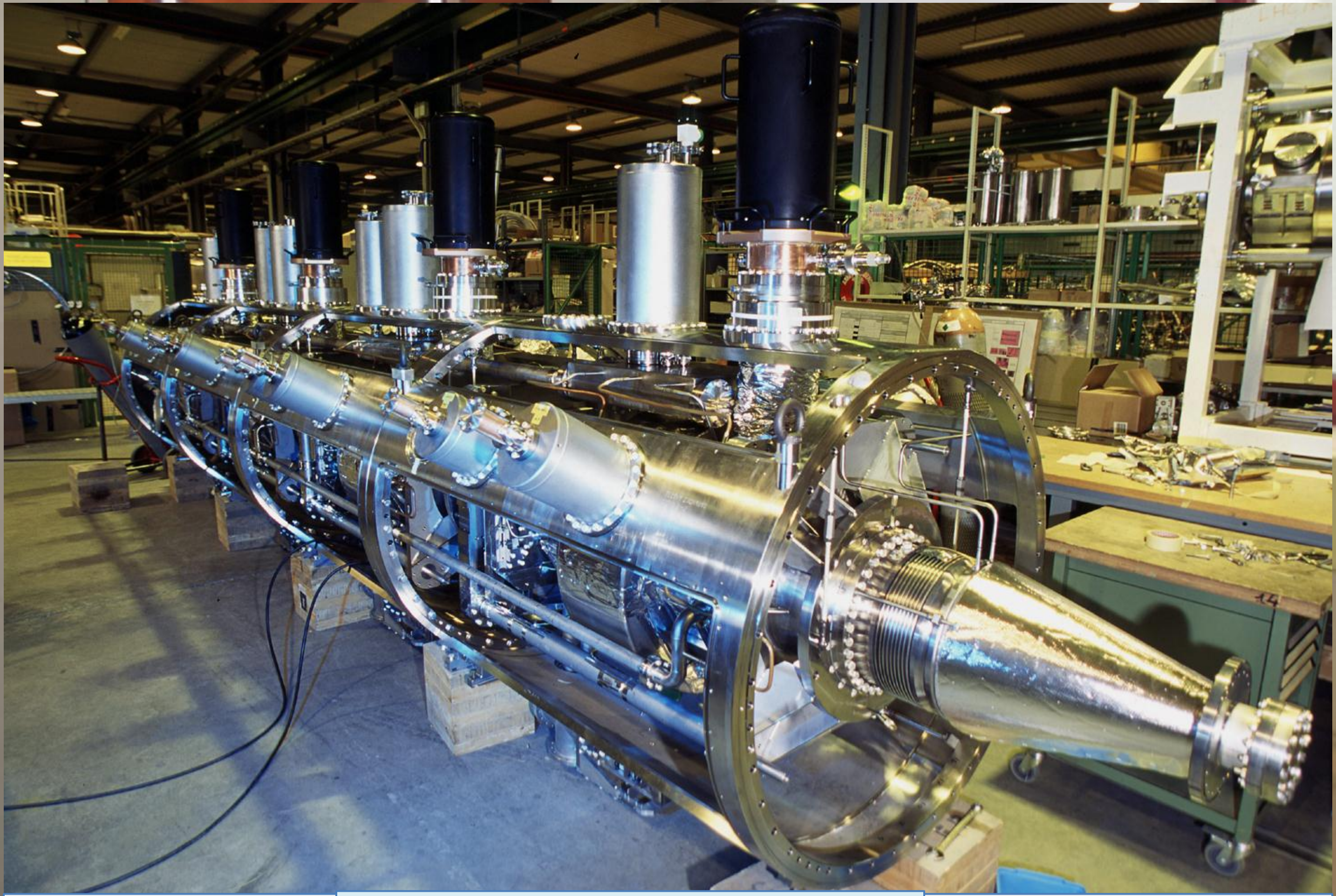
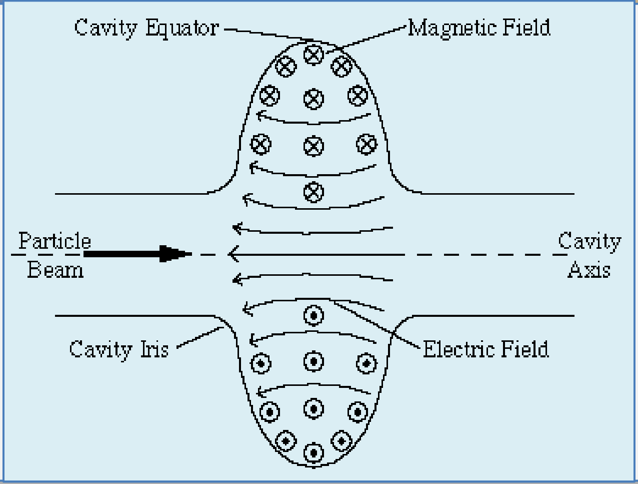
LHC
ab ovo usque ad mala

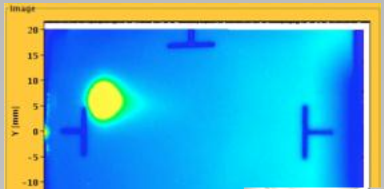
Mike Lamont on behalf of the LHC team

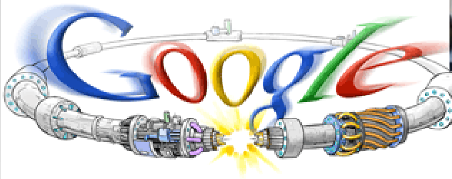



Cavity Equator
Magnetic Field
Particle Beam
Cavity Axis
Cavity Iris
Electric Field

LHC Timeline

August 2008
First injection test



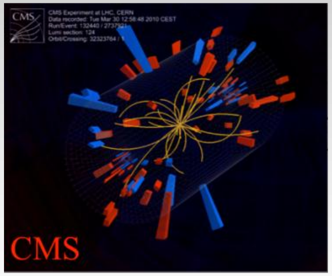


September 10, 2008
First beams around

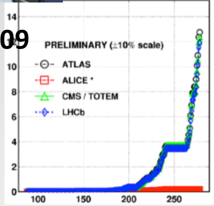
September 19, 2008
Disaster
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

November 29, 2009
Beam back

March 30, 2010
First collisions at 3.5 TeV

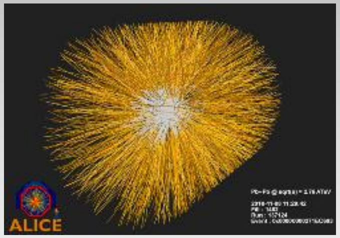


April 2010
Squeeze to 3.5 m



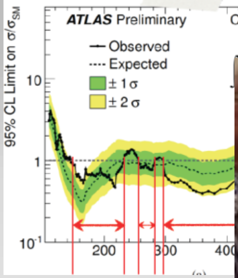
October 14 2010
1e32
248 bunches

November 2010
Ions



June 28 2011
1380 bunches

1380



August
2.3e33,
1380 bu

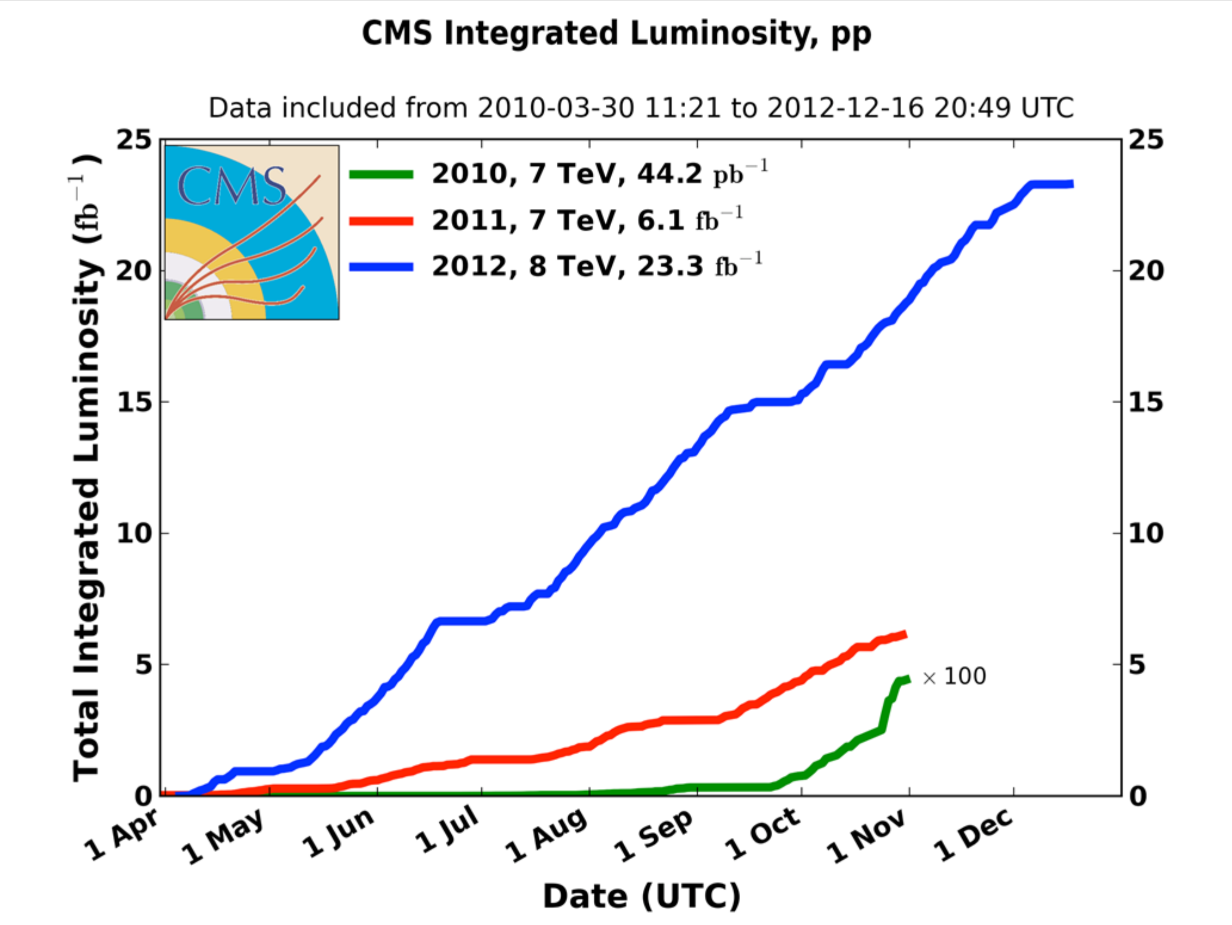
6 June, 2012
6.8e33

18 June, 2012
6.6 fb^{-1}
to ATLAS & CMS

4 July, 2012

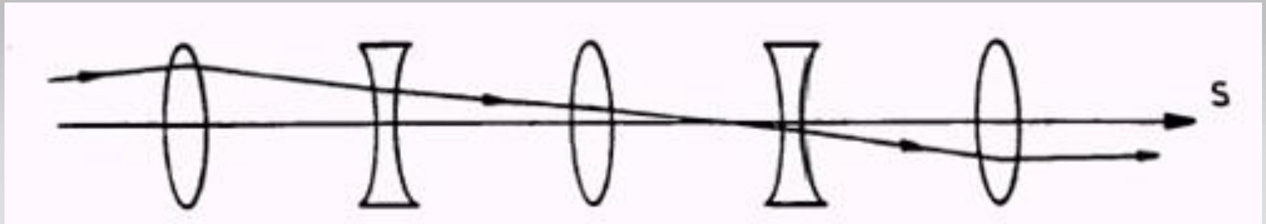
2008
2009
2010
2011
2012

Integrated luminosity 2010-2012

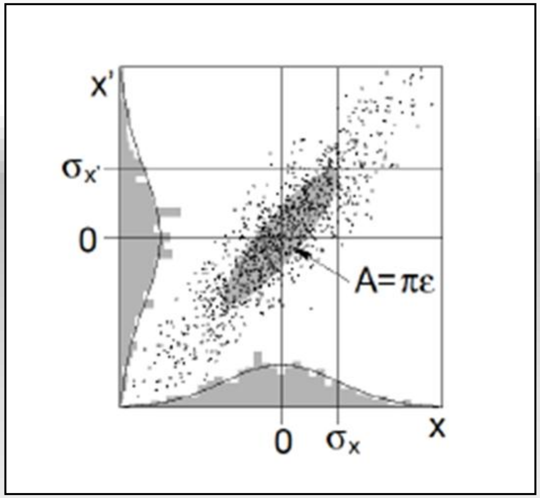


- 2010: **0.04 fb^{-1}**
    - ☐ 7 TeV CoM
    - ☐ Commissioning
- 2011: **6.1 fb^{-1}**
    - ☐ 7 TeV CoM
    - ☐ … exploring the limits
- 2012: **23 fb^{-1}**
    - ☐ 8 TeV CoM
    - ☐ … production

Emittance



$$x(s) = \overbrace{A\sqrt{\beta_x(s)}}^{\text{Amplitude}}\overbrace{\cos\left(\phi(s)+\phi_0\right)}^{\text{Phase}}$$



Ellipse area in (x,x') plane

Emittance shrinks naturally as we go up in energy

Normalized emittance

(give or take blow-up from other sources)

remains constant

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

Squeezing in ATLAS

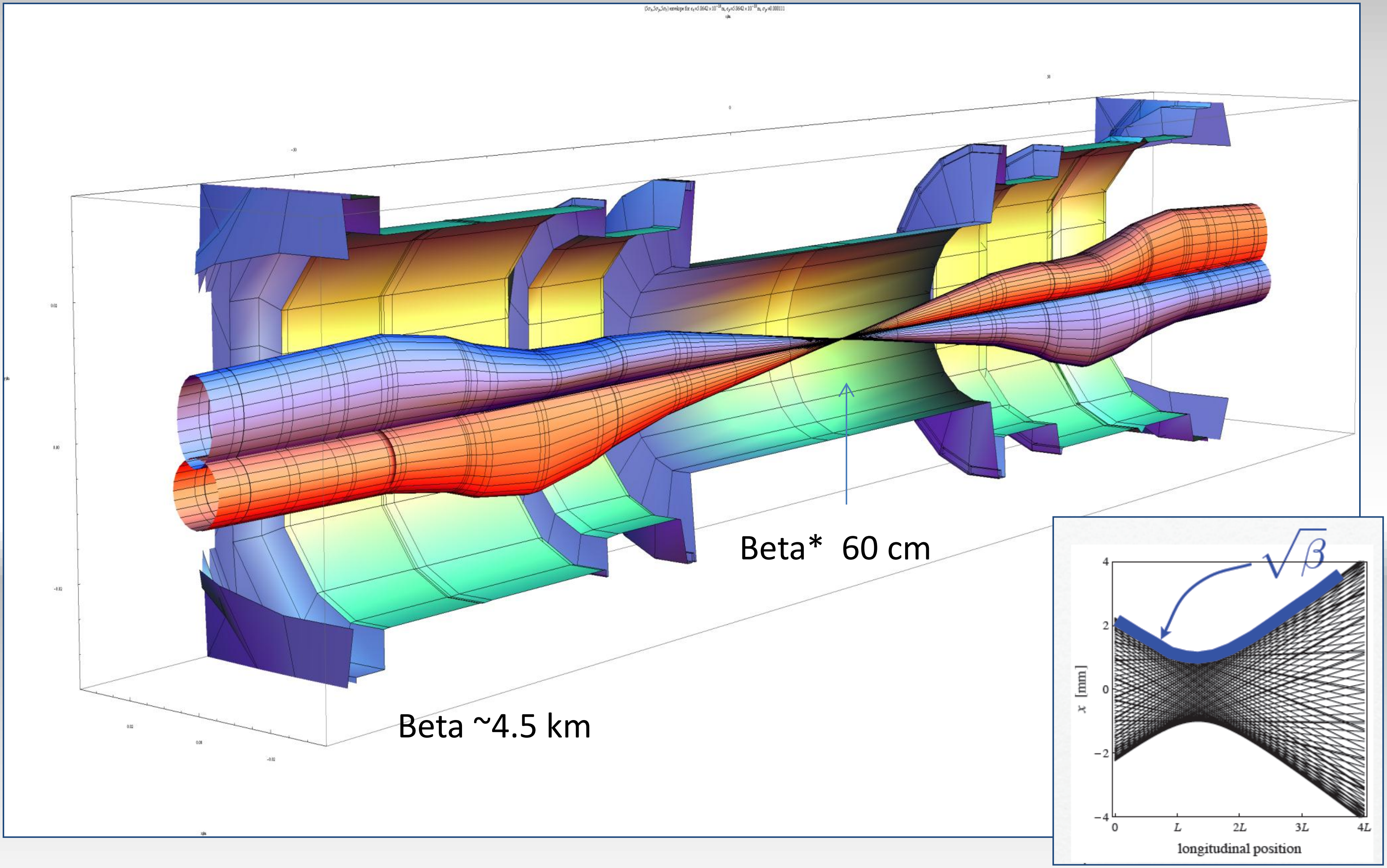


Image courtesy John Jowett

Luminosity

$$L = \frac{N^2 k_b f}{4 p s^*_x s^*_y} F = \frac{N^2 k_b f g}{4 p e_n b^*} F$$

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**

$$s^* = \sqrt{b^* e}$$

ε_n = 2.5 μm
ε = 5.9 x 10^{-4} μm
σ* = 18.8 μm
(p = 4 TeV, β* = 0.6m)

Peak performance 2012 – the numbers

Energy [TeV]	4.0	**Gain wrt 2011: 1.14**
β^* [m] IP 1/IP2/IP5/IP8	0.6/3.0/ 0.6/ 3.0	**Aggressive, exploiting available aperture, tight collimator settings, stability** **Gain wrt 2011: 1.67**
Bunch spacing [ns]	50	**Exploiting important advantage that high bunch intensities bring (luminosity proportional to N^2)**
Normalized emittance [μm]	~2.5 at collision	**67 % of nominal – again injector performance and ability to conserve PSB-PS-SPS(-LHC)**
Bunch intensity [protons per bunch]	1.6 – 1.7 x 10^{11}	**150% of nominal** **Gain wrt 2011: 1.14**
Number of bunches	1374 1368 collisions/IP1&5	**Given by 50 ns**
Total intensity	2.2 x 10^{14}	**70 % of nominal – some issues**
Peak luminosity [$cm^{-2}s^{-1}$]	7.73 x 10^{33}	mean pile-up>30, peak pile-up >40

Performance from injectors 2012

Design report with 25 ns:
- 1.15×10^{11} ppb
- Normalized emittance 3.75 μm

Bunch spacing [ns]	Protons per bunch [ppb]	Norm. emittance H&V [μm] Exit SPS
50	1.7×10^{11}	1.8
25	1.2×10^{11}	2.7

N.B. the importance of 50 ns in the performance so far.
This at the expense of high pile-up.

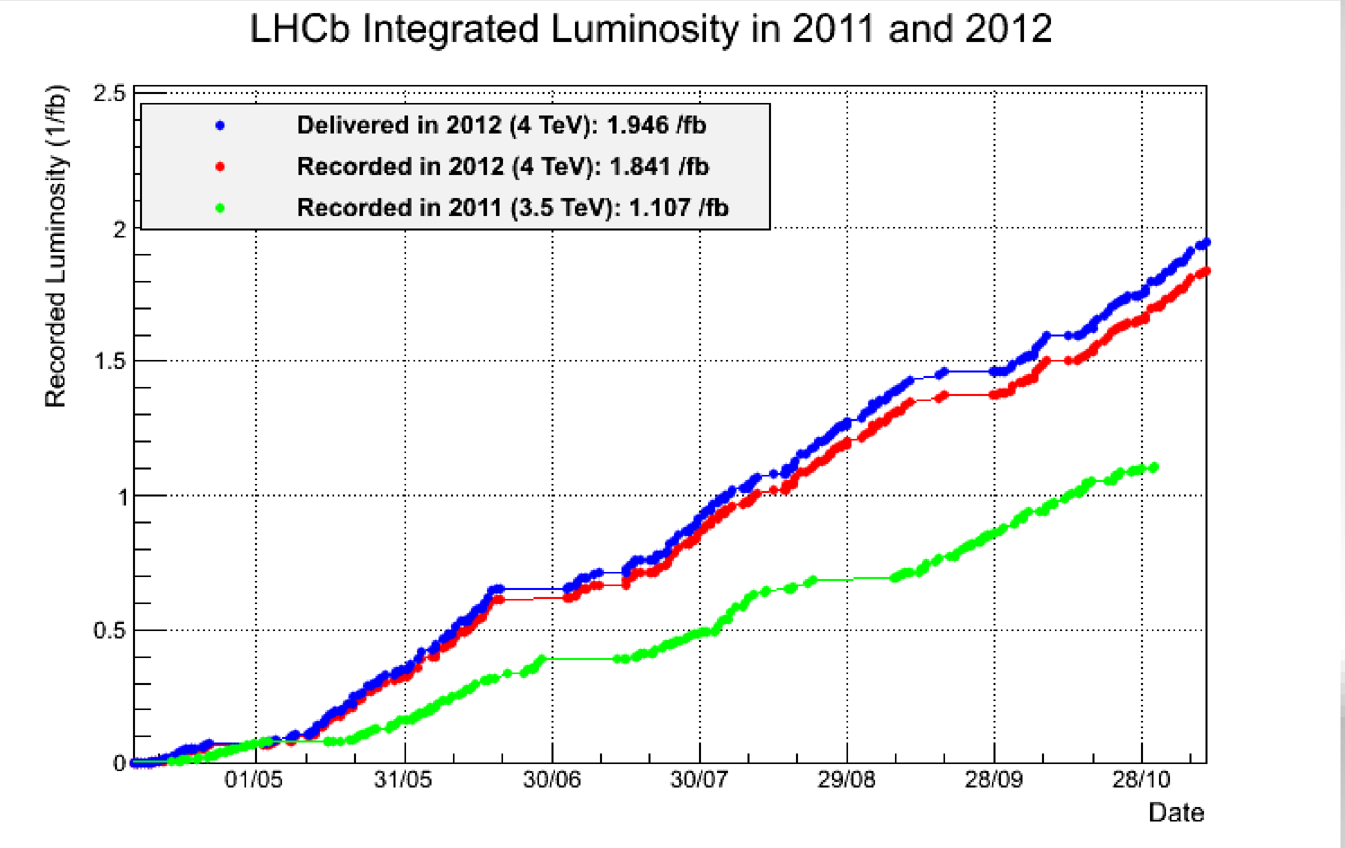
(And they are in the process of re-inventing themselves again)

Performance

77 % of design luminosity:

- 4/7 design energy
- nominal bunch intensity++
- ~ 70 % nominal emittance
- β^* = 0.6 m (design 0.55 m)
- half nominal number of bunches

ALICE and LHCb (and TOTEM and ALFA)

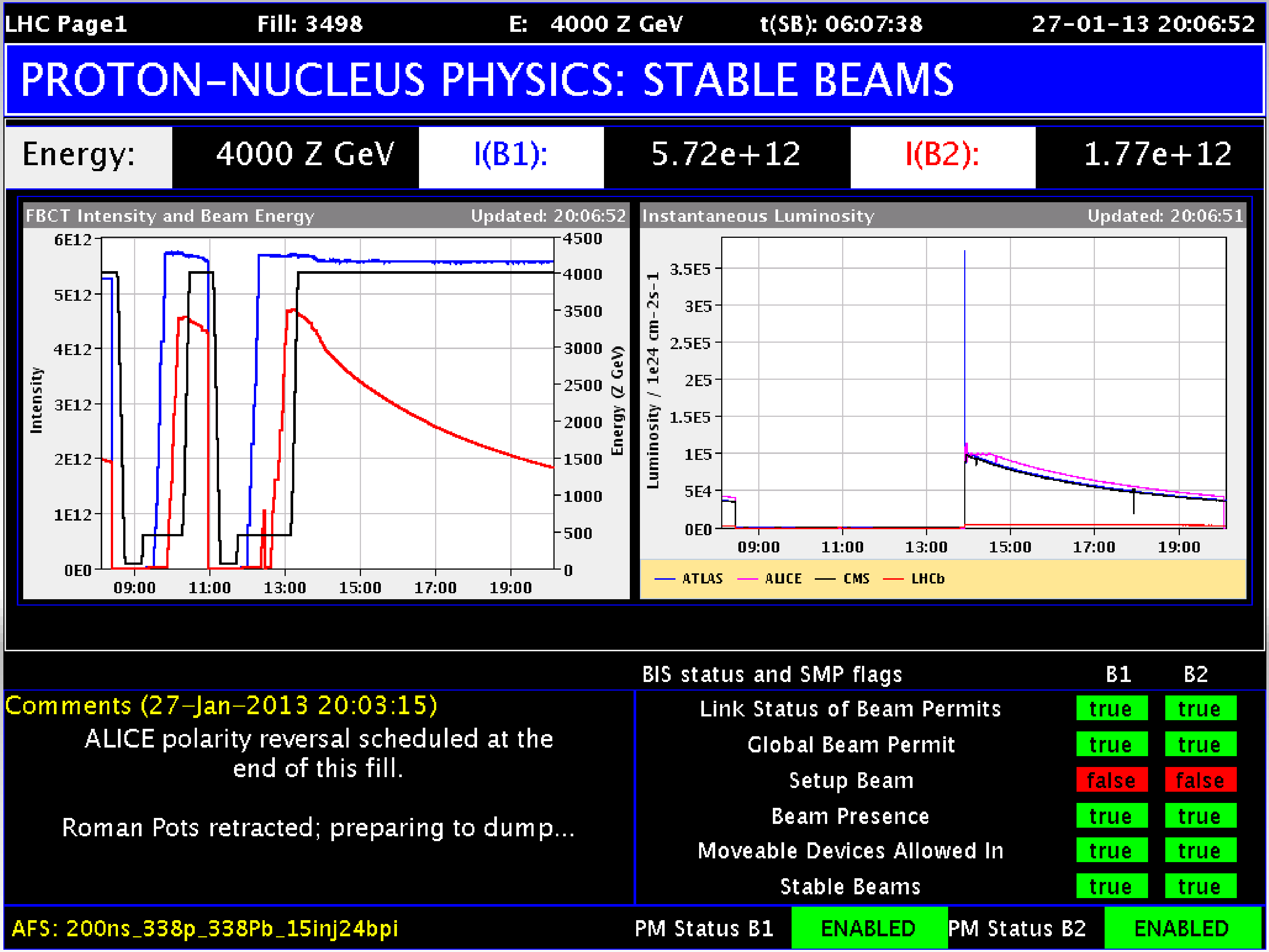


Luminosity levelling at around 4e32 $cm^{-2}s^{-1}$ via transverse separation (with a tilted crossing angle)

Not completely trivial!

- ALICE enjoyed some sustained running at around 5e30 $cm^{-2}s^{-1}$ with collisions between enhanced satellites on main bunches
- Successful beta* = 1 km run for TOTEM and ALFA: With t_{min} ~ 0.0004 GeV^2 first LHC measurement in Coulomb-Nuclear Interference region

Proton-lead



LHC Page1 Fill: 3498 E: 4000 Z GeV t(SB): 06:07:38 27-01-13 20:06:52

PROTON-NUCLEUS PHYSICS: STABLE BEAMS

Energy: 4000 Z GeV I(B1): 5.72e+12 I(B2): 1.77e+12

Comments (27-Jan-2013 20:03:15)

ALICE polarity reversal scheduled at the end of this fill.

Roman Pots retracted; preparing to dump...

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 200ns_338p_338Pb_15inj24bpi PM Status B1 ENABLED PM Status B2 ENABLED

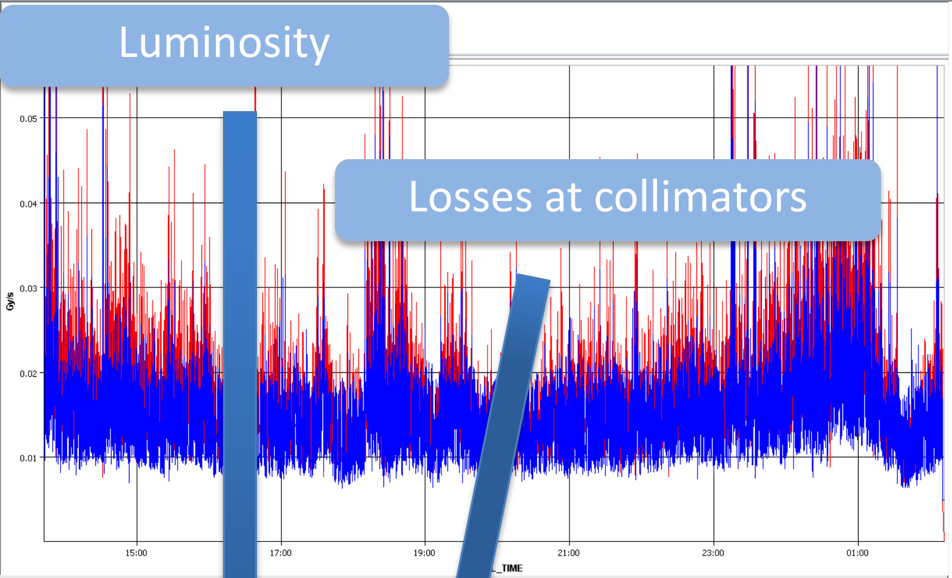
WHAT WE HAVE LEARNT SO FAR…

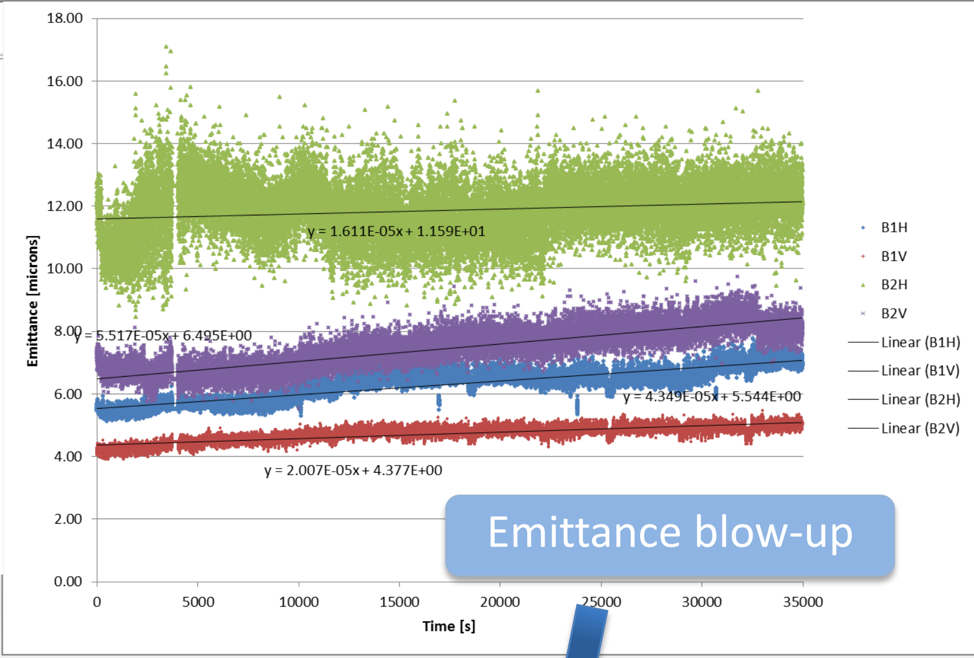
In general - beam

- **Excellent single beam lifetime** – vacuum
- **Excellent magnetic field quality**
- Low tune modulation, low power converter ripple, low RF noise
- **Beam-Beam**
  - Head-on is not a limitation
  - Long range taken reasonably seriously
- **Collective effects** – had some fun here:
  - Single and coupled bunch instabilities

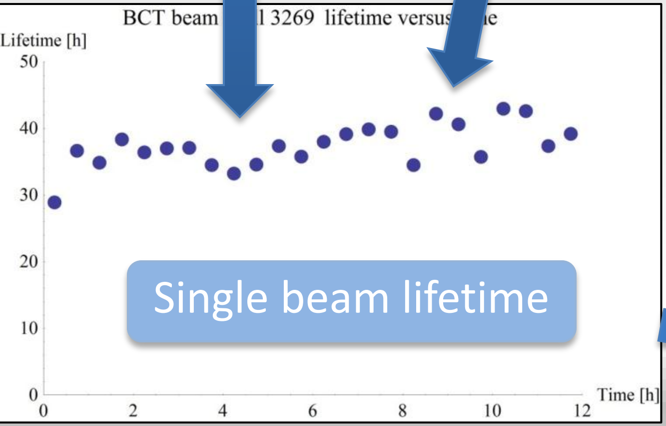
Luminosity

Losses at collimators

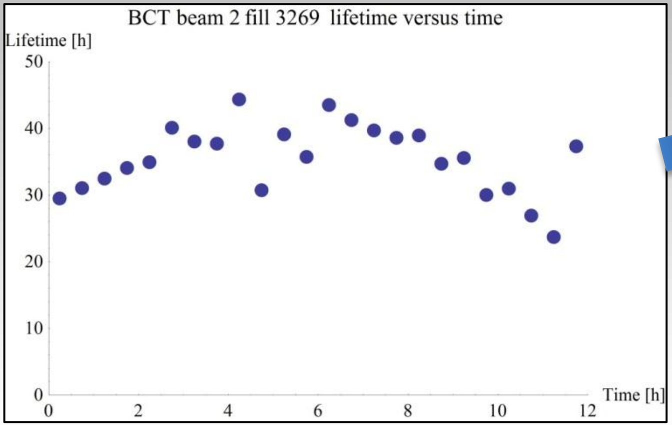


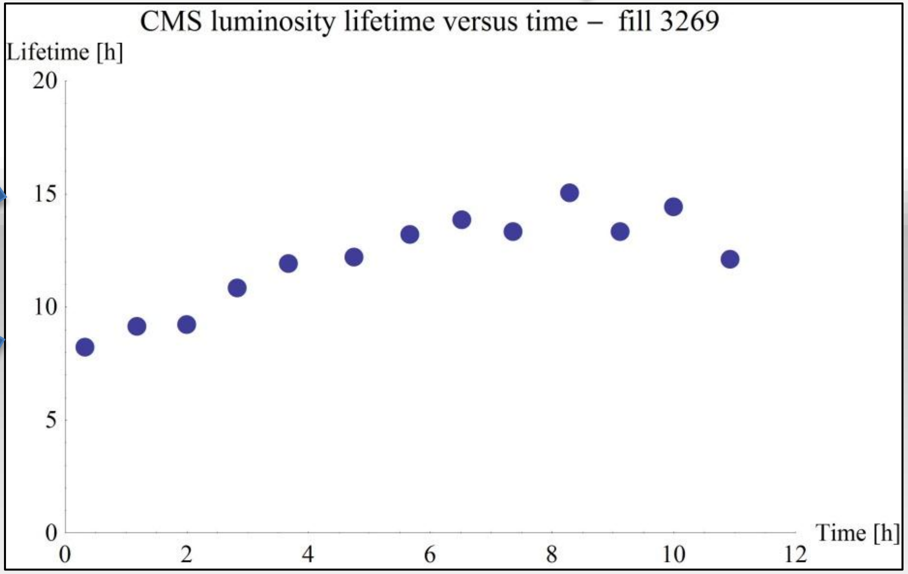


Emittance blow-up



Single beam lifetime





Reasonably comfortable life in Stable Beams

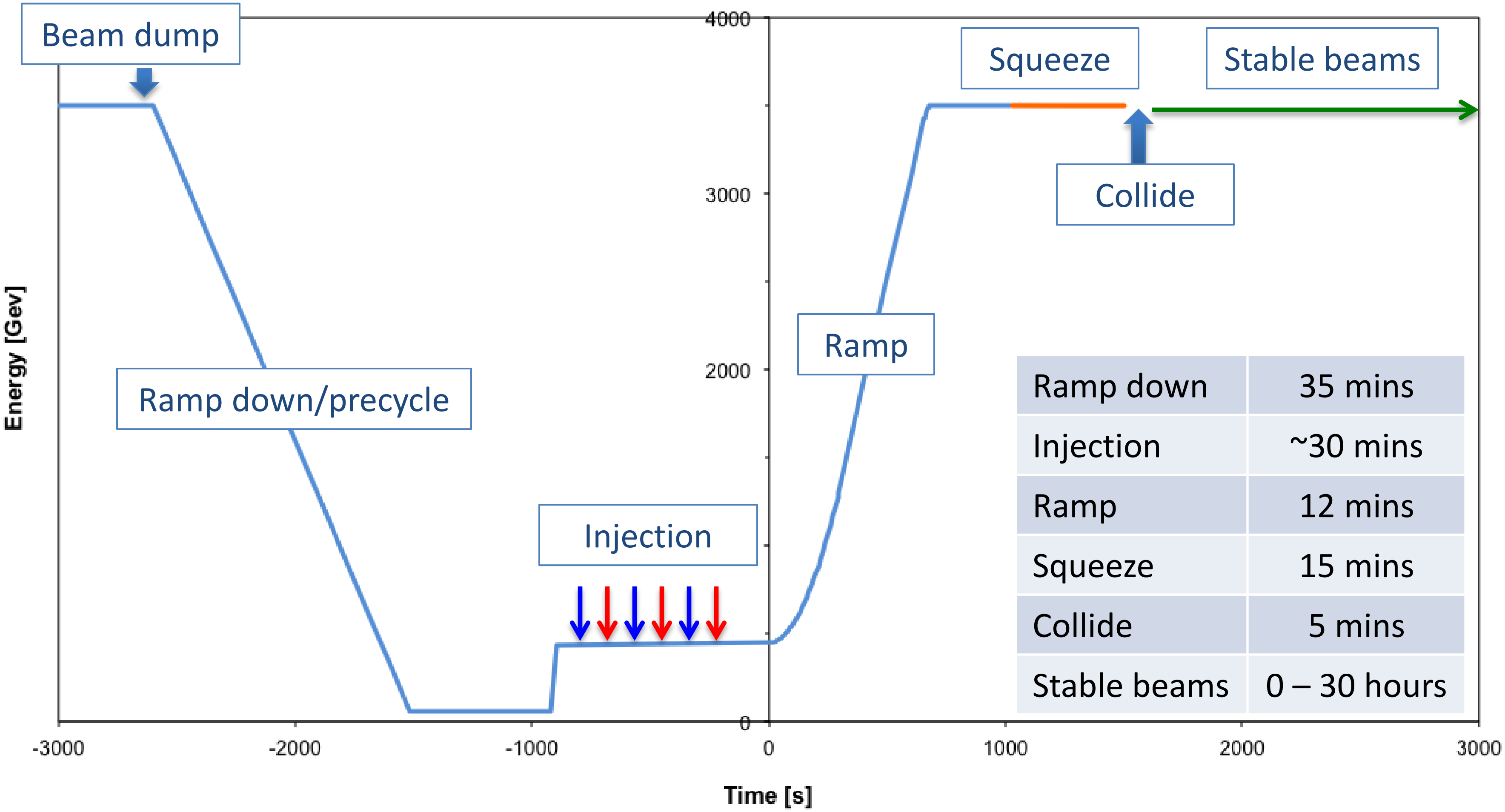
In general – optics etc.

- **Linear optics**: remarkably close to model, corrected to excellent
- **Very good magnetic model**
  - including dynamic effects
- **Better than expected aperture**
  - tolerances, alignment
- **β* reach established and exploited**
  - aperture, collimation, optics

Operational robustness

- Pre-cycle, injection, 450 GeV, ramp, squeeze, collide:
  - devils in the details - we have some fun - but remarkably robust
  - good lifetime throughout the whole process (on the whole)
- **Machine remarkably reproducible**
  - **optics, orbit, collimator set-up, tune…**

Nominal cycle

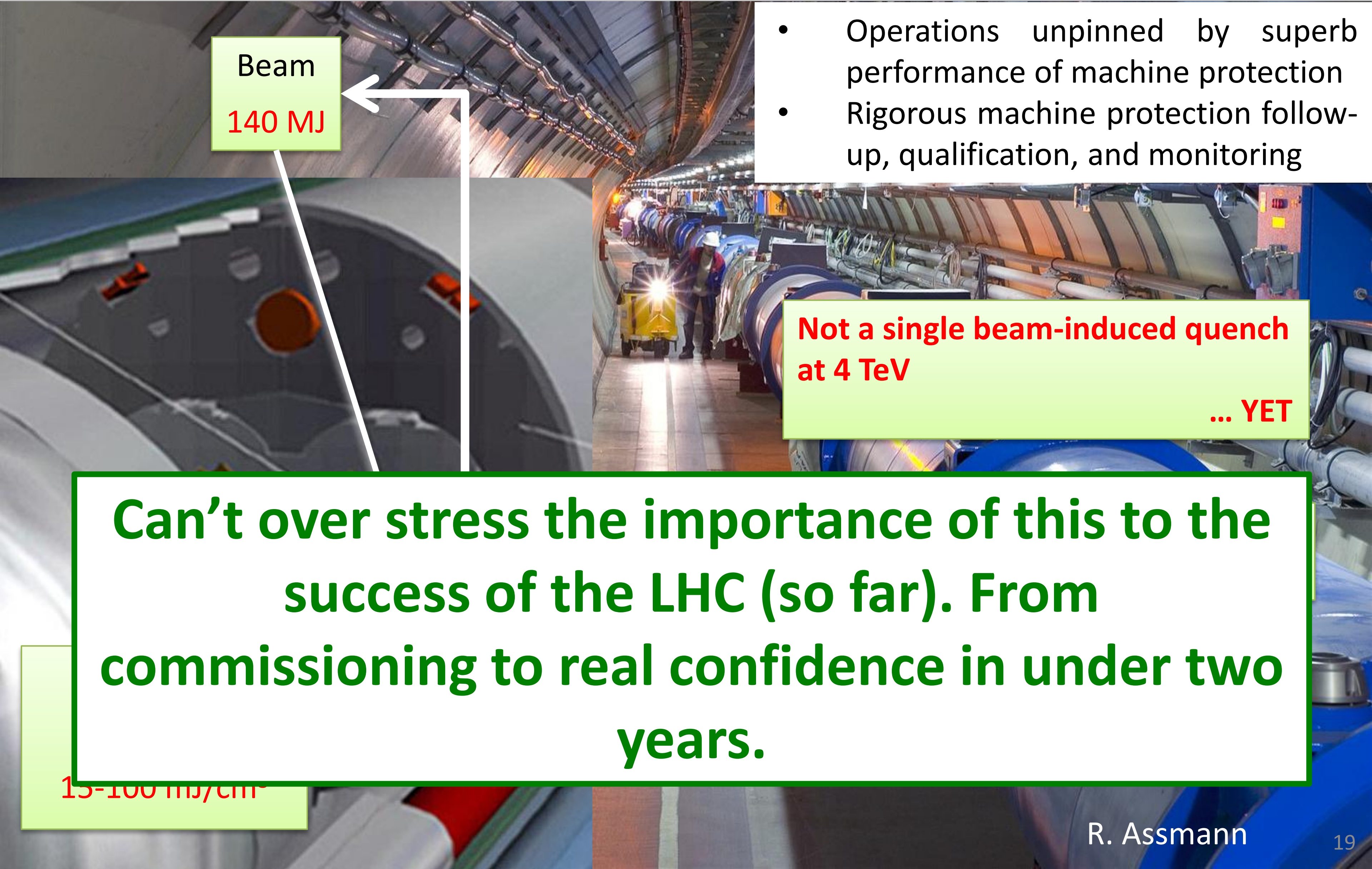


Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

Turn around 2 to 3 hours on a good day

Machine protection – the challenge met

- Operations unpinned by superb performance of machine protection
- Rigorous machine protection follow-up, qualification, and monitoring



Beam

140 MJ

Not a single beam-induced quench at 4 TeV

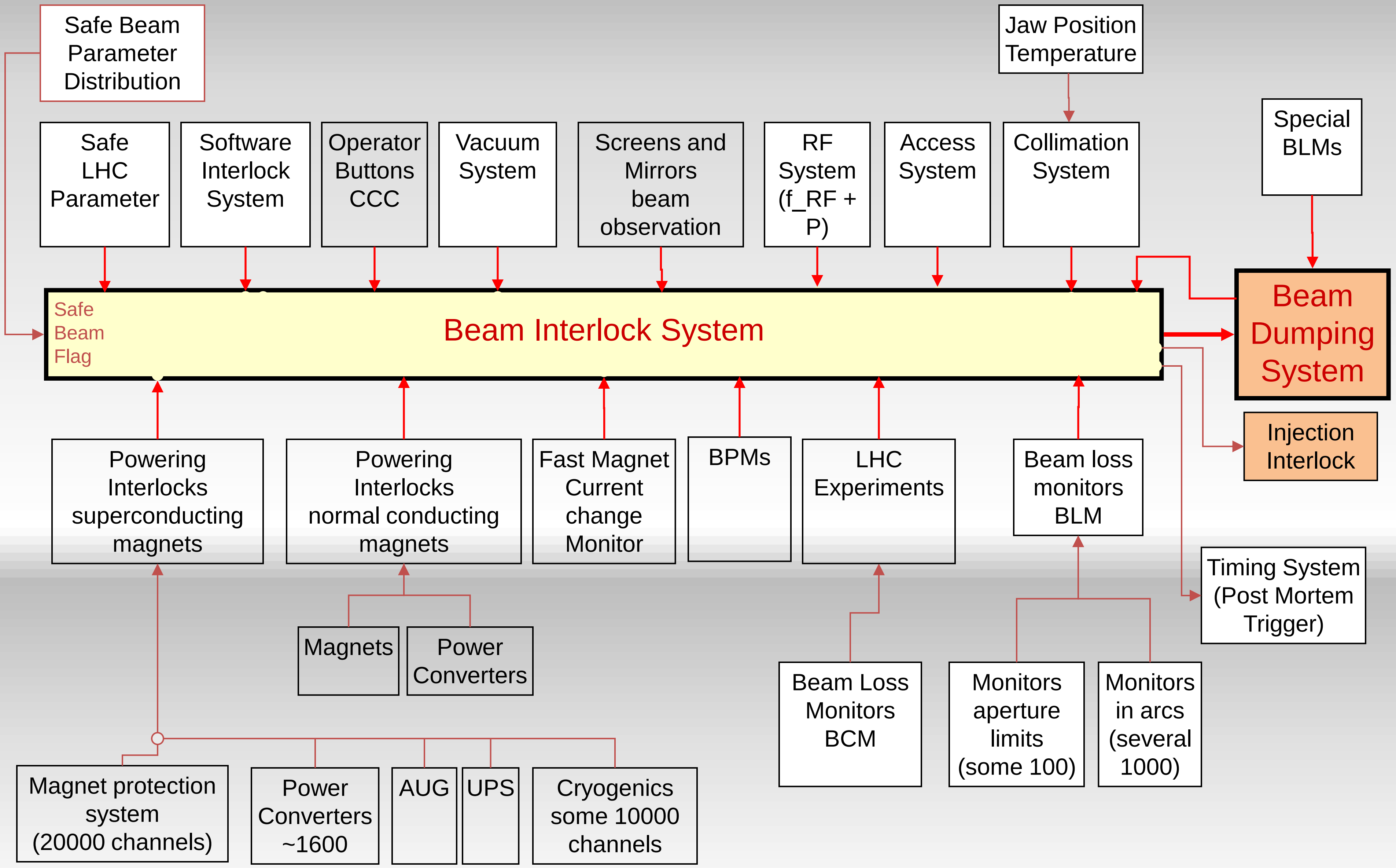
… YET

15-100 mJ/cm

Can't over stress the importance of this to the success of the LHC (so far). From commissioning to real confidence in under two years.

R. Assmann

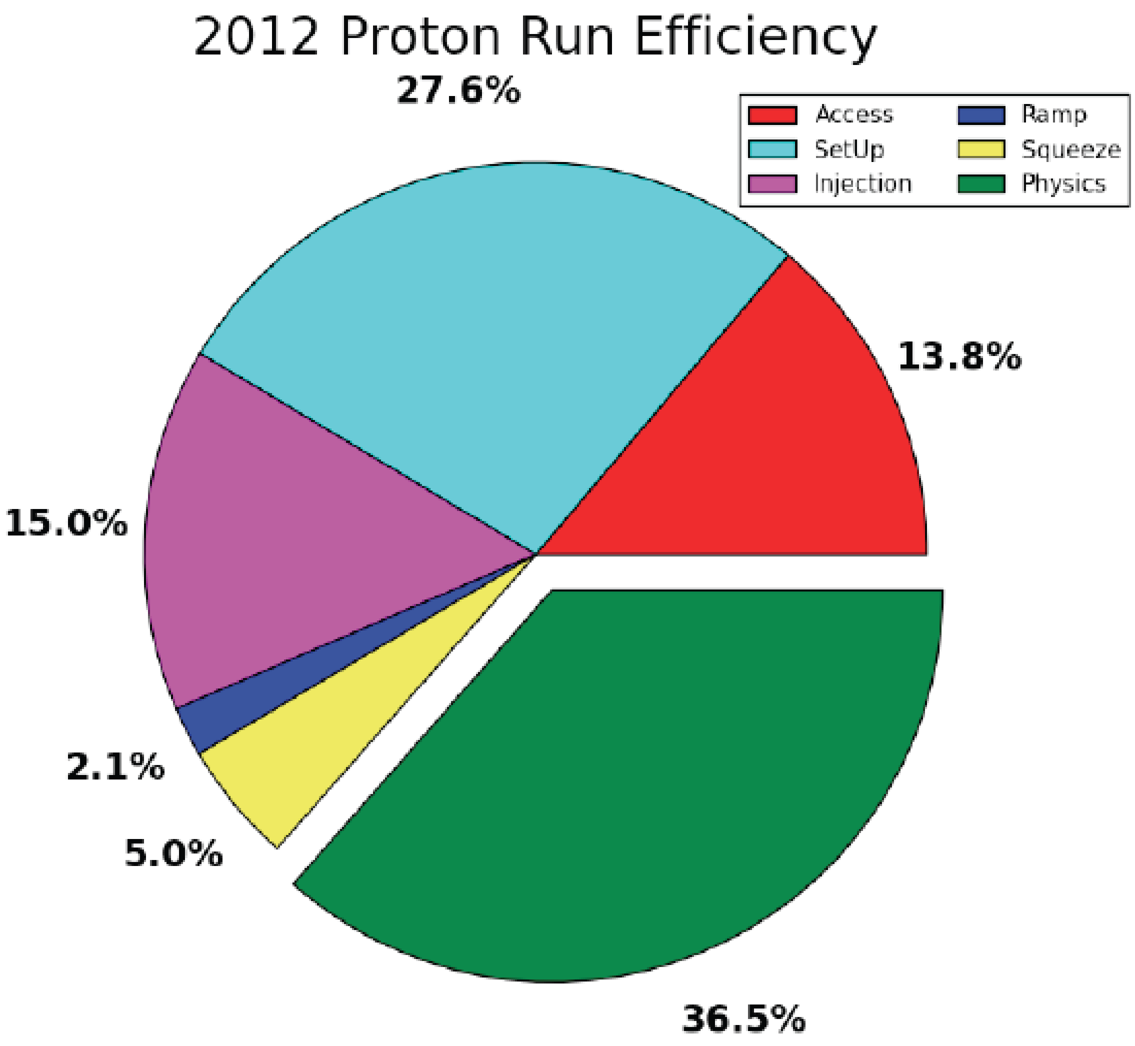
Machine protection



LHC Collimators | Beam: B1 | Set: HW Group:LHC COLLIMATORS 23-05-2012 22:10:55

L(mm) MDC	IP1	PRS R(mm)
3.24	TCL.5R1.B1	-3.93
10.4	TCTH.4L1.B1	-9.11
8.96	TCTVA.4L1.B1	-3.43
	IP2	
5.05	TCTH.4L2.B1	-4.85
7.9	TCTVA.4L2.B1	-2.62
54.97	TDI.4L2	-54.91
19.92	TCDD.4L2	-20.02
27.96	TCLIA.4R2	-27.97
24.87	TCLIB.6R2.B1	-24.98
	IP3	
4.28	TCP.6L3.B1	-3.62
2.94	TCSG.5L3.B1	-3.68
1.15	TCSG.4R3.B1	-3.44
2.92	TCSG.A5R3.B1	-2.96
3.34	TCSG.B5R3.B1	-3.34
6.2	TCLA.A5R3.B1	-7.2
6.2	TCLA.B5R3.B1	-6.22
5.74	TCLA.6R3.B1	-5.72
4.14	TCLA.7R3.B1	-4.11
	IP5	
5.2	TCTH.4L5.B1	-14.32
7.04	TCTVA.4L5.B1	-5.4
3.6	TCL.5R5.B1	-3.58
	IP6	
4.35	TCDQA.A4R6.B1	
4.77	TCSG.4R6.B1	-4.51
	IP7	
1.33	TCP.D6L7.B1	-0.84
1.33	TCP.C6L7.B1	-1.69
0.94	TCP.B6L7.B1	-1.61
1.85	TCSG.A6L7.B1	-2.01
1.92	TCSG.B5L7.B1	-2.66
2.1	TCSG.A5L7.B1	-2.58
1.42	TCSG.D4L7.B1	-1.55
2.98	TCSG.B4L7.B1	-1.29
2.93	TCSG.A4L7.B1	-1.27
2.8	TCSG.A4R7.B1	-1.4
2.78	TCSG.B5R7.B1	-2.02
2.22	TCSG.D5R7.B1	-2.66
2.48	TCSG.E5R7.B1	-2.39
3.08	TCSG.6R7.B1	-3.54
2	TCLA.A6R7.B1	-1.34
2.66	TCLA.B6R7.B1	-3.36
4.37	TCLA.C6R7.B1	-1.5
1.7	TCLA.D6R7.B1	-2.14
1.5	TCLA.A7R7.B1	-2.32
	IP8	
5.24	TCTH.4L8.B1	-5.43
3.3	TCTVB.4L8	-9.28
	TI2	
1.06	TCDIV.20607	-2.72
4.45	TCDIV.29012	-0.48
3.49	TCDIH.29050	-4.35
2.55	TCDIH.29205	-2.44
5.69	TCDIV.29234	-0.53
3.49	TCDIH.29465	-2.34
9.44	TCDIV.29509	-3.7

2012 Physics Run: Overall Availability

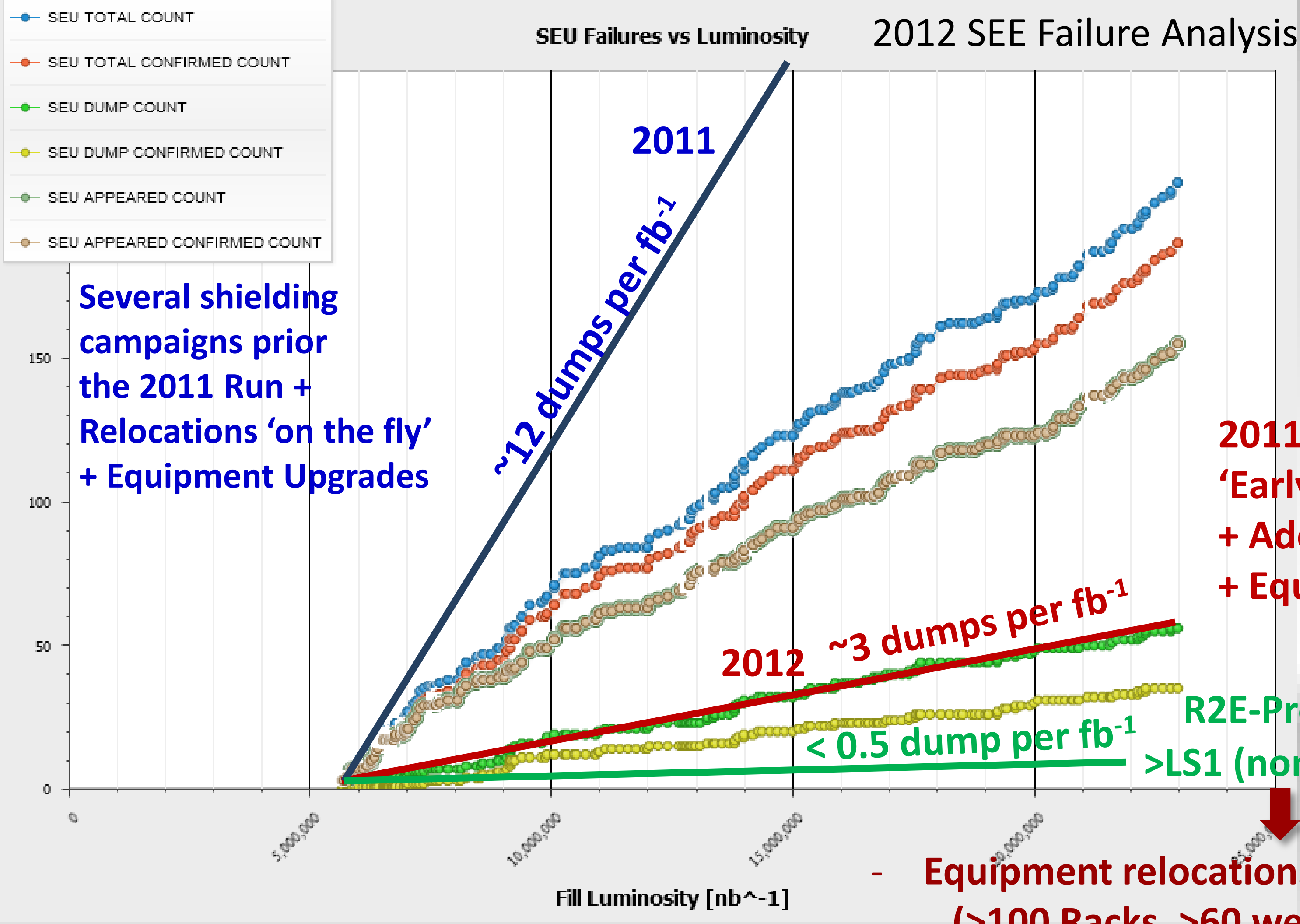


SB Time: 73.2 days   Total Time: 200.5 days

Alick Macpherson

R2E: Past/Present/Future

2012 SEE Failure Analysis



2011

~12 dumps per fb^{-1}

Several shielding campaigns prior the 2011 Run + Relocations 'on the fly' + Equipment Upgrades

2012 ~3 dumps per fb^{-1}

< 0.5 dump per fb^{-1}

2011/12 xMasBreak
'Early' Relocation
+ Additional Shielding
+ Equipment Upgrades

R2E-Project aiming for …
>LS1 (nominal -> ultimate)

- Equipment relocations @ 4 LHC Points (>100 Racks, >60 weeks of work)
- Additional shielding
- Critical system upgrades (QPS, FGC)

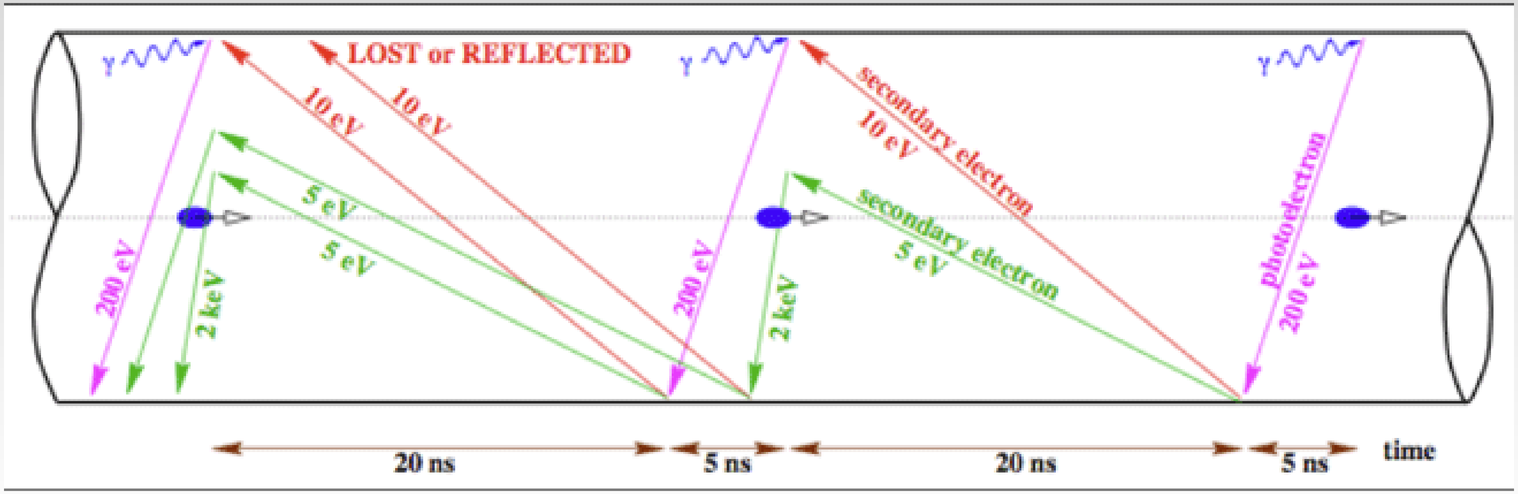
Markus Brugger

Machine performing well,
huge amount of experience &
understanding gained,
good system performance,
excellent tools, reasonable availability
following targeted consolidation.

This is the legacy for post LS1

ISSUES & POSSIBLE LIMITATIONS (TWO OF THEM...)

25 ns & electron cloud



- Typical e⁻ densities: $n_e=10^{10}–10^{12}\ m^{-3}$ (~a few nC/m)
- Typical e⁻ energies: <~ 200 eV (with significant fluctuations)

Electron cloud: possible consequences

- **single-bunch instability**
- **multi-bunch instability**
- **emittance growth**
- **gas desorption from chamber walls**
- **excessive energy deposition on the chamber walls (heat load)** - important for the LHC in the cold sectors
- **particle losses, interference with diagnostics**,…

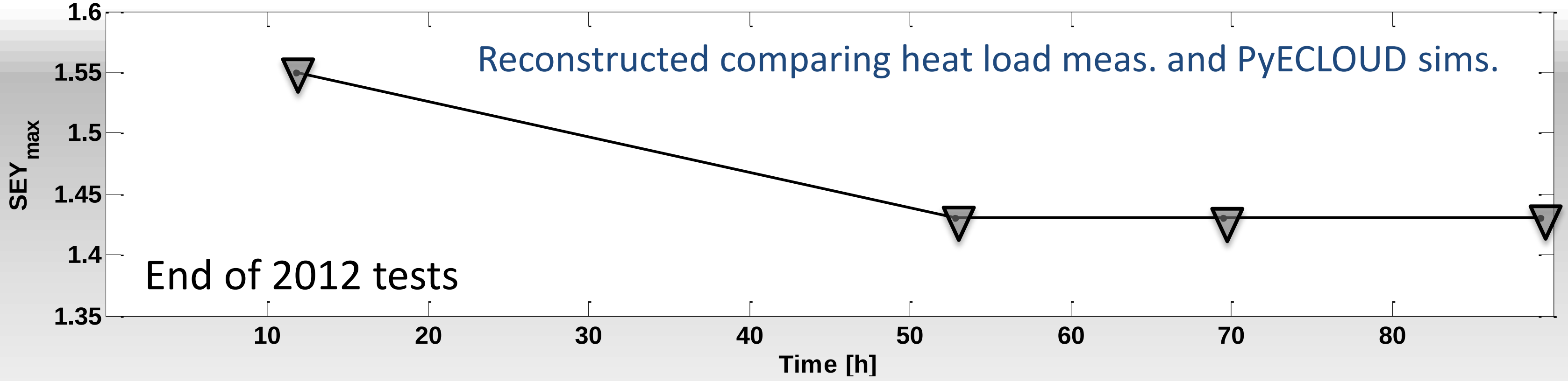
Electron bombardment of a surface has been proven to reduce drastically the secondary electron yield of a material.

This technique, known as **scrubbing**, provides a mean to suppress electron cloud build-up and its undesired effects

25 ns & electron cloud

- From the experience with the 25 ns scrubbing run and electron cloud free environment after scrubbing at 450 GeV seem not be reachable in acceptable time.
- **Operation with high heat load and electron cloud density (with blow-up) seems to be unavoidable with a corresponding slow intensity ramp-up .**

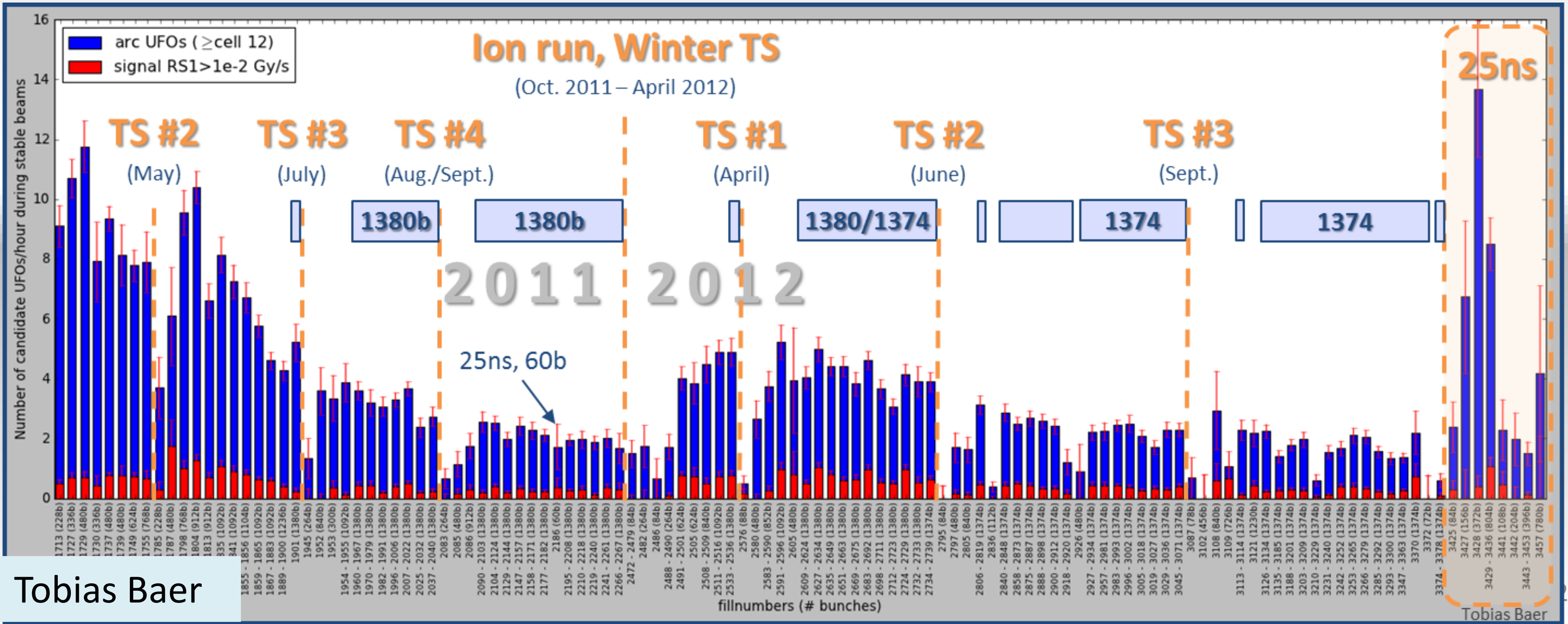
The **SEY evolution significantly slows down** during the last scrubbing fills (more than expected by estimates from lab. measurements and simulations)


Reconstructed comparing heat load meas. and PyECLOUD sims.

End of 2012 tests

UFOs (Unidentified Falling Objects)

- **UFOs: showstopper for 25 ns and 6.5 TeV?**
  - 10x increase in rate and harder UFOs
- UFO “scrubbing”: does it work? What parameters?
- Deconditioning expected after LS1
- Operational scenario to be developed:
  - start with lower energy and/or 50 ns beam…
  - Adjust beam loss monitor thresholds based on quench tests



LONG SHUTDOWN 1 (LS1)

The main 2013-14 LHC consolidations

1695 Openings and final reclosures of the interconnections

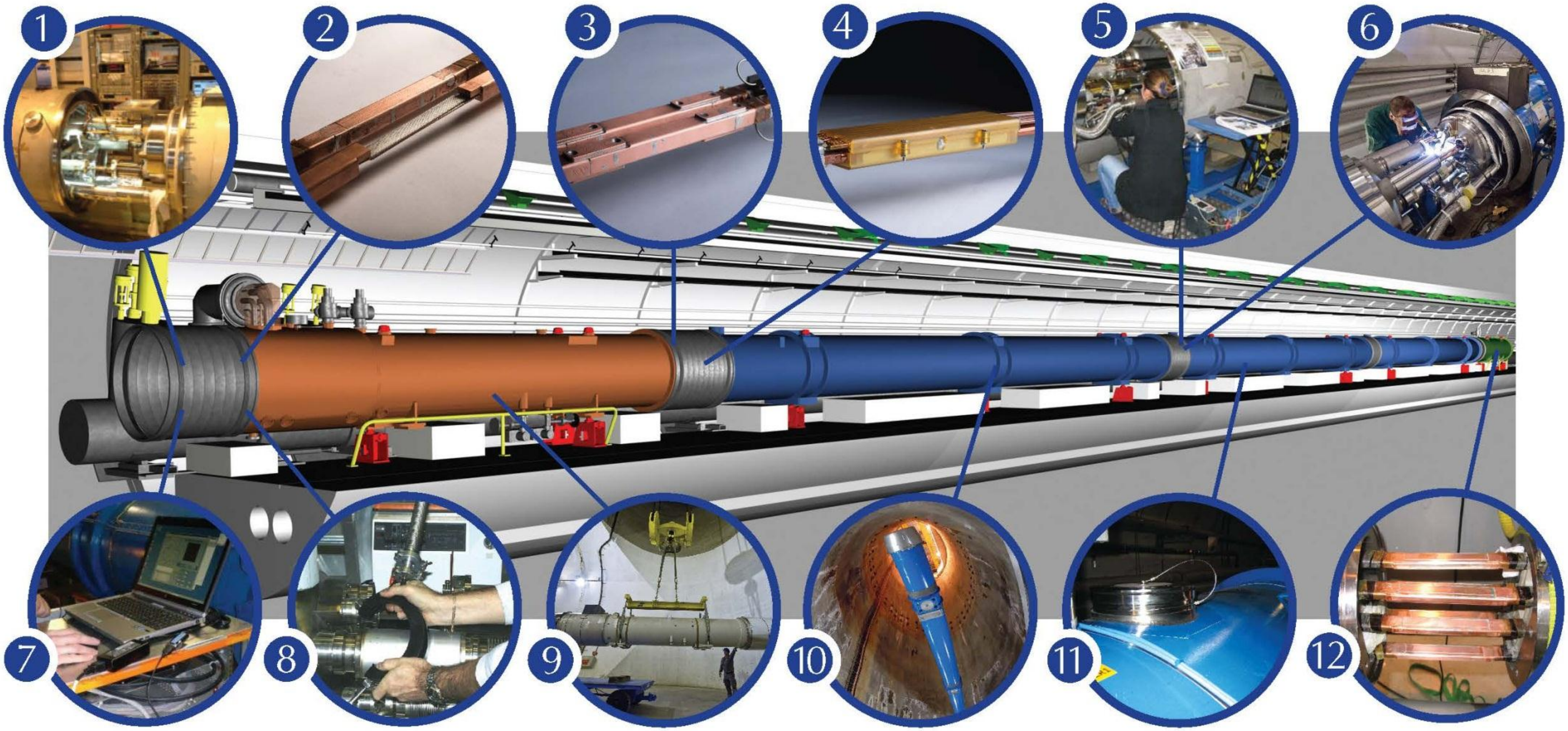
Complete reconstruction of 1500 of these splices

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

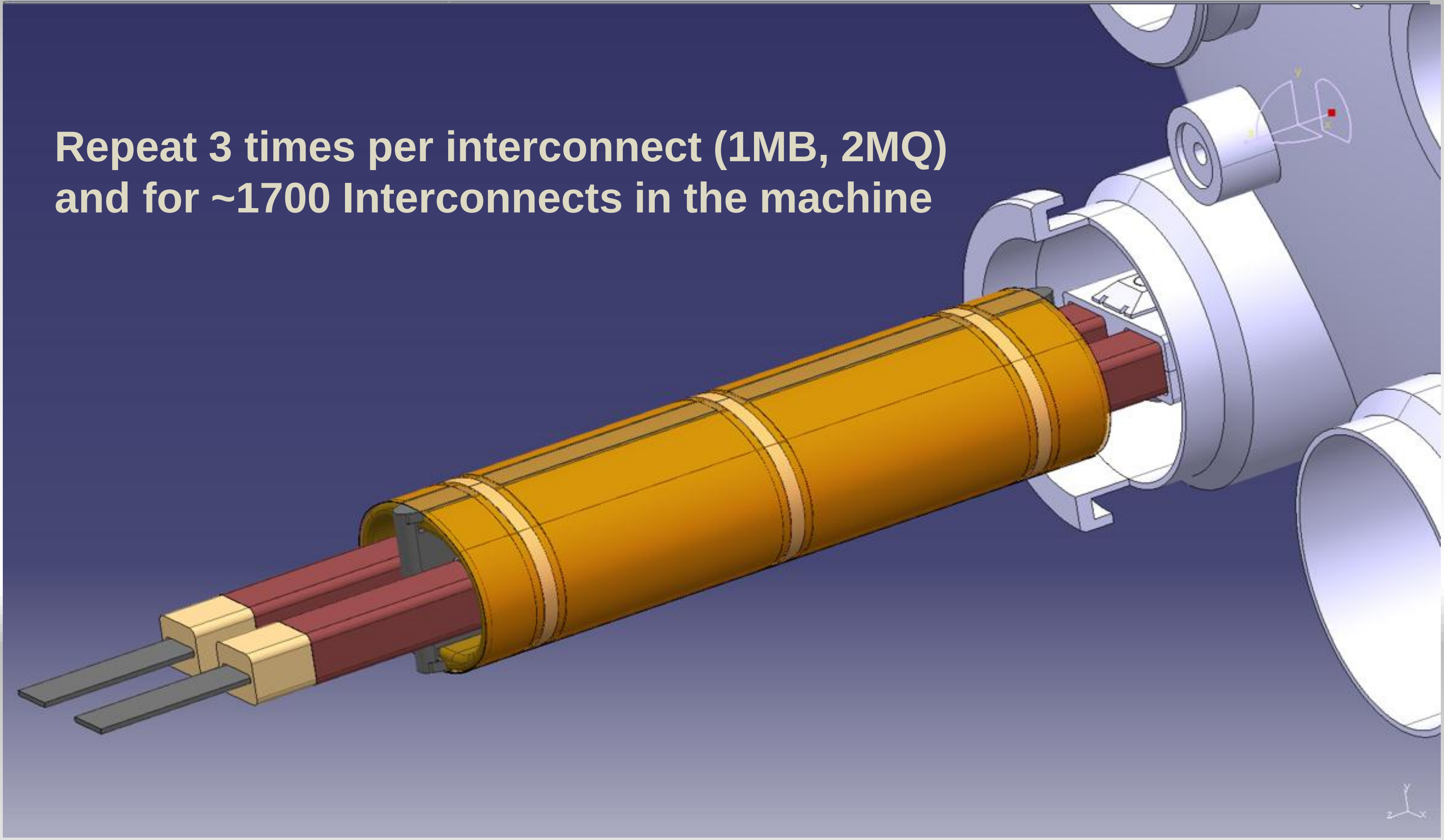
4 quadrupole magnets to be replaced

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 feedboxes

LHC MB circuit splice consolidation proposal



Repeat 3 times per interconnect (1MB, 2MQ) and for ~1700 Interconnects in the machine

Phase III

Insulation between bus bar and to ground, Lorentz force clamping

AFTER LS1

Post LS1 energy

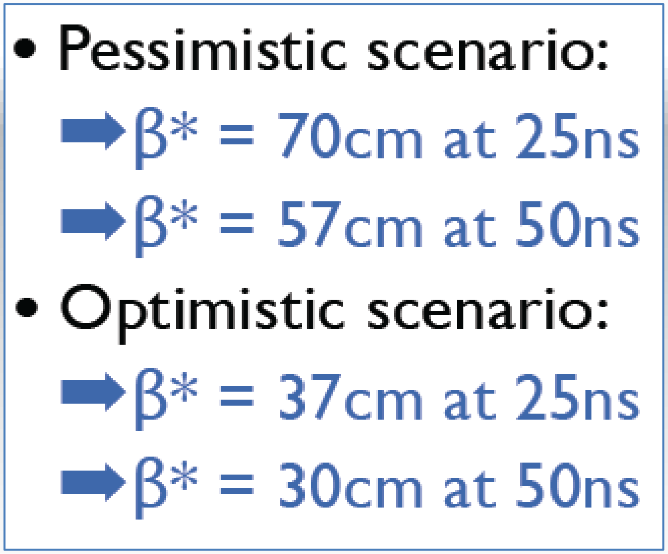
- Magnets coming from 3-4 do not show degradation of performance
- Our best estimates to train the LHC (with large errors)
  - ~ 30 quenches to reach 6.25 TeV
  - ~ 100 quenches to reach 6.5 TeV
- The plan
  - Try to reach 6.5 TeV in four sectors in **JULY to SEPTEMBER 2014** (NB updated after Aspen)
  - Based on that experience, we decide if to go at 6.5 TeV or step back to 6.25 TeV

Ezio Todesco – Chamonix 12

β^* & crossing angle

- β^* reach depends on:
  - available aperture
  - collimator settings, orbit stability
  - required crossing angle which in turn depends on
    - emittance
    - bunch spacing

Beta* reach at 6.5 TeV



- Pessimistic scenario:
  - ➡ $\beta^* = 70$cm at 25ns
  - ➡ $\beta^* = 57$cm at 50ns
- Optimistic scenario:
  - ➡ $\beta^* = 37$cm at 25ns
  - ➡ $\beta^* = 30$cm at 50ns

Belen Salvachua Ferrando at Evian 12

50 versus 25 ns

	50 ns	25 ns
GOOD	• Lower total beam current • Higher bunch intensity • Lower emittance	• **Lower pile-up**
BAD	• **High pile-up** • Need to level • Pile-up stays high • High bunch intensity – instabilities…	• More long range collisions: larger crossing angle; higher beta* • Higher emittance • Electron cloud: need for scrubbing; emittance blow-up; • Higher UFO rate • Higher injected bunch train intensity • Higher total beam current

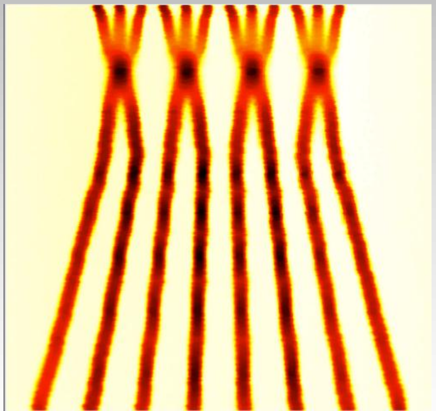
Expect to move to 25 ns because of pile up…

Beam from injectors LS1 to LS2

		Bunch intensity [10^{11} p/b]	Emittance [mm.mrad] Exit SPS	Into collisions
25 ns ~nominal	2760	1.15	2.8	3.75
25 ns BCMS	2520	1.15	1.4	1.9
50 ns	1380	1.65	1.7	2.3
50 ns BCMS	1260	1.6	1.2	1.6

BCMS = Batch Compression and (bunch) Merging and (bunch) Splittings

LIU team



Batch compression & triple splitting in PS

Potential performance

	Number of bunches	Bunch intensity LHC FT[1e11]	β*X/ β*sep/ Xangle	Emit LHC [μm]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi per year [fb^{-1}]
25 ns	2760	1.15	55/43/189	3.75	0.93 x 10^{34}	**25**	**~24**
25 ns low emit	2520	1.15	45/43/149	1.9	1.7 x 10^{34}	**52**	**~45**
50 ns	1380	1.6	42/43/136	2.5	1.6 x 10^{34} level to 0.8 x 10^{34}	**87 level to 44**	**~40***
50 ns low emit	1260	1.6	38/43/115	1.6	2.3 x 10^{34} level to 0.8 x 10^{34}	**138 level to 44**	**~40***

- 6.5 TeV
- 1.1 ns bunch length
- 150 days proton physics
- 85 mb visible cross-section
- * different operational model – caveat - unproven

All numbers approximate

In words

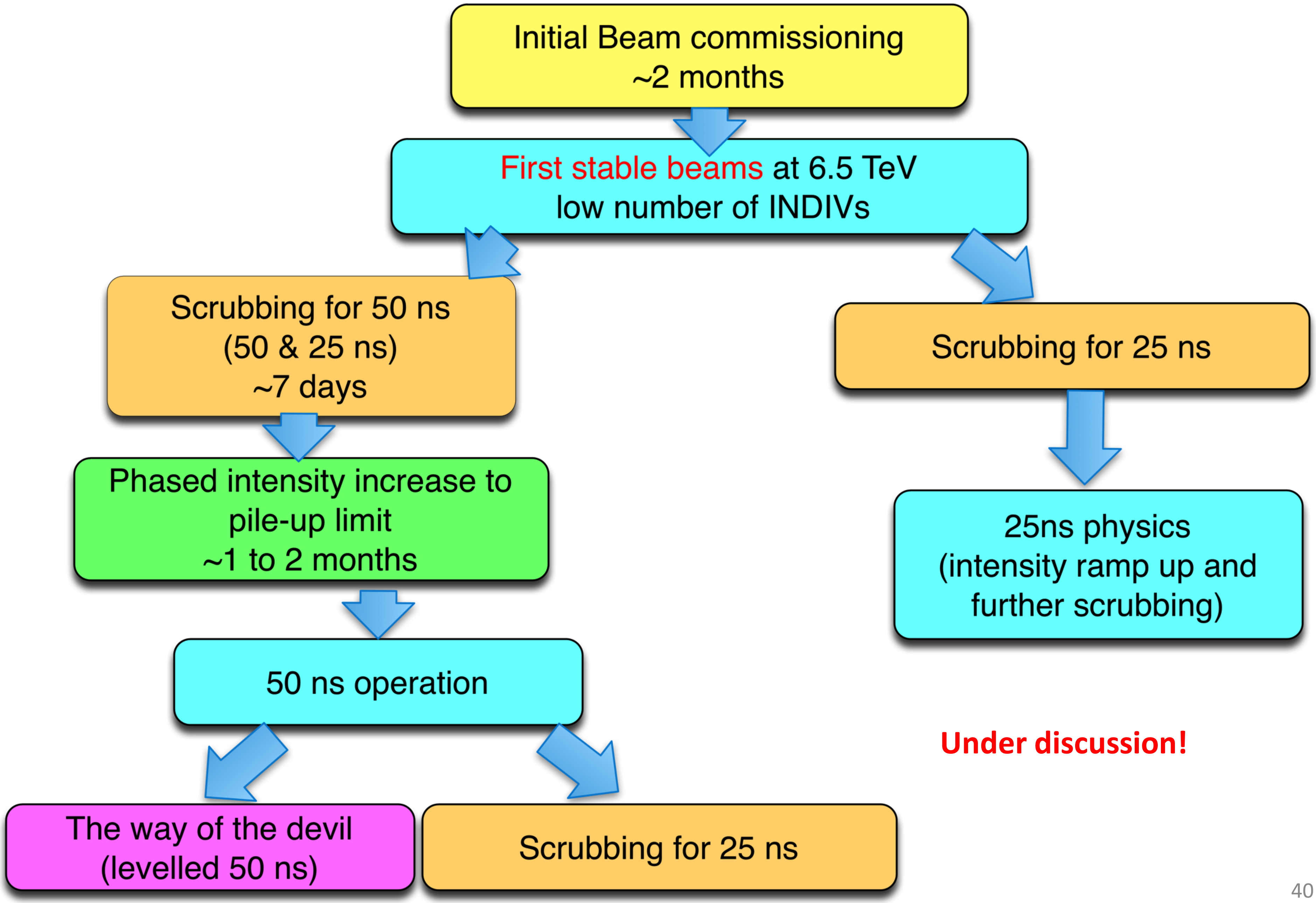
- **Nominal 25 ns**
  - gives more-or-less nominal luminosity

- **BCMS 25 ns**
  - gives a healthy 1.7 x 10^{34}
  - peak $<\mu>$ around 50

- **Nominal 50 ns**
  - gives a virtual luminosity of 1.6 x 10^{34} with a pile-up of over 80
  - levelling mandatory

- **BCM 50 ns**
  - gives a virtual luminosity of 2.3 x 10^{34} with a pile-up of over 100
  - levelling even more mandatory

Start-up 2015



Initial Beam commissioning
~2 months

First stable beams at 6.5 TeV
low number of INDIVs

Scrubbing for 50 ns
(50 & 25 ns)
~7 days

Phased intensity increase to pile-up limit
~1 to 2 months

50 ns operation

The way of the devil
(levelled 50 ns)

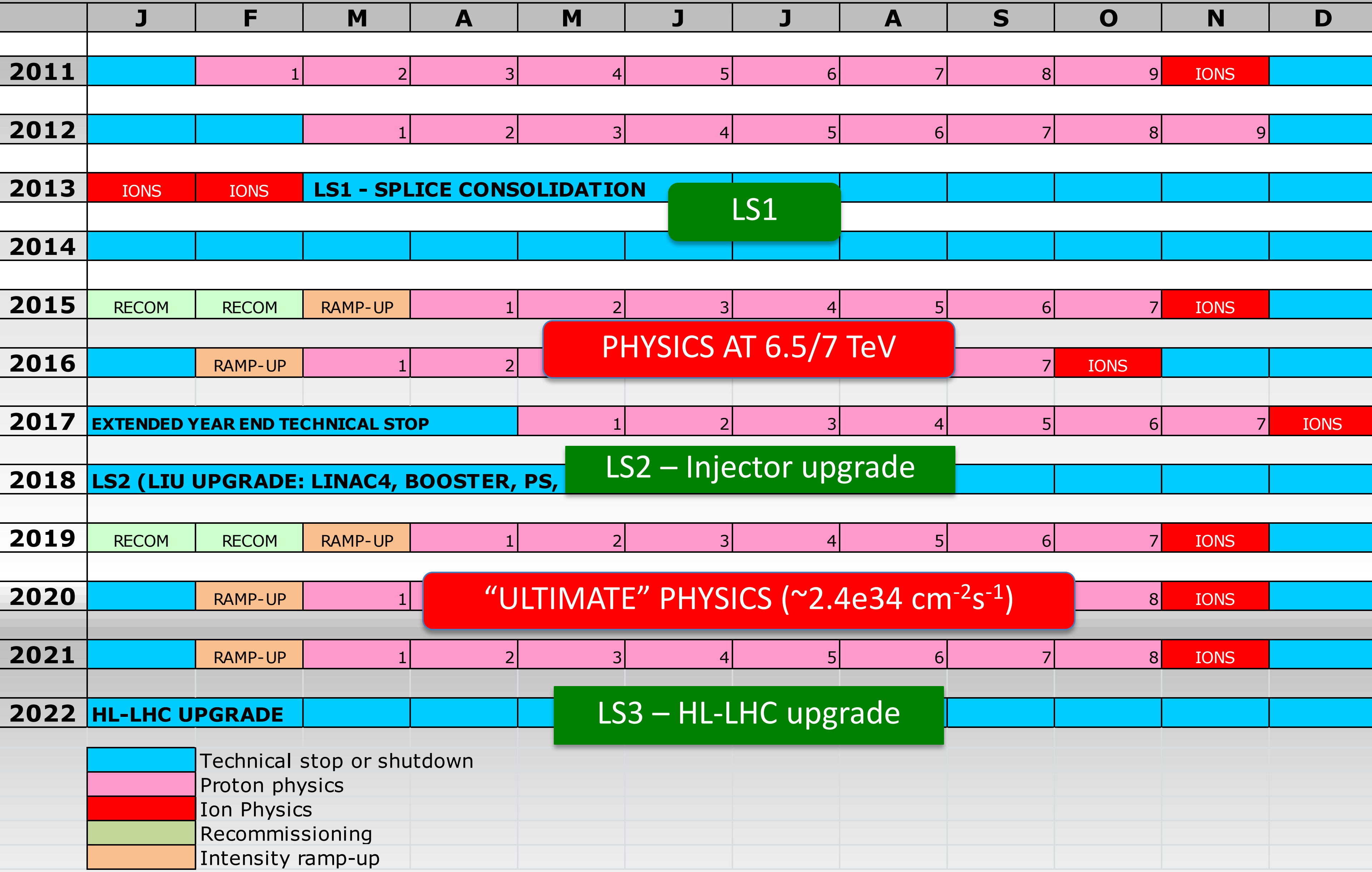
Scrubbing for 25 ns

Scrubbing for 25 ns

25ns physics
(intensity ramp up and further scrubbing)

Under discussion!

Evolving 10 year plan



	J	F	M	A	M	J	J	A	S	O	N	D
2011	🟦	1	2	3	4	5	6	7	8	9	IONS	🟦
2012	🟦	🟦	1	2	3	4	5	6	7	8	9	🟦
2013	IONS	IONS	**LS1 - SPLICE CONSOLIDATION**					🟦	🟦	🟦	🟦	🟦
2014	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
2015	RECOM	RECOM	RAMP-UP	1	2	3	4	5	6	7	IONS	🟦
2016	🟦	RAMP-UP	1	2					7	IONS	🟦	🟦
2017	**EXTENDED YEAR END TECHNICAL STOP**				1	2	3	4	5	6	7	IONS
2018	**LS2 (LIU UPGRADE: LINAC4, BOOSTER, PS,**								🟦	🟦	🟦	🟦
2019	RECOM	RECOM	RAMP-UP	1	2	3	4	5	6	7	IONS	🟦
2020	🟦	RAMP-UP	1							8	IONS	🟦
2021	🟦	RAMP-UP	1	2	3	4	5	6	7	8	IONS	🟦
2022	**HL-LHC UPGRADE**		🟦	🟦	🟦				🟦	🟦	🟦	🟦

LS1

PHYSICS AT 6.5/7 TeV

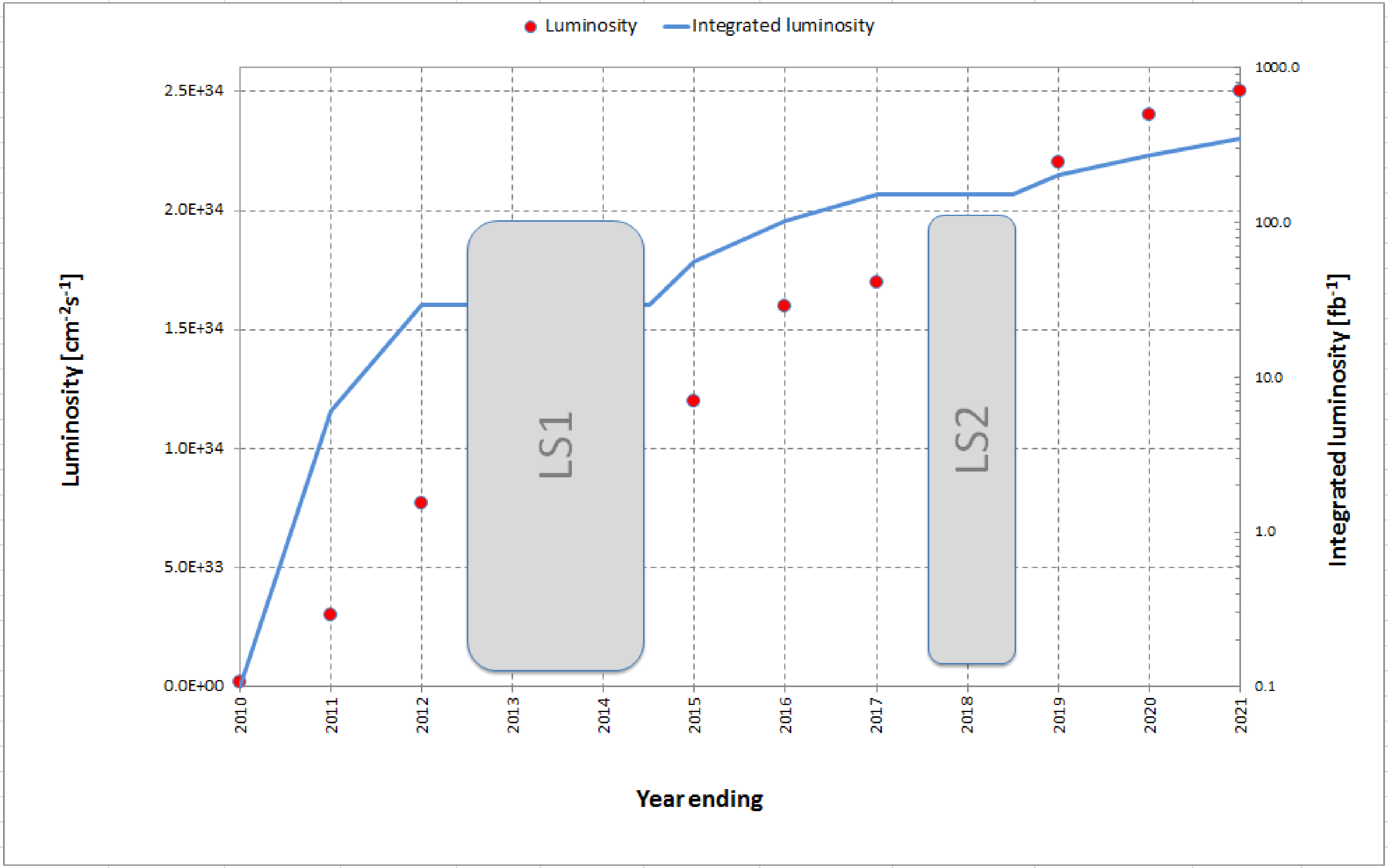
LS2 – Injector upgrade

"ULTIMATE" PHYSICS (~2.4e34 $cm^{-2}s^{-1}$)

LS3 – HL-LHC upgrade

🟦 Technical stop or shutdown
🟪 Proton physics
🟥 Ion Physics
🟩 Recommissioning
🟧 Intensity ramp-up

Projected performance to LS3



Total integrated luminosity: 300 – 400 fb^{-1}

HL-LHC beam parameters at 7 TeV

Stretched Baseline Parameters following 2nd HL-LHC/LIU meeting 8 November 2012

Parameter	nominal	25ns	50ns
nb	2808	2808	1404
Nb	1.15E+11	2.2E+11	3.5E+11
ε_n [mm-mrad]	3.75	2.50	3

HL-LHC 25 ns

Bunch current	2.2e11 ppb
Normalized emittance	2.5 micron
Beta*	15 cm
Crossing angle	590 microrad
Geometric reduction factor	0.305
Peak luminosity	7.4e34 $cm^{-2}s^{-1}$
Virtual luminosity	24e34 $cm^{-2}s^{-1}$
Levelled luminosity	5e34 $cm^{-2}s^{-1}$
Levelled <pile-up>	140

Conclusions

- LHC operation has shown the results of excellent design, construction, and installation
- Injector complex has performed exceptionally
- Both the above have been fully exploited to give very acceptable performance
- Carrying forward a wealth of experience from operation at 3.5 and 4 TeV.
- There are issues for post LS1 operations. Measures to address these are under close examination.

A well-deserved toast to all who have built such a marvelous machine, and to all who operate it so superbly

(first 7 TeV collisions on 30th March 2010)

First 7 TeV collisions – another view

You lucky, lucky buggers!!!

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

Acta est fabula, plaudite!