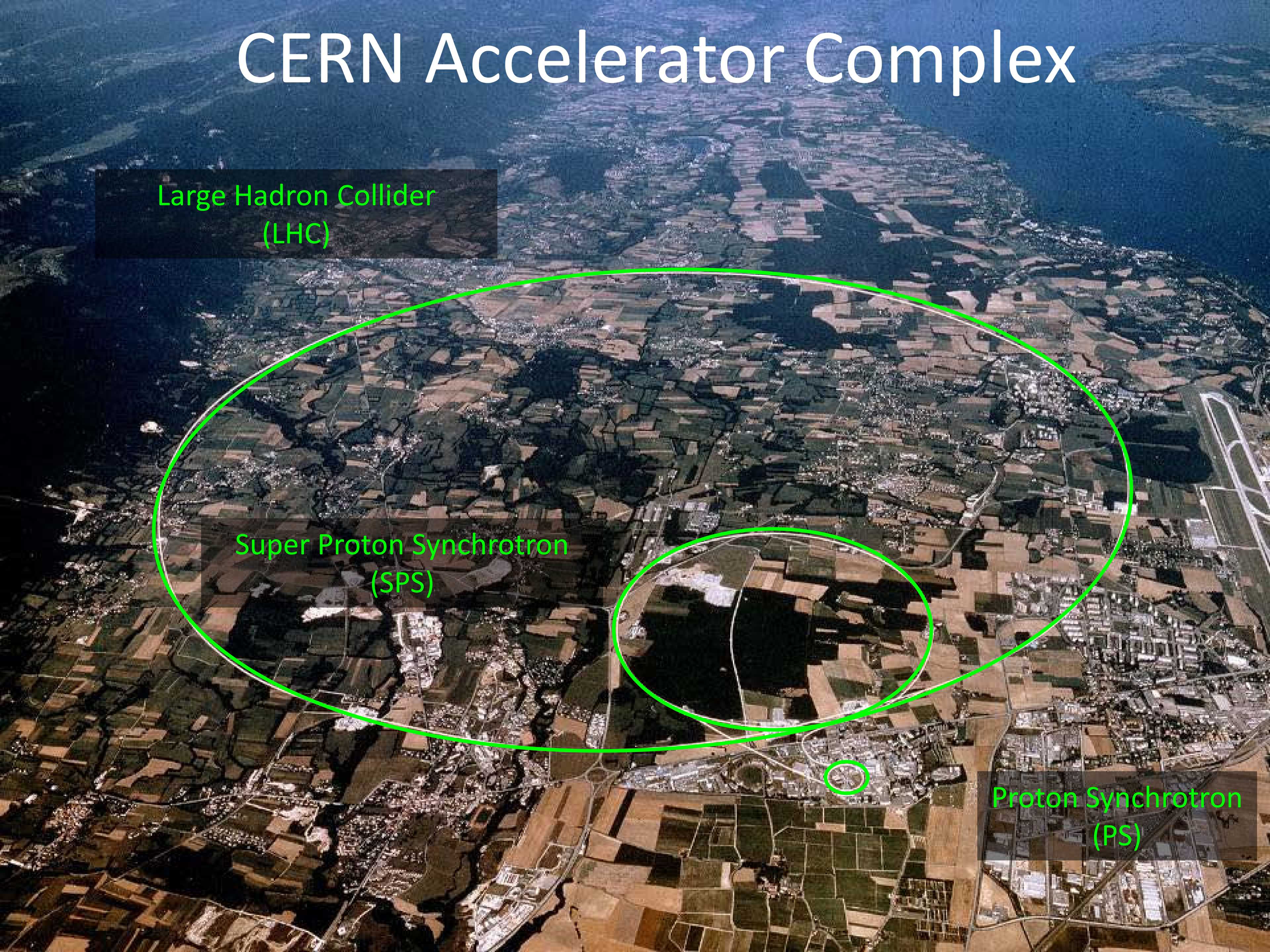
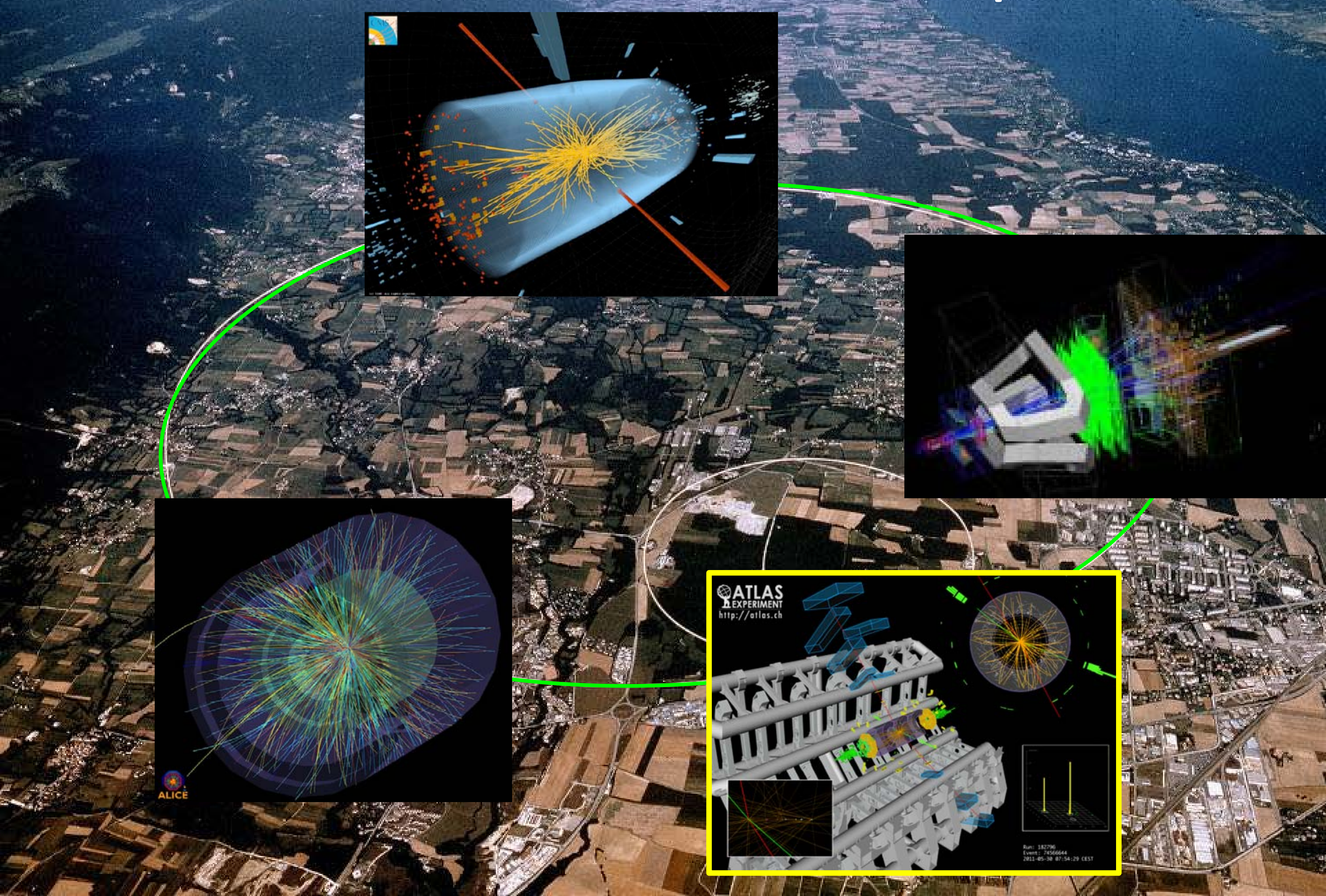
LHC Beam Operation

R. Giachino CERN SNEAP 2012

CERN Accelerator Complex



CERN Accelerator Complex



Outline

LHC machine

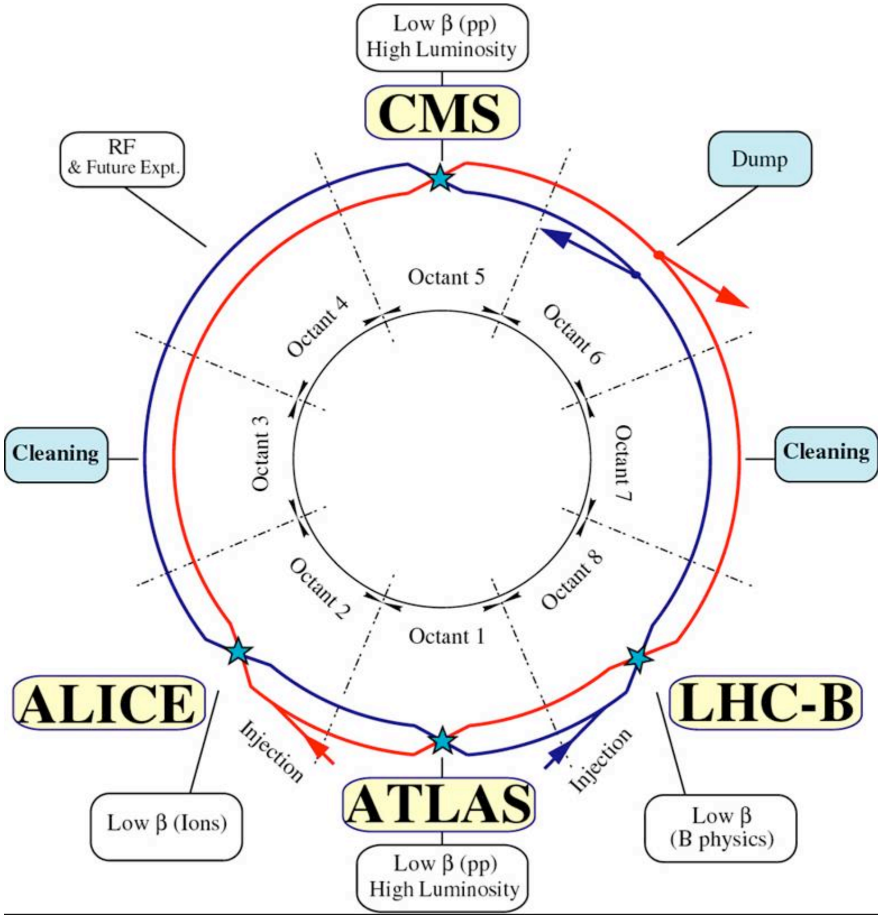
Machine protection

Operational performance

LHC outlook

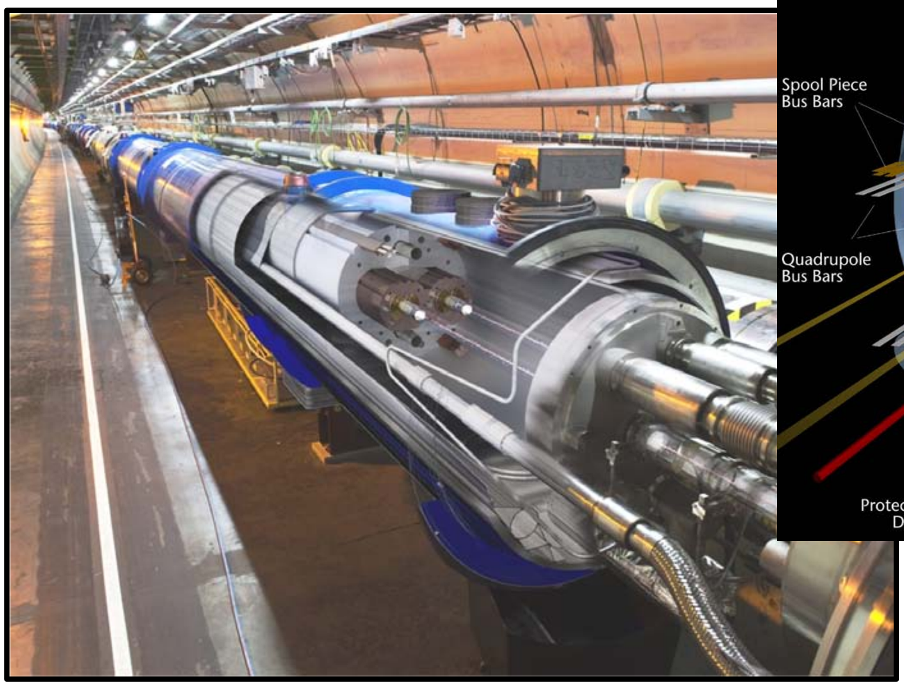
Conclusions

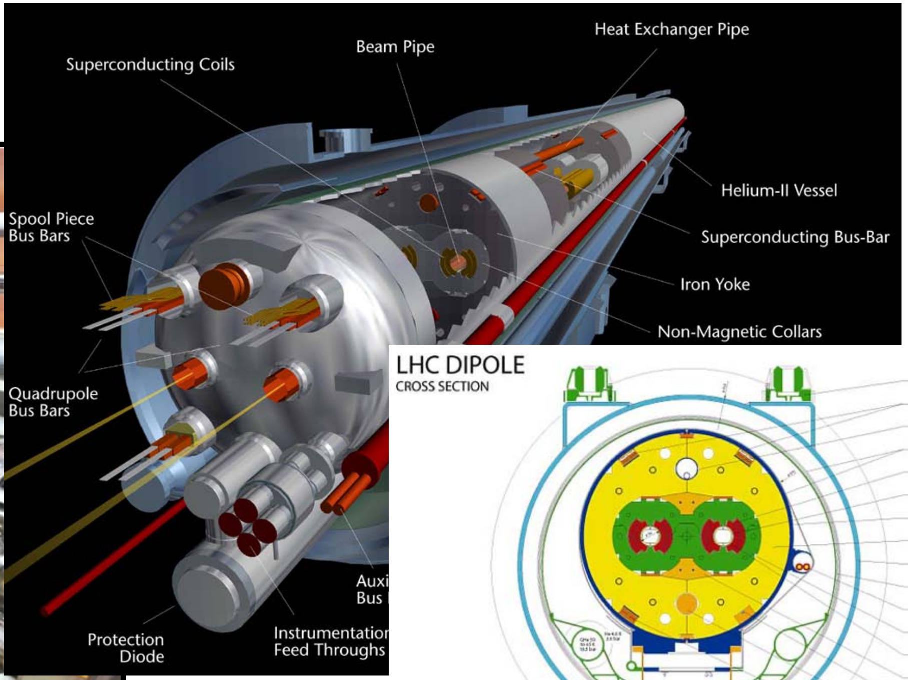
- A schematic view of the 26.7 km-long LHC ring composed of 8 arcs and 8 long straight sections (LSSs)

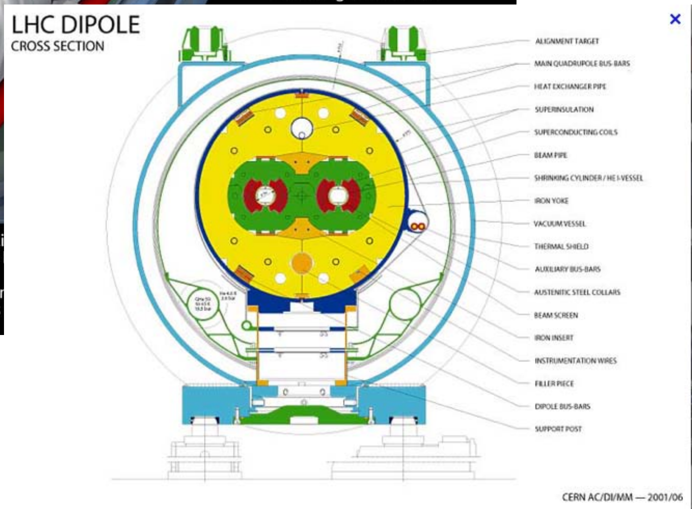


LHC dipole magnet

- 1232 dipole magnets. B field 8.3 T (11.8 kA) @ 1.9 K (super-fluid Helium)
- 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.

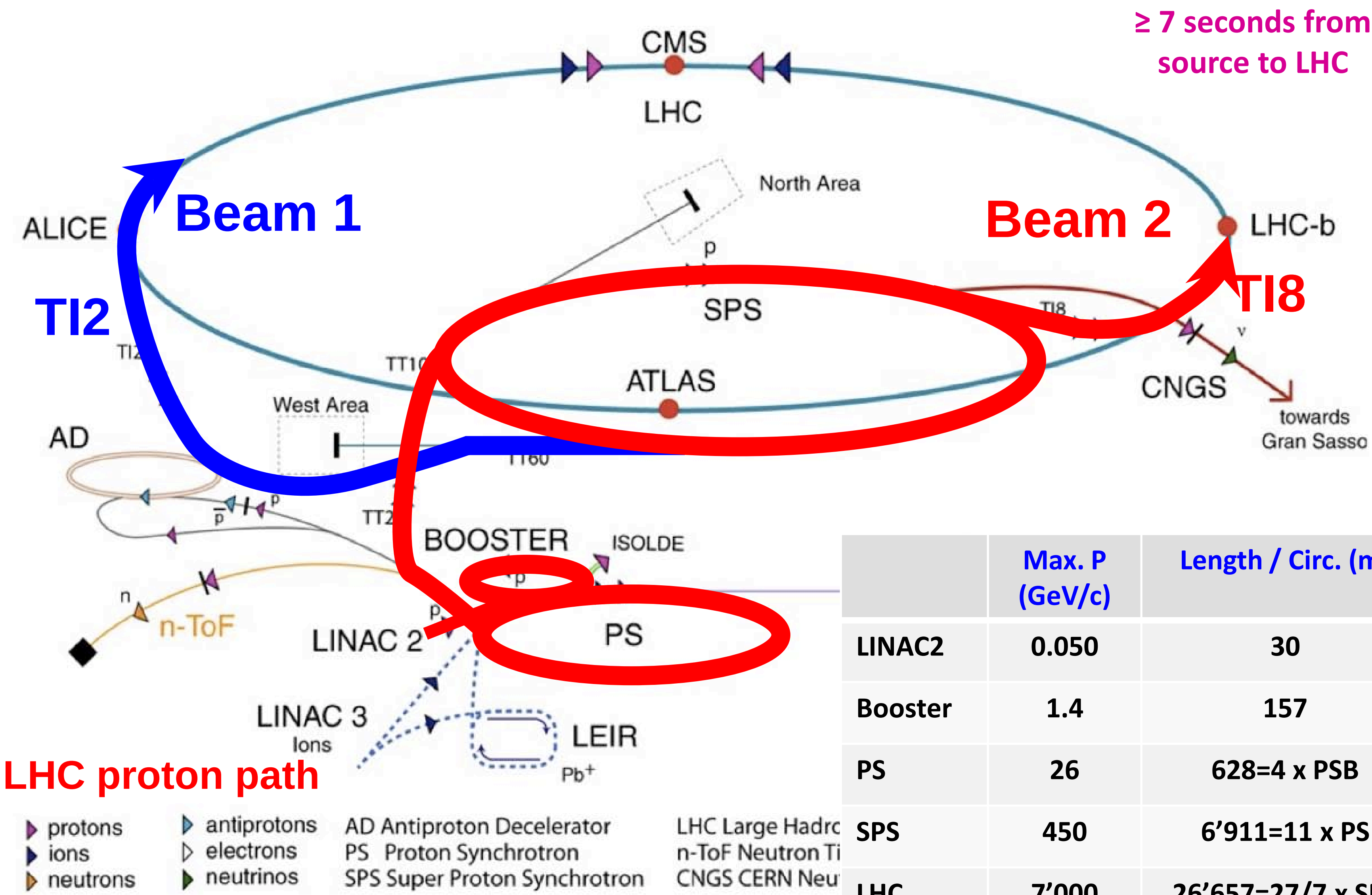






LHC accelerator complex

≥ 7 seconds from source to LHC



	Max. P (GeV/c)	Length / Circ. (m)
LINAC2	0.050	30
Booster	1.4	157
PS	26	628=4 x PSB
SPS	450	6'911=11 x PS
LHC	7'000	26'657=27/7 x SPS

LHC energy: the way down

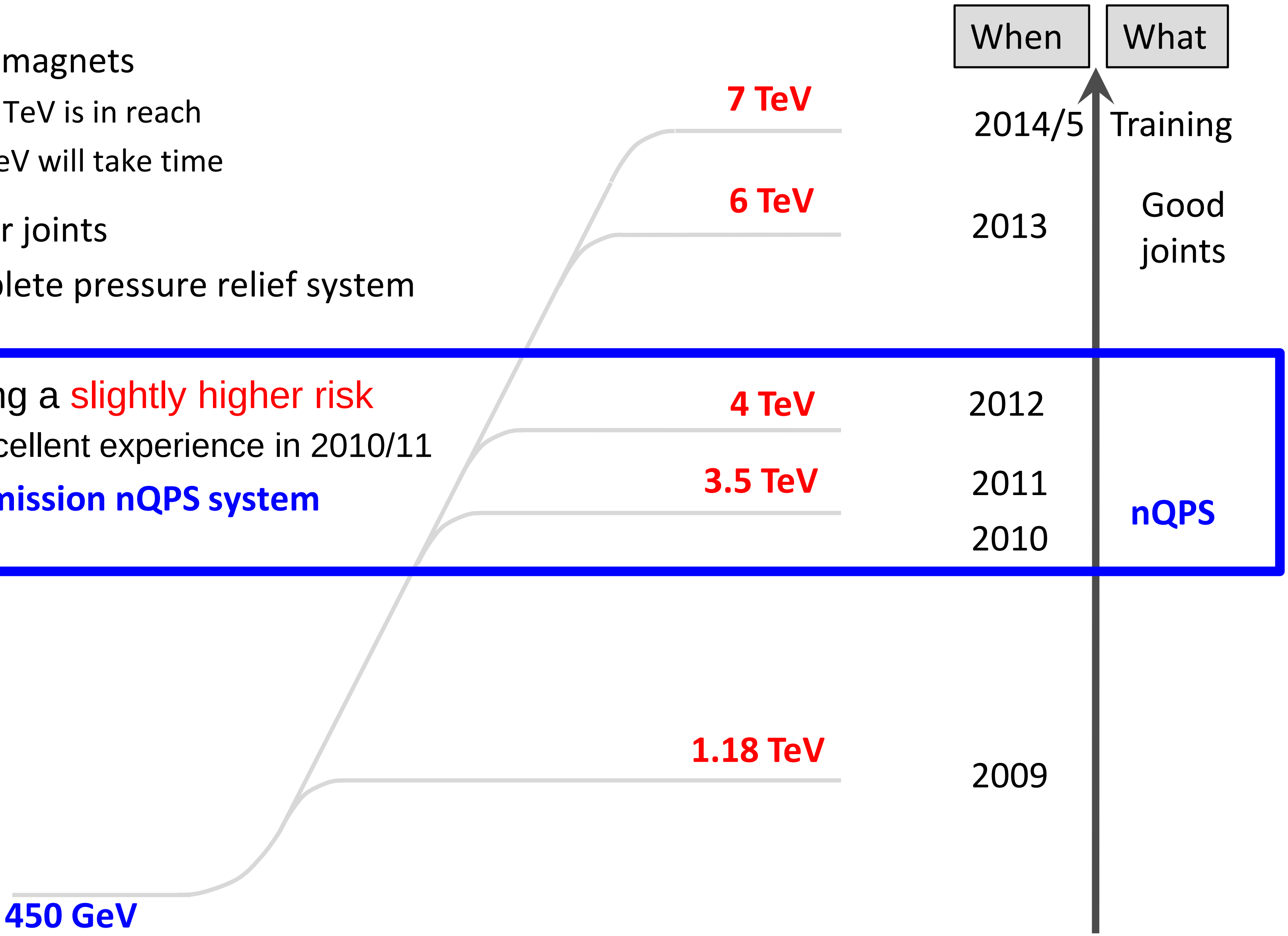
- **All main magnets commissioned for 7TeV operation before installation**
- **Detraining** found when hardware commissioning sectors in 2008
  - 5 TeV poses no problem
  - Difficult to exceed 6 TeV
- Machine wide investigations following S34 incident showed problem with joints
- Waiting for **new Quench Protection System** (nQPS)

Energy	Current	When	Why
7 TeV	**12 kA**	2002-2007	**Design**
5 TeV	**9 kA**	Summer 2008	**Detraining**
3.5 TeV	**6 kA**	Late 2008 Spring 2009	**Joints**
1.18 TeV	**2 kA**	Nov. 2009	**nQPS**
450 GeV			

LHC target energy: the way up

- ❑ Train magnets
  - 6.5 TeV is in reach
  - 7 TeV will take time
- ❑ Repair joints
- ❑ Complete pressure relief system

- ❑ Taking a slightly higher risk
  - Excellent experience in 2010/11
- ❑ **Commission nQPS system**



Day Nine – September 19th 2008

On Day Onenot all circuits **had been commissioned**

Final Commissioning Main Dipole Circuit 34

- Electrical Fault at 5.2 TeV in dipole bus bar, between quadrupole and dipole

Post-Analysis: R = 220 nΩ, nominal = 0.35nΩ

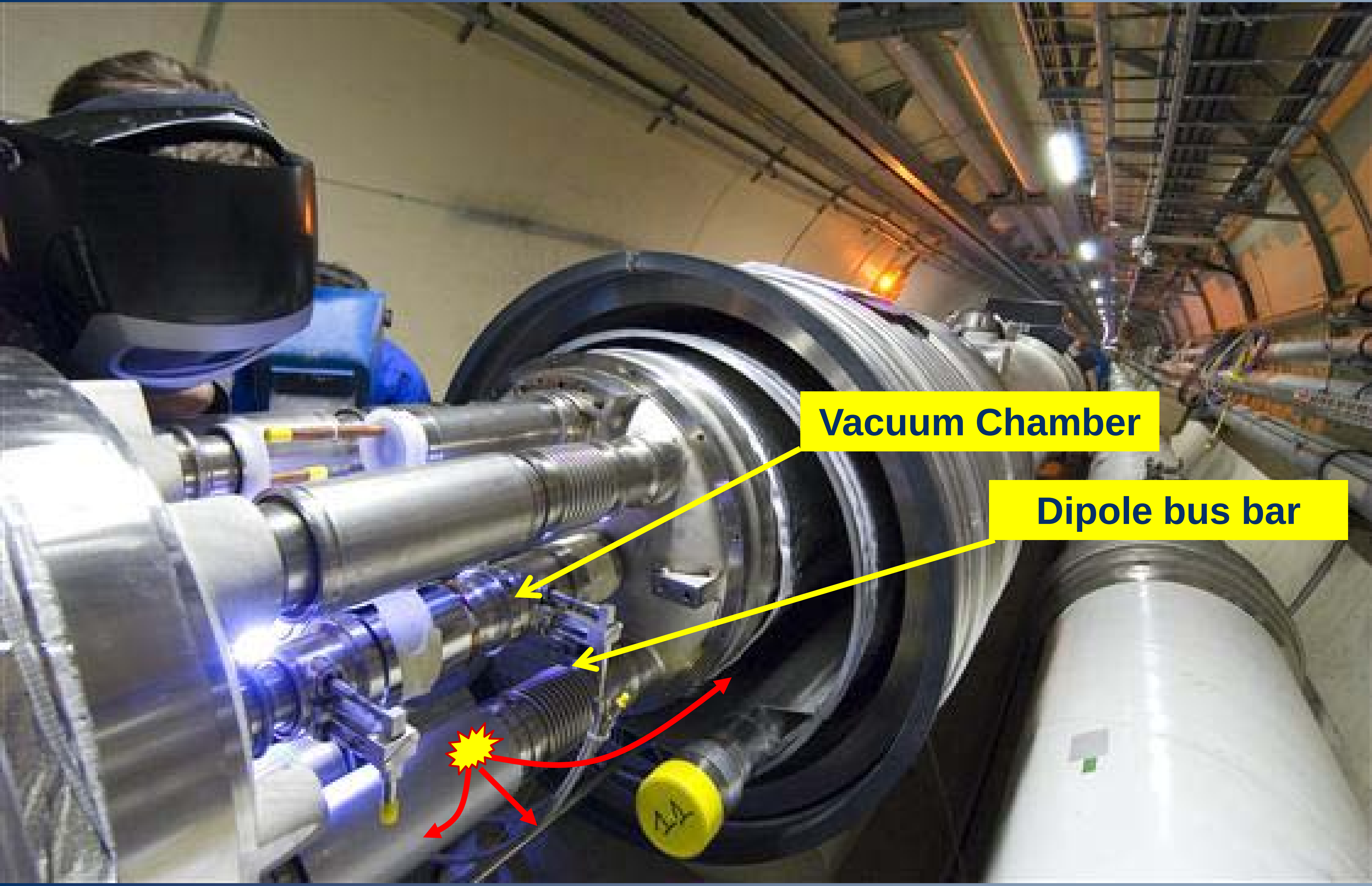
- Electrical Arc developed and punctured helium enclosure

Post-Analysis: 400 MJ dissipated in cold-mass and arcing

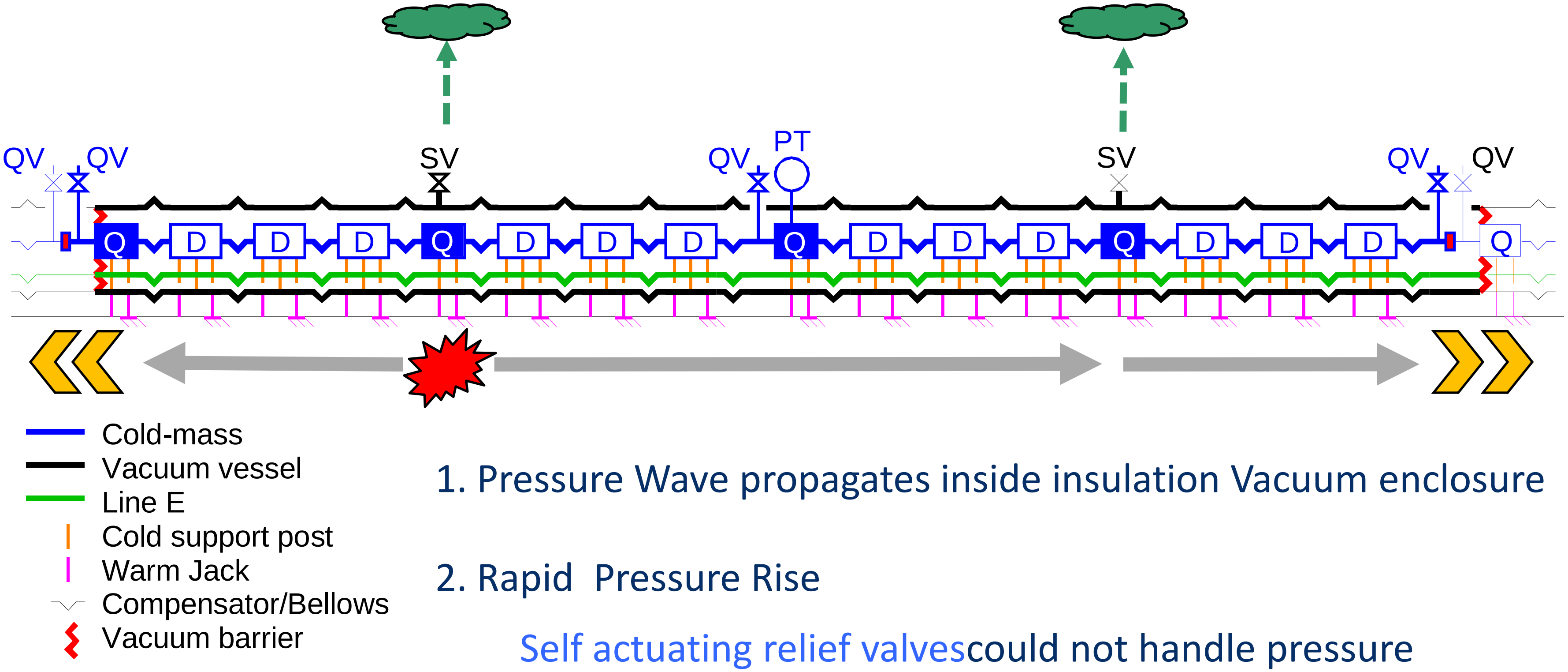
- Helium Release into the insulating vacuum

Post-Analysis:Pressure wave caused most damage

Electrical Fault and Arc



Pressure wave



1. Pressure Wave propagates inside insulation Vacuum enclosure

2. Rapid Pressure Rise

   Self actuating relief valvescould not handle pressure

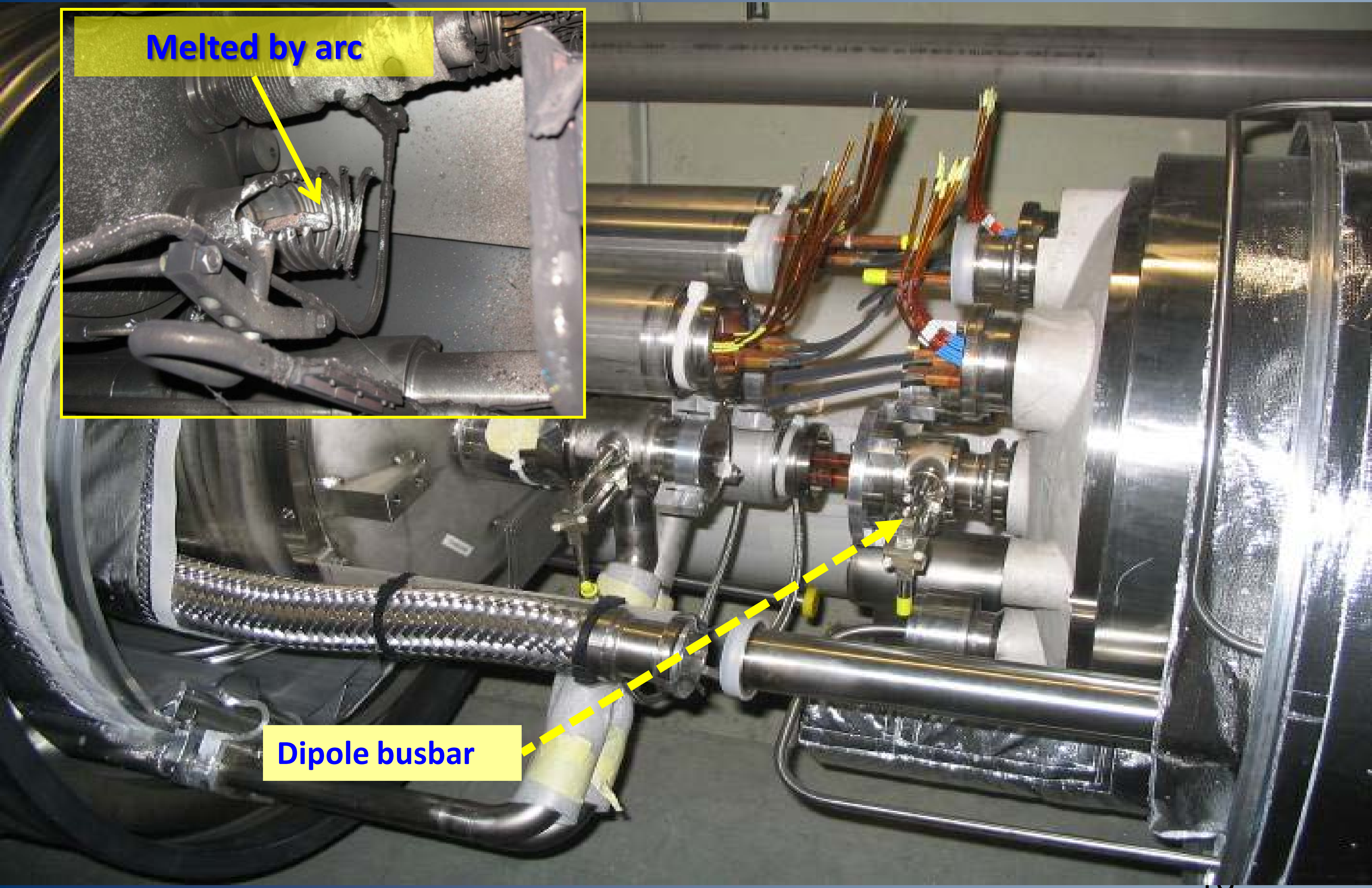
   Design:2Kg He/s Incident: ~20 kg He/s

3. Forces on the vacuum barriers (every second cell)

   Design:1.5 bar Incident: ~8 bar

   - Several QuadrupolesDisplaced by ~50 cm
   - Cryogenic line connections damaged
   - Vacuum to atmospheric pressure

Magnet Interconnection



Collateral Damage

Quadrupole support

Quadrupole-dipole interconnection

Main Damage Area: 700m

- 39 dipoles and 14 quadrupoles effected
- moved to surface:
- 37 replaced and 16 repaired

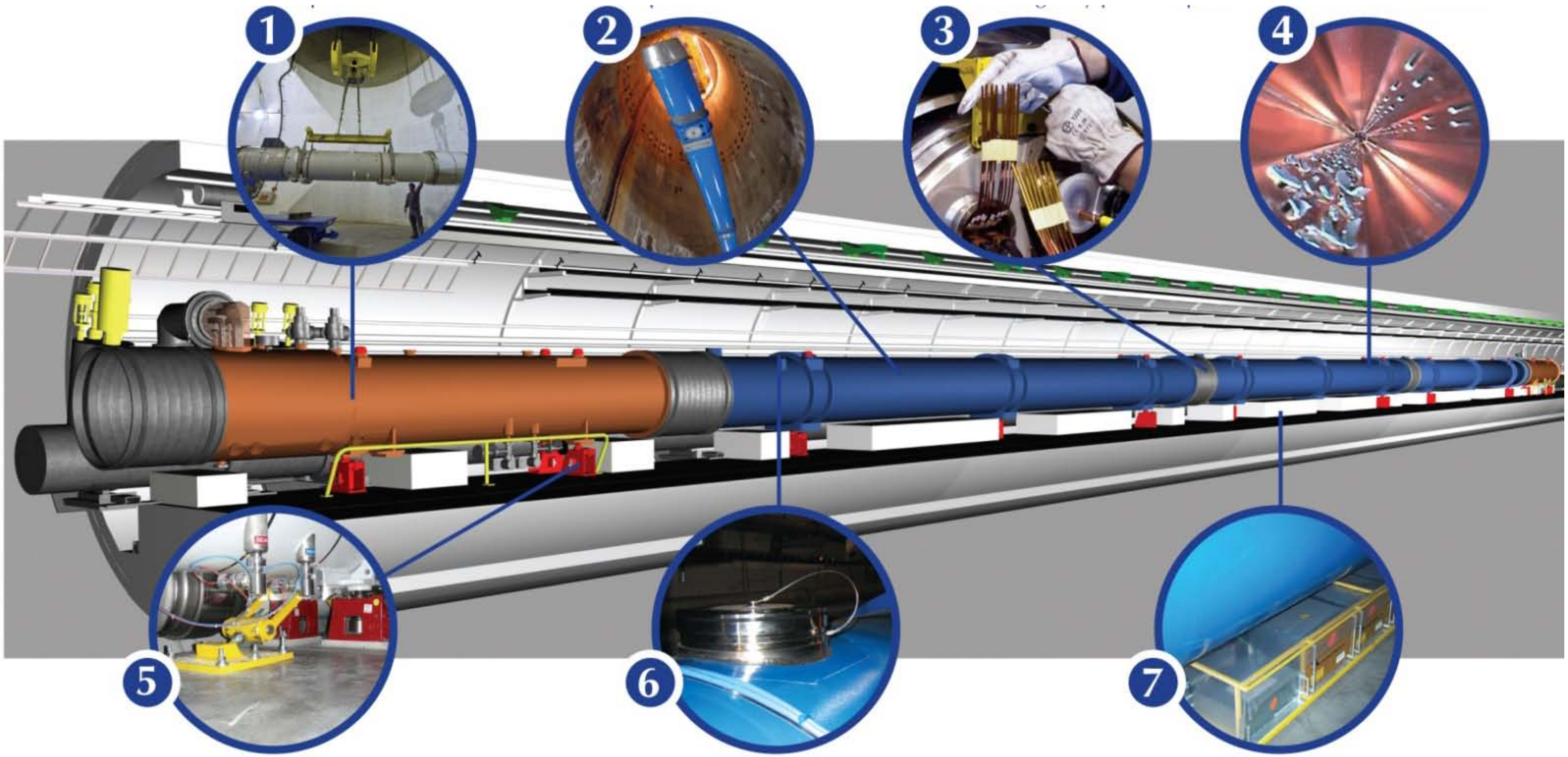
LHC repair and consolidation

14 quadrupole magnets replaced

39 dipole magnets replaced

204 electrical inter-connections repaired

Over 4km of vacuum beam tube cleaned



New longitudinal restraining system for 50 quadrupoles

Almost 900 new helium pressure release ports

6500 new detectors and 250km cables for new Quench Protection System to protect from busbar quenches

Collateral damage mitigation

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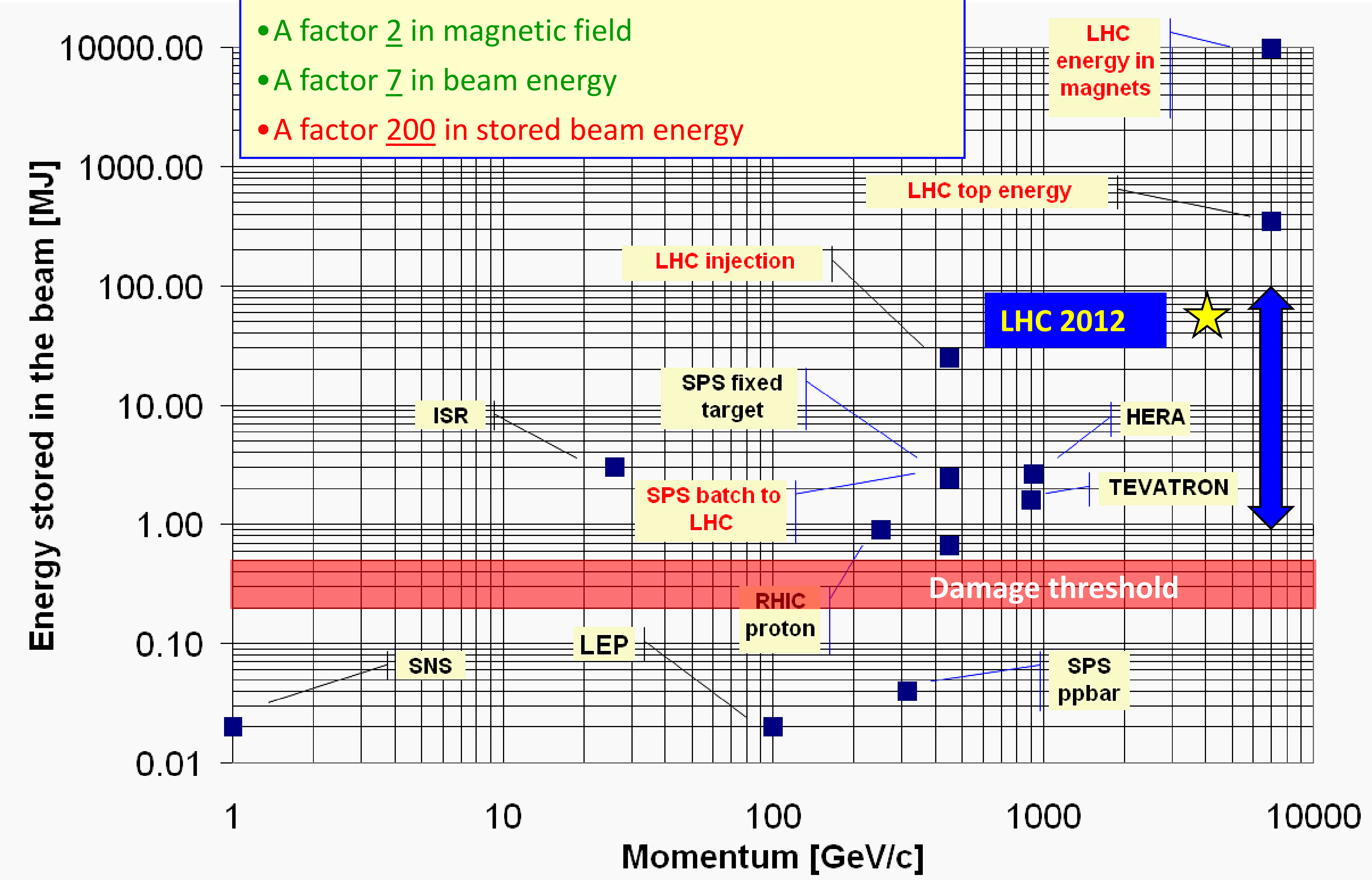
Stored energy

Increase with respect to existing accelerators :

- A factor 2 in magnetic field
- A factor 7 in beam energy
- A factor 200 in stored beam energy



Technological Challenges

Kinetic Energy of **200m Train at 155 km/h**

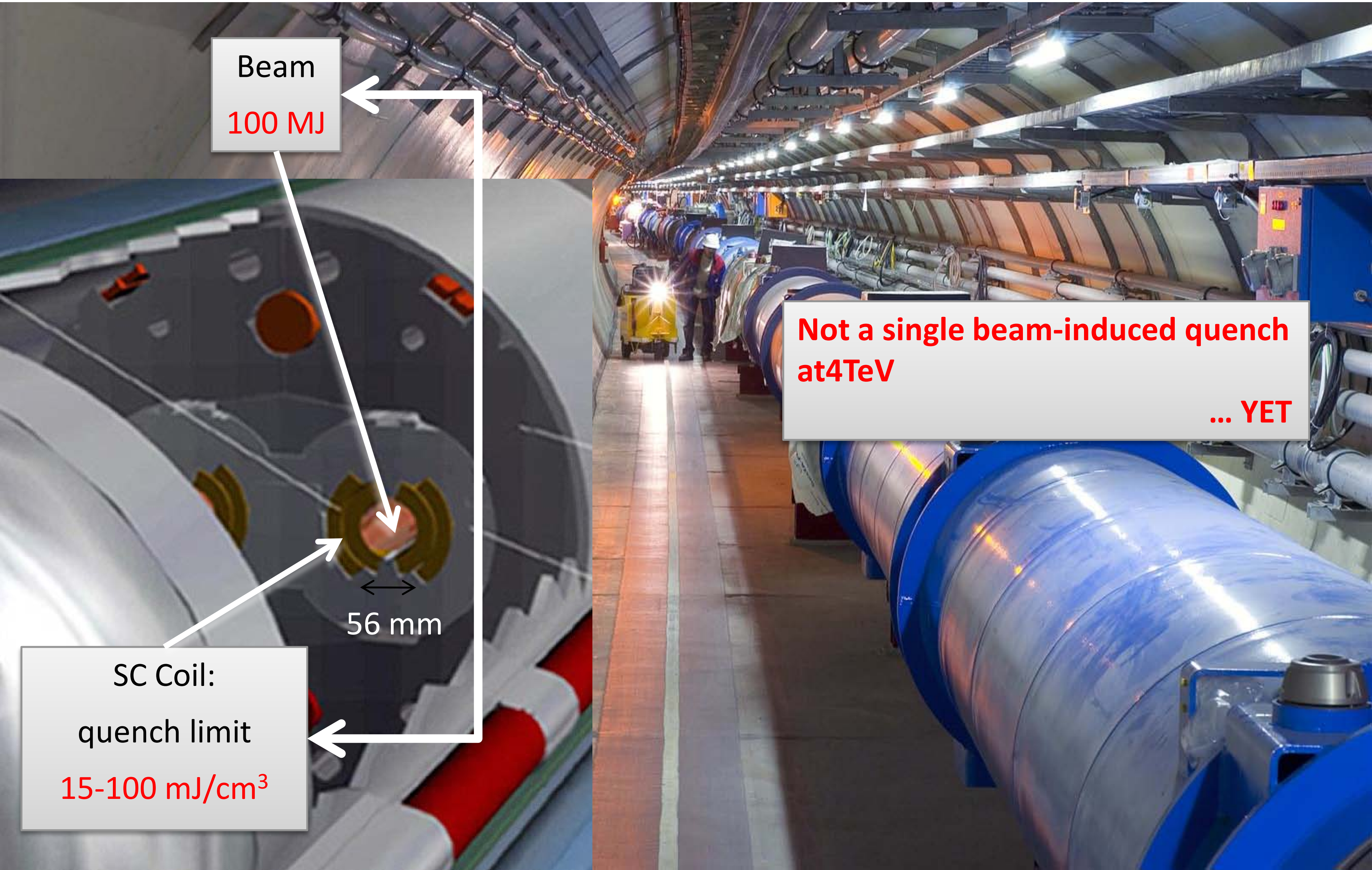
Kinetic Energy of **Aircraft Carrier at30 Knot**

Stored energy**per beam is 360 MJ**

Stored energy **in the** magnet**circuits is 9 GJ**

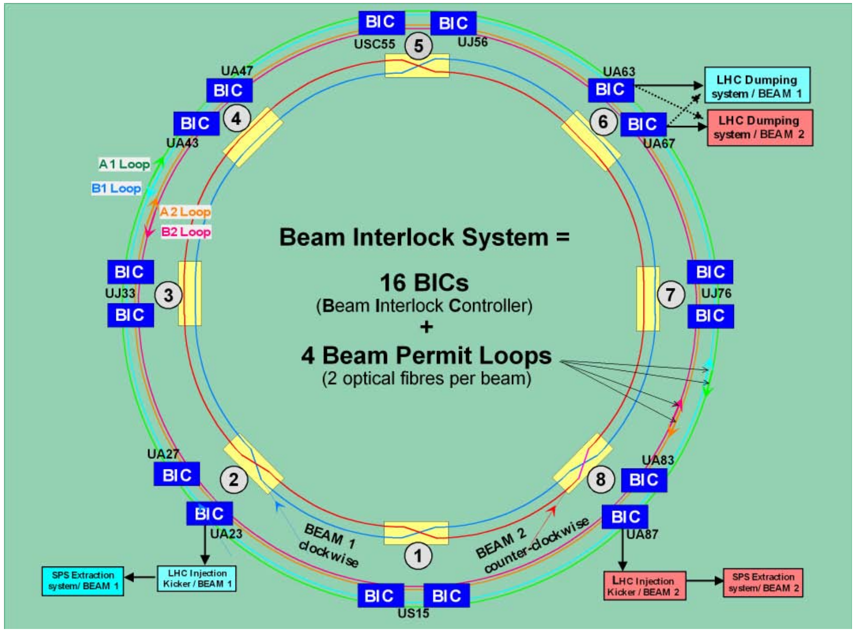
Machine protectionchallenge

Situation at4TeV (inSeptember 2012)



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



LHC Beam Operation

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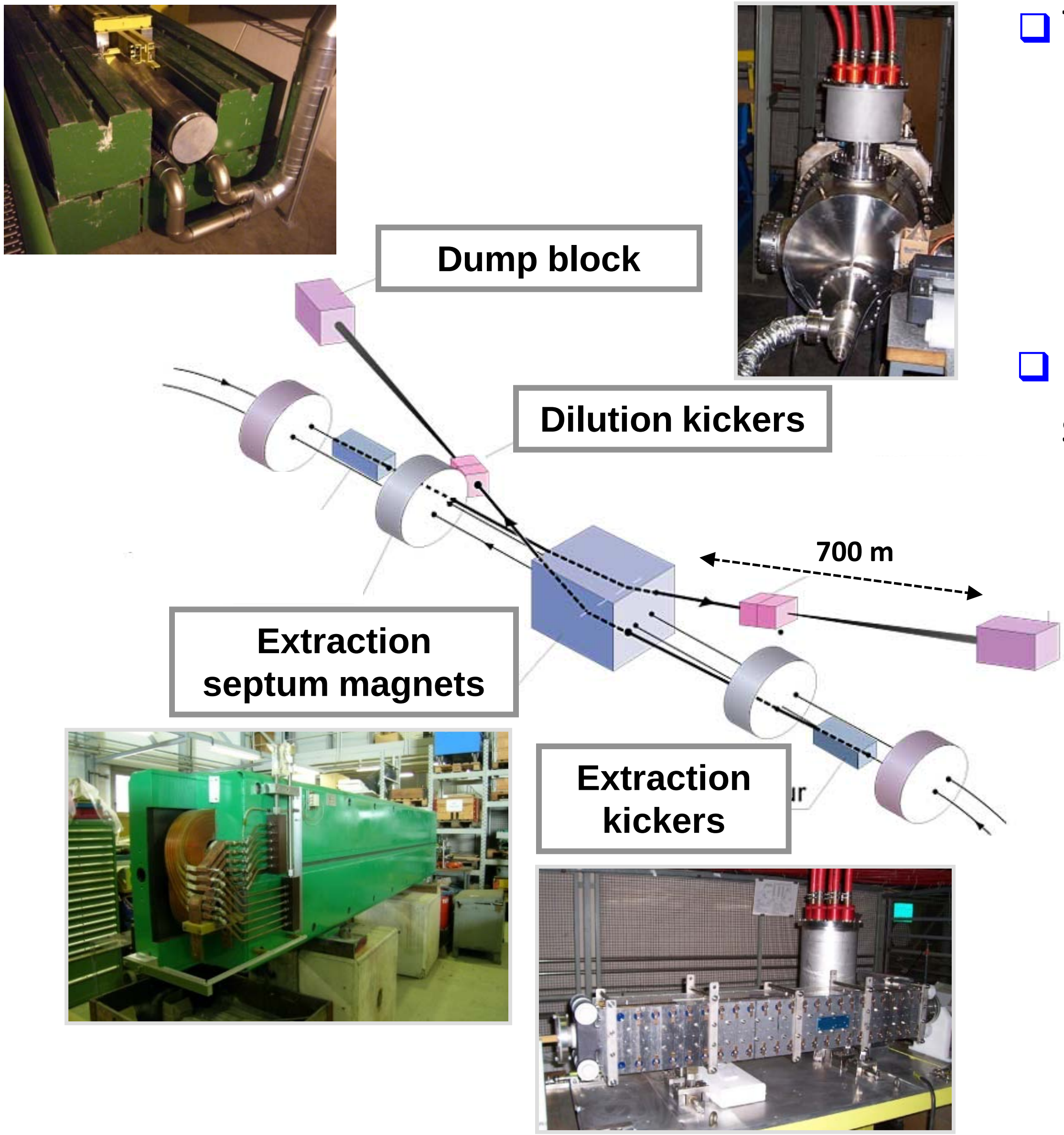
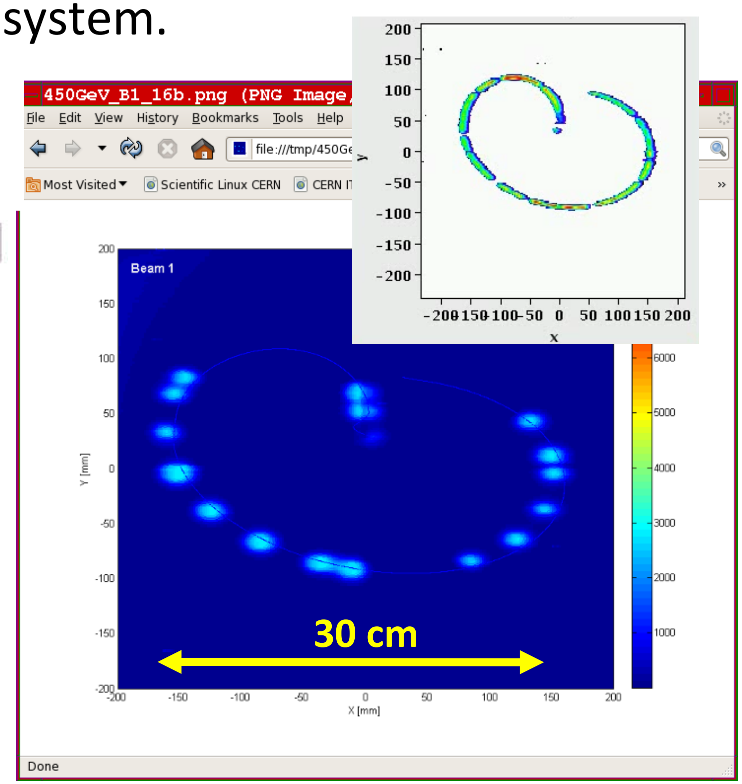
Beam dumping system



- The dump is the only LHC element capable of absorbing the nominal beam.
- Ultra-high reliability and fail-safe system.



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 $3x10^{13}$p (2 MJ)**.
- Vacuumto atmospheric pressure, Downtime ~ 3 days.

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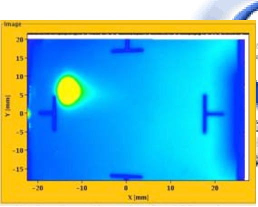
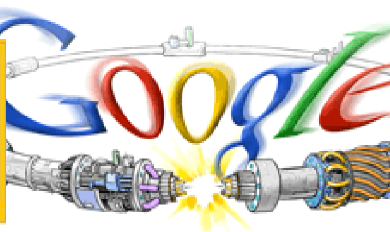
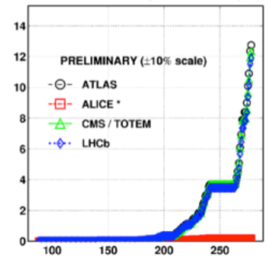
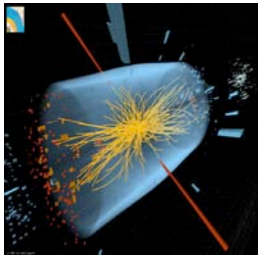
- LHC milestones

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

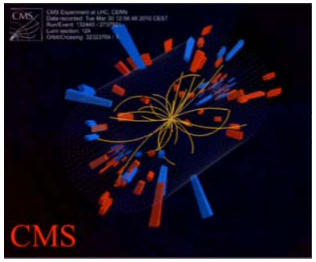
September, 19 2008
Incident

March 30, 2010
First collisions at 3.5 TeV

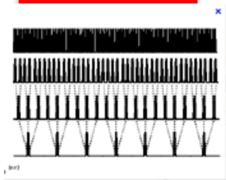
November 2010
Ion run

June, 28 2011
1380 bunches

July, 2012
5 fb^{-1}



1380



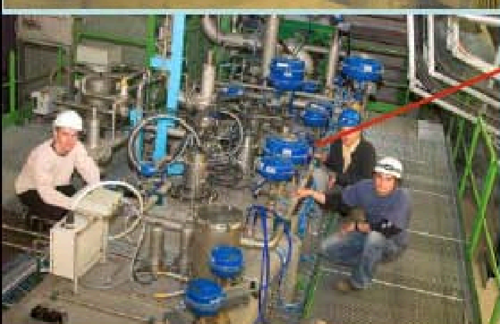
5 fb^{-1}

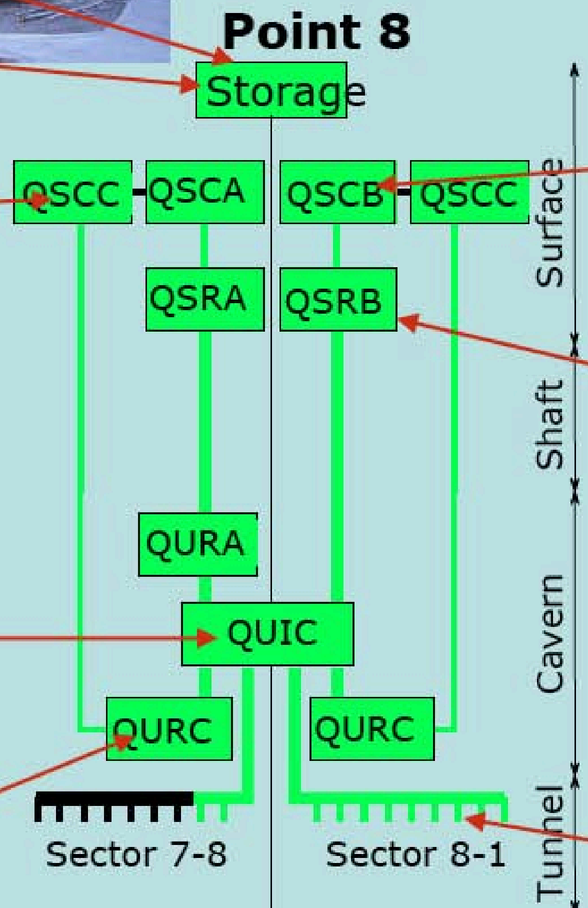
Parameters evolution: 2010-2012

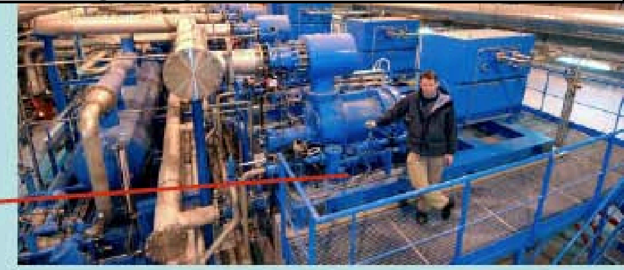
$$L = \frac{k_b N^2 f \gamma}{4 \pi \beta^* \varepsilon} F$$

Parameter	2010	2011	2012	Nominal
Energy (TeV)	3.5	3.5	4.0	7.0
N (10^{11} p/bunch)	**1.2**	**1.45**	**1.58**	1.15
k (no. bunches)	368	1380	1374/ 1380	2808
Bunch spacing (ns)	150	75 / 50	50	25
Stored energy (MJ)	25	112	140	362
ε (μm rad)	**2.4-4**	**1.9-2.4**	**2.2-2.5**	3.75
β^* (m)	3.5	1.5→ 1	0.6	0.55
L ($cm^{-2}s^{-1}$)	**2×10^{32}**	**3.5×10^{33}**	**7.6×10^{33}**	10^{34}

- 24 km of superconducting magnets @1.9 K
- 88 tons of superfluid helium at 1.9 K
- 8 x 18kW @ 4.5 K
- 1’800 superconductingmagnets



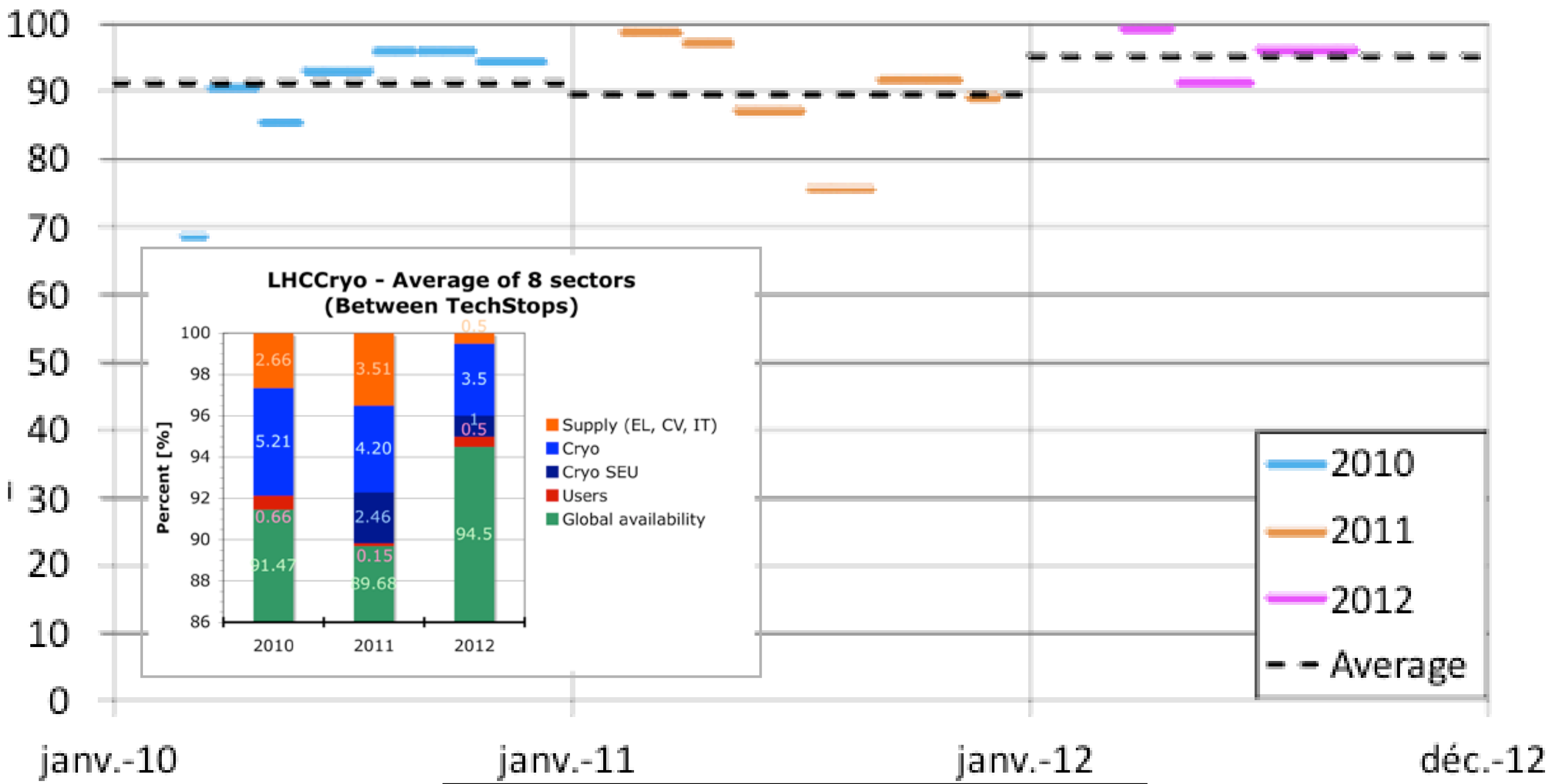




Unprecedented !

Courtesy Serge Claudet

Overall LHC cryogenics availability



Xmas stops

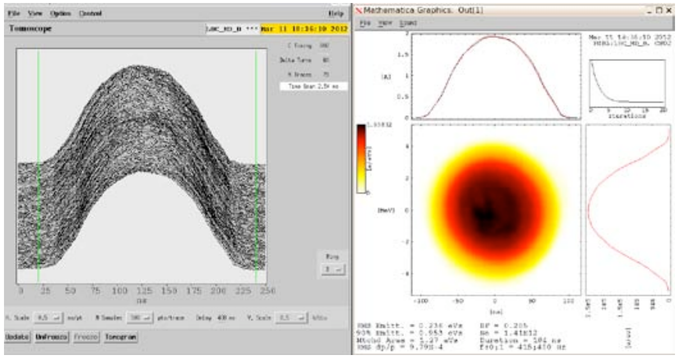
9 weeks14 weeks

OK with cryo need (light maintenance)

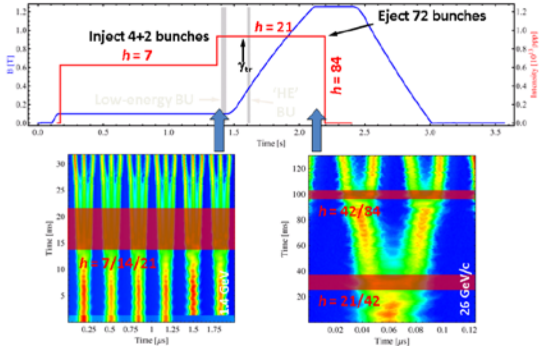
Technical stops (3-5 days)

2010	2011	2012
6/7 in 2010	**5** in 2011	**3** in 2012
Fully used by cryo		Comfortable

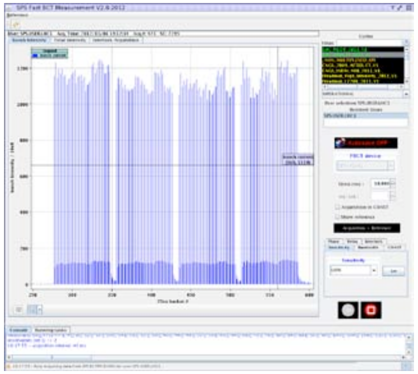
LHC beam journey



Emittance measurement at 1.4 GeV



Bunch splitting at 1.4 GeV



Single bunch intensity at 26 GeV

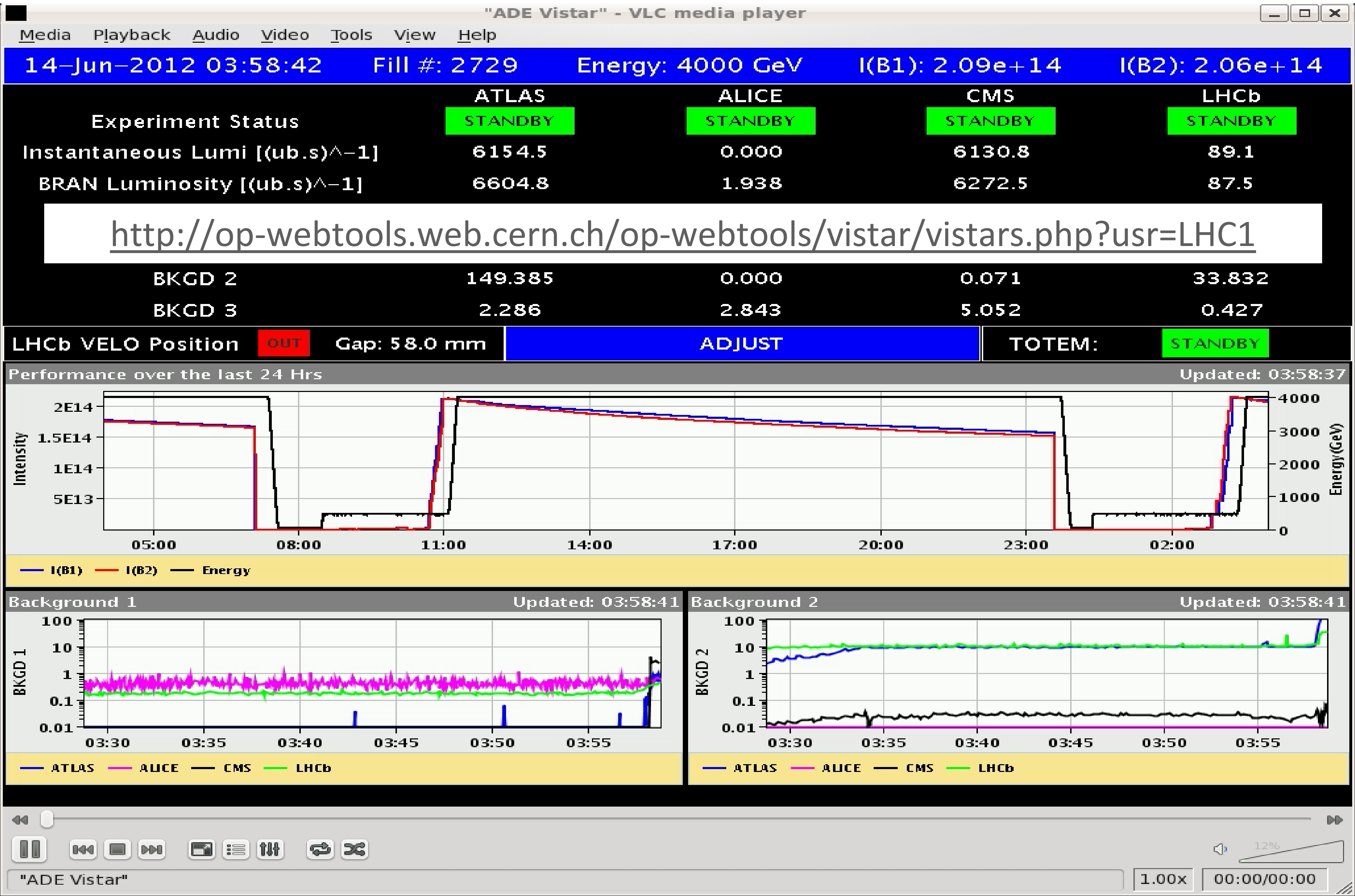
Booster & CPS	SPS injection	SPS extraction	LHC Injection	LHC Ramp
1.4GeV/26 GeV	26 GeV	450 GeV	450 GeV	4 / 7 TeV

Total intensity 2·10 ^{14} /beam

Beam losses end of ramp warning

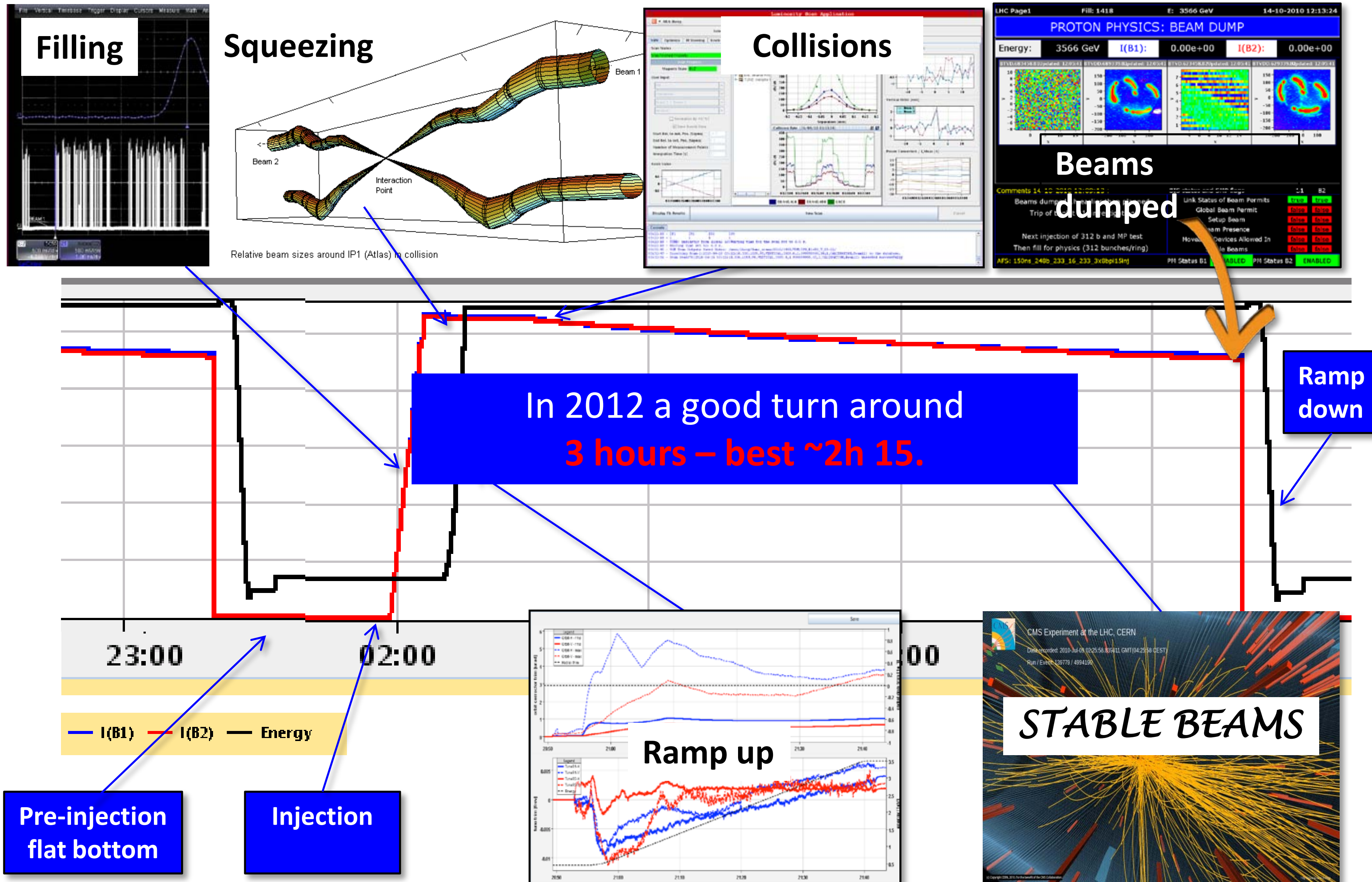
Luminosity adjustments

Operational cycle



http://op-webtools.web.cern.ch/op-webtools/vistar/vistars.php?usr=LHC1

Operational cycle

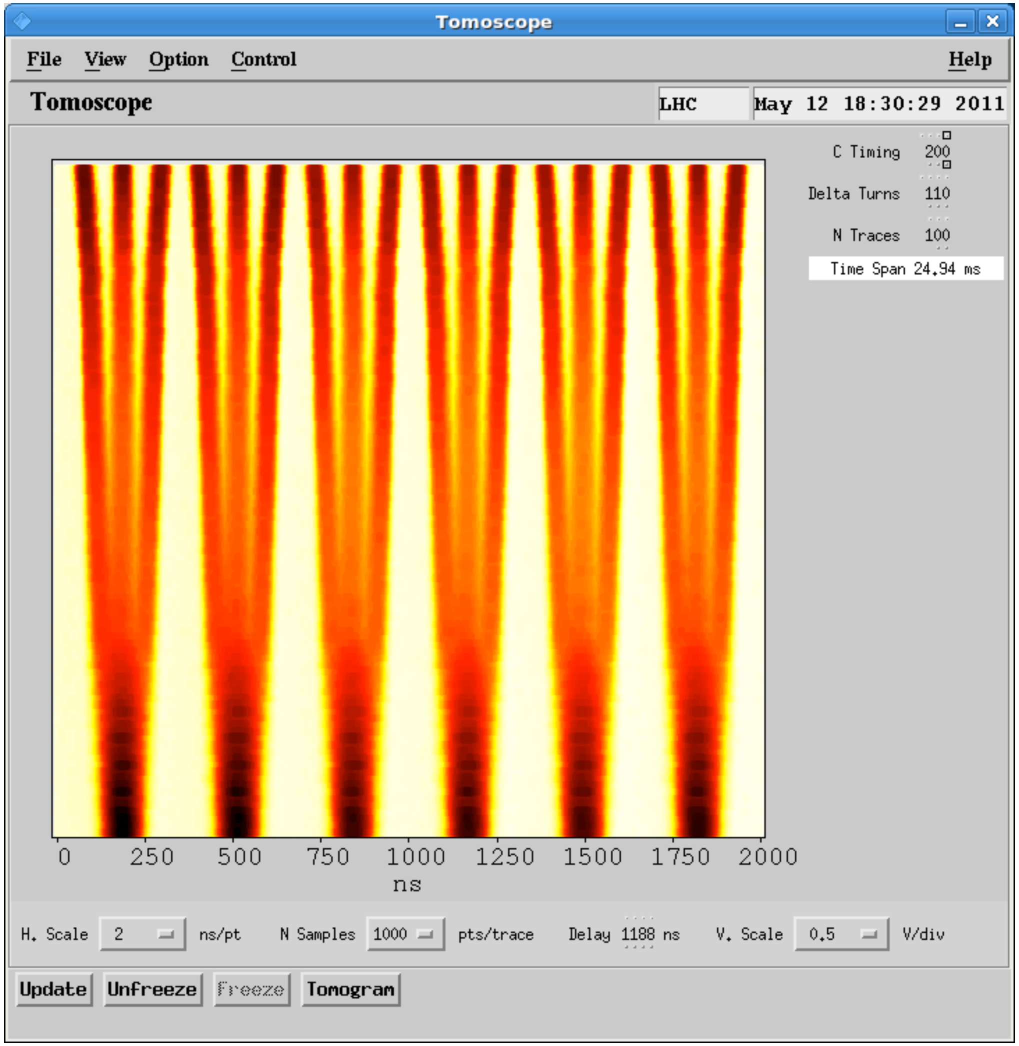


Beam from injectors

This year we've mostly been taking the 50 ns beam.

Excellent performance – better than nominal bunch intensity and less than nominal beam size

Years in the preparation



LHC Beam Operation

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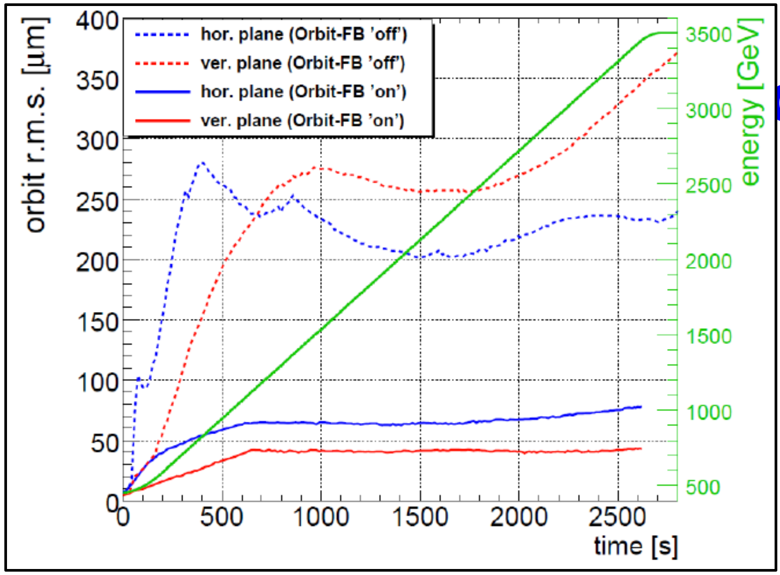
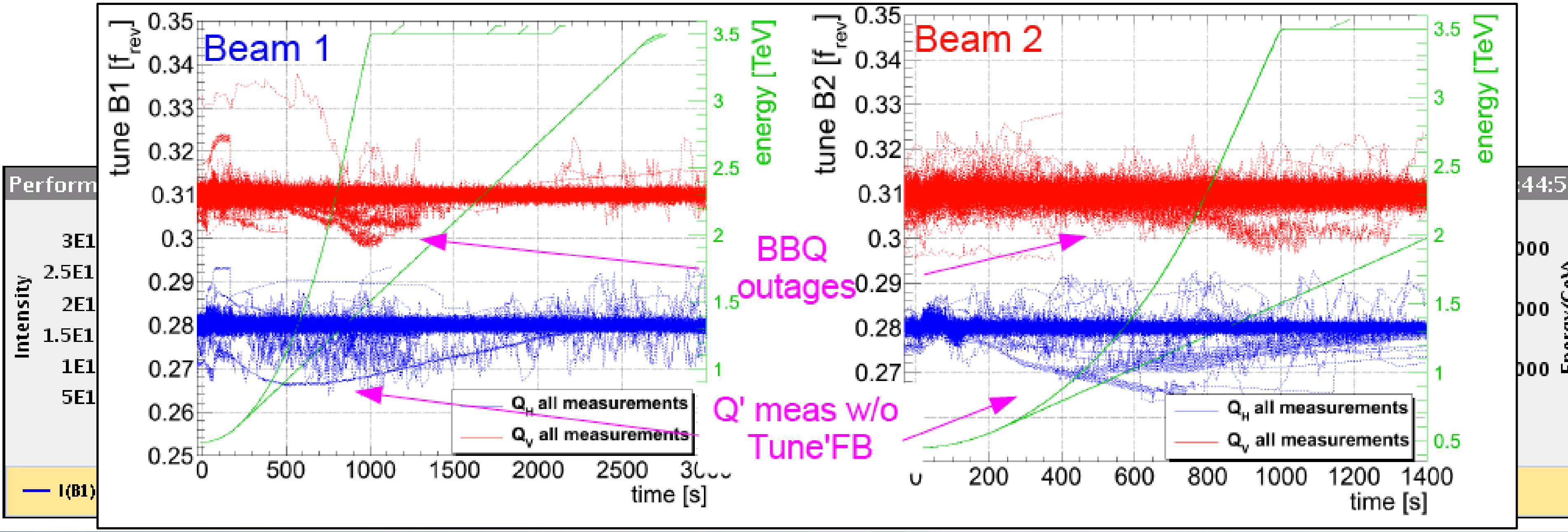
Ramp & Tune and Orbit feedback



d essentially without loss

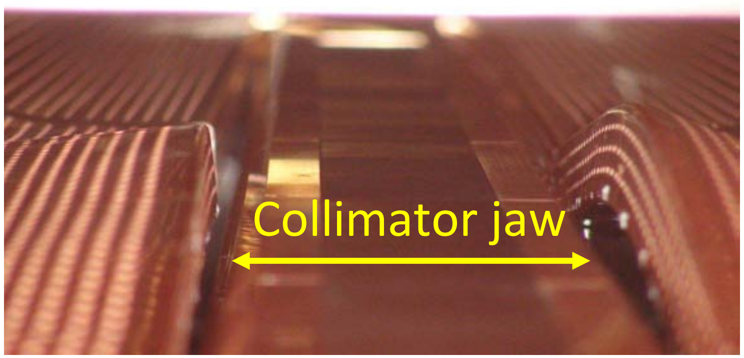
- Tune & Orbit feedback
- Mandatory in ramp and squeeze
- Commissioning not without some issues but now fully operational



High intensity beam issues

Beam stored intensity of ≥ 2x10^{14}protons (1380 bunches,50 ns), issues related to high intensity and tight collimators have affected LHC operation in 2011/12

- *Vacuum pressure increases,*
- ***Heating of elements by the beam induced fields (injection kickers, collimators, lately also synchrotron light mirrors),***
- *Losses due to dust particles falling into the beam (UFO),*
- ***Beam losses due to tails,***
- ***Beam instabilities leading to emittance blow-up.***
  - ***2012: Lost 35 fills due to those issues.***
  - ***2011: Only 1 fill lost.***

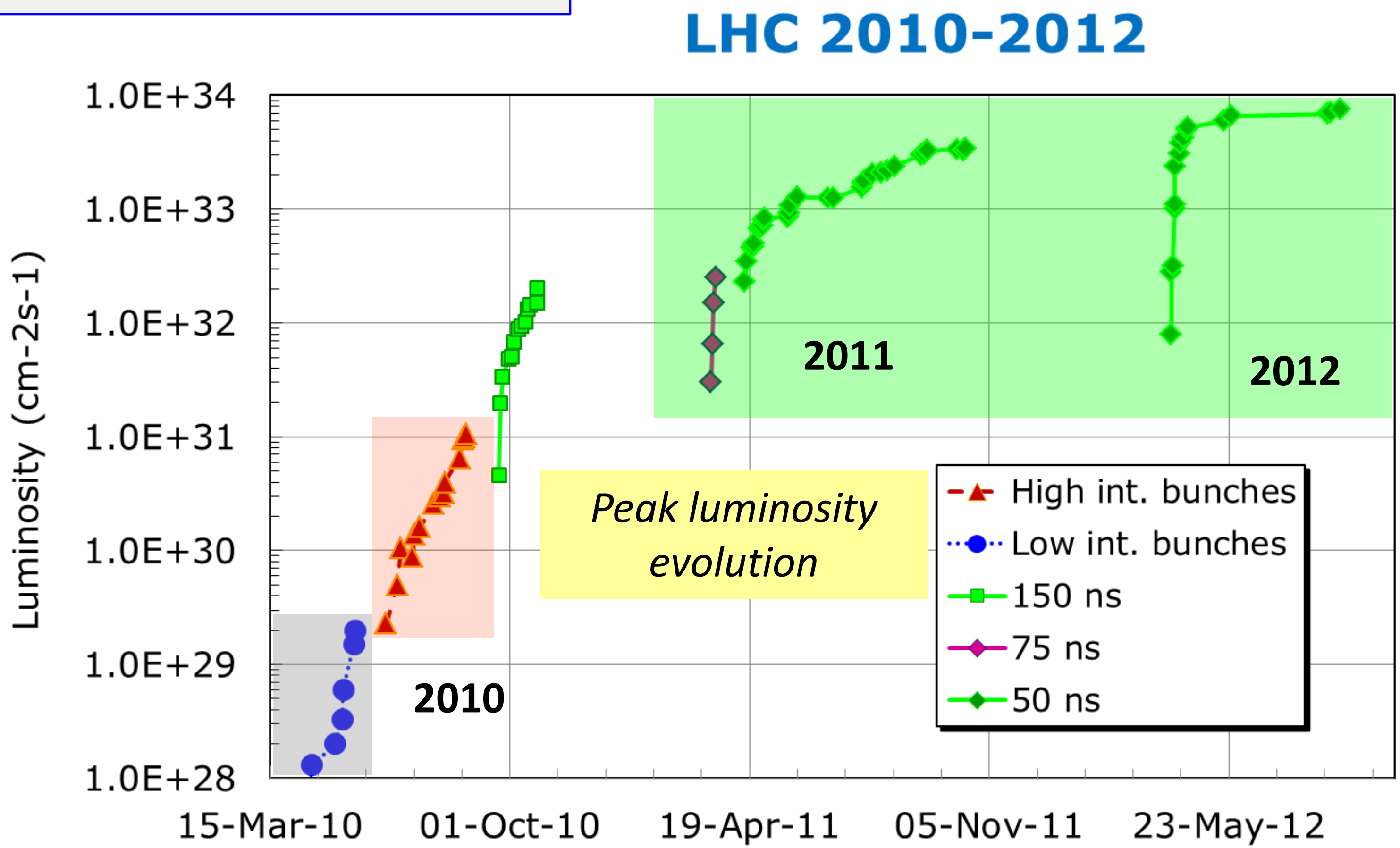


LHC luminosity progress in 2010-12

Low bunch intensity operation, first operational exp. with MPS

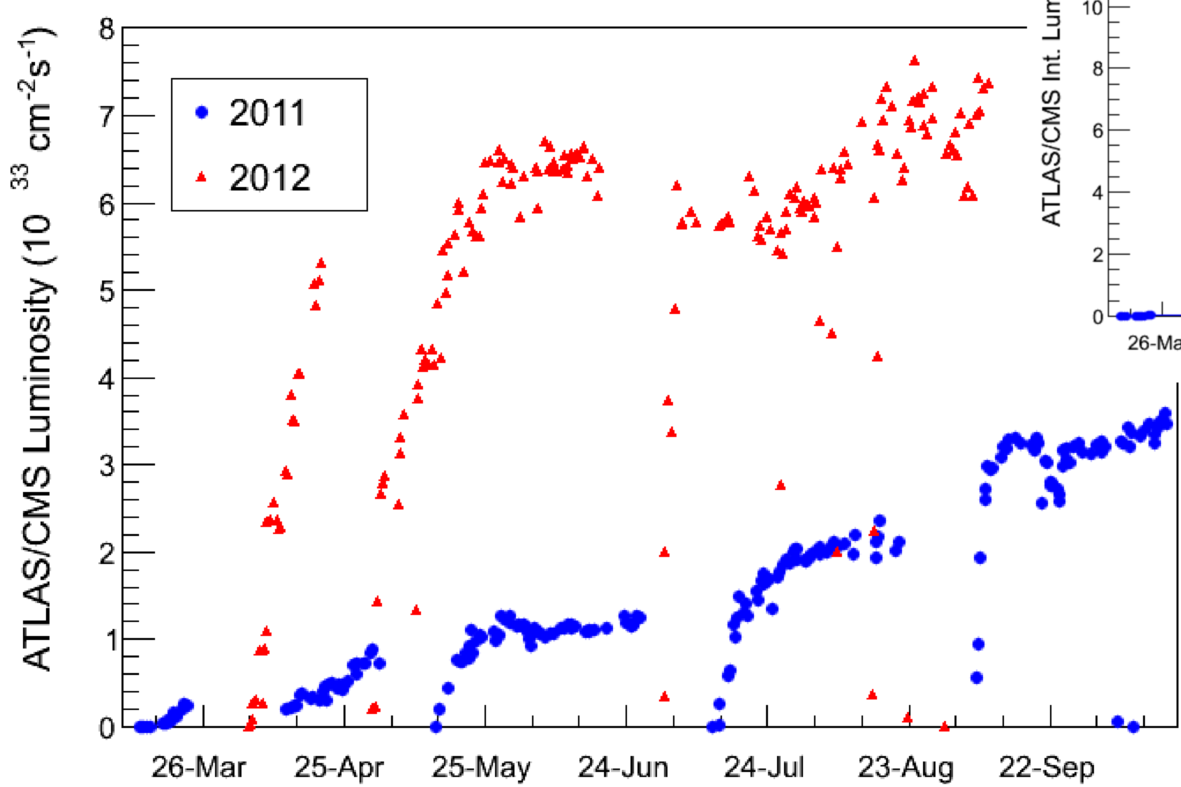
Ramping up to 1 MJ, stability run at 1-2 MJ

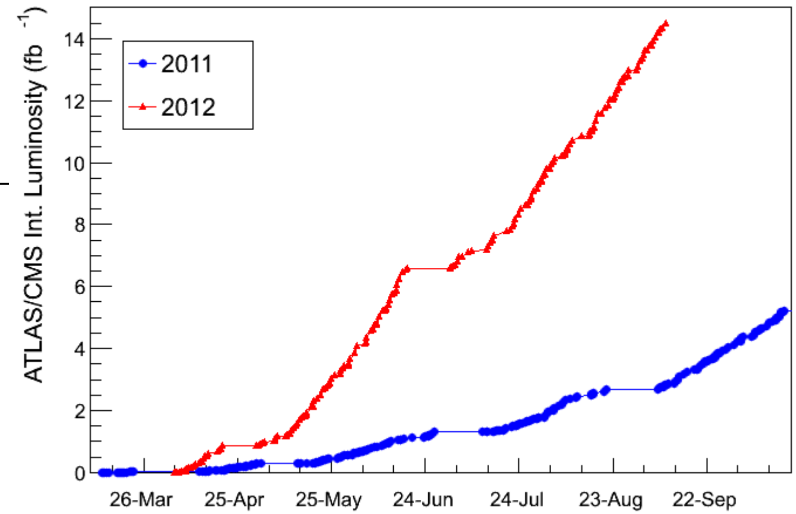
Reach out for the fb's!



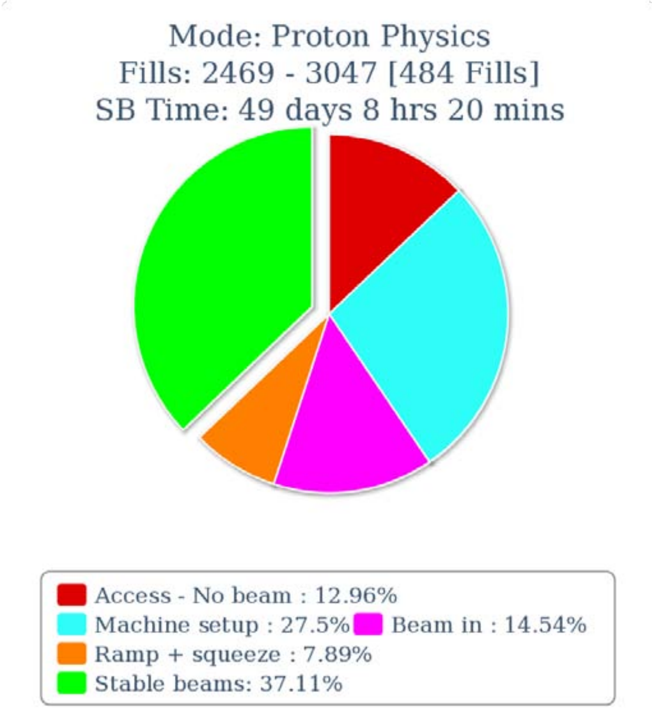
Integrated luminosity ATLAS/CMS in 2012 ~ **14.7 fb^{-1}**

- *Fast ramp up possible based on 2011 experience*
- *Best week: 1.35 fb^{-1}, theoretical max close to 2 fb^{-1}*
- ***Expect ~22-25 fb^{-1}at the end of 2012***
- *Peak L = 7.6×10^{33} $cm^{-2}s^{-1}$*

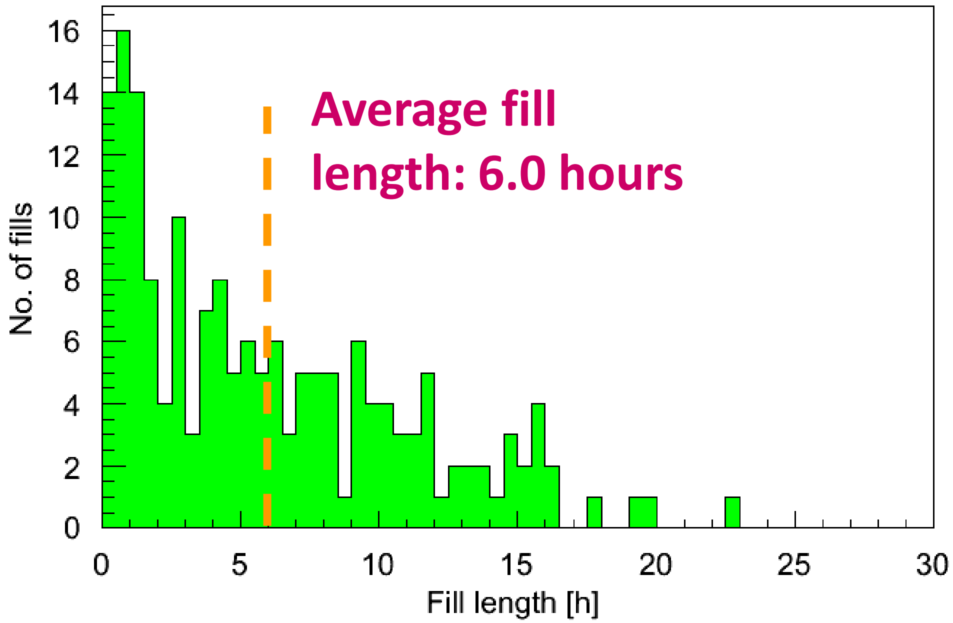




Efficiency



- Spent 37% of scheduled time with stable beams in 2012
  - *Compared to 33% in 2011*



- Fill lengths comparable in 2011 and 2012.
  - *Fill length determined mostly by 'failures'.*
  - *Only ~25% of fills are dumped by operation.*

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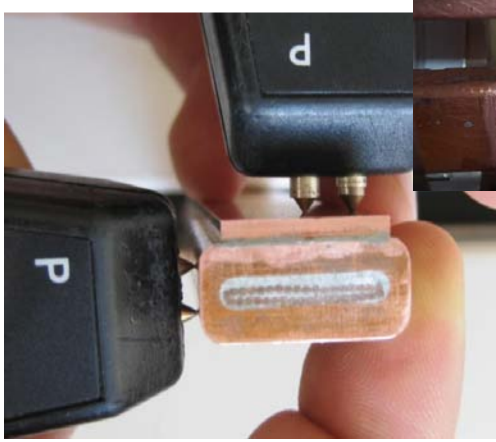
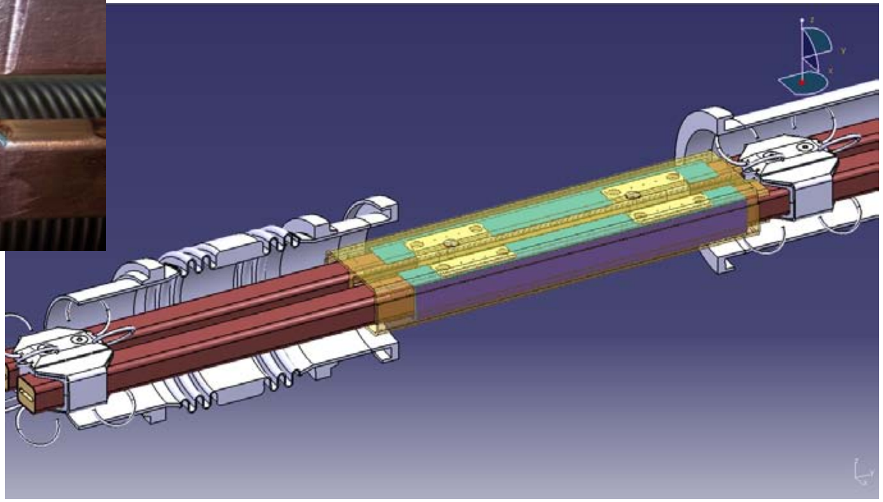
The next's years at LHC

- 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.

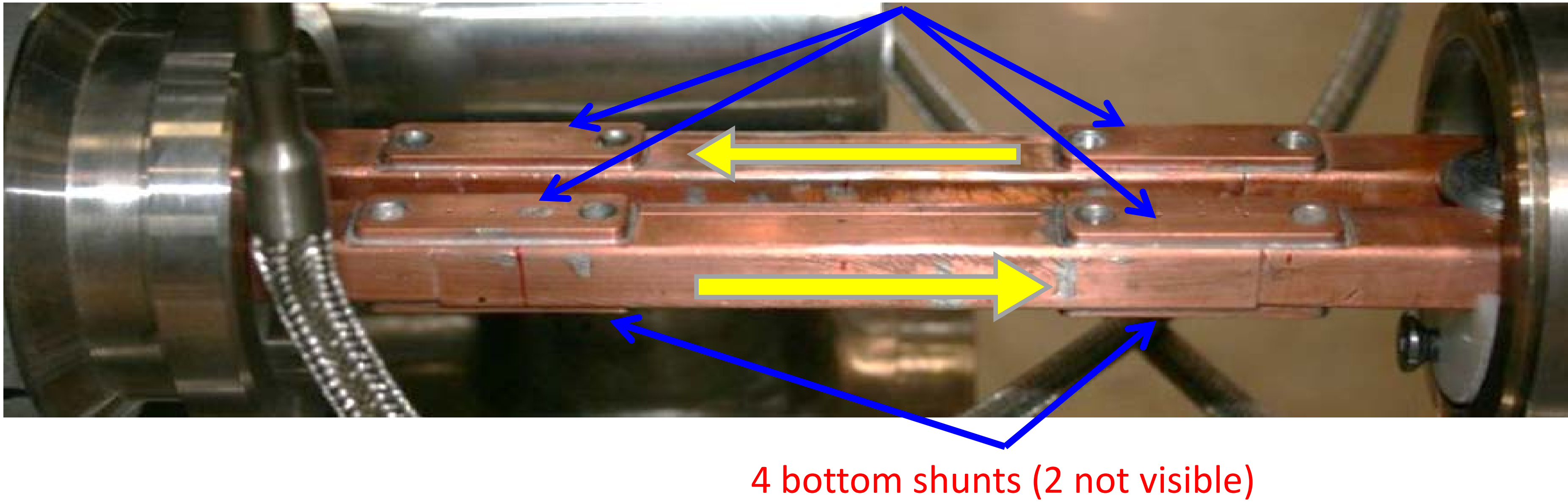




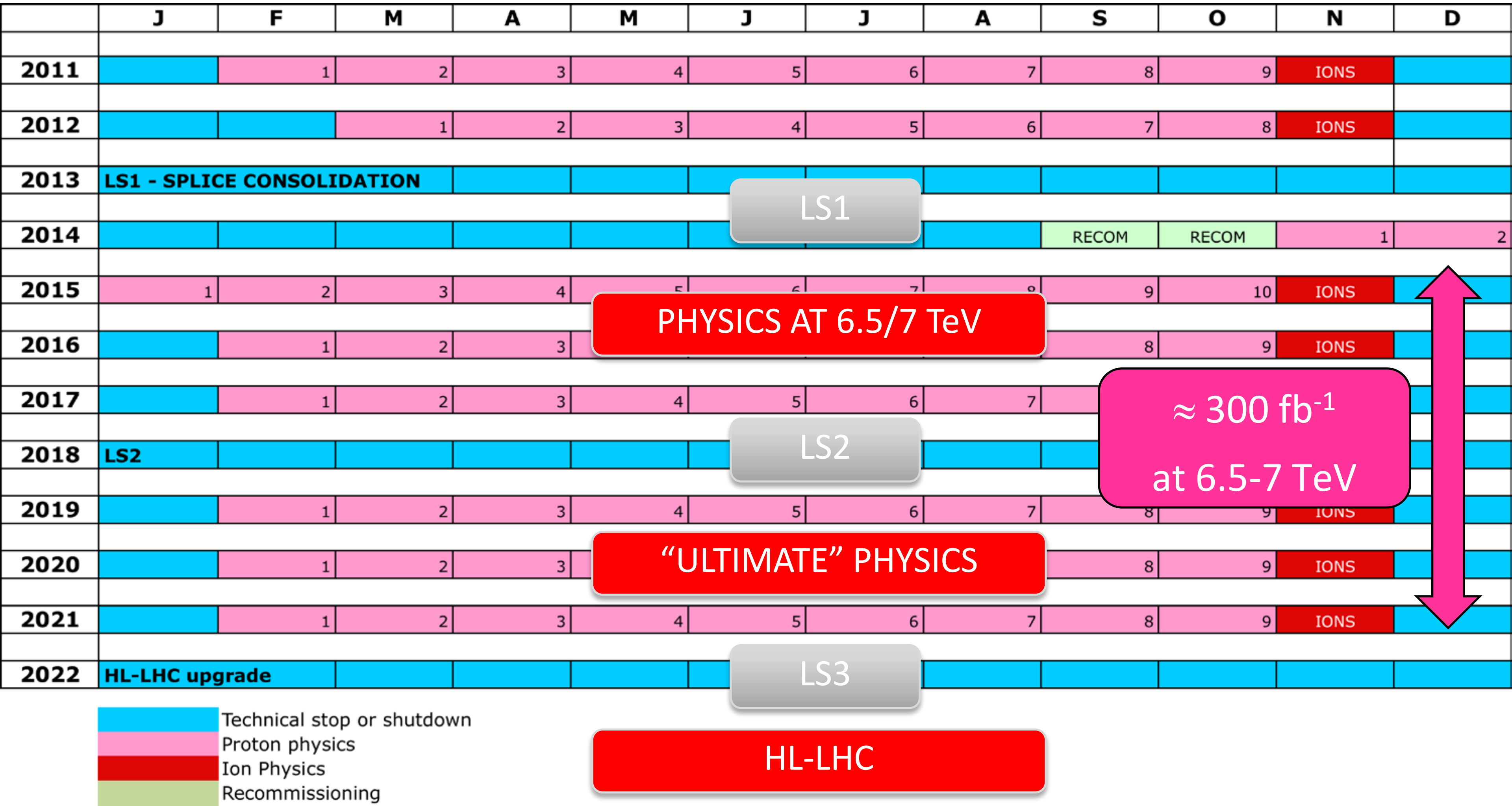
Joint consolidation

- The main objective of LS1 is to repair defective joints and to consolidate all the joints.

An example of the consolidated joint.



10 year plan



NB: not yet approved

2013 – 2014

Long Shutdown 1 (LS1) consolidate for 6.5 / 7TeV

- Measure all splices and repair defective splices,
- Consolidate interconnects with new design (clamp, shunt),
- Finish installation of pressure release valves (DN200),
- Magnet consolidation,
- Measures to further reduce radiation to electronics: relocation, redesign, …
- Install collimators with integrated button BPMs (tertiary collimators and a few secondary collimators),
- Experiments consolidation/upgrades.

Luminosity ≈ 10^{34} $cm^{-2}s^{-1}$ at 6.5-7 TeV

Summary

- **The LHC is doing incredible well, even if we are operating close to the edge of what it can be done.**
- **Luminosity results a factor 10 higher then originally foreseen at this stage!**
- LHC Machine Protection Systems have been working well***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.
- **We have to remain vigilant to maintain current level of safety of MPS systems** while increasing efforts on increasing MPS availability.

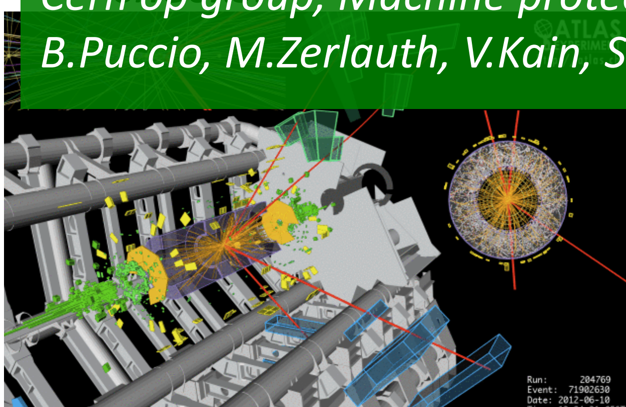
- ***LHC operation at 7 TeV will be a new challenge***

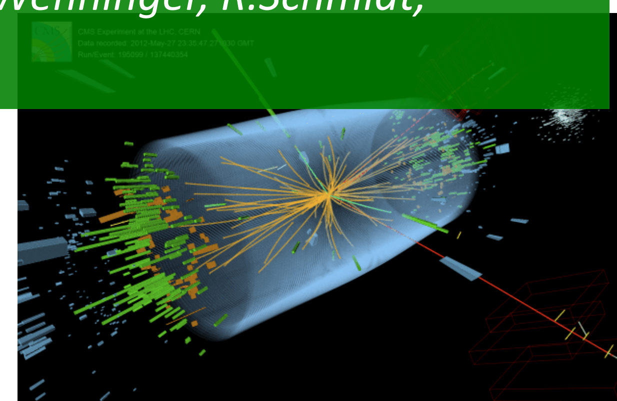
Summary

- **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 FabiolaGianotti, *"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."*

Thank you for your attention

Acknowledgement:
Cern op group, Machine protection WG, B.Todd, M.Lamont, J.Wenninger, R.Schmidt, B.Puccio, M.Zerlauth, V.Kain, S.Redaelli, G.Arduini,





Potential performance

	Beta* [cm]	Ib SPS	Emit SPS [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi [fb^{-1}]
25 ns	50	1.2e11	2.8	1.2e34	28	32
25 ns low emit	50	1.2e11	1.4	2.2e34	46	57
50 ns level	50	1.7e11	2.1	1.7e34 level 0.9e34	76 level 40	40 – 50*

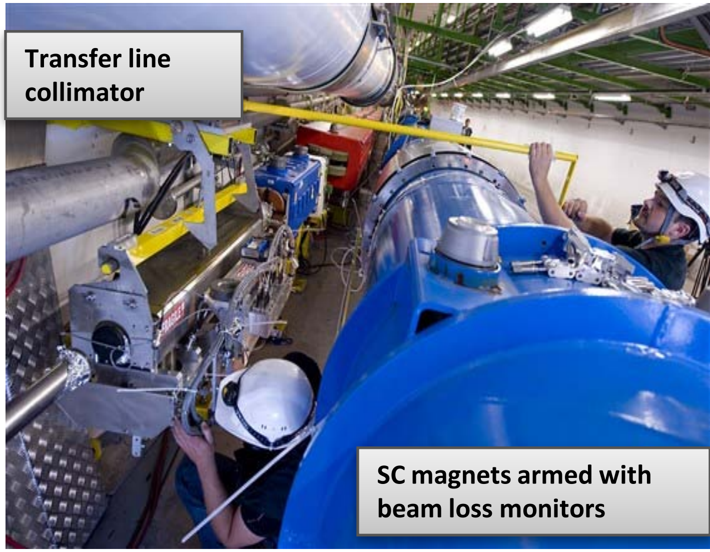
All numbers approximate!

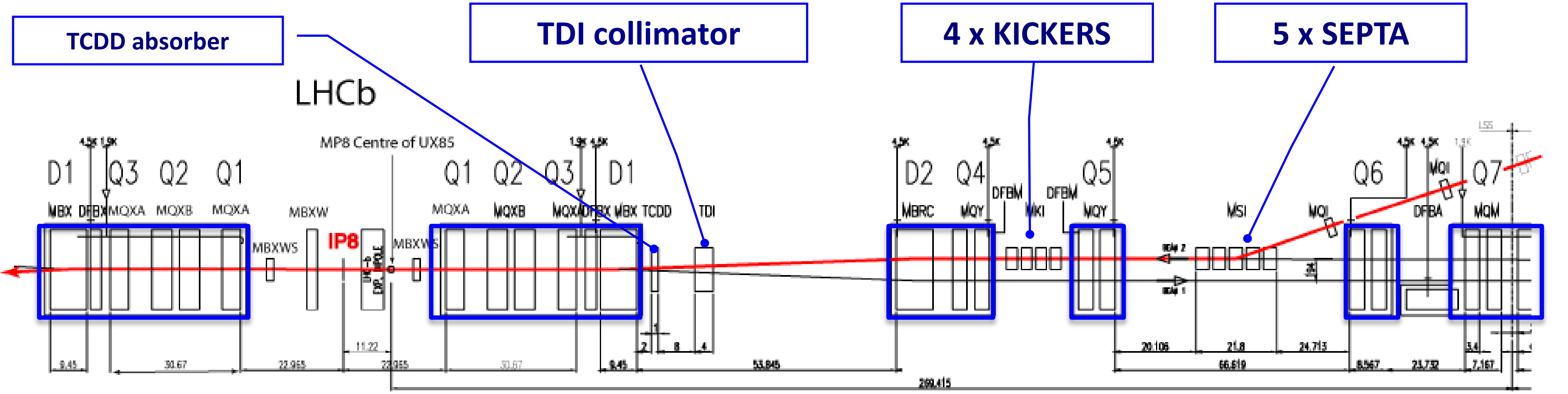
- 150 days proton physics
- 5% beam loss, 10% emittance blow-up in LHC
- 10 sigma separation
- 70 mb visible cross-section
- * different operational model - caveat

50 versus 25 ns

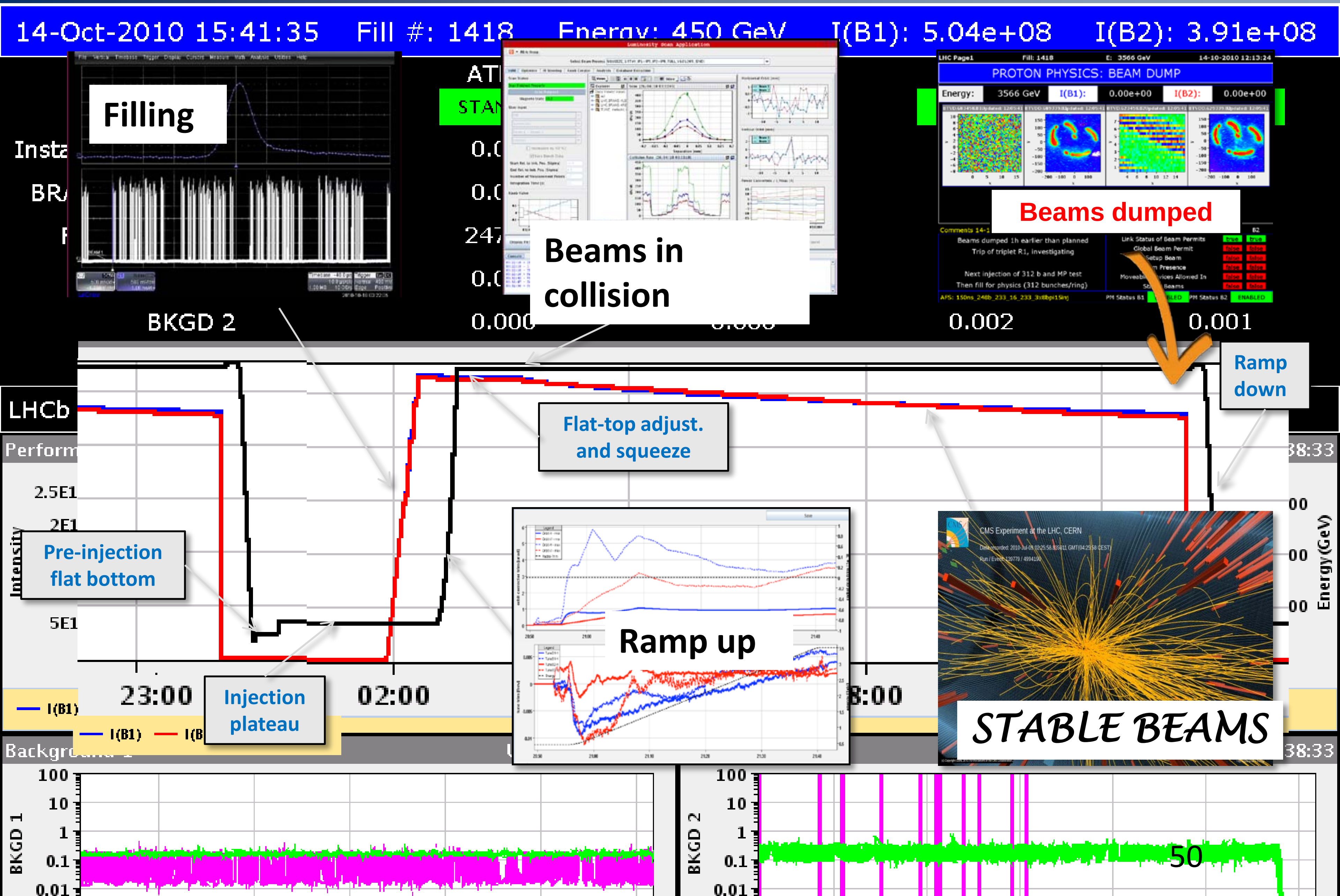
- 50-ns beam: smaller emittance from the PS
  - less splittings in the PS; i.e. less charge in the PSB
  - ~2 vs ~3.5 micron at LHC injection
- 25-ns beam: emittance growth due to e-cloud in the SPS and LHC
  - to be improved by scrubbing in the LHC, and a-C coating in the SPS
- 25-ns has more long-range collisions
- Total current limit (by vacuum; RF) → limit # bunches
- Bunch train current limits in SPS & LHC → limit # bunches
- UFO rate seems to greatly increase for 25-ns spacing
- Ultimately we will (try to) transit to 25-ns spacing because of pile up

- **Complex process – wrestle with**:
  - Re-phasing, synchronization, transfer, capture
  - Timing, injection sequencing, interlocks
  - Injection Quality checks – SPS and LHC
  - Beam losses at injection, gap cleaning
- **Full program beam based checks performed**
  - Carefully positioning of collimators and other protection devices
  - Aperture, kicker waveform





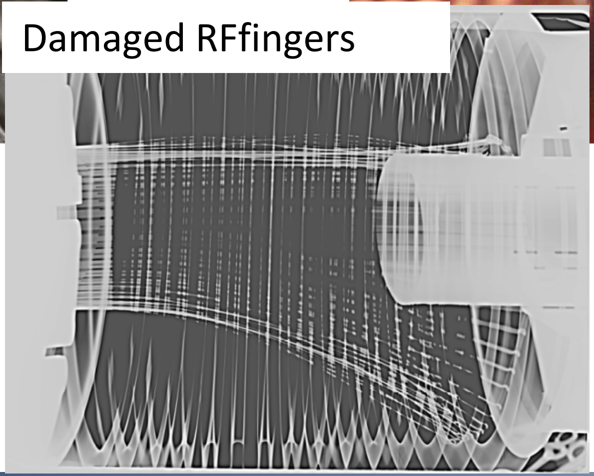
Operational cycle



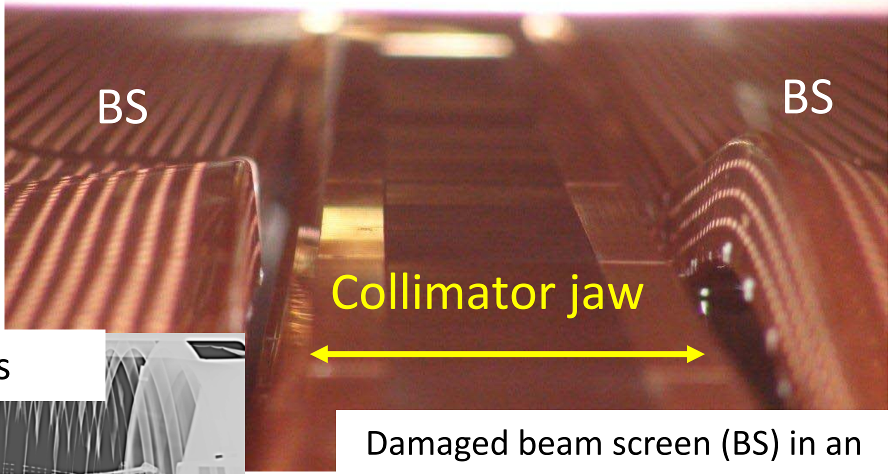
Heating damage

- High intensity beams may deposit large amounts of power in incorrectly shielded components.
  - *Design, manufacturing or installation errors may lead to partial or total damage of accelerator components.*
  - *So far they have not limited, could be fixed or mitigated.*

Damaged mirror of the synchrotron light telescope



Damaged RFfingers



Damaged beam screen (BS) in an injection protection device

Operational challenges at 7 TeV

Performance and startup at 7 TeV may be impacted by:

- Electron cloud effects with 25 ns beams,
- UFOs at higher energy and with 25 ns beams,
- Emittance growth and instabilities in the cycle,
- Magnets operated much closer to quench limit,
- Total intensity limitations in the LHC,
- Radiation to electronics,
- And the things that we will discover…

Operational robustness

- Injecting dangerous beams routinely
  – Vigilance always required
- Ramp & squeeze & collide essentially without loss
  – Excellent reproducibilityand stability
  – Feedbacks (tune, orbit, transverse) indispensable
  – Almost exclusive coverage by the sequencer for nominal operation
- Software, controls, databases, measurement and analysis tools provide rich functionality

LS1 and LS2

2013 – 2014: Long Shutdown 1 (LS1) consolidate for 6.5 / 7TeV

- Measure all splices and repair defective splices,
- Consolidate interconnects with new design (clamp, shunt),
- Finish installation of pressure release valves (DN200),
- Magnet consolidation,
- Measures to further reduce radiation to electronics: relocation, redesign, …
- Install collimators with integrated button BPMs (tertiary collimators and a few secondary collimators),
- Experiments consolidation/upgrades.

Luminosity ≈ 10^{34} $cm^{-2}s^{-1}$ at 6.5-7 TeV

2018: LS2 to prepare for 'ultimate LHC':

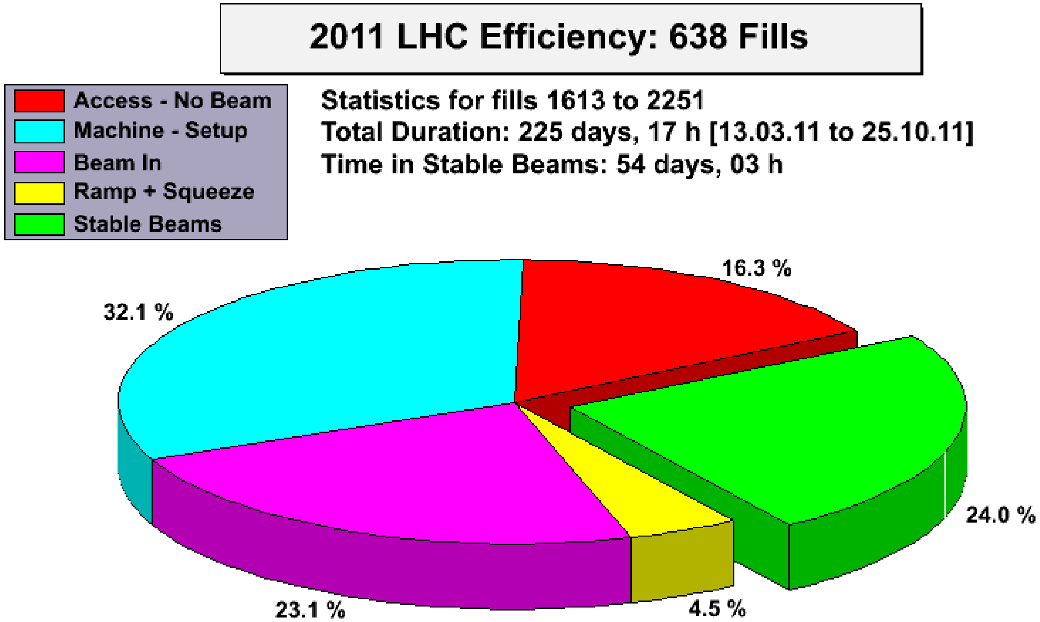
- Phase II collimation upgrade,
- Major injectors upgrade (LINAC4, 2GeV PS Booster, SPS coating, …).

Luminosity ≈$2{\times}10^{34}cm^{-2}s^{-1}$ at 6.5-7 TeV.

Efficiency/Availability

- **30% efficiency** for stable beams during **180 days for physics** (54 days in stable beams)

- Other scheduled periods:
  - 18 days technical stops
  - 10 days scrubbing run
  - ~17 days of MD



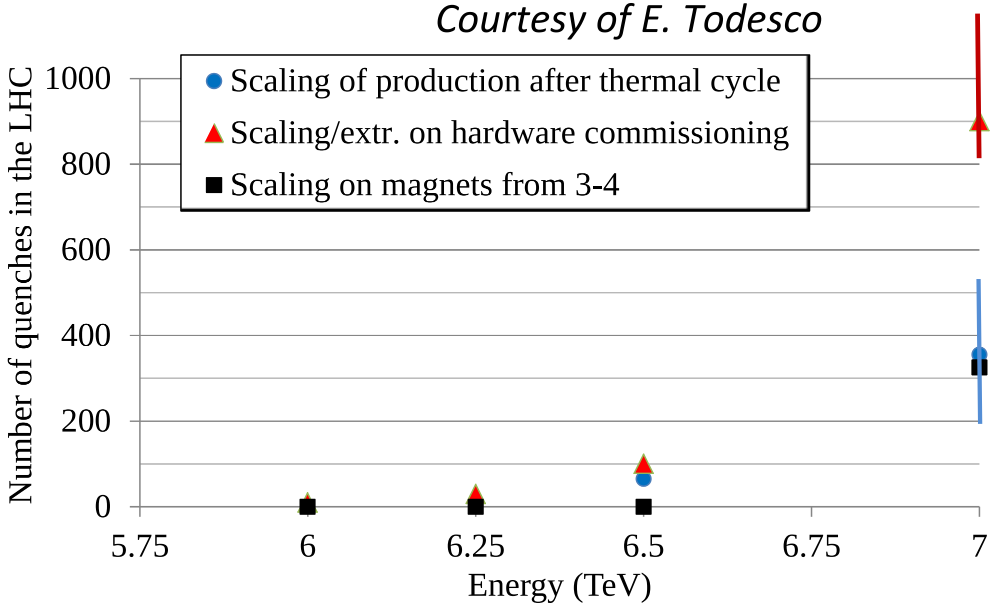
Pretty good!

Energy after LS1

- In 2008 attempts to commission the first LHC sector to 7 TeVrevealed a problem on the magnets from one manufacturer.
  - *The magnets that had been trained on test stands started to quench again.*
  - *The number of quenches increased rapidly beyond 6.5 TeV.*
- Extrapolations showed that the number of training quenches required to reach 7 TeV is too large.
  - *Time and risk to the magnets.*

Courtesy of E. Todesco

- For those reasons we will most likely restart at **6.5 TeV**, or slightly above depending on time and experience during the re-commissioning.



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Injector beams after LS1

- New ideas and concepts will be implemented in the PS to produce beams with higher intensity and smaller emittance.
- Possible beams after LS1 (not yet demonstrated).

					Nominal
		50 ns	**50 ns**	**25 ns**	**25 ns**
PS ejection	Bunches / train	32	24	48	**72**
SPS ejection	Bunch intensity	$1.7 \cdot 10^{11}$	$1.7 \cdot 10^{11}$	$1.15 \cdot 10^{11}$	$\mathbf{1.2 \cdot 10^{11}}$
	Emittance [μm]	1.5	1.2	**1.4**	**2.8**
No bunches in LHC		~1340	~1300	~2600	**2808**
Relative luminosity		**2**	**2.4**	**1.85**	**1**
Relative pile-up		**4.1**	**5.2**	**2**	**1**

Courtesy of H. Damerau

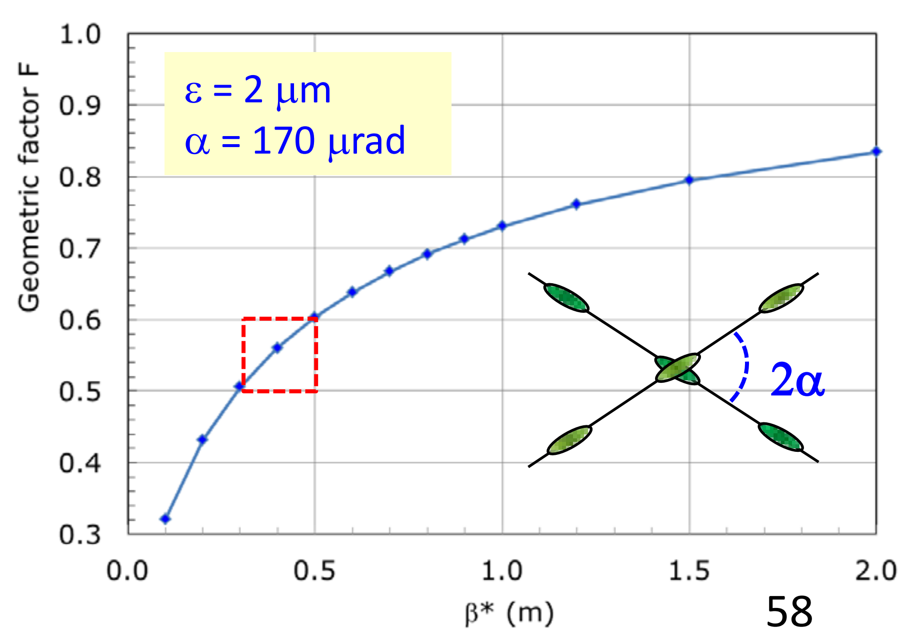
- The quoted emittance values (and luminosities) do not include any blowup in the LHC (presently ~ +0.6 μm).

β* reach at 6.5-7 TeV

- The β* reach depends on:
  - *The collimator settings and margins between collimators and with respect to apertures (we have a few scenarios…),*
  - *The beam type &emittance (25 ns / 50 ns) → crossing angle.*

- Possible range of smallest β* at 6.5-7 TeV:
  - 0.4 m ≤ β* ≤ 0.5 m for 25 ns beams,
  - 0.3 m ≤ β* ≤ 0.4 m for 50 ns beams.

Loss of ~40-50% due to geometrical effect (crossing angle) !



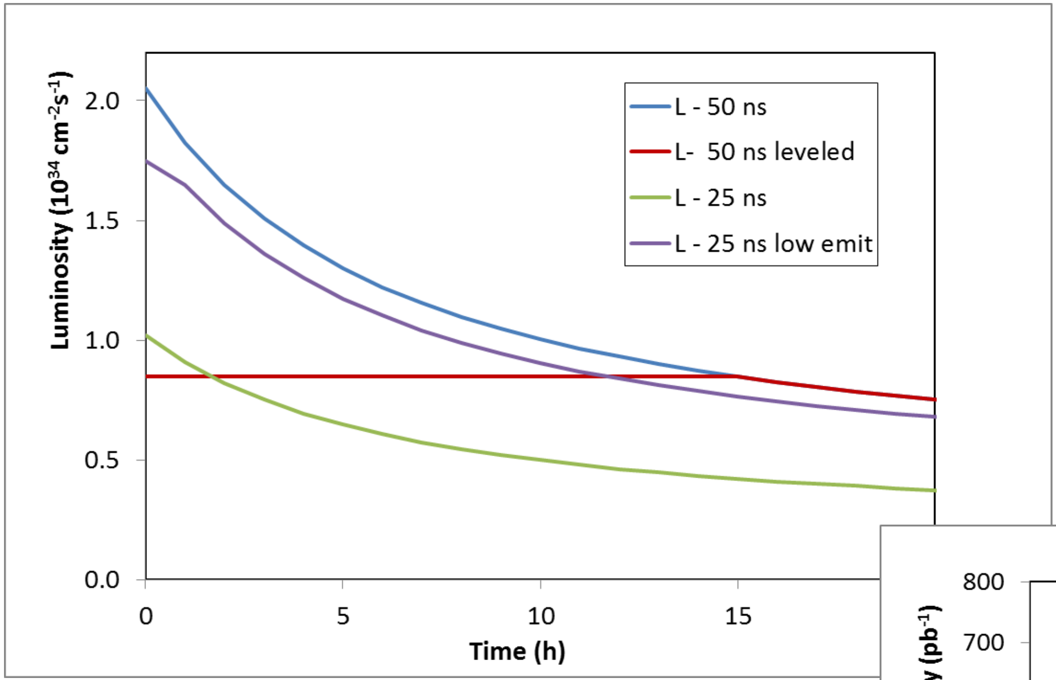
Luminosity at 6.5 TeV

3 out of many possible scenarios…

	k	N_b [10^{11} p]	ε [μm]	β* [m]	L [10^{34} $cm^{-2}s^{-1}$]	Pile-up	Int.L [fb^{-1}]
50 ns	1380	1.70	1.5	**0.4**	2.05	104*	~30
25 ns low emit	2600	1.15	1.4	**0.4**	1.73	47*	~50
25 ns standard	2800	1.20	2.8	**0.5**	1.02	25	~30

- The 50 ns beam pile-up is too high. The luminosity must be leveled down to limit pile-up. Assuming max. pile-up of 40.
- The integrated Luminosity is based on 120 days of production, 35% efficiency.

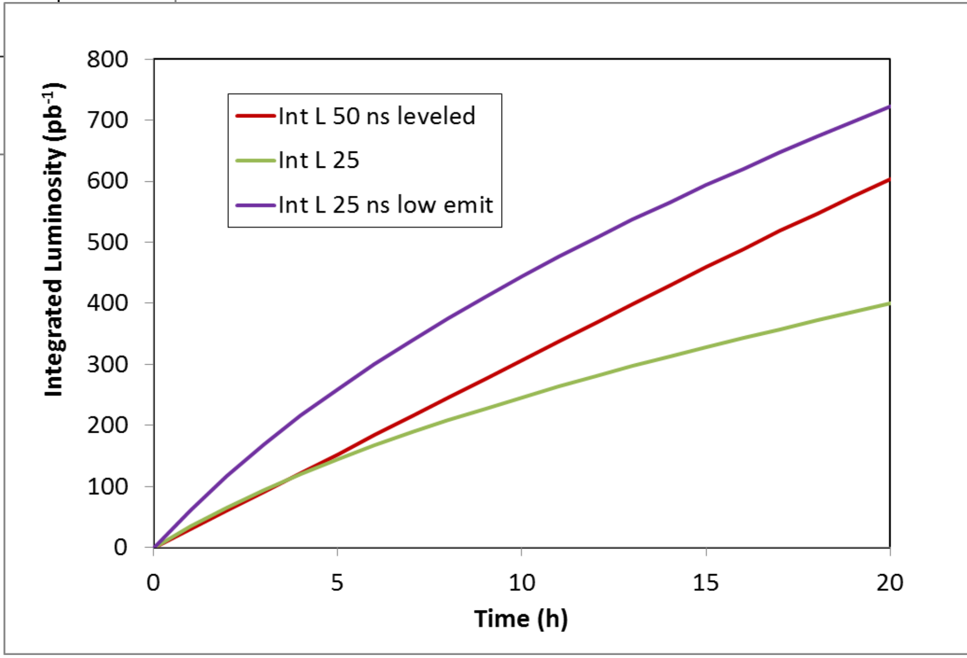
Performance comparison



Standard 25 ns and 50 ns with levelling…

…are equivalent in integrated luminosity for fill lengths up to 5-6 hours.

Low emittance 25 ns provides higher performance due to higher luminosity for same or lower pile-up.



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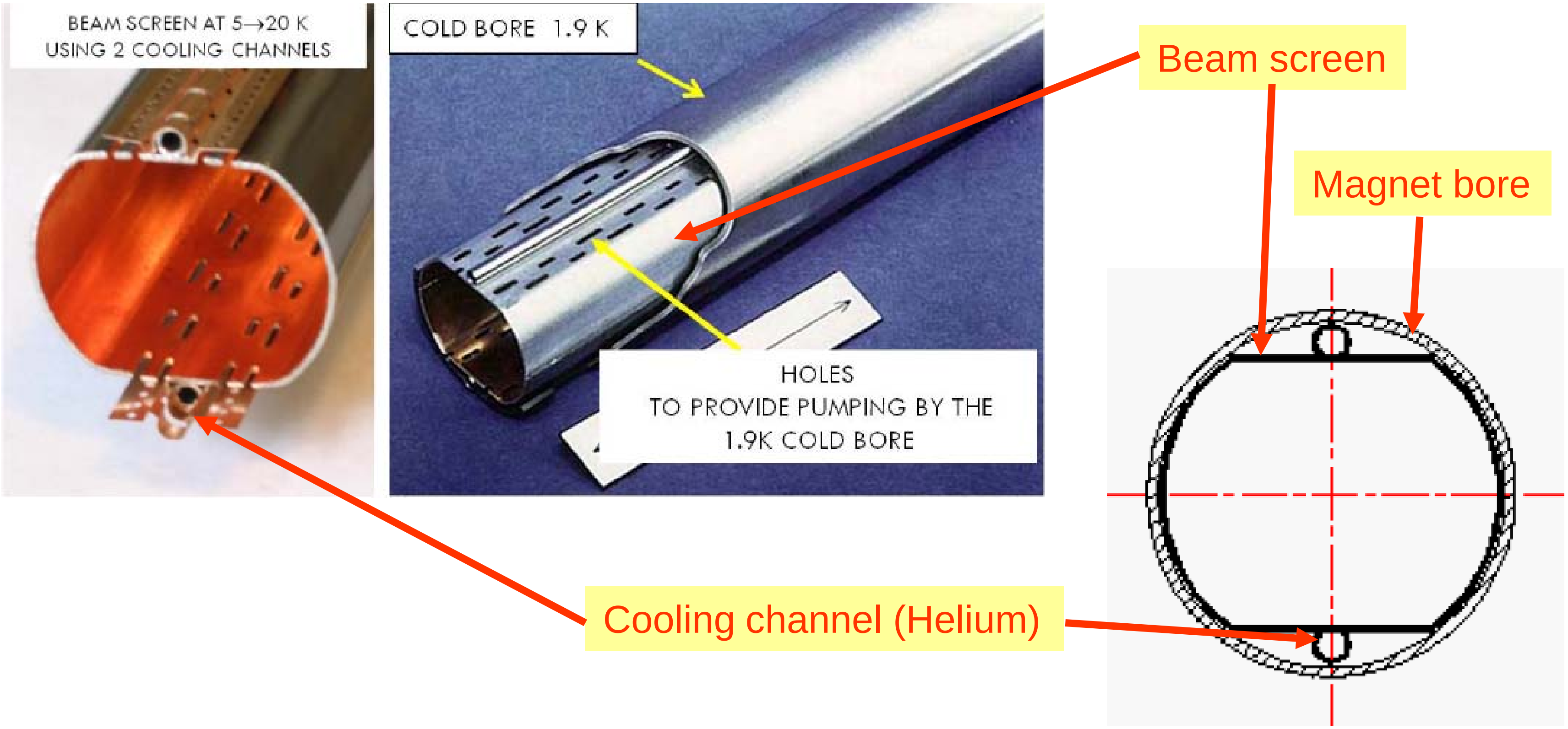
Scenario for startup after LS1

- It is quite likely that the machine will start up with 50 ns in order to deliver rapidly some integrated luminosity.
  - *Easy to reach high luminosity (even if limited by pile-up),*
  - *Lower stored energy,*
  - *Less / no e-clouds, fewer UFOs,*
  - *Long and good operational experience at 3.5/4 TeV.*
- Then, unless there is a major problem, we will probably devote some time (~2 weeks) to prepare the machine for 25 ns beams.
  - *E-cloud reduction by scrubbing,*
- … before switching to 25 ns beams.
  - *Ramping up of the number of bunches and of bunch intensity.*

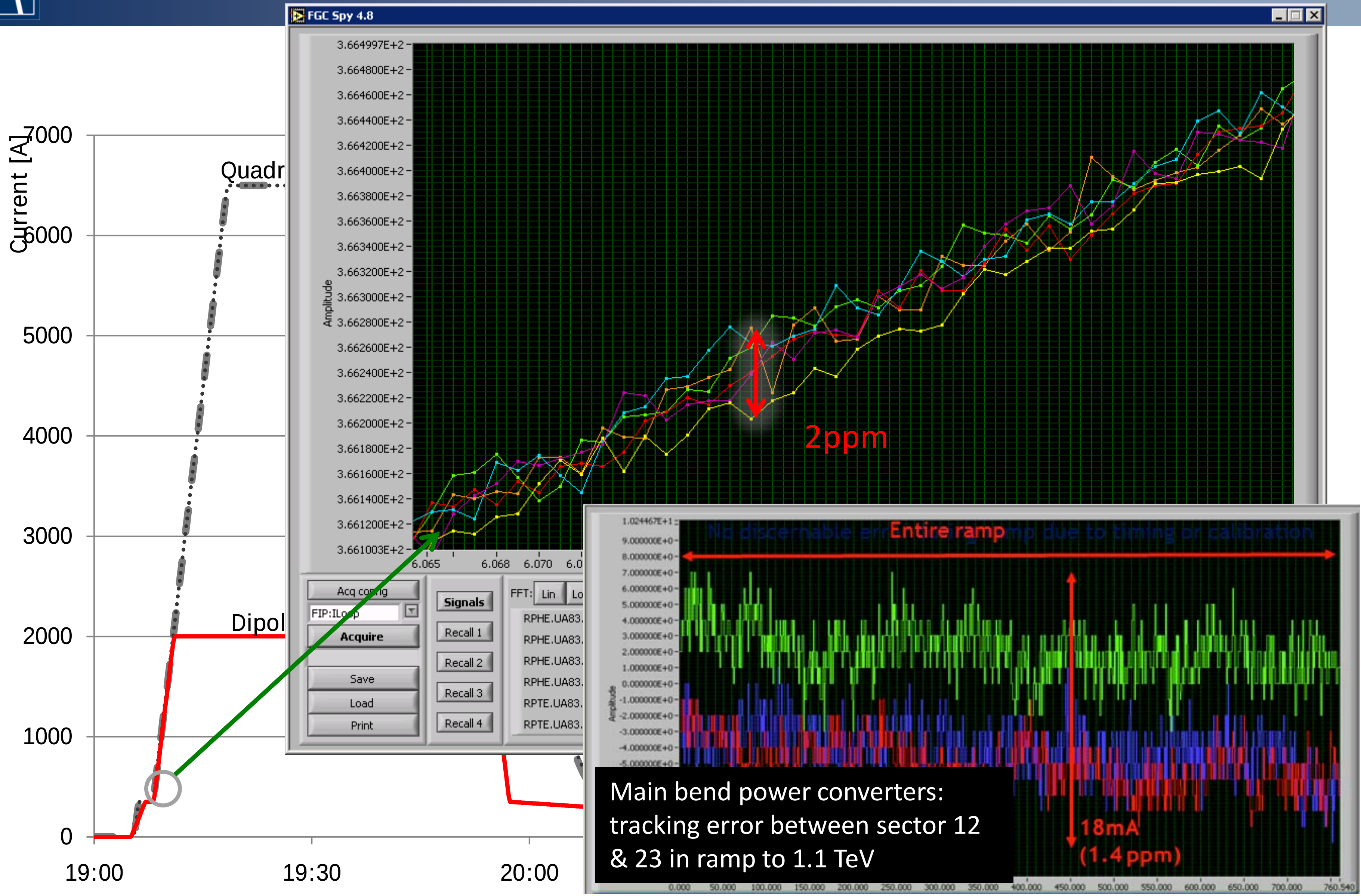
Wait and see !!

Vacuum chamber

- The beams circulate in two ultra-high vacuum chambers, P ~10^{-10} mbar.
- A Copper beam screen protects the bore of the magnet from heat deposition due to image currents, synchrotron light etc from the beam.
- The beam screen is cooled to T = 4-20 K.



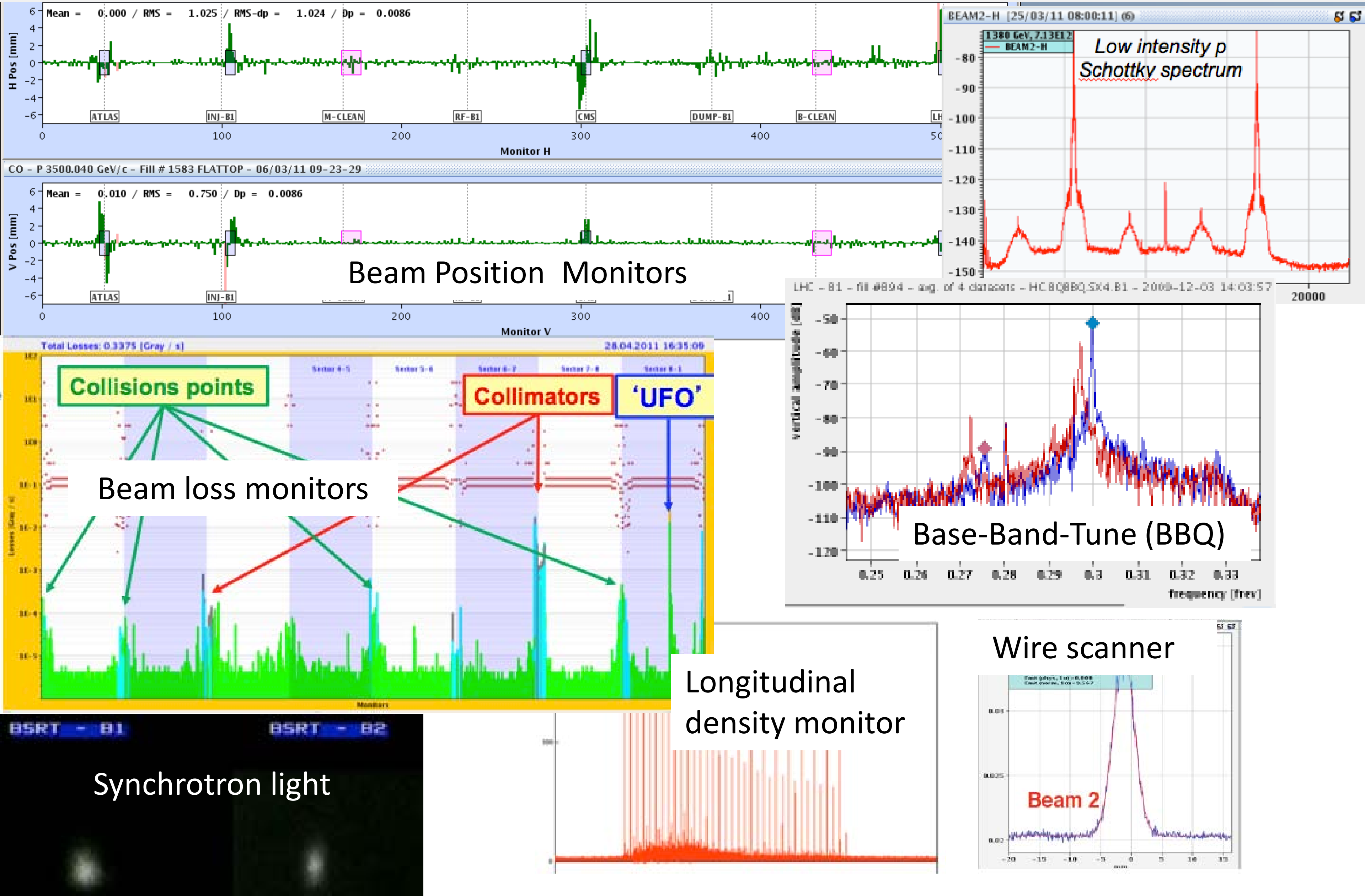
Tracking between the three main circuits of sector 78



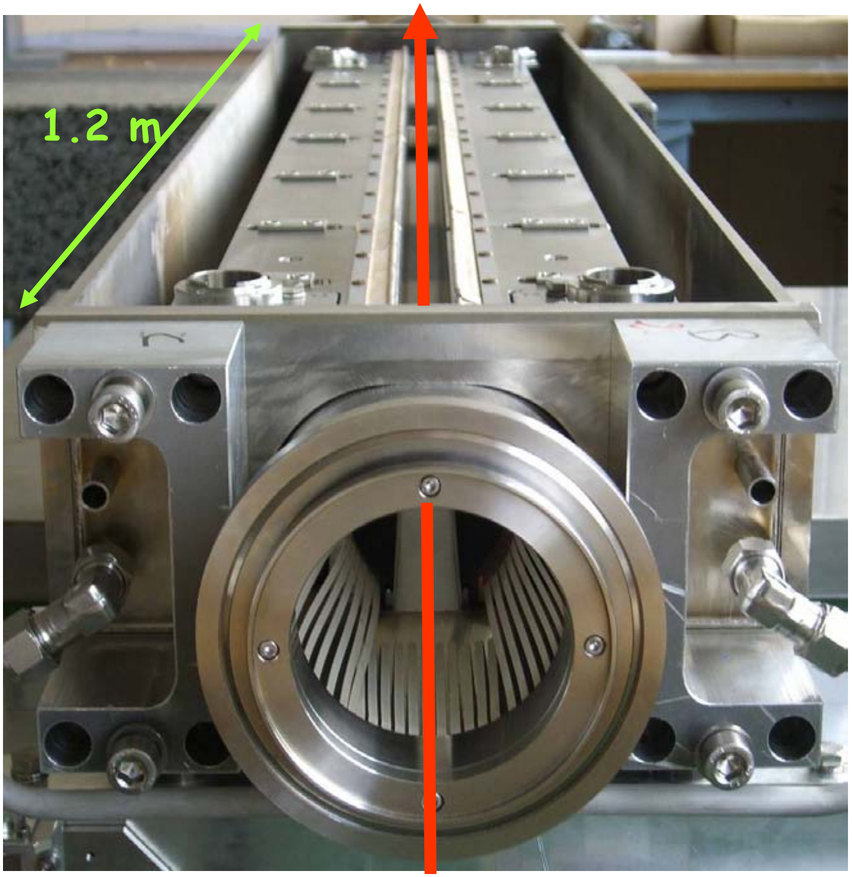
Phenomenal performance from the power converters

Courtesy Freddy Bordry& Dave Nisbet

Beam Instrumentation: brilliant – the enabler



Collimation



beam

Two warm cleaning insertions

IR3: Momentum cleaning
- **1 primary (H)**
- **4 secondary (H,S)**
- **4 shower abs. (H,V)**

IR7: Betatron cleaning
- **3 primary (H,V,S)**
- **11 secondary (H,V,S)**
- **5 shower abs. (H,V)**

Local IP cleaning: 8 tertiary coll.

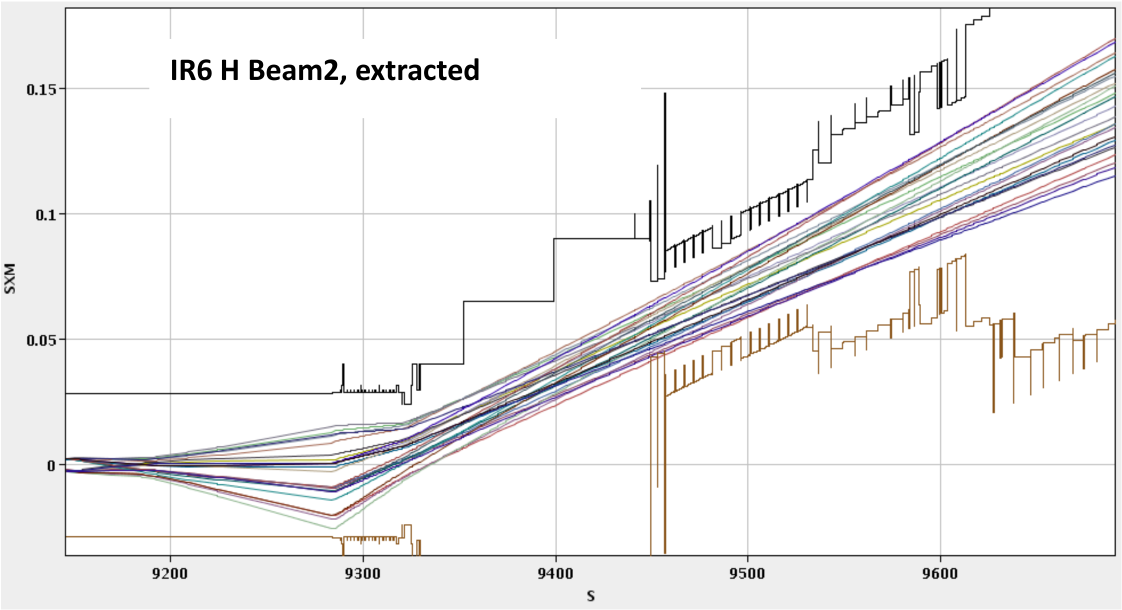
Total = 108 collimators

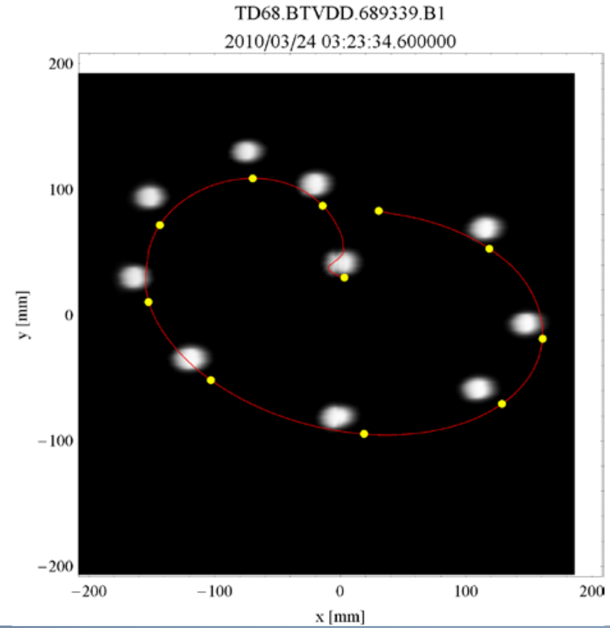
About 500 degrees of freedom.

Beam Dump System (LBDS)

Absolutely critical. Rigorous and extensive program of commissioning and tests with beam.

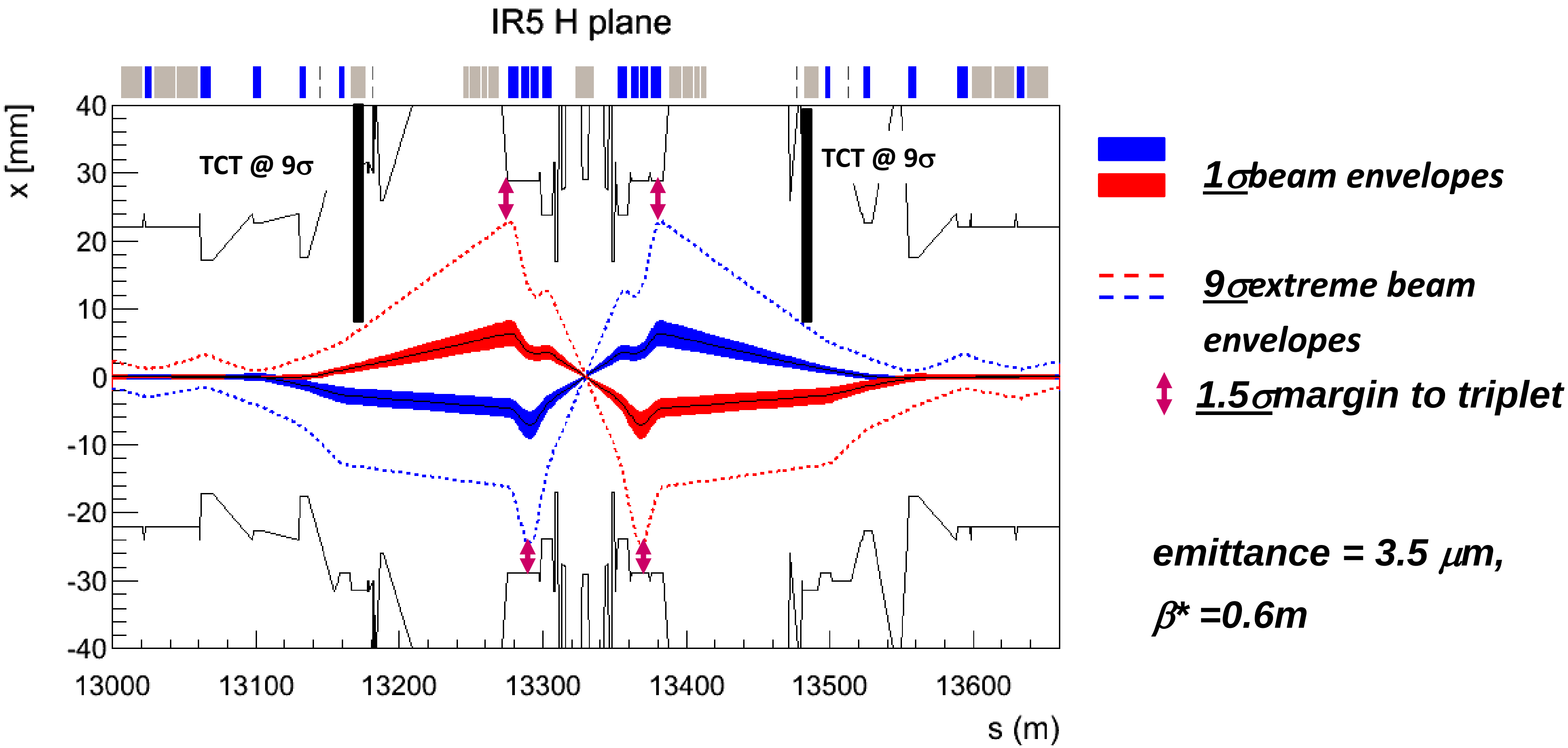
- Expected about two asynchronous dumps per year – one to date with beam





β* evolution

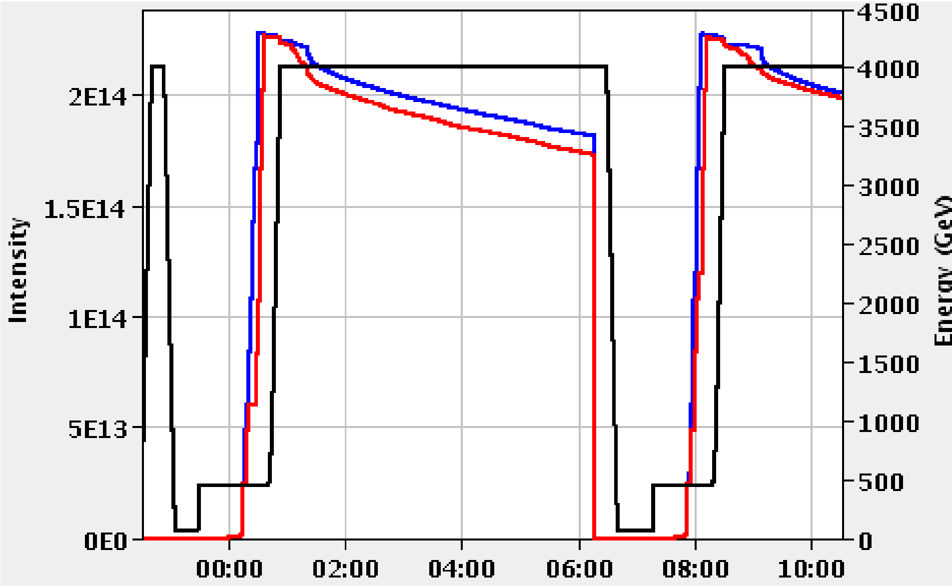
Date	β* (m)	Reason
Startup 2011	1.5	Interpolation of aperture measurement at 450 GeV
Sept. 2011	1.0	Aperture measurement at 3.5 TeV
2012	0.6	4 TeV (-0.1 m) and tighter collimator settings



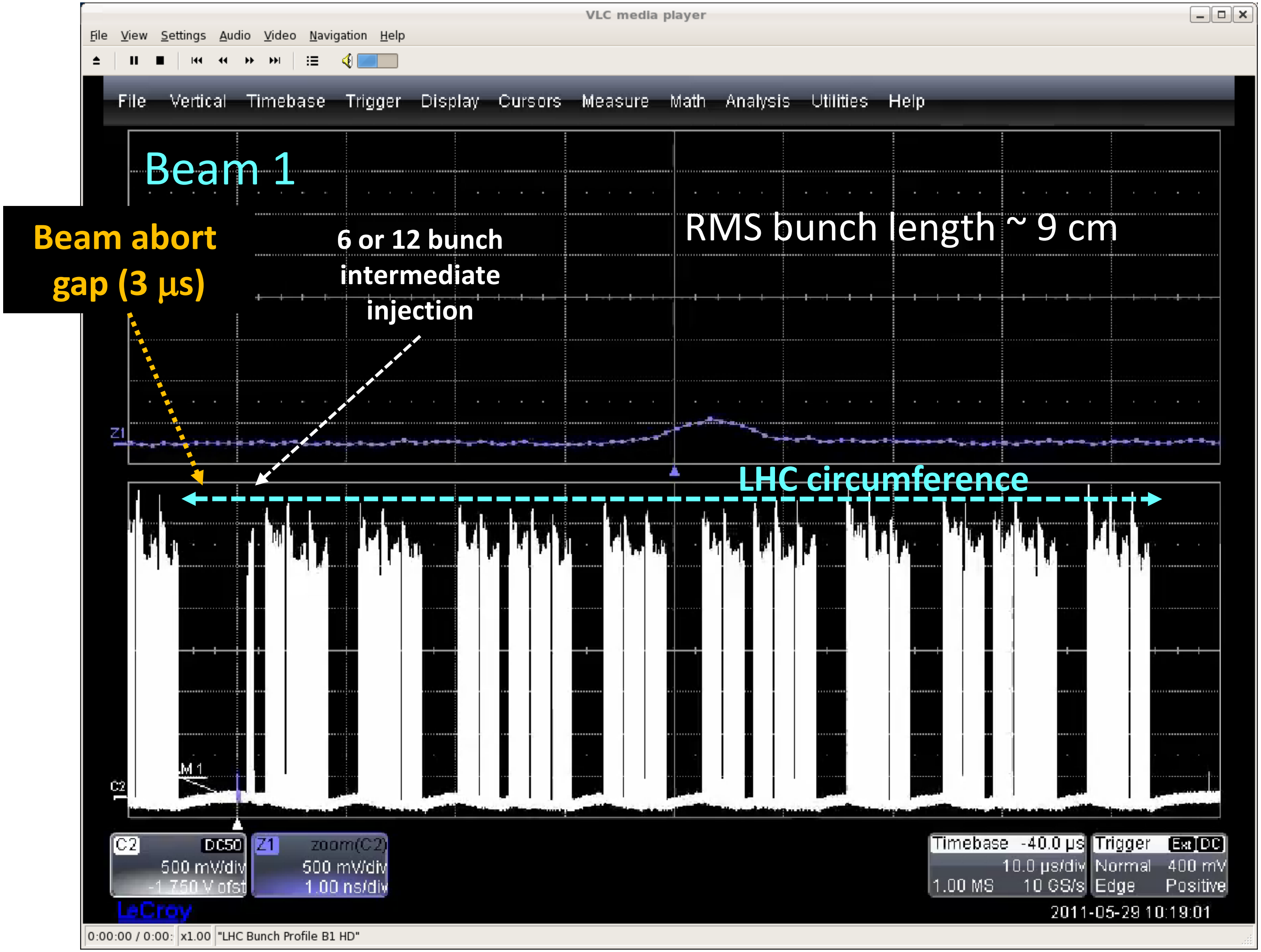
Beam instabilities

- In 2012 instabilities have become more critical due to higher bunch intensity and tighter collimators settings. Cures:
  - ***Transverse feedback*** *('damper') that measures the oscillations and sends corrective deflections,*
  - ***Non-linear magnetic fields*** *(sextupoles, octupoles, beam-beam interaction at the collision points) that produce a frequency spread among particles:*
    - *Particles at different amplitudes oscillate at different frequencies → prevents coherent motion ('Landau damping').*

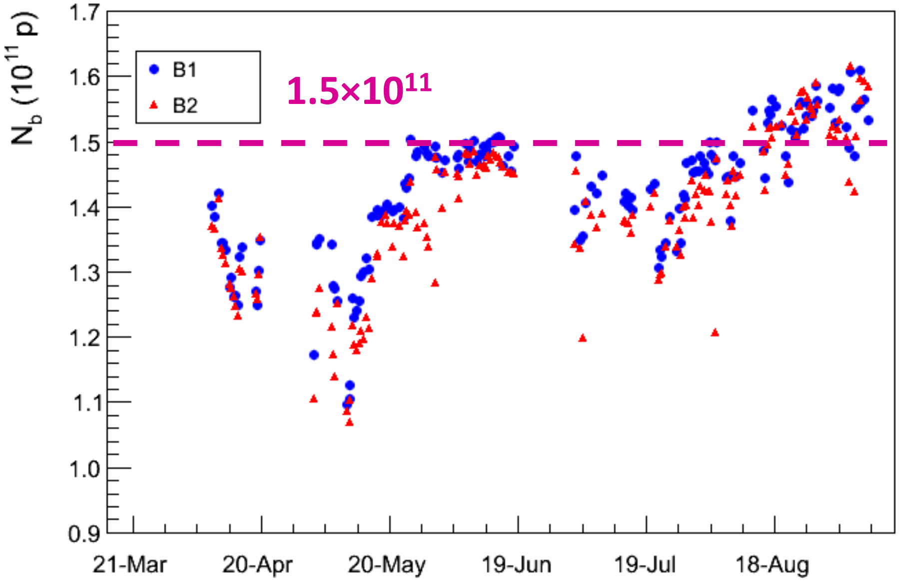
- Things are now ~ under control, but we are operating on the 'edge'.
  - *And we have more losses on beam 2 – not understood.*



1092 bunches with 50 ns spacing

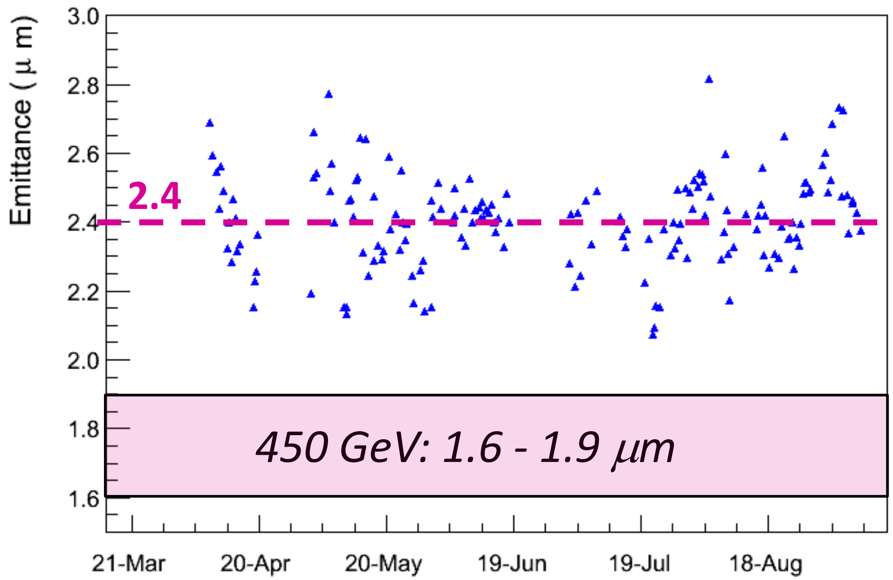


Bunch parameters 2012



Bunch intensities when beams are brought in collisions are now > 1.5×10^{11} p.

- *But we are at the limit of what can be delivered out of the PS.*



Emittances are relatively stable around 2.4 μm.

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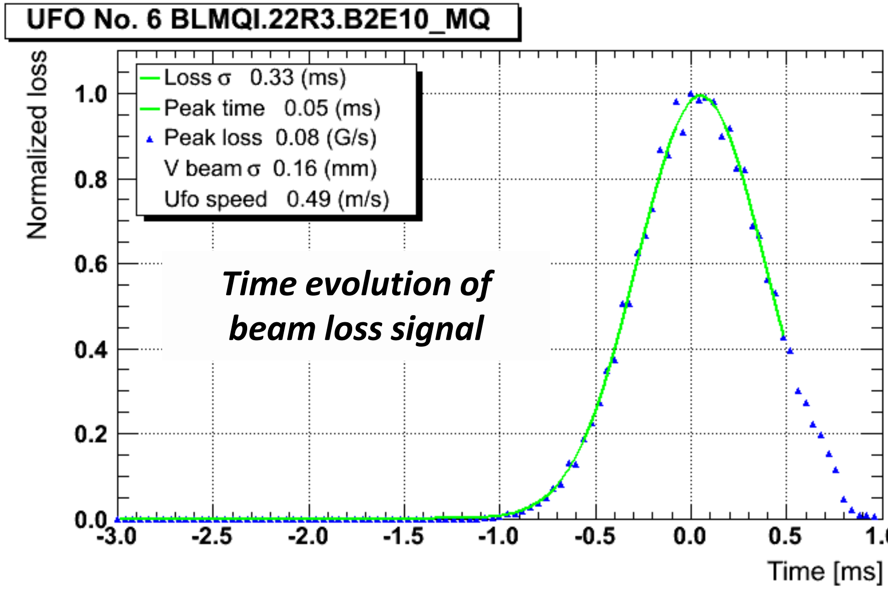
And what about 25 ns beams?

- Between 2010 and 2012 we have reduced the bunch spacing for regular operationto 50 ns.
- But the nominal 25 ns beams have not been used so far for normal operation because:
  - *50 ns beams provide higher peak luminosity, at the price of high pile-up,*
  - *25 ns beams suffer much more from electron cloud effects.*

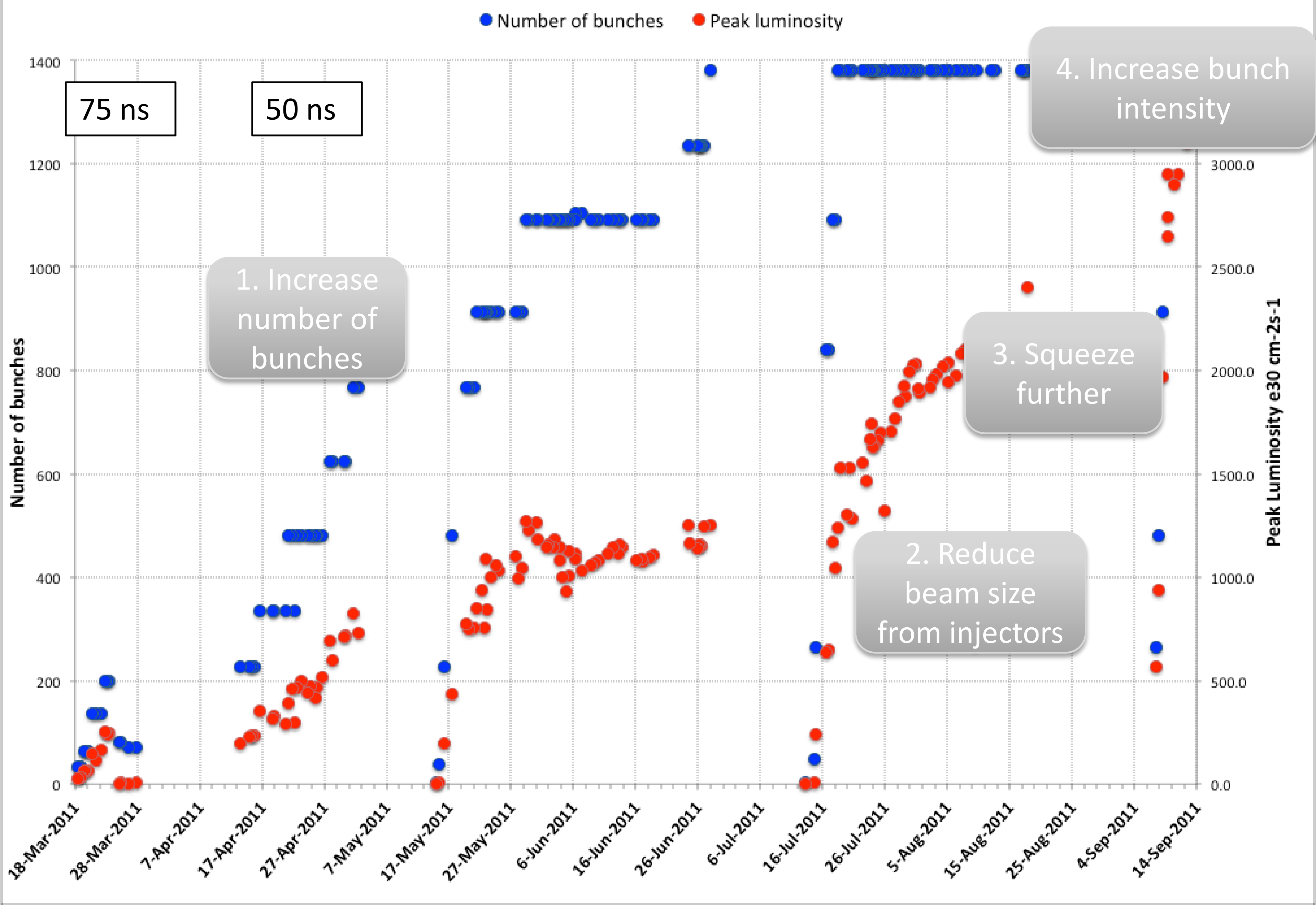
    $\Rightarrow$ *estimate 10 days (scrubbing, etc) to be ready for operation.*
- Successful tests of 25 ns beams were performed at injection (~2000 bunches stored) and 3.5 Tev (pilot fill with 60 bunches) in 2011.
- In 2012 the tests will continue in order to prepare operation with 25 ns beams at 6.5-7 TeV.

Surprise, surprise

- Very fast beam losses (time scale of ~millisecond) in the super-conducting regionsof the LHC have been a surprise for the LHC – nicknamed UFOs (Unidentified Falling Object). If the loss is to high, the beams are dumped to avoid a magnet quench.
  - *2010: 18 beam dumps,*
  - *2011: 17 beam dumps,*
  - *2012: 13 beam dumps so far.*
- We are now certain that the UFOs are small (10's μm) dust particles falling into the beam.
  - *Triggered by the presence of the fields of the beam. Mechanism for removing the dust from the surface is not fully understood.*



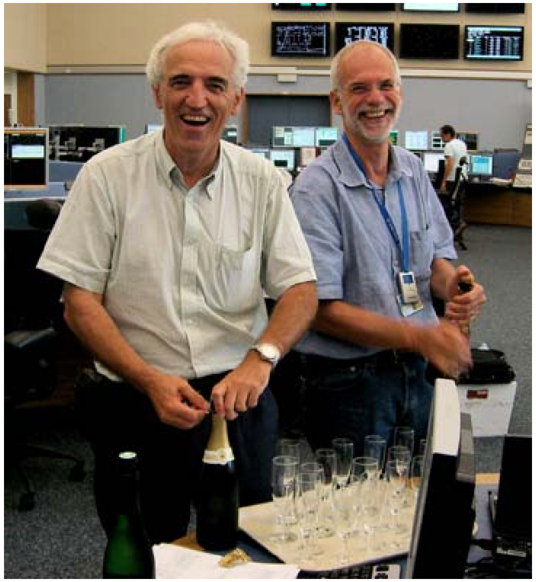
2011



Number of bunches
Peak luminosity
75 ns
50 ns
1. Increase number of bunches
2. Reduce beam size from injectors
3. Squeeze further
4. Increase bunch intensity
Number of bunches
Peak Luminosity e30 cm-2s-1
1400
1200
1000
800
600
400
200
0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
18-Mar-2011
28-Mar-2011
7-Apr-2011
17-Apr-2011
27-Apr-2011
7-May-2011
17-May-2011
27-May-2011
6-Jun-2011
16-Jun-2011
26-Jun-2011
6-Jul-2011
16-Jul-2011
26-Jul-2011
5-Aug-2011
15-Aug-2011
25-Aug-2011
4-Sep-2011
14-Sep-2011

PERSONAL COMPETANCIES

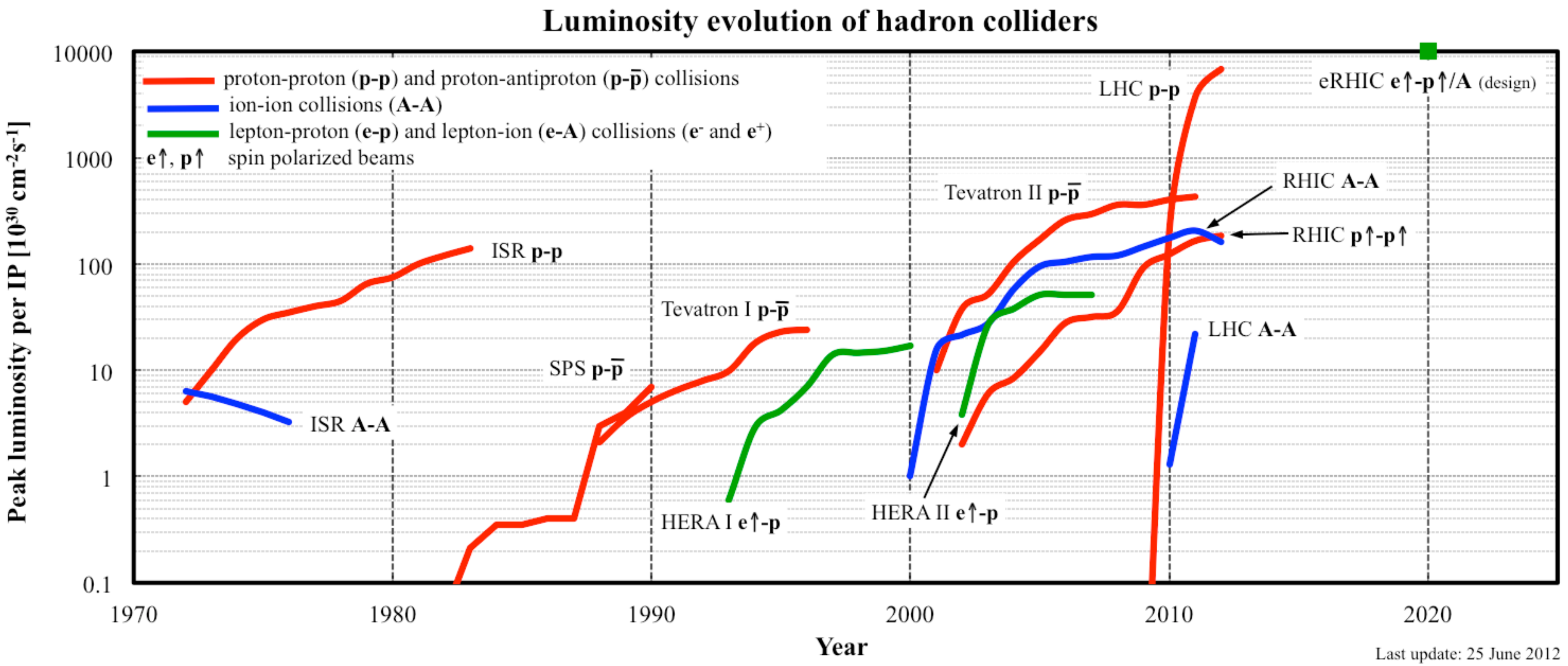
Leadership



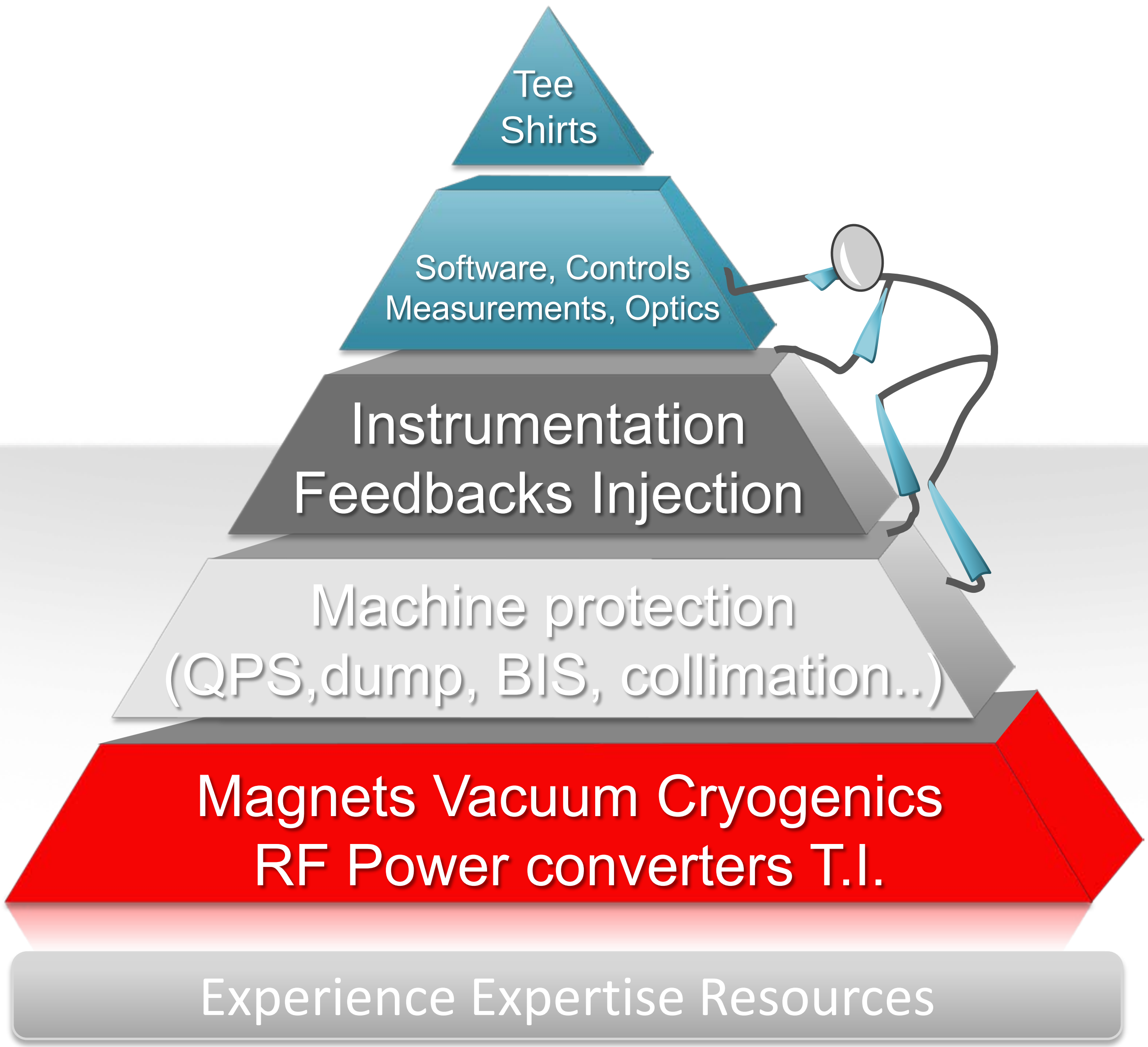
Ability to relax

Teamwork

Luminosity evolution hadron colliders

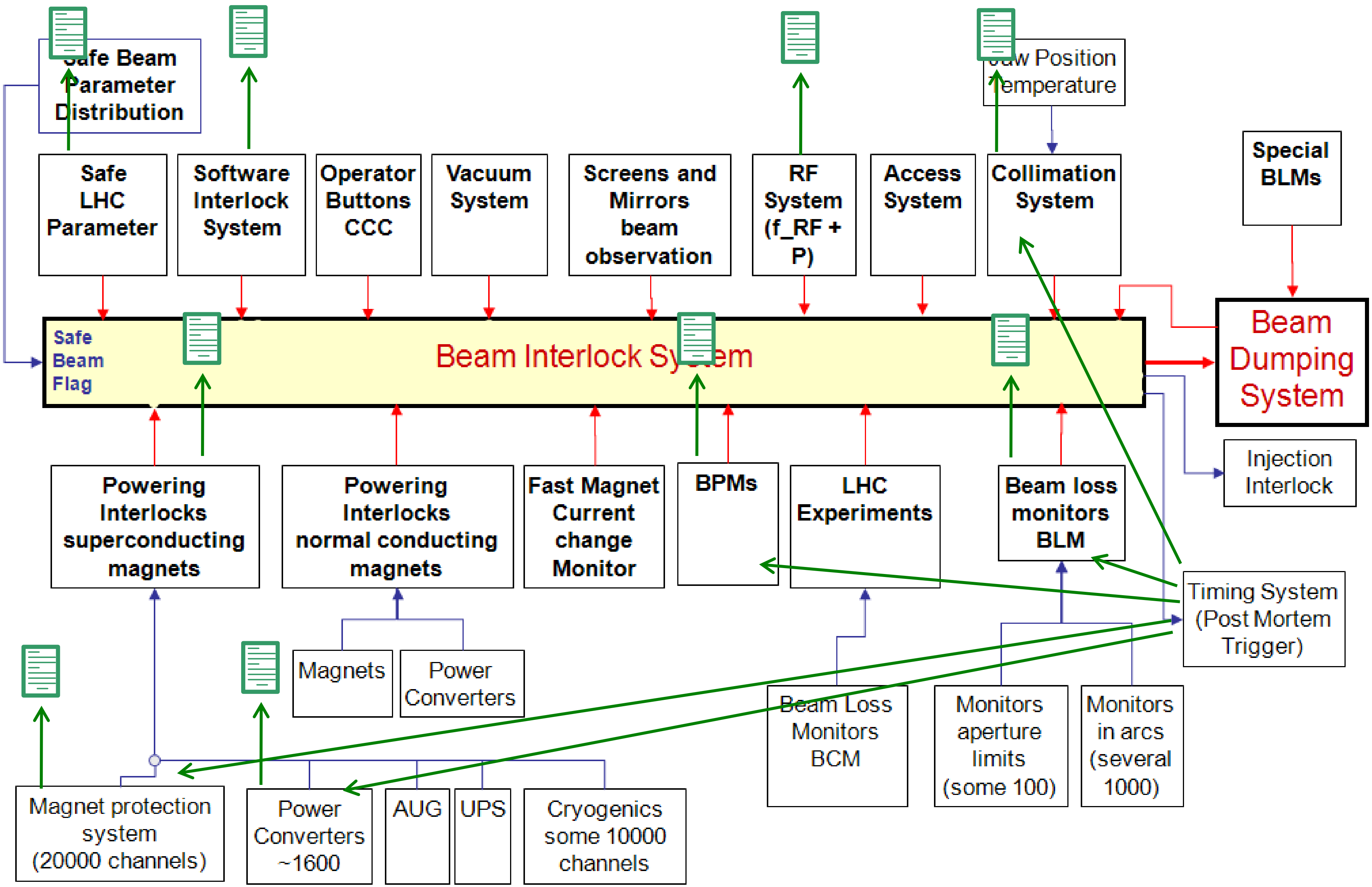


Maslow's Hierarchy of Needs

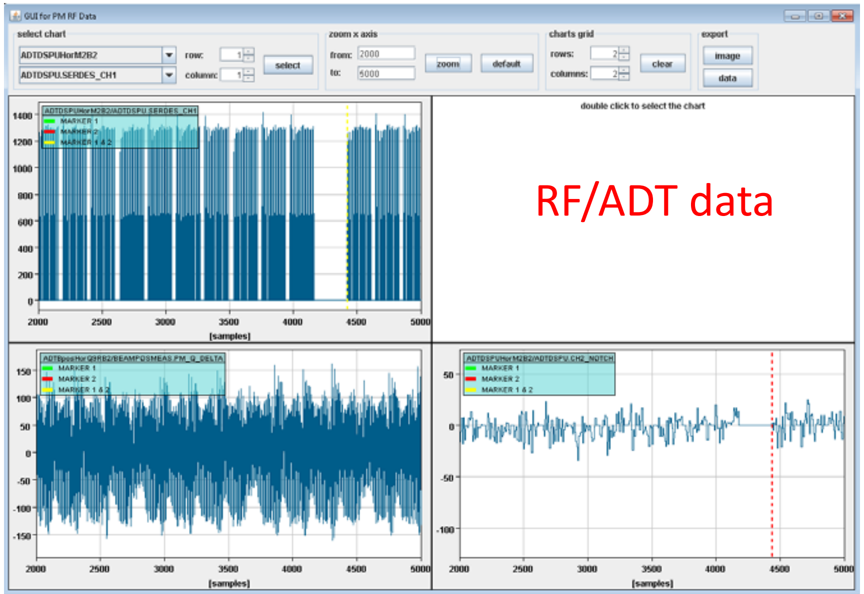


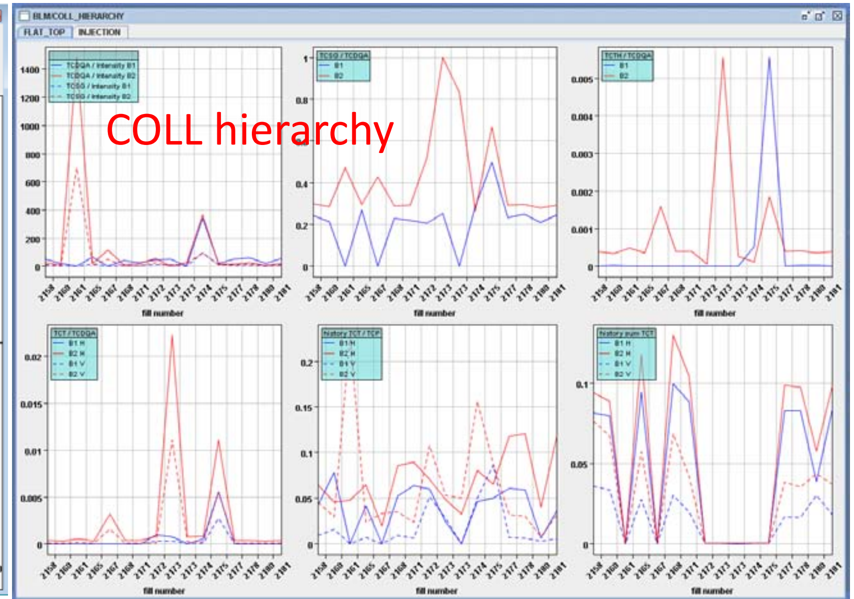
We delivered 5.6 fb^{-1} to Atlas in 2011 and all we got was a blooming tee shirt

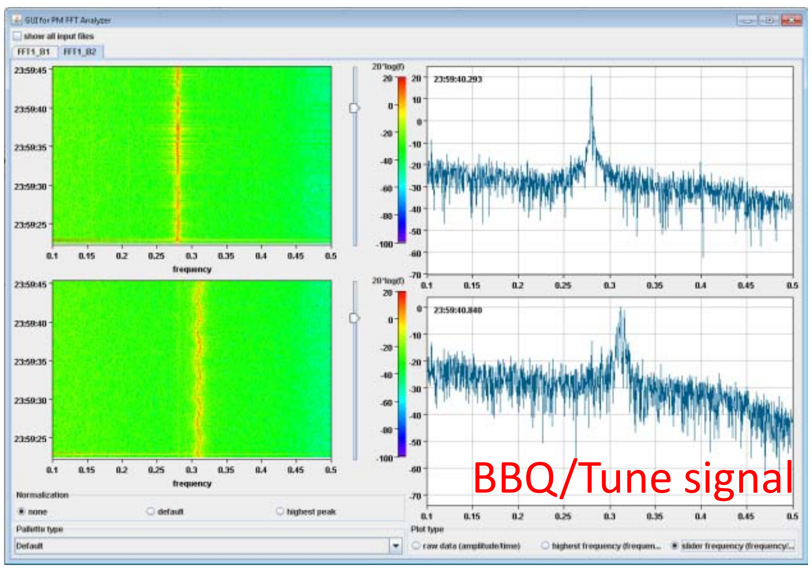
Transient data recording after a beam dump (PM)

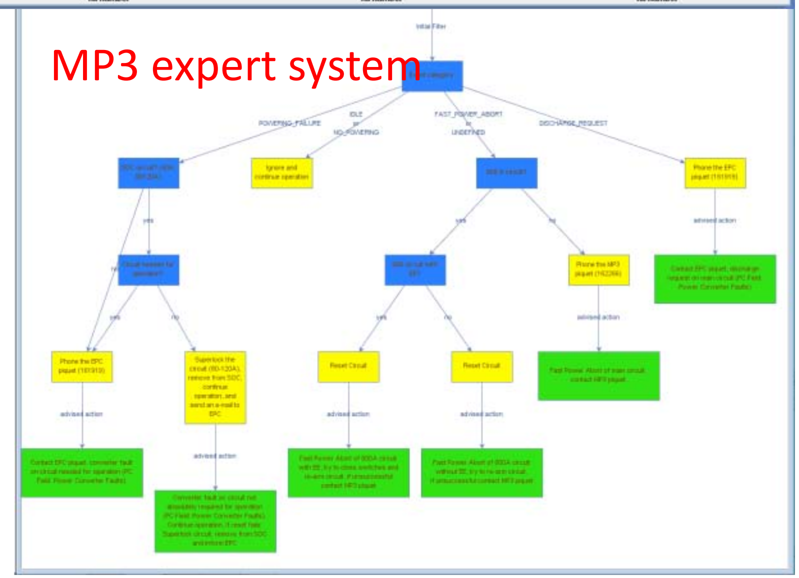


Analysis modules for beam PM

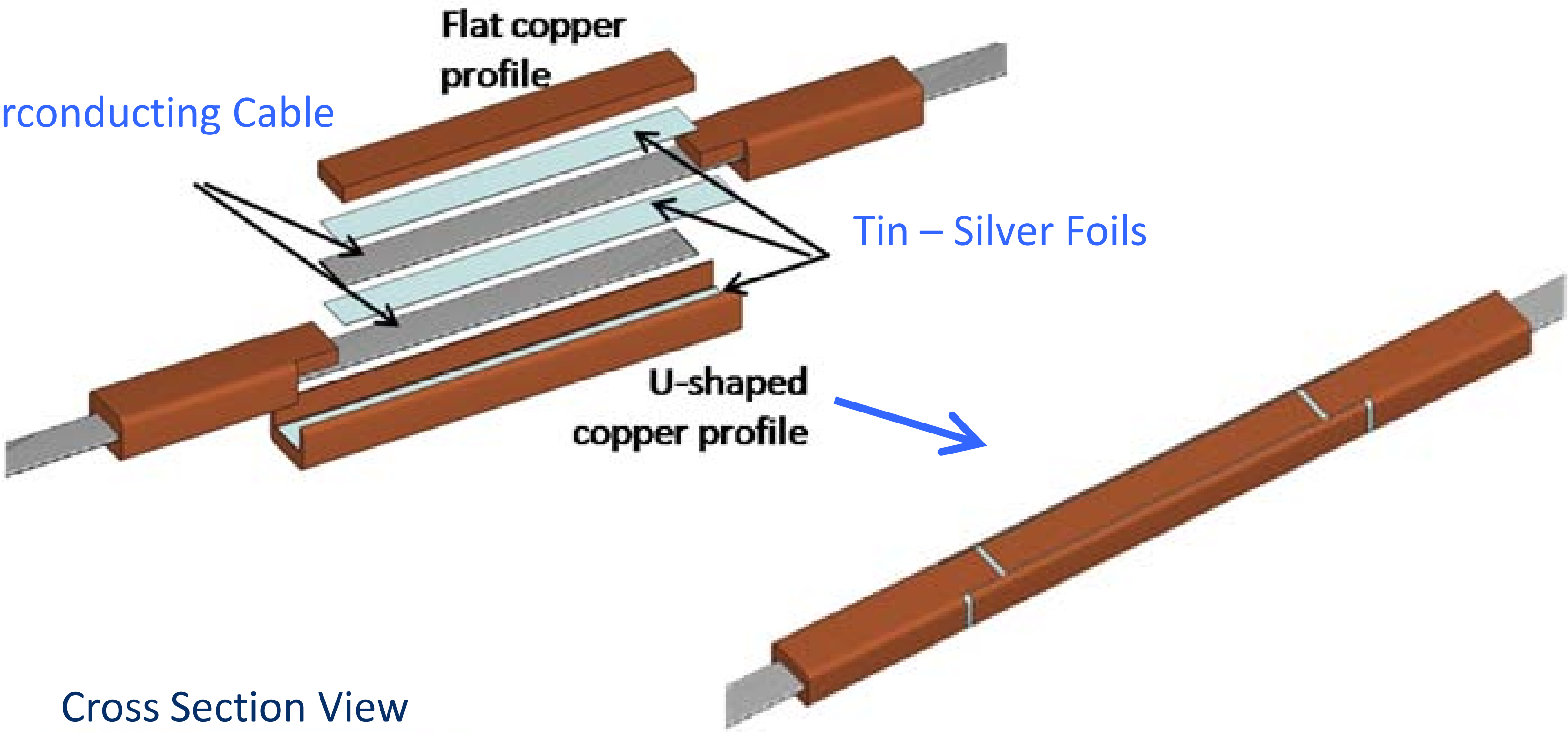




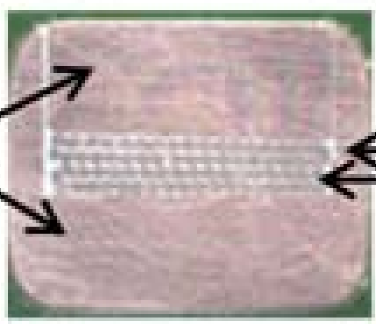




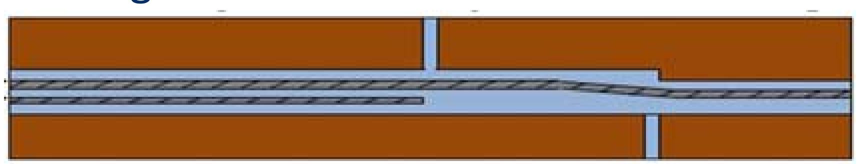
Ideal 13 kA Connection Scheme



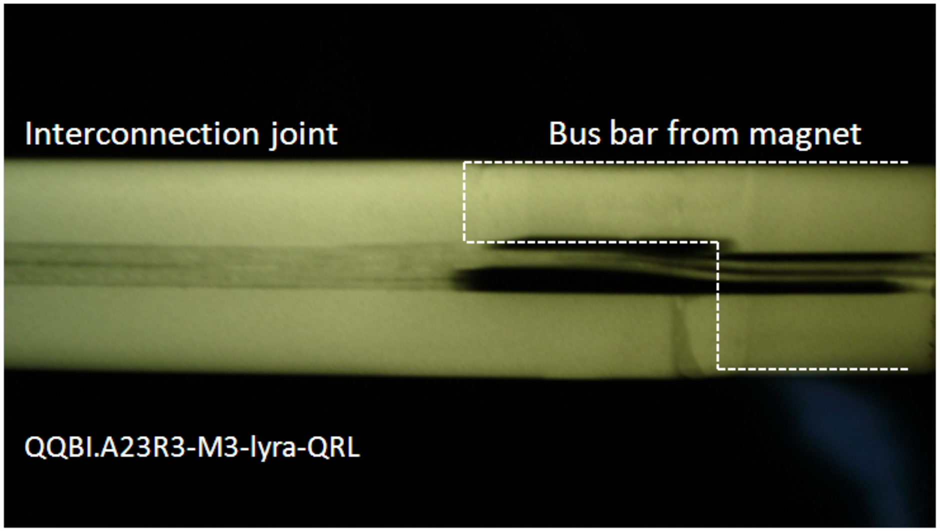
Cross Section View



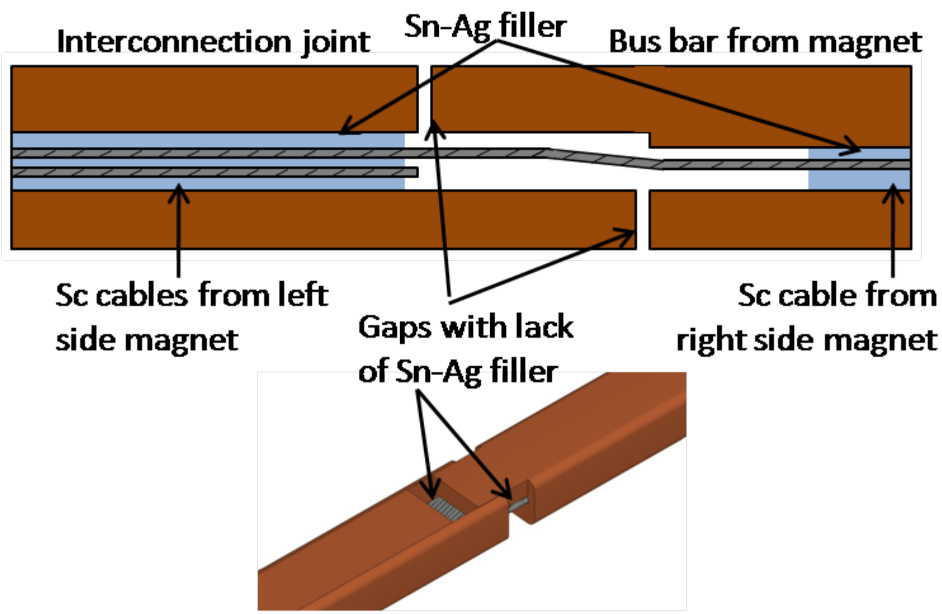
Longditudinal View – filled with Solder



Observed Interconnections



Defective interconnetion-bus bar transition γ-ray picture (left) and scheme (right)



Protection Functions

Beam Protection:	Beam**Energy** →	**Beam Dump**

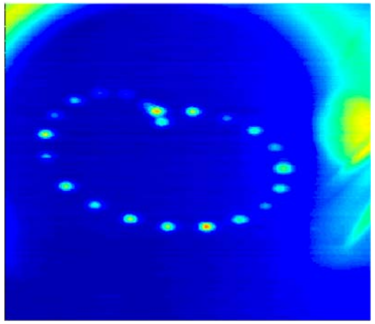
100x energy of TEVATRON

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

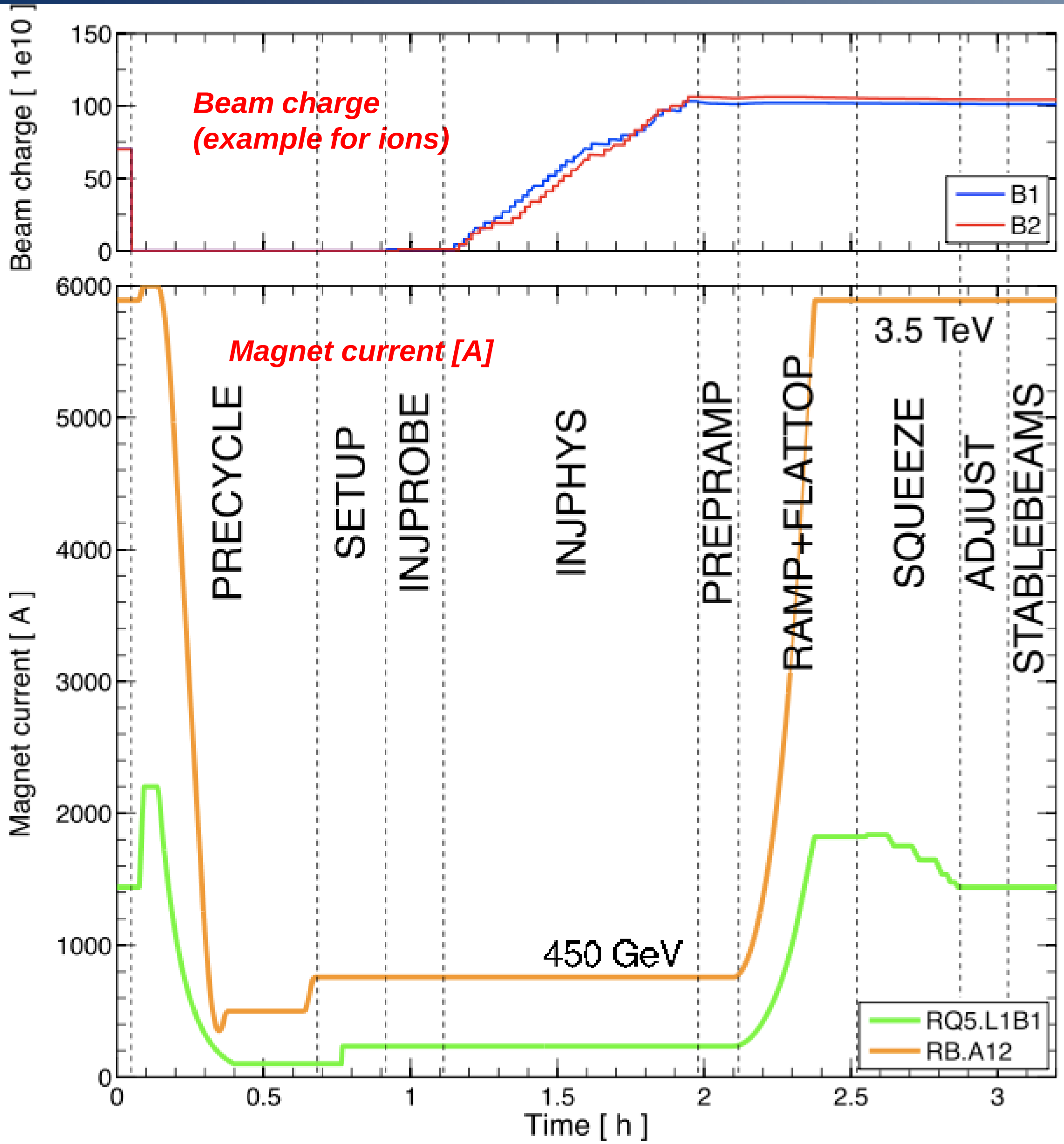
Beam is 'painted' diameter 35cm



Concrete Shielding

ong absorber Graphite = 800 C

Operational cycle



Cycle:

- ***Injection***
- ***Ramp***
- ***Squeeze***
- ***Collide beams***
- ***Stable physics beams***
- ***Ramp down/cycle***

In 2012 a good turn around **3 hours – best ~2h 15.**

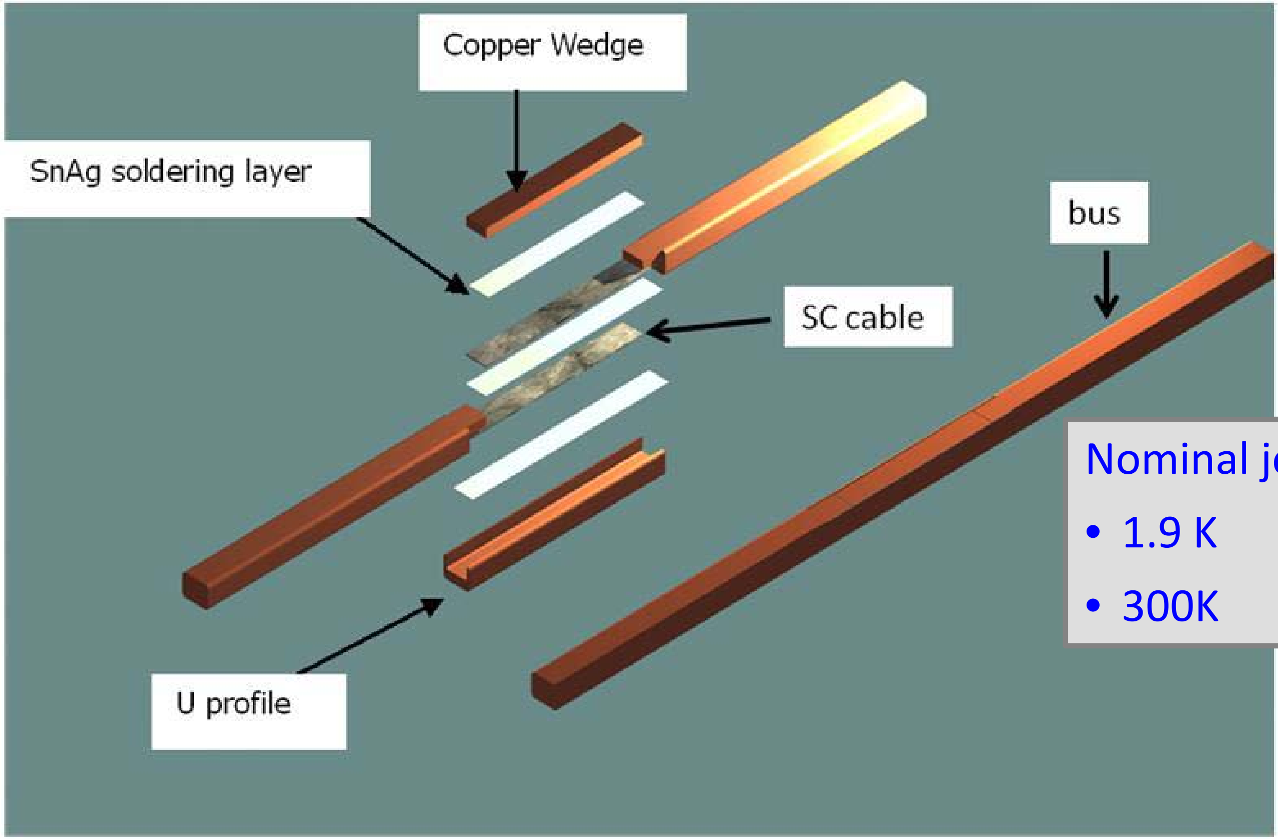
During the '**squeeze**' phase, the betatron function at the collision points (β^*) is reduced to increase the luminosity.

Cannot be done at injection,the beam is too large !

Courtesy S. Redaelli

Bus-bar joint (splice)

- ~24'000 bus-bar (=current conductors) joints in the main circuits.
  - *After the incident 2008, a new protection system had be to design and installed for the joints.*
- ~10'000 joints are at the interconnection between magnets.



Nominal joint resistance:

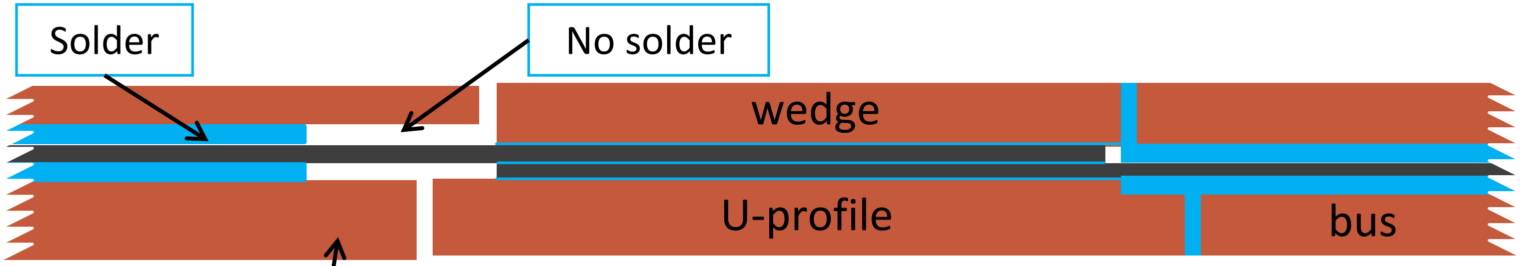
- 1.9 K **0.3 nΩ**
- 300K **~10 µΩ**

Joint quality

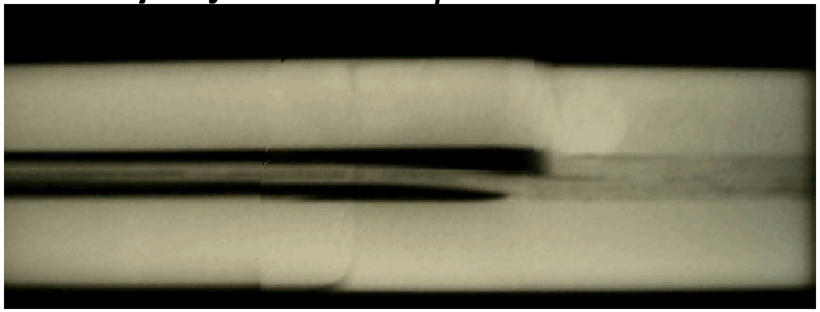
- The copper stabilizes the bus bar in the event of a cable quench (=bypass for the current while the energy is extracted from the circuit).

  Protection system in place in 2008 not sufficiently sensitive.

- A copper bus bar with reduced continuity coupled to a badly soldered superconducting cable can lead to a serious incident.



X-ray of joint



- During repair work in the damaged sector, inspection of the joints revealed systematic voids caused by the welding procedure.