Un boson nommé Higgs
LHC : Le chemin
vers la haute performance
Colloque de clôture - G. Veneziano
Collège de France
Jörg Wenninger
CERN Beams Department
Operation group
24.05.2013
Acknowledgments to my OP group colleagues for slides and plots
1

Outline

Introduction

LHC magnets and early commissioning

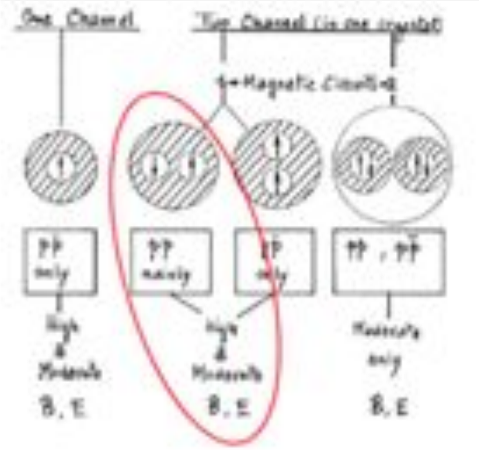
LHC performance 2010-2012

Mastering the challenges

Towards top energy

Upgrades

1984
ECFA-CERN workshop



June 1994
first full scale prototype dipole

1994 project approved by council (1-in-2)

SSC cancelled

June 2007 First sector cold

November 2009
Start of Run 1

April 2008
Last dipole down

50% delivered

1984 | 9 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10

LEP: full scale LHC prototype

First set of twin 1 m prototypes
Over 9 T

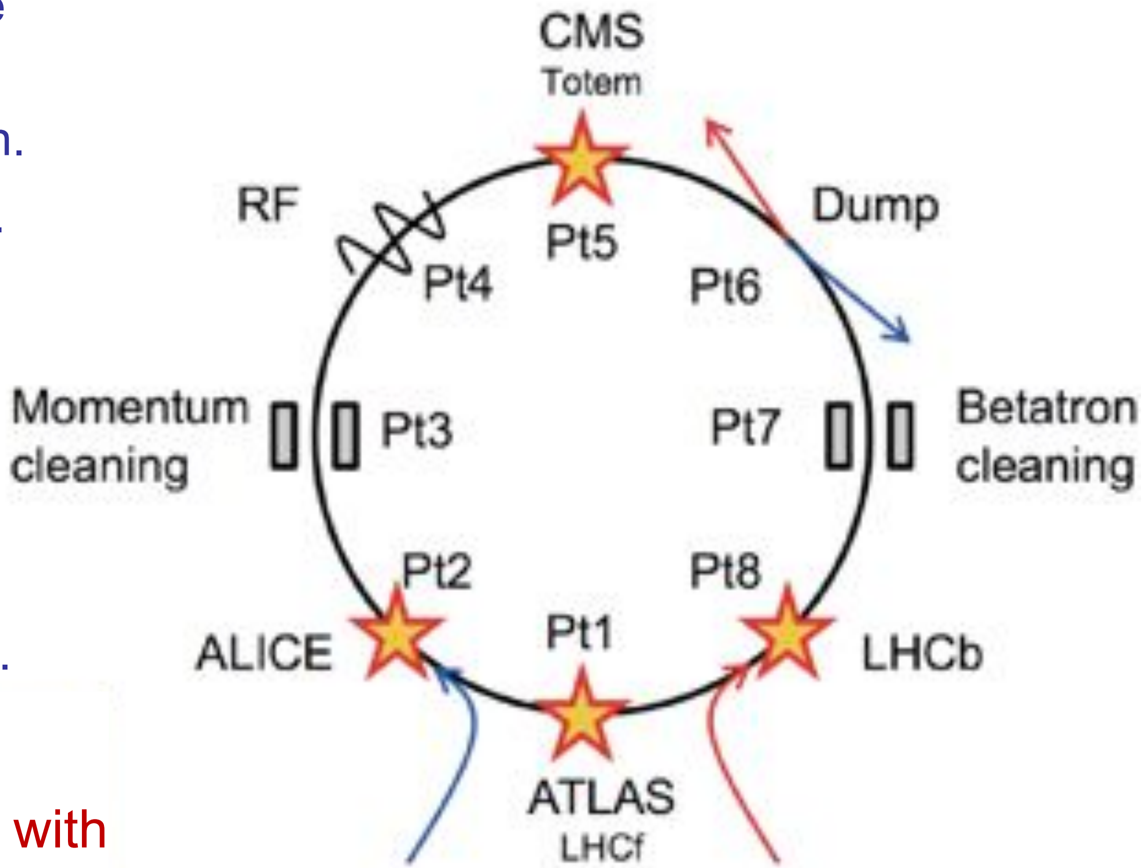
2002 String 2

November 2006
1232 delivered

September 2008

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}).

The Large Hadron Collider LHC

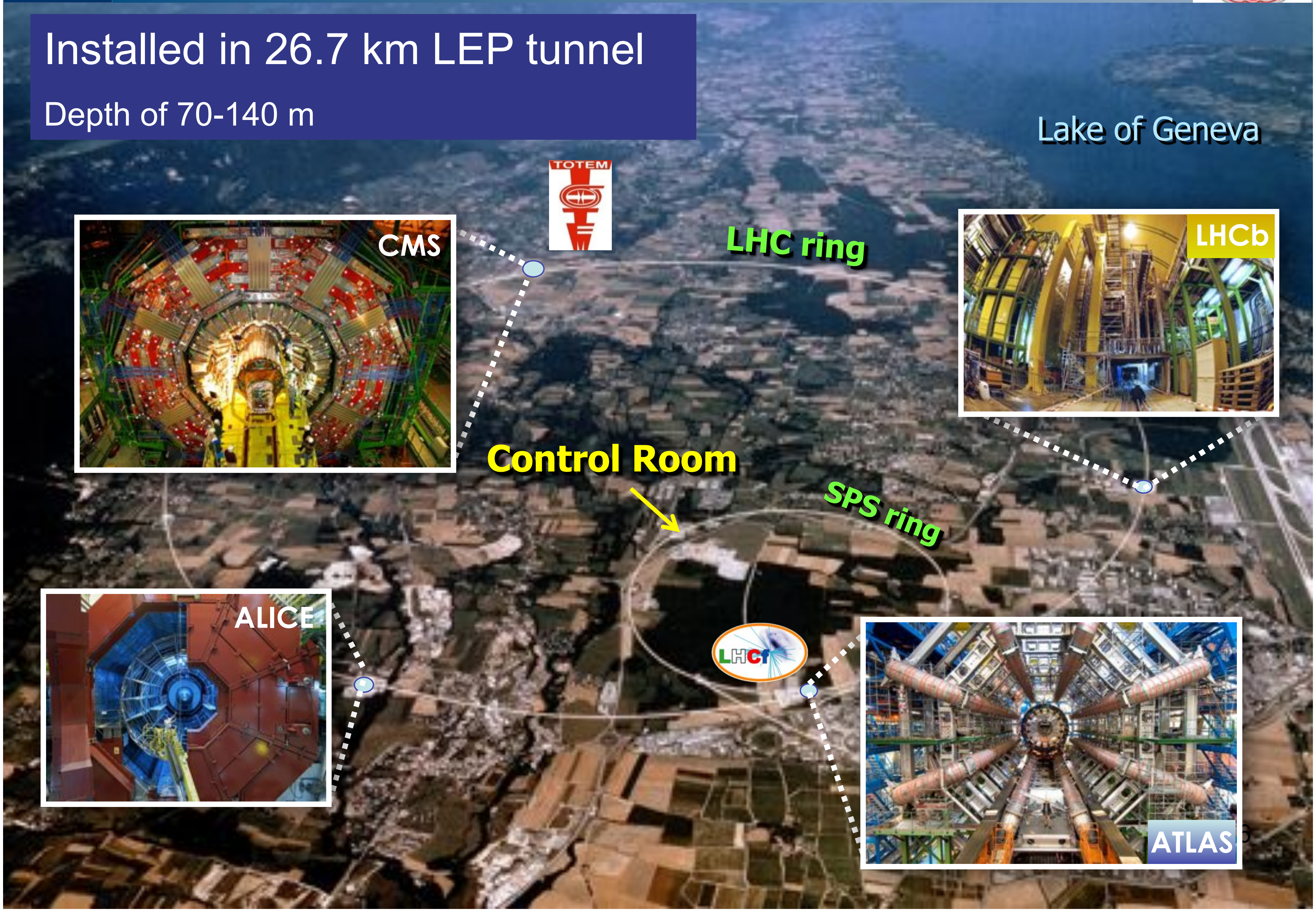
Installed in 26.7 km LEP tunnel

Depth of 70-140 m

The Large Hadron Collider LHC

Installed in 26.7 km LEP tunnel

Depth of 70-140 m



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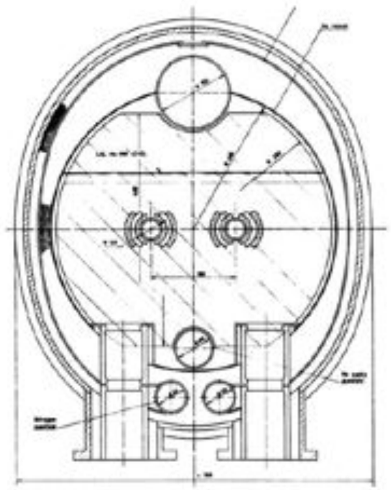
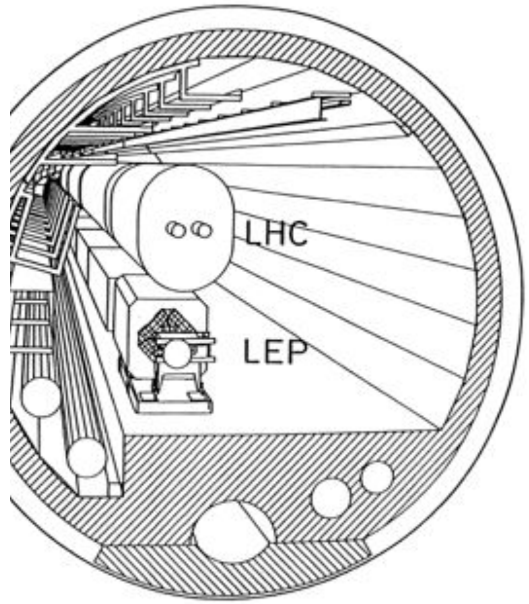
‘Bold beginning’

Challenges & choices:

- High magnetic fields – 8T,
  - ⇒ *super-conducting magnets*
- 2 in 1 design,
- Superfluid Helium,
- Luminosity ~1×10^{33} $cm^{-2}s^{-1}$
  - ⇔ *limit to 4 events / bunch crossing !*



1984



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA-CERN WORKSHOP

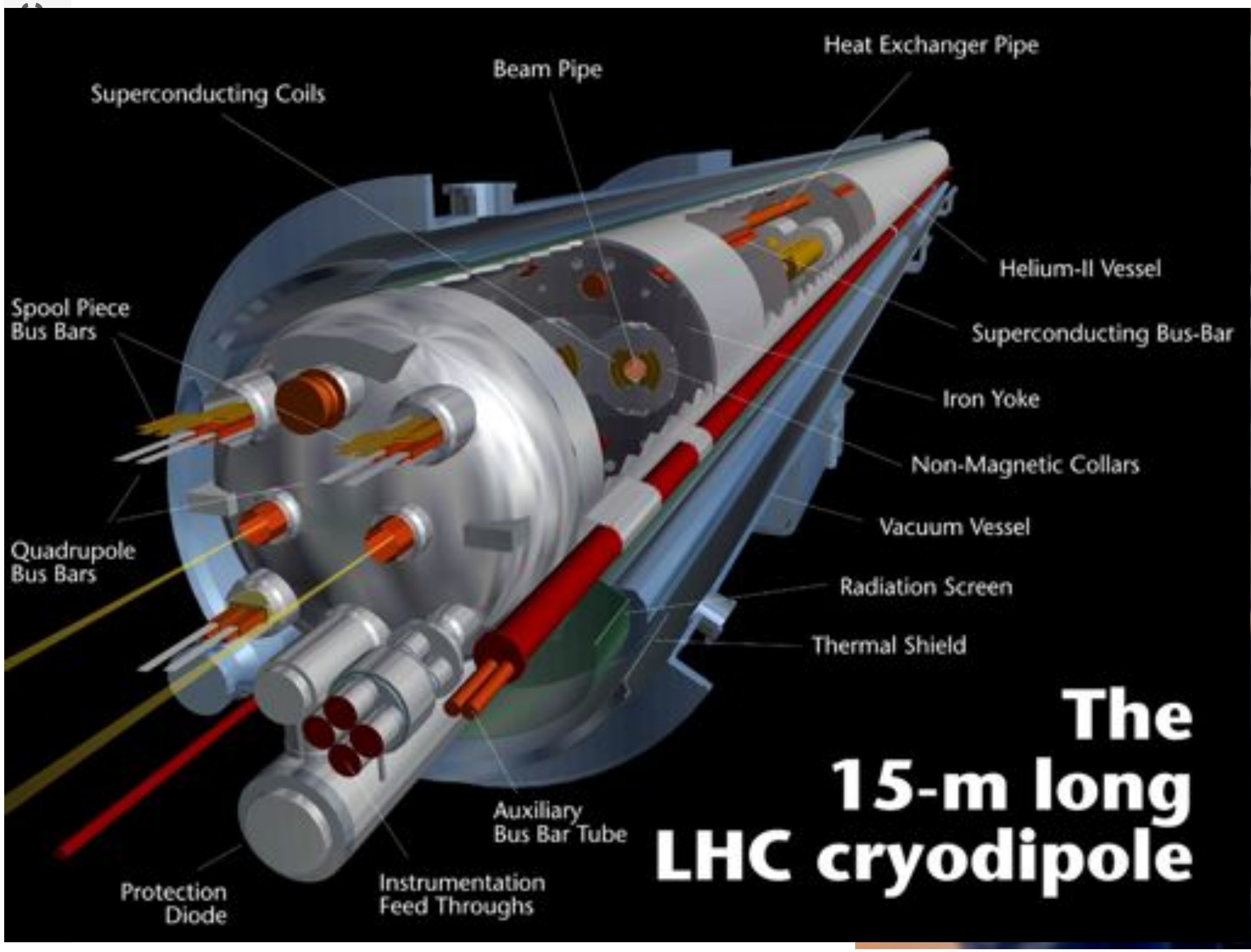
held at Lausanne and Geneva,
21-27 March 1984

Parameters remained rather stable over time, except for luminosity:

- Pushed to ~1×10^{34} $cm^{-2}s^{-1}$ to compete with SSC.

Beautiful technology

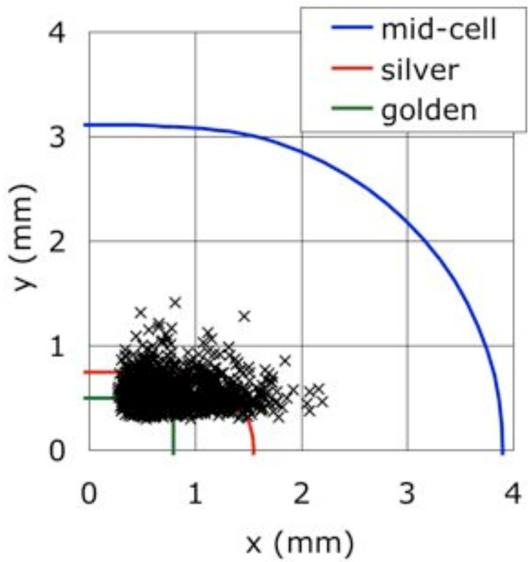
- 1232 NbTi superconducting dipole magnets – each 15 m long
- Magnetic field of 8.3 T (current of 11.8 kA) @ 1.9 K (super-fluid Helium).
  - *But they do not like beam loss – quench with few mJ/cm³.*

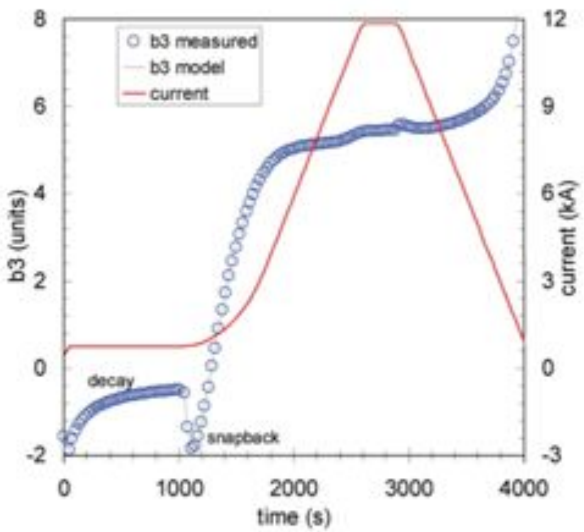


Building them is not enough !

- Field quality tracking and adjustment.
  - *Field quality vitally important for beam stability.*
- Magnet sorting.
  - *Not all magnets are created equal !*
  - *Optimize aperture and field quality: install good magnets where it is critical and less good magnets where it doesn't matter so much.*
- Magnet modeling.
  - *Characterize the important dynamic effects in anticipation of corrections.*

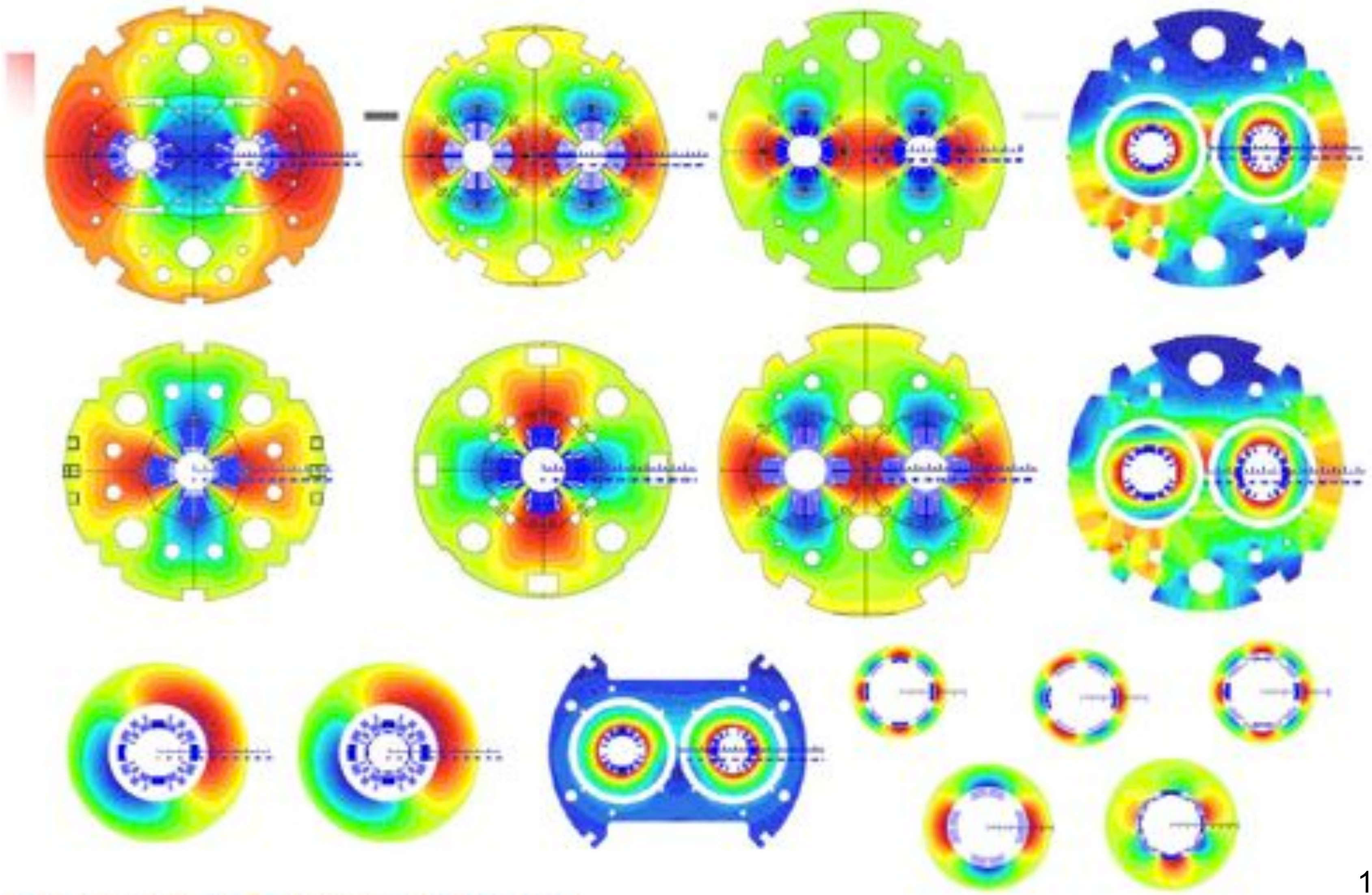
Geometry of dipoles





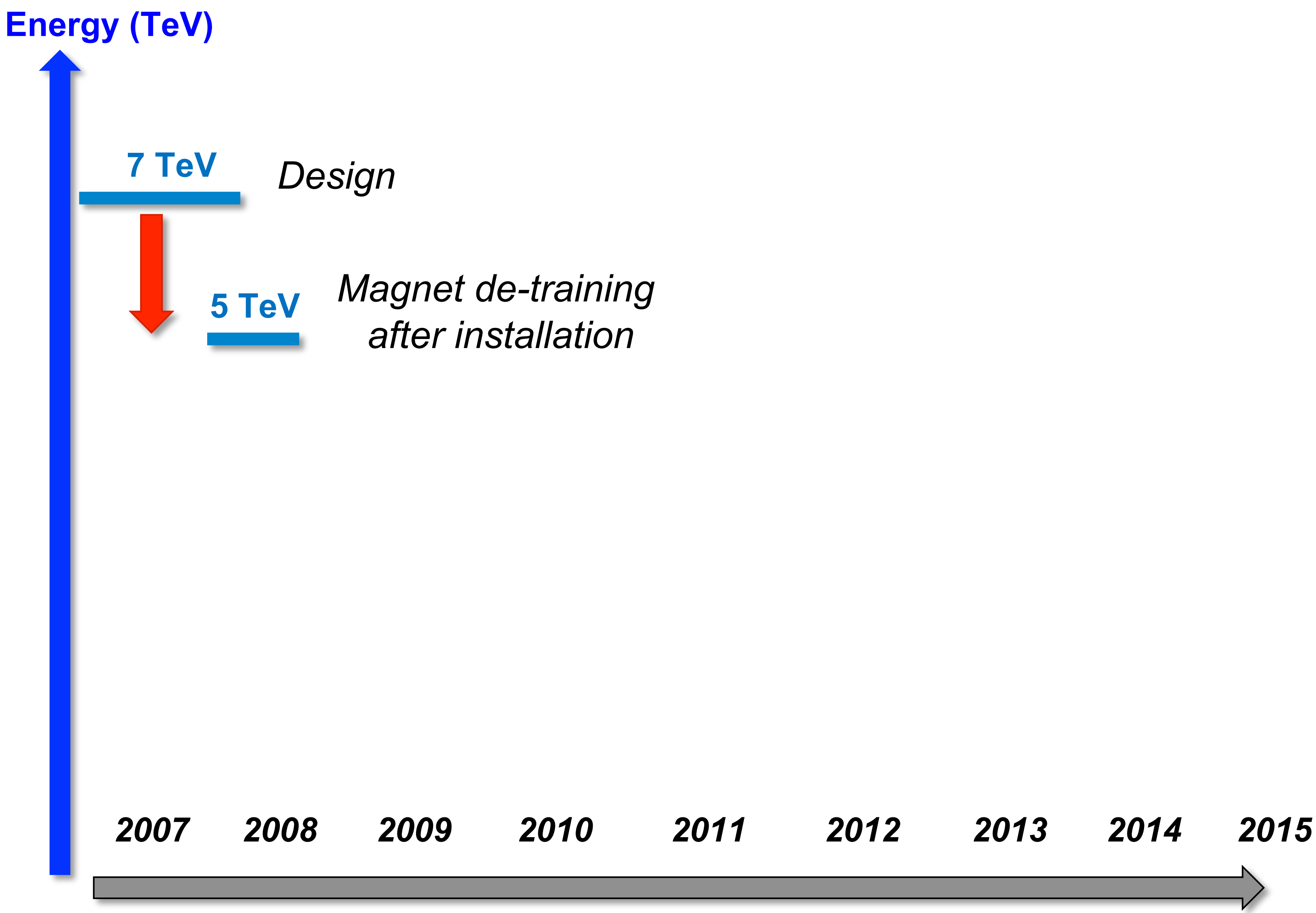
The superconducting magnet zoo

~ 8000 SC magnets – LHC is not just dipoles



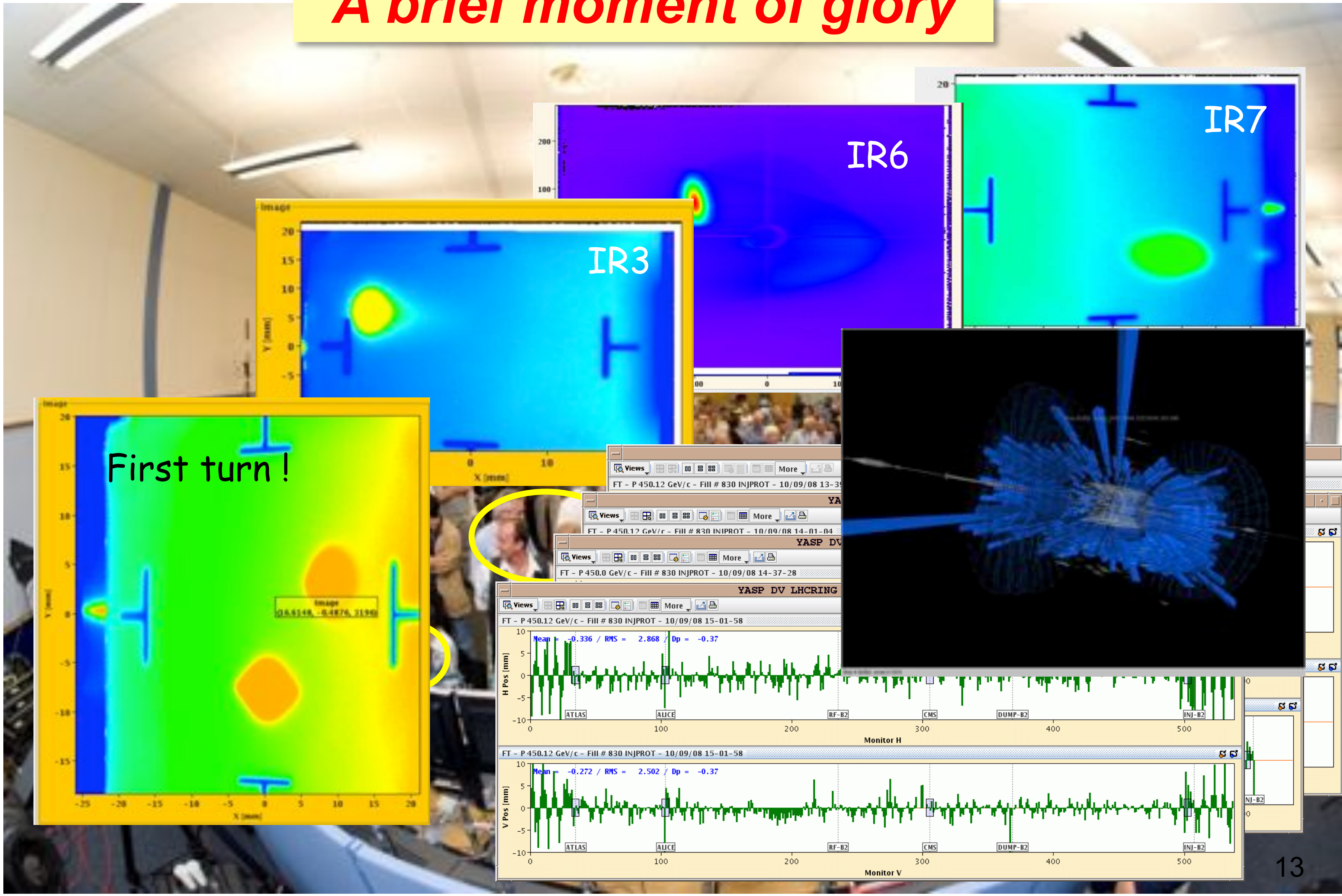
By courtesy of S. Russenschuck (CERN)

LHC energy evolution

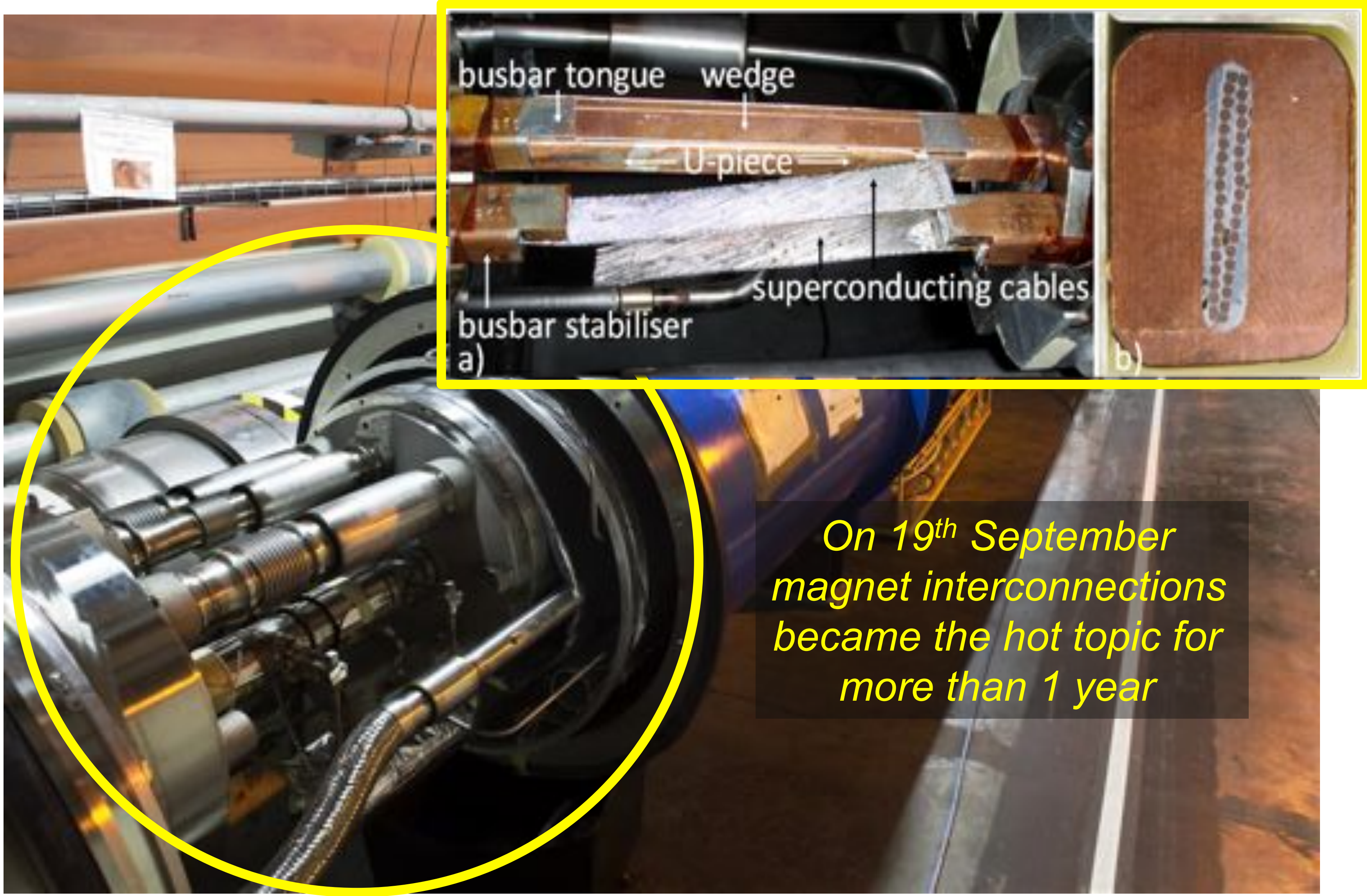


September 10th 2008

A brief moment of glory



LHC magnet interconnection

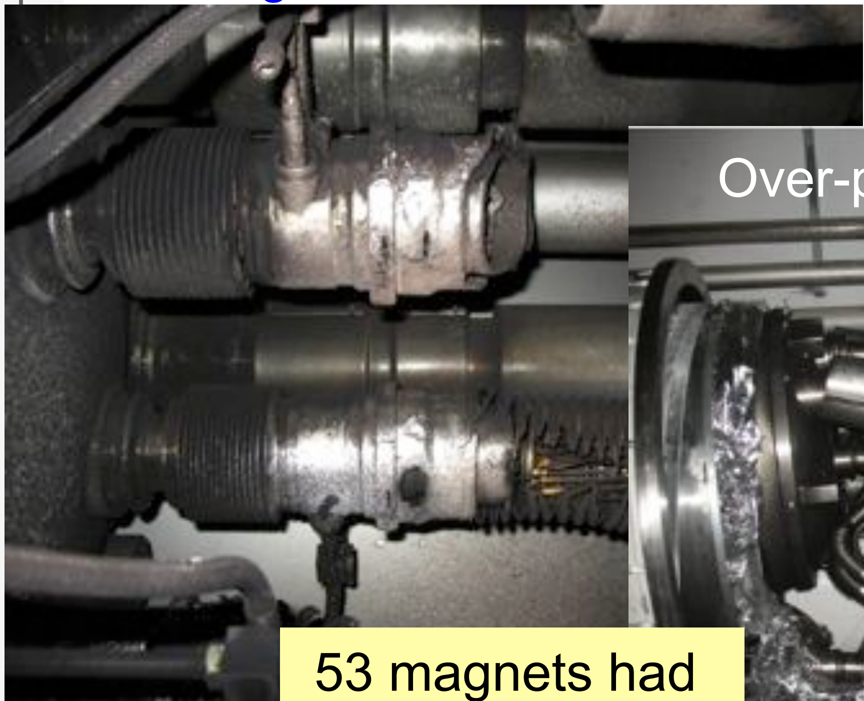


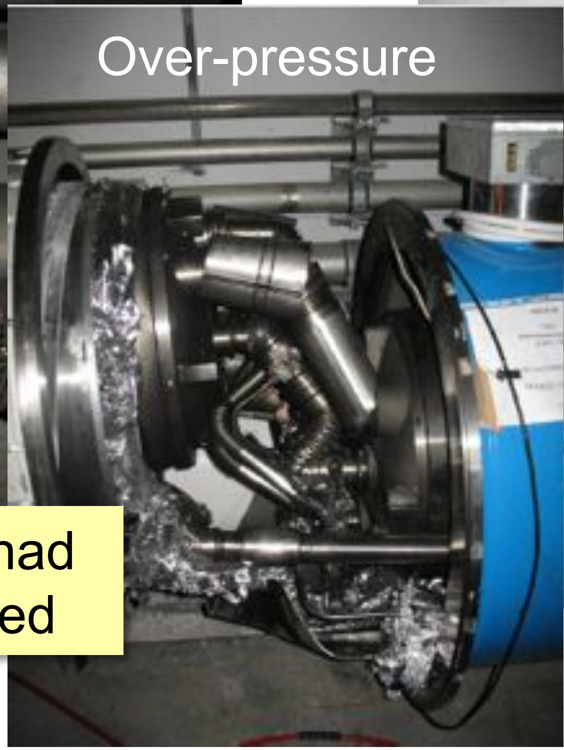
On 19th September magnet interconnections became the hot topic for more than 1 year

Incident September 19th 2008

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

Arcing in the interconnection





53 magnets had to be repaired

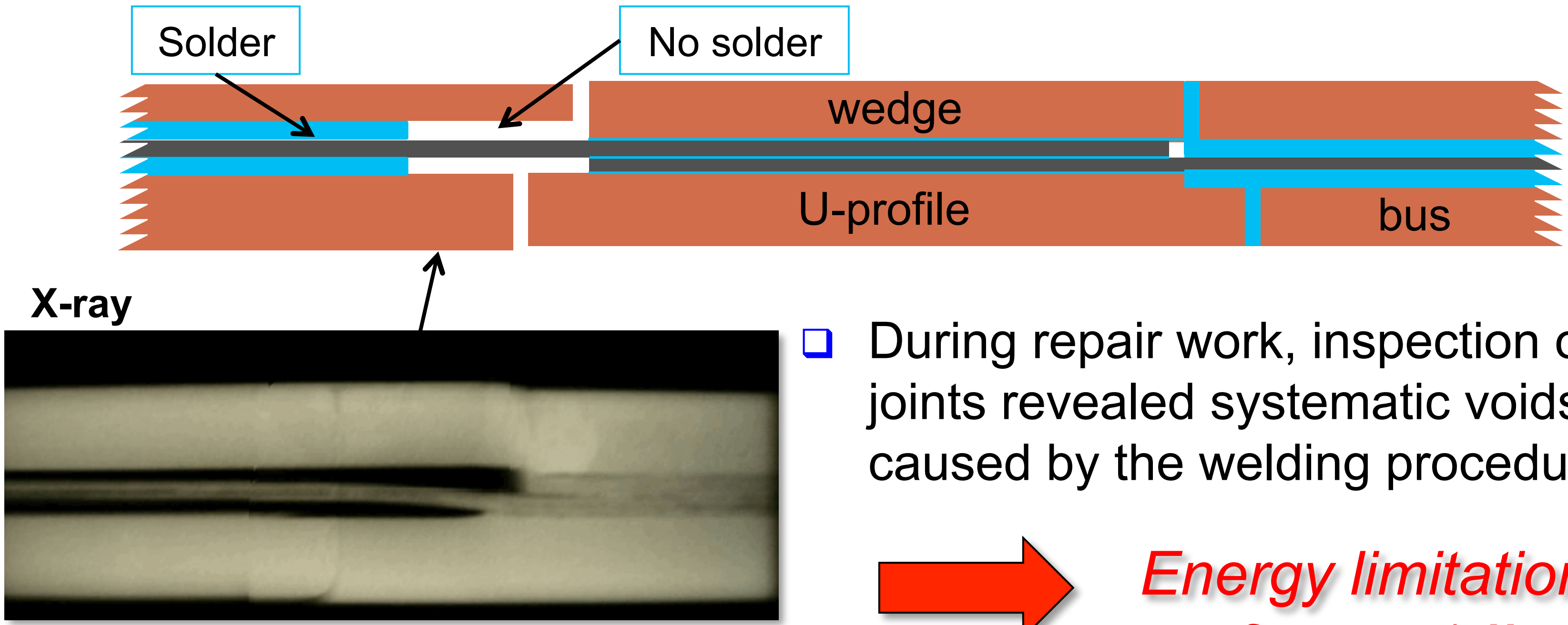
Magnet displacement

More problems on the joints

- 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.

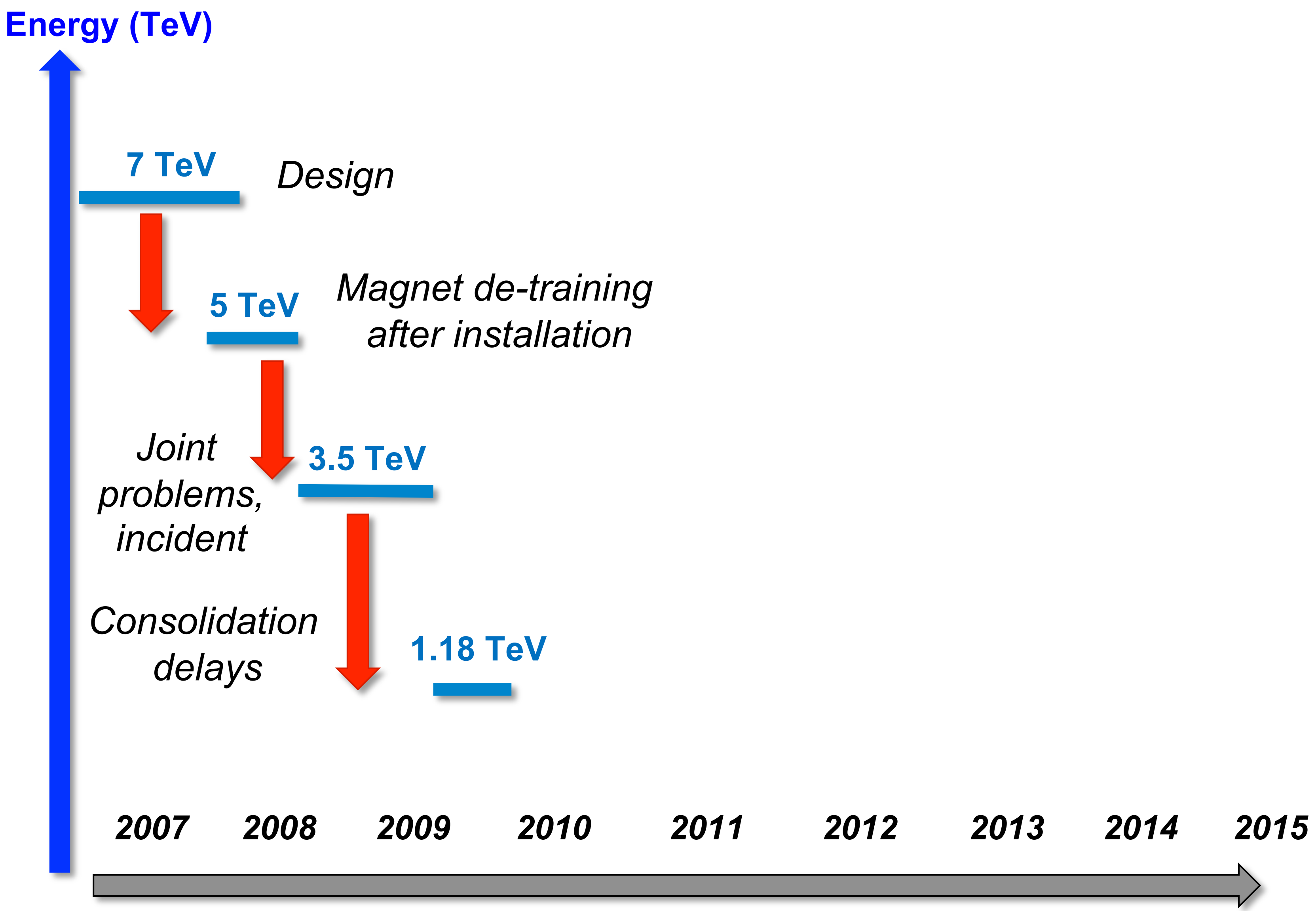
- A copper bus bar with reduced continuity coupled to a badly soldered superconducting cable can lead to a serious incident.



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

→ ***Energy limitation for run 1 !!***

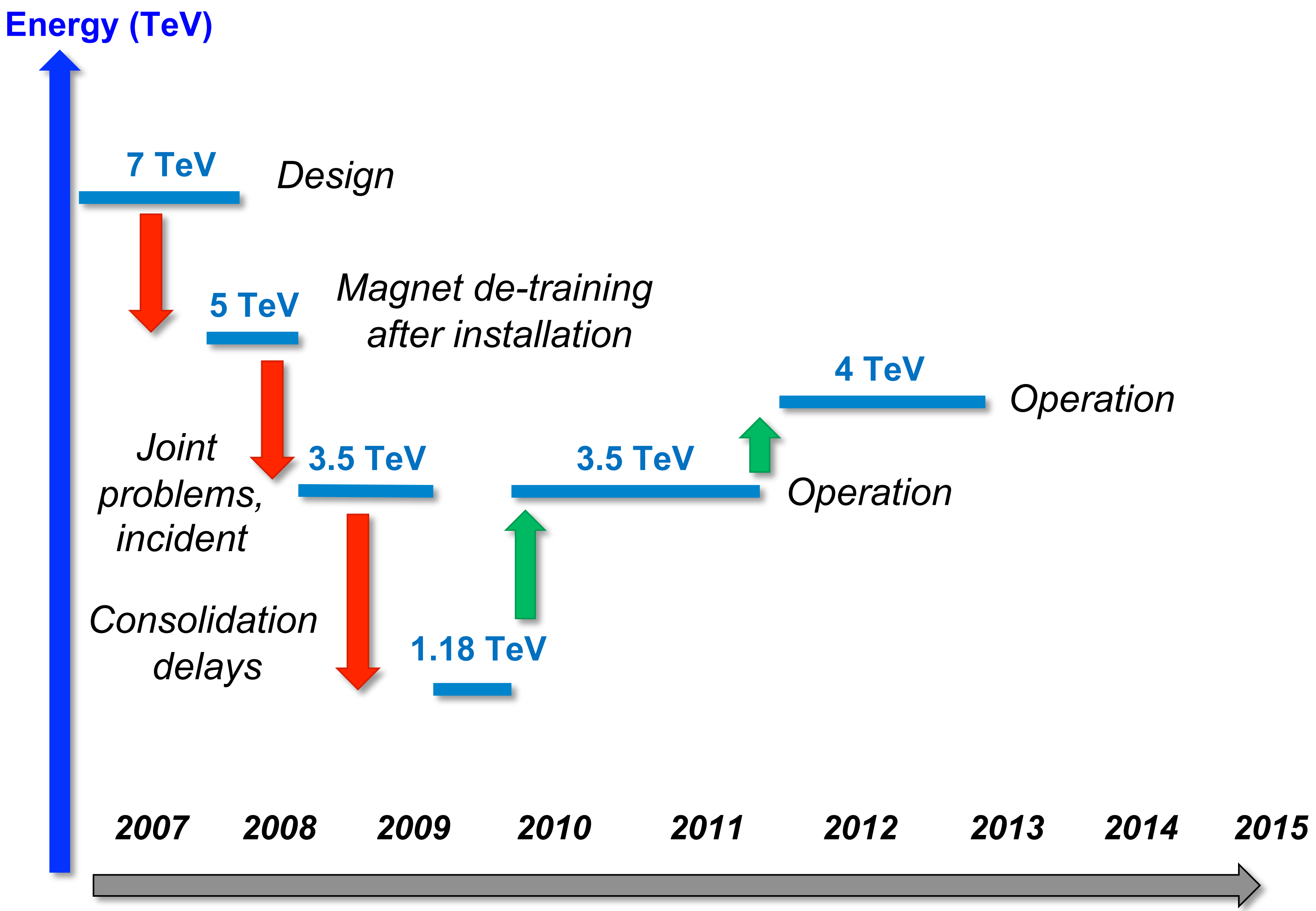
LHC Energy Evolution



LHC is back !

20th November 2009: after 14 months of repair

LHC Energy Evolution



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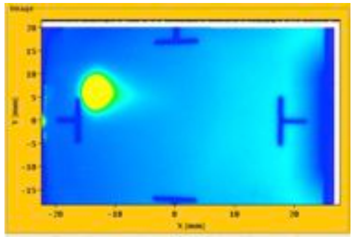
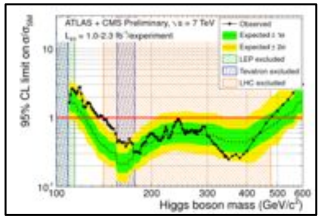
The LHC run1 timeline

August 2008
First Injection tests



September 10, 2008
Circulating beams

November 20, 2009
Beams back



December 2011
5.6 fb^{-1}

June 28, 2011
1380 bunches

1380

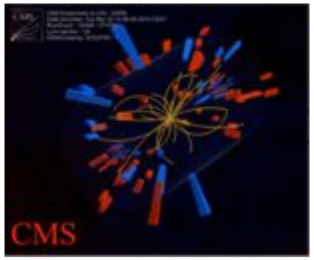
Energy: 4 TeV

March 2012
4 TeV

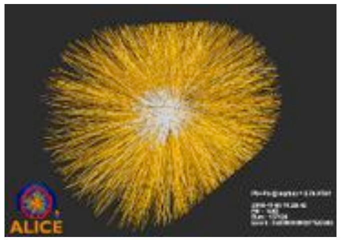
2008 | 2009 | 2010 | 2011 | 2012

September 19, 2008
Incident

March 30, 2010
First collisions at 7 TeV CM



November 2010
First Lead ion run



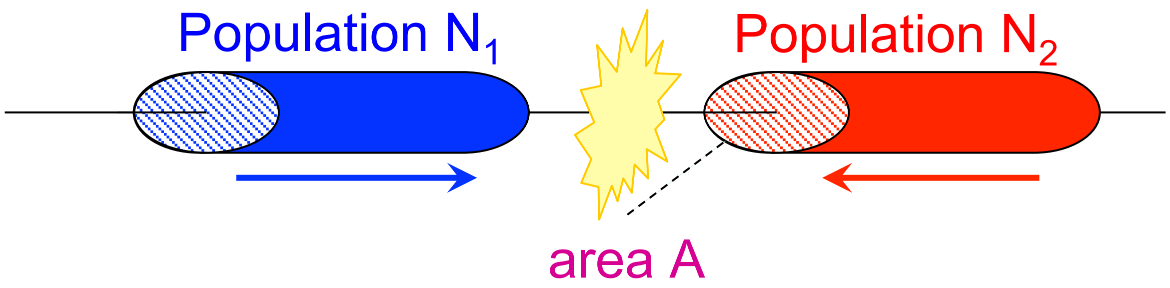
July 4, 2012
Higgs seminar

Collider luminosity

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

$$dN / dt = L\sigma$$

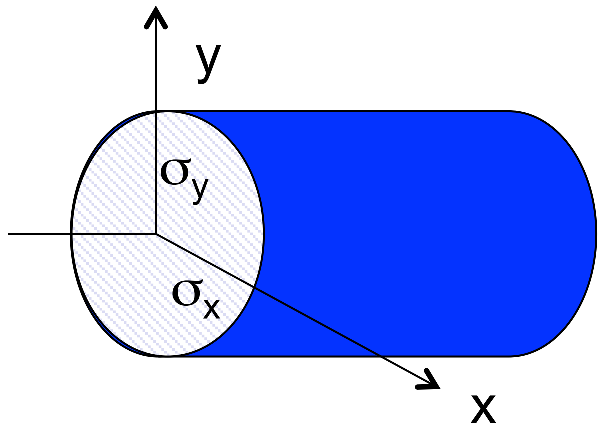
unit of L :
1/(surface × time)



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

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

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



*** refers to the IP***

- σ^*_x, σ^*_y : *transverse rms beam sizes.*
- ***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.*

LHC design

k = 2808
N = 1.15×10^11^ ($N = 1.15\times10^{11}$)
$\sigma^*_x = \sigma^*_y = 16\ \mu m$

To maximize L we need:
- Large N, large k,
- Smallest possible σ.

...or some optimum combination !

Optimizing luminosity

What limits the parameters affecting the luminosity?

	Injectors (pre-accelerators)	LHC
N	Define intensity limit	Limit may be lower than injector limit (stability, heating, losses..)
k	Correlated to N	Maximum ~2800 bunches (min. spacing of 25 ns)
σ	Define phase-space volume of the beam (emittance ε)	Preservation of emittance Focusing at the collision point (β)

$$\sigma(s) = \sqrt{\beta(s)\varepsilon / \gamma}$$

$$\sigma^*_x \sigma^*_y = \beta^* \varepsilon / \gamma$$

ε phase space volume of the beam, γ = E/m.

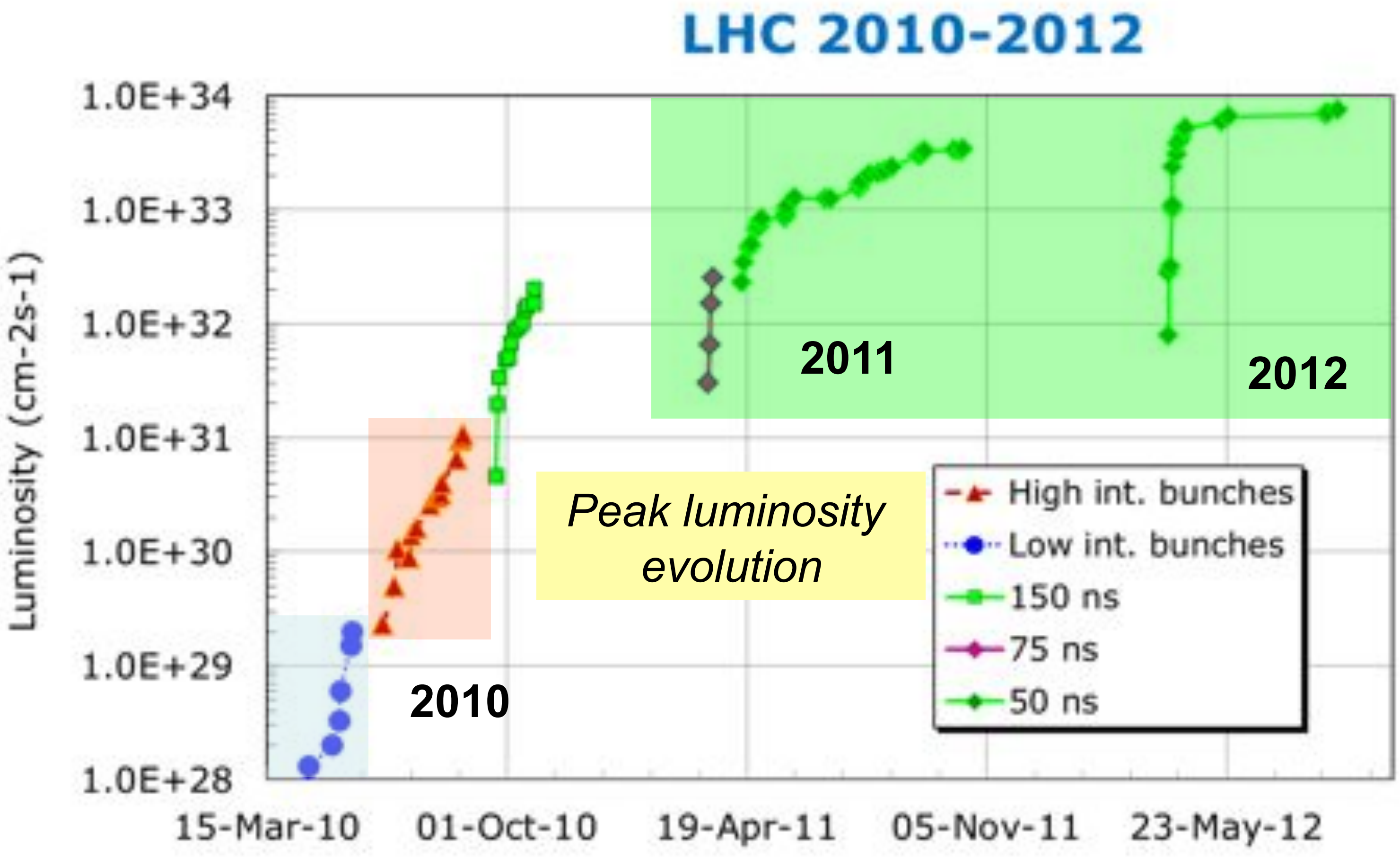
β beam envelope (betatron) function, defined by optics of the LHC, varies along the circumference (s)

LHC progress 2010-2012

Low bunch intensity operation, first operational experience with LHC

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

Reach out for records & Higgs !

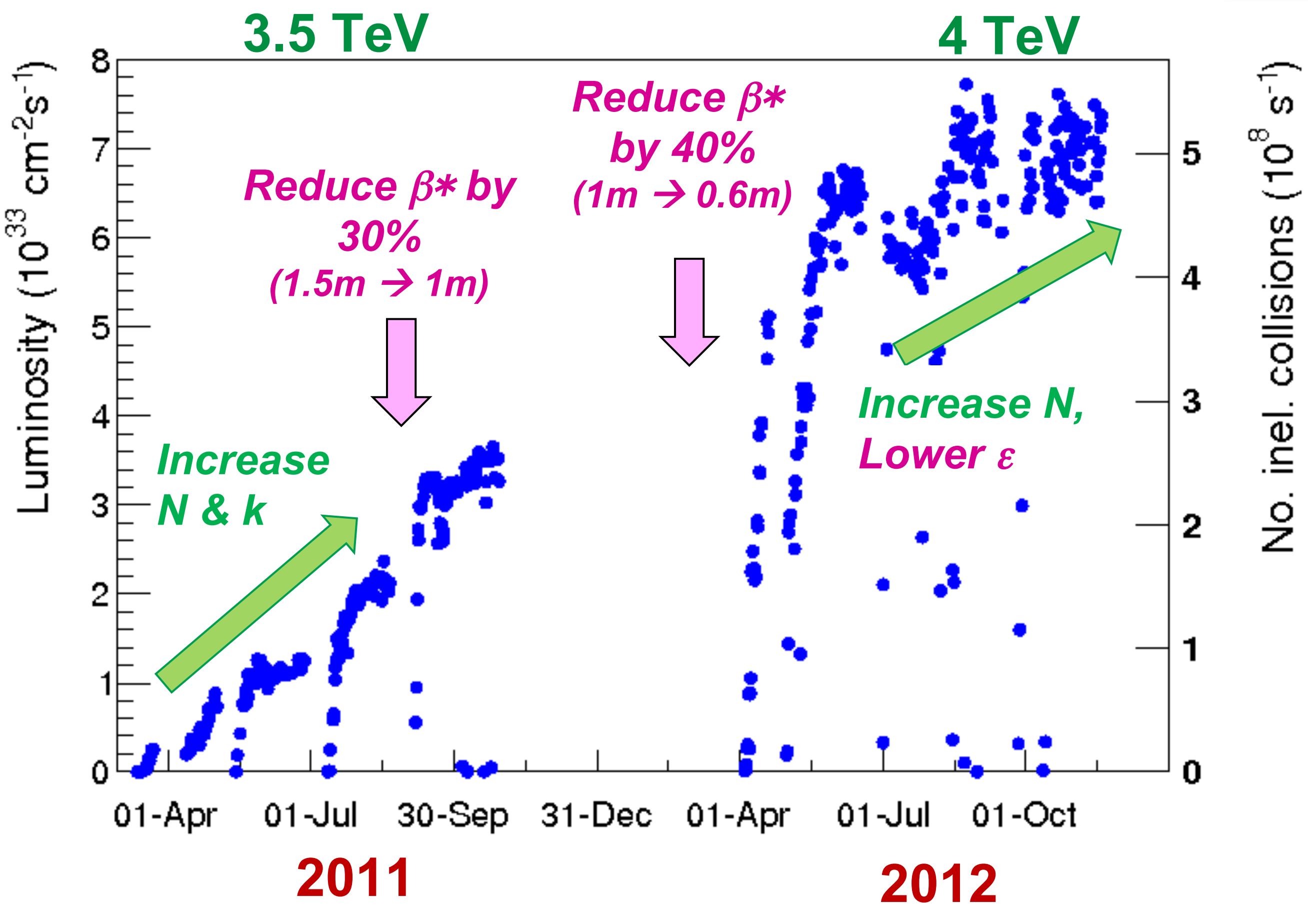


High luminosity 2011-2012

Over the last 2 years the luminosity was progressively increased:

- *Through the beam intensity (mainly 2011),*
- *By beam size (β^*,ε/γ) reduction at the IP.*

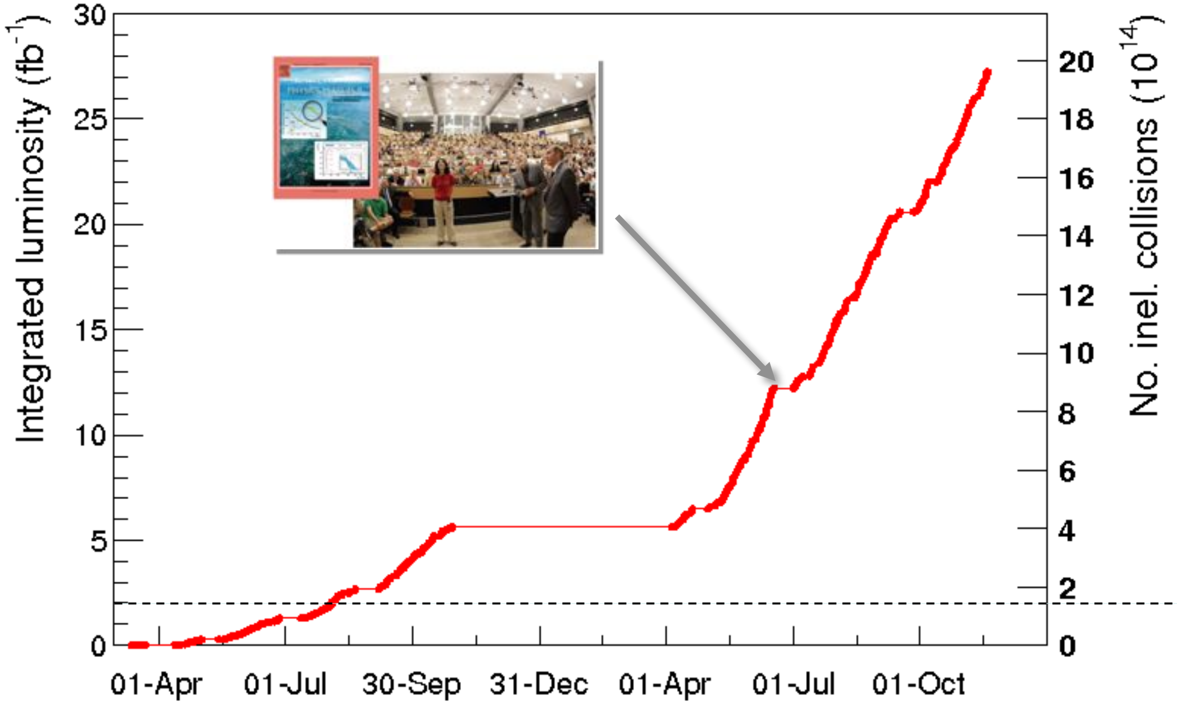
Limited by beam stability

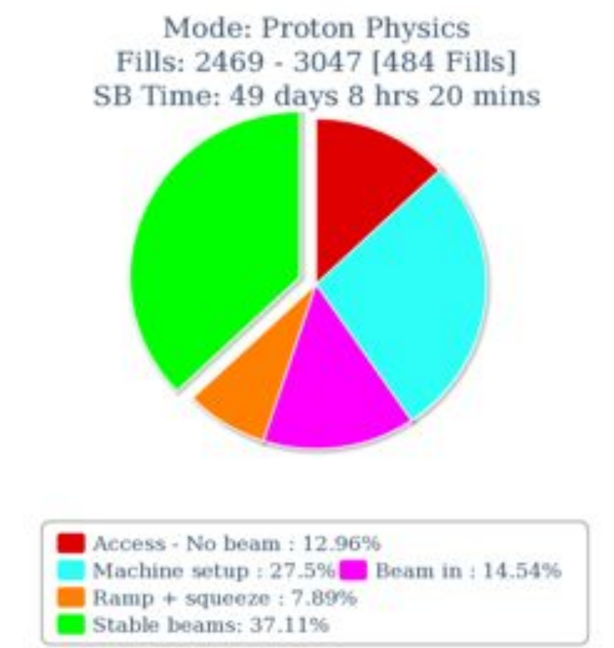


Luminosity production 2011-2012

The integrated luminosity of both ATLAS/CMS reaches now **~28 fb^{-1}** or **~2×10^{15}** inelastic pp interactions in each detector.

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





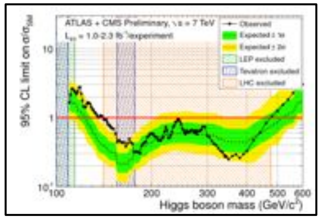
Initial target defined around 2009/2010

LHC 2012 versus Design

	Design	2012
Collision energy:	7+7 TeV	4+4 TeV
Bunch spacing (ns):	25	50
Number of bunches k:	2808	1374
Number of particles per bunch N:	1.15×10^{11}	1.6×10^{11}
Beam emittance ε (μm):	3.75	2.3
Beam size at ATLAS/CMS (μm):	16	18
Circulating beam current:	0.58 A	0.42 A
Stored energy per beam:	360 MJ	140 MJ
Peak luminosity ($cm^{-2}s^{-1}$):	10^{34}	7.7×10^{33}

2012 peak L scaled to 7 TeV : ~2×10^{34}

The LHC run1 timeline – the end



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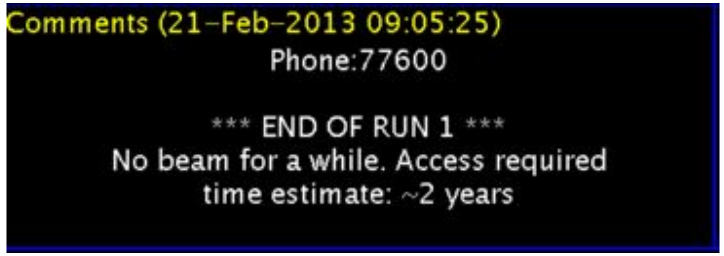
March 2012
4 TeV



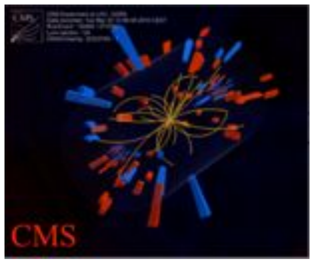
February 21, 2013
Long shutdown 1

June 28, 2011
1380 bunches

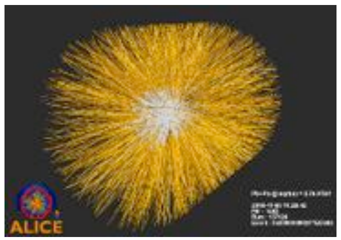
1380

200 | 2010 | 2011 | 2012 | 2013

March 30, 2010
First collisions at
7 TeV CM

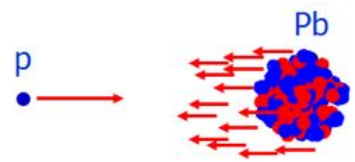


November 2010
First Lead ion run



July 4, 2012
Higgs seminar

January 2013
Protons & Lead



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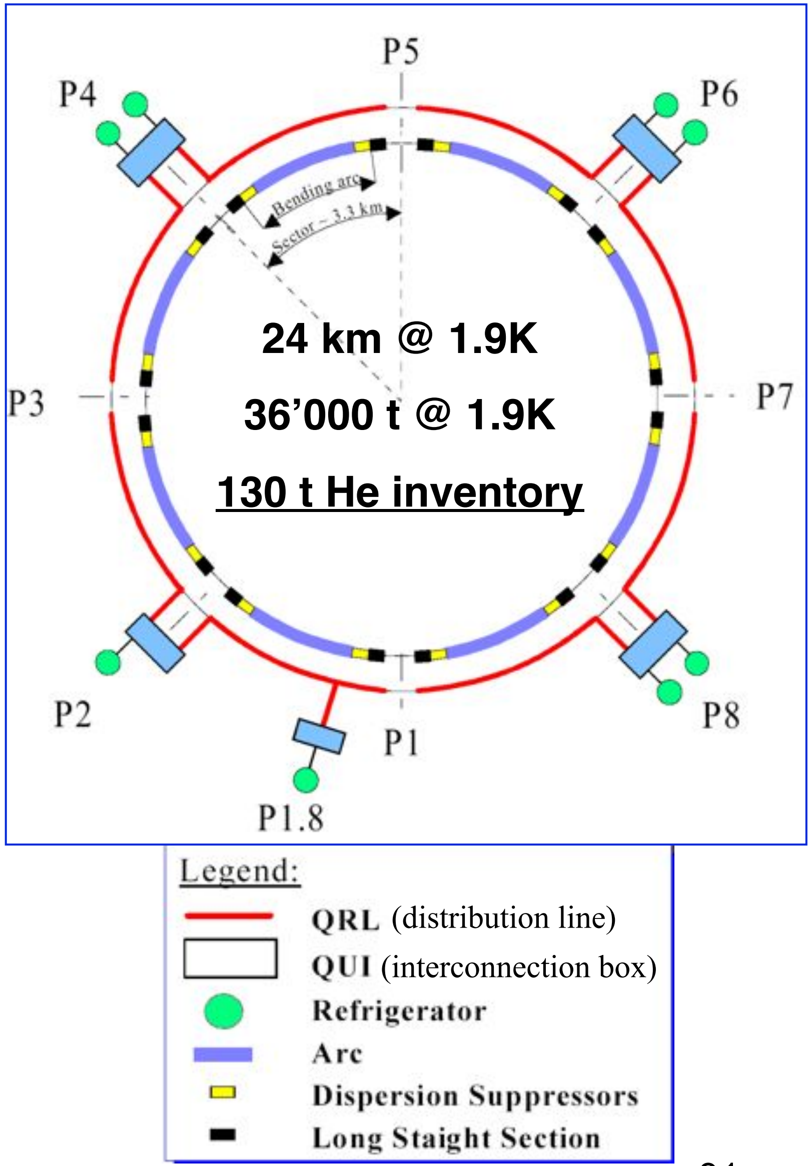
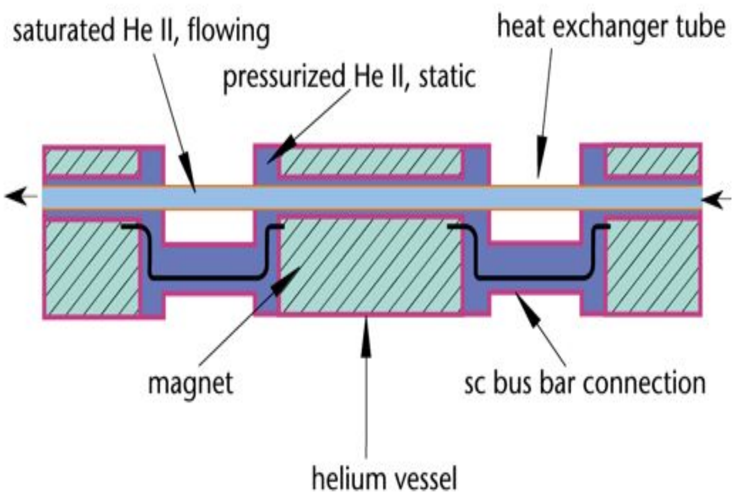
Cryogenics challenge

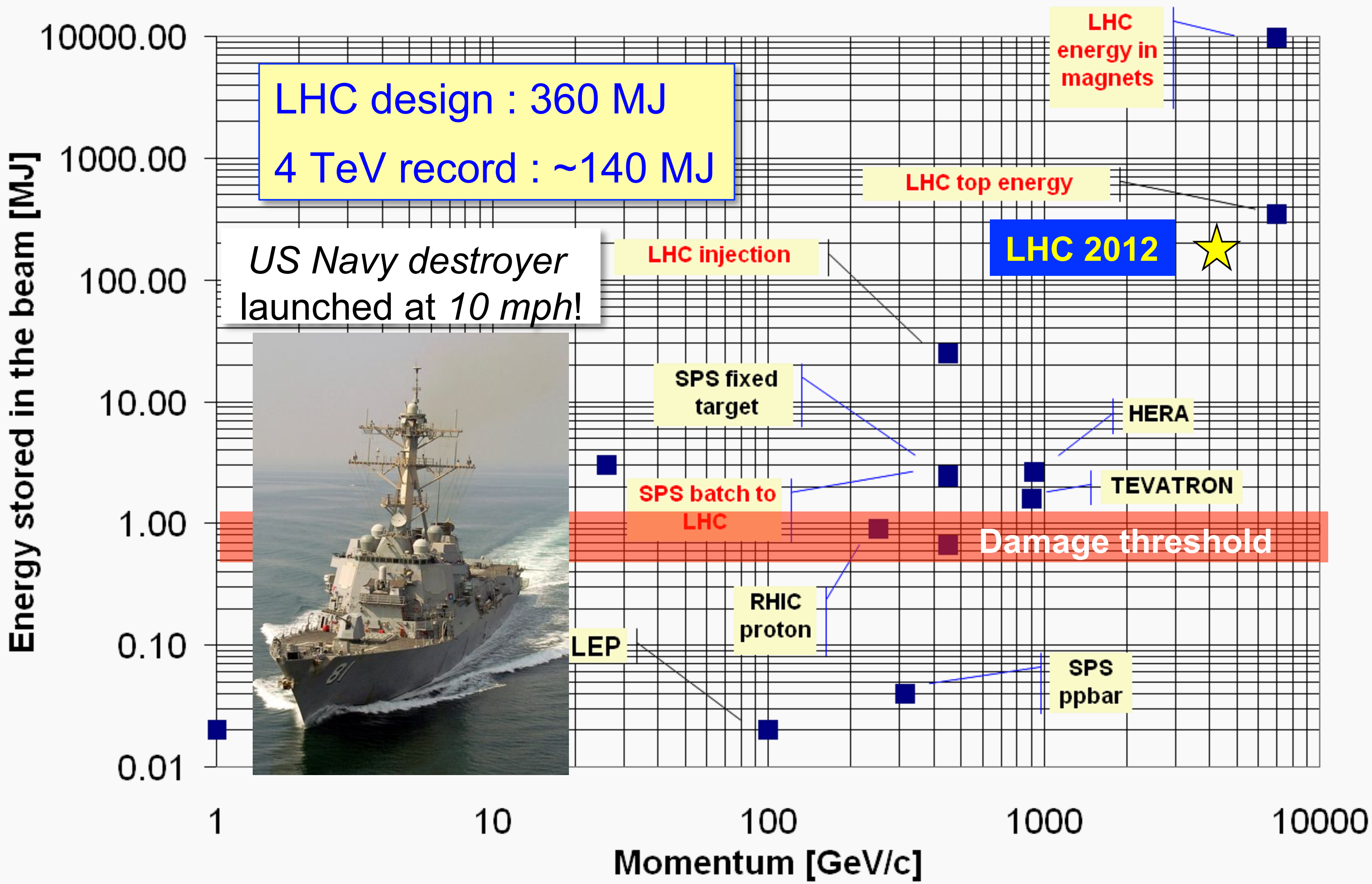
- A HUGE system !!
- Most of the LHC magnets are cooled with superfluid He at 1.9K.
  - *Very low viscosity.*
  - *Very high thermal conductivity.*
- In 2012 the availability of the cryogenics reached ~95%!
  - Availability ~97% if external failures are excluded !!





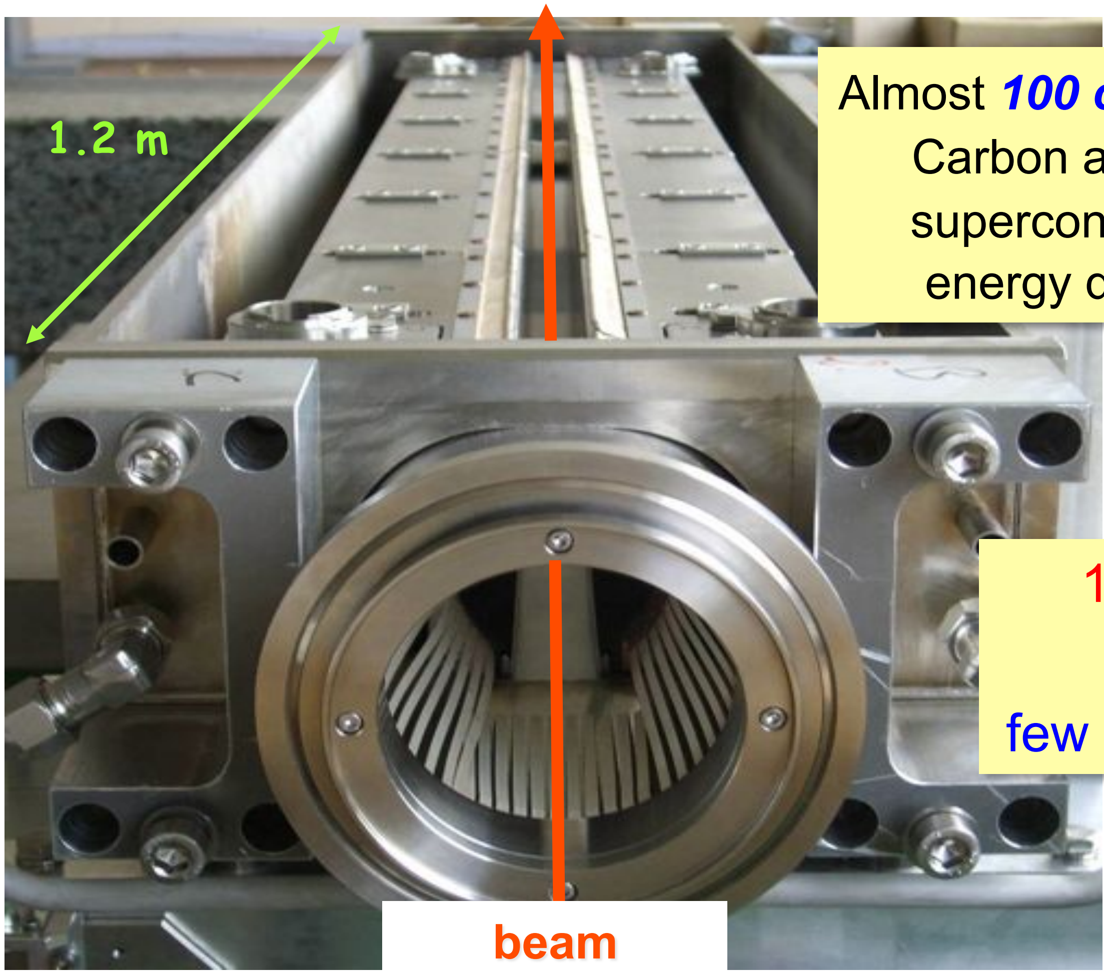
Stored energy challenge

Superb performance of the machine protection system



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.*

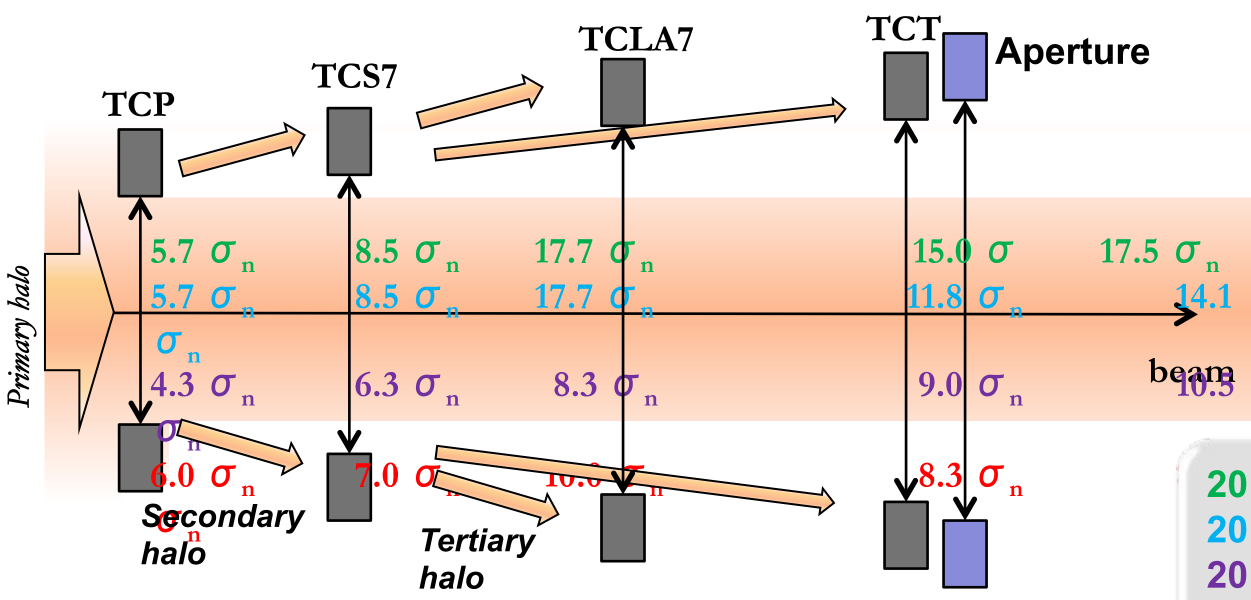


Almost ***100 collimators***, mostly made of Carbon and Tungsten, protect the superconducting magnets against energy deposition from the beam

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.
  - ~99.99% of the protons that were lost from the beam were intercepted.
  - ***No magnet was quenched in operation at 3.5/4 TeV.***



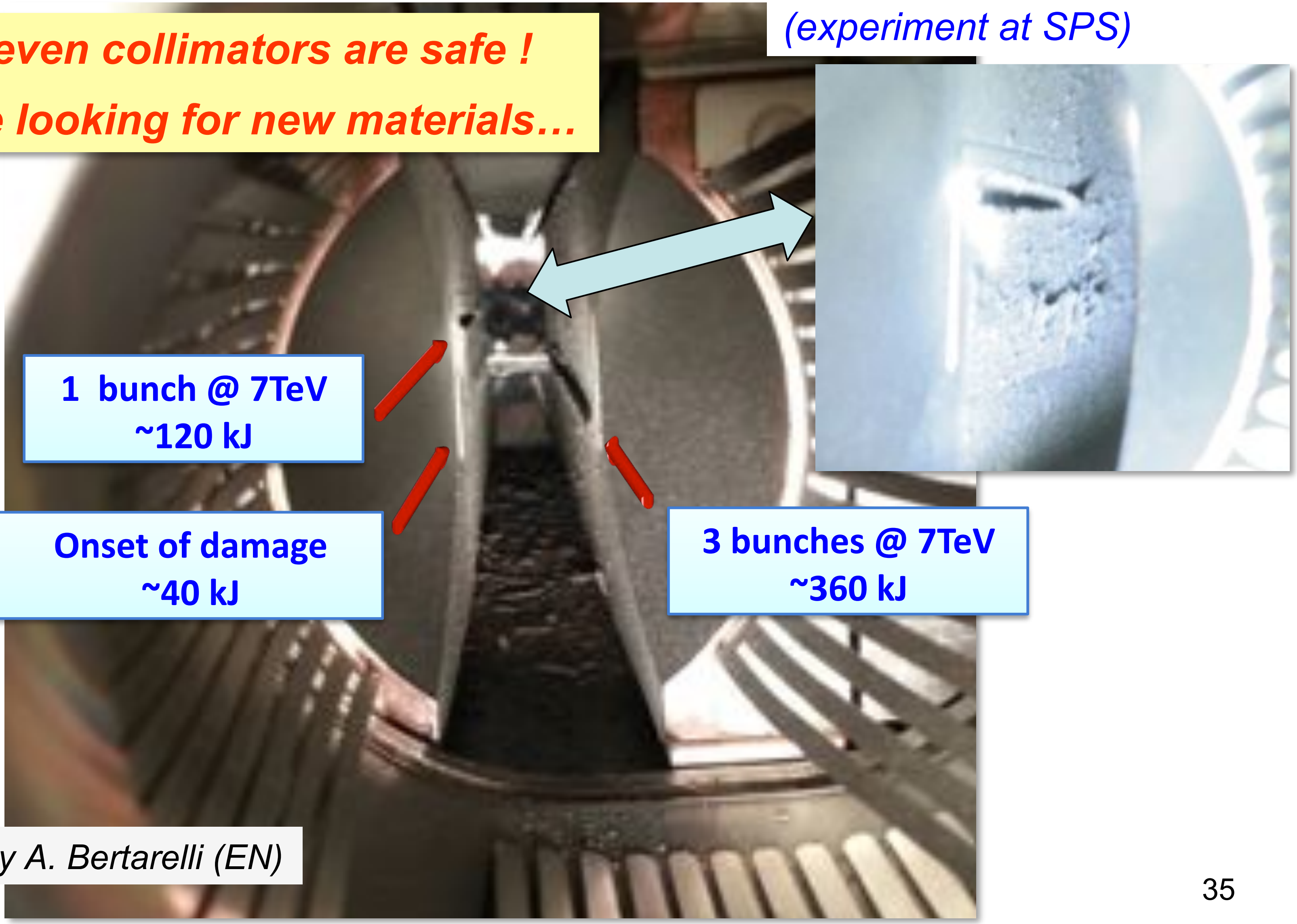
Courtesy R. Bruce

Effect of direct beam impact on a Tungsten collimator

Not even collimators are safe !

We are looking for new materials…

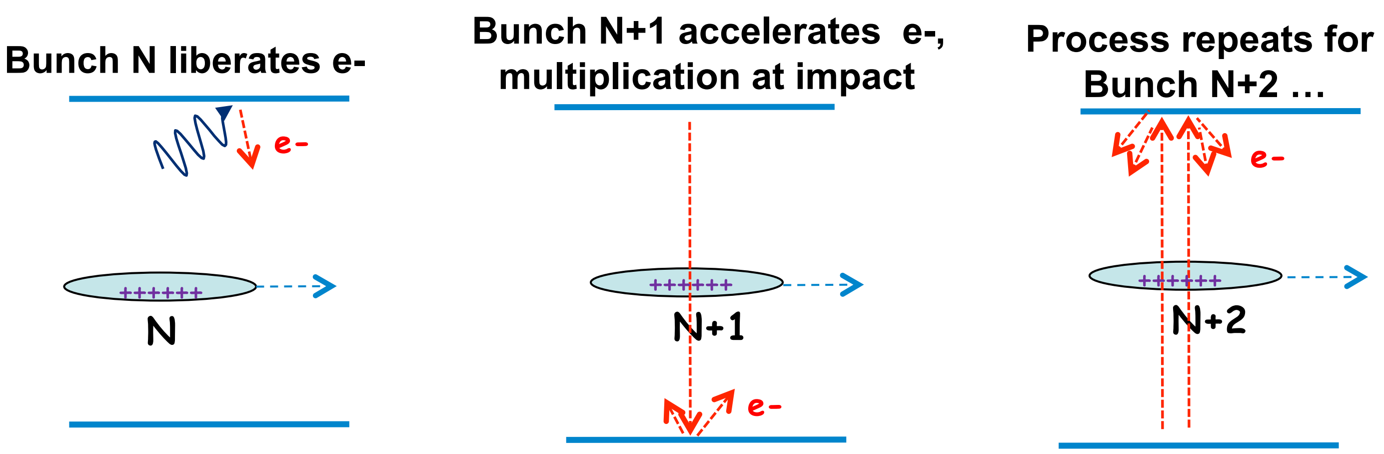
(experiment at SPS)



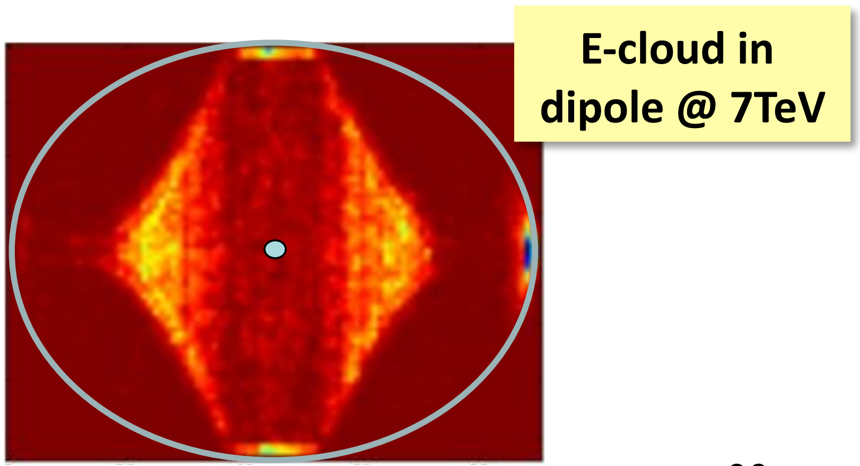
Courtesy A. Bertarelli (EN)

Electron cloud challenge

- 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!*
  - *Electron energies are in the 10 to few 100 eV range.*



Electron cloud mitigation

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

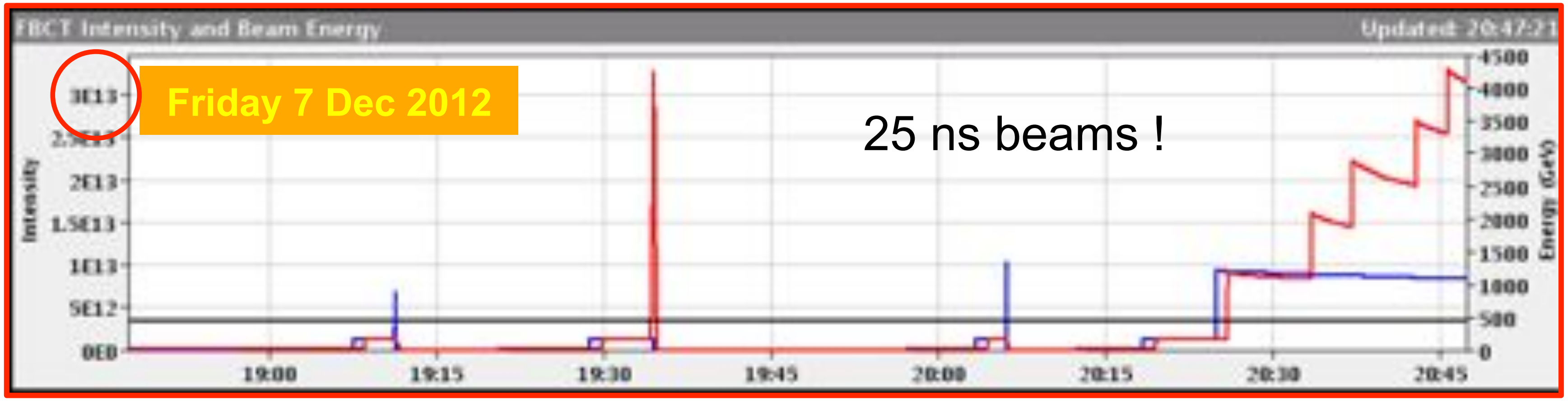
With 50 ns spacing e-clouds are much weaker than with 25 ns !

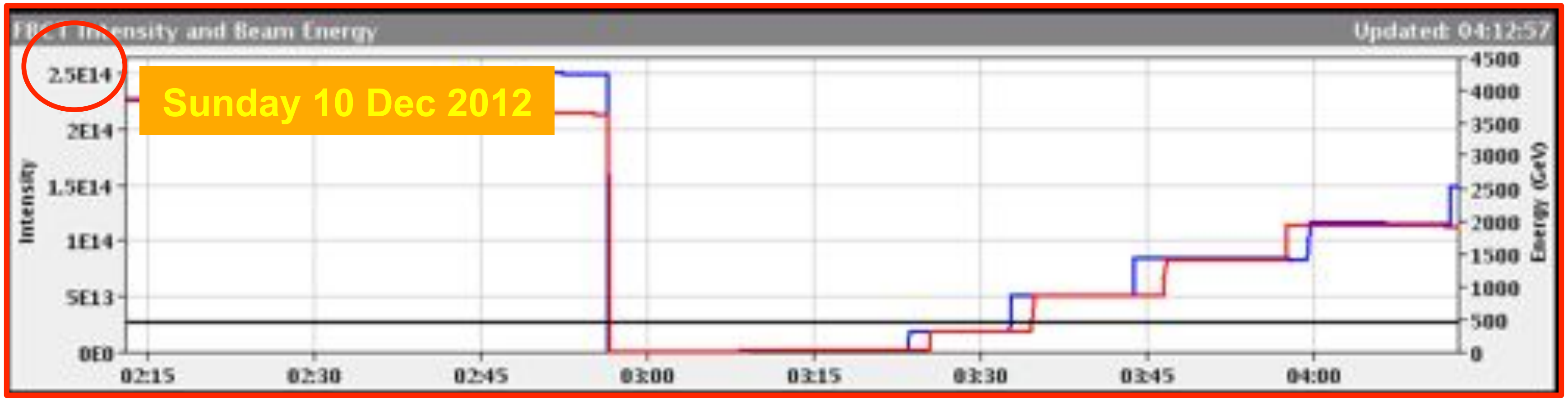
→ One of the main reason to operate so far with 50 ns.

- The e-cloud can 'cure itself': the impact of the electrons cleans the surface (Carbon migration), reduces the electron emission probability and eventually the cloud disappears**.**
- ***'Beam scrubbing'*** consists in producing e-clouds deliberately with the beams in order to reduce the SEY until the cloud 'disappears'.
  - *Done at 450 GeV where fresh beams can be injected easily.*
- In April 2011 50 ns beams were used to '***scrub'*** the vacuum chamber at 450 GeV to prepare operation at 3.5 TeV.
  - *Further slow improvement during operation at 3.5 TeV and 4 TeV.*
  - *Operation with nominal 25 ns spacing will require further scrubbing.*

Beam scrubbing

- Evident improvement on **beam lifetime**





Courtesy G. Iadarola

Flexible beams challenge

- We made full use of the flexibility of the LHC and of its injector chain.
- Beams with 50 ns bunch spacing are 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.*
- And it will come even better in 2015.

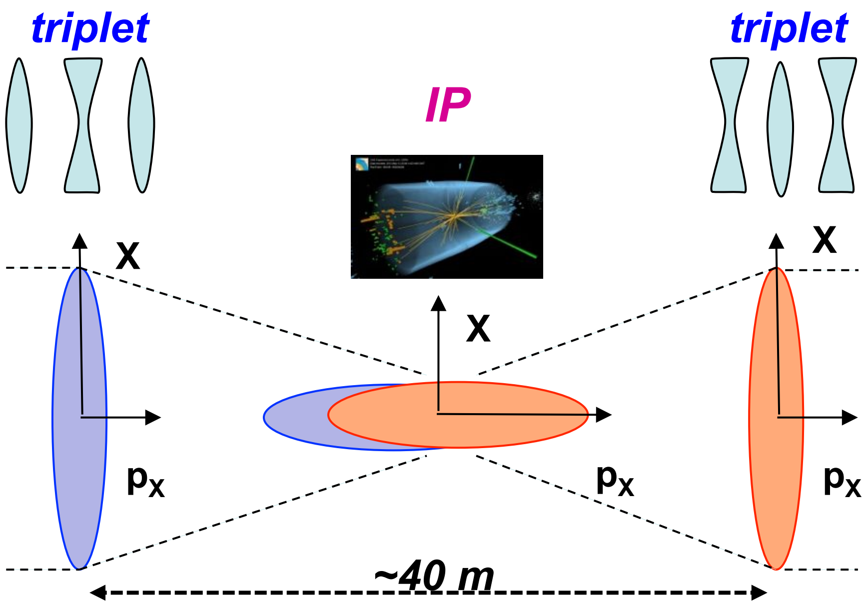
LHC beam parameters (LHC injection)

	Spacing	N (p/bunch)	ε [μm]	Relative luminosity / Bunch Crossing
2012 →	50 ns	1.65×10^{11}	1.8	4
	25 ns design	1.15×10^{11}	3.5	1
	25 ns low ε	1.2×10^{11}	1.4	2.7

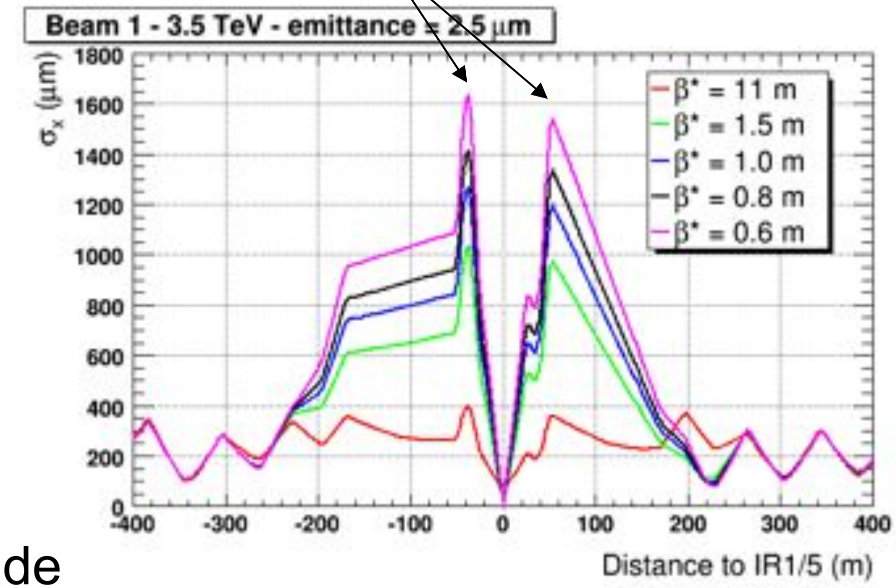
The 'Dream Beam' for 2015 / 7 TeV

Aperture challenge

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



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



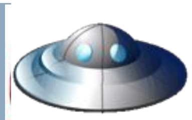
- This excellent performance was made possible by better than anticipated alignment and control of the trajectories.

Smaller sizes σ*, factor ~2-3

⇒ **The price of the high luminosity with fewer collisions: for each bunch crossing there are up to ~35 interactions.**

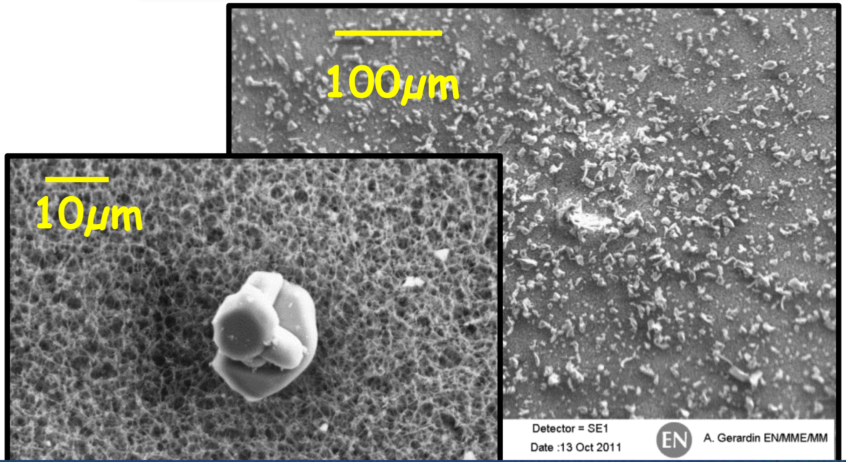
⇒ **‘Hats off’ to ALTAS & CMS for handling this pile-up !!**

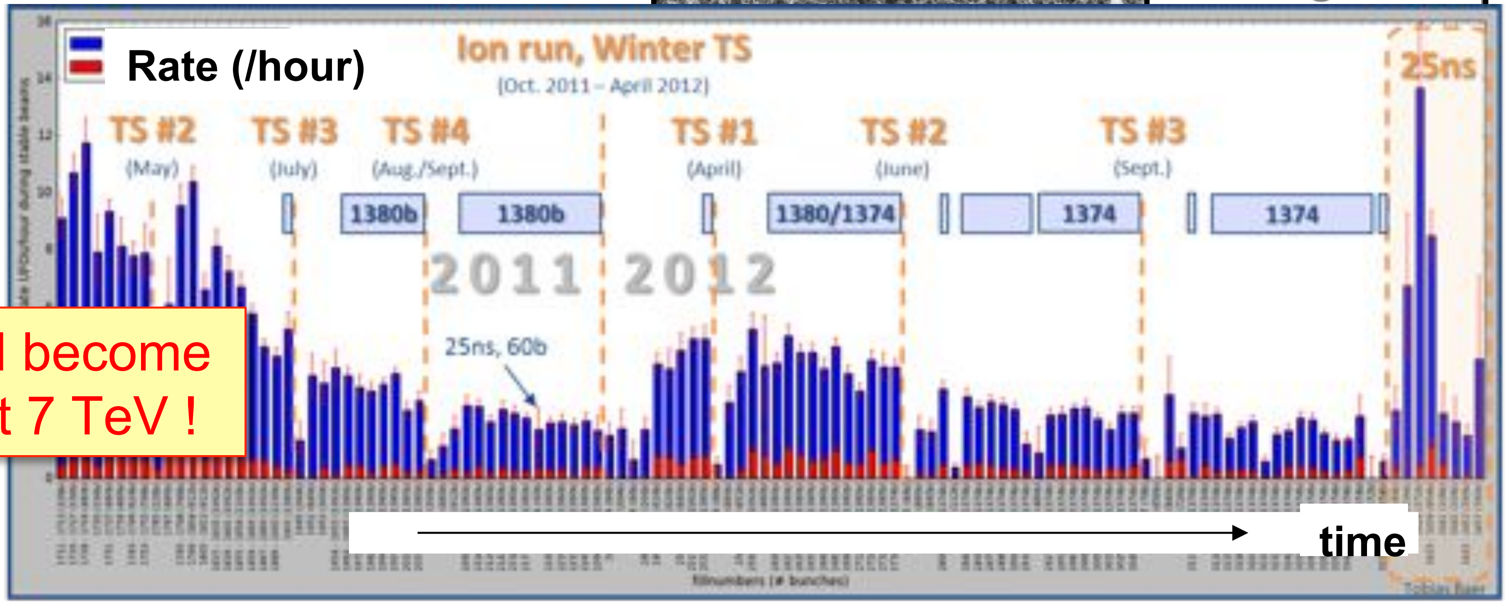
Surprising 'Unidentified Falling Objects'



- Very fast and localized beam losses were observed as soon as the LHC intensity was increased in 2010.
- The beam losses were traced to **dust particles falling into the beam** – '**UFO**'.
- If the losses are too high, the beams are dumped to avoid a magnet quench.
  - ~20 beams dumped / year due to UFOs.
  - We observe conditioning of the UFO-rate from ~10/hour to ~2/hour.

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





UFOs could become an issue at 7 TeV !

Outline

Introduction

LHC magnets and early commissioning

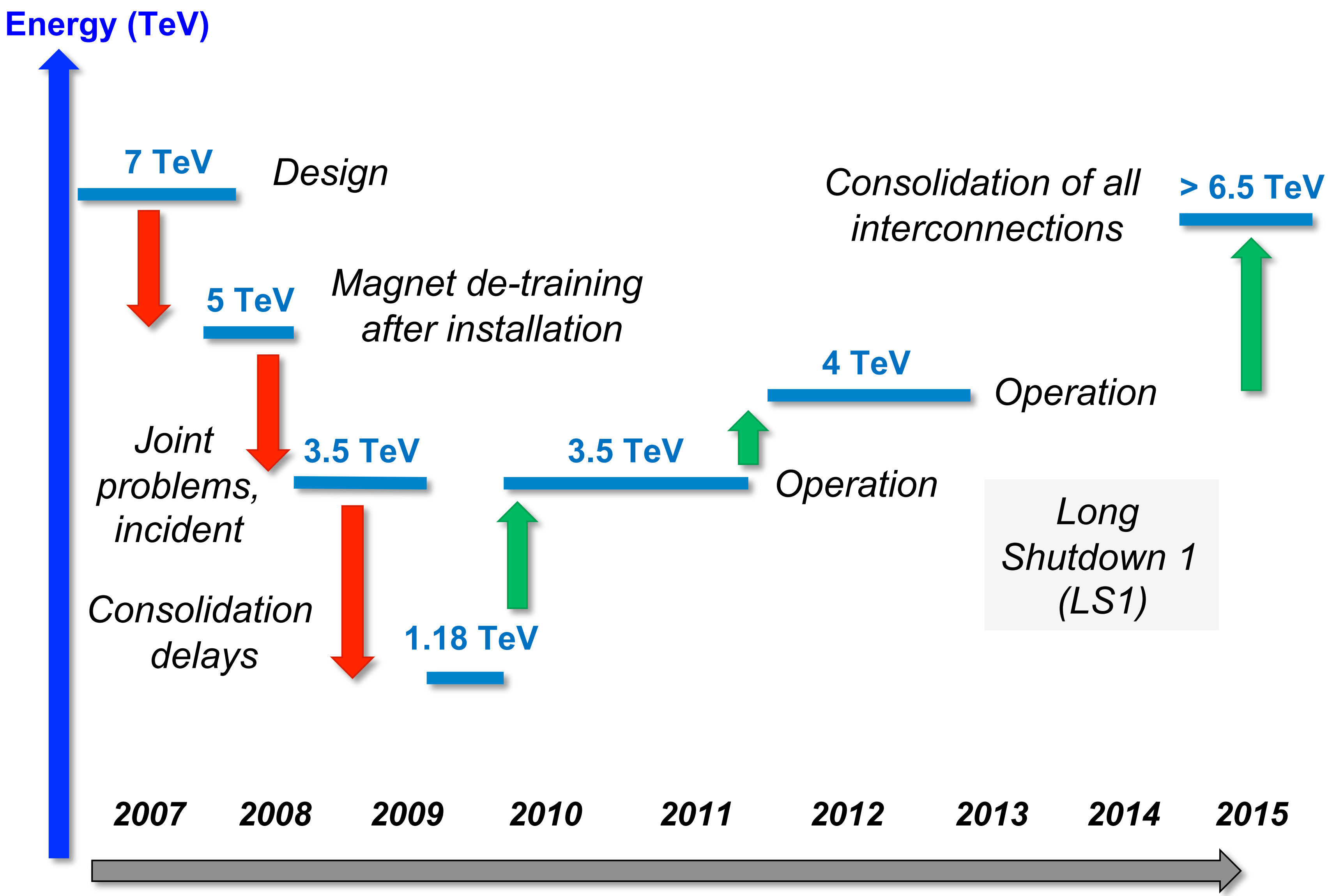
LHC performance 2010-2012

Mastering the challenges

Towards top energy

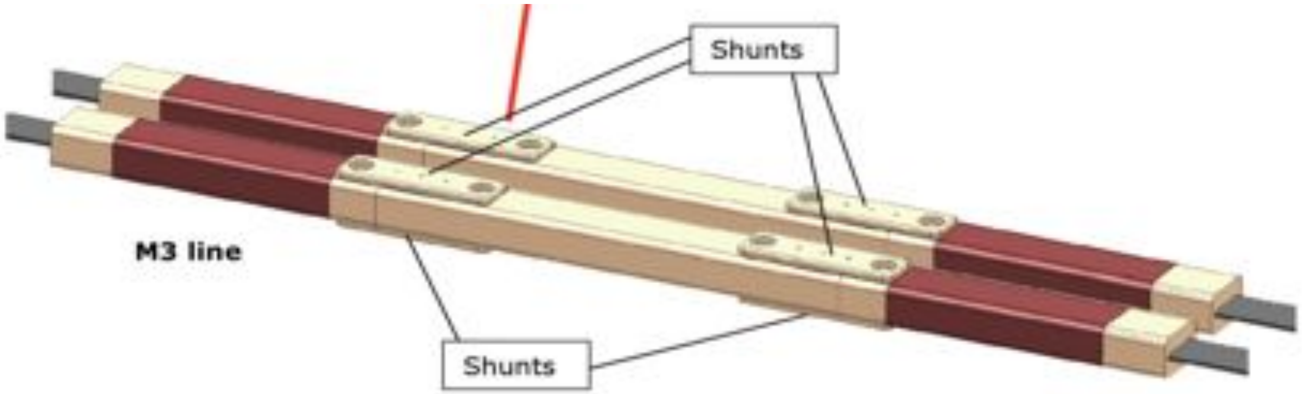
Upgrades

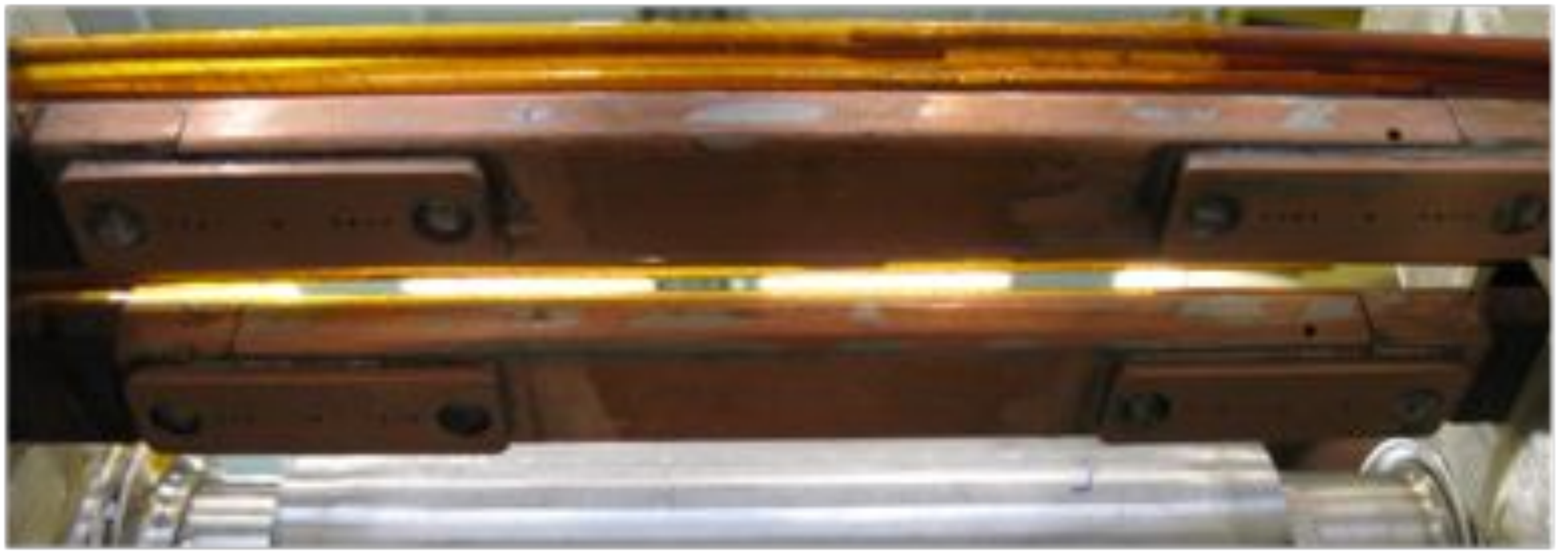
LHC energy evolution



Preparing for nominal energy

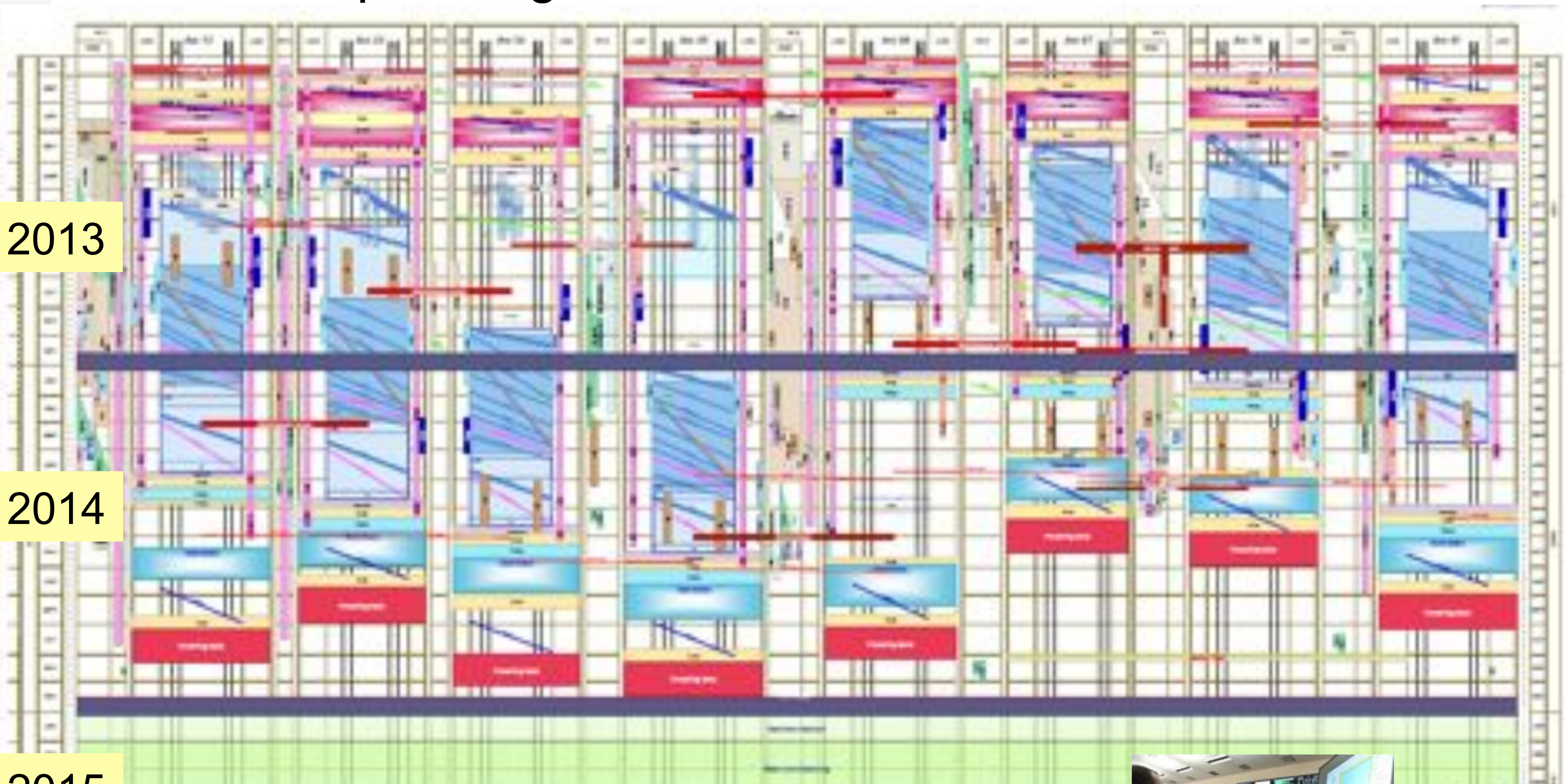
- Around 10’000 high current magnet interconnections will be checked, re-done if needed. All of them will consolidated – 12 months of work.
  - *No more S34 incident in the future.*





The next objective

Turn this planning...



2013

2014

2015

…into beam in 2015

Luminosity projections

Two out of many possible scenarios @ 6.5 TeV

Beam	k	N_b [10^{11} p]	ε [μm]	β* [m]	L [10^{34} cm^{-2}s^{-1}]	Event pile-up	Int. L [fb^{-1}]
50 ns	1260	1.70	1.6	**0.4**	**2.0**	110*	~30
25 ns low ε	2520	1.15	1.9	**0.4**	**1.5**	42*	~50
25 ns standard	2760	1.15	3.7	**0.5**	**0.85**	23	~30

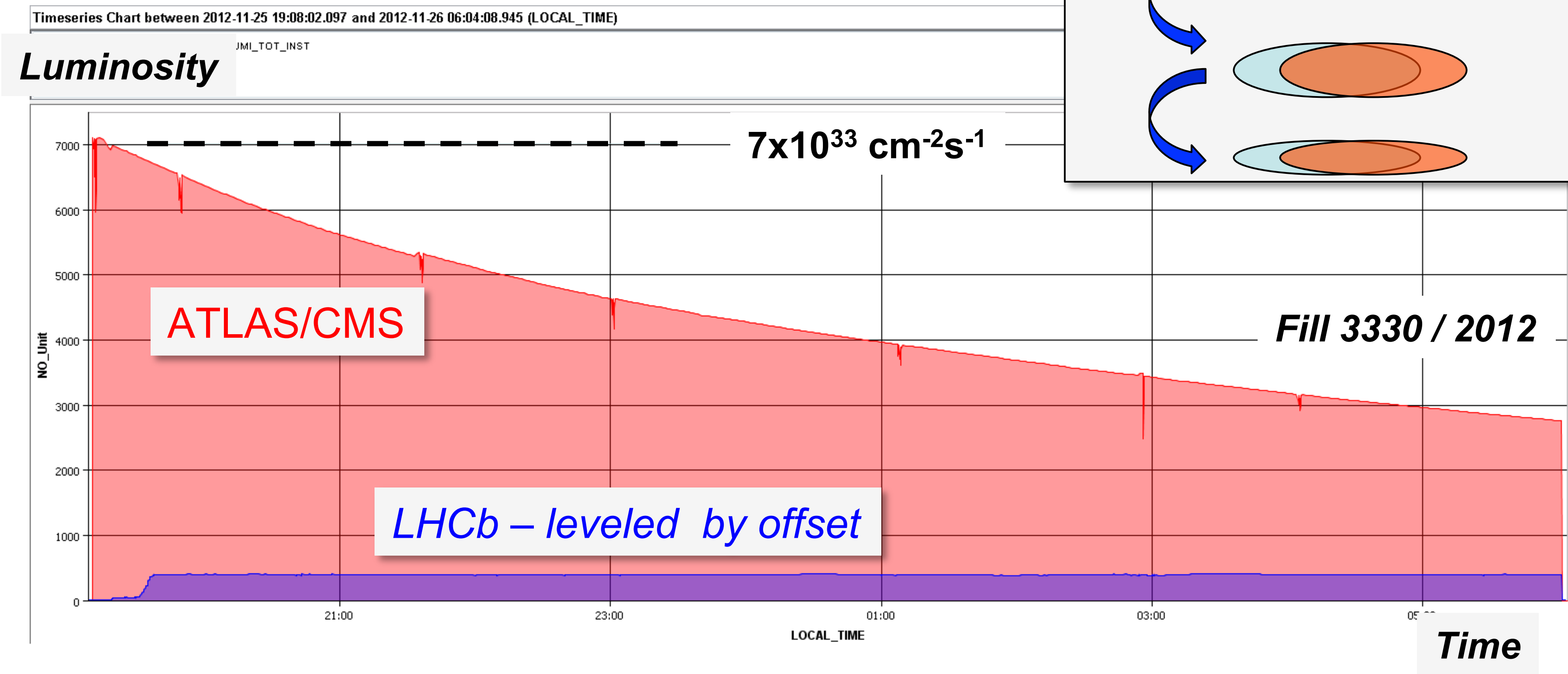
- The cryogenic limit to the luminosity is expected ~ 1.75×10^{34} cm^{-2}s^{-1} !
  - *Cooling limit of the triplet quadrupoles (collision debris)*.
- Many scenarios imply luminosity levelling to control pile-up
  - *Discussion & optimization between machine & experiments.*

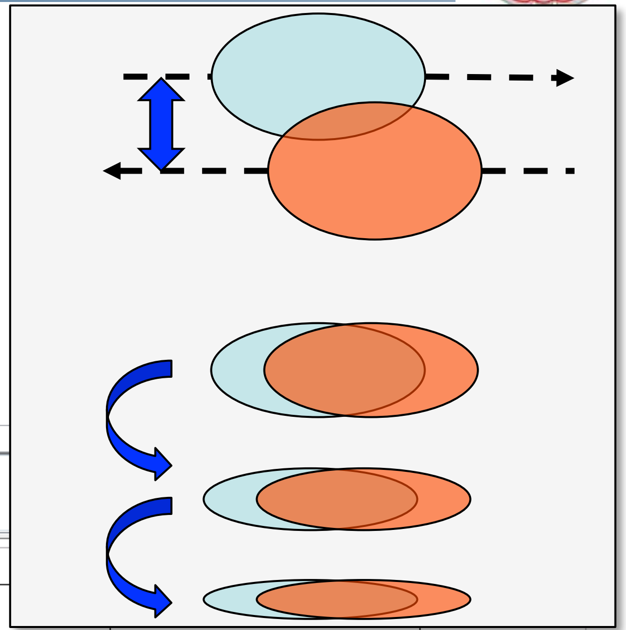
(*) leveled down to a pile-up of ~40.

Int. L based on 120 days of production/year, 35% efficiency.

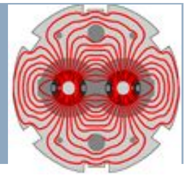
Leveling luminosities

- 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).
  - *Better / mandatory for beam stability.*





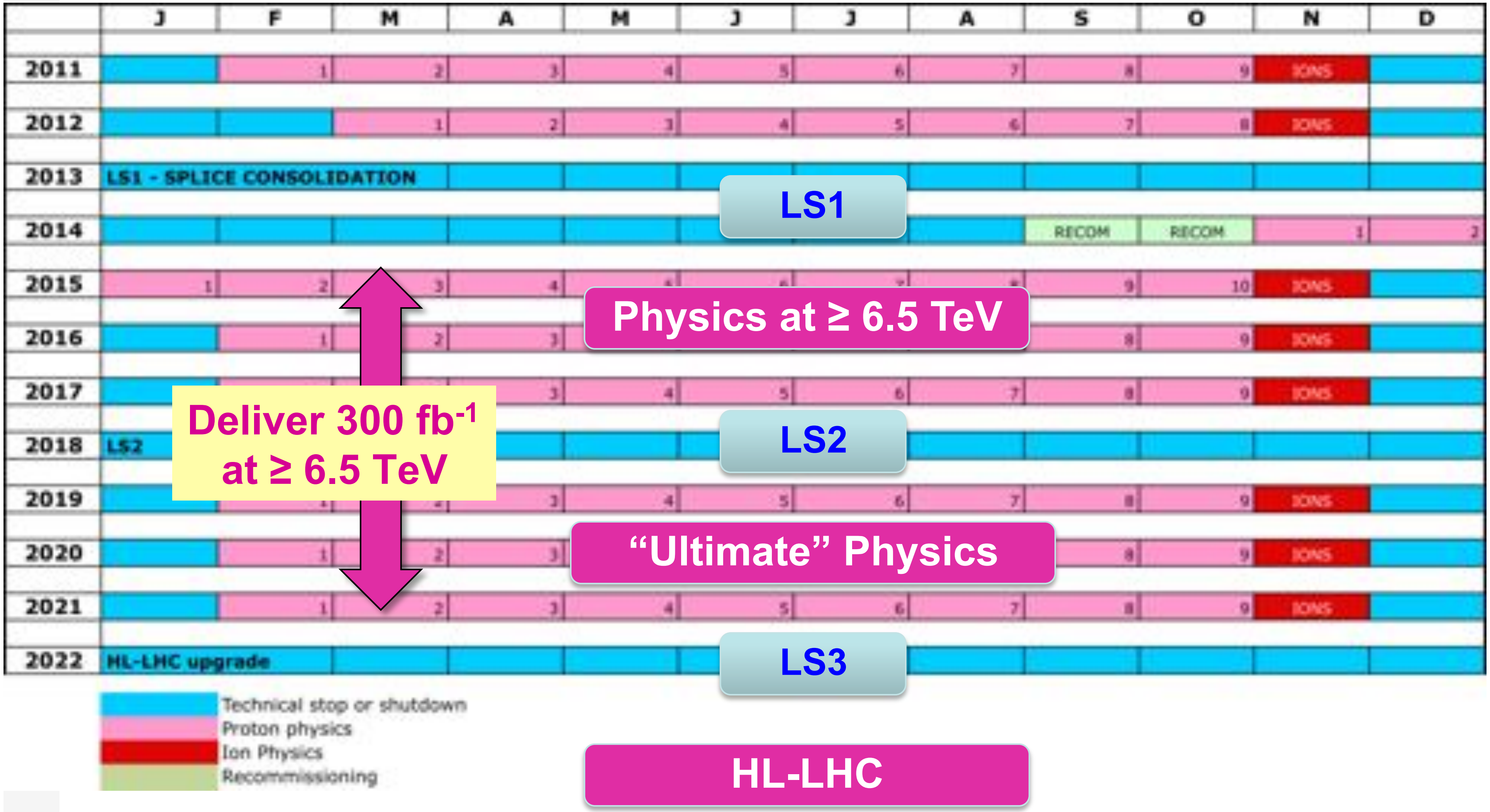
LHC operation script for 2015



- During magnet re-commissioning in 2014 we will define the target energy for the run : ≥ 6.5 TeV.
  - *Experience of 2008: 6.5 TeV OK, 7 TeV may require too much training.*
- Early in 2015 we will explore the LHC at 6.5+ TeV with low intensity.
  - *Full system commissioning up to first collisions ~ 2 months.*
- The first serious luminosity and some intensity ramp up will be made with 50 ns spacing.
  - *We think that we know how to do that!*
- This will be followed by preparation of the LHC for 25 ns operation – electron cloud reduction at injection – 2 weeks.
- …and finally intensity ramp up and production at 25 ns.

The first months of 2015 will be interesting…

The next few years



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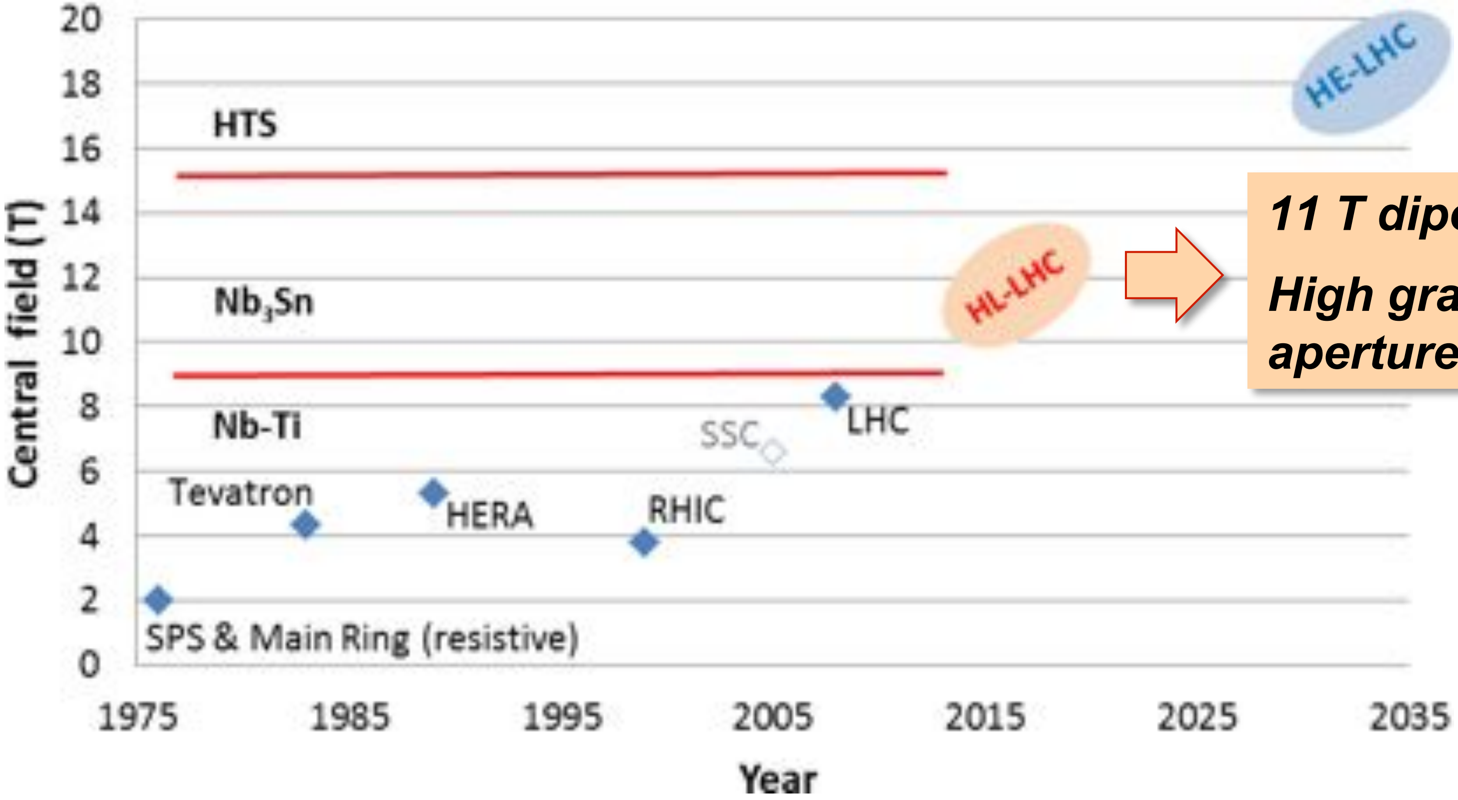
HL-LHC

- Aim for a 10-fold increase in integrated luminosity.
  - *3000 fb^{-1} in 10 years as compared to 300 fb^{-1}.*
- An increase in luminosity needed – but the event pile-up has to be controlled.
  - *Peak luminosity ≥10^{35} $cm^{-2}s^{-1}$*

    ⇔ *Smaller beam sizes at IPs, higher beam brightness*
  - *ATLAS / CMS peak luminosity ~5×10^{34} $cm^{-2}s^{-1}$, pile-up of 135 !!*
- Major accelerator component developments.
  - *Nb_3Sn large aperture quadrupoles,*
  - *11 T Nb_3Sn dipoles,*
  - *Crab-cavities.*

Higher Fields

- With HL-LHC we will see the first high(er) field Nb_3Sn magnets in an operating accelerator.

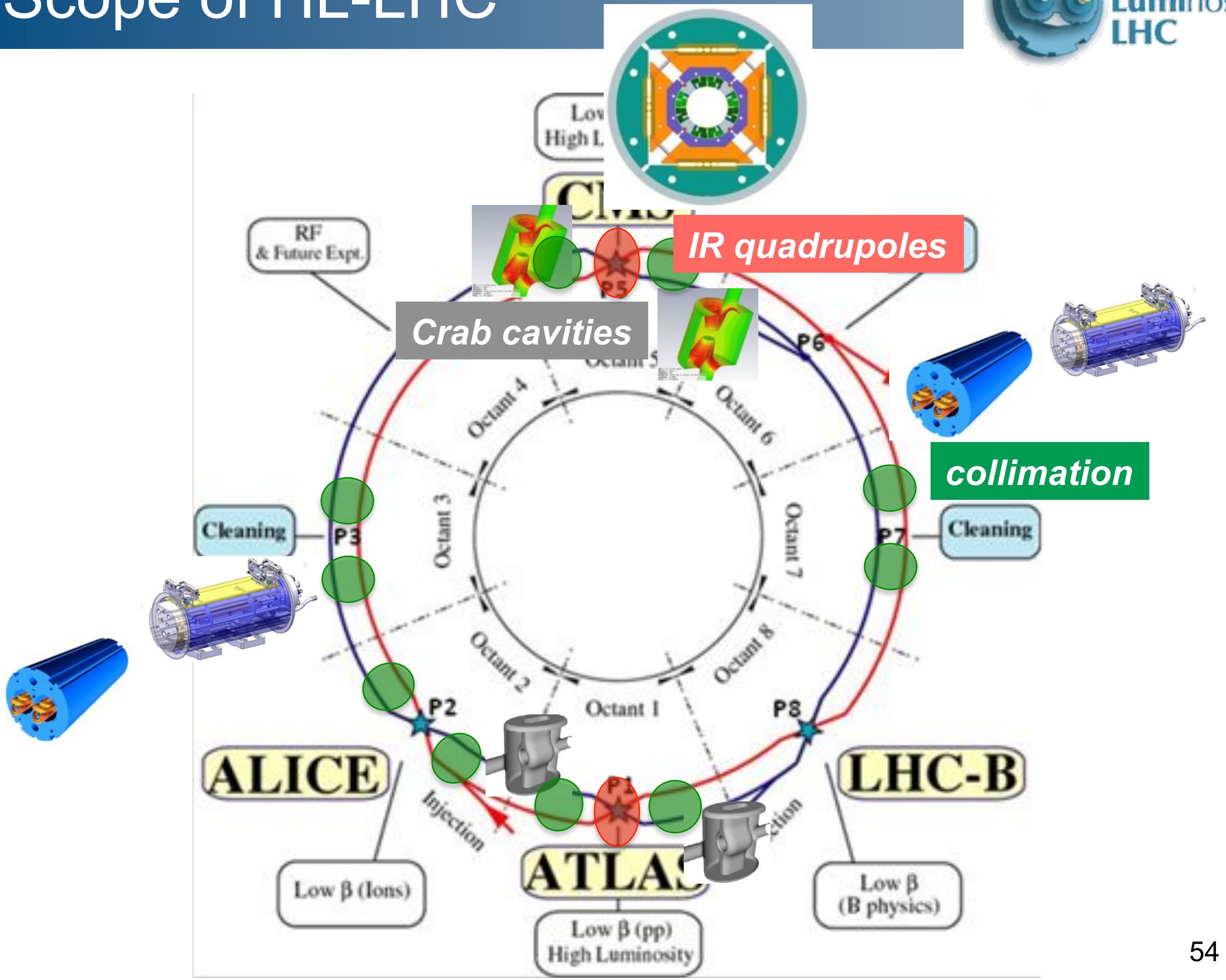


11 T dipoles

High gradient & large aperture quadrupoles

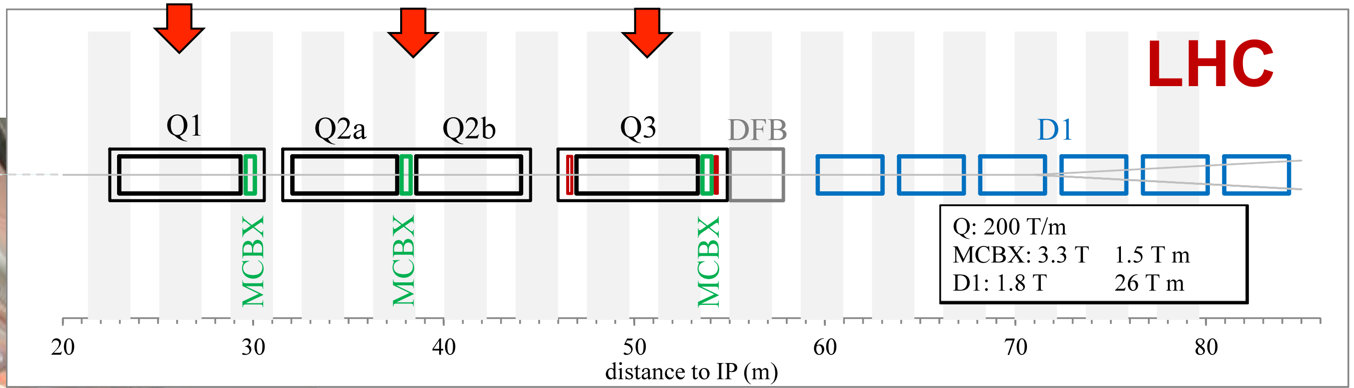
Courtesy L. Bottura & L. Rossi

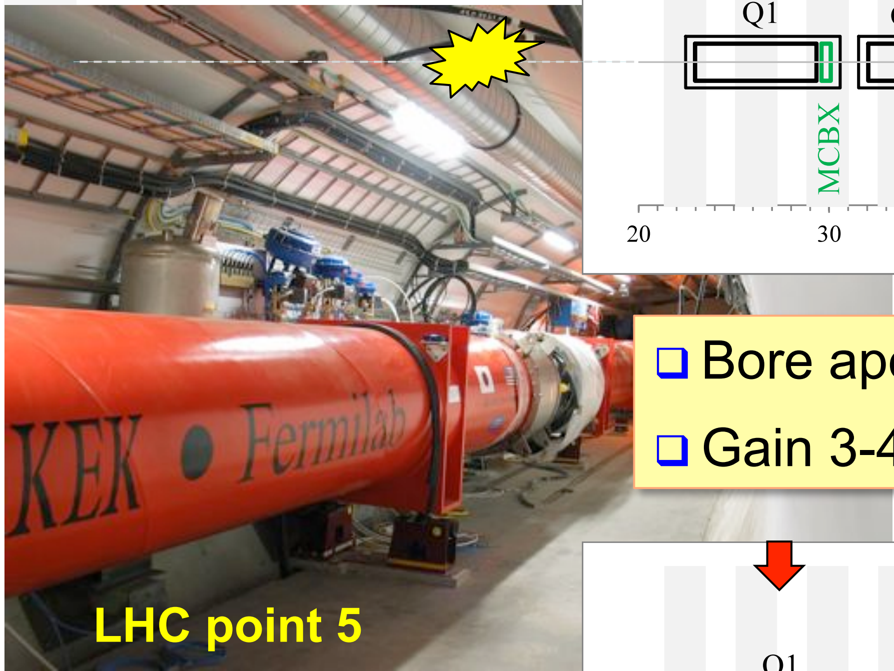
Scope of HL-LHC



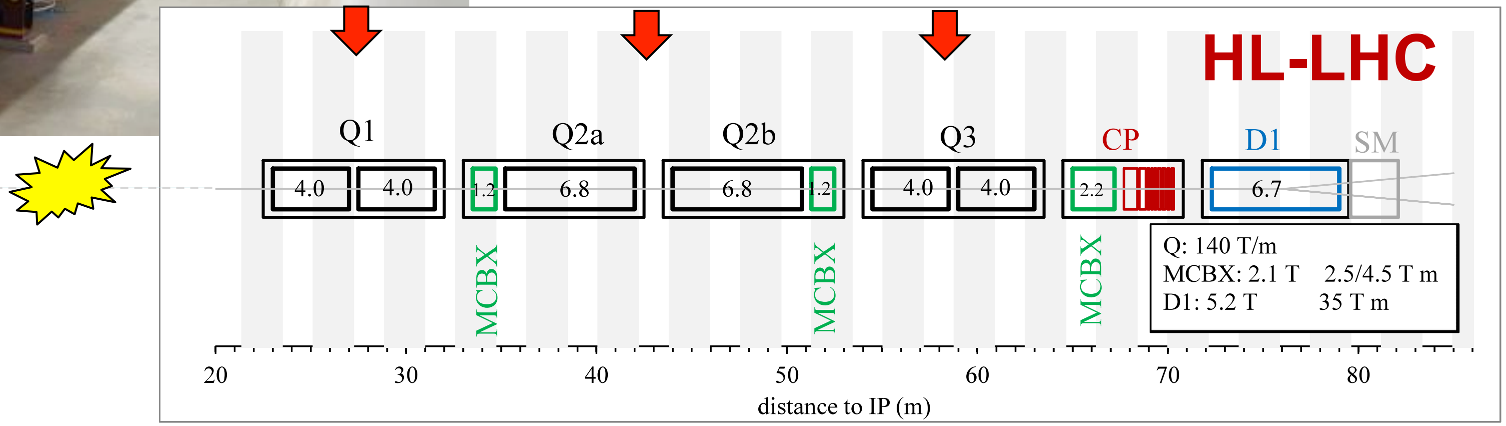
Triplet Area ATLAS/CMS

IP

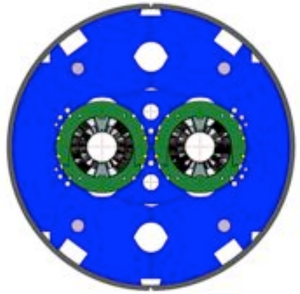




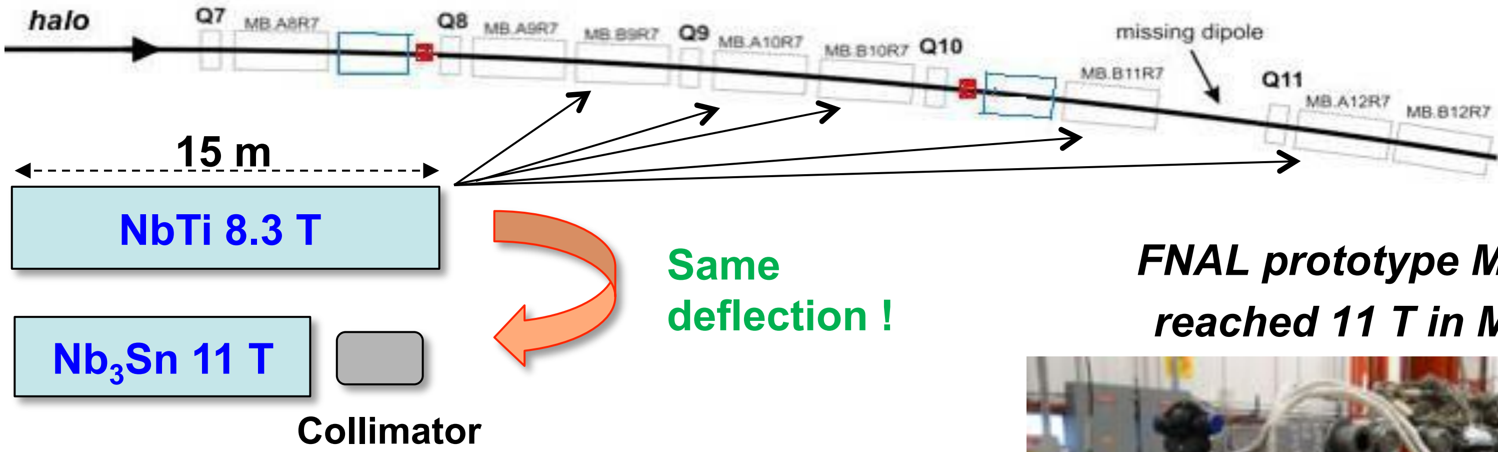
- Bore aperture : 70 → 150 mm.
- Gain 3-4 in beam area (β^* 15 cm).



High field dipoles



The goal is to develop a 10 m long 11.2 T Nb_3Sn dipole to replace a standard LHC dipole and provide space for collimators downstream of the straight sections.



- A long magnet prototype is expected in 2015, with aim to demonstrate accelerator grade quality in 2016.
- Priority / need not fully established. Review next week…

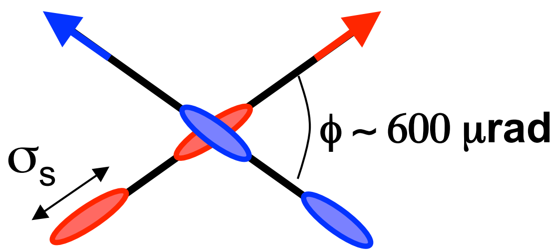
FNAL prototype MBHSP02 reached 11 T in May 2013

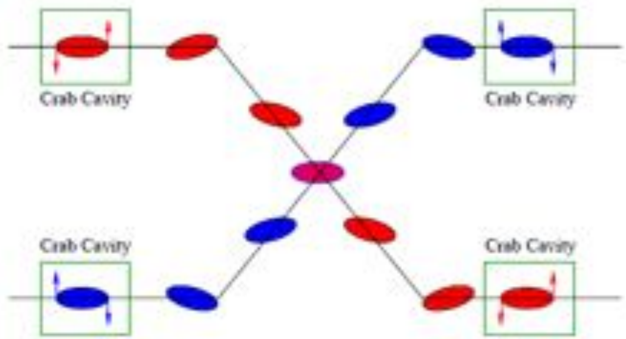
Crab-cavities

- Crab-cavities (CC) are RF cavities used to deflect the bunch head and tail transversely to counteract the luminosity loss from the large crossing angles and small beam sizes at HL-LHC.
  - *To be installed on both sides of ATLAS and CMS.*

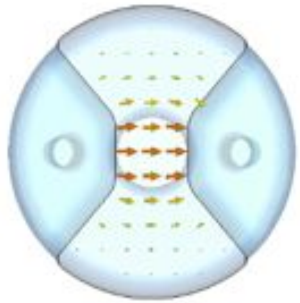
$$\frac{L_0}{\sqrt{1+\left(\frac{\sigma_s \phi}{2\sigma_{x/y}}\right)^2}} \approx \frac{L_0}{5} \rightarrow L_0$$

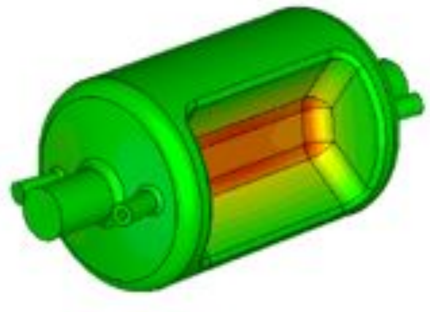
no CC





Transverse Electric Field

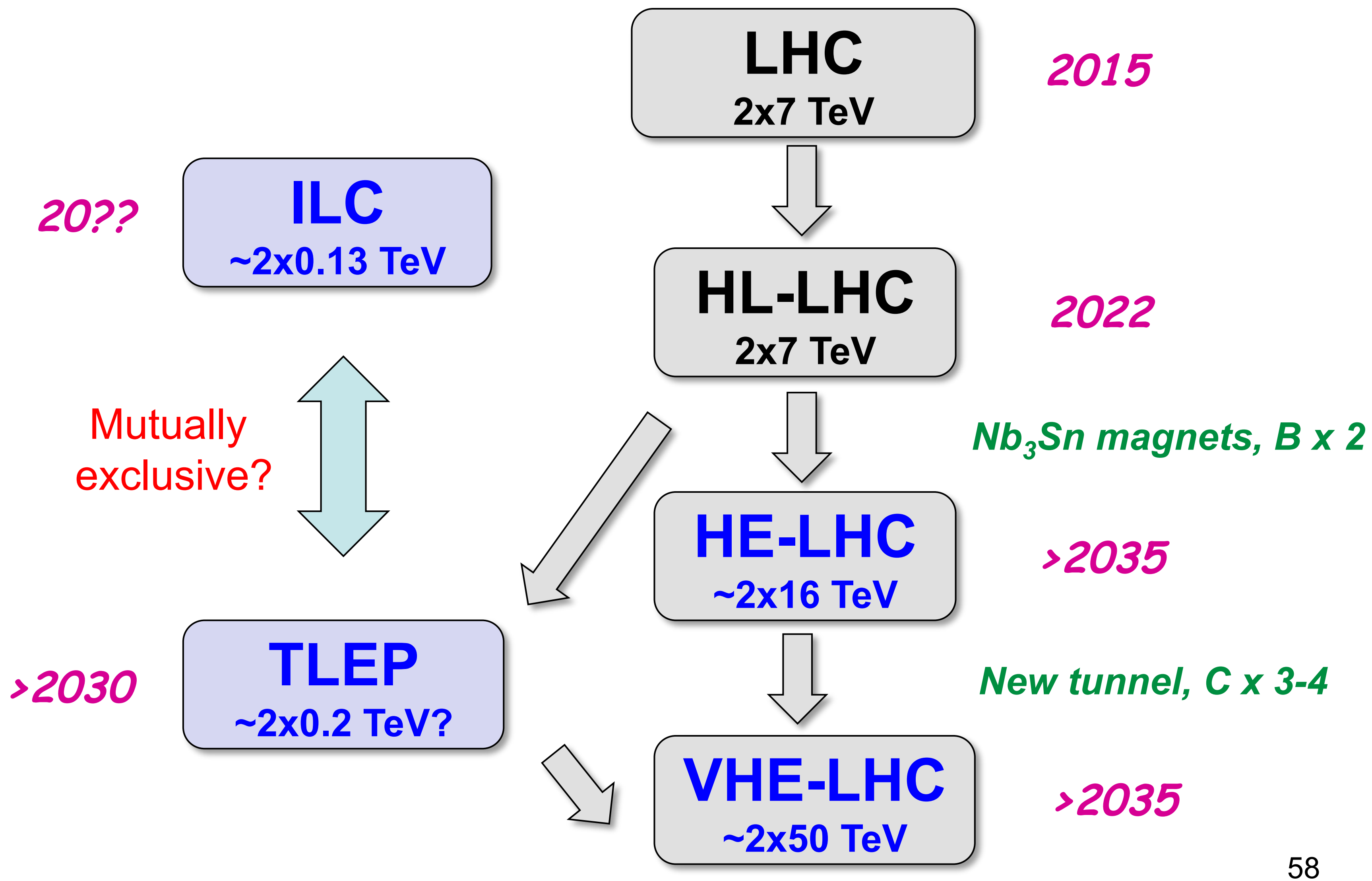




- CCs have never been used in a hadron machine - there are many challenges: noise on the beam, machine protection etc.

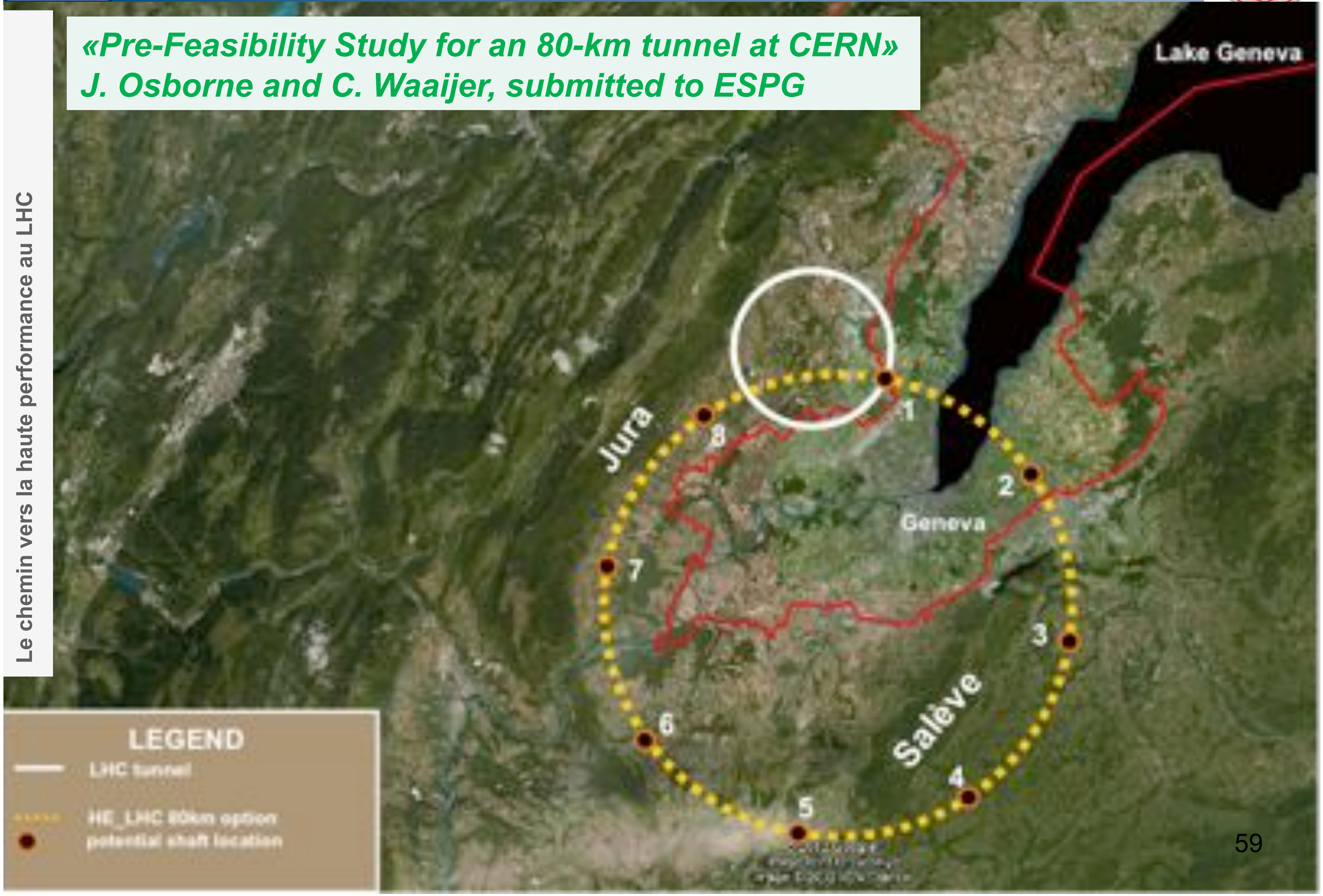
And then?

Lepton line   Hadron line



80 km tunnel study

«Pre-Feasibility Study for an 80-km tunnel at CERN»
J. Osborne and C. Waaijer, submitted to ESPG

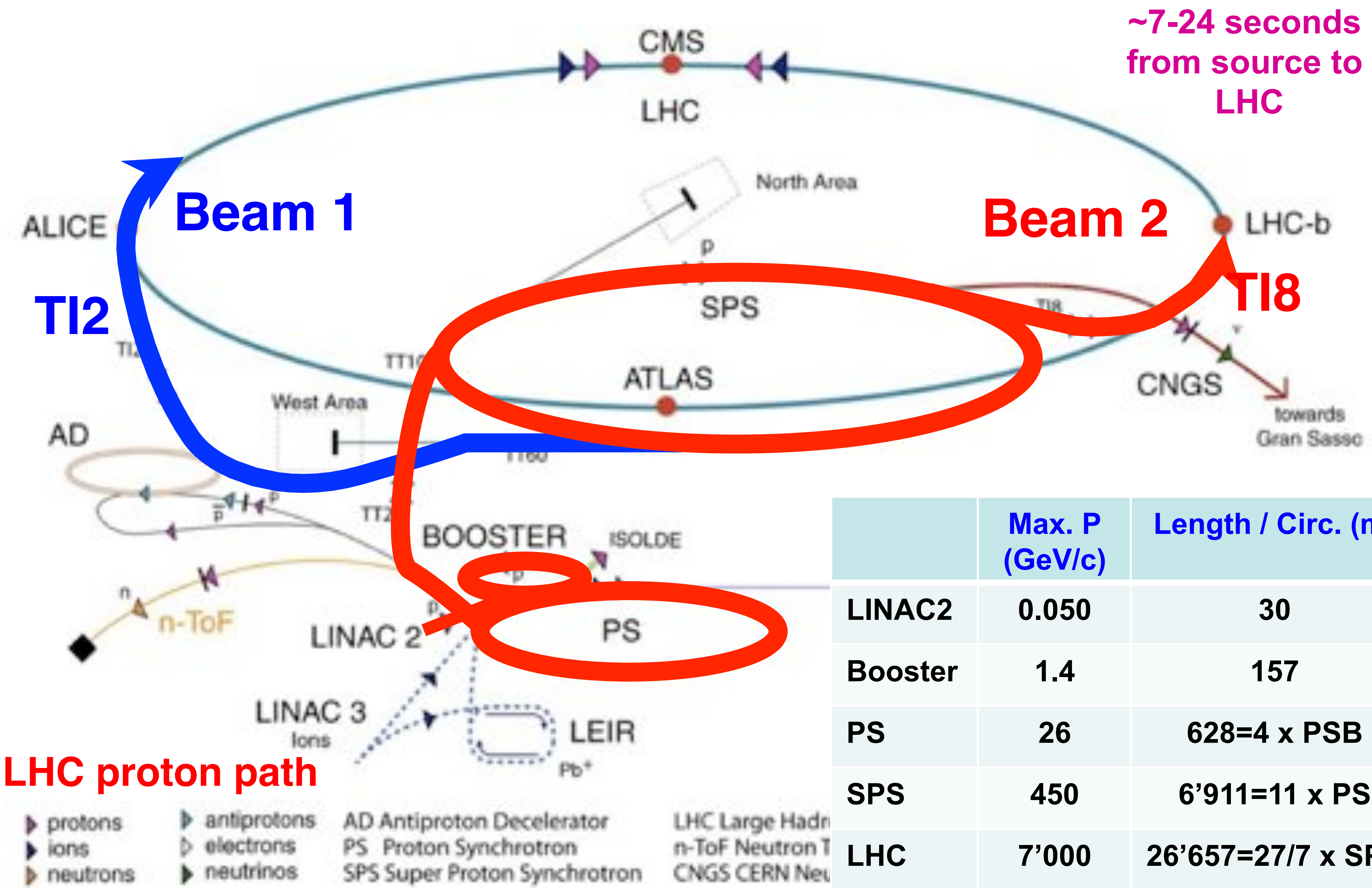


Outlook

- The progress in the performance of the LHC has been breath-taking.
  - *We are the first to be amazed – above design after 3 years !*
- The LHC is performing better than expected - thanks to the quality of the design, the construction, the operation and the injectors.
  - *The interface of the magnets was the only weak spot…*
- Expectations for 2015 are very high – the work to meet them is in full swing (and not just in the tunnel).
  - *Guido and Fabiola are waiting for the next party !*

Thank you for the attention!

LHC accelerator complex



	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

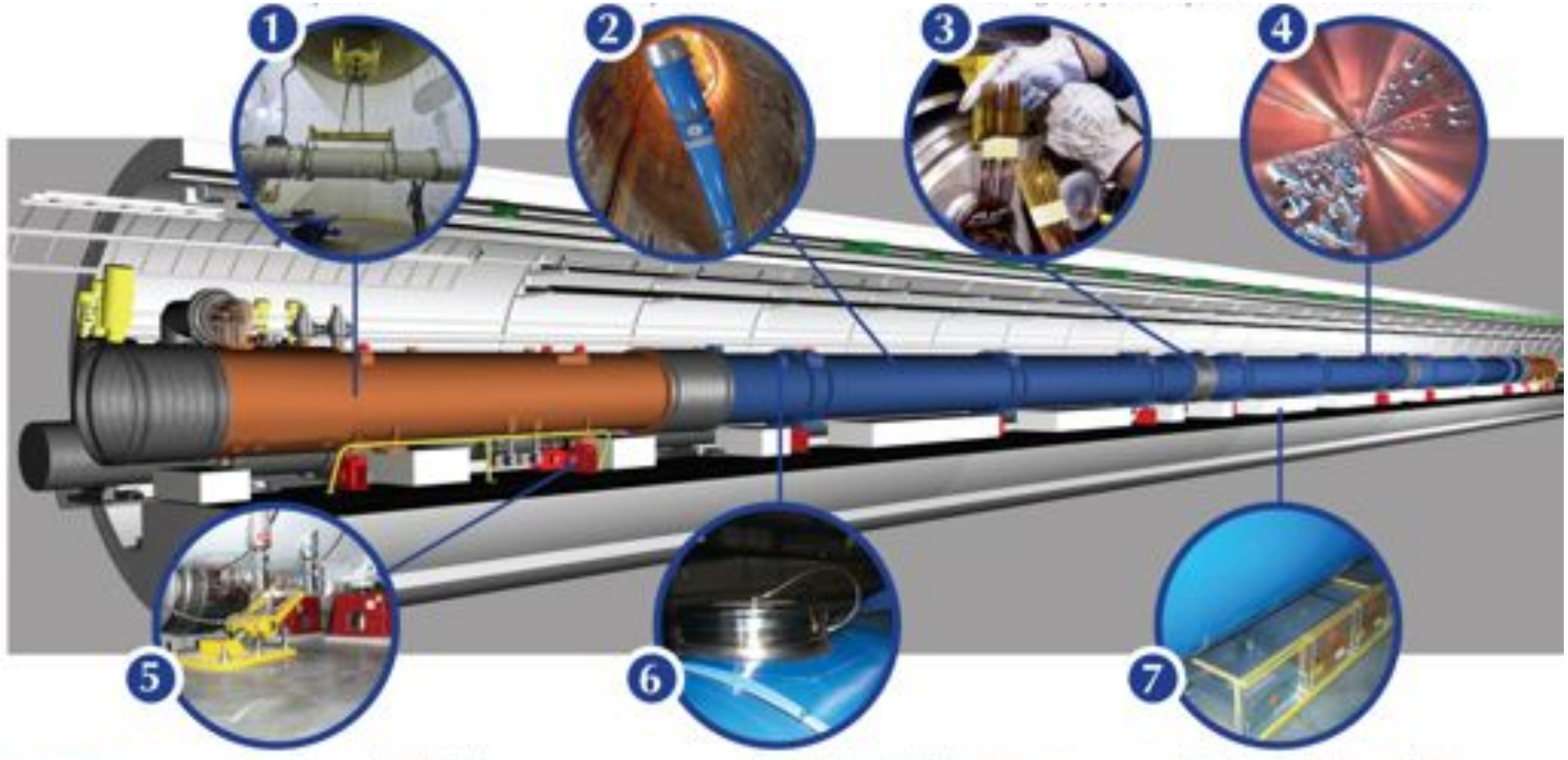
LHC repair and consolidation

14 quadrupole magnets replaced

39 dipole magnets replaced

204 electrical inter-connections repaired

Over 4km of vacuum beam tube cleaned



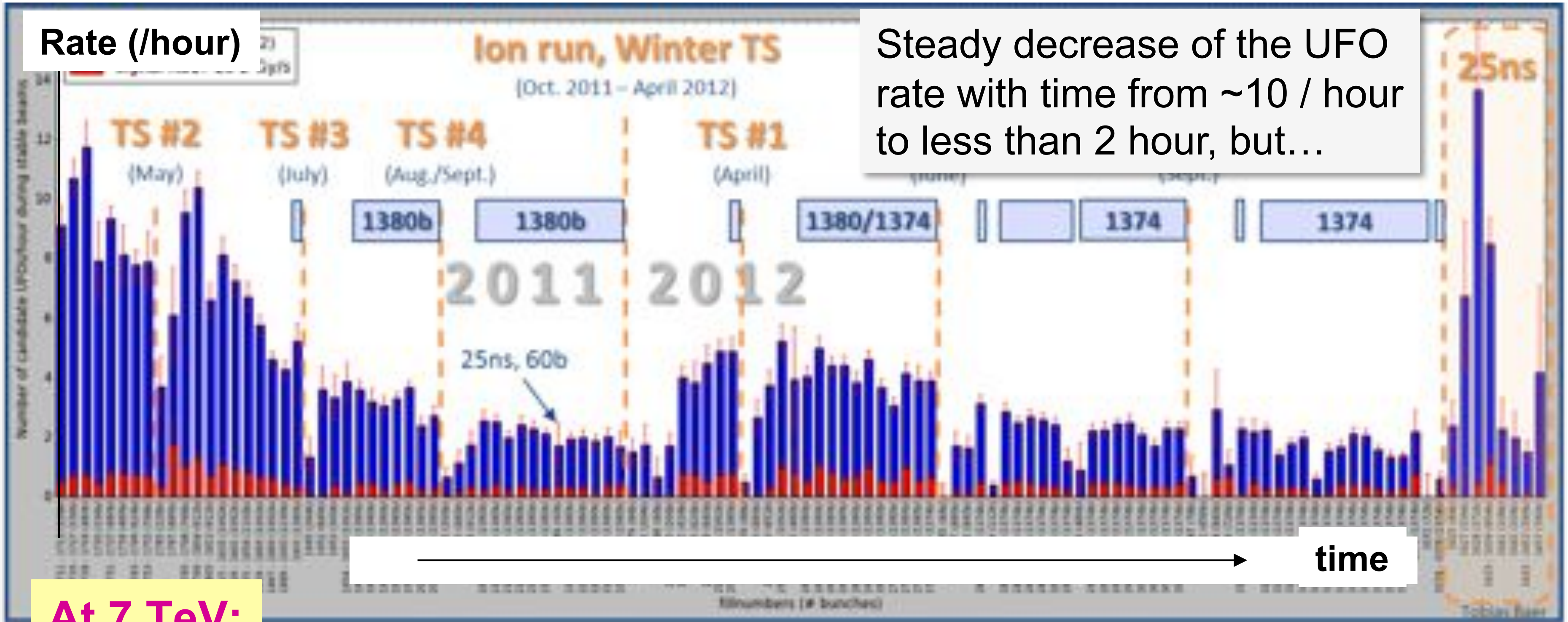
New longitudinal restraining system for 50 quadrupoles

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

UFO frequency and future issues

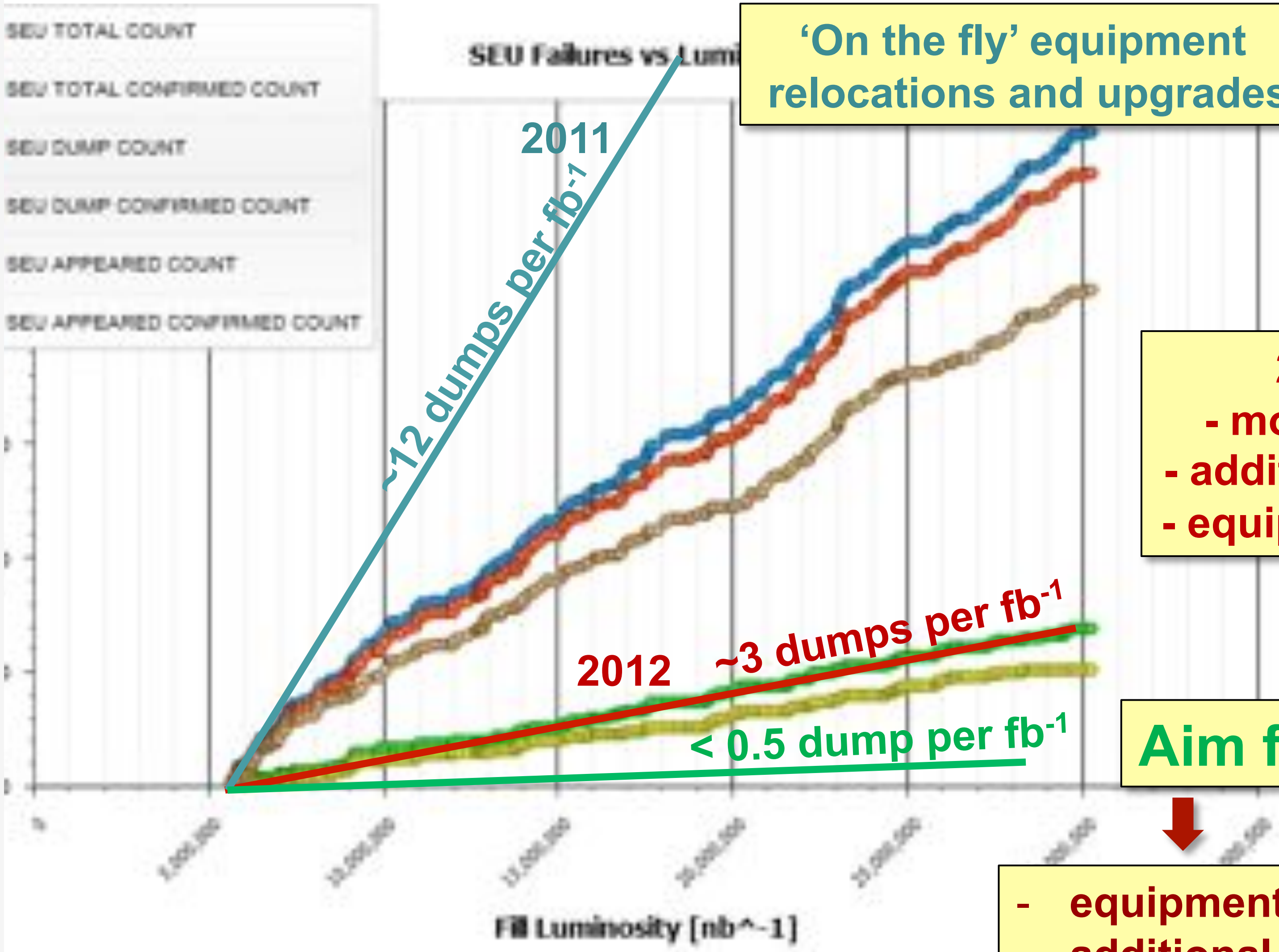


At 7 TeV:

- The energy deposition in the magnets will increase by a factor 2-3,
- The tolerable loss will go down by a factor 4-5 (quench margin smaller),

→ at 7 TeV UFOs could cause one beam loss / dump per DAY !!
Could become a serious issue !!

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.

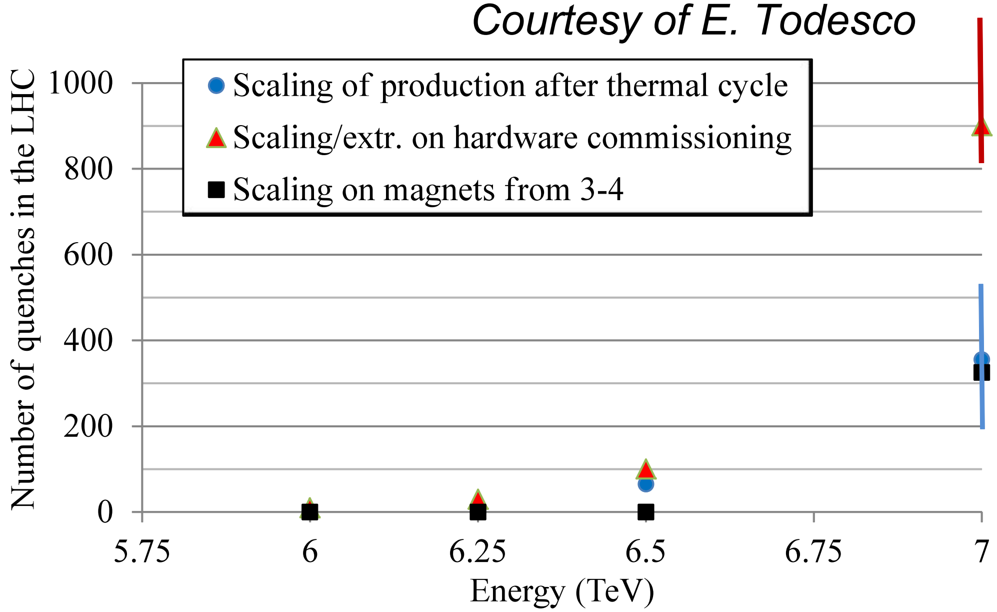
Courtesy G. Spezia

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 showed that the number of training quenches required to reach 7 TeV is rather large.
  - *Time and risk for 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.



Parameters and challenges

	LHC	HL-LHC	HE-LHC	VHE-LHC
Energy (TeV)	7	7	16	50
Dipole B (T)	8.33	8.33	20	20
Injection (TeV)	0.45	0.45	>1	>3 (?)
No. bunches	2800	2800	2800	8400
Stored energy (MJ)	360	~700	~600	5400
SR* power (W/m)	0.2	0.4	4	36
L (10^{34} $cm^{-2}s^{-1}$)	1	5	5	5
Events / BC*	27	135	135	135

- New injectors,
- Stored energy in the beams,
- Heat load on the vacuum chamber.

Performance limited by event pile-up !?

SR* = Synchrotron radiation, BC* = Bunch crossing

Event sequence on Sept. 19th

- Last commissioning step of the main dipole circuit in sector 34 : ramp to 9.3kA (5.5 TeV).
- At 8.7kA an electrical fault developed in the **dipole bus bar** located in the interconnection between quadrupole Q24.R3 and the neighboring dipole.

  Later correlated to a local resistance of ~220 nΩ – nominal value 0.35 nΩ.

- An electrical arc developed which punctured the helium enclosure.

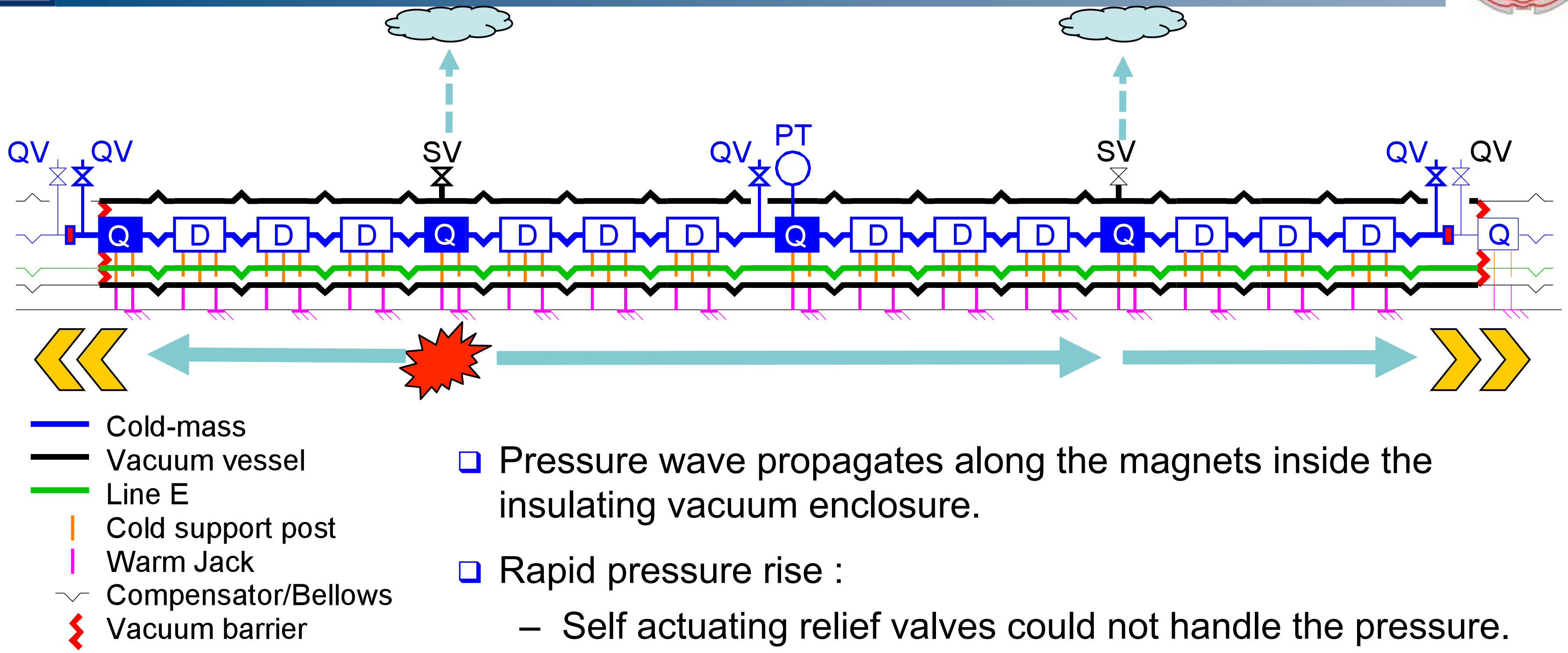
  Secondary arcs developed along the arc.

  Around 400 MJ from a total of 600 MJ stored in the circuit were dissipated in the cold-mass and in electrical arcs.

- Large amounts of Helium were released into the insulating vacuum.

  In total 6 tons of He were released.

Pressure wave



- Pressure wave propagates along the magnets inside the insulating vacuum enclosure.
- Rapid pressure rise :
  - Self actuating relief valves could not handle the pressure.
    designed for 2 kg He/s, incident ~ 20 kg/s.
  - Large forces exerted on the vacuum barriers (every 2 cells).
    designed for a pressure of 1.5 bar, incident ~ 8 bar.
  - Several quadrupoles displaced by up to ~50 cm.
  - Connections to the cryogenic line damaged in some places.
  - Beam vacuum to atmospheric pressure.