Achievements from the LHC machine

Mike Lamont for the LHC team

- The challenges encountered in run 1
- The prospects for run 2
- Longer perspectives up to 2035
- Describe what worked better than planned, what was more difficult than planned, and the lessons learnt for the future.

And some things that should not have been forgotten were lost. History became legend, legend became myth.

Myth

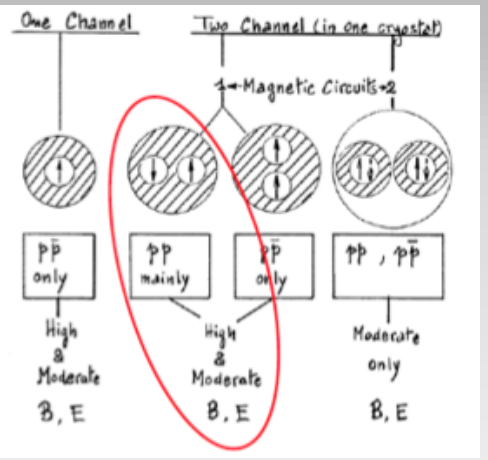
A traditional story, esp. one that involves gods and heroes and explains a cultural practice or natural phenomenon.

- Conception
- Birth
- Initiation
- Descent into the underworld
- Trial and Quest with the possibility of Hubris followed by Nemesis
- Withdrawal from community for meditation and preparation
- Resurrection and rebirth
- Ascension, apotheosis, and atonement

Repeat as required

And they often involve rings

Conception

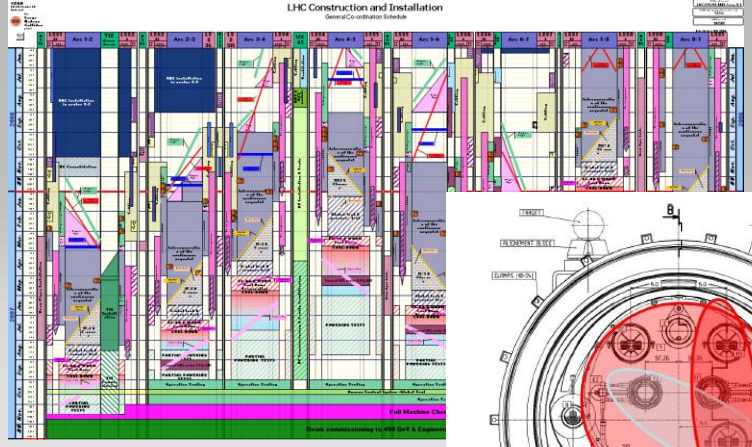


Initiation

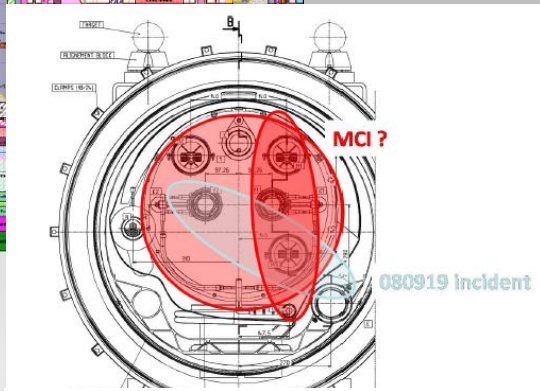
LHC approved by the Elders

Rival stumbles

SSC cancelled



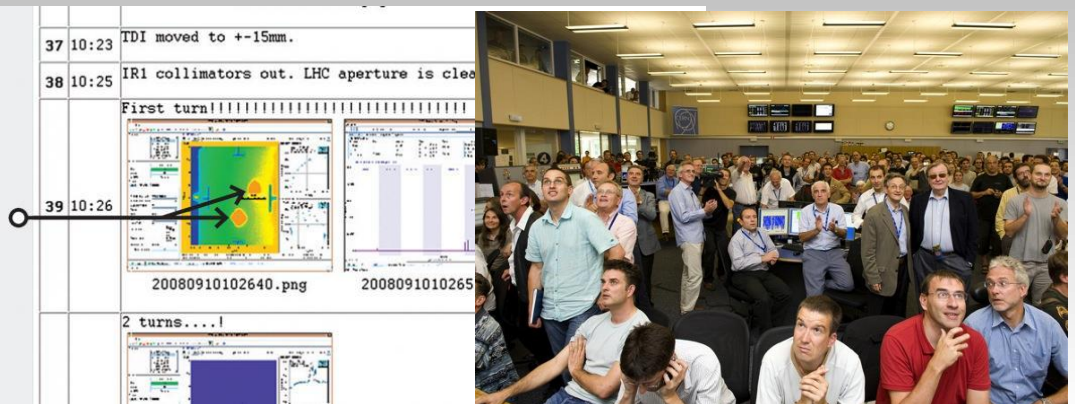
Birth – overdue



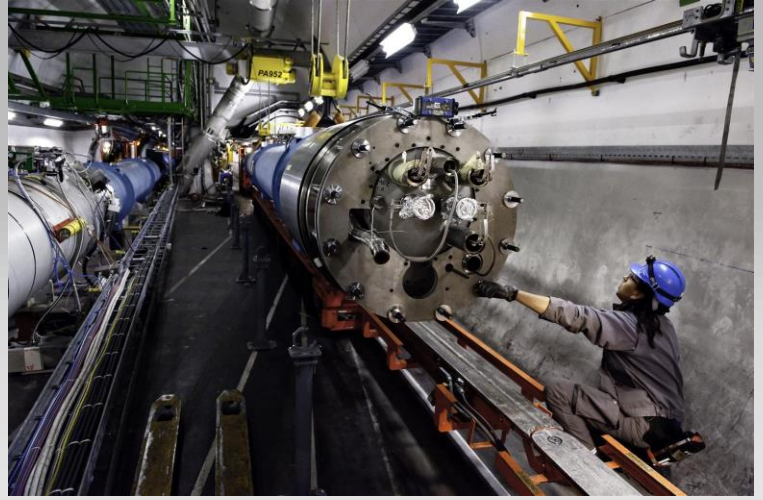
Withdrawal from community for mediation and preparation

198 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10

Hubris (?) September 10, 2008



Nemesis September 19, 2008

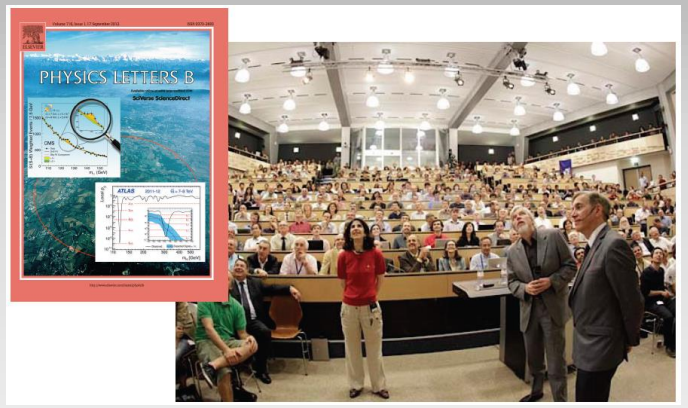


Trial/descent in the underworld

November 29, 2009

Resurrection and rebirth

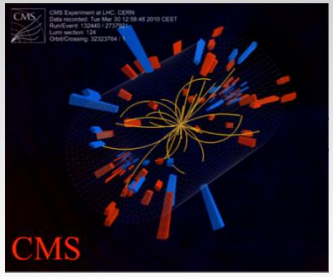
Apotheosis and atonement



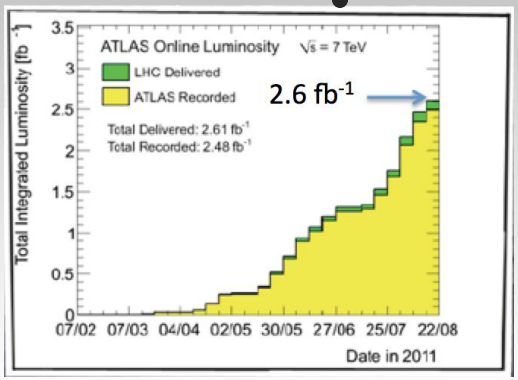
4 July, 2012

2009 | 2010 | 2011 | 2012 | 2013

March 30, 2010
First collisions at 3.5 TeV



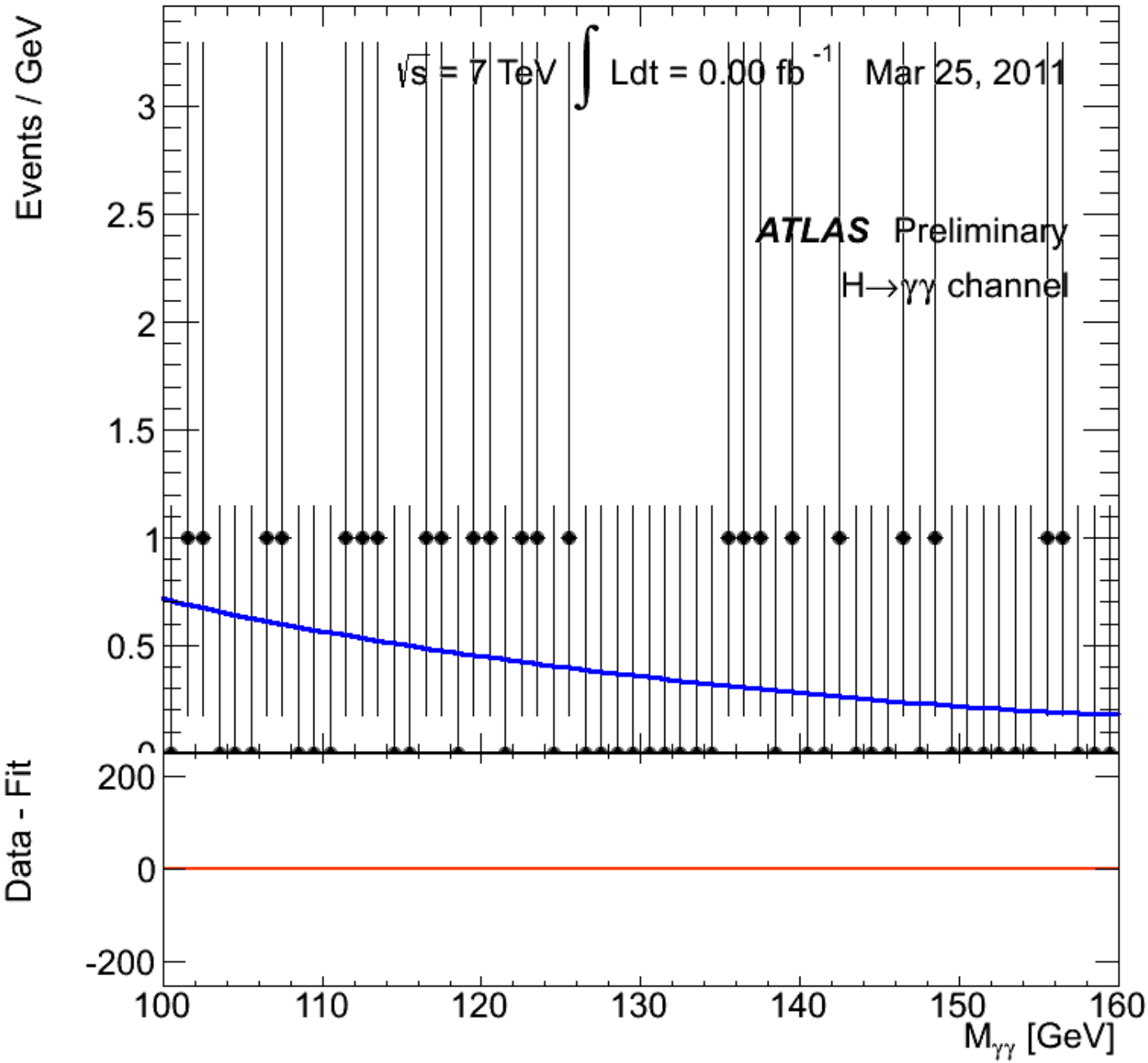
Ascension



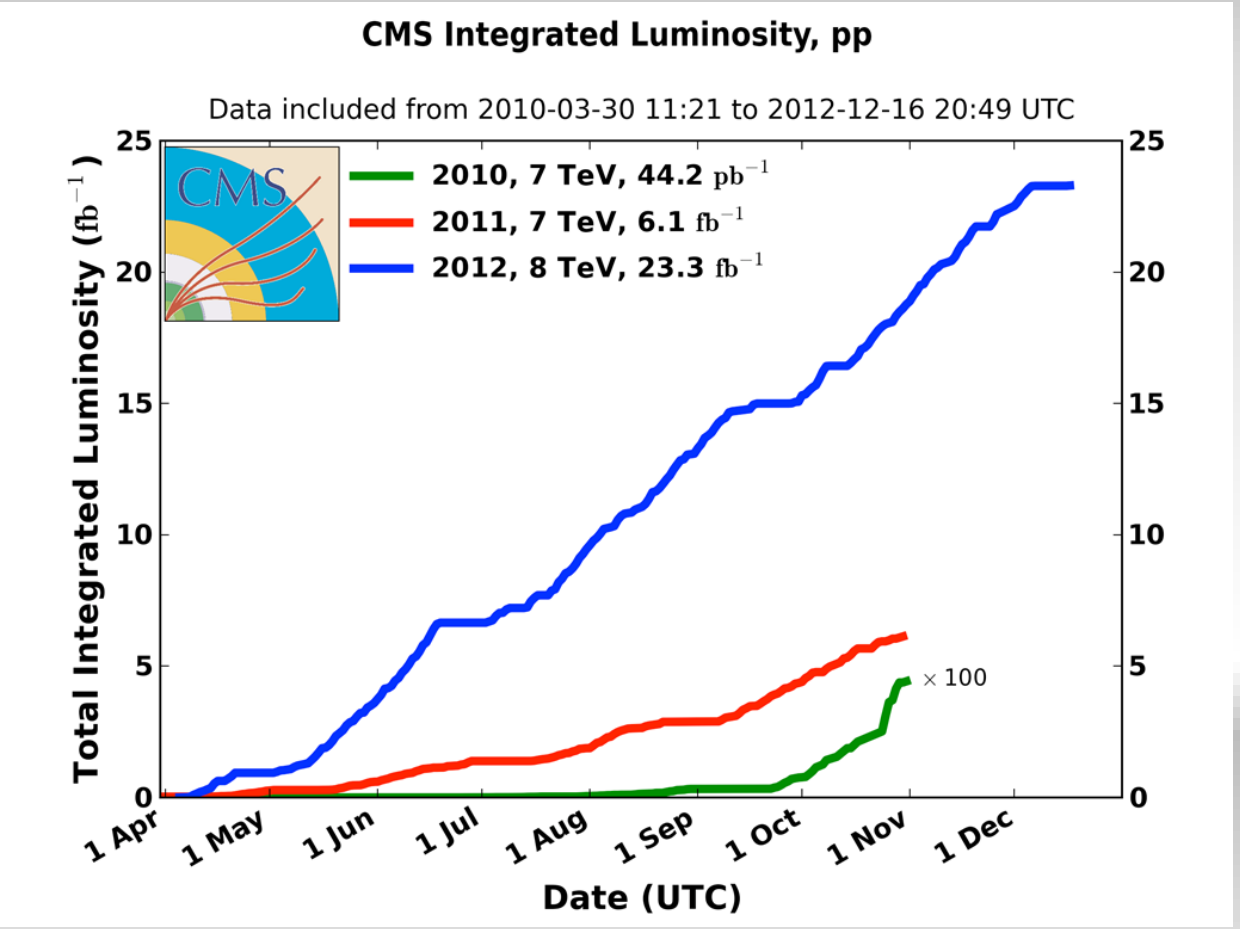
Heroic subplot

And let us not forget Fortuna

- Late
- Over budget
- Blew it up after 9 days
- Costly, lengthy repair
- Rival coming up fast on the outside
- Had to run at half energy
- And yet…


√s = 7 TeV ∫ Ldt = 0.00 fb -1 Mar 25, 2011
ATLAS Preliminary
H→γγ channel
Events / GeV
Data - Fit
M γγ [GeV]
3
2.5
2
1.5
1
0.5
200
0
-200
100
110
120
130
140
150
160

Integrated luminosity 2010-2012



- 2010: **0.04 fb^{-1}**
  - 7 TeV CoM
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - 7 TeV CoM
  - Exploring the limits
- 2012: **23.3 fb^{-1}**
  - 8 TeV CoM
  - Production

This was not luck.

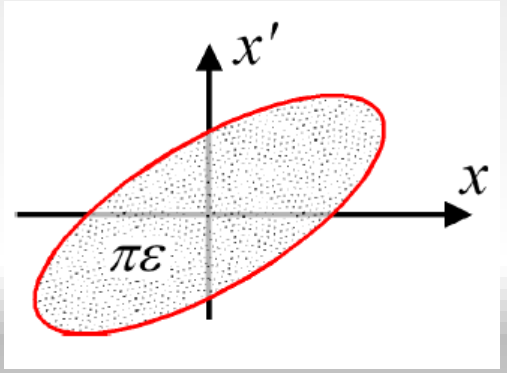
It was important.

It was important.

Luminosity

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

N	**Number of particles per bunch**
k_b	**Number of bunches**
f	Revolution frequency
σ*	**Beam size at interaction point**
F	Reduction factor due to crossing angle
ε	Emittance
ε_n	**Normalized emittance**
β*	**Beta function at IP**



$$s^* = \sqrt{\beta^* \varepsilon}$$

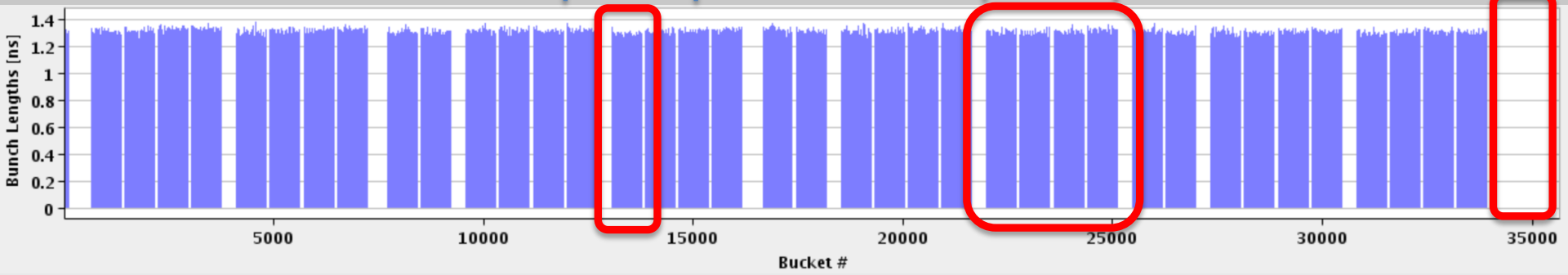
$$\varepsilon_n = \beta\gamma\varepsilon$$

Round beams, beam 1 = beam 2

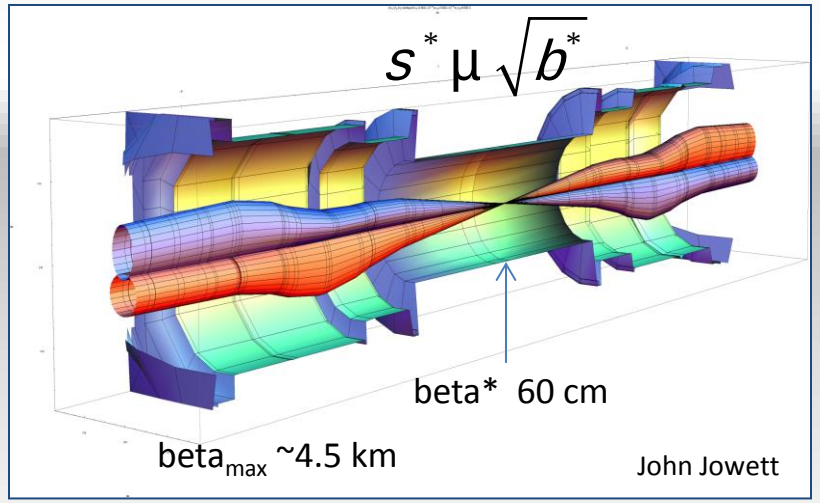
1 PS batch
(36 bunches)

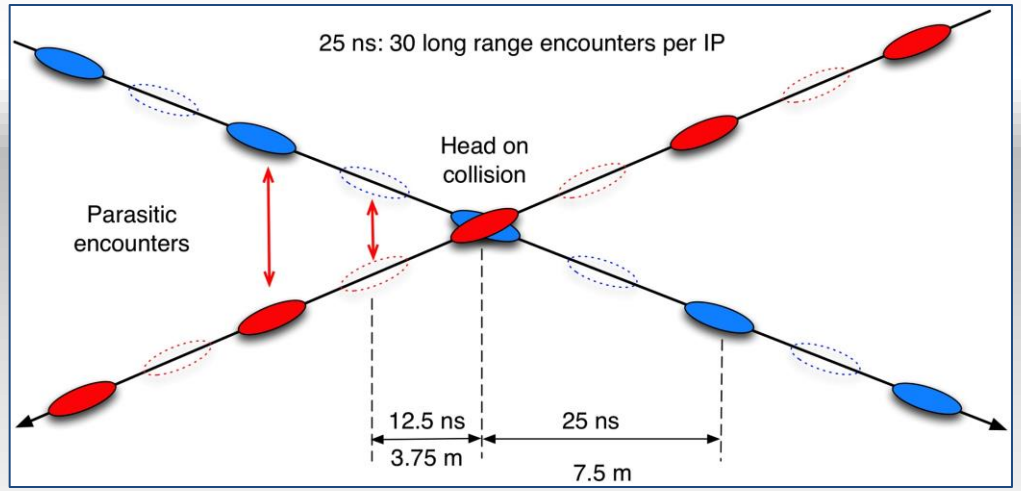
1 SPS batch
(144 bunches)

Abort gap



26.7 km - 1380 bunches in 2012, ~2800 in 2015

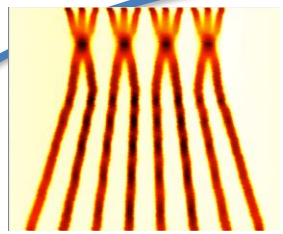




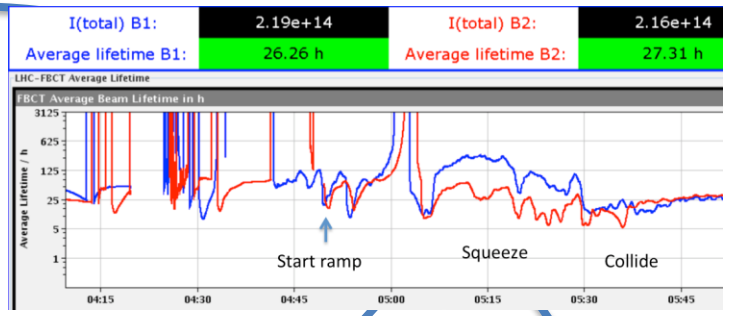
Peak performance through the years

	2010	2011	2012	Nominal
Bunch spacing [ns]	150	50	50	25
No. of bunches	368	1380	1380	2808
beta* [m] ATLAS and CMS	3.5	1.0	0.6	0.55
Max **bunch intensity** [protons/bunch]	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
Normalized **emittance** [mm.mrad]	~2.0	~2.4	~2.5	3.75
Peak luminosity [$cm^{-2}s^{-1}$]	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}	1.0×10^{34}

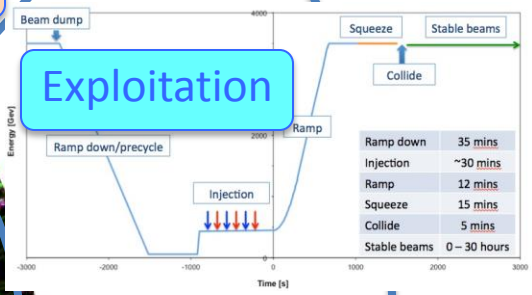
Teamwork



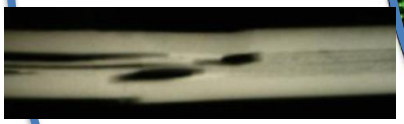
Beam from injectors



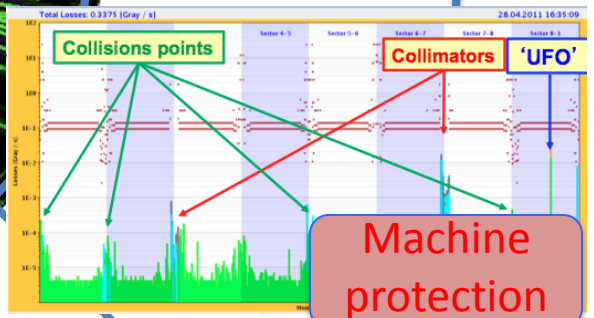
Beam in LHC



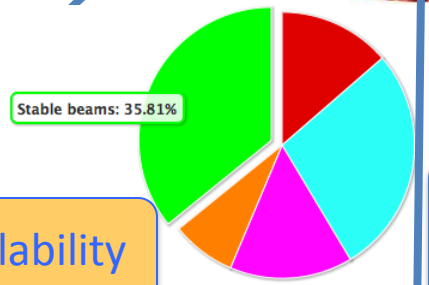
Exploitation



Mitigation



Machine protection



System performance

Availability

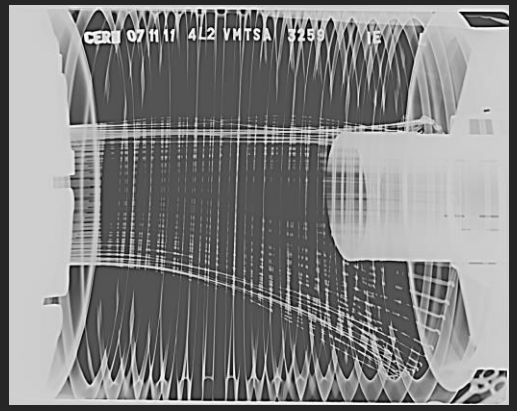
RF, power converters, collimators, beam dumps, injection, magnets, vacuum, transverse feedback, machine protection, magnets, magnet protection, beam instrumentation, beam based feedbacks, controls, databases, high level software, cryogenics, survey, technical infrastructure, access, radiation protection

LHC Eightfold Path

Some Run 1 challenges…

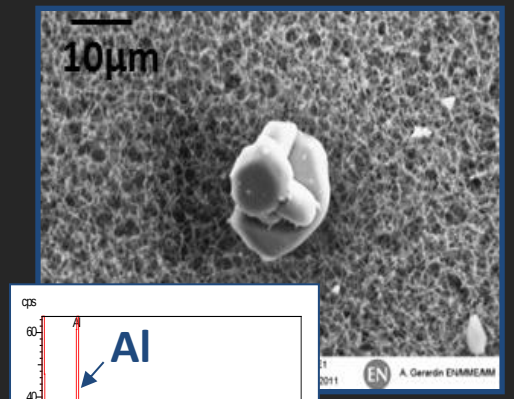
Beam induced heating

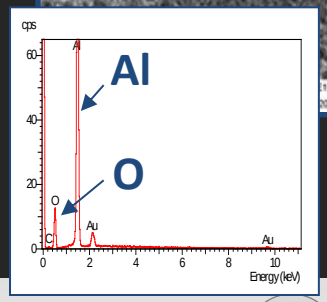
- Local non-conformities (design, installation)
  - Injection protection devices
  - Sync. light mirrors
  - Vacuum assemblies



UFOs

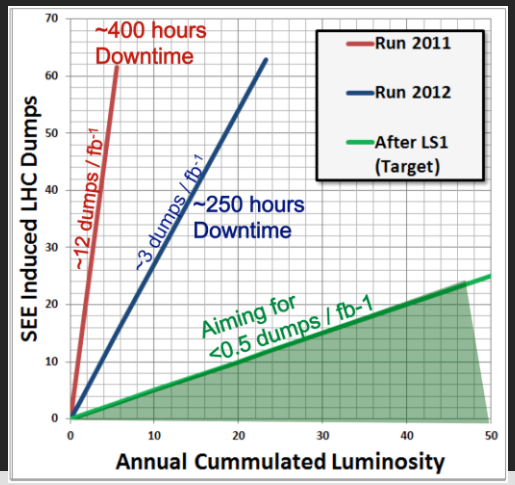
- 20 dumps in 2012
- Timescale 50-200 µs
- Conditioning observed
- Worry about 6.5 TeV





Radiation to electronics

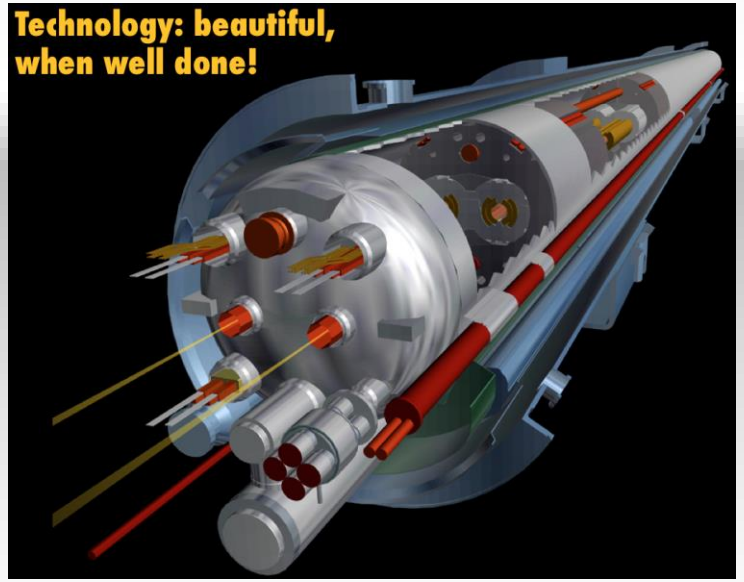
- Concerted program of mitigation measures (shielding, relocation…)
- Premature dump rate down from 12/fb^{-1} in 2011 to 3/fb^{-1} in 2012

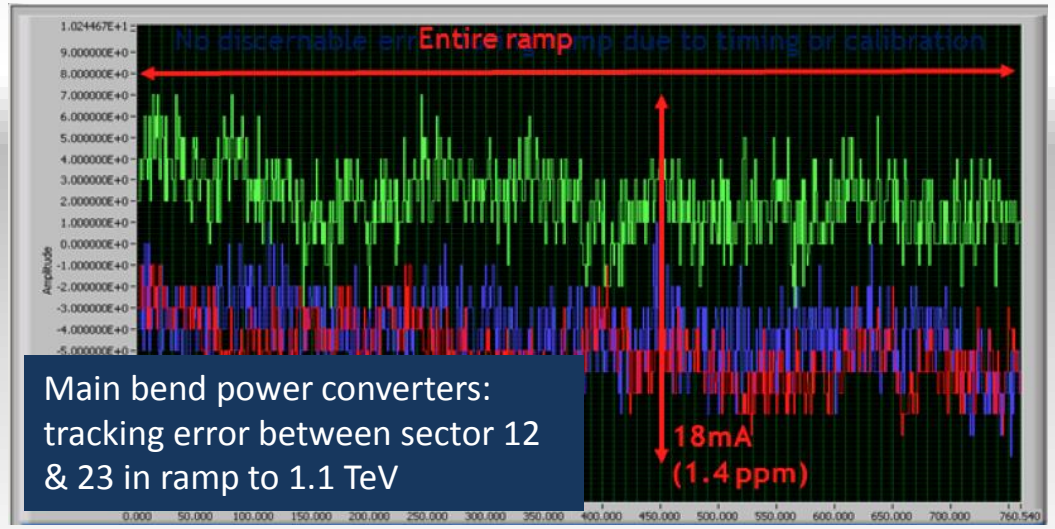


Meta-lessons (1/2)

Up to near design performance
(at lower than design energy) reasonably quickly

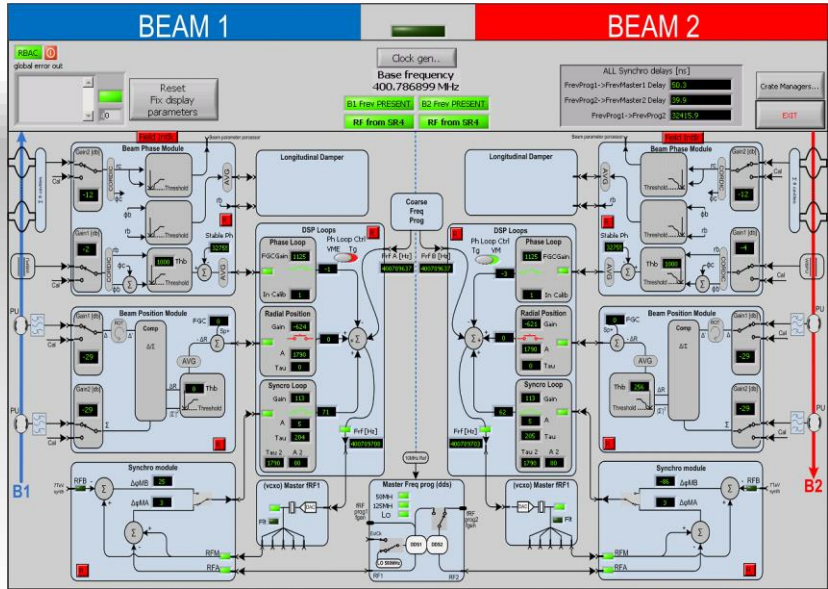
- Foundations
  - Superconducting magnets – long development, industrialization, **quality control**
  - Vacuum, cryogenics, RF, powering, **protection**





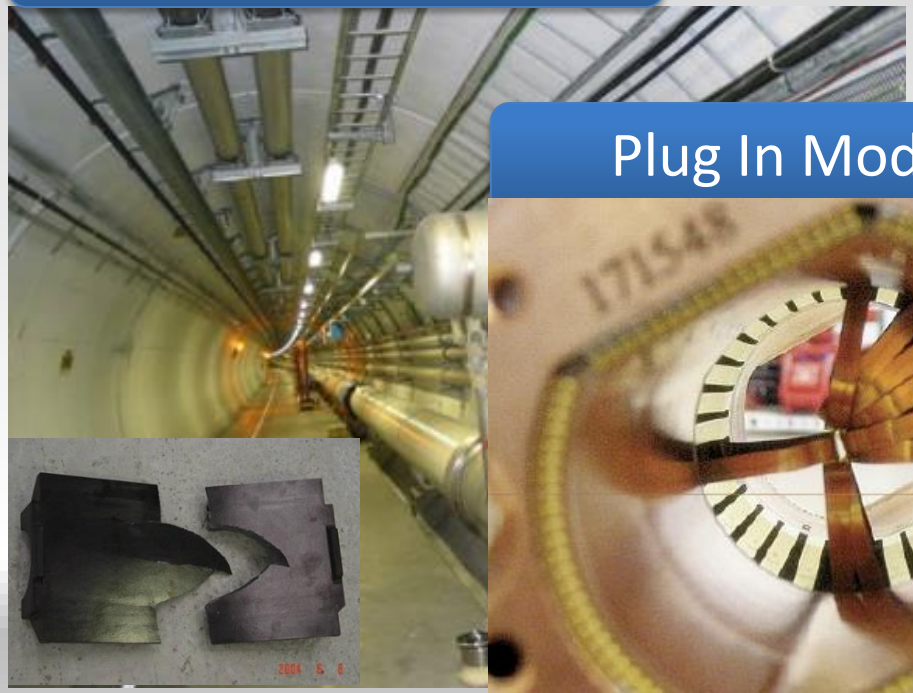
Meta-lessons (2/2)

- System expertise and experience
  - Continuity, compartmentalization
  - LEP: cryogenics, S/C RF, operations
  - Ability to tackle problems…
- Preparation
  - Dry runs, tests with beam, hardware commissioning
  - **We were late…** “Unprecedented state of readiness”
- Exploitation
  - Systems (Beam Instr., controls…)
  - Resources
  - Understanding
  - Technology



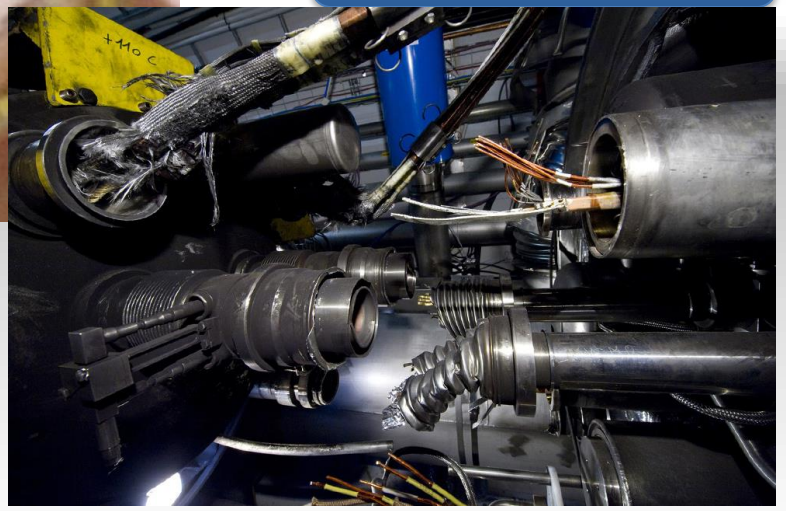
Ability to tackle problems…

Cryogenic supply line



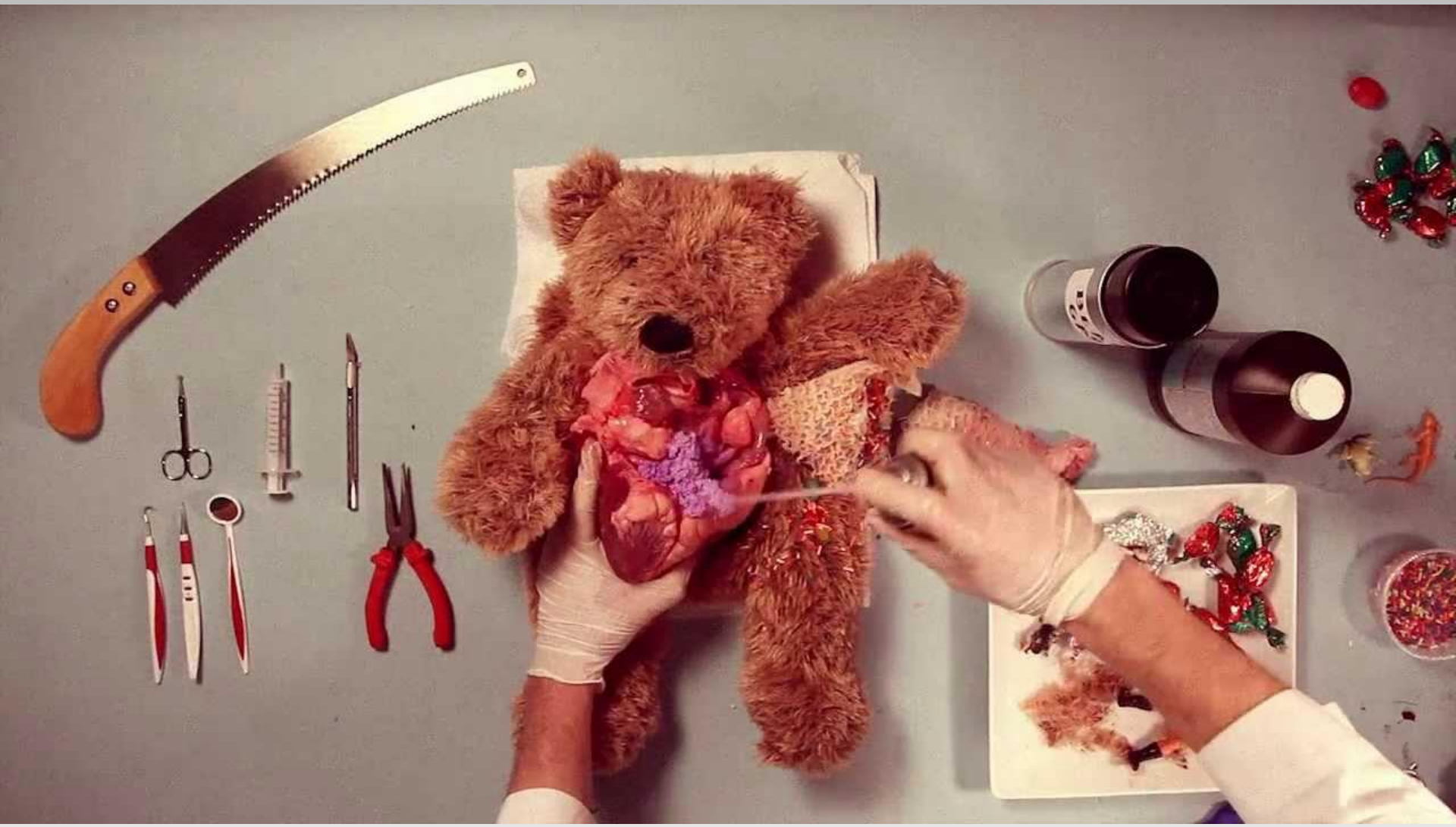
Plug In Modules

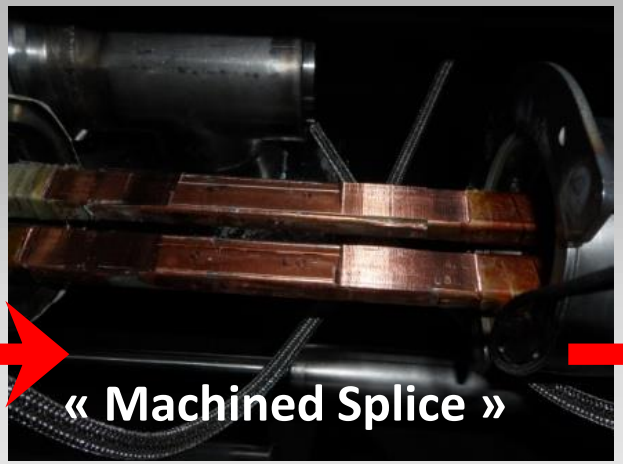
The incident

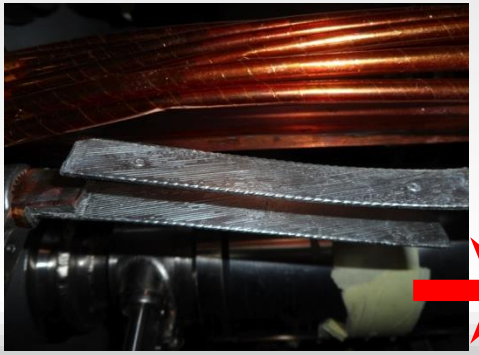


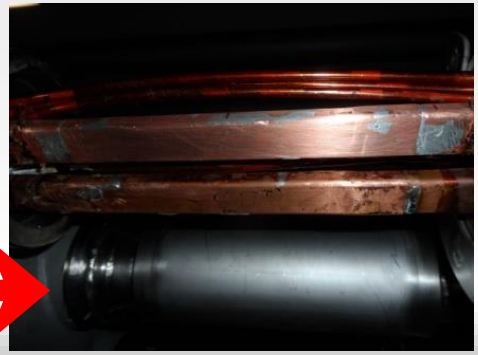
The LHC has undergone open heart surgery

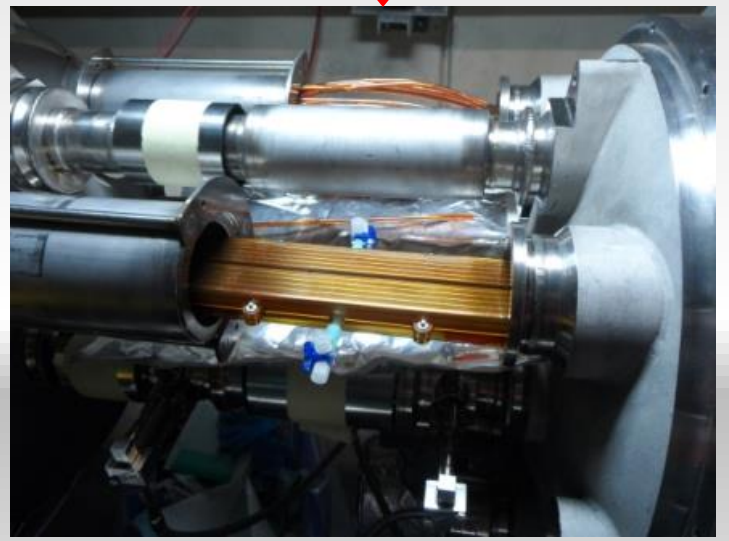
Descent into the underworld






« Cables »


« New Splice »


« Insulation box »

- Total interconnects in the LHC:
  - 1,695 (10,170 high current splices)
- Number of splices redone: ~3,000 (~ 30%)
- Number of shunts applied: > 27,000

And a lot more besides…

Superconducting Magnets and Circuits Consolidation (SMACC)

Monumental effort

- Over 350 persons involved
- Including preparation: ~1,000,000 working hours
- No serious accidents!

Jean-Philippe Tock

Collaborations with NTUA (Athens), WUT (Wroclaw) and support of DUBNA

SMACC project : Closure of the last interconnection – 18.06.2014
Activity led by A Musso (TE-MSC)

LHC - 2015

- Target energy: 6.5 TeV
  - to be confirmed at end of powering tests
- Bunch spacing: 25 ns
  - strongly favored by experiments (pile-up limit around 50)
- Beta*: 80 to 40 cm

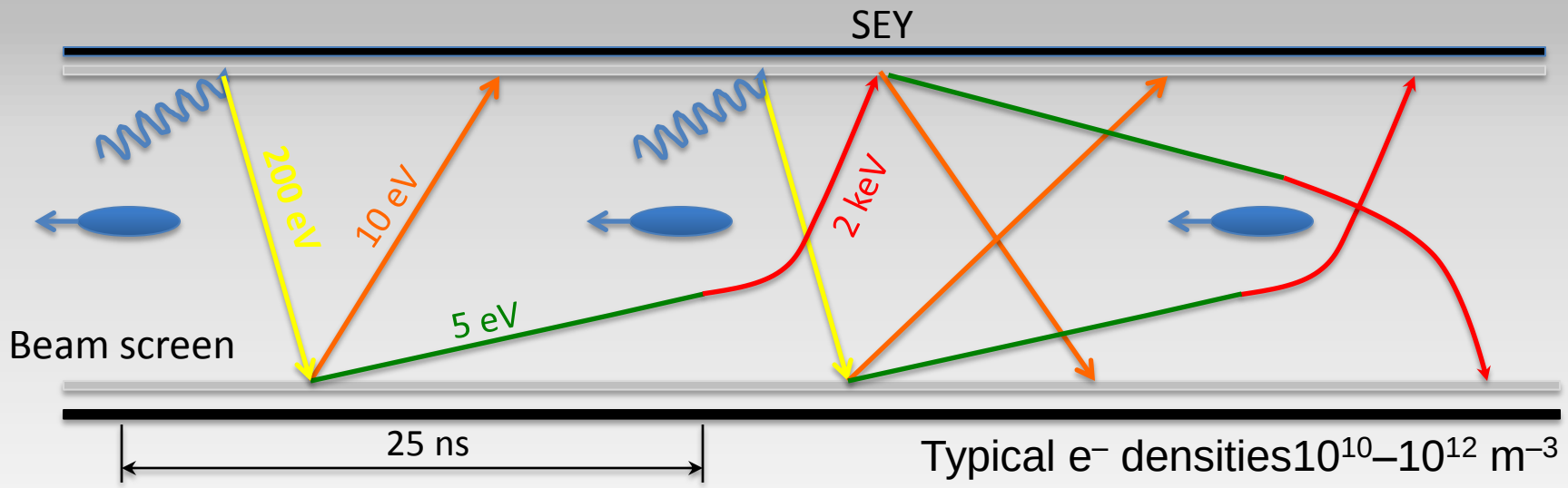
Energy

- Lower quench margins
- Lower tolerance to beam loss
- Lower intensity set-up beams
- Hardware closer to maximum (beam dumps, power converters etc.)

25 ns

- E-cloud, UFOs
- More long range collisions
- Larger crossing angle, higher beta*
- Higher total beam current
- Higher intensity per injection

25 ns & electron cloud



Possible consequences:

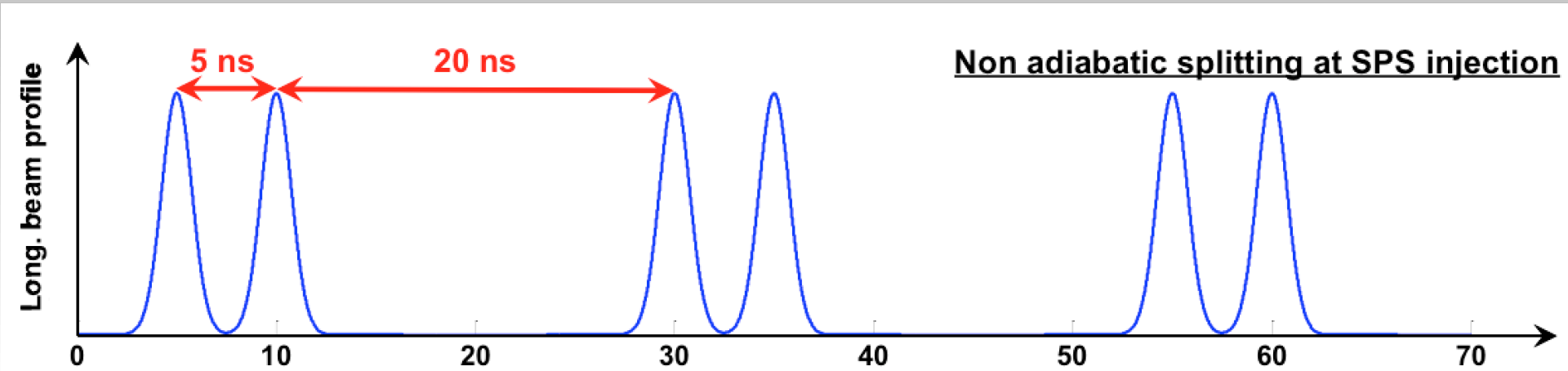
- instabilities, emittance growth, desorption – bad vacuum
- excessive energy deposition in the cold sectors

Electron bombardment of a surface has been proven to reduce drastically the **secondary electron yield (SEY)** of a material. This technique, known as **scrubbing**, provides a mean to suppress electron cloud build-up.

Electron cloud significantly worse with 25 ns

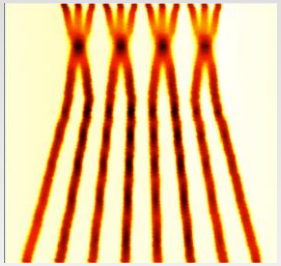
Electron cloud 2015

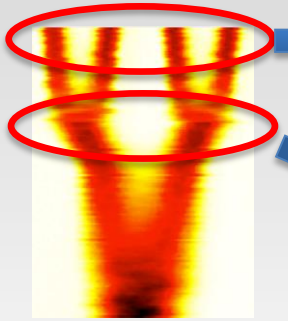
- More scrubbing than in 2012 is mandatory
- "Doublet" Scrubbing Beam (5+20) ns being developed in the SPS looks very attractive
- A two stage scrubbing strategy is foreseen:
  - Scrubbing 1 (50 ns and 25 ns) to allow for operation with 50 ns beams at 6.5 TeV
  - Scrubbing 2 (25 ns and Doublet) to allow for operation with 25 ns beams at 6.5 TeV



Beam from the injectors 2015

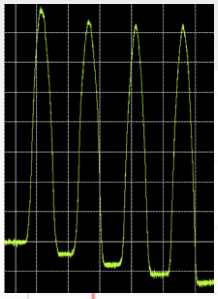
Batch Compression, Merging and Splitting in PS



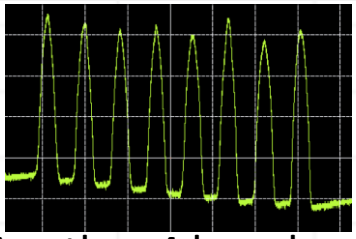


25 ns bunch spacing
48 bunches

50 ns bunch spacing
24 bunches



4 bunches



Another 4 bunches

High brightness
BCMS beam

25 ns	Intensity (p/b)	Emittance (μm) (from SPS)
Design	1.15×10^{11}	3.5
Standard	1.3×10^{11}	2.4

2015 - potential performance

- Start with 50 ns – scrub – 25 ns operation
- Conservative beta* to start
- Conservative bunch population
- Reasonable emittance into collisions
- Assuming same machine availability as 2012…

	Nc	beta* [cm]	ppb	EmitN [um]	Lumi [cm-2s-1]	Days (approx)	Int lumi	Pileup
50 ns	1300	80	1.2e11	2.5	4.6e33	21	~1 fb^{-1}	27
25 ns (1)	2496	80	1.1e11	2.5	7.4e33	75	6.8 fb^{-1}	22
25 ns (2)	2496	40	1.1e11	2.5	1.3e34	46	9.2 fb^{-1}	39

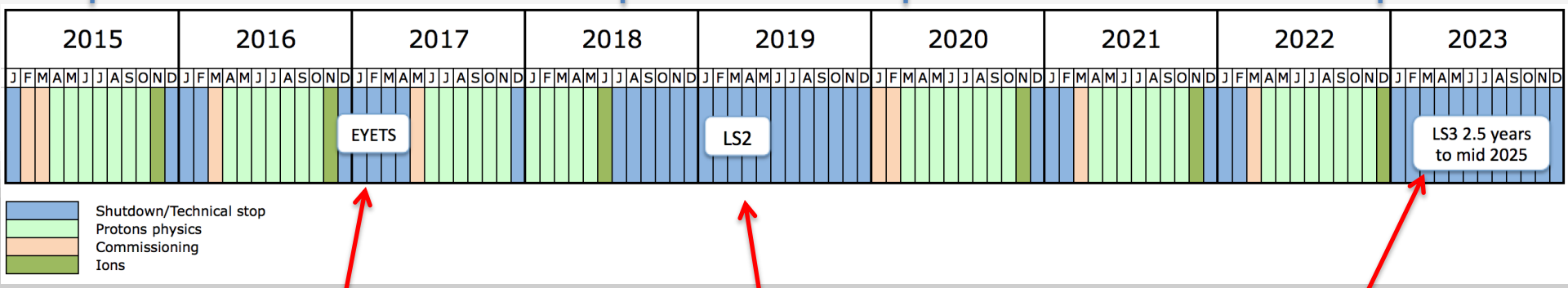
Will lay the foundations for Run 2…

10 year plan

- Long years – 13 weeks Christmas stop
- Interspersed with long shutdown every 3 to 4 years
- Ions very much part of the plan

Run 2: 13 to 14 TeV c.m. with peak luminosity of ~1.7x10^{34} cm^{-2} s^{-1}

Run 3: 14 TeV c.m. with peak luminosity of ~2x10^{34} cm^{-2} s^{-1}

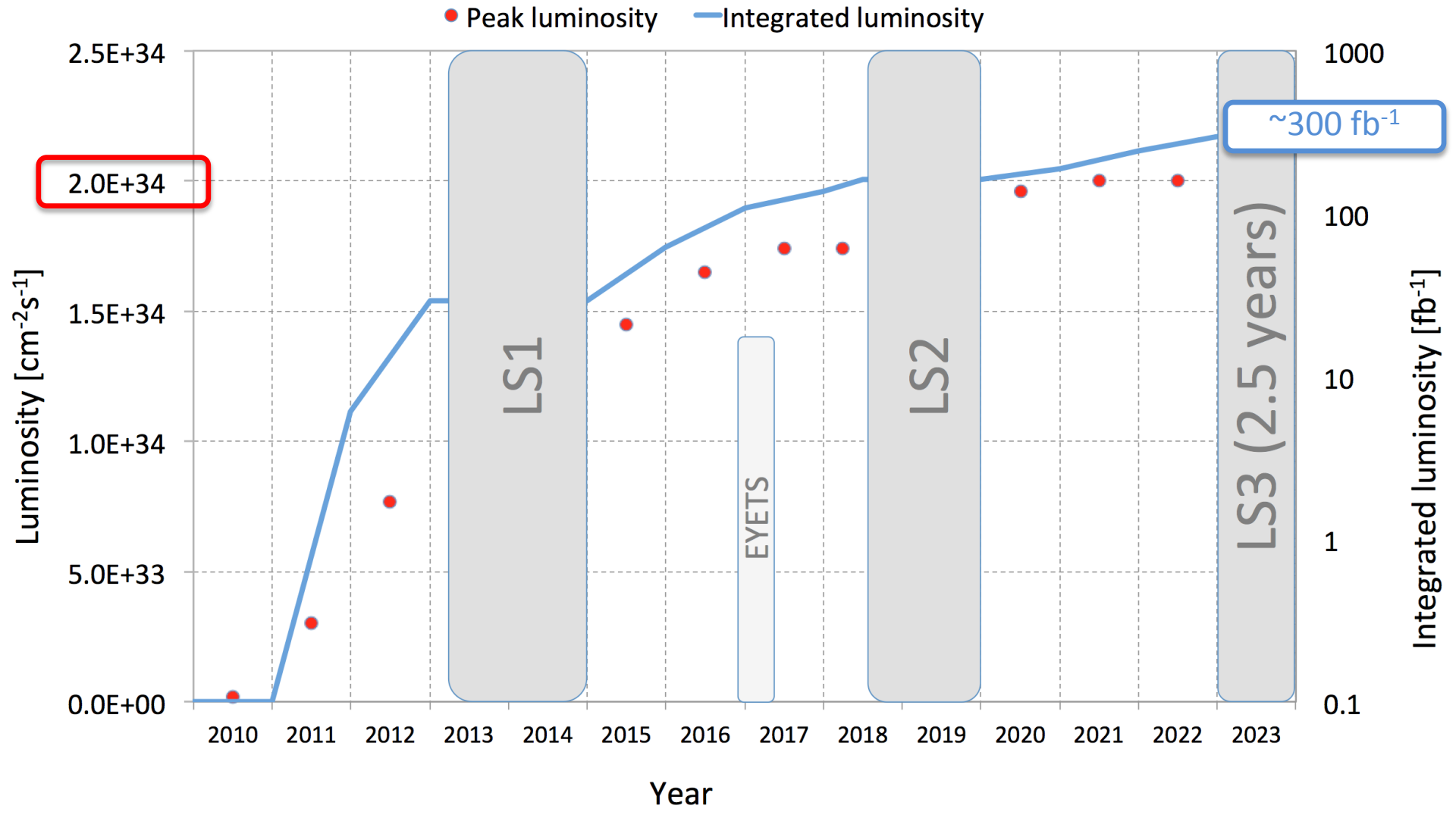


EYETS ~5 months
Extended year end technical stop (CMS)

LS2: 18 months
Connection of LINAC4
LHC Injectors Upgrade

LS3: 30 months
High Luminosity LHC

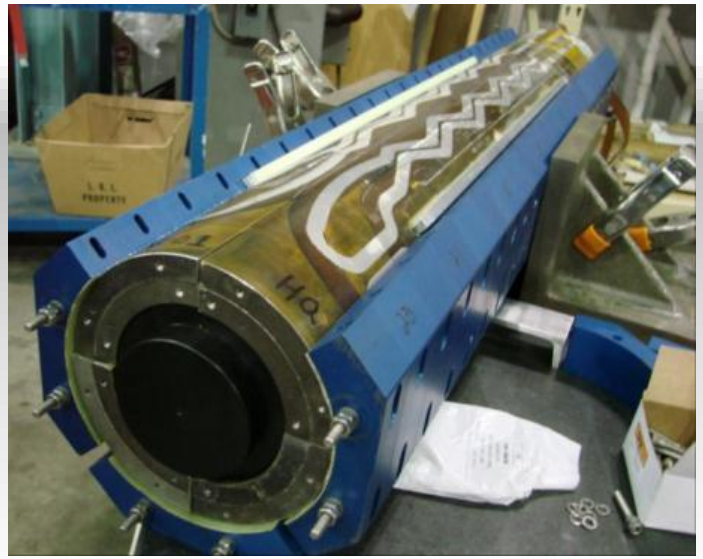
10 year luminosity evolution



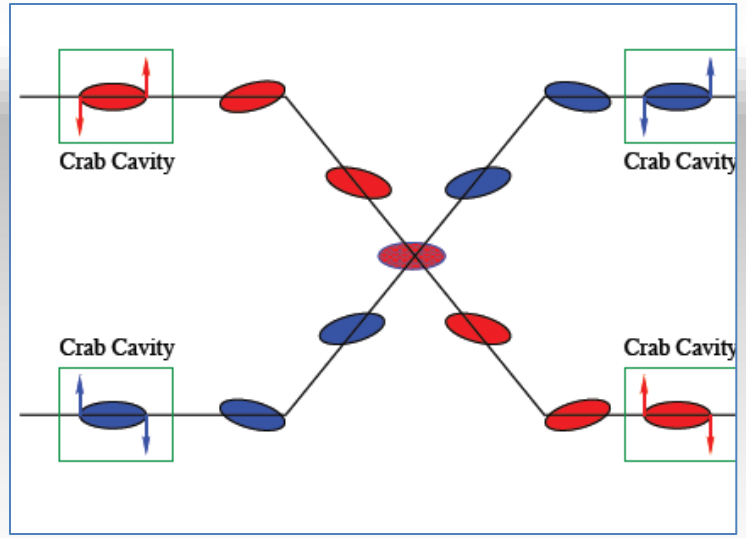
Usual caveats apply

HL-LHC: main thrusts

- Lower beta* (~15 cm)
  - New inner triplet magnets - wide aperture Nb_3Sn quads
  - Large aperture NbTi separator magnets
- Higher bunch intensities from injectors
  - While maintaining healthy beam sizes
- Compensate effect of large crossing angle
  - Crab cavities

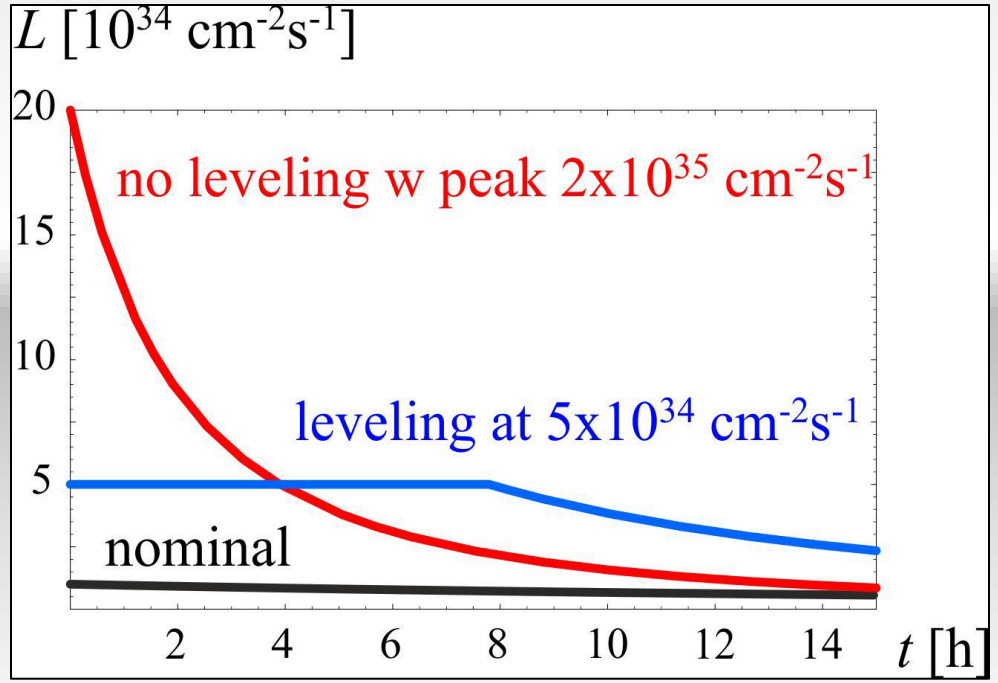


LARP: HQ02



HL-LHC

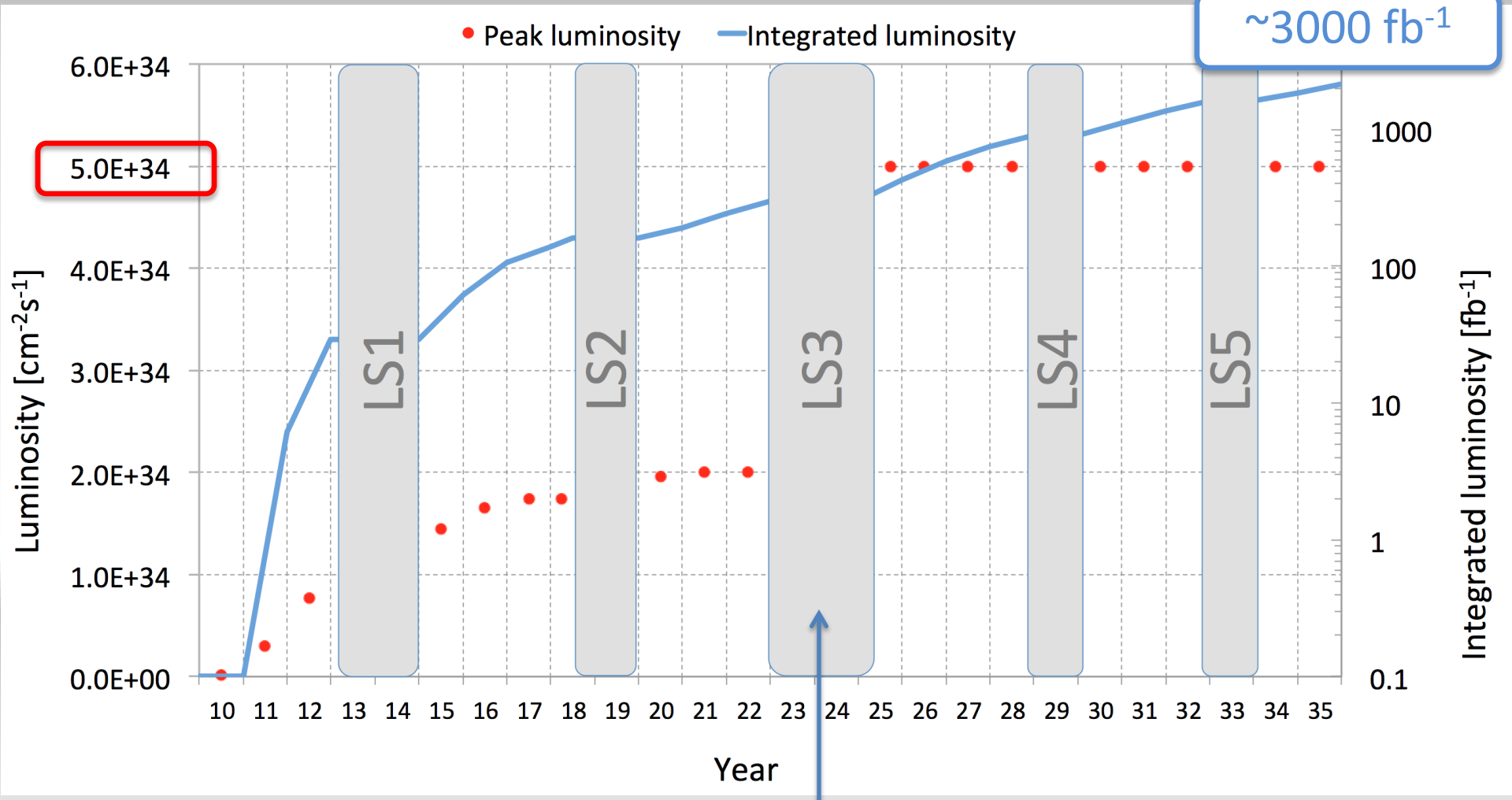
- 3000 fb^{-1} delivered in the order of 10 years
- High “virtual” luminosity with levelling anticipated
- Challenging demands on the injector complex
  - major upgrades foreseen



5 x 10^{34} $cm^{-2}s^{-1}$ levelled luminosity
Pile-up ~140
3 fb^{-1} per day
~250 fb^{-1} /year

See Oliver Brüning’s talk on Thursday

2010 - 2035



LS3: HL-LHC upgrade – machine and experiments

Conclusions

- LHC enjoying benefits of the decades long international design, construction, installation effort
- Good exploitation from commissioning through Run 1
- Foundations firmly laid for Run 2 & 3 close to or at design energy
- HL-LHC upgrade well established with provisional planning out to 2035

The Myth of Sisyphus

…The struggle itself toward the heights is enough to fill a man's heart. One must imagine Sisyphus happy.

Albert Camus

The Myth of S[illegible]s

Bugger - this is bloody heavy.

English philosopher