LHC status after the long shutdown and prospects for run 2

CEA – Saclay

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Acknowledgments to my OP group colleagues for slides and plots

Outline

Introduction

Long Shutdown 1

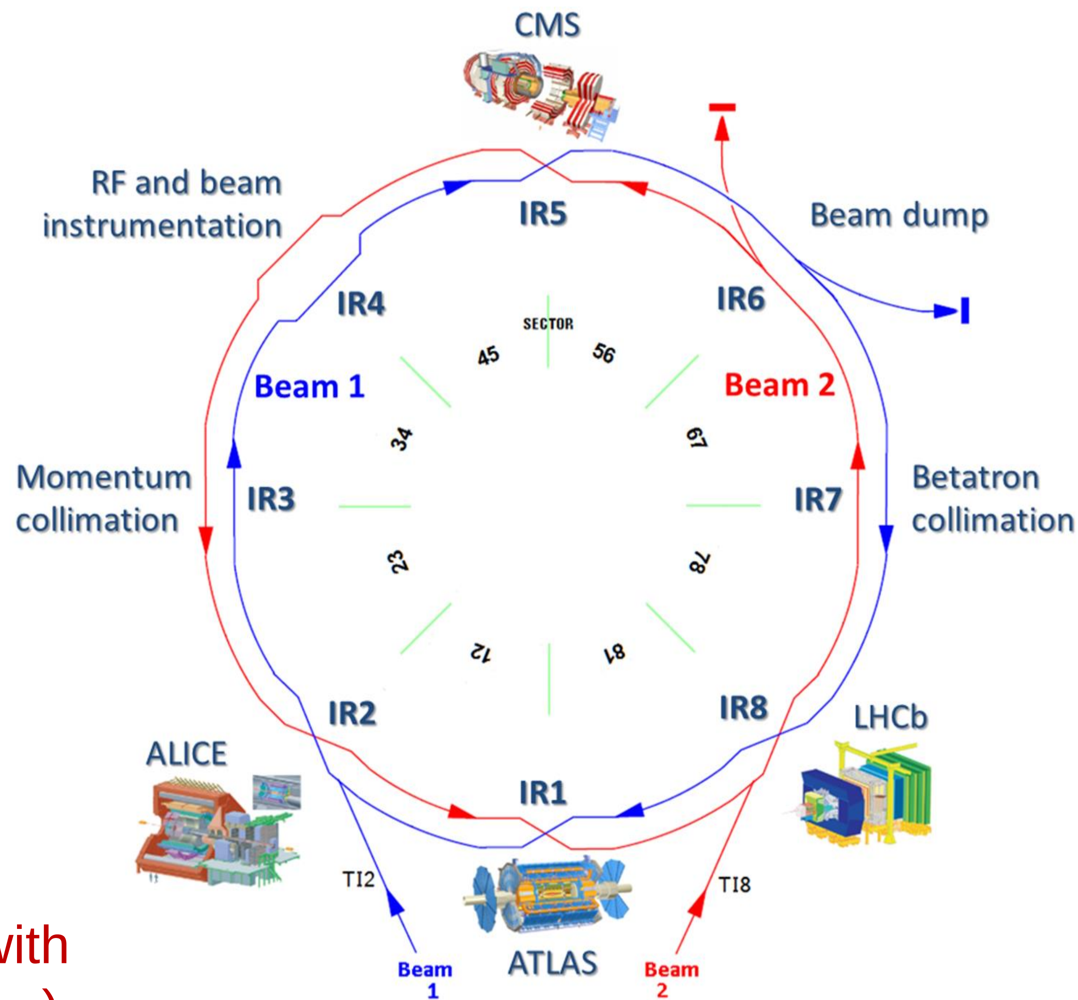
LHC prospects for Run 2

Beam commissioning 2015

Conclusions

LHC ring layout

- Total length 26.66 km, in the former LEP tunnel.
- 8 arcs (sectors), ~3 km each.
- 8 straight sections of 700 m.
- beams cross in 4 points.

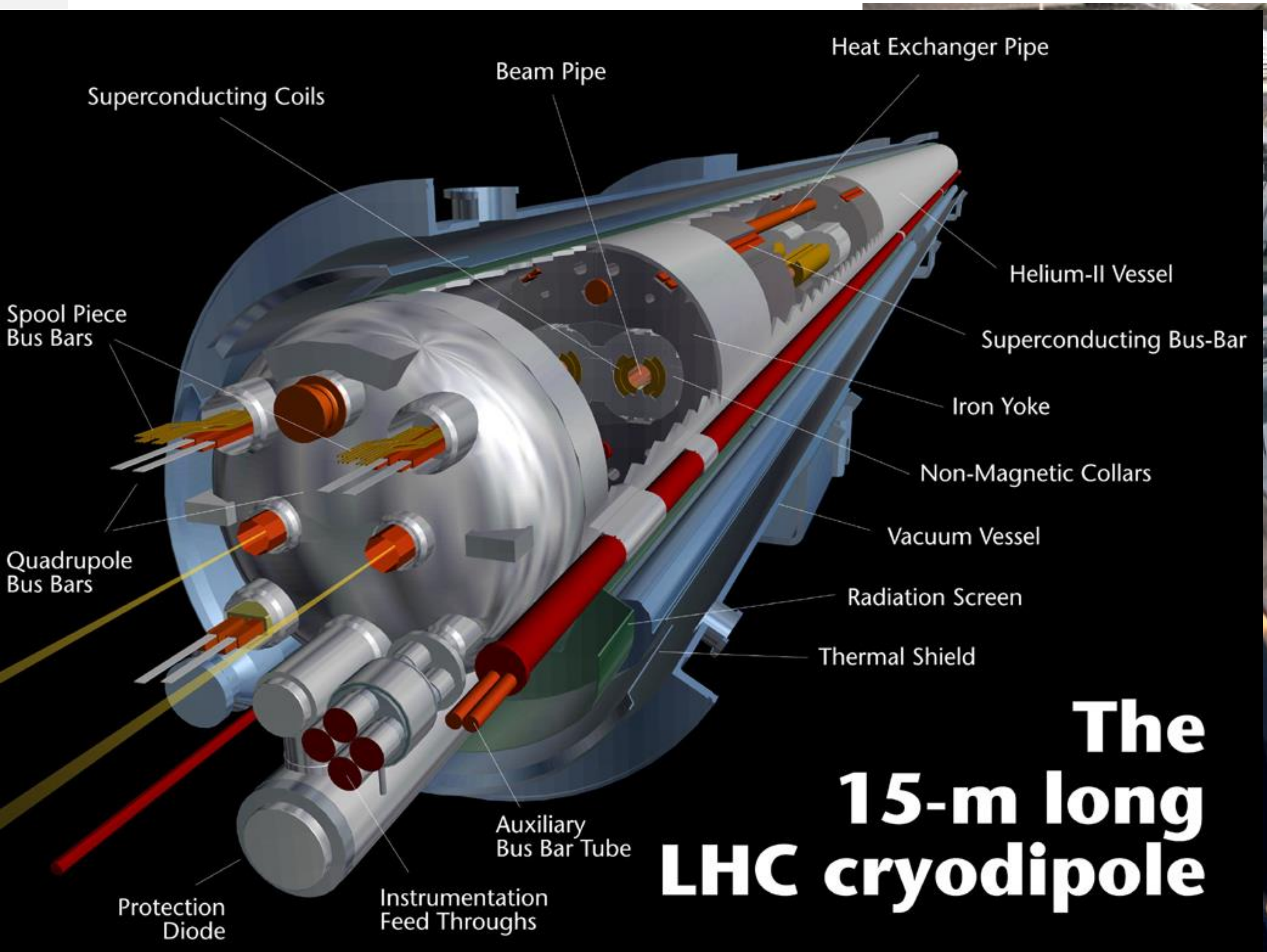


- 2-in-1 magnet design with separate vacuum chambers.
- **2 COUPLED rings**.

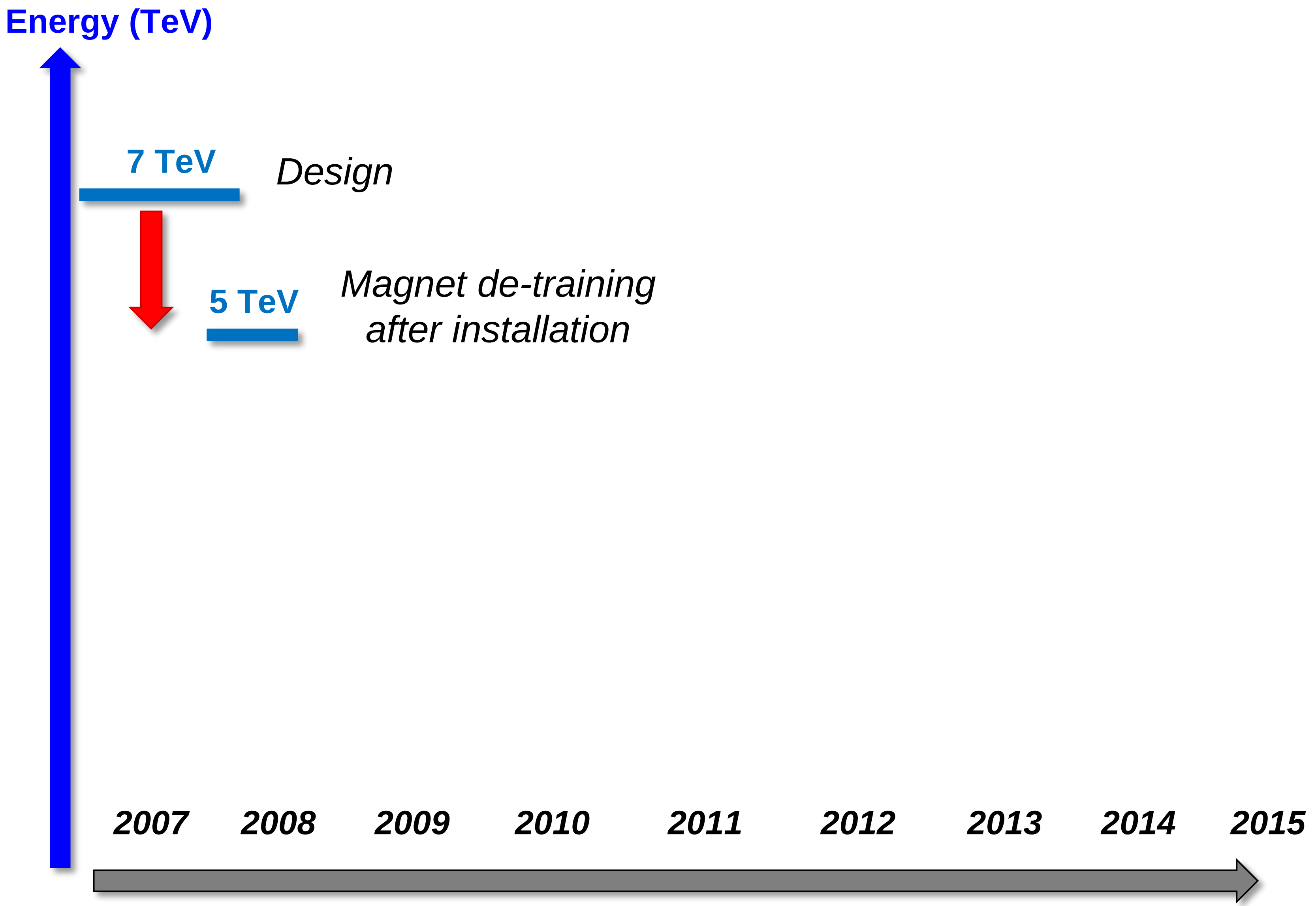
The LHC can be operated with protons and ions (so far Pb_{208}).

Key technology

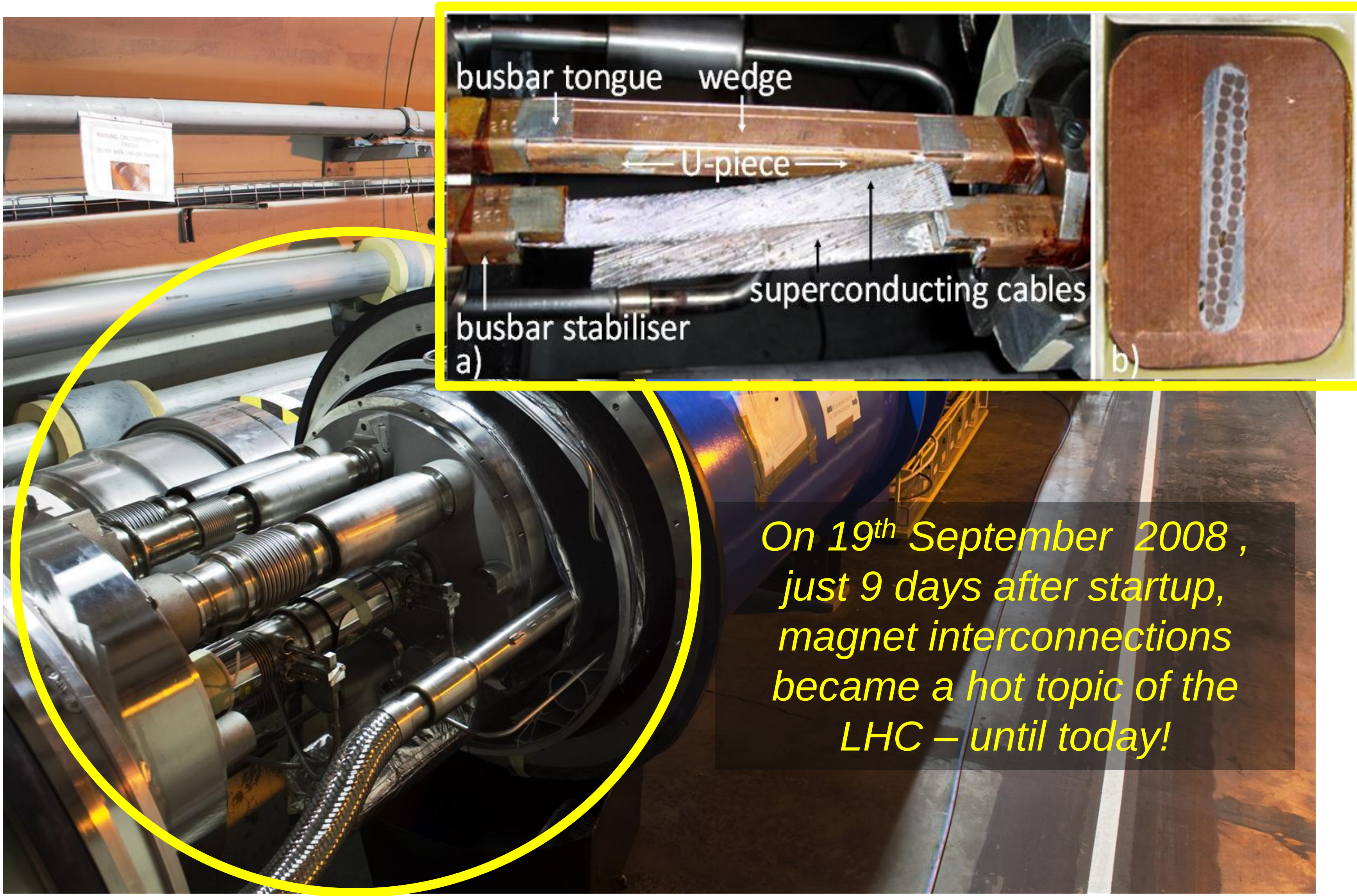
- 1232 NbTi superconducting dipole magnets – each 15 m long
- Magnetic field of 8.3 T (current of 11.8 kA) @ 1.9 K (super-fluid Helium).
    - *But they do not like beam loss – quench with few mJ/cm³.*



LHC energy evolution



LHC magnet interconnection



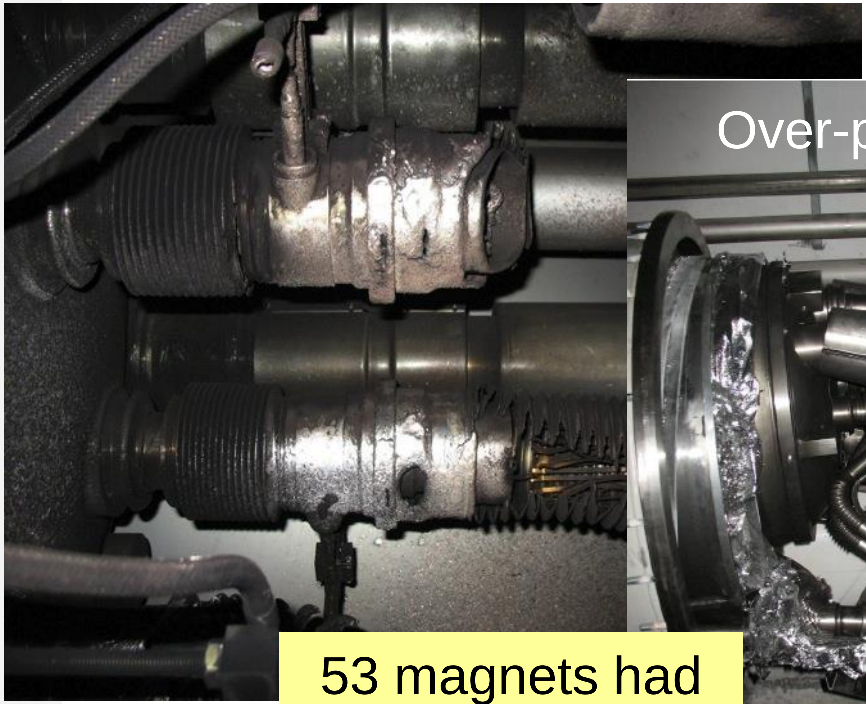
On 19th September 2008, just 9 days after startup, magnet interconnections became a hot topic of the LHC – until today!

Incident September 19th 2008

An electrical arc in a defect interconnection of sector 34 provoked a Helium pressure wave that damaged ~700 m of the LHC and polluted the beam vacuum over more than 2 km…

- *Resistance at 1.9 K was ~200 nΩ instead of 2 nΩ – soldering issue !*

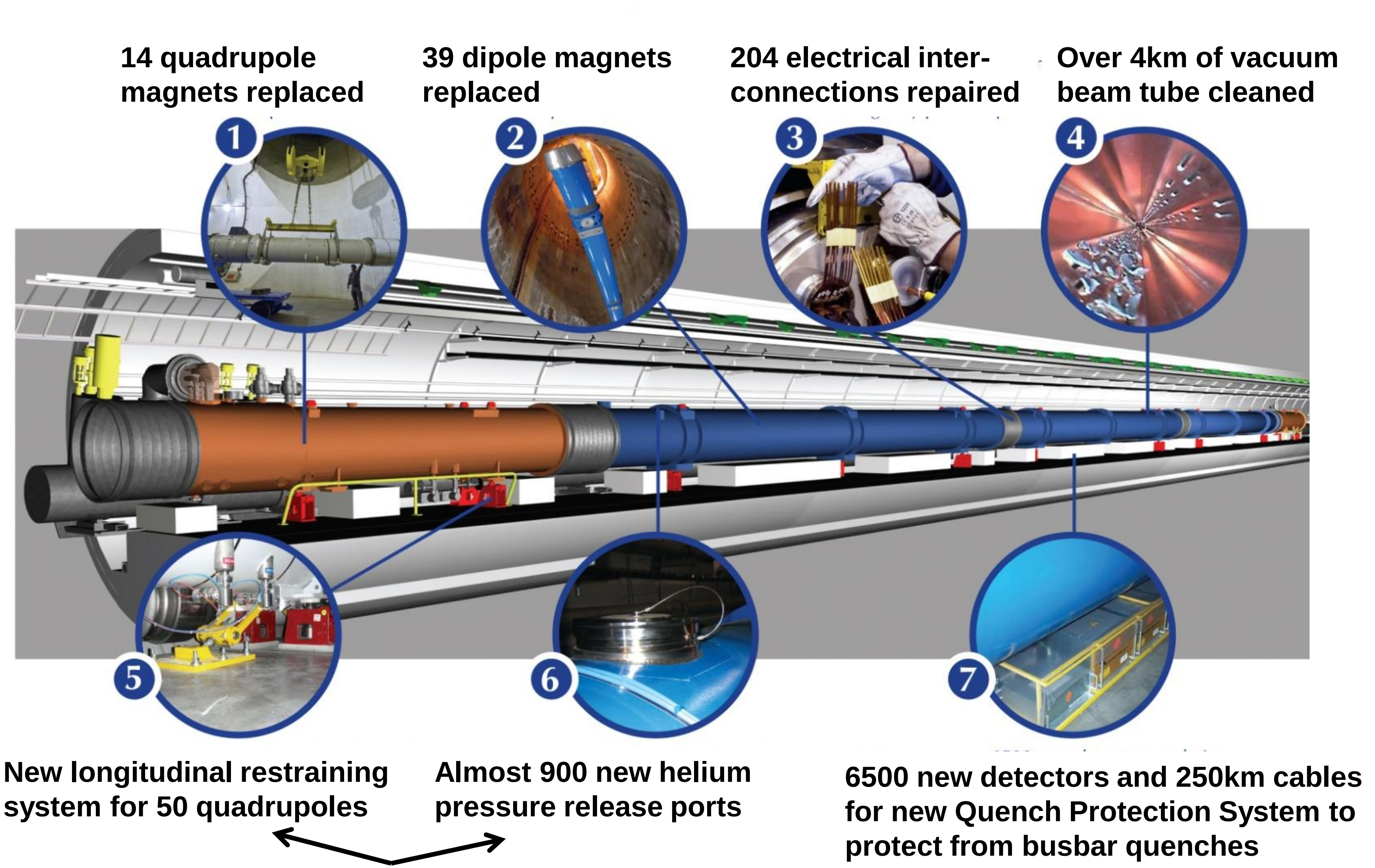
Arcing in the interconnection



53 magnets had to be repaired

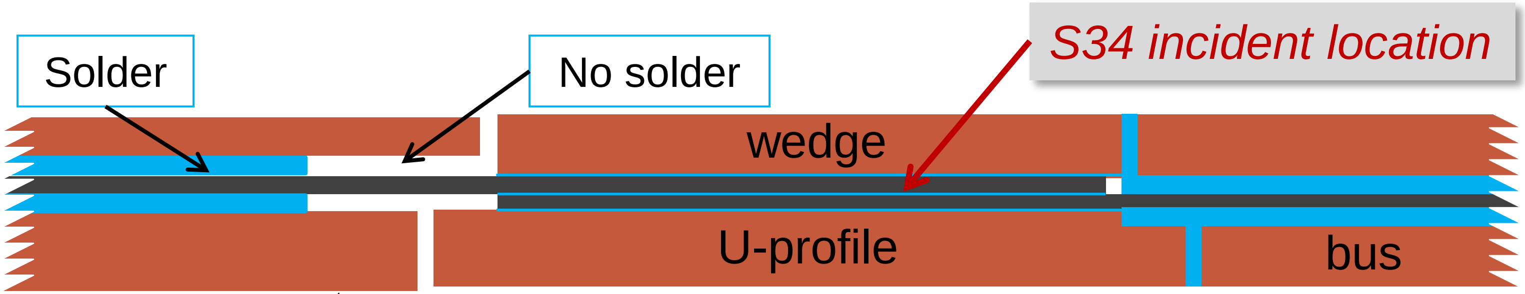
Magnet displacement

LHC repair and consolidation

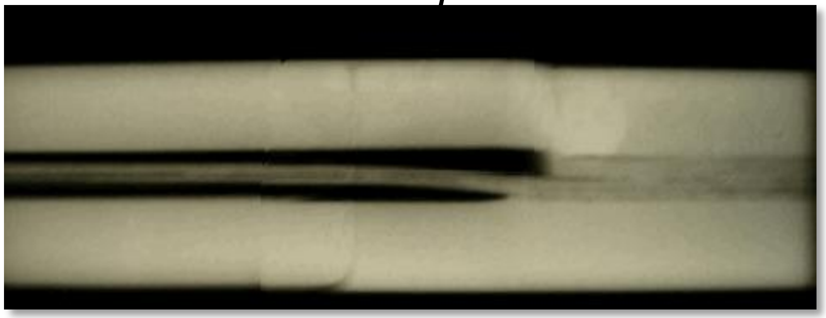


More problems on the joints

- The super-conducting bus bar that carries the current is stabilized by copper in the event of a cable quench (=bypass for the current while the energy is extracted from the circuit).
- During repair work of S34, inspection of the joints revealed systematic voids caused by the welding procedure (and lacking quality control).



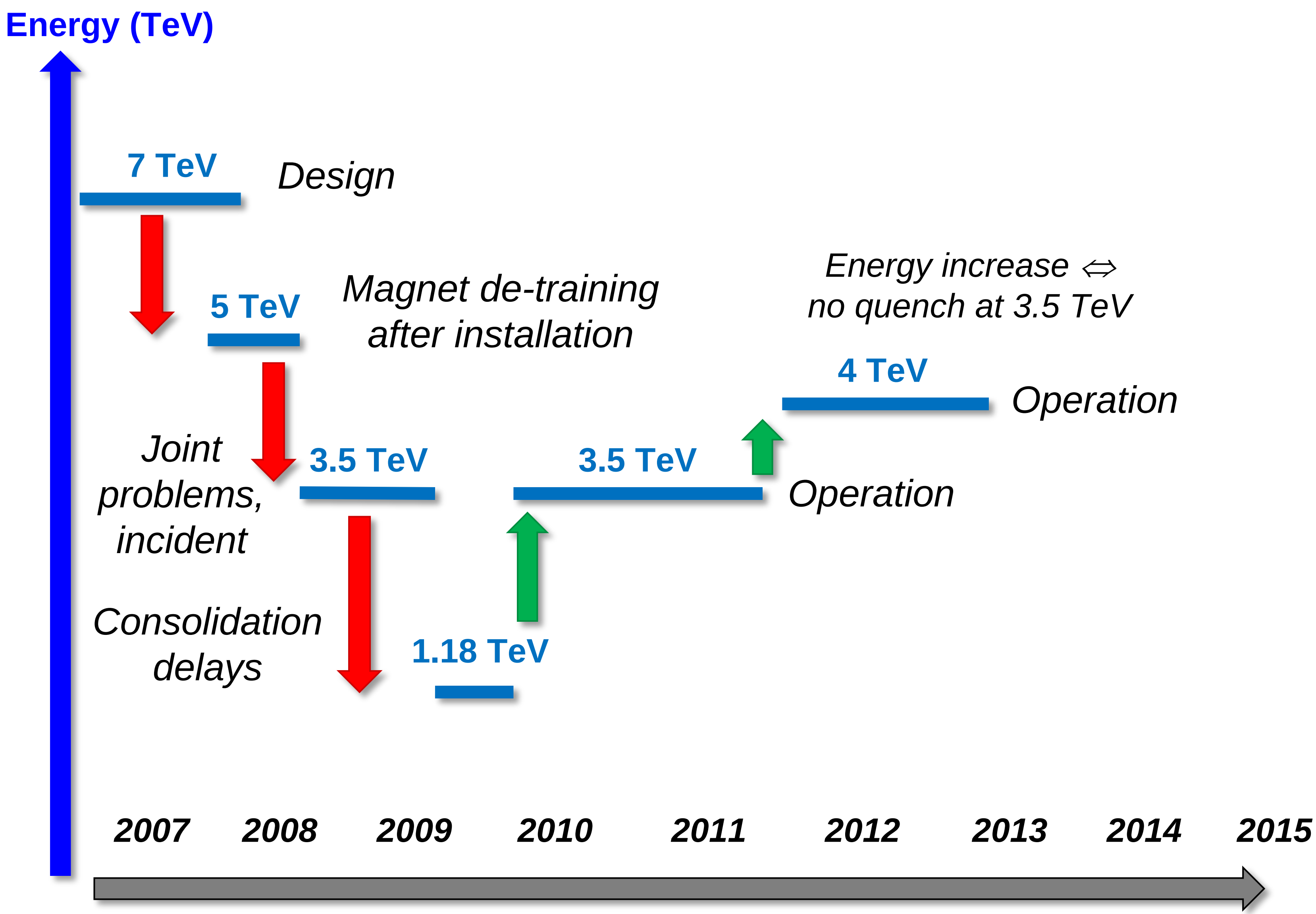
X-ray



- A copper bus bar with reduced continuity can lead to a serious incident when the nearby magnet quenches – too small Cu cross-section!

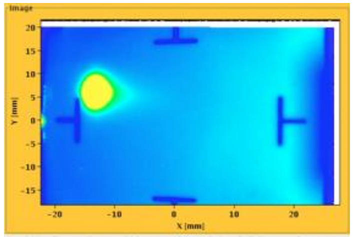
Energy limitation for run 1 !!

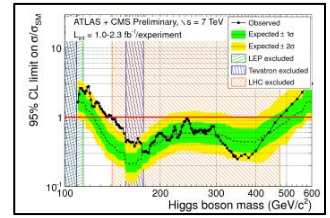
LHC Energy Evolution



The LHC run1 timeline

August 2008
First Injection tests





December 2011
5.6 fb^{-1}

Energy: **4 TeV**

March 2012
4 TeV

September 10, 2008
Circulating beams

November 20, 2009
Beams back

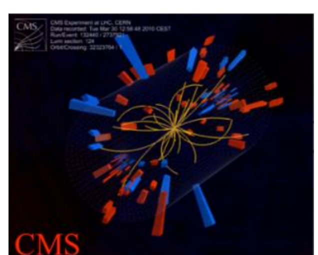
June 28, 2011
1380 bunches

1380

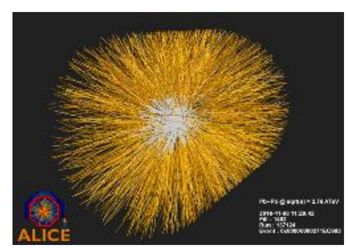
2008 | 2009 | 2010 | 2011 | 2012

September 19, 2008
Incident

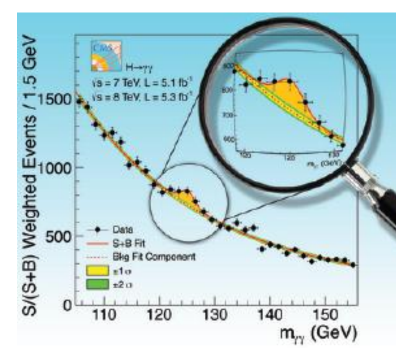
March 30, 2010
First collisions at 7 TeV CM



November 2010
First Lead ion run



July 4, 2012
Higgs Seminar



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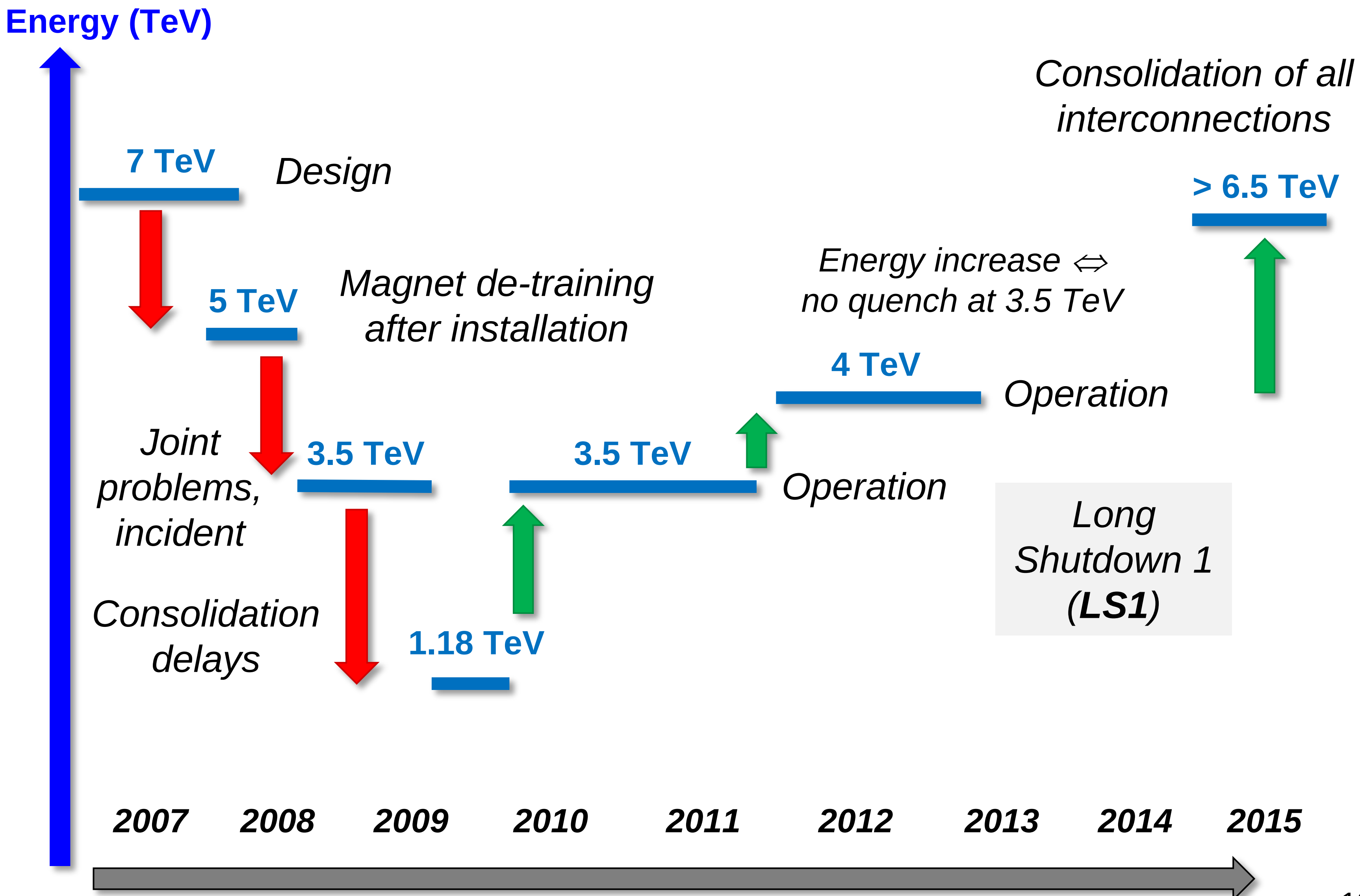
LHC energy evolution



Main LS1 activities

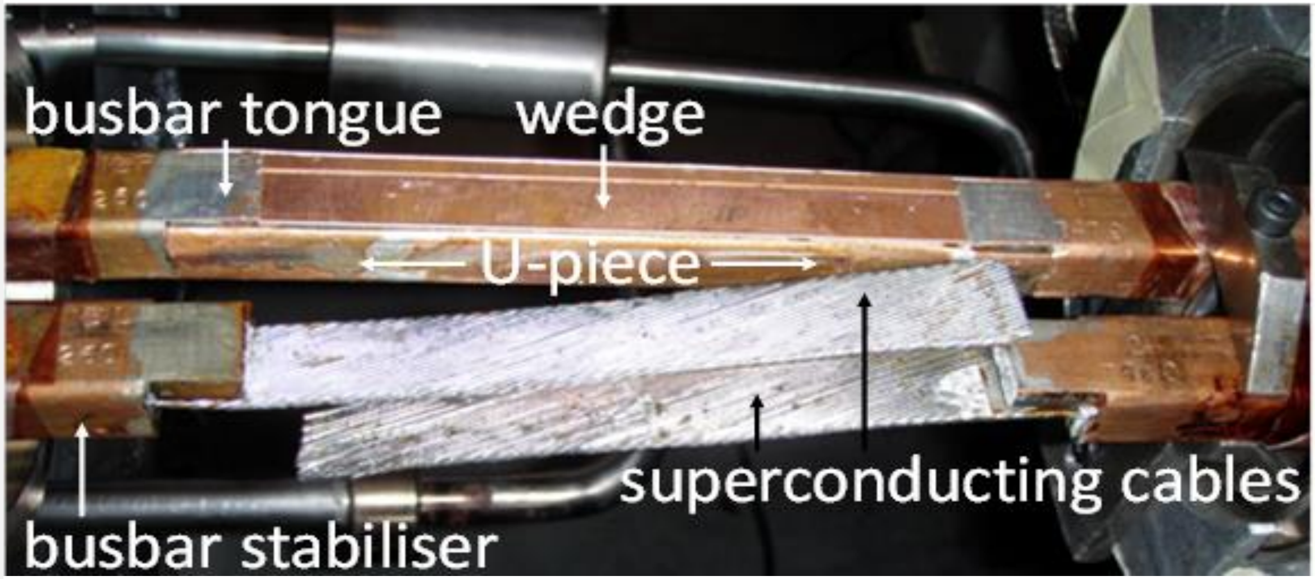
- Repair and consolidation of the magnet interconnections,
- Replacements of ‘weak’ magnets,
- Relocation of electronics to reduce impact of radiation (Single Event Upsets),
- General maintenance of the cooling-ventilation system and of the cryogenic plants,
- Upgrades, changes and fixes in essentially all systems !

After LS1 we have a ‘new’ machine

(but with experience on how to run it !)

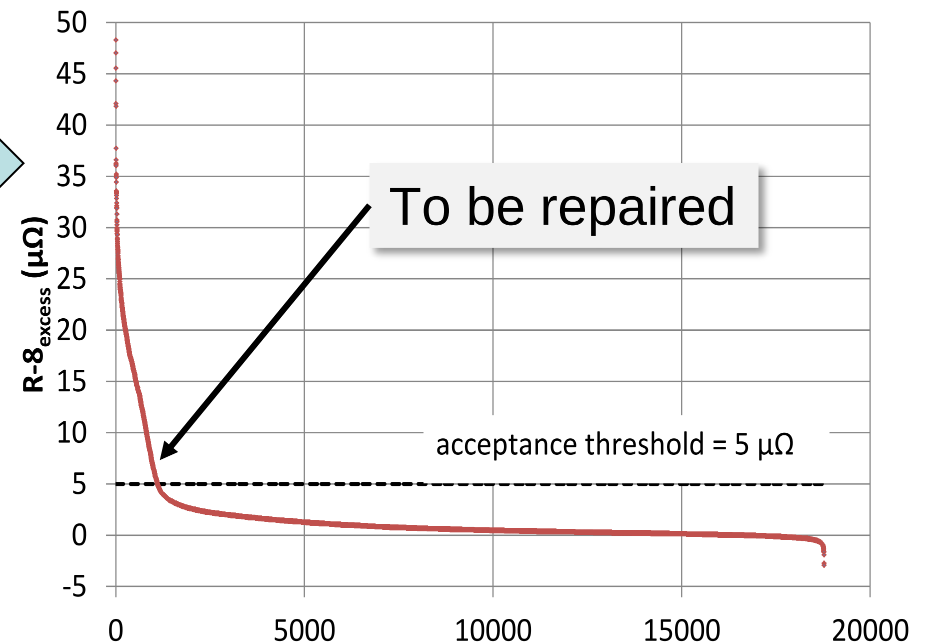
13 kA cable interconnections

- Consolidation of the cable interconnections was the main driver of LS1
- As a first step, electrical resistance measurements (at room T) along the interconnection and quality checks were performed for 10’000 high current magnet interconnections. As a result 30% had to be de-soldered and redone.
  - *15% due to excess resistance,*
  - *15% due to geometrical issues – not expected !*
    - *Flatness, width, deformations.*



Resistance results

- Distribution of excess resistance sorted by descending excess value.
  - *2 values (for left and right side) for each interconnection.*



Largest excess resistances for each LHC sector

Sector	Max R_{excess} Dipoles (µΩ)	Max R_{excess} Quadrupoles (µΩ)
56	29	21
67	35	32
78	72	107
81	42	34
12	30	46
23	28	43
34	34	36
45	48	35

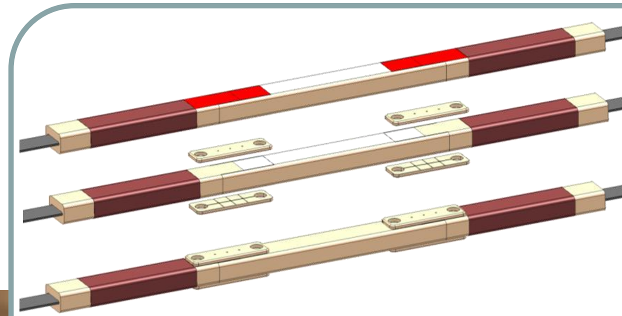
The max. excess R estimated in 2009 was ≈70-80 µΩ for the dipoles

→ base for 3.5 TeV max energy !

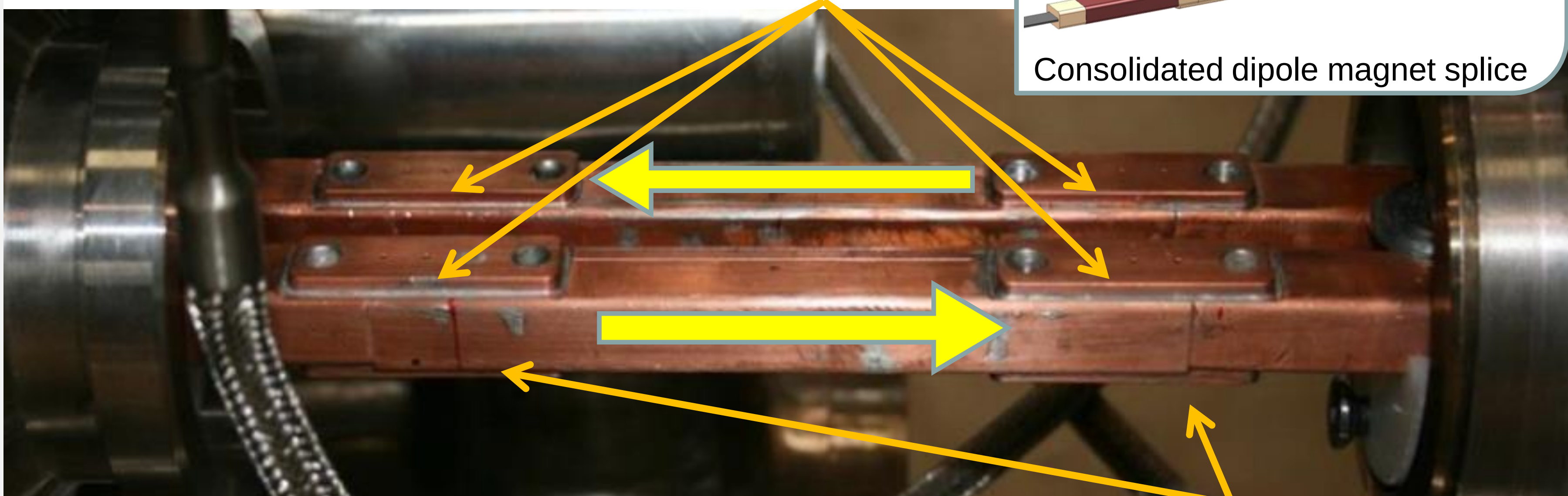
- Good resistance values:
  - *~6 µΩ for dipoles,*
  - *~10 µΩ for quadrupoles*.
- S78 (first installed) has the worst outliers – was expected.
  - *A quench of the worst interconnect at a energy ≥ 4 TeV could have triggered a 19th September-like incident.*

13 kA cable interconnections

- Once the quality (electrical resistance and shape) was within tolerance, the high current magnet interconnections were consolidated with bypass shunts to increase the Cu cross-section at the junctions of the cables.

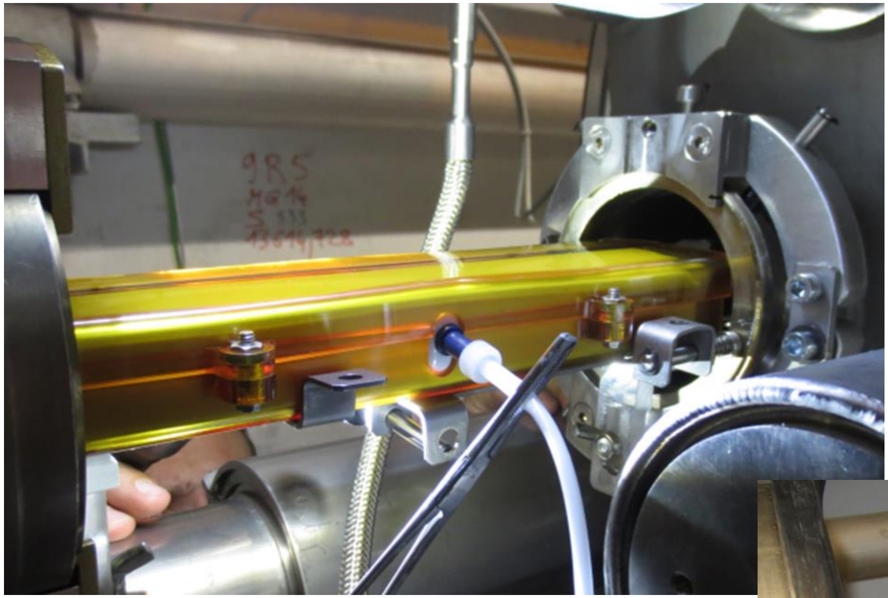


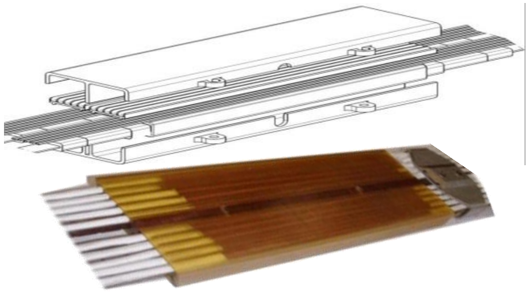
Consolidated dipole magnet splice



13 kA cable interconnections

- The interconnections were finally surrounded by an improved mechanical stabilization and electrical insulation system ('insulation box').

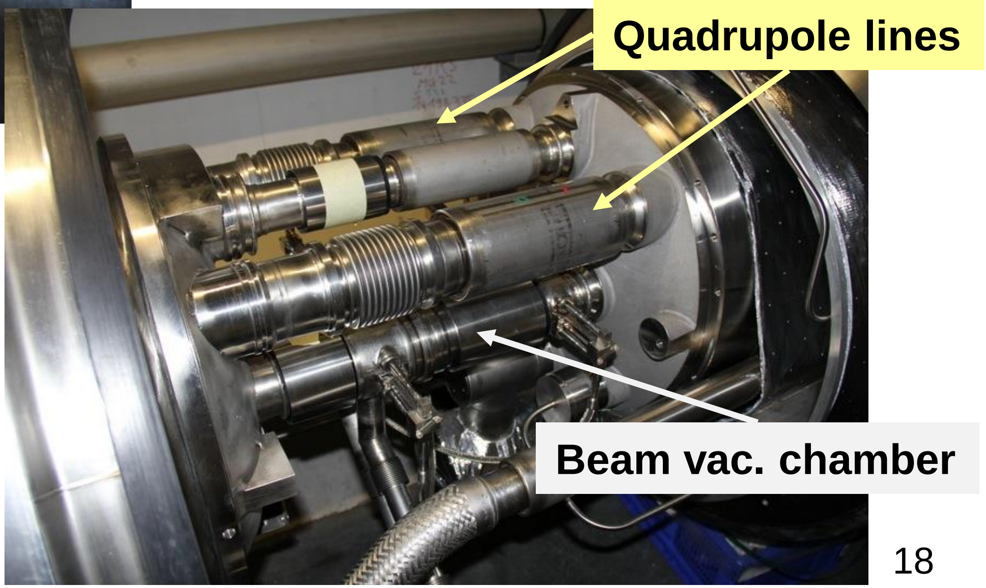




Consolidated electrical insulation system

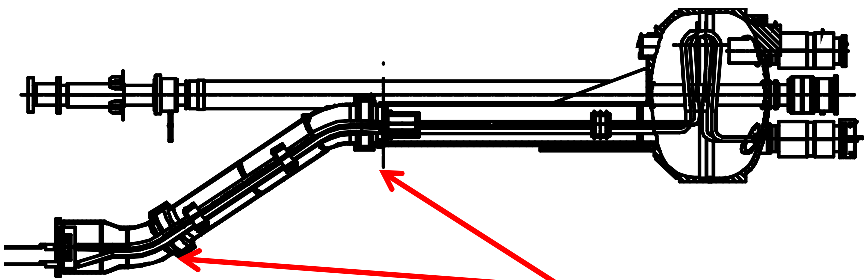
After welding:

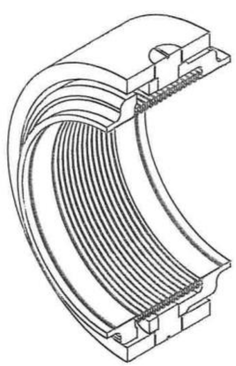
ready for leak tests

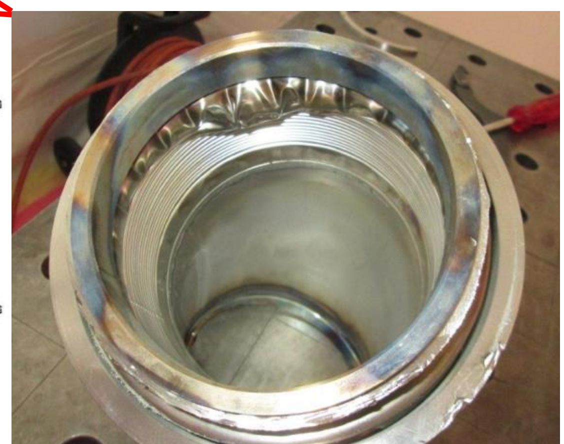


Connection box DFBA issues

- A bad surprise was waiting on some bellows inside the connection boxes between room temperature and super-conducting cables (‘DFB’).
- Bellows were found ‘imploded’ on 4 of them, 2 requiring repair on the surface in a workshop.
  - *Cold Helium most likely diffused (through cracks in the weldings) between the sheets of the multi-sheet bellows. During warm up the Helium was trapped, building up an over-pressure that ruptured the bellows.*

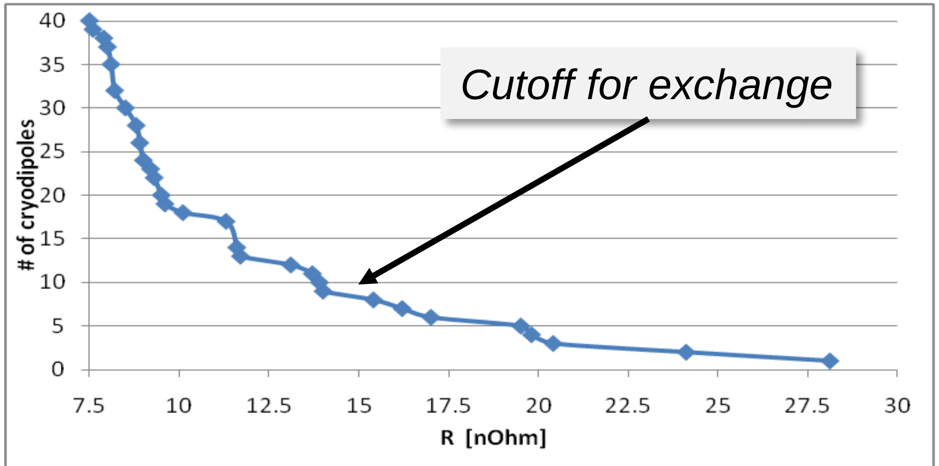




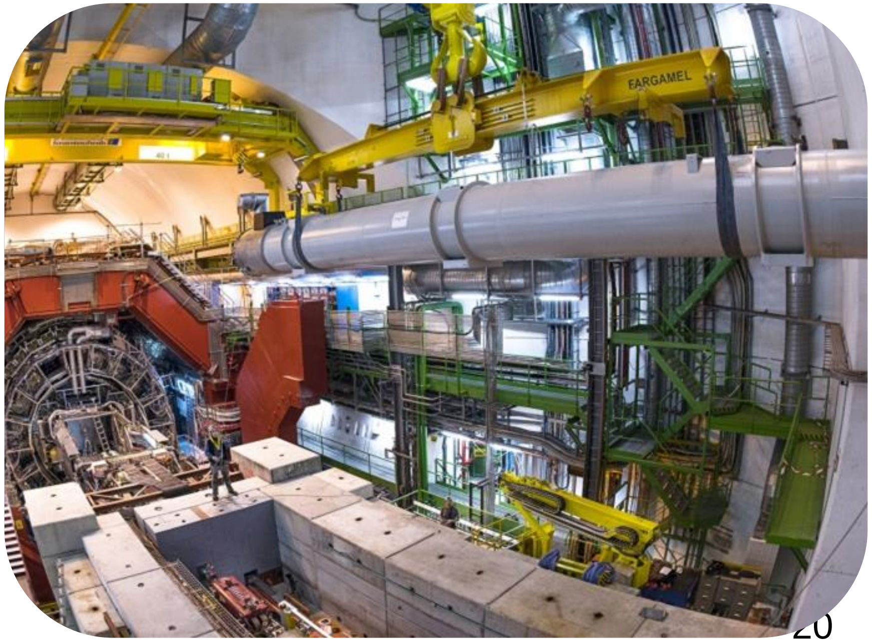


Magnet exchange

- 18 cryo-magnets were exchanged:
  - *Large internal resistance @ 1.9 K.*
    - Confirmed by inspections: imperfect soldering.
  - *Problems with quench protection, electrical isolation,*
  - *S34 magnet exchanges.*
- 15 additional magnet will be exchanged in LS2 (2018).



Internal resistance @ 1.9 K [nΩ]



The main 2013-14 LHC consolidations

1695 Openings and final reclosures of the interconnections

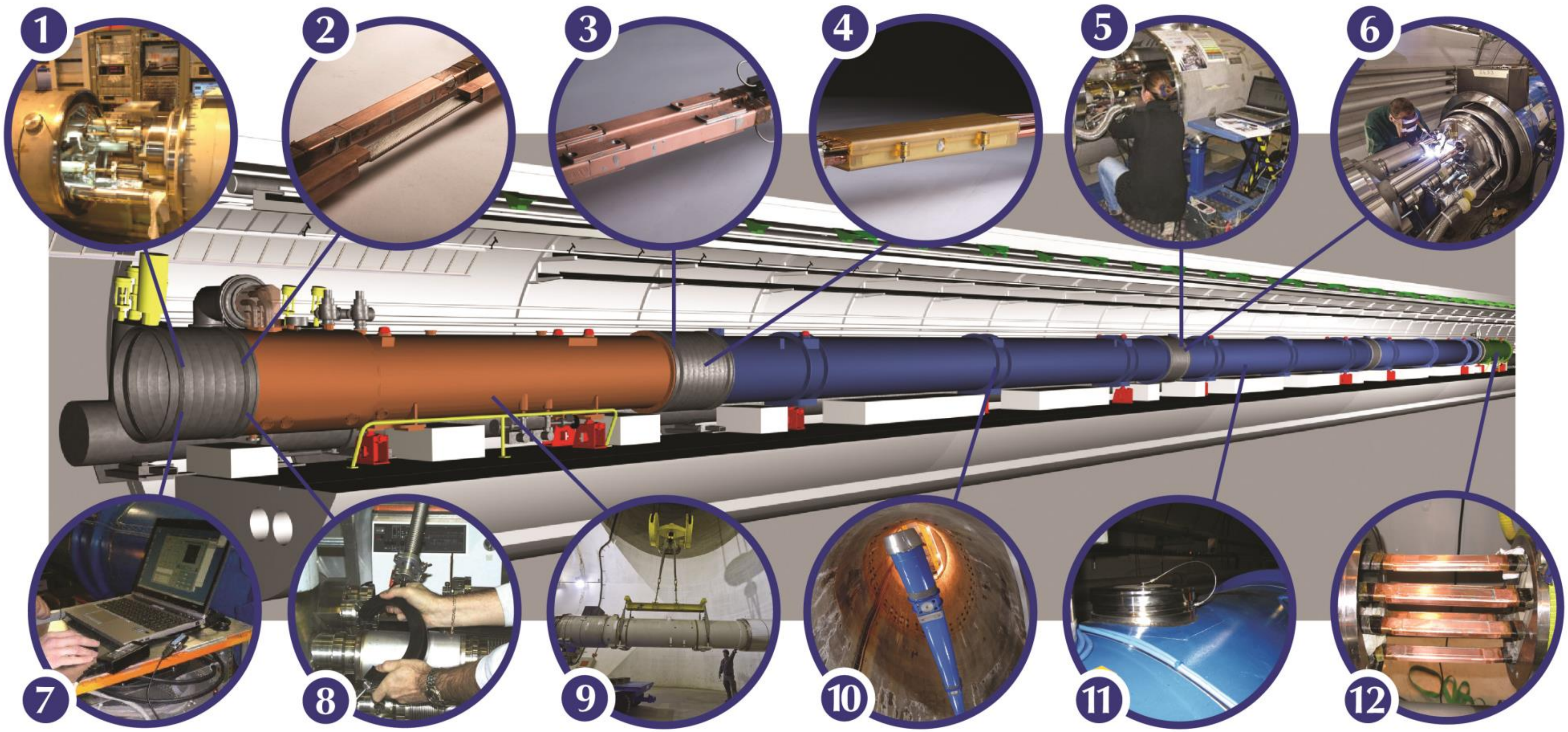
Complete reconstruction of 3000 of these splices

Consolidation of the 10170 13kA splices, installing 27 000 shunts

Installation of 5000 consolidated electrical insulation systems

300 000 electrical resistance measurements

10170 orbital welding of stainless steel lines



18 000 electrical Quality Assurance tests

10170 leak tightness tests

3 quadrupole magnets to be replaced

15 dipole magnets to be replaced

Installation of 612 pressure relief devices to bring the total to 1344

Consolidation of the 13 kA circuits in the 16 main electrical feed-boxes

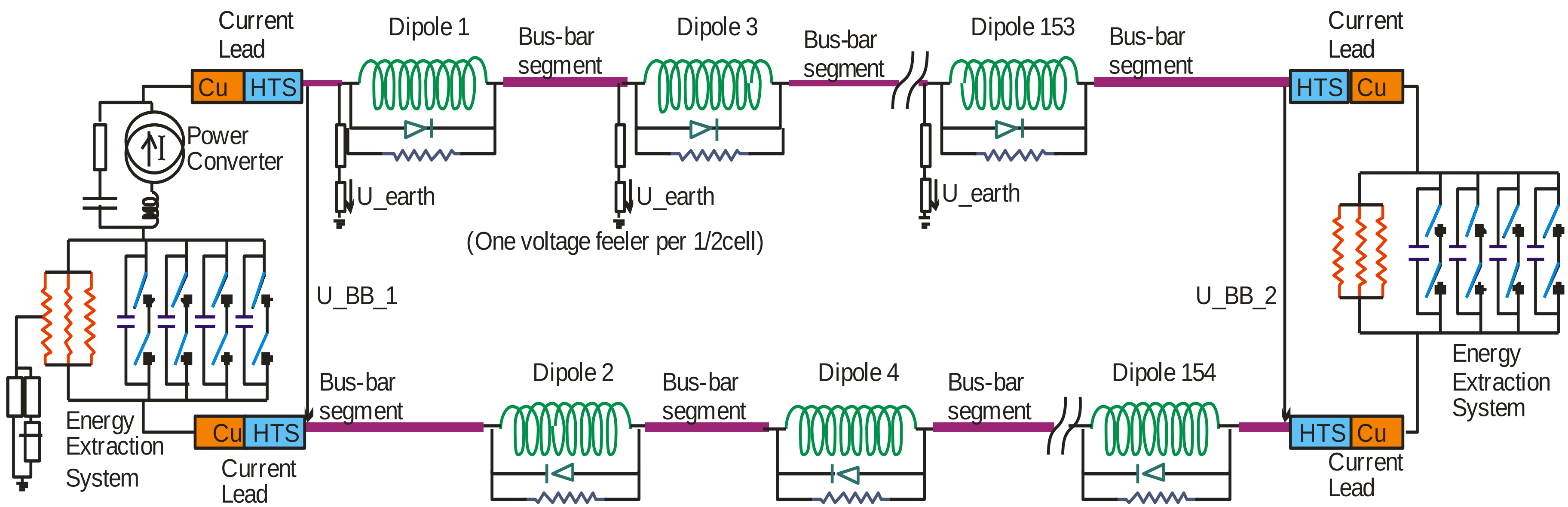
Shutdown status

- All the scheduled and repair work is finishing and the machine is prepared for cool-down and powering.
  - *5 out of 8 sectors are cold / in cool-down.*
    - ✓ Sector 67 is at 1.9 K ready for powering,
    - ✓ Sector 81 is at 20K,
    - ✓ Sector 12 is cooling down to 20K,
    - ✓ Sectors 45 ad 78 are cooling down to 80K.

- Current issues:
  - ✓ *Vacuum leak in sector 23 – localized and fixed,*
  - ✓ *Sextupole circuit with Earth fault in S34 – not critical, will be condemned,*
  - *Quench protection electronics damage during high voltage qualification (ELQA) tests – apparently due to an isolation problem on a new design. Old system available for replacement → delay for sector 67.*

- Each of the large dipole and quadrupole circuits has a large number of discontinuities which can be external or internal to the magnets.
  - *The 8 dipoles circuits have ~28'000 discontinuities !*
- The discontinuities between magnets (interconnects) as well ad the bypass diodes of the quadrupoles were checked an consolidated during LS1.
- The main unchecked discontinuities are in the dipole bypass diodes.

→ **CSCM** (*Copper Stabilizer Continuity Measurement*) test



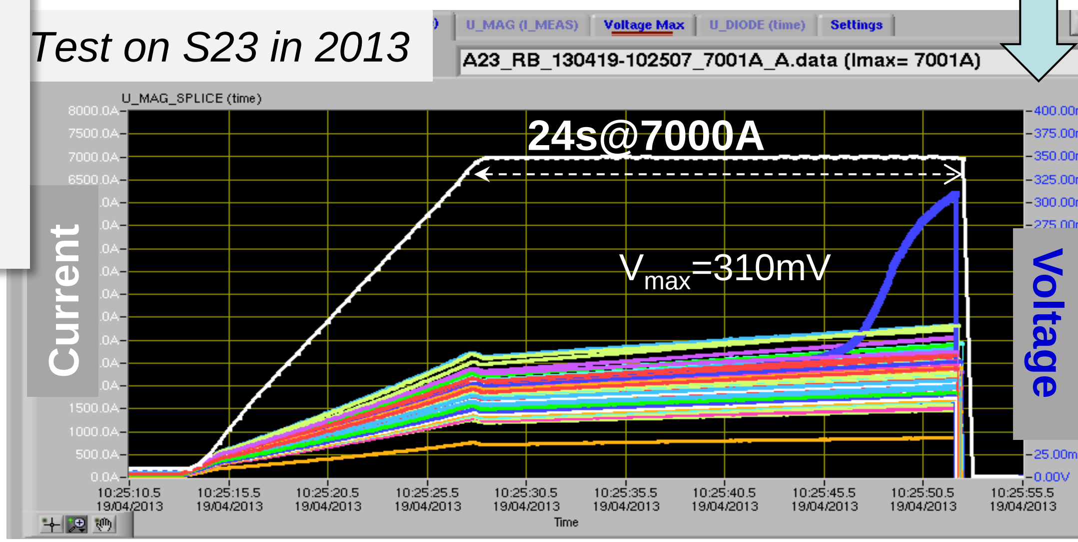
CSCM

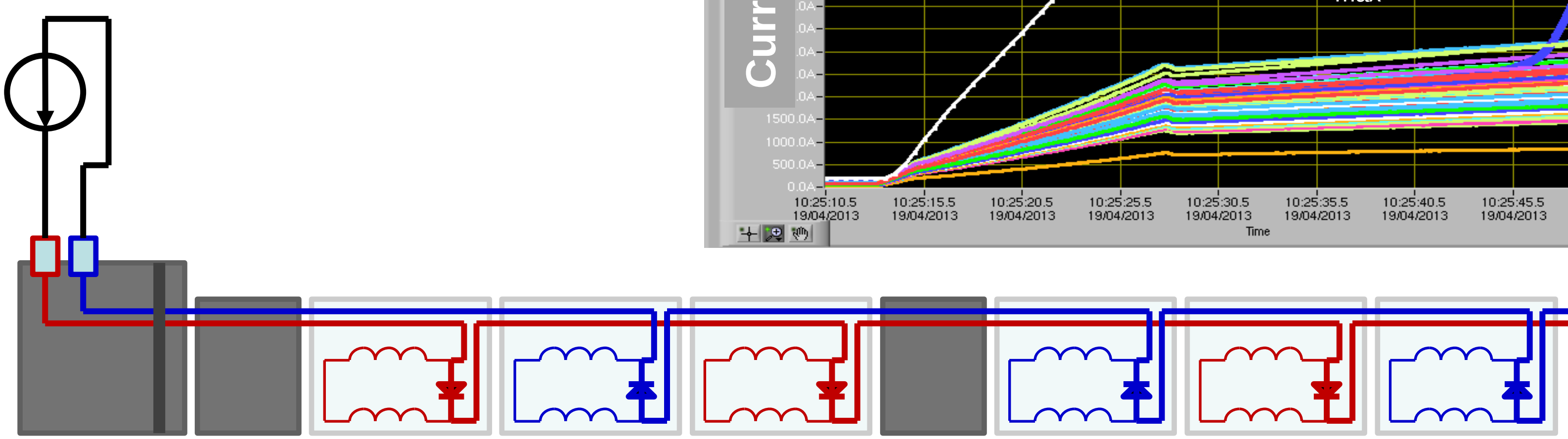
The CSCM is a test to ***ensure*** that the current can safely bypass the magnets if case of a quench. Requires a reconfiguration of the powering and protection
→ 2 weeks / sector → was recently added to the schedule !

- Stabilize a sector around 20 K, ***the magnets are not superconducting***.
- Send a current pulse of up to 11 kA (ramp up in 6 steps).
- Excessive resistance leads to thermal run-away and increasing voltage → observe voltages over interconnections.

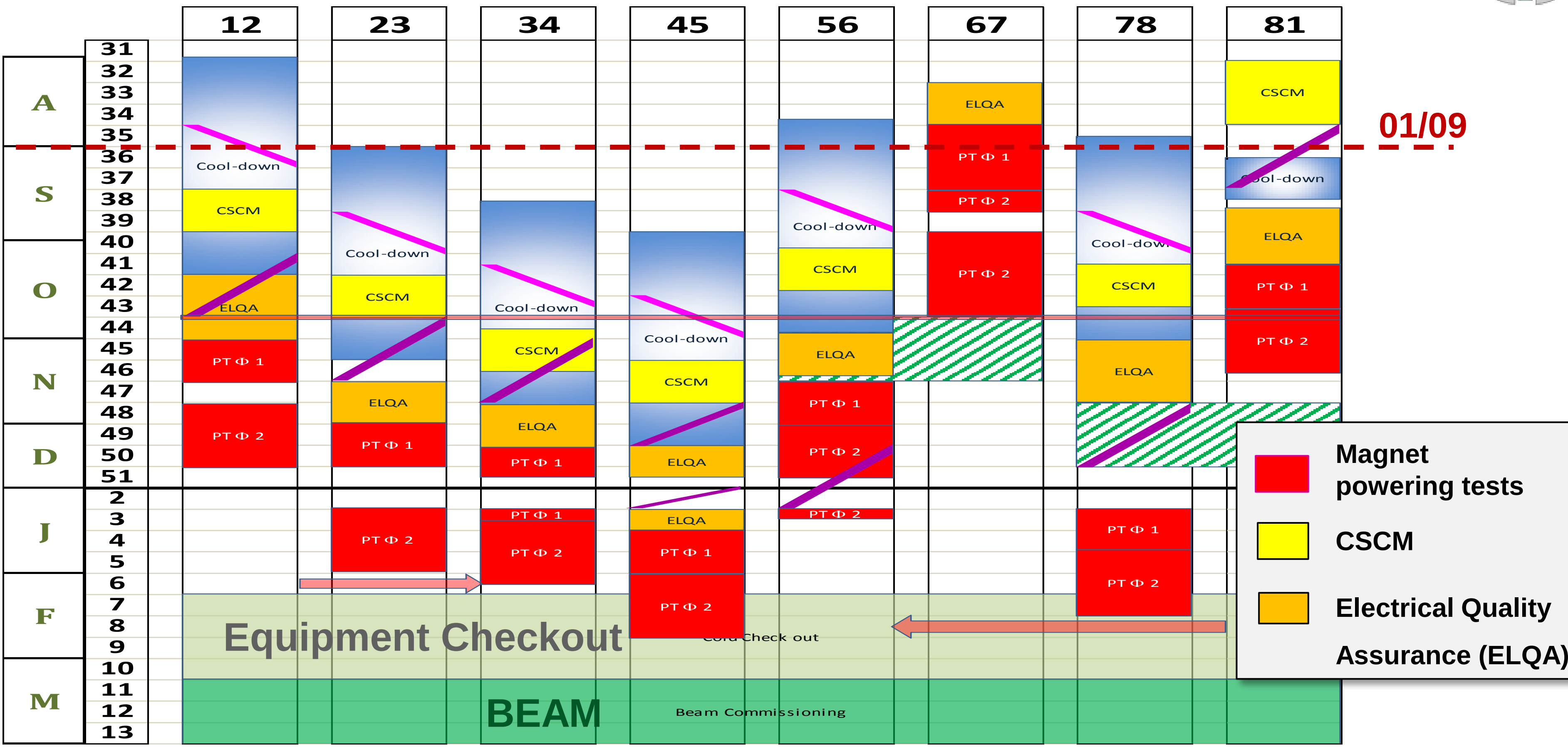
Status

- Type test in S23 in 2013, 3 bad interconnections were localized.
- **Sectors 67 and 81 were tested and validated for 7 TeV.**





The ‘latest’ planning – towards beam



- We are entering >5 months of magnet tests.
  - *Powering tests should have started last week – delay due to problem during HV testing.*
  - *First dipole magnets > 6 TeV in October.*
- Beam injection tests into 1-2 sectors may take place in Jan/Feb.
  - *S23 (B1) or S67+S78 (B2)*
- Beam commissioning starts 2nd week of March!

Energy after LS1

- In 2008 attempts to commission the first LHC sector to 7 TeV revealed 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 show that the number of training quenches required to reach 7 TeV is very large.
  - *Training the magnets is part of the powering tests.*
- We are planning to restart at **6.5 TeV**.
  - *We will have a clearer picture towards the end of 2014.*

Energy [TeV]	I_{oper} [A]	$I_{max,HWC}$ [A]	Exp. No. training quenches
6	10120	10220	5-10
6.1	10300	10400	10-20
6.2	10470	10570	20-30
6.3	10640	10740	30-40
6.4	10810	10910	50-80
6.5	**10980**	**11080**	**90-130**
6.6	11160	11260	>150
6.7	11330	11430	>300

Courtesy of A. Verweij

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Goals of Run 2 (→ 2018)

- Operate the LHC at 6.5 TeV (or higher).
- Operate with 25 ns bunch spacing.
  - *50 ns spacing not favored due to pile-up.*
- Maximize the integrated luminosity.
  - *Small focusing – β* as small as possible.*
  - *Highest possible efficiency.*

The run in 2015:

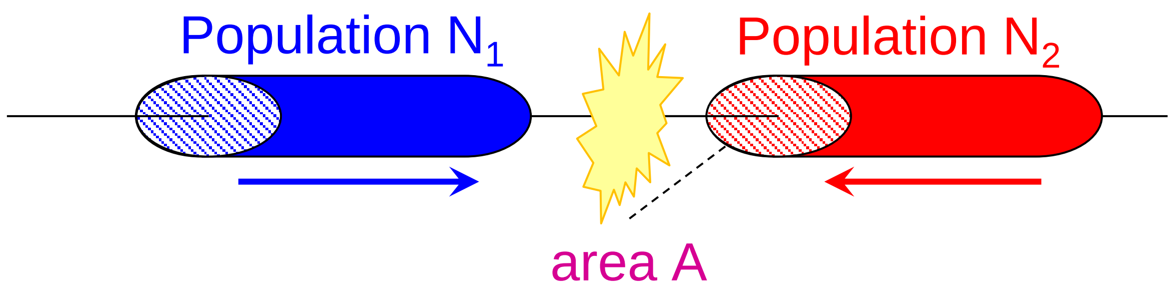
- The learning year of Run 2 (6.5 TeV, 25 ns etc),
- Top priority is to establish reliable operation with 25 ns spacing.

Collider luminosity

The key parameter for the experiments is the event rate dN/dt. For a physics process with <u>*cross-section* σ</u> it is proprotional to the collider **<u>Luminosity *L*</u>**:

$$\boxed{dN / dt = L\sigma}$$

unit of L :
1/(surface × time)

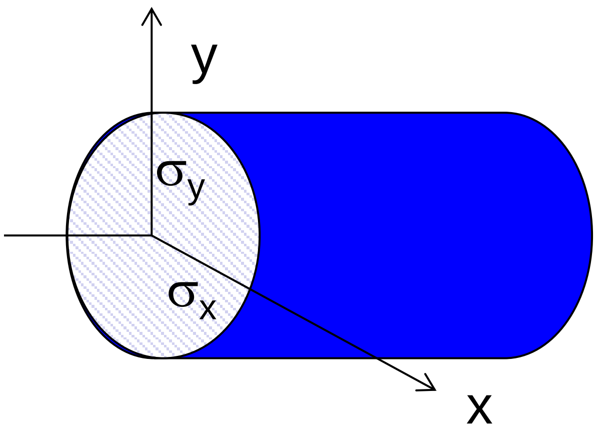


$$\text{Collision rate} \;\propto\; \sigma \times \underbrace{\frac{N1 \times N2}{A} \times \text{encounters/second}}_{L}$$

Collider luminosity

Expression for the luminosity L (for equal particle populations, Gaussian profiles and round beams) :

$$L = \frac{k\, f\, N^2}{4\pi\, \sigma_x^* \sigma_y^*} F = \frac{k\, f\, N^2}{4\pi\, \beta^* \varepsilon} F$$



- ***σ^*_x, σ^*_y*** *: transverse rms beam sizes.*
  - $(\sigma^*)^2 = \beta^* \varepsilon$
- ***β^**** *: betatron (envelope) function ⇔ optics*
- ***ε*** *: beam emittance (pahse space volume)*
- ***k*** *: number of particle packets / bunches per beam.*
- ***N*** *: number of particles per bunch.*

k×N : total beam intensity

- ***f*** *: revolution frequency = 11.25 kHz.*
- ***F*** *: geometric correction factor (crossing angles...).*

LHC design

k = 2808
N = 1.15×10^{11}
$\sigma^*_x = \sigma^*_y$ = 16 μm

****** refers to the IP***

During Run 1 beams with 50 ns bunch spacing were used operationally since April 2011 instead of the design 25 ns spacing.

- *More luminosity with 50 ns beams, smaller beams, easier to operate.*
- *Much less susceptible to electron clouds → see later.*
- *But luminosity concentrated in ½ as many bunch crossings → pile-up !*

LHC beam parameters (LHC injection)

	Spacing	k	N (p/bunch)	ε [μm]	Relative luminosity / Bunch Crossing
2012 →	**50 ns**	**1380**	**1.65 x10^{11}**	**1.8**	**4**
	25 ns design	2750	1.15 x10^{11}	3.5	1

$$L = \frac{\boxed{kN_b^{\,2}}\, f\,\gamma}{4\pi\,\beta^* \boxed{\varepsilon}} F$$

Beams for Run 2

- A new production scheme providing much lower emittances (at the price of reduced k) was developed in 2011/2012 – the BCMS scheme (Batch Compression and Merging Scheme).
- We will start 25 ns operation with the standard or low emittance version.
  - *An emittance blow-up factor has to be applied (injection → collisions)– in particular for 25 ns beams ⇒ $\Delta\varepsilon \sim +0.5\ \mu m$.*
- Other 25 ns beam variants exist in case the electron cloud is not fully controlled (with 'holes') ⇒ fewer bunches (<2000).

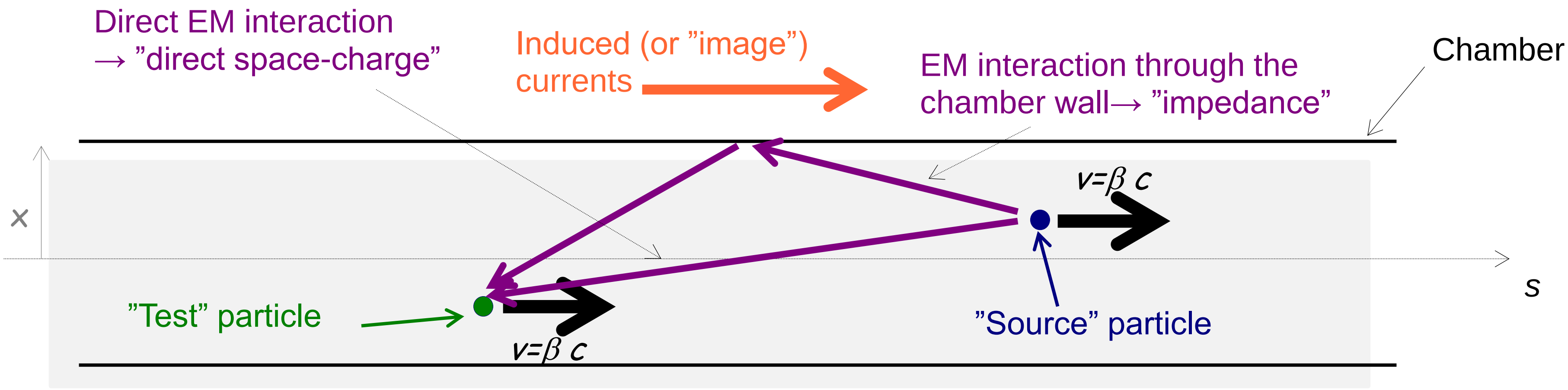
$$L = \frac{\boxed{kN_b^2} f \gamma}{4\pi \beta^* \boxed{\varepsilon}} F$$

LHC beam parameters (LHC injection)

Spacing	k	N (p /bunch)	ε [μm]	Relative luminosity / Bunch Crossing
50 ns	1380	1.7×10^{11}	1.6	4.7
25 ns standard	2750	1.3×10^{11}	2.4	1.9
25 ns BCMS	2600	1.3×10^{11}	1.3	3.4
25 ns design	**2750**	**1.15**$\times10^{11}$	**3.5**	**1**

Limits to the bunch population

- High bunch population and tight bunch spacing make the beams prone to instabilities related to wake-fields i.e. to **self-generated fields** (‘impedance’).

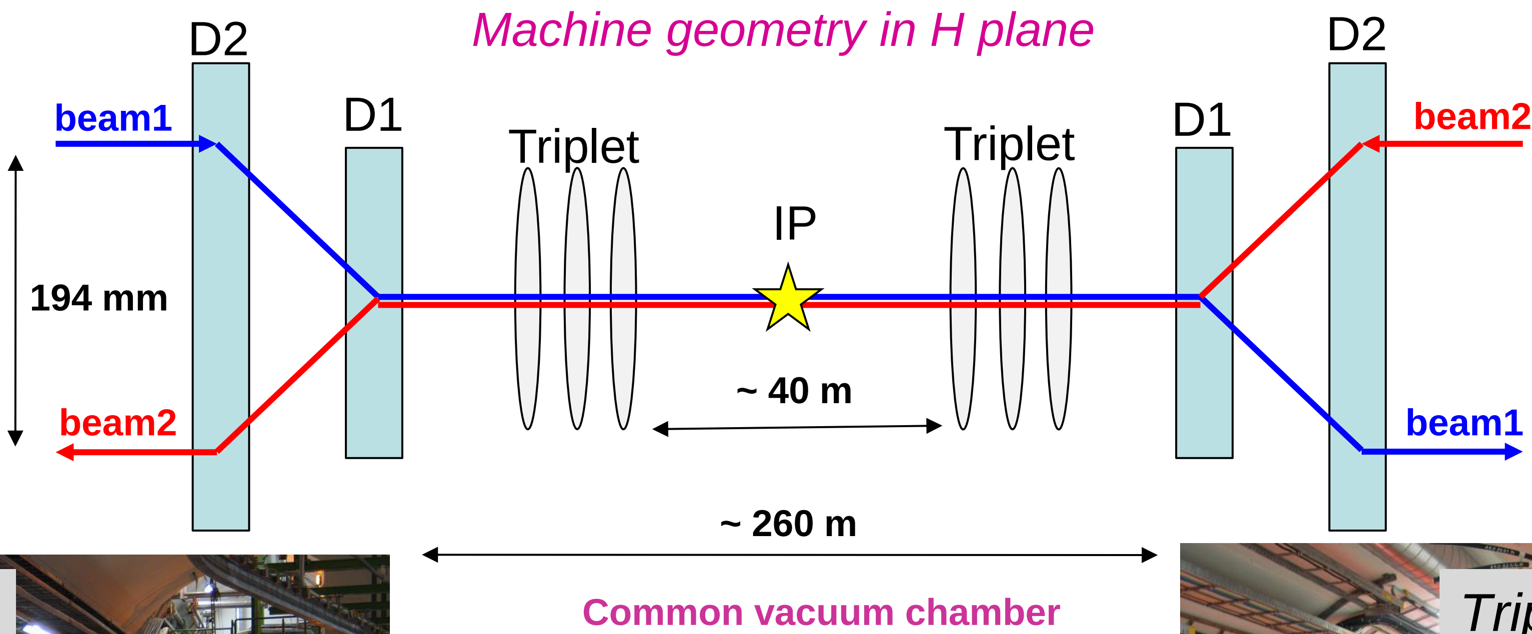


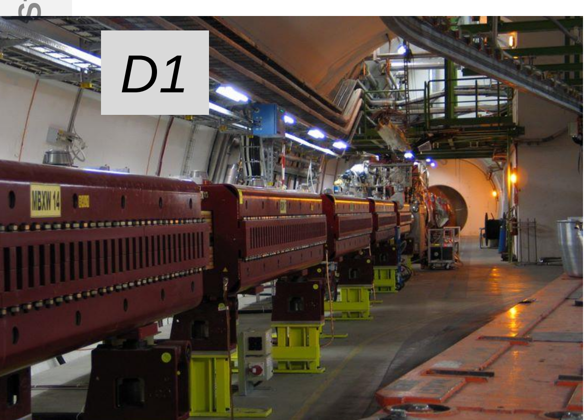
- In 2012 instabilities became critical due to higher bunch intensity and tighter collimators settings – collimators are main drivers !
- Cures that we will have to use again in Run 2:
  - Transverse feedback – ‘kicks’ the bunches back to the center of the vacuum chamber,
  - Non-linear magnetic fields (sextupoles, octupoles, **beam-beam – collisions !**) that produce a frequency spread among particles – kill coherent motion.

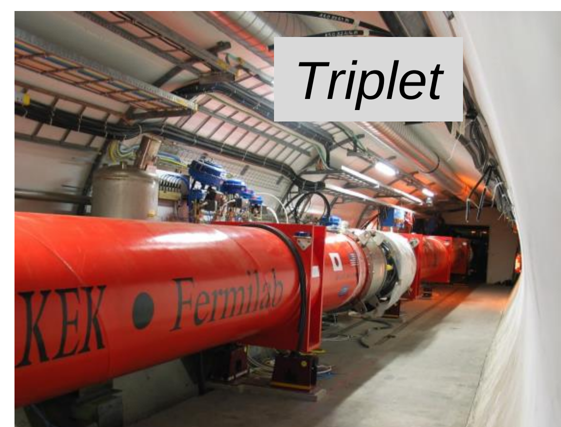
Interaction regions geometry

- In the IRs, the beams are first combined into a single common vacuum chamber and then re-separated in the horizontal plane,
- The beams move from inner to outer bore (or vice-versa),
- The triplet quadrupoles focus the beam at the IP.

D1,D2 : separation/recombination dipoles

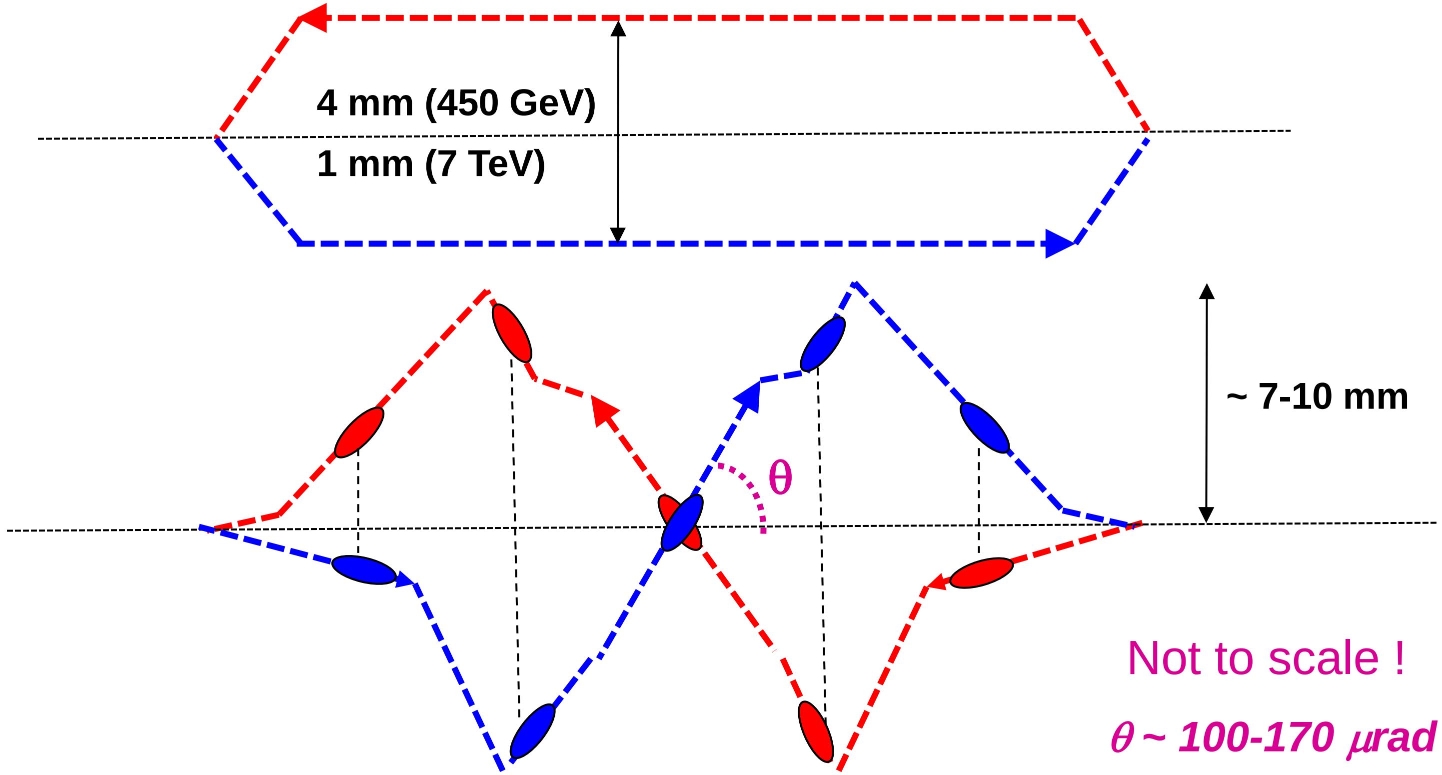






Separation and crossing

- Because of the tight bunch spacing and to prevent undesired parasitic collisions in the common vacuum chamber:
  - Parallel separation in one plane, collapsed to bring the beams in collision.
  - Crossing angle in the other plane (vertical for ATLAS, horizontal for LHCb).
  - Both extend beyond the common region.

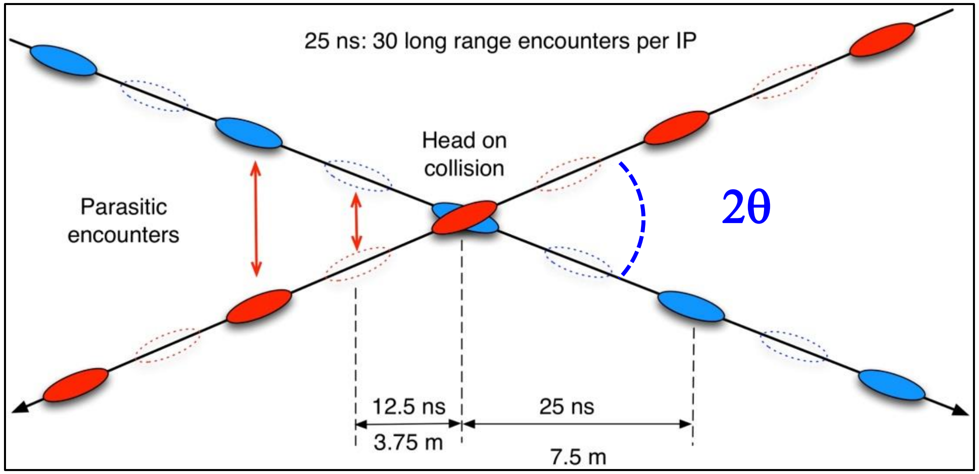


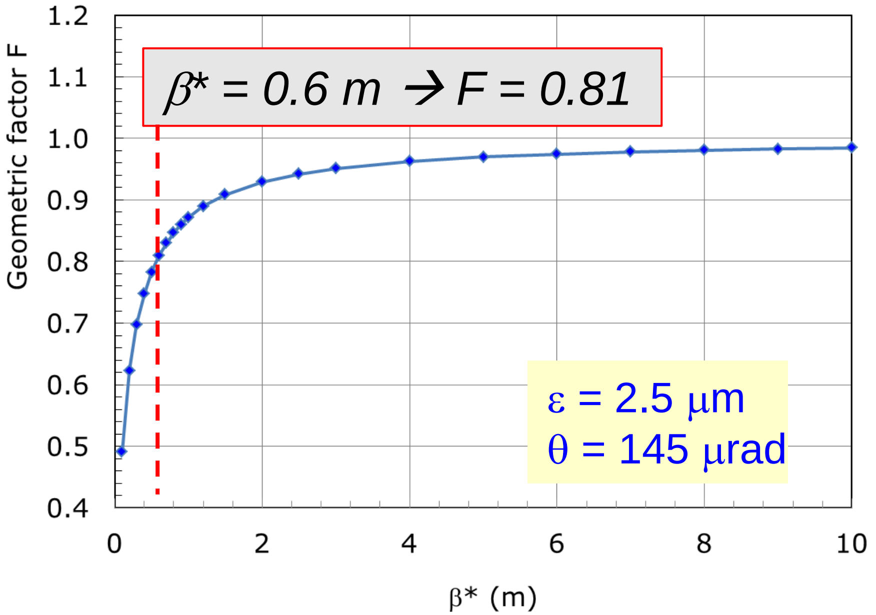
- Needed to minimize the electromagnetic interactions between the beams (***beam-beam*** effects) in the common vacuum chamber.
  - Min. separation ~11-12 beam sizes
- Drawbacks:
  - Geometric luminosity reduction factor due to **bunch length σ_s** and crossing angle becomes significant for low β^*

$$F = \frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma^*_{x/y}}\tan\theta\right)^2}} = \frac{1}{\sqrt{1+\frac{\sigma_s^2}{\beta^*\varepsilon}\tan^2\theta}}$$

  - Reduction of the aperture

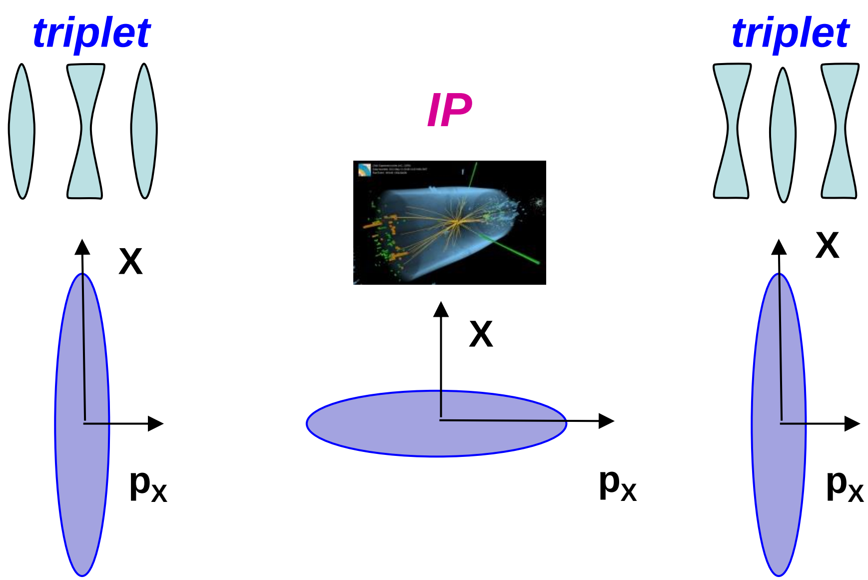
$$L = \frac{kN_b^2 f\gamma}{4\pi\beta^*\varepsilon}\boxed{F}$$



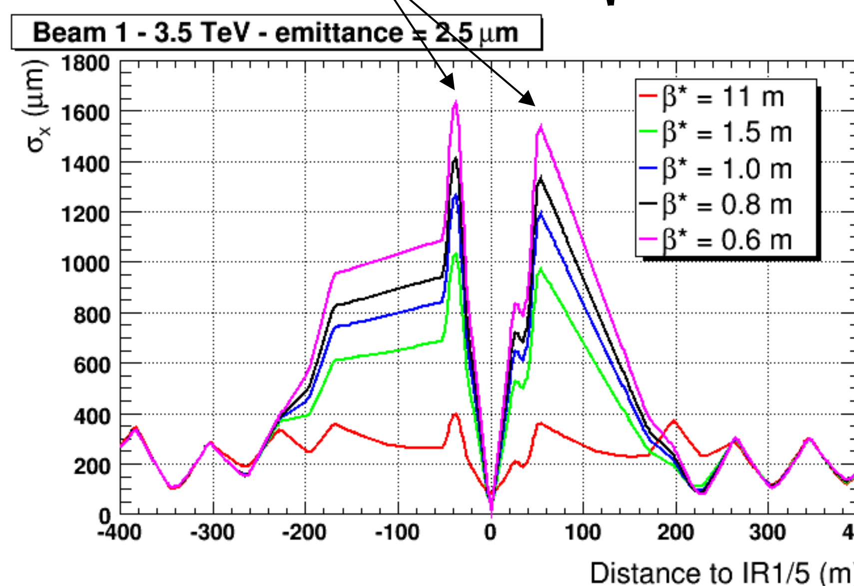


Aperture and β*

- Focusing (lowering β*) at the collision point is limited by the aperture of the triplet quadrupoles ⇔ phase space conservation.



$$\sigma_{triplet} \propto \sqrt{\frac{\varepsilon}{\beta^{*}\gamma}}$$



- During run 1 the apertures were better than expected thanks to small alignment errors and mechanical tolerances, allowing to reach a smaller than anticipated β*.

$$L = \frac{k N_b^{\,2} f \gamma}{4\pi \boxed{\beta^{*}} \varepsilon} F$$

Aperture and β*

- The minimum β* depends on the available aperture, the required crossing angle and the margin within the collimation system and between the last collimator and the triplet quarupoles.
  - *If the collimators are too tight, beam instabilities may be triggered that limit the beam intensity – optimization β* versus intensity reach – difficult to make precise predictions !*
- Scaling the Run 1 performance with conservative collimator settings one arrives at **β* of 65 to 70 cm** (**design 55 cm**).

	θ (μrad)	β* (cm)
Run 1 – 50 ns	145	60
Run 2 – 25 ns startup	160	65-70
Run 2 – 25 ns pushed	150	40

$$L = \frac{kN_b^{\,2} f \gamma}{4\pi \boxed{\beta^*} \varepsilon} F$$

- There are proposals to start with **'relaxed' β* of 1 m** and push β* only at a later stage when the machine and the 25 ns beam are better understood.
  - *A similar change (from β* 1.5 m to 1 m) was made in Sept. 2011 over 1 week.*
  - *Relax operation in the first months.*

General optics considerations

- In parallel to the choice of β* there is a discussion on the general beam optics:
  - *re-use the same optics as for Run 1,*
  - *or move to an ATS-compatible optics (→ HL-LHC type optics).*
- Both options provide β* down to 40 cm, but the ATS-compatible optics opens the possibly to develop and test the HL-LHC optics schemes. The ATS-compatible version also provides flexibility for non-round beams (different β* in the 2 transverse planes).
- The ATS-compatible optics requires however an initial loss of 5 cm or so in β* as it is more critical for machine protection.
  - *Direct impact of beam on the collimator in front of the CMS triplet is more critical – less tolerant to alignment errors…*

The main choices of optics and β* for the startup will probably be made by the end of September 2014

Luminosity projections

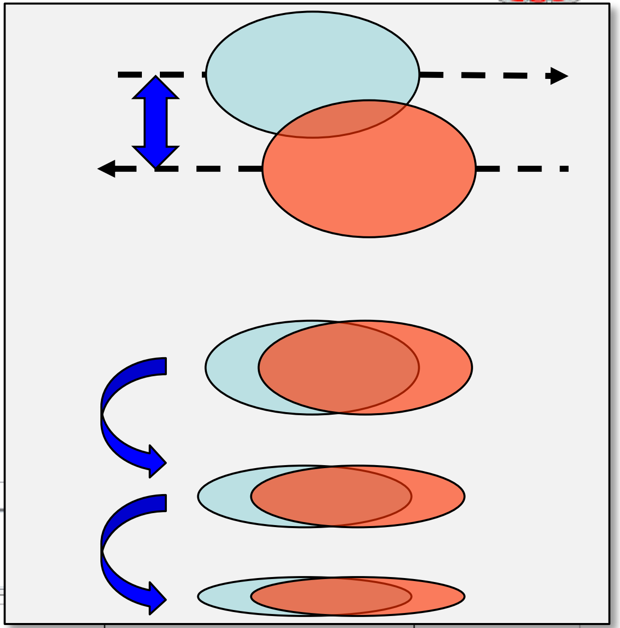
Some scenarios @ 6.5 TeV

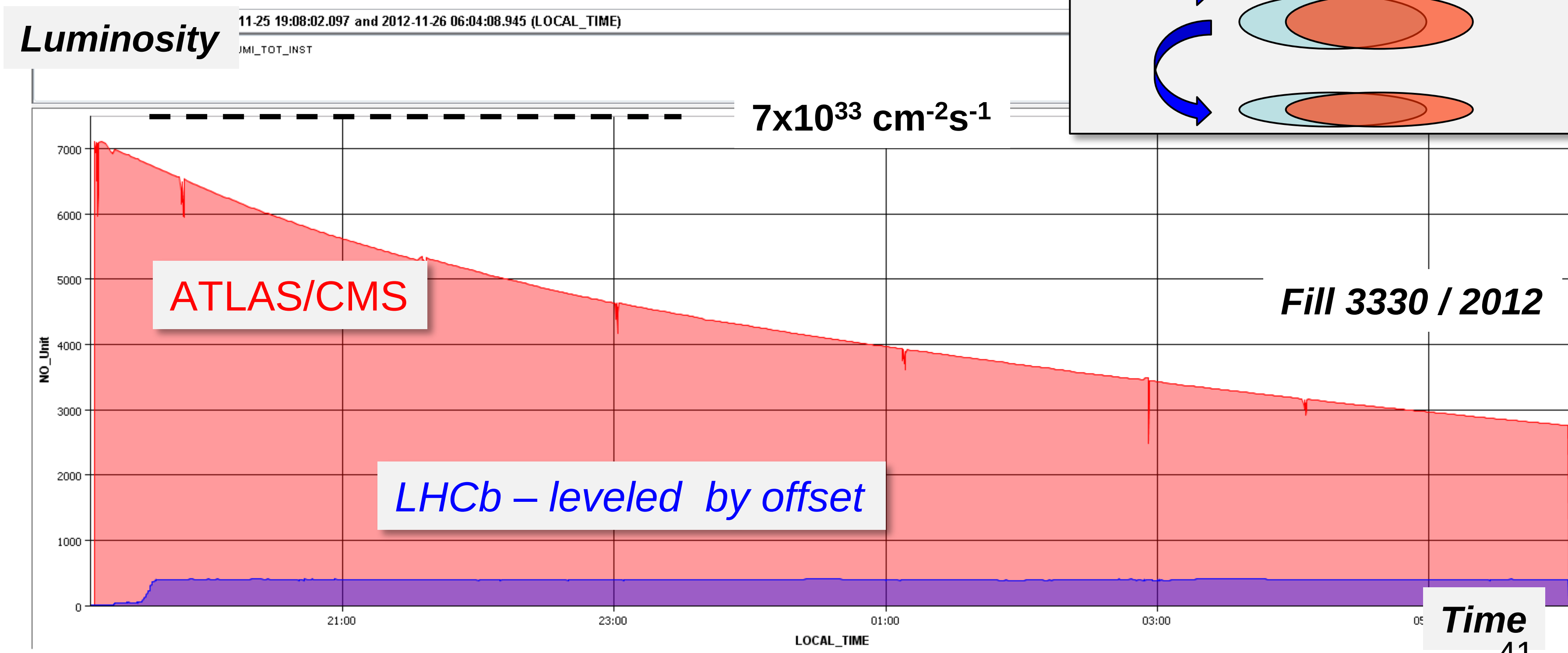
Beam	k	N_b [10^{11} p]	ε [μm]	β^* [m]	Peak L [10^{34} cm^{-2}s^{-1}]	Event pile-up	Int. L [fb^{-1}]
25 ns: initial	2760	1.2	3.0	**0.65**	**0.95**	26	~25
25 ns: pushed	2520	1.2	2.0	**0.4**	**1.7**	51	~40-50
50 ns	1360	1.60	2.2	**0.4**	**1.65**	90	~30

- The cryogenic limit to the luminosity is expected ~ 1.75×10^{34} cm^{-2}s^{-1} !
  - *Cooling limit of the triplet quadrupoles (collision debris)*.
- The 50 ns scenario (fallback) will require luminosity leveling. The pushed 25 ns scenario is at the limit.
  - *Discussion & optimization between machine & experiments.*
  - *Current assumption on the maximum average pile-up :*
    - *- **50** for decaying luminosity, **30-40** for leveled luminosity (~flat).*

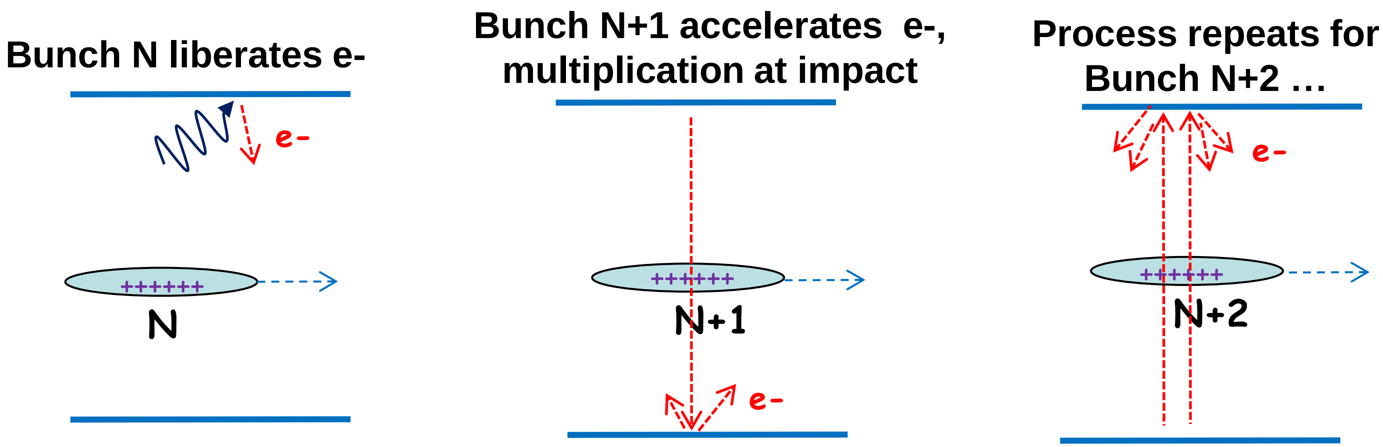
Leveling luminosities

- In run 1 we have leveled the luminosity of LHCb by adjusting the *offsets between the beams*.
- In run 2 we are considering to level luminosities by adjusting β* (beam size at IP) – if required.
  - *Better / mandatory for beam stability.*
  - *Baseline leveling tool for HL-LHC.*





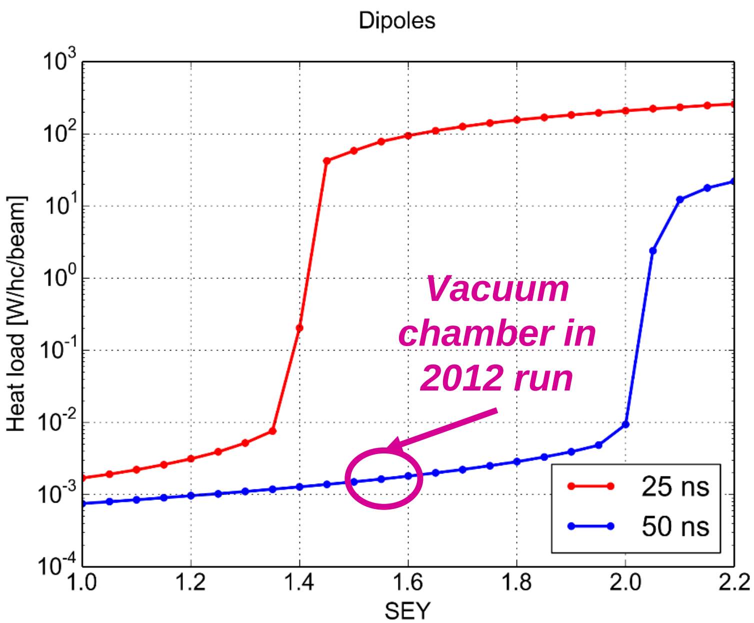
- In high intensity accelerators with positively charged beams and closely spaced bunches electrons liberated on vacuum chamber surface can multiply and build up a cloud of electrons.



- The cloud triggers *vacuum pressure increases* and *beam instabilities! It may deposit excessive heat on the vacuum chamber walls → cryogenic cooling issues !*
    - *Electron energies are in the 10 to few 100 eV range.*

Electron cloud mitigation

- Strong reduction of e-clouds with larger bunch spacing:



With 50 ns spacing e-clouds are much weaker than with 25 ns !

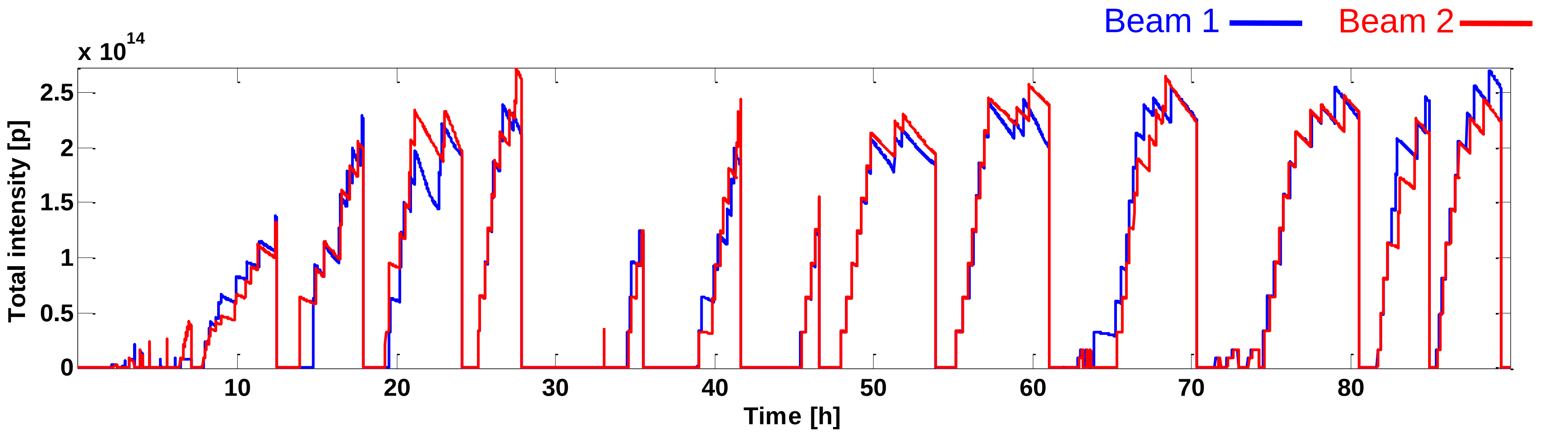
→ The main reason to operate in Run 1 with 50 ns spacing

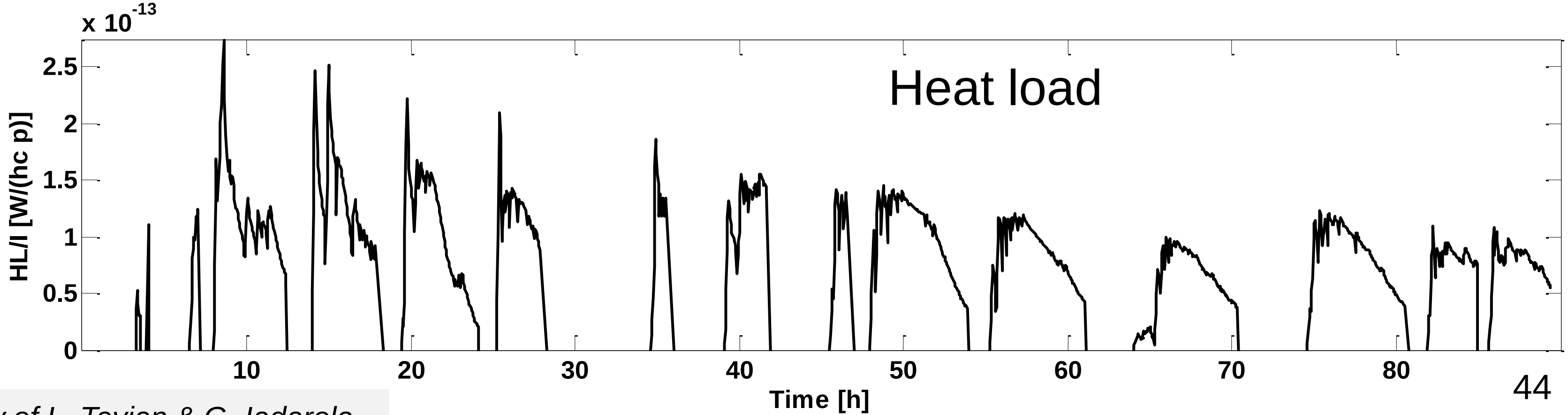
- Cure for e-clouds: conditioning by beam-induced electron bombardment ("**scrubbing**") leading to a progressive reduction of the SEY.
  - *e-clouds are produced deliberately with the beams to bombard the surface of the chamber to reduce the SEY until the cloud 'disappears' (self-destruction).*
  - *Performed at 450 GeV where fresh beams can be injected easily.*
  - *Scrubbing for 50 ns beams (2011-12) was done with 50 ns AND 25 ns beams.*

The December 2012 scrubbing run

3.5 days of test scrubbing for 25 ns beams at 450 GeV

- Ring filled with up to 2748 bunches,
- Slower than anticipated improvement on beam quality and heat load.
- With such an e-cloud activity we can only fill ~1400 bunches @ 6.5 TeV!

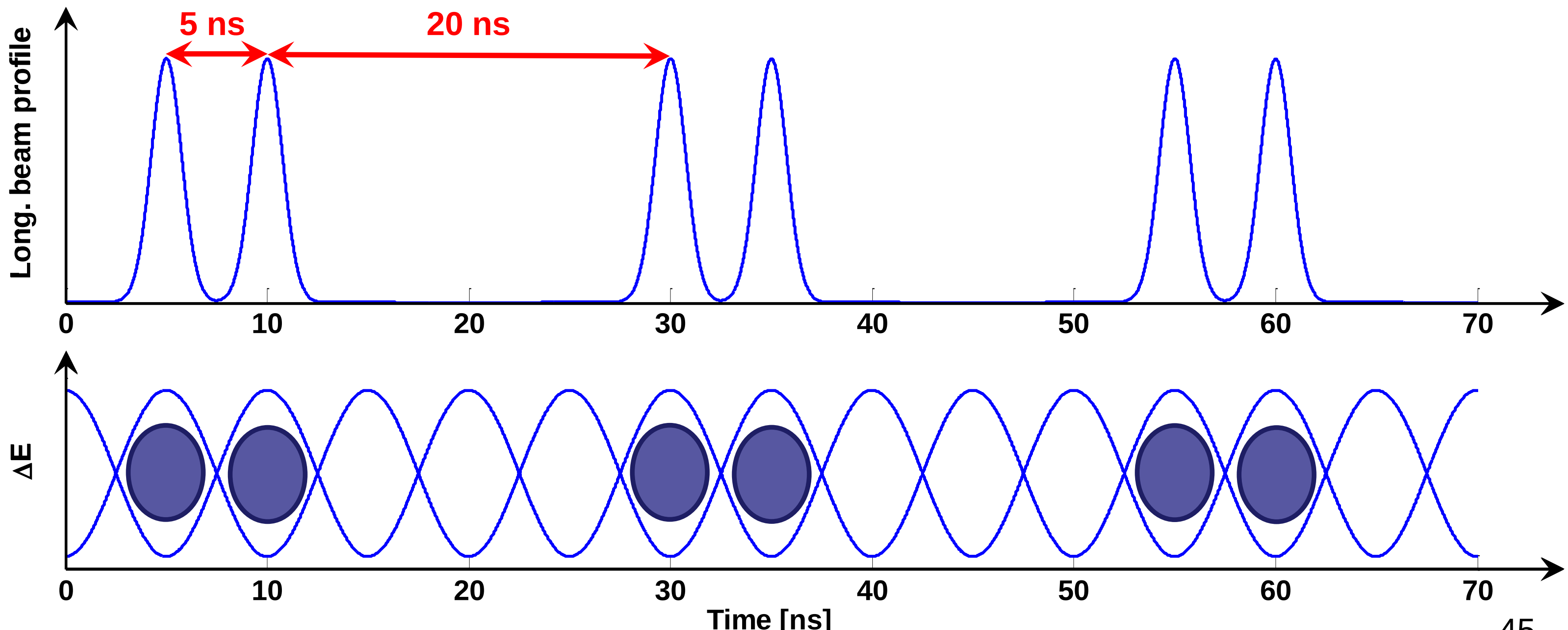




Courtesy of L. Tavian & G. Iadarola

Doublet beam

- The scrubbing observed with 25 ns in 2012 was slower than expected – it is apparently not effective enough in the dipole magnets.
- To enhance the e-cloud generation for scrubbing: idea to use doublet-beams with 5 ns spaced bunch doublet.
  - *Generated at RF capture in the SPS - done !*
  - *To be confirmed that this beam can be accelerated in the SPS and injected into LHC !*



Scrubbing planning

450GeV | 6.5 TeV

Commissioning (low intensity / luminosity) → **Vacuum conditioning 50 ns (5-7 days)** → **Scrubbing with 25ns (2 days)** → **50ns intensity ramp up + physics**

450GeV | 6.5 TeV

25 ns scrubbing (5 days) → **Scrubbing with doublet beams (5 days)** → **Scrubbing qualification 25 ns test ramps (5 days)**

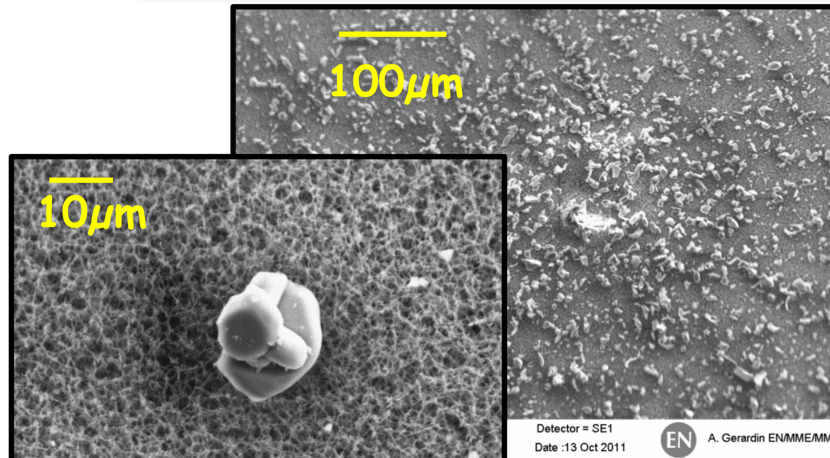
6.5 TeV

25 ns intensity ramp up + physics

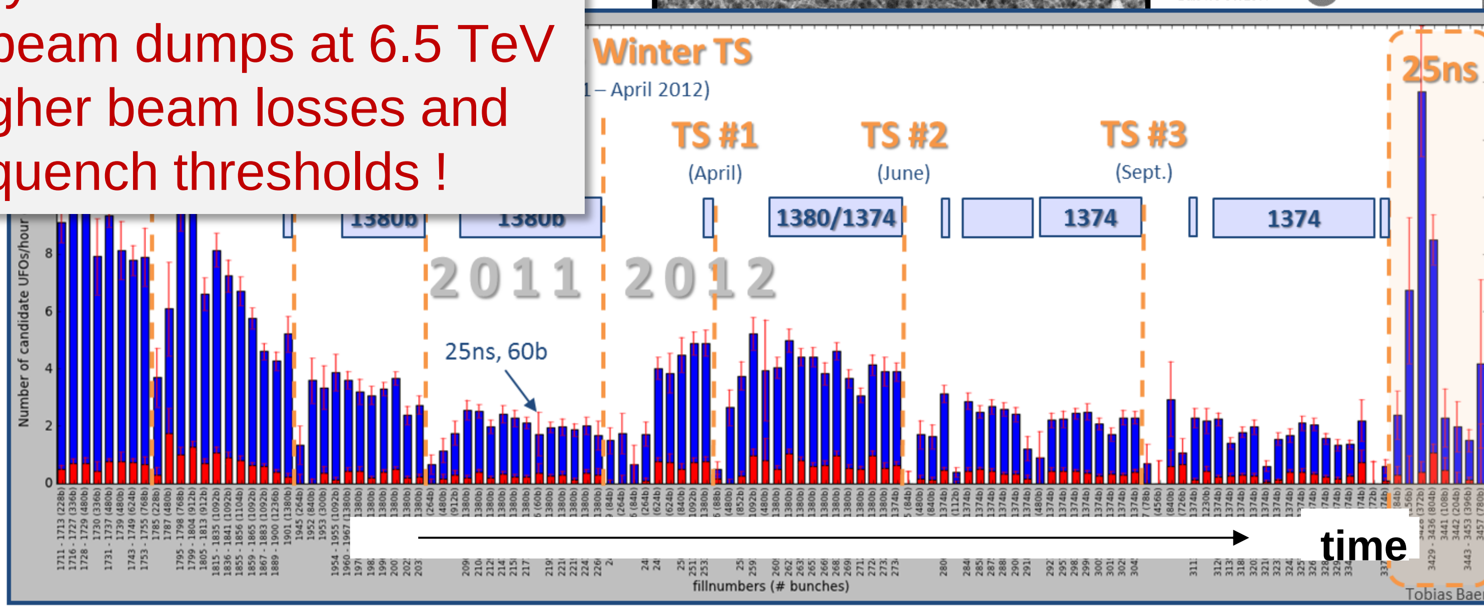
The UFO unknown

- Very fast and localized beam losses were observed during Run 1, traced to **dust particles falling into the beam** – '**UFOs**'.
- If the losses are too high, the beams are dumped to avoid a magnet quench.
  - ~20 beams dumped / year due to UFOs.
  - Conditioning of the UFO-rate with time was observed.

In one accelerator component UFOs were traced to Aluminum oxide particles.



UFOs may become a source of numerous beam dumps at 6.5 TeV due to higher beam losses and lower quench thresholds !



Outline

Introduction

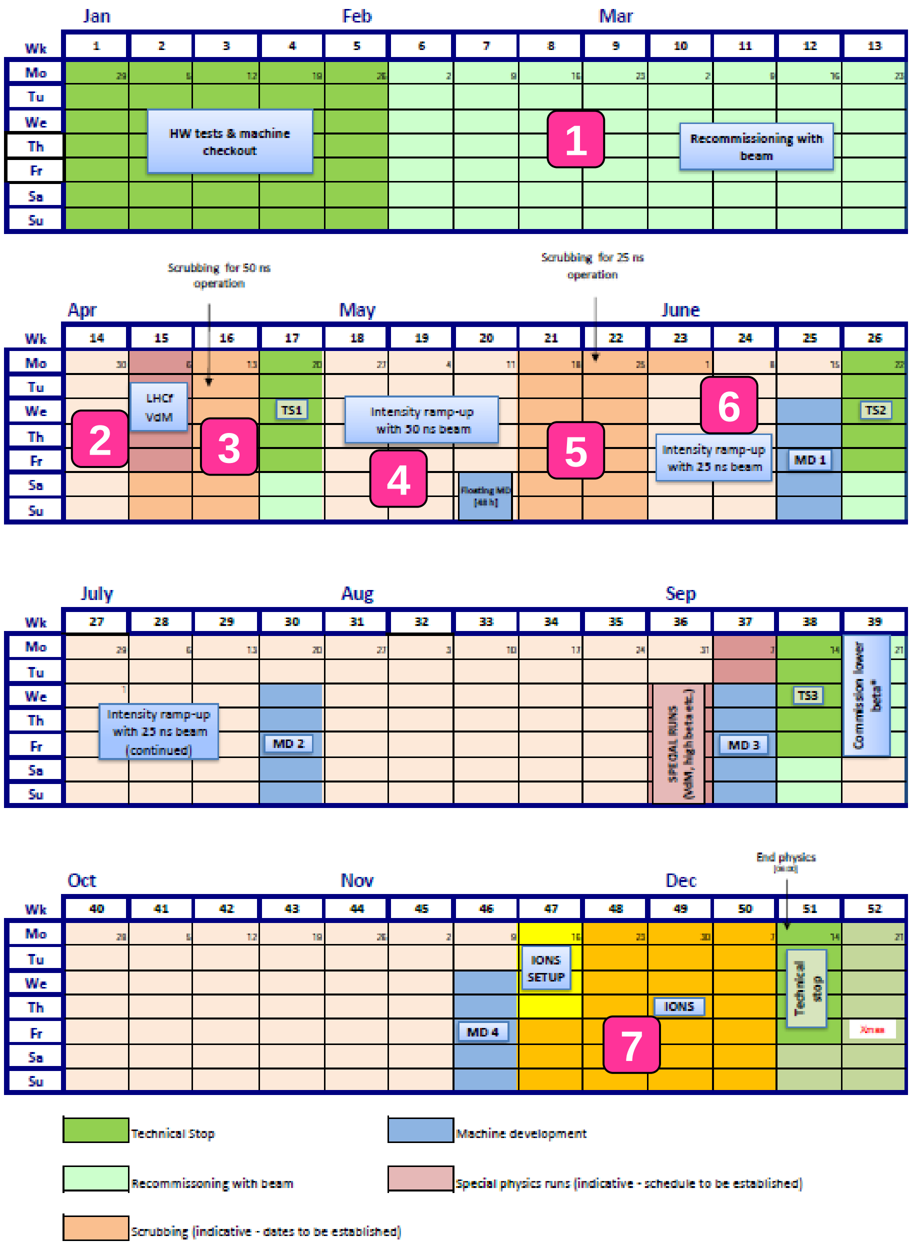
Long Shutdown 1

LHC prospects for Run 2

Beam commissioning 2015

Conclusions

Draft beam schedule 2015

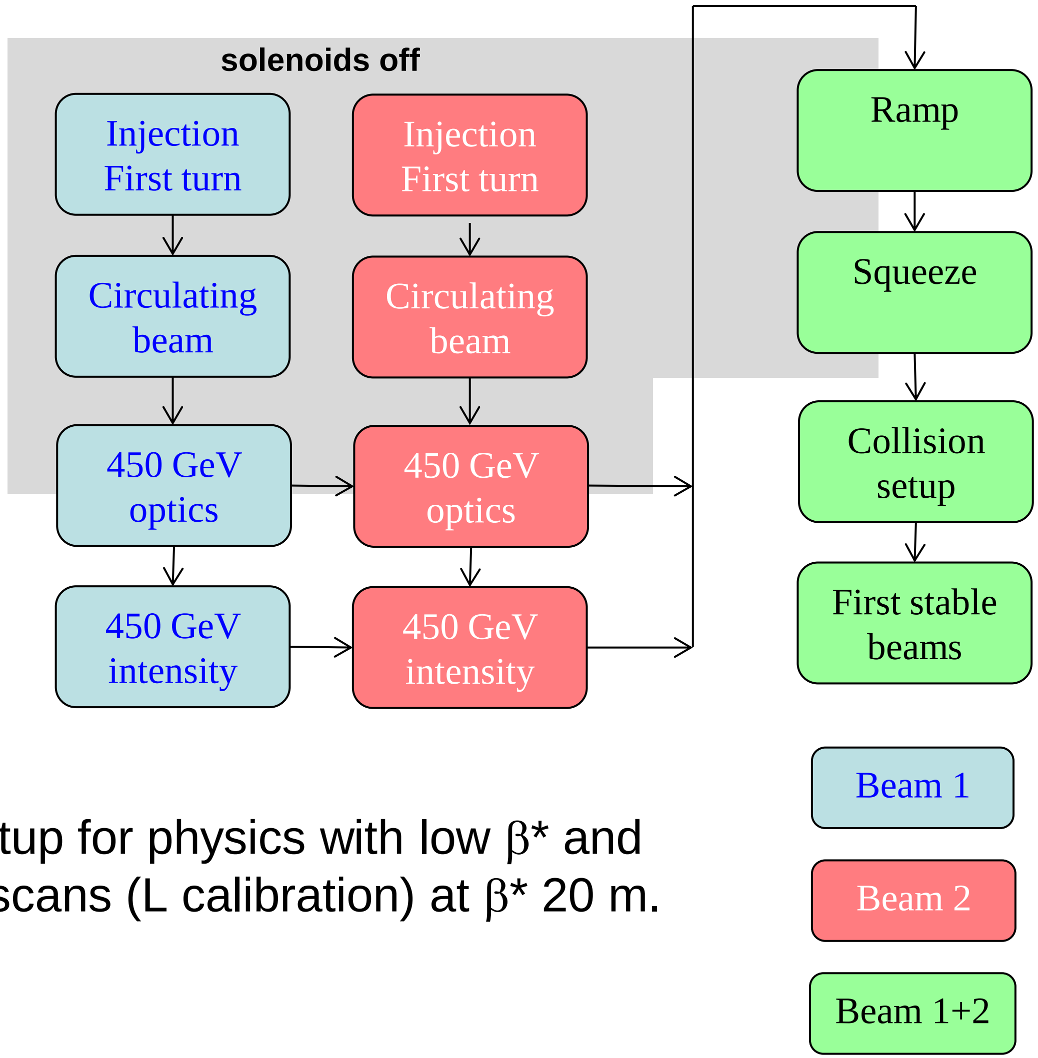


The start date of beam is shifted by 5 weeks with the latest schedule wrt this figure!

- **Main phases:**
  1. **Low intensity commissioning (2 months)**
  2. **First physics with a few isolated bunches, LHCf run**
  3. **First scrubbing run (50 ns)**
  4. **50 ns operation (up to 1380 bunches/beam)**
  5. **25 ns scrubbing run**
  6. **25 ns operation**
  7. **Ion run**

Low intensity commissioning

- The low intensity commissioning phase prepares the machine for the first low intensity collisions ('pilot physics').
  - *All systems have to be re-commissioned, many activities in // to the main stream.*
    - An important activity is the setup and validation of the collimation system.
  - *Estimated time ~45 days (non stop @ 100% efficiency) for 60 scheduled days.*



- In 2015 we have to prepare a setup for physics with low β* and a setup for LHCf / van De Meer scans (L calibration) at β* 20 m.

On the road to 25 ns

First physics with a few isolated bunches

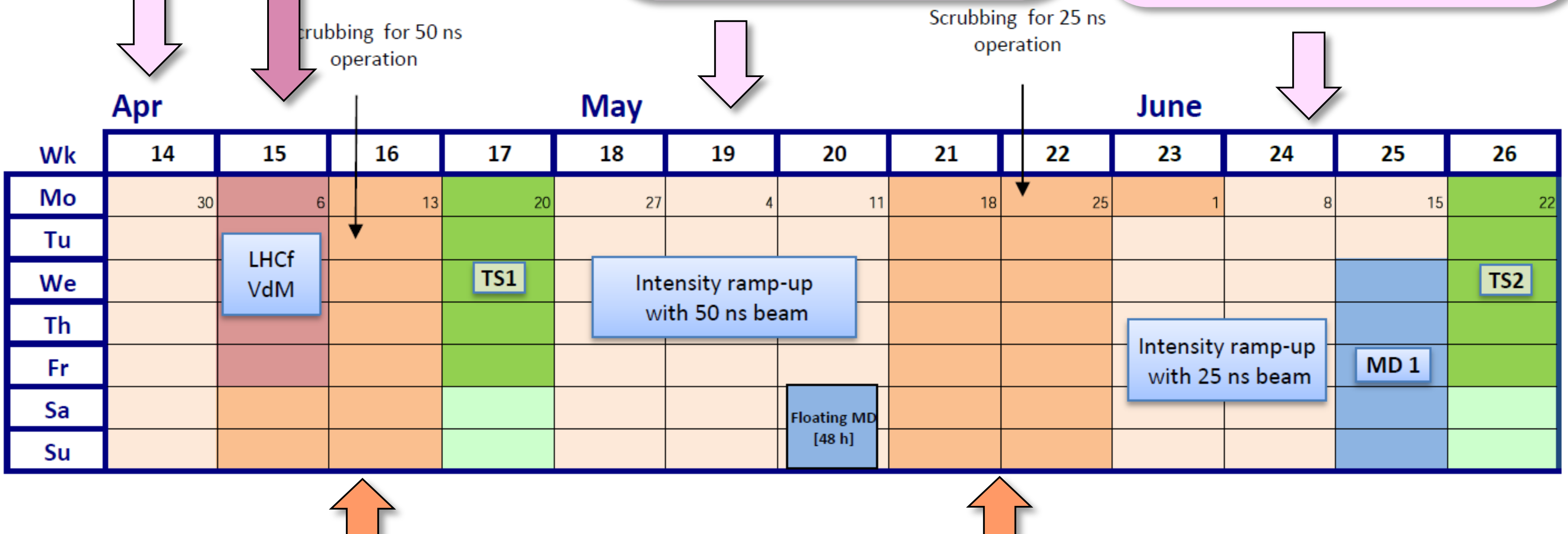
LHCf run, VdM scan luminosity calibration

50 ns operation :

- Gain experience with high intensity beams – no e-cloud,
- Reproduce 2012-like conditions – ramp up to 1380 bunches,
- Not aimed at delivering a lot of **int. luminosity** ($\leq$ **1 fm^{-1}**),
- May need more than 3 weeks.

25 ns operation :

- Ramping up intensity,
- $\approx$ 3 months of effective operation,
- Estimated **int. luminosity** around **8-15 fm^{-1}**.



50 ns scrubbing run

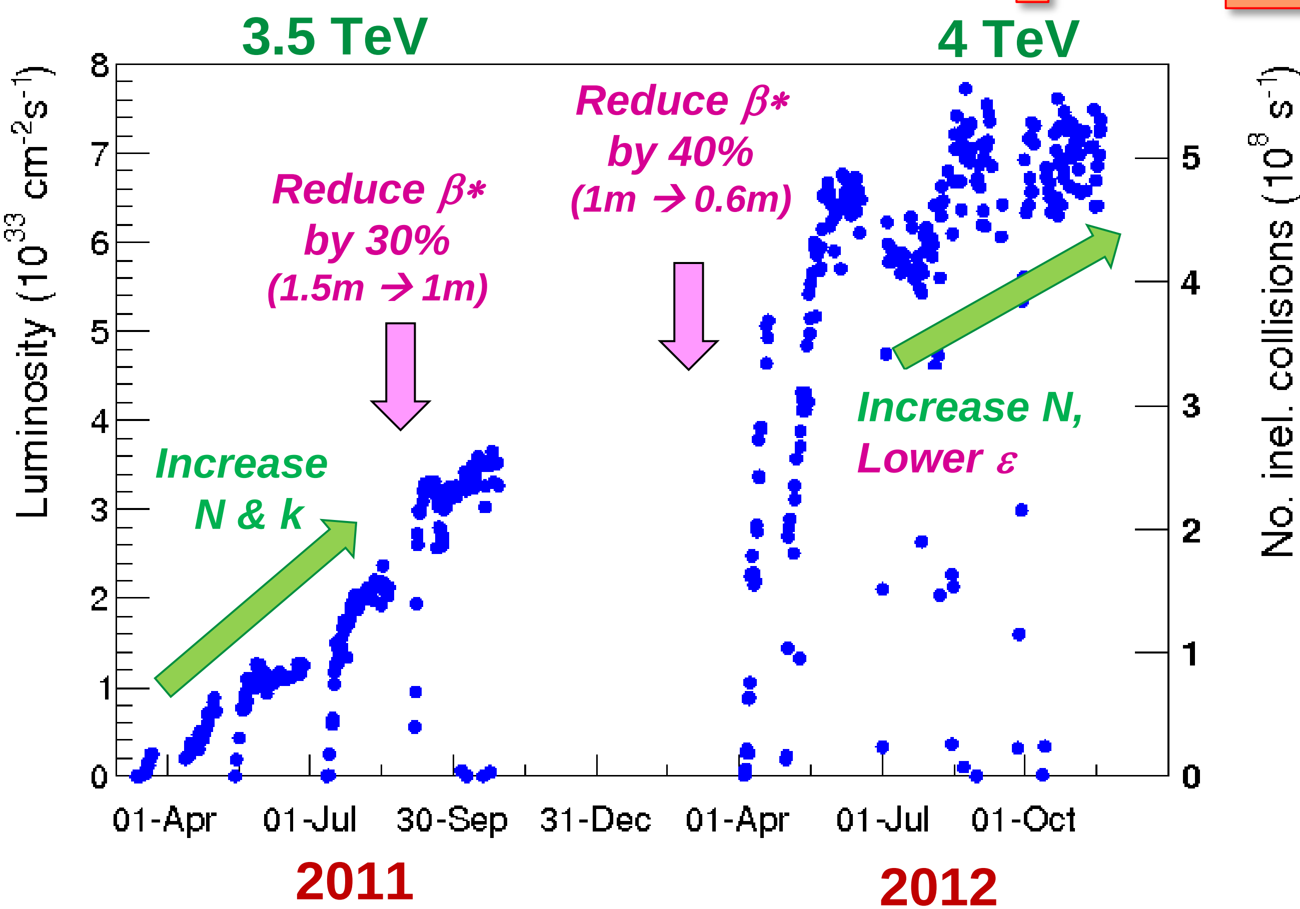
25 ns scrubbing run

High luminosity 2011-2012

The initial intensity ramp up in 2014 with 50 ns should be similar to the initial ramp up in Apr-Jul 2011 (duration?).

Followed by a second ramp up with 25 ns.

Limited by beam stability



Outlook

- The long shutdown is finally nearing completion.
- We are in front of a long commissioning period for the magnets, for the other machine components and finally for the beam.
- With the experience of Run 1 the commissioning and start-up planning is well established.
- Where we may find the main surprises and challenges:
  - Magnet performance and stability at 6.5 TeV,
  - E-clouds with 25 ns !
  - UFOs

Thank you for your attention!

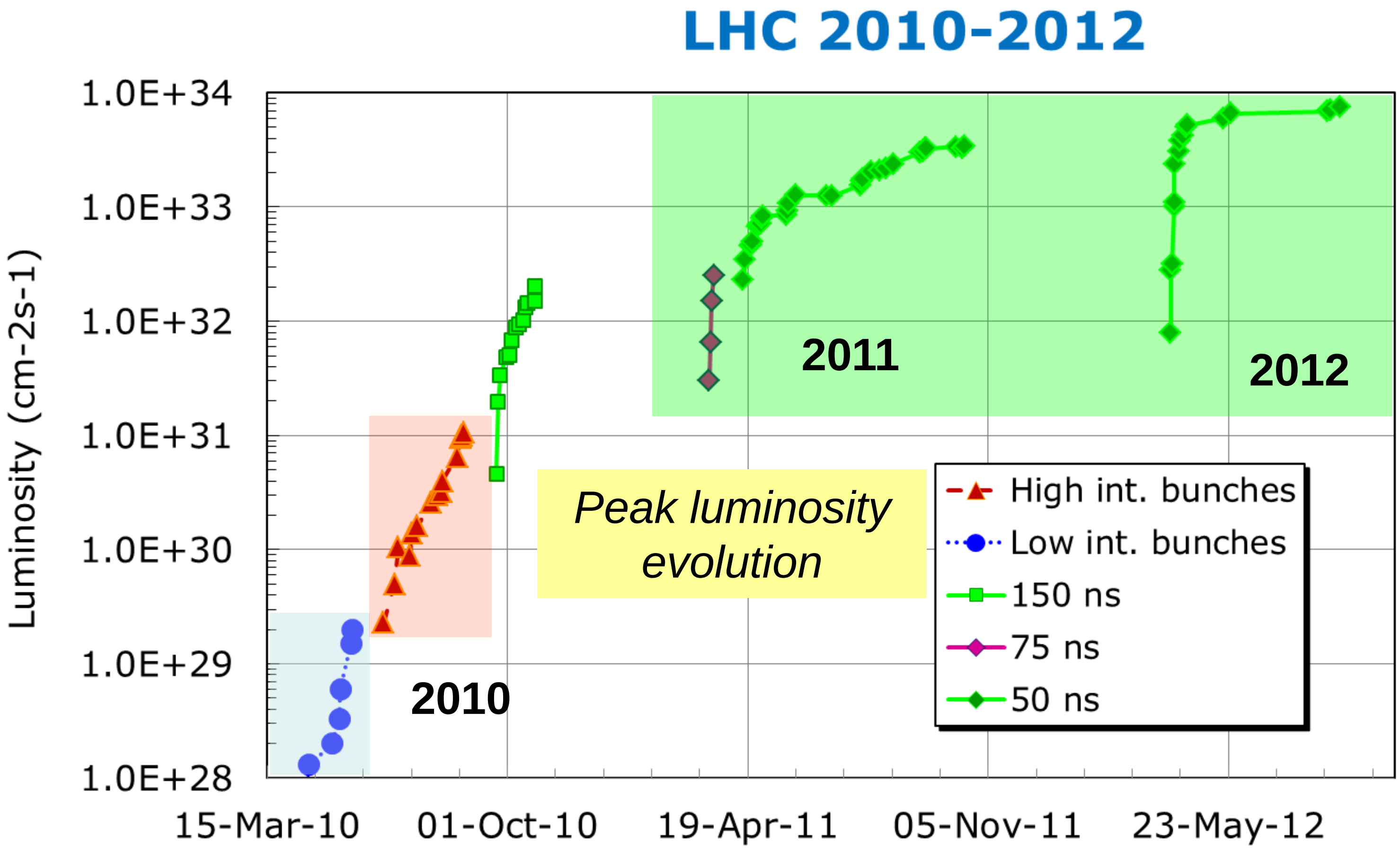
… and be ready for the next events !

LHC progress 2010-2012

Low bunch intensity operation, first operational exp. with LHC

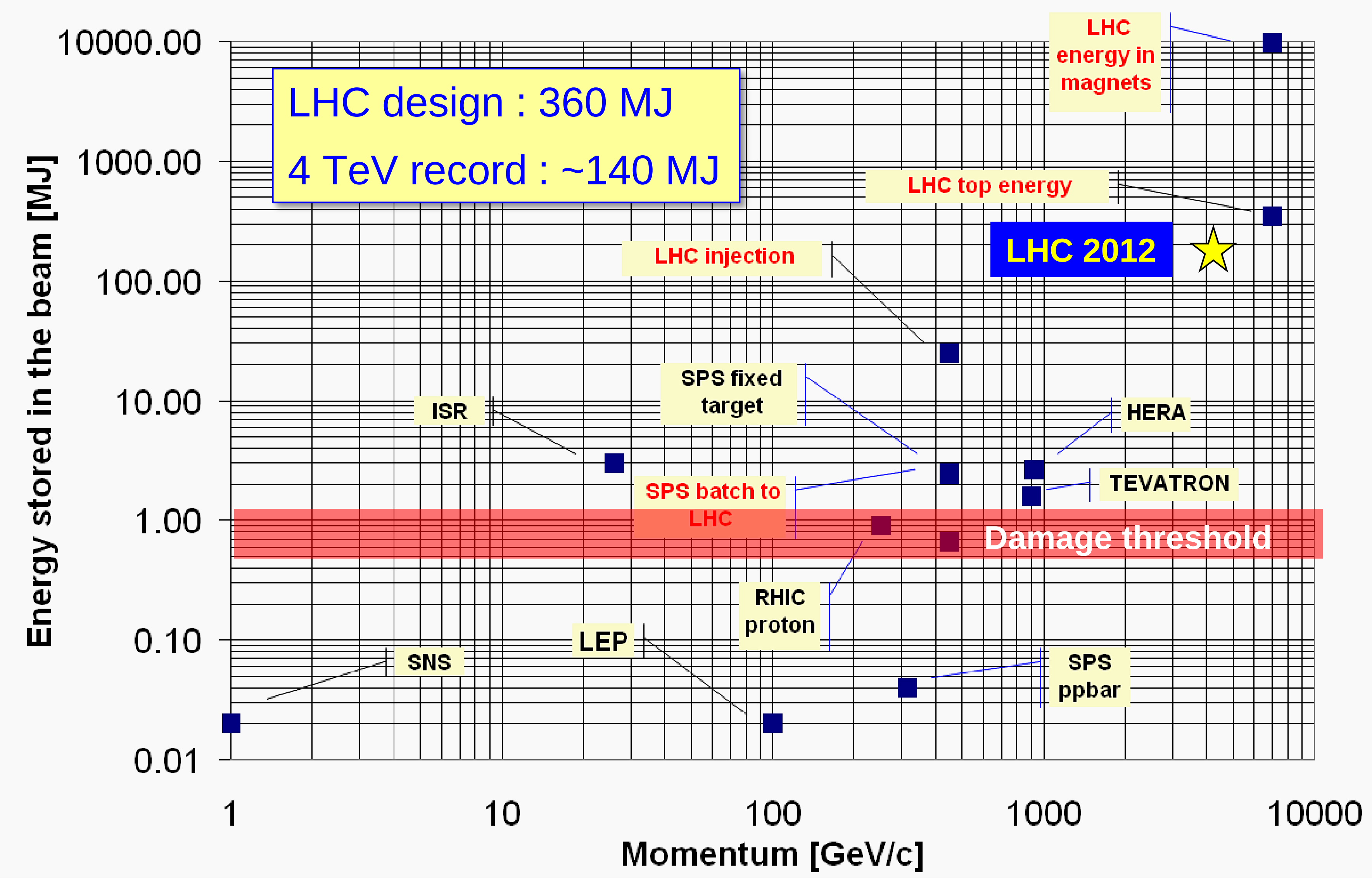
~1 MJ stored energy, learning to handle 'intense' beams

Reach out for records & Higgs !



Stored energy challenge

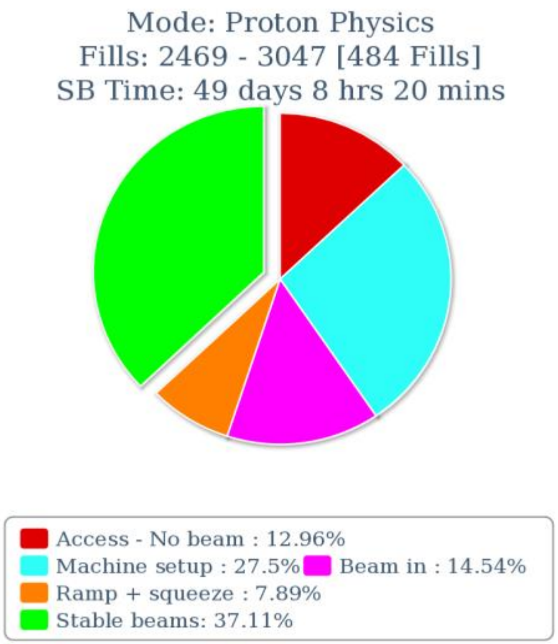
Superb performance of the machine protection system

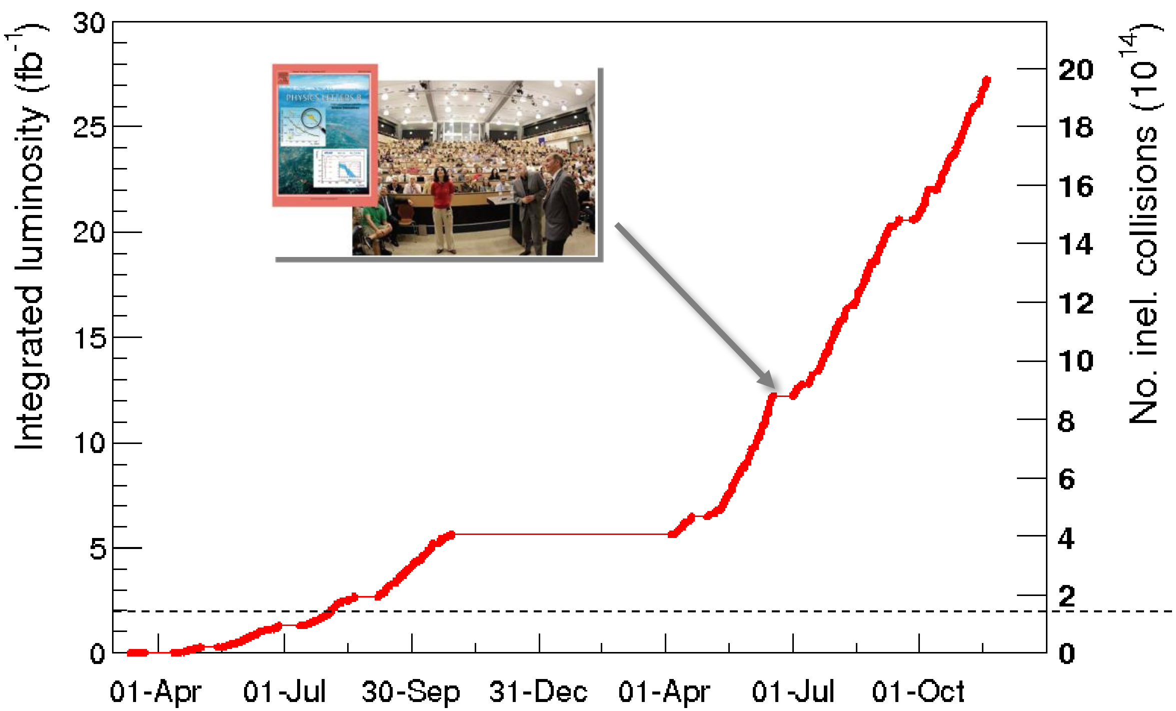


Luminosity production 2011-2012

The integrated luminosity of both ATLAS/CMS reaches now **~28 fb^{-1}**.

- *We spend 37% of the scheduled time delivering collisions to the experiments ('stable beams').*

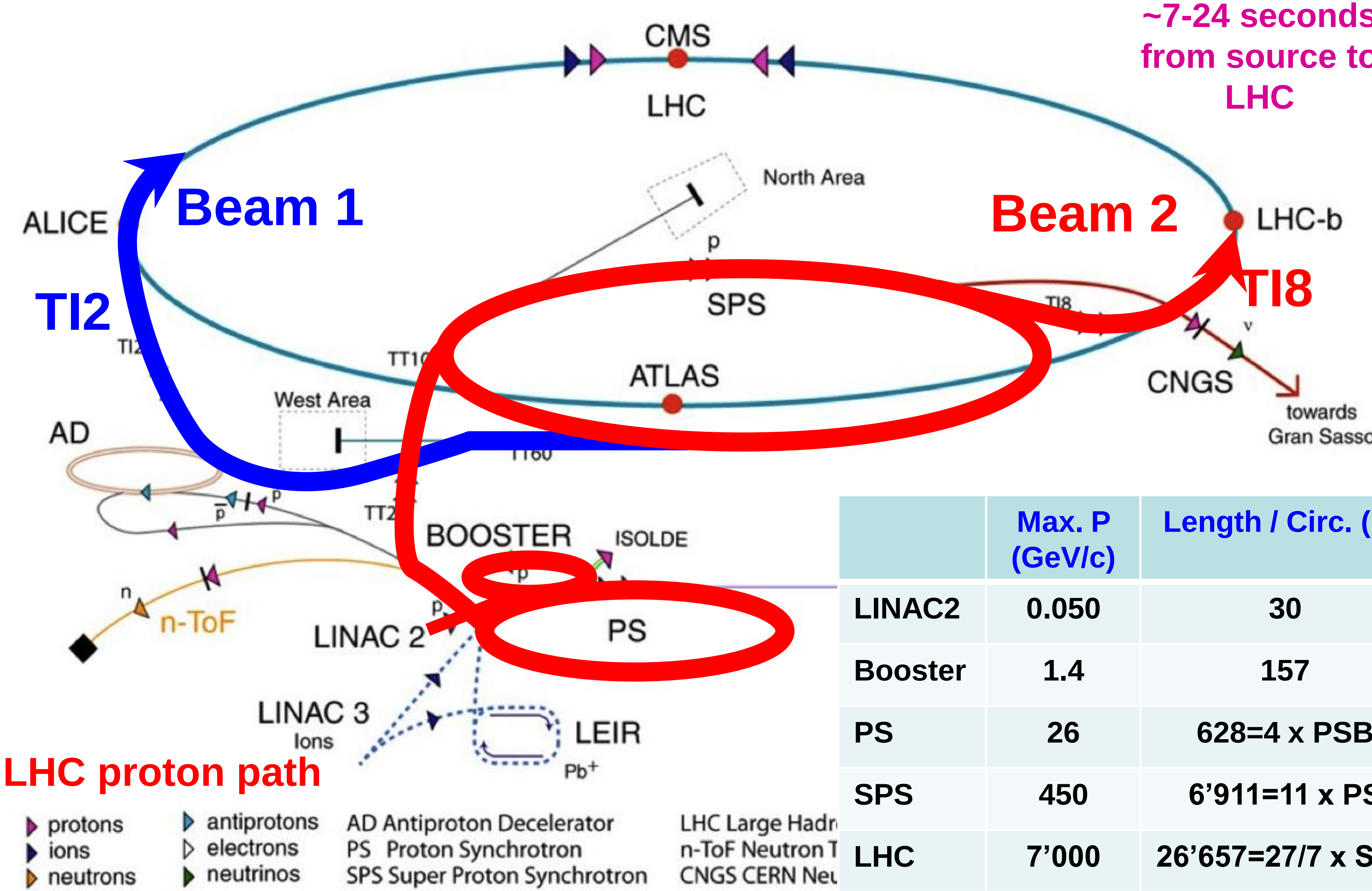




Initial target around 2009/2010

LHC accelerator complex

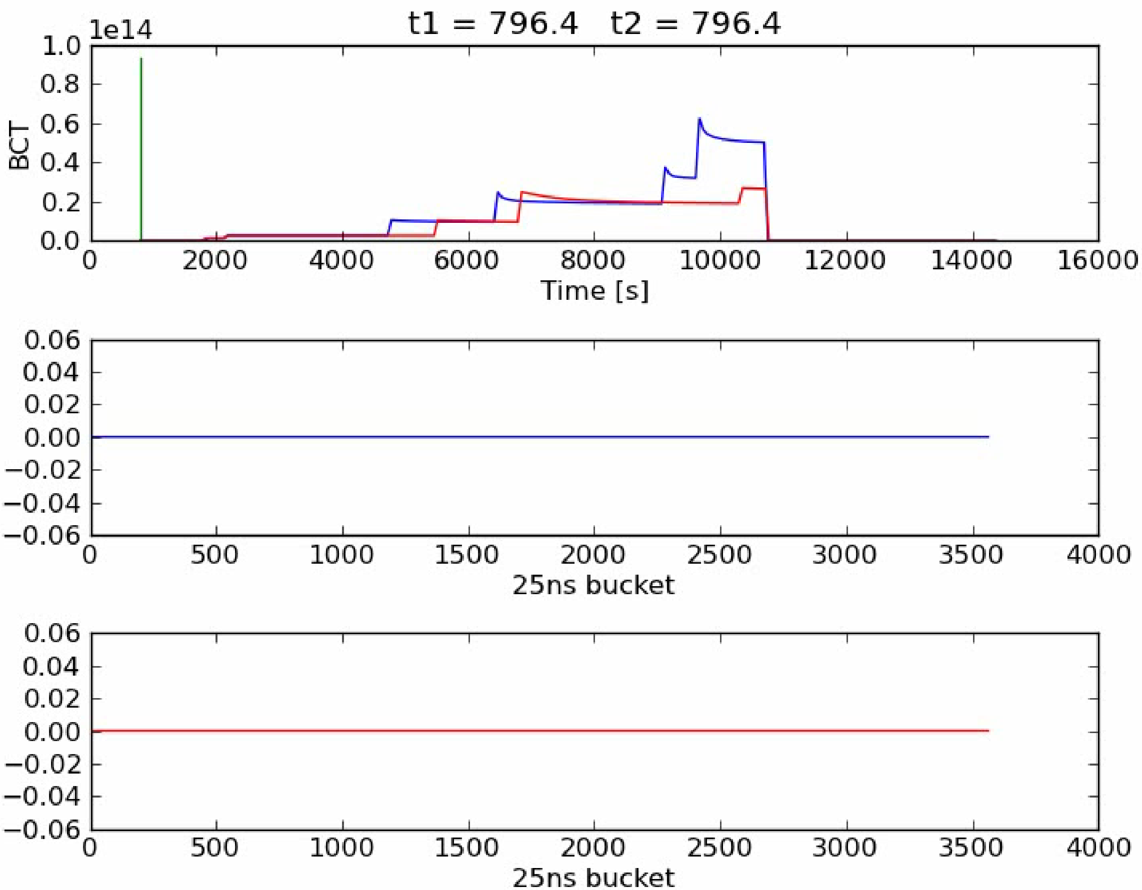
~7-24 seconds from source to LHC



	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

Electron cloud effects

2012 25 ns beam injection tests (10 July 2012)



Beam 1 —— Beam 2 ——

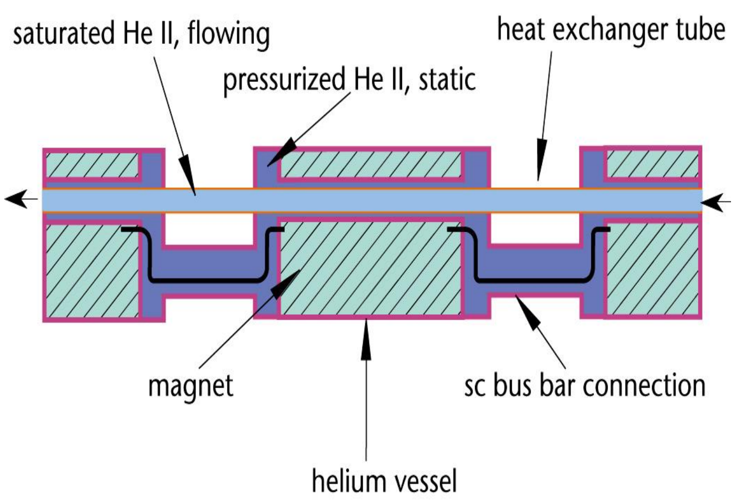
Bunch-by-bunch population Beam 1

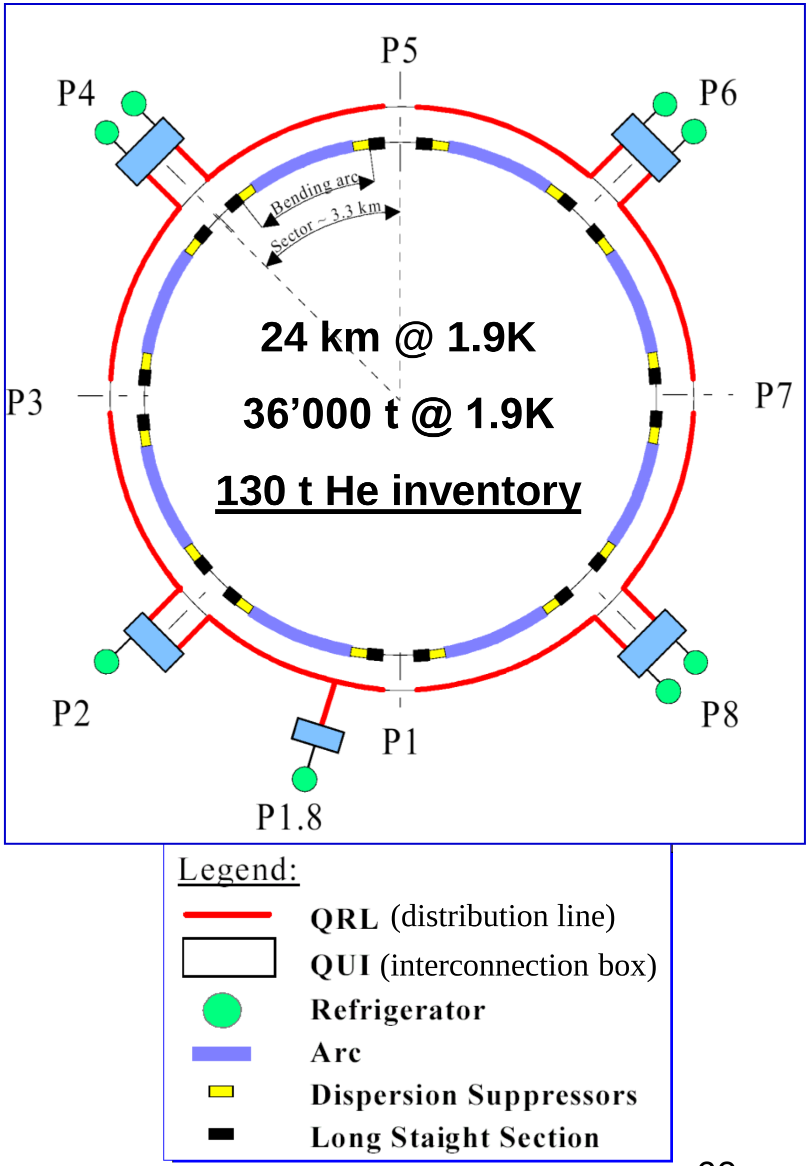
Bunch-by-bunch population Beam 2

G.Rumolo

Cryogenics challenge

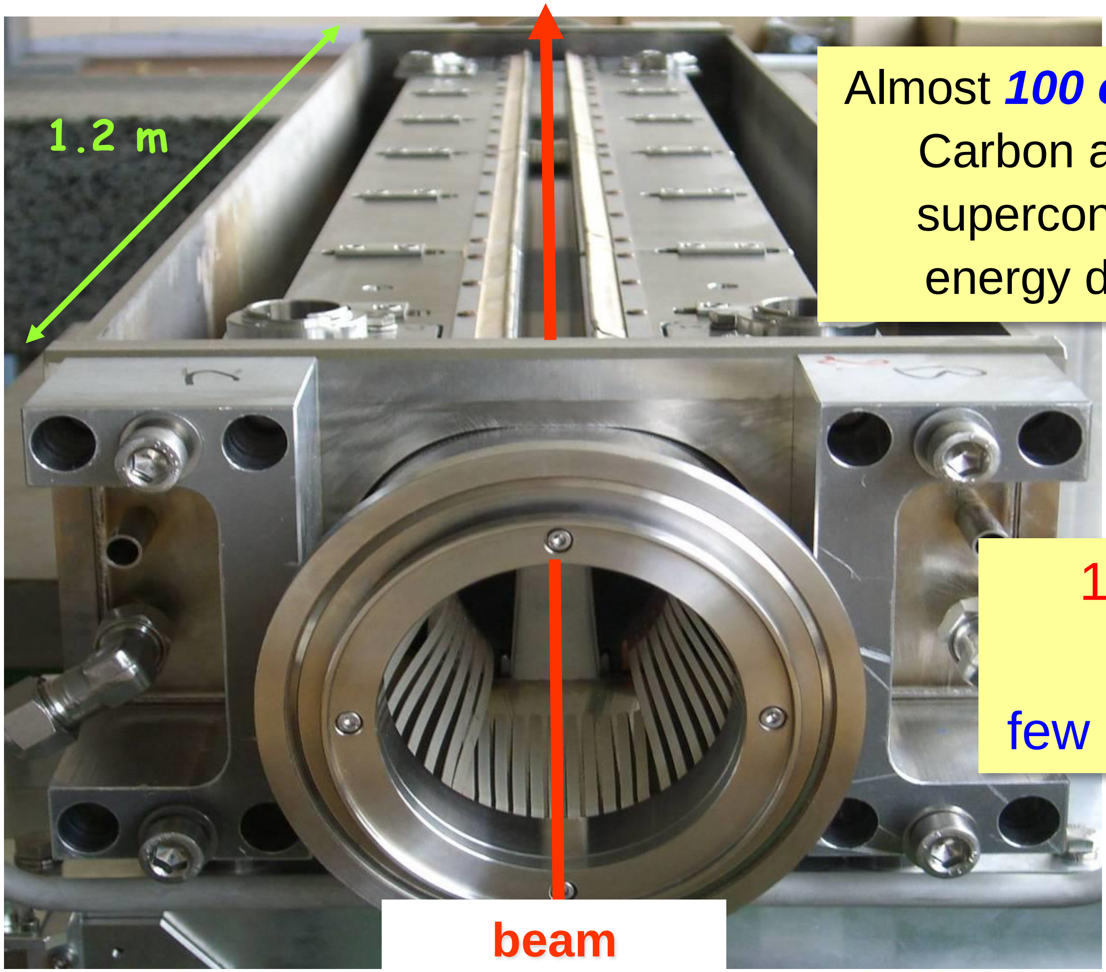
- A HUGE system !!
- Most of the LHC magnets are cooled with superfluid He at 1.9K.
  - *Very low viscosity.*
  - *Very high thermal conductivity.*
- In 2012 the availability of the cryogenics reached ~95%!
  - Availability ~97% if external failures are excluded !!





Beam collimation challenge

- The LHC requires a complex multi-stage collimation system to operate at high intensity.
  - *Previous hadron machines used collimators only for experimental background conditions.*

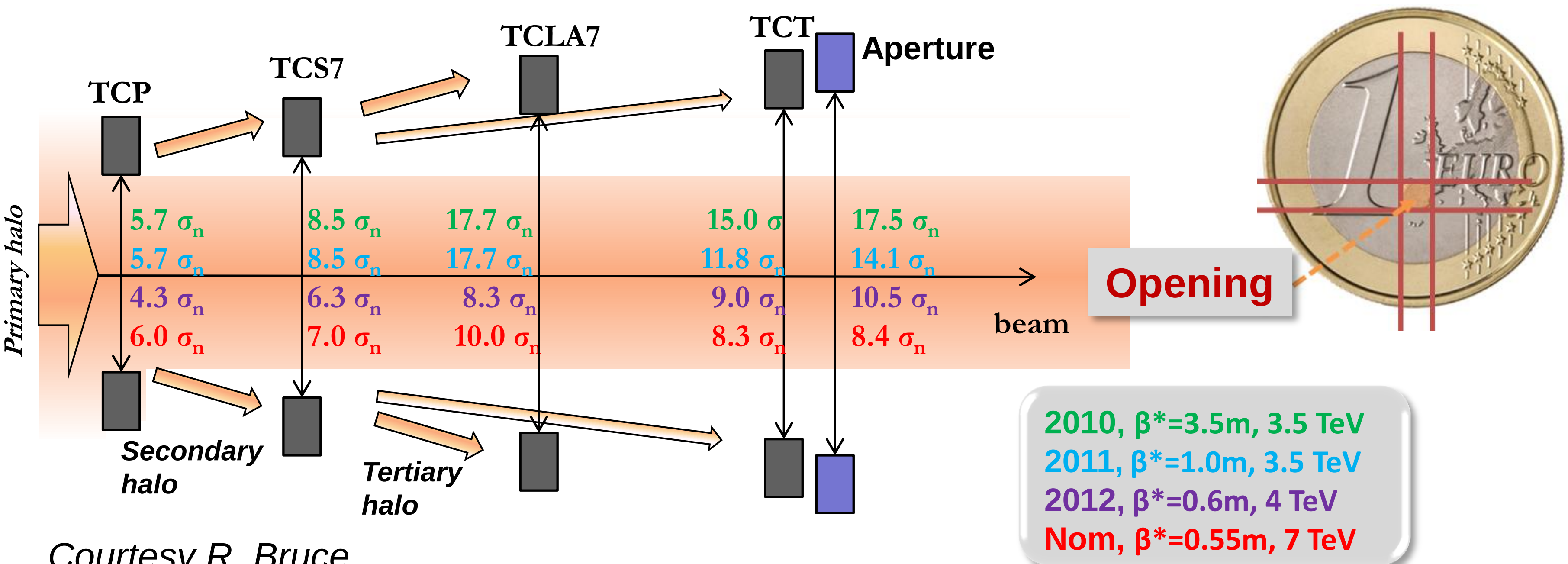


Almost ***100 collimators***, mostly made of Carbon and Tungsten, protect the superconducting magnets against energy deposition from the beam

140 MJ in each beam
versus
few mJ to quench a magnet

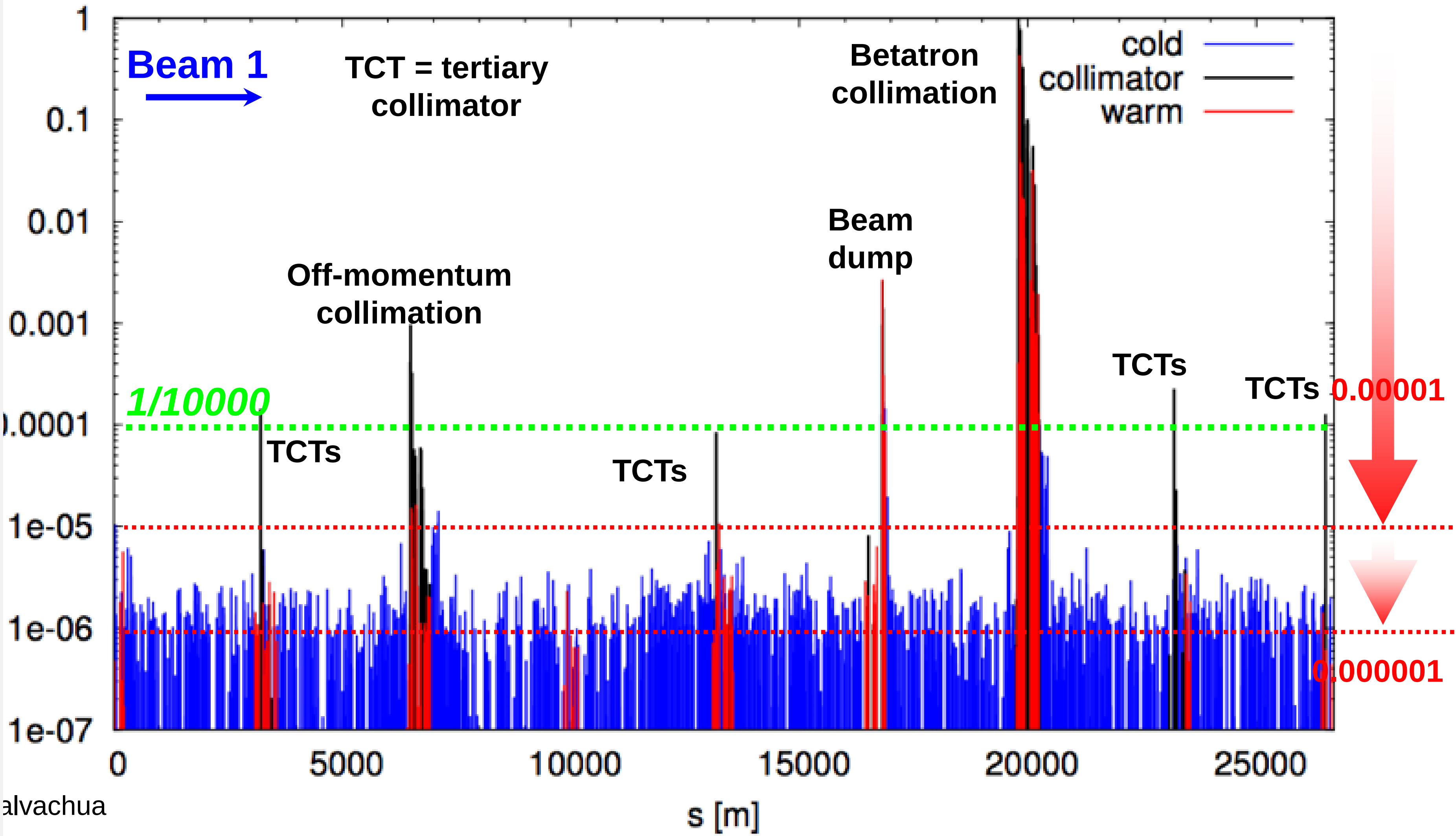
Beam collimation challenge

- To be able to absorb the energy of the protons, the collimators are staged – primary, secondary, tertiary – multi-stage system.
- The system worked perfectly – also thanks to excellent beam stabilization and machine reproducibility – only one setup / year.
  - ~99.99% of the protons that were lost from the beam were intercepted.
  - ***No magnet was quenched in operation at 3.5/4 TeV.***



Courtesy R. Bruce

Collimation cleaning at 4 TeV

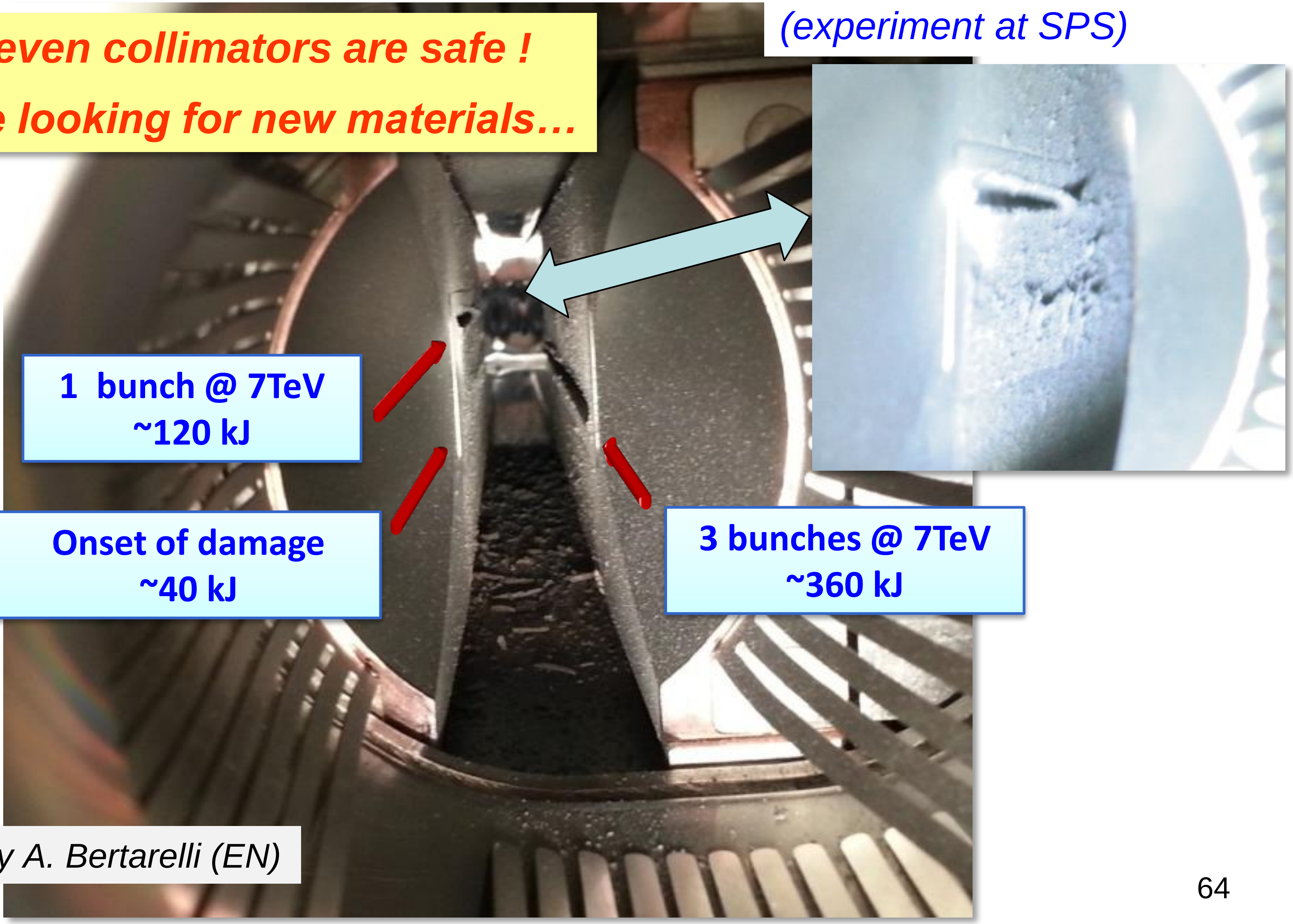


alvachua

Not without risk !

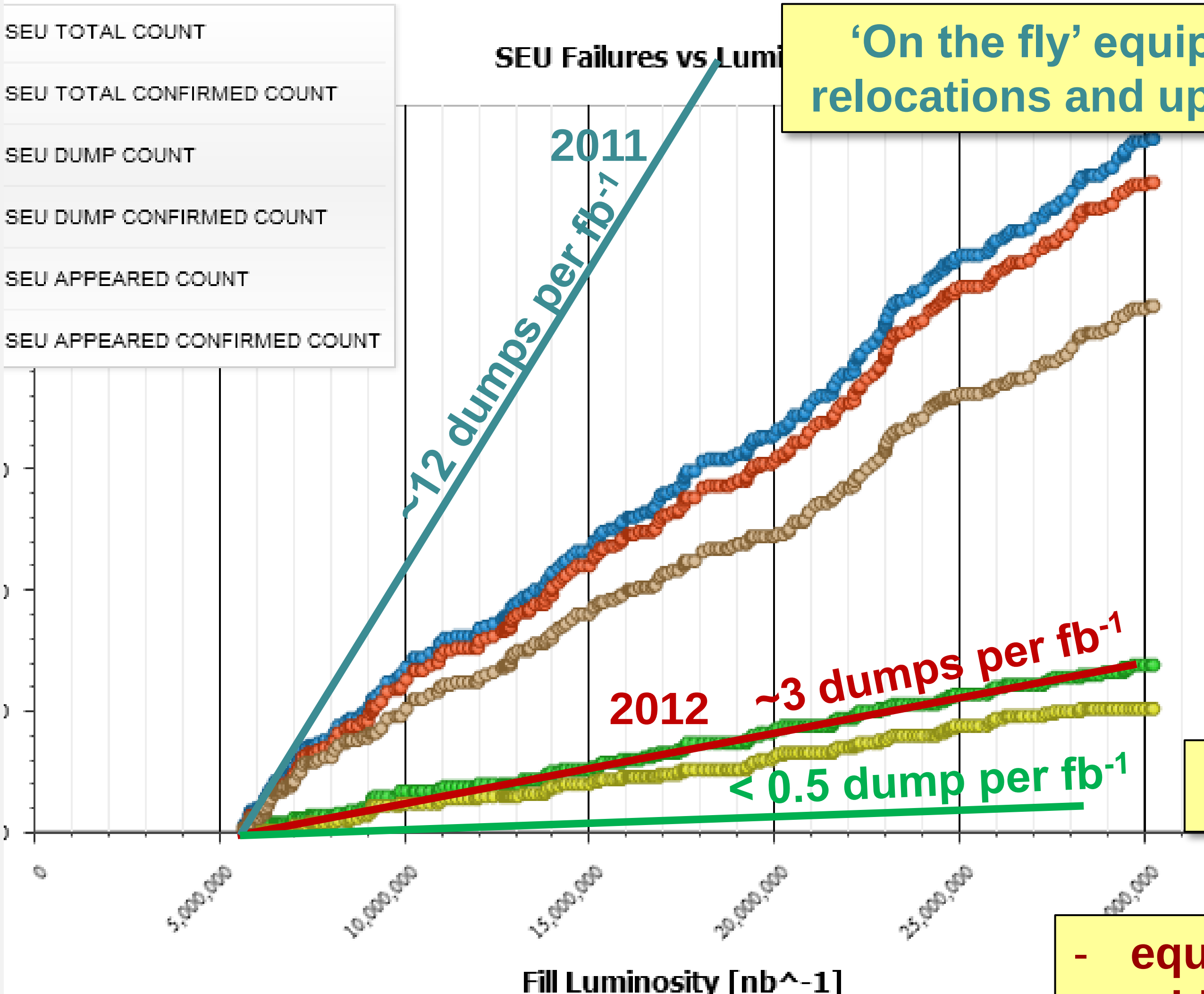
Effect of direct beam impact on a Tungsten collimator

(experiment at SPS)



Courtesy A. Bertarelli (EN)

Radiation to Electronics (R2E)



'On the fly' equipment relocations and upgrades

2011-2012:
- **more relocation.**
- **additional shielding,**
- **equipment upgrades**

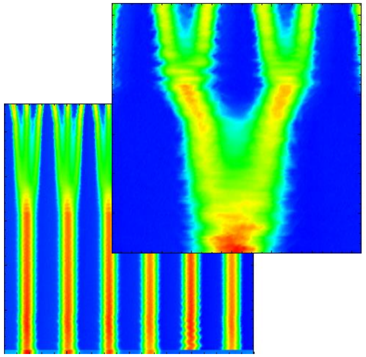
Aim for >LS1

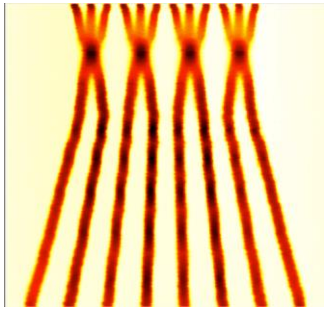
- **equipment relocation,**
- **additional shielding,**
- **critical system upgrades.**

Courtesy G. Spezia

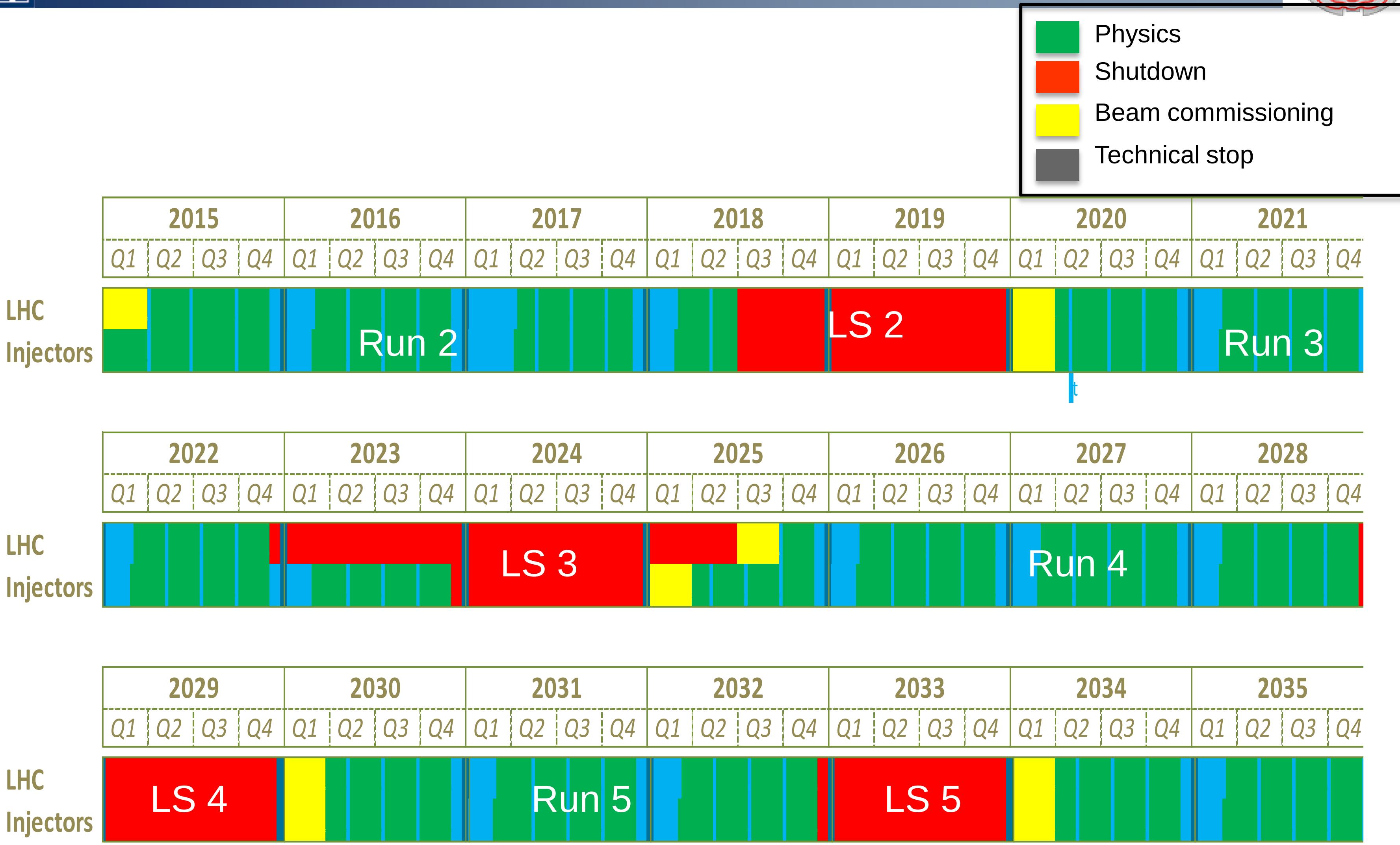
beam production schemes

	25 ns standard	25 ns BCMS
(PS injections) and splittings	(4+2) x3 x2 x2	(4+4) /2 x3 x2 x2
bunches per PS batch	72	48
max number of injections into SPS	4	6 / 5
bunch population [10^{11} p/b]	1.3	1.3
ε^*[μm] at LHC injection	2.4	1.3
number of bunches/ring	2748	2604 / 2508
colliding pairs IP1/5	2736	2592 / 2496





Beyond Run2



(Extended) Year End Technical Stop: (E)YETS

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators (December 2013)