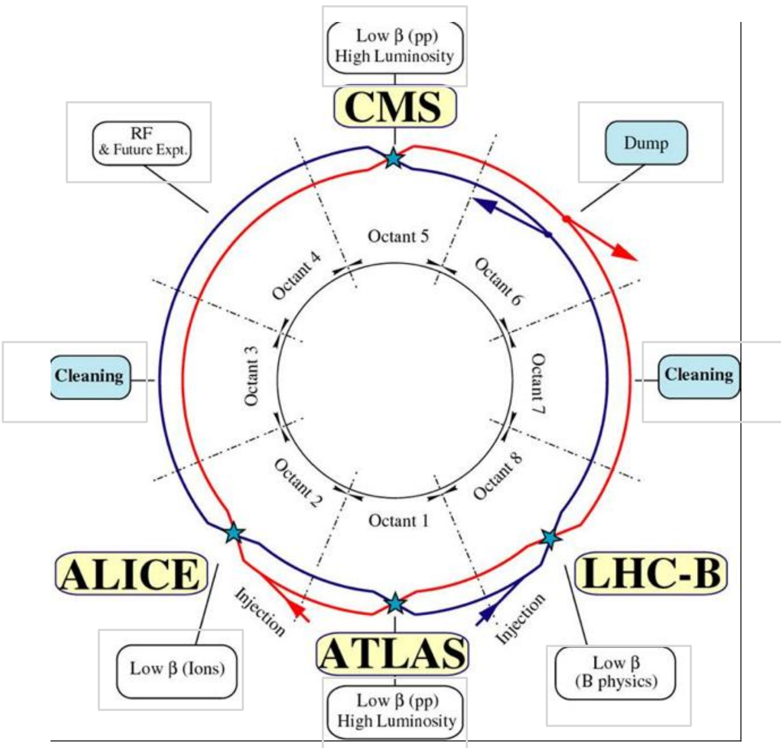


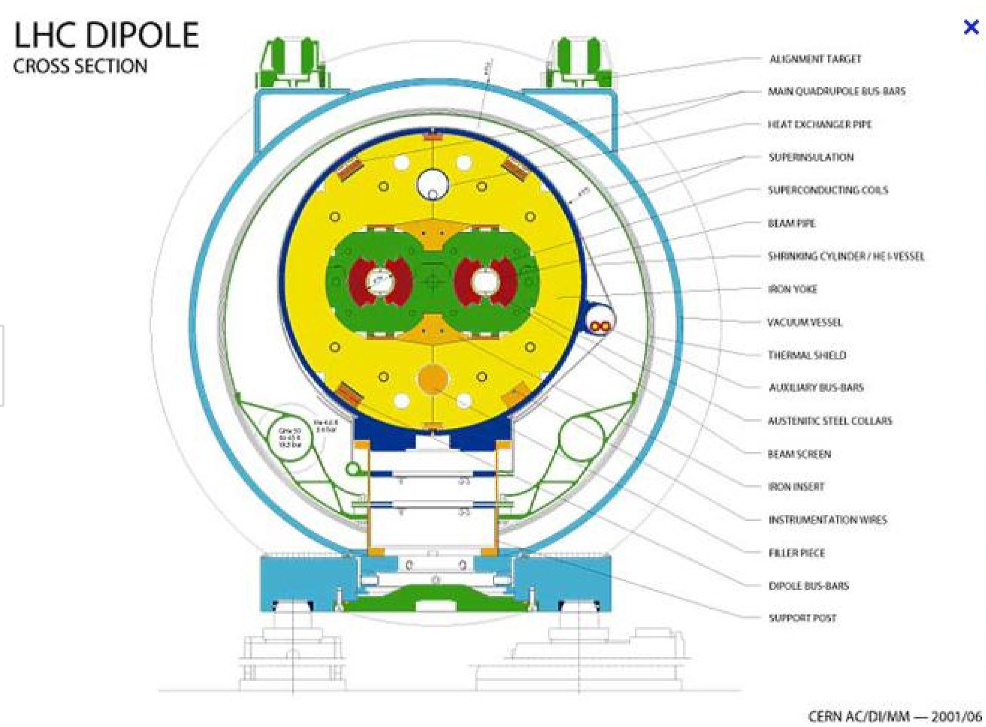
July, 2012
$5\ fb^{-1}$

$5\ fb^{-1}$



- A schematic view of the 26.7 km-long LHC ring composed of 8 arcs and 8 long straight sections (LSSs)
- A two-in-one magnet design, the counter-rotating proton beams circulate in separated vacuum chambers and cross each other only in the experimental interaction regions.



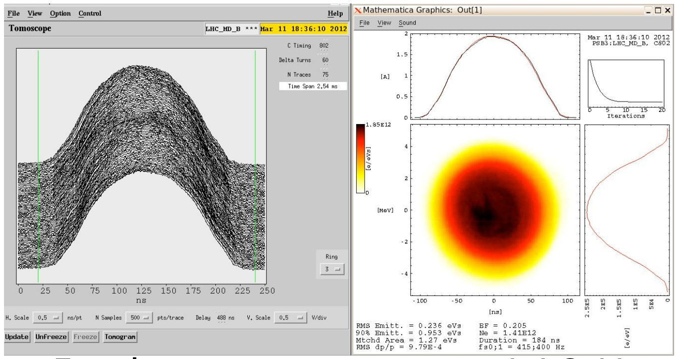


LHC Parameters

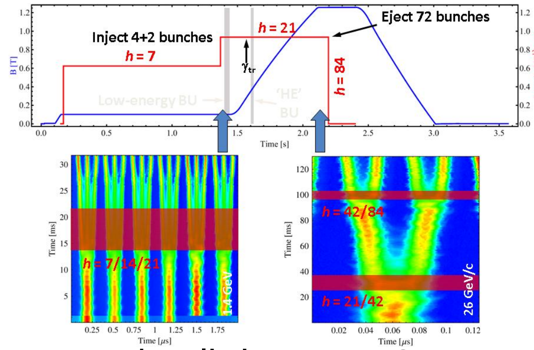
- LHC parameters for proton operation 2012

Parameter	Value		
	Design	2011	2012
Beam energy [TeV]	7.0	3.5	4.0
Peak luminosity [$10^{33} cm^{-2} s^{-1}$]	10	3.6	6.6
Stored energy [MJ]	362	112	115
Bunch intensity [10^{10} p]	11.5	14.5	15
Number of bunches	2808	1380	1380
Bunch spacing [ns]	25	50	50
Norm. transv. emittance [μm]	3.5	2.4	2.4
β^* in IR1/IR5 [m]	0.55	1.0	0.6

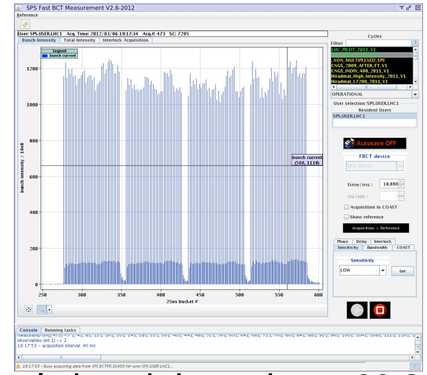
LHC beam journey



Emittance measurement at 1.4 GeV

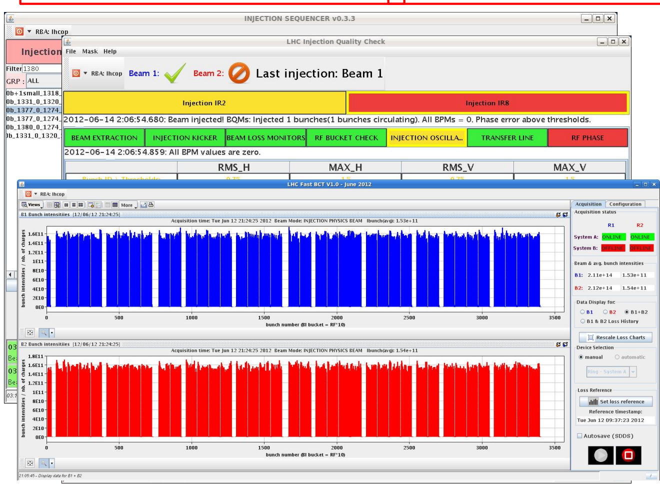


Bunch splitting at 1.4 GeV

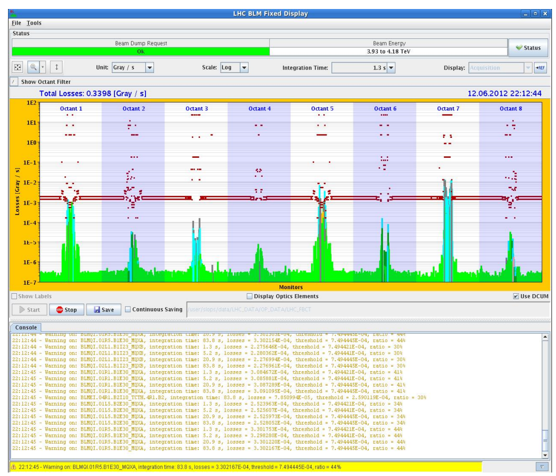


Single bunch intensity at 26 GeV

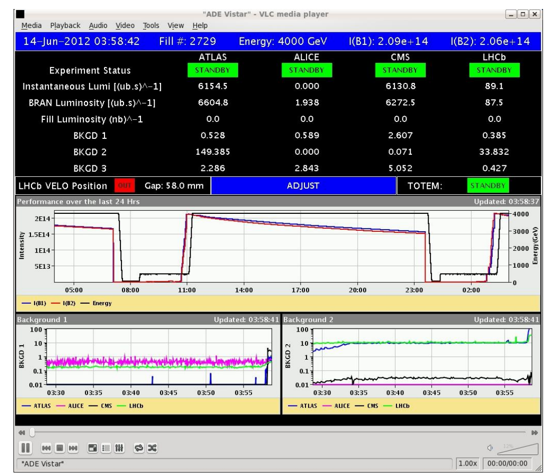
Booster & CPS	SPS injection	SPS extraction	LHC Injection	LHC Ramp
1.4GeV/26 GeV	26 GeV	450 GeV	450 GeV	4 / 7 TeV



Total intensity $2 \cdot 10^{14}$ /beam

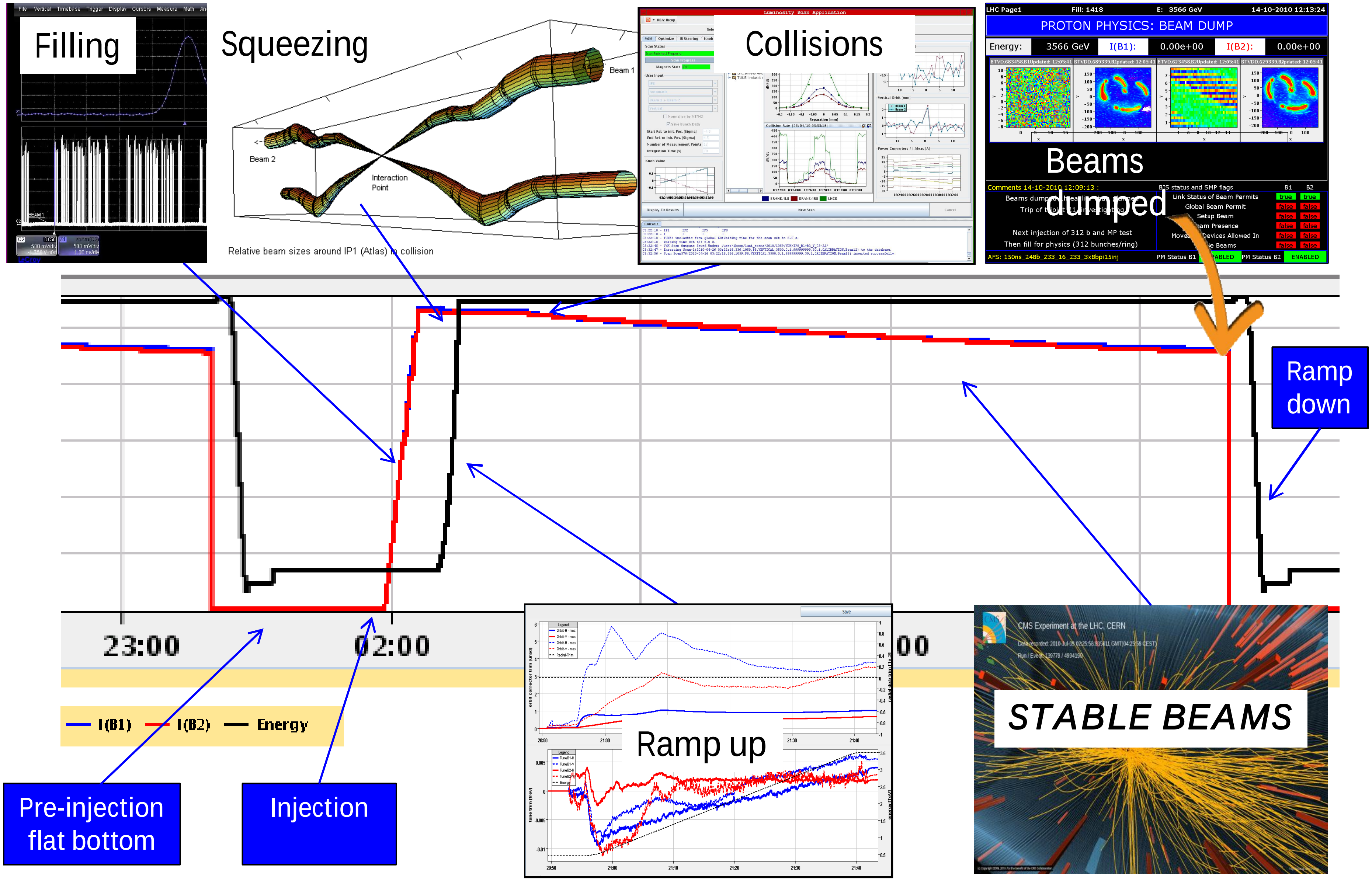


Beam losses end of ramp warning



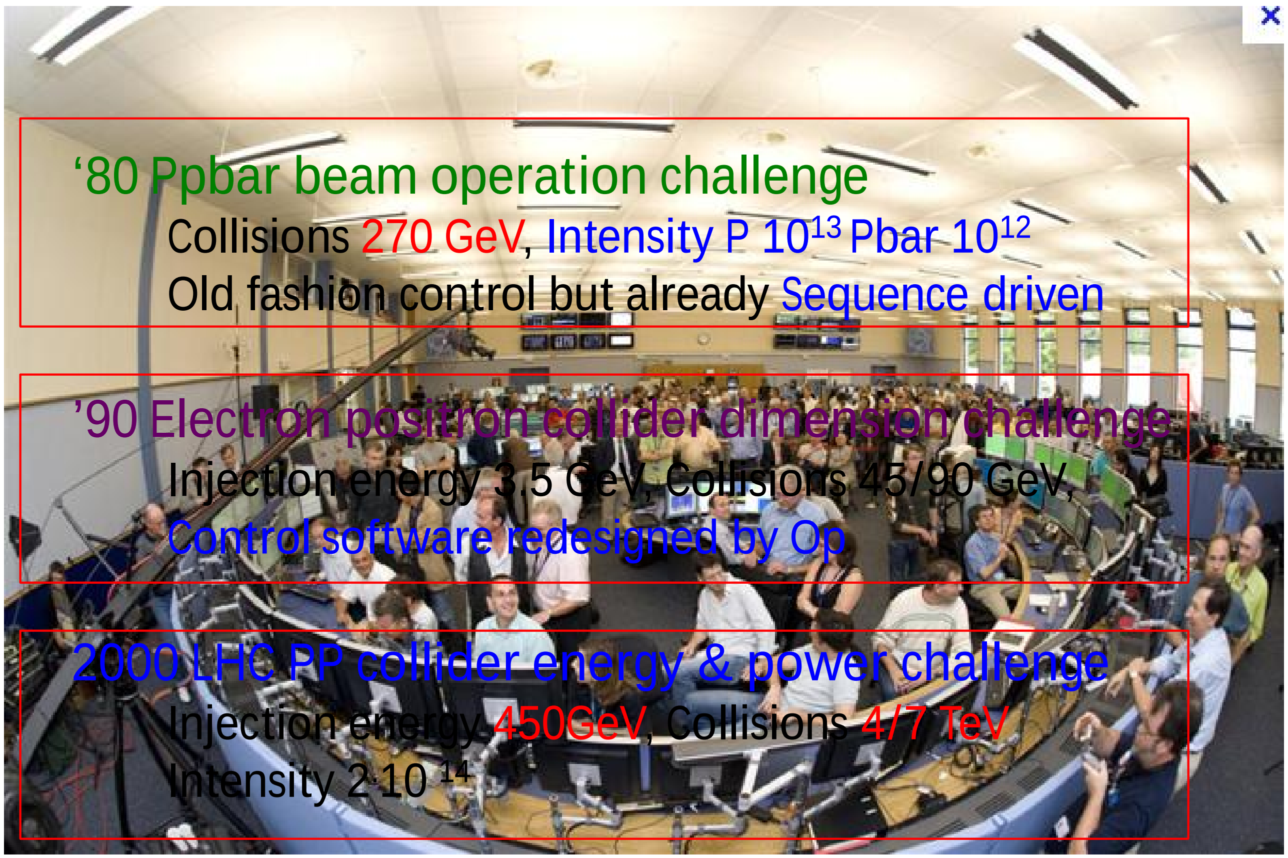
Luminosity adjustments

Operating machine



Cern OP experience

- LHC machine operation
  - 2006 one OP group working in the Cern Control Centre
  - Direct line to the Injectors chain (Booster, CPS, SPS)
  - Share PPbar and Electron Positron collider experience



‘80 Ppbar beam operation challenge

Collisions 270 GeV, Intensity P 10^{13} Pbar 10^{12}

Old fashion control but already Sequence driven

’90 Electron positron collider dimension challenge

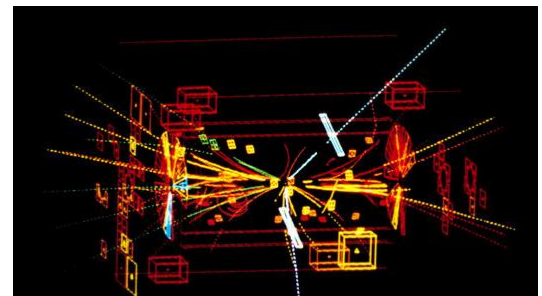
Injection energy 3.5 GeV, Collisions 45/90 GeV,

Control software redesigned by Op

2000 LHC PP collider energy & power challenge

Injection energy 450GeV, Collisions 4/7 TeV

Intensity $2\,10^{14}$



Z particle event in UA1 detector

LEP control room first beam

Kinetic Energy of 200m Train at 155 km/h

Kinetic Energy of Aircraft Carrier at 50 km/h

Stored energy per beam is 360 MJ

Stored energy in the magnet circuits is 9 GJ

Beam Protection: Beam Energy → Beam Dump

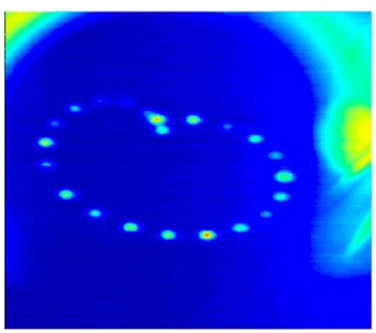
100x energy of TEVATRON

0.000005% of beam lost into a magnet = quench

0.005% beam lost into magnet = damage

Failure in protection – complete loss of LHC is possible

Beam is ‘painted’
diameter 35cm



Concrete
Shielding

ong absorber Graphite
= 800°C

Killer beam & downtime

- LHC operation is several orders of magnitude more dangerous.

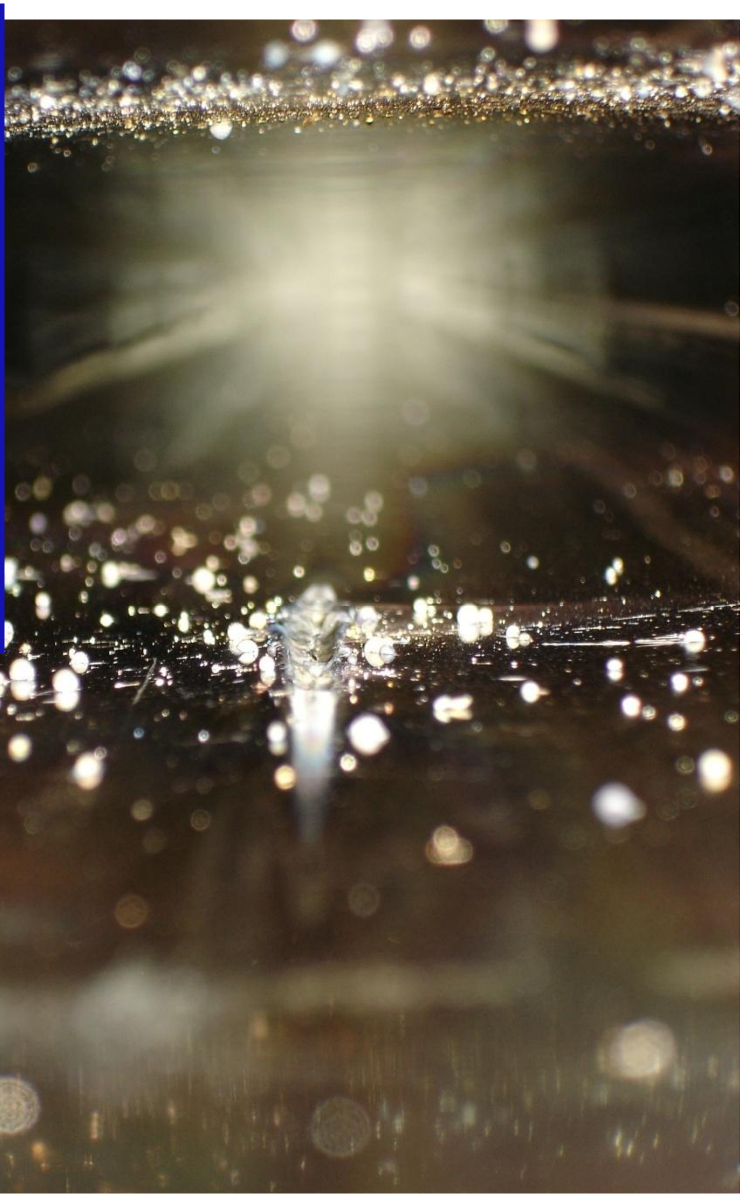
LHC 50 ns	Intensity x bunch	Nr bunches	Energy [GeV]	Intensity	Energy [MJ]
flat bottom PSB	9.50E+11	1	0.5	9.50E+11	0.0001 x4
flat top PSB	9.50E+11	1	1.4	9.50E+11	0.0002 x4
flat bottom CPS	9.50E+11	6	1.4	5.70E+12	0.0013
flat top CPS	1.58E+11	36	26.0	5.70E+12	0.0237
flat bottom SPS	1.58E+11	144	26.0	2.28E+13	0.0948
flat top SPS	1.55E+11	144	450.0	2.23E+13	1.6090
flat bottom LHC	1.52E+11	1380	450.0	2.10E+14	15.1389 x2
flat top LHC	1.50E+11	1380	4000.0	2.07E+14	132.6456 x2

- Magnet quench (or a few magnets): a few hours
- Collimator replacement: a few days to 2 weeks (including bake out if needed)
- Superconducting magnet replacement : 2 months (warming up, cooling down)
- Damage to an LHC experiment: many months

- Beam accidents could lead to damage of superconducting magnets, and to a release of the energy stored in the magnets (coupled systems)
- *Experience with the accident in sector 34 in 2008 : one year downtime!!*

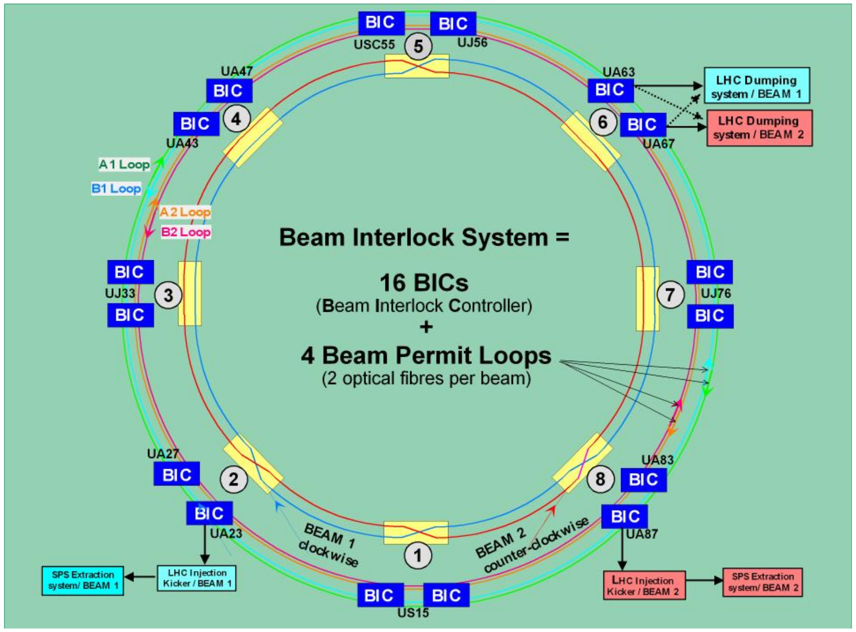
When the MPS is not fast enough…

- At the SPS the MPS was been ‘assembled’ in stages over the years, but not following a proper failure analysis.
- As a consequence the MPS cannot cope with every situation! It is now also covered by the Machine Protection WG but would require new resources…
- Here an example from …. 2008 ! The effect of an impact on the vacuum chamber of a 400 GeV beam of 3×10^{13} p (2 MJ).
- Vacuum to atmospheric pressure, Downtime ~ 3 days.



LHC machine protection Interlock

- LHC Beam interlock system
  - Interact with all LHC systems involved in the protection of the machine.
  - Safe Machine Parameters, Safe Beam Flag, Beam Presence Flag, Mask and Unmasking mechanism
  - Interface with the Beam dumping system and the SPS extraction system.
- SPS Extraction / LHC Injection Beam interlock system
  - Protects the transfer lines from SPS to the LHC.
  - Protects the LHC against bad injection.
- Software Interlock system
  - Detailed surveillance of many machine parameters
- Machine Protection Diagnostics
  - Detailed post mortem analysis
- Remote Base Access Control system
  - Token assigned to change parameters



Safe Machine Parameters

Safe Machine Parameters

receives accelerator information

generates flags & values

directly transmitted and / or broadcast

Injection procedure

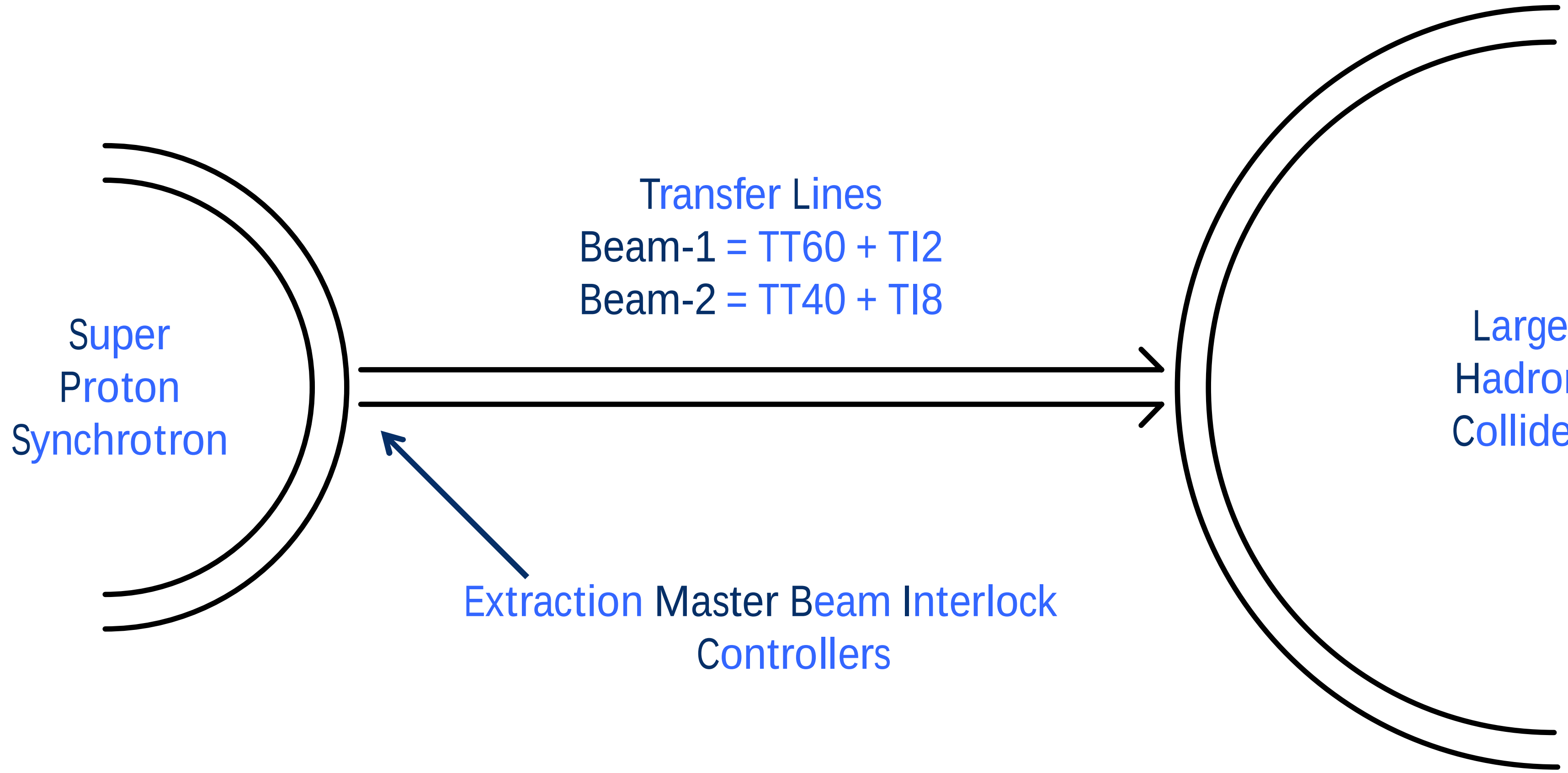
Extraction Interlocks

protection configuration

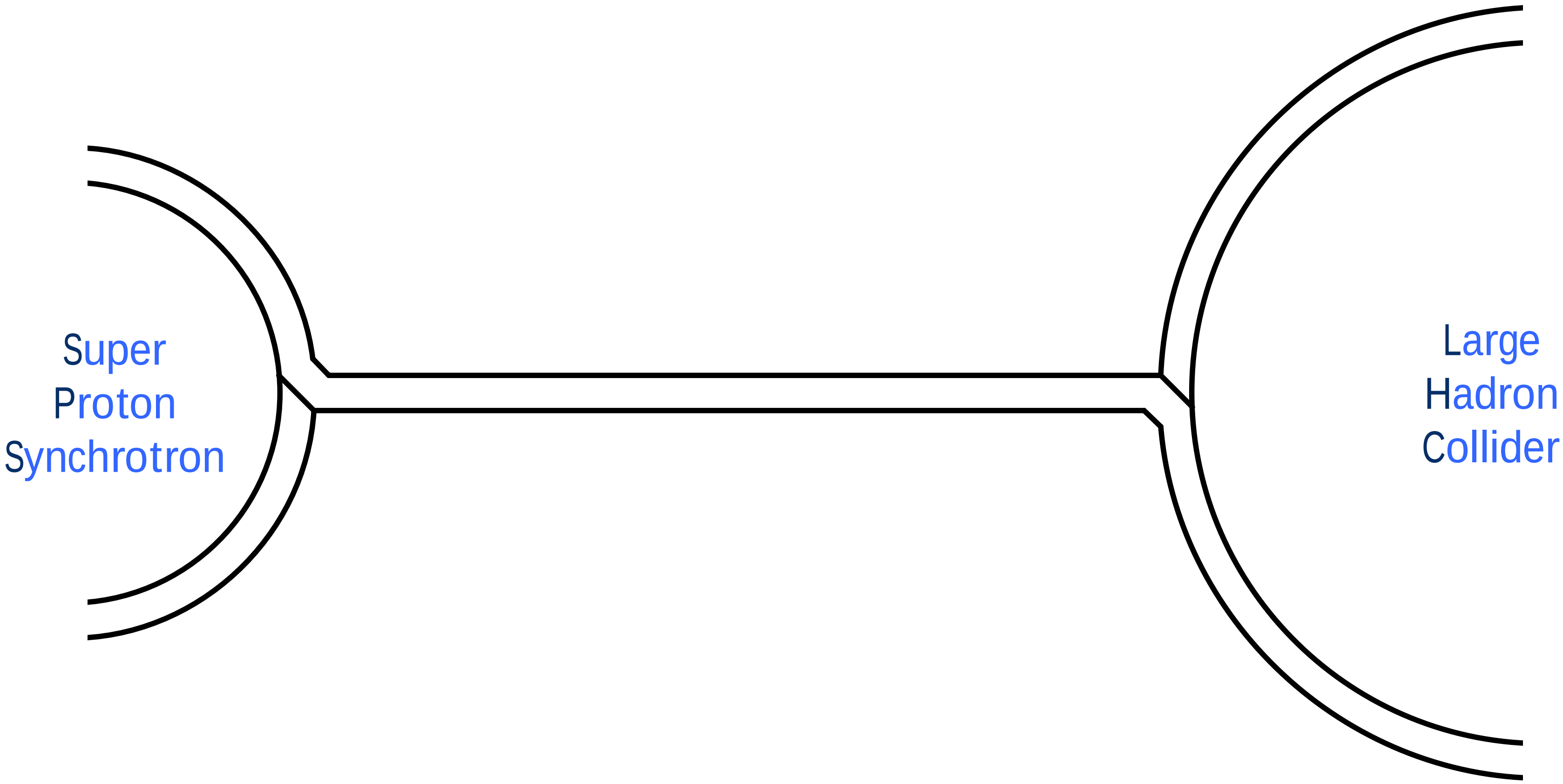
Beam Interlocks
Collimation
Beam Loss Monitors ...

*fast *safe *reliable *available

Extraction Interlocks



Extraction Interlocks

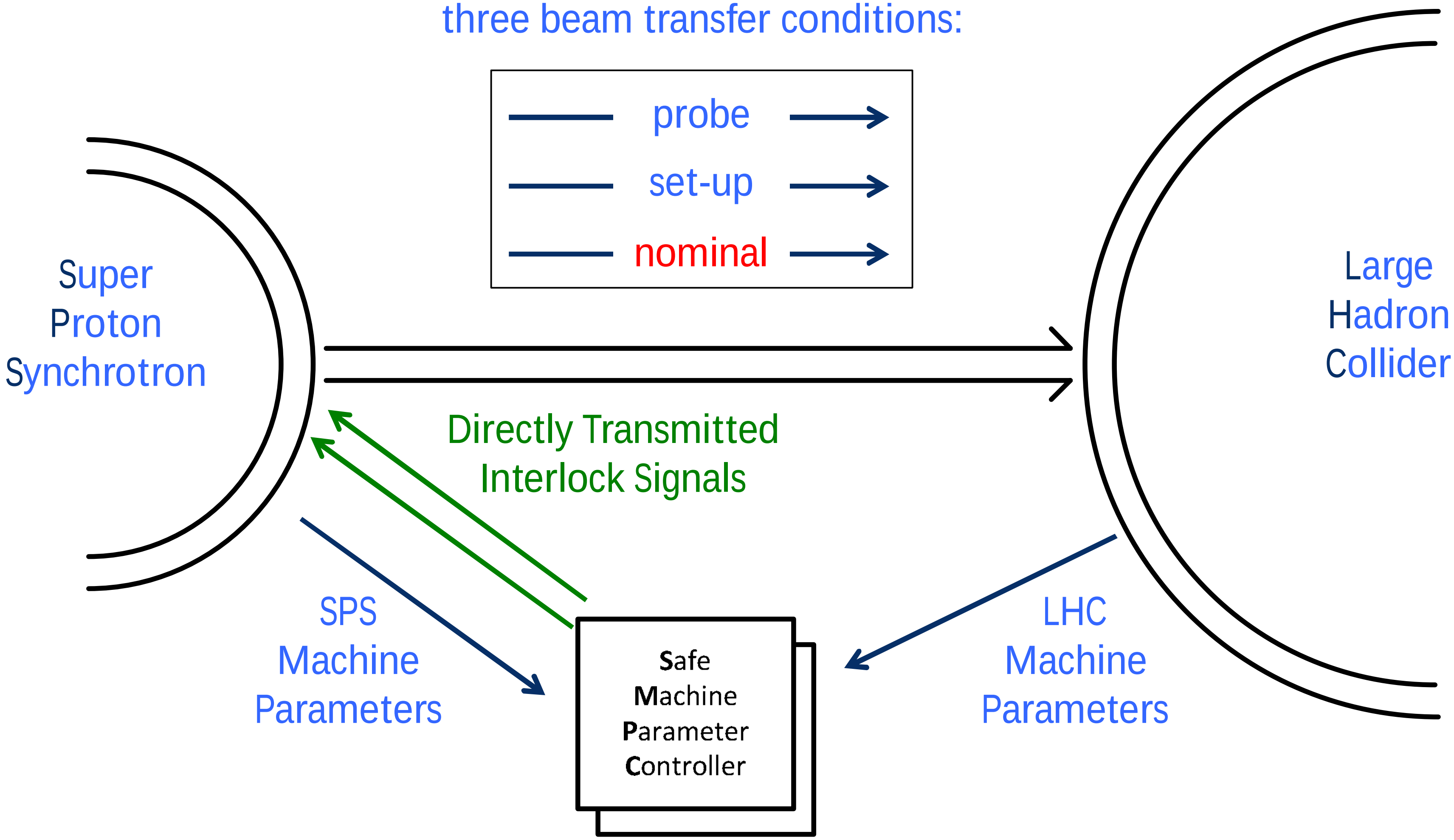


Extraction Interlocks

Beam presence flag = False Only Safe bean can be injected ($1*10^9$)

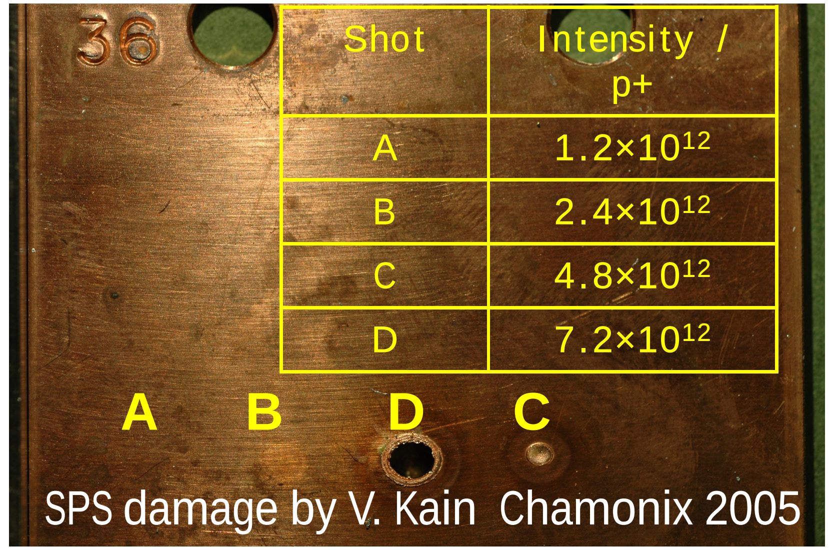
Beam presence flag = True Any beam can be injected into LHC

three beam transfer conditions:



Safe beam flag evolution

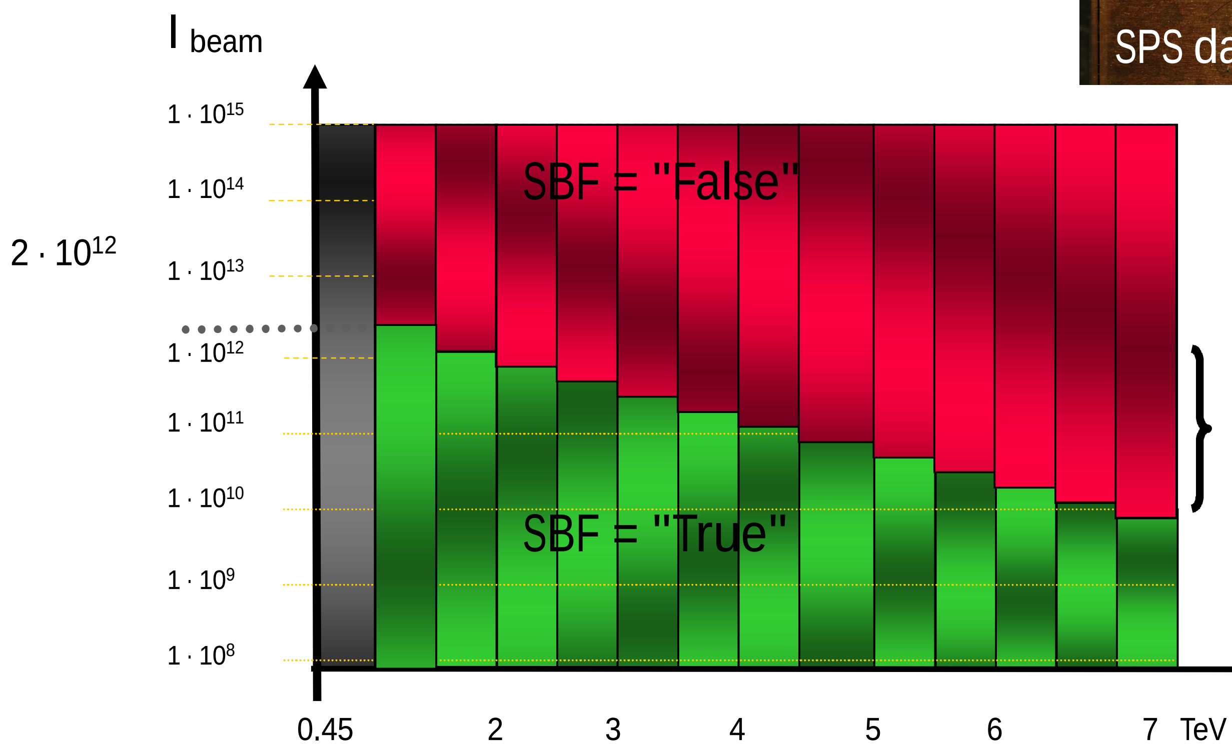
- The Safe Beam Flag depends:
  - on the beam energy and intensity



Shot	Intensity / p+
A	1.2×10^{12}
B	2.4×10^{12}
C	4.8×10^{12}
D	7.2×10^{12}

Estimated damage level for fast losses

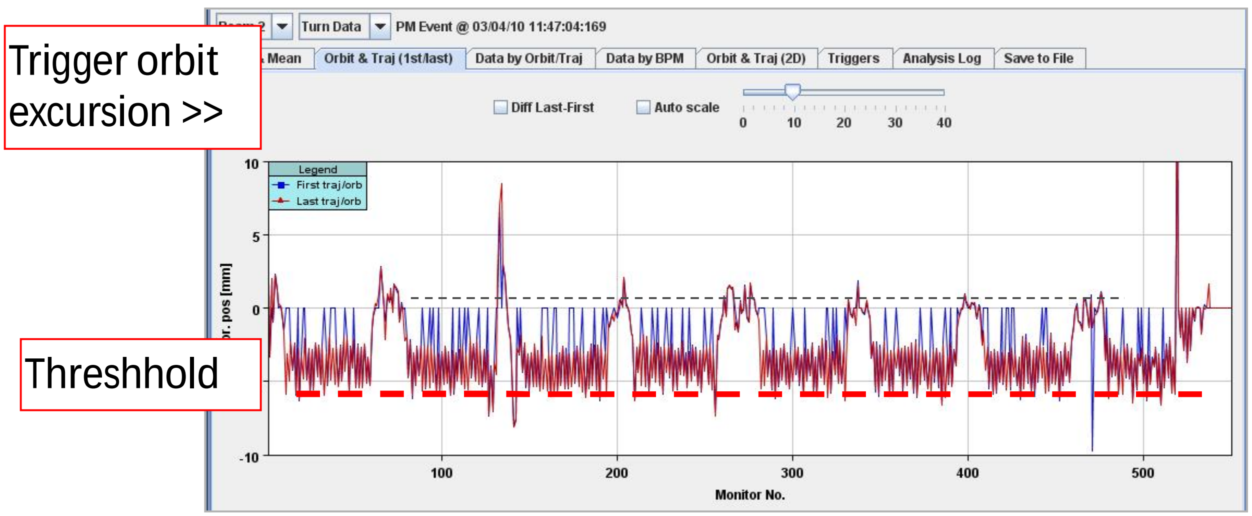
- at 450GeV $\Rightarrow \sim 2 \cdot 10^{12}$ protons
- at 7 TeV $\Rightarrow \sim 1 \cdot 10^{10}$ protons



In this intensity range,
a safe beam becomes unsafe
during acceleration

Software interlock

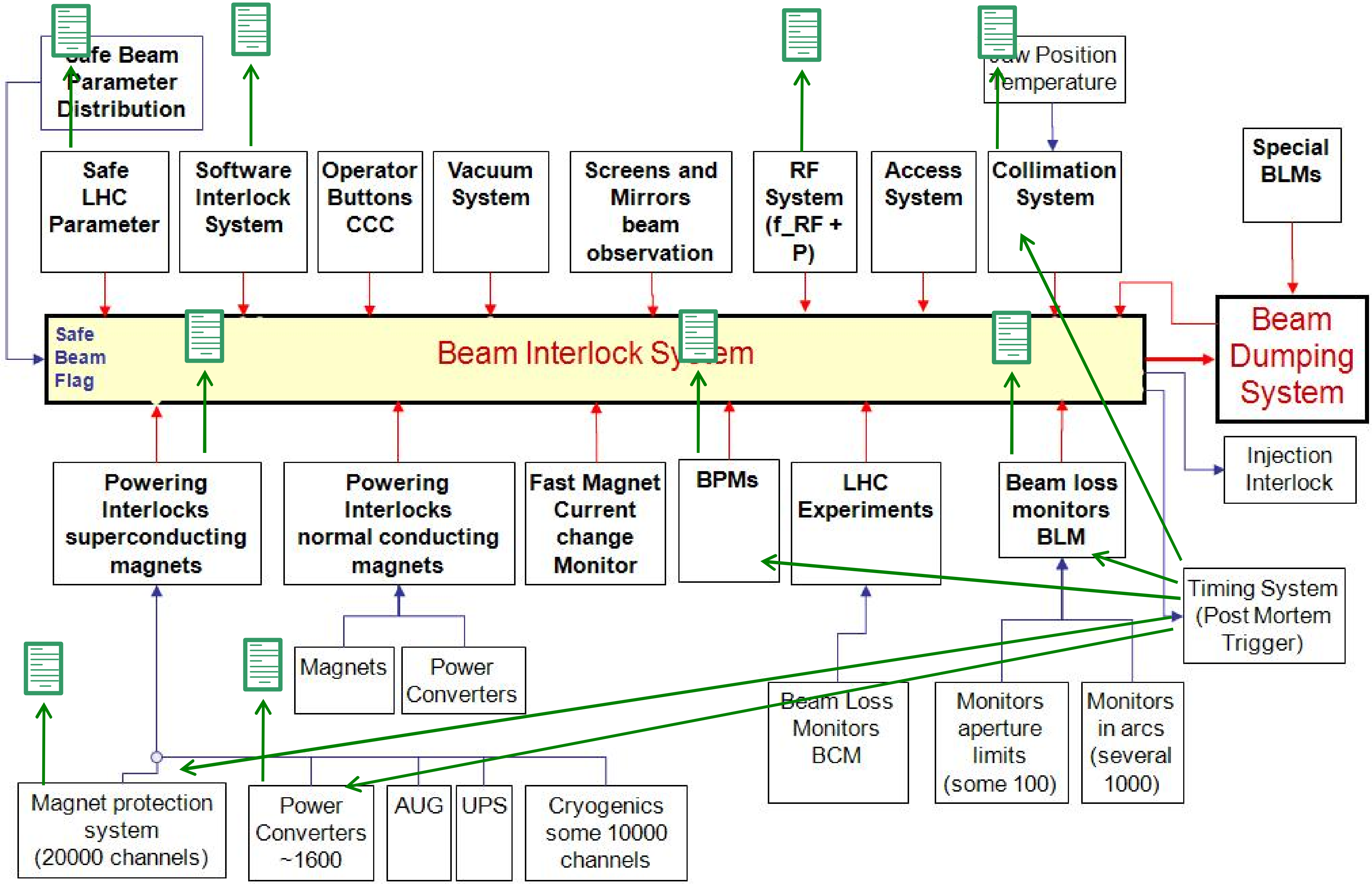
- On large accelerators it is not always possible to cover all failure mechanisms with a hardware system:
  - It needs something more flexible like adding a new interlock if not too time critical
- Survey the control system components relevant for machine protection
  - as additional protection layer, with possibility to abort beam if necessary
- Provide additional protection for complex but less critical conditions
  - (> 12 BPMs over 6 mm for beam 2 horizontal plane (too large RF frequency change)



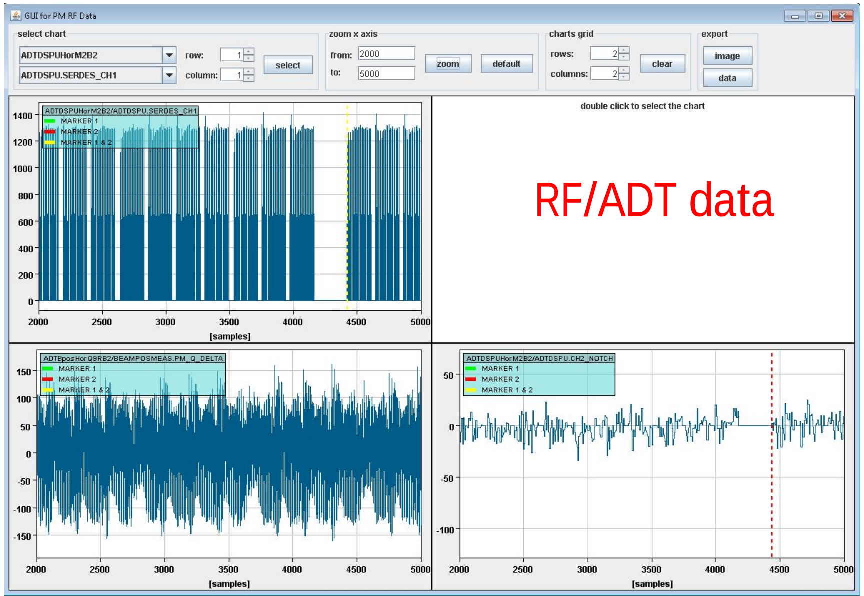
Post Mortem user interface

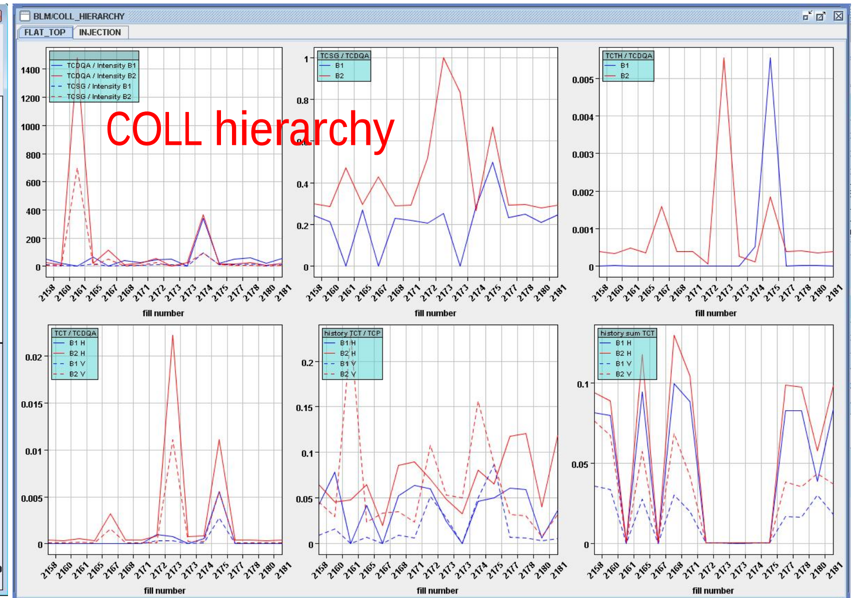
- LHC Post Mortem system is an automated post-operational analysis of transient data recordings from LHC equipment systems
- Meant to support machine protection by helping the operations crews and experts in understanding the machine performance and beam dump events and answer fundamental questions:
  - *What happened? (ie the initiating event / event sequence leading to dump/incident)*
  - *Did the protection systems perform as expected (automated Post operational checks)?*
  - *Assist in trend analysis, statistics of machine performance, …*
- Each beam dump generates ~ 1GB of PM data which is automatically analysed in typically < 1 min

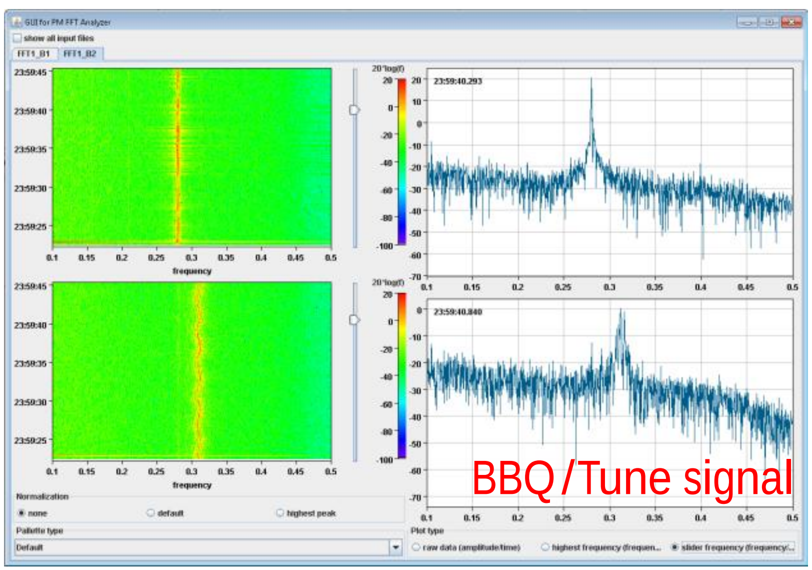
Transient data recording after a beam dump (PM)

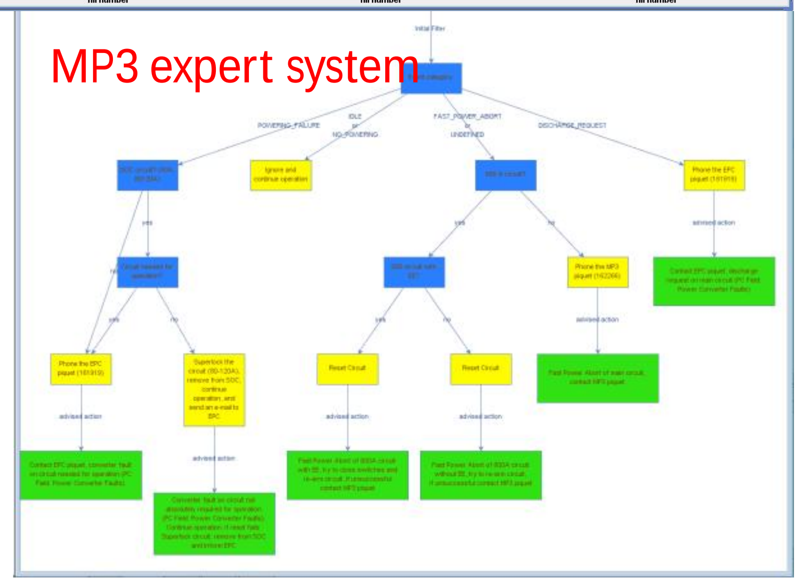


Analysis modules for beam PM









Who’s operating the LHC

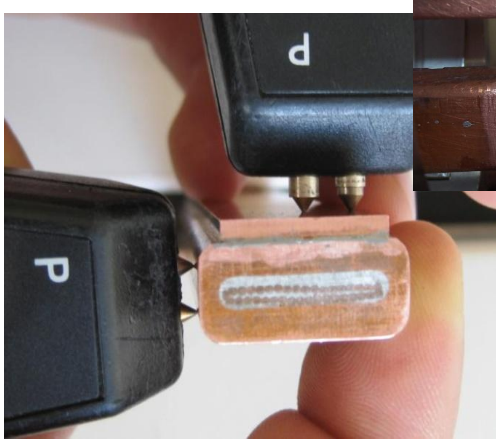
- LMC LHC machine committee (50)
  - Responsible for strategic decision short & long-term
  - Highest organ for accelerator technical decisions
- LHC Coordinators (6)
  - Senior accelerator physicists responsible for the weekly LHC performances
- LHC Machine protection committees (6-12)
  - Responsible for approval of energy or intensity increase
- LHC Engineers In Charge (7)
  - Responsible day to day operation when in charge or during his/her special activity.

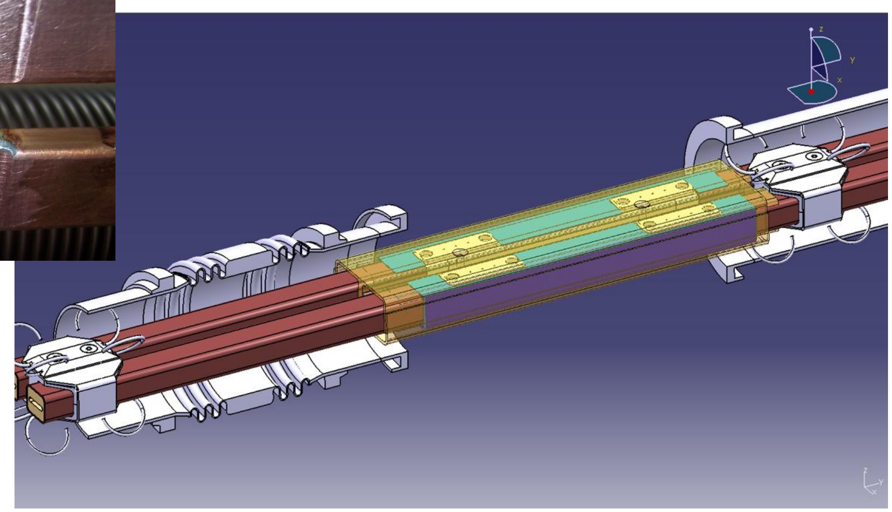
All of them

The entire operation team in the control centre is sharing the stressful moments as well as the records achievement

The next's years at LHC

- Since the accident of September 2008 the LHC has been operated at ½ its nominal energy.
- In March 2013 the LHC will be stopped for approximately 1 ½ years to perform a complete repair of the defect soldering.
- Towards the end of 2014 the LHC will come back online at its full energy for the next adventure of particle physics.





Summary

- LHC Machine Protection Systems have been working well during 2011 run *thanks to a lot of loving care and rigor of operation crews and MPS experts.*
- No quenches with circulating beam.
- No evidence of major loopholes or uncovered risks, additional active protection will provide further redundancy.
- LHC is a stressfully operation, we are confident on our Machine Protection System which capture most failure before effect on the beam are seen.
- We have to remain vigilant to maintain current level of safety of MPS systems while increasing efforts on increasing MPS availability.

Summary

- CERN experiments observe particle consistent with long-sought Higgs boson
- *"We observe in our data clear signs of a new particle, at the level of 5 sigma, in the mass region around 126 GeV. The outstanding performance of the LHC and ATLAS and the huge efforts of many people have brought us to this exciting stage,"* said ATLAS experiment spokesperson Fabiola Gianotti, *"but a little more time is needed to prepare these results for publication."*
- *"The results are preliminary but the 5 sigma signal at around 125 GeV we're seeing is dramatic. This is indeed a new particle. We know it must be a boson and it's the heaviest boson ever found,"* said CMS experiment spokesperson Joe Incandela. *"The implications are very significant and it is precisely for this reason that we must be extremely diligent in all of our studies and cross-checks."*