LHC Machine Upgrades

L. Ponce

On behalf of the LHC Operation Team

Agenda

- Performances in 2012
- Potential issues for future operation
- Long Shut Down 1: preparation for 7 TeV
- LHC after LS1 and to LS2
- HL-LHC potential performance

Luminosity: collider figure of merit

- Key parameter for the experiments is the event rate dN/dt, proportional to the collider **Luminosity *L*** for a physics beam process of given cross section

$$L = \frac{N^2 k_b f}{4\pi\sigma_x^*\sigma_y^*}F = \frac{\boxed{N^2 k_b} f\gamma}{4\pi \boxed{\varepsilon_n \beta^*}}F$$

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

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**

To maximize L we need:

- Large N, large k,
- Smallest possible *β** or *ε* .

2012 parameters:

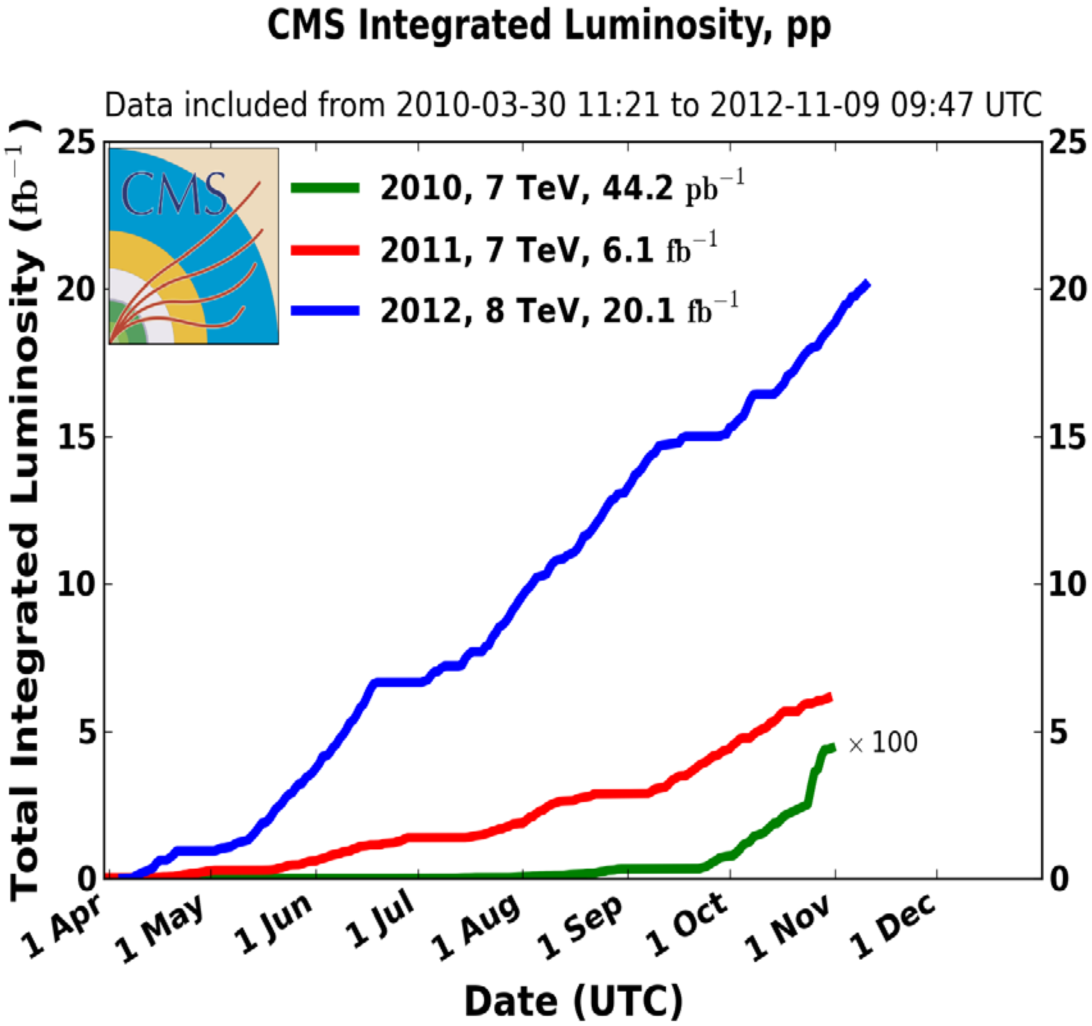
ε_n = 2.5 μm

ε = 5.9 x 10^{-4} μm

σ^* = 18.8 μm

(p = 4 TeV, β^* = 0.6m)

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

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 microns**

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

- Emittances smaller than nominal.
- PS close to the limit of beam stability, injecting close to 1.9×10^{11} ppb into SPS.

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)

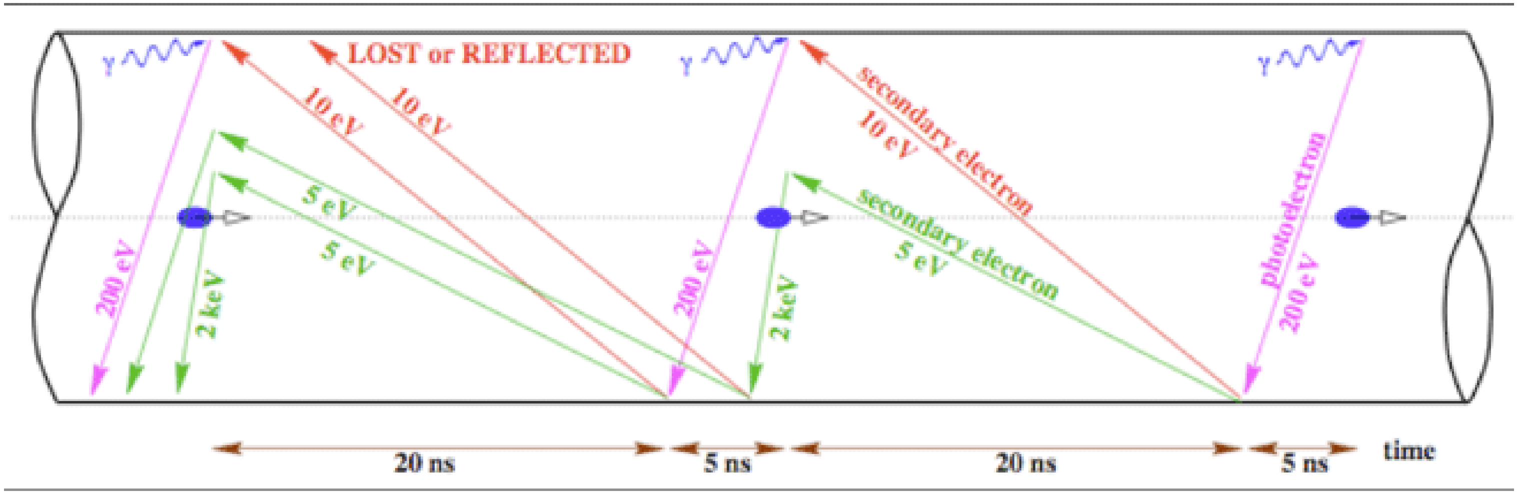
Performance in words

77 % of design luminosity:

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

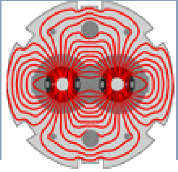
ISSUES & POSSIBLE LIMITATIONS (TWO OF THEM…)

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



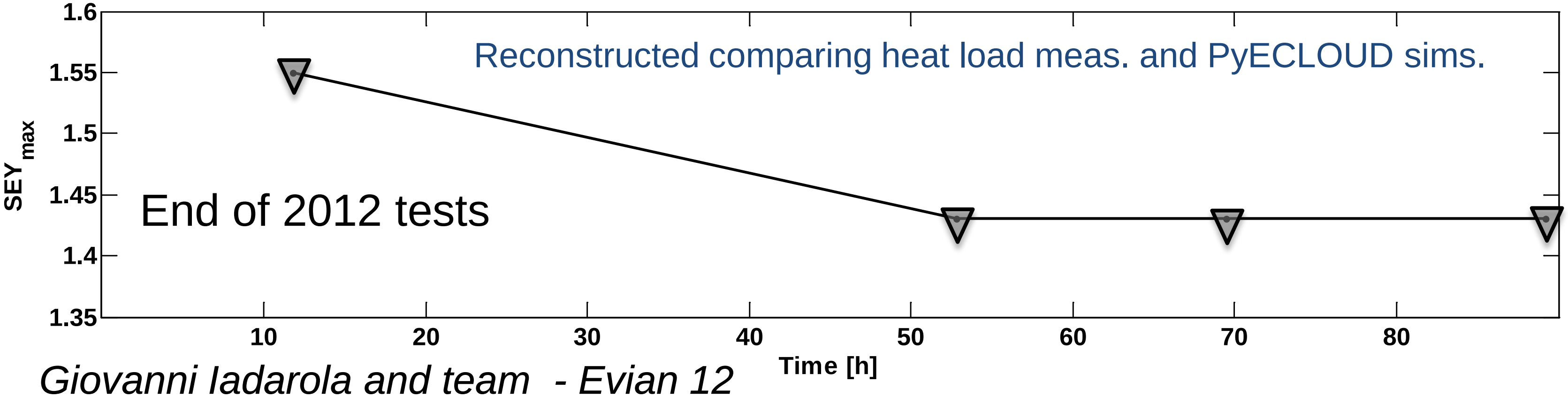
- **single-bunch instability**
- **multi-bunch instability**
- **emittance growth**
- **gas desorption from chamber walls**
- **excessive energy deposition on the chamber walls (heat load)** - important for the LHC in the cold sectors
- **particle losses, interference with diagnostics**,…

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 .**

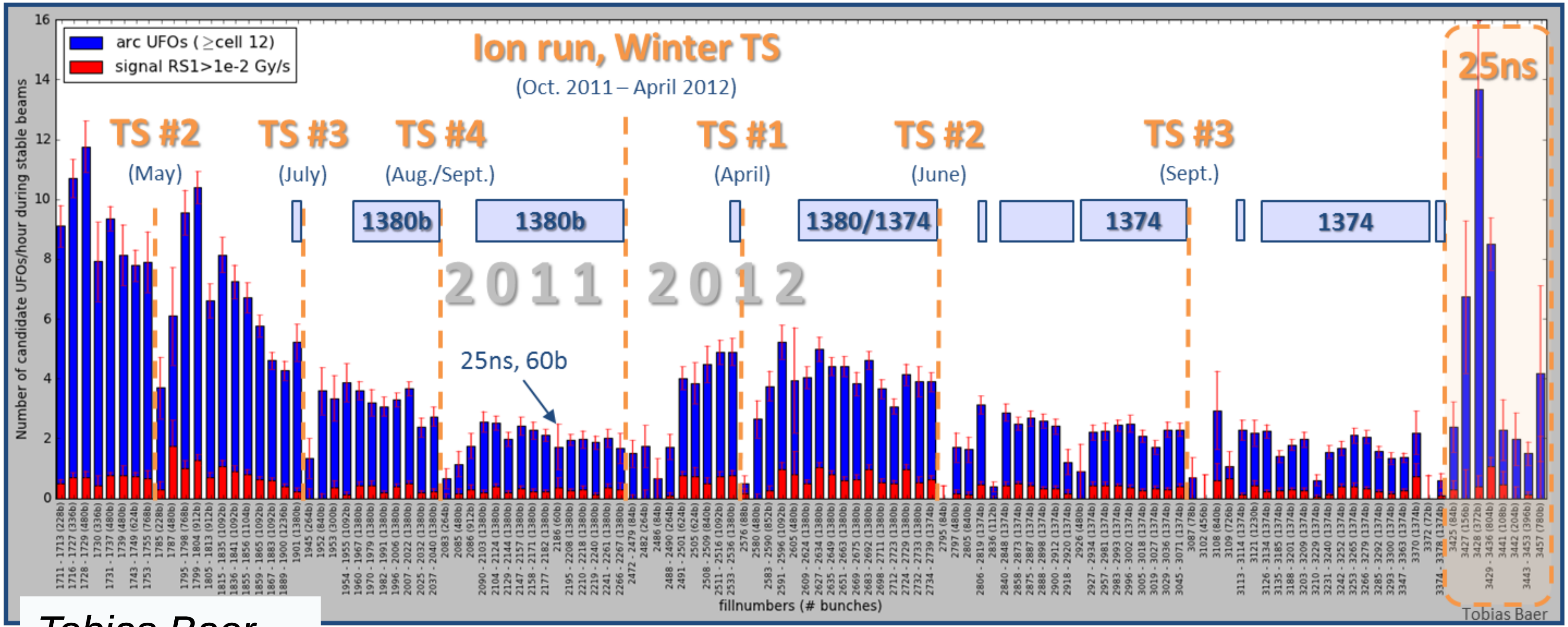
The **SEY evolution significantly slows down** during the last scrubbing fills (more than expected by estimates from lab. measurements and simulations)



Giovanni Iadarola and team - Evian 12

UFOs (Unidentified Falling Objects)

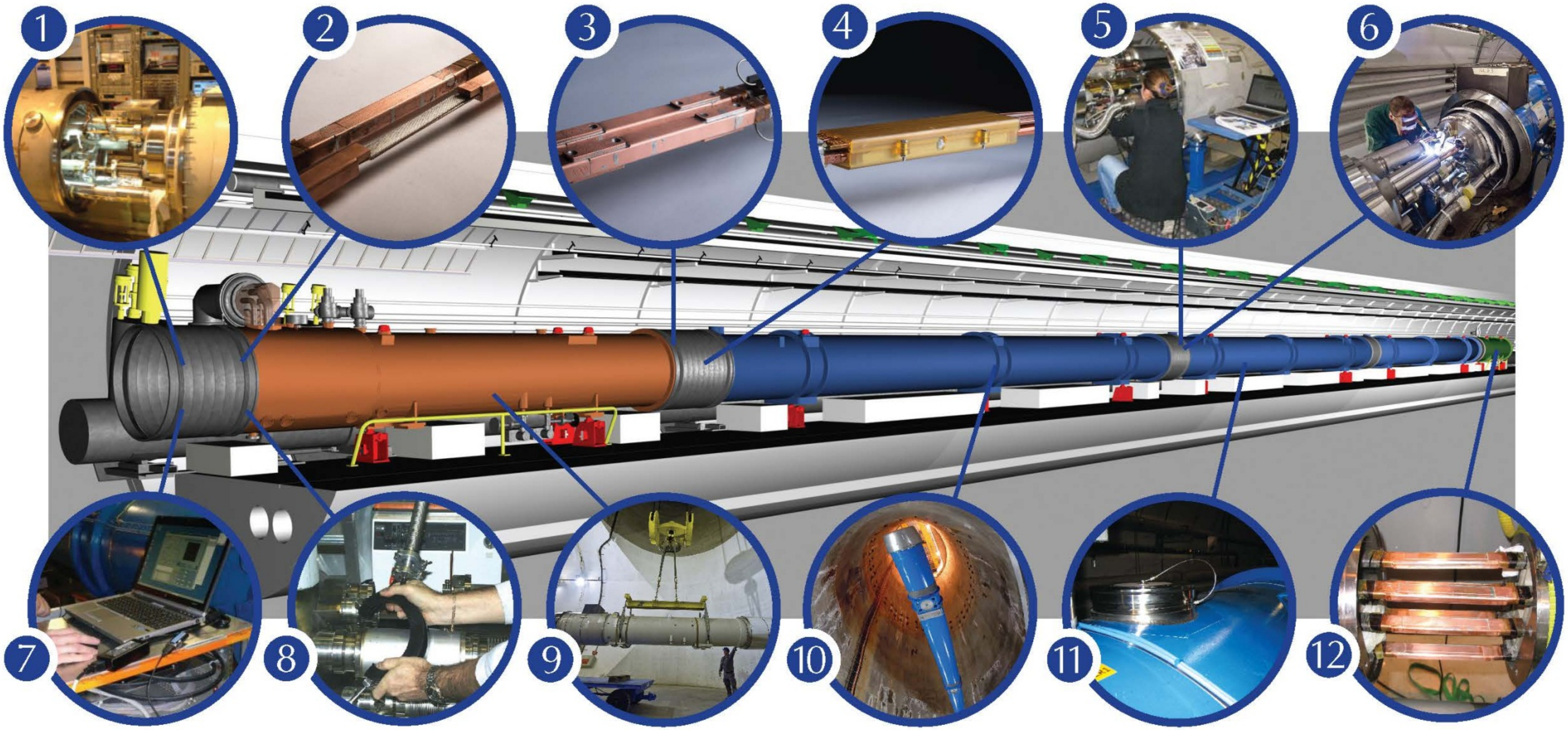
- **UFOs: showstopper for 25 ns and 6.5 TeV?**
  - 10x increase in rate and harder UFOs
- UFO “scrubbing”: does it work? What parameters?
- Deconditioning expected after LS1
- Operational scenario to be developed:
  - start with lower energy and/or 50 ns beam…
  - Adjust beam loss monitor thresholds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



Tobias Baer

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

AFTER LS1

Post LS1 energy

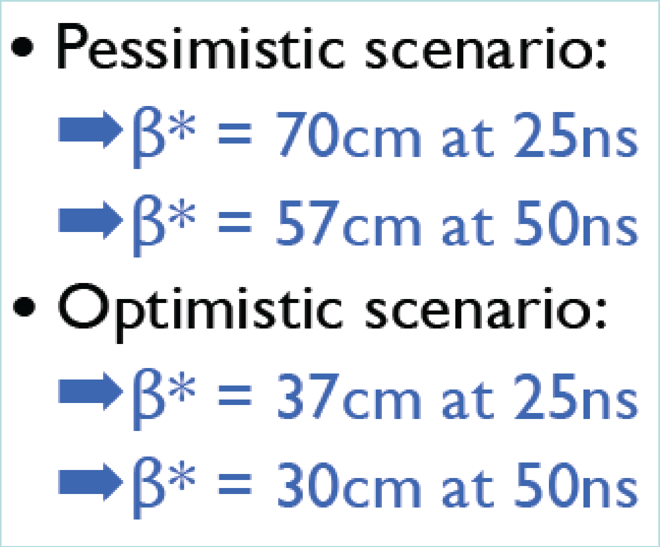
- Magnets coming from sector 3-4 do not show degradation of performance
- Our best estimates to train the LHC (with large errors)
  - ~ 30 quenches to reach 6.25 TeV
  - ~ 100 quenches to reach 6.5 TeV
- The plan
  - Try to reach 6.5 TeV in four sectors in **JULY to SEPTEMBER 2014**
  - Based on that 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:
  - ➡ β^* = 70cm at 25ns
  - ➡ β^* = 57cm at 50ns
- Optimistic scenario:
  - ➡ β^* = 37cm at 25ns
  - ➡ β^* = 30cm 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

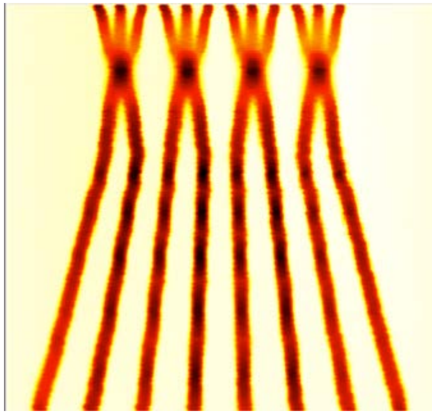
Expect to move to 25 ns because of pile up…

Beam from injectors LS1 to LS2

LIU team

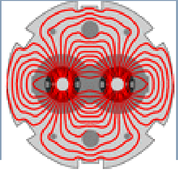
		Bunch intensity [10^{11} p/b]	**Emittance [mm.mrad] Exit SPS**	**Into collisions**
25 ns ~nominal	2760	1.15	2.8	3.75
25 ns BCMS	2520	1.15	1.4	1.9
50 ns	1380	1.65	1.7	2.3
50 ns BCMS	1260	1.6	1.2	1.6

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



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***

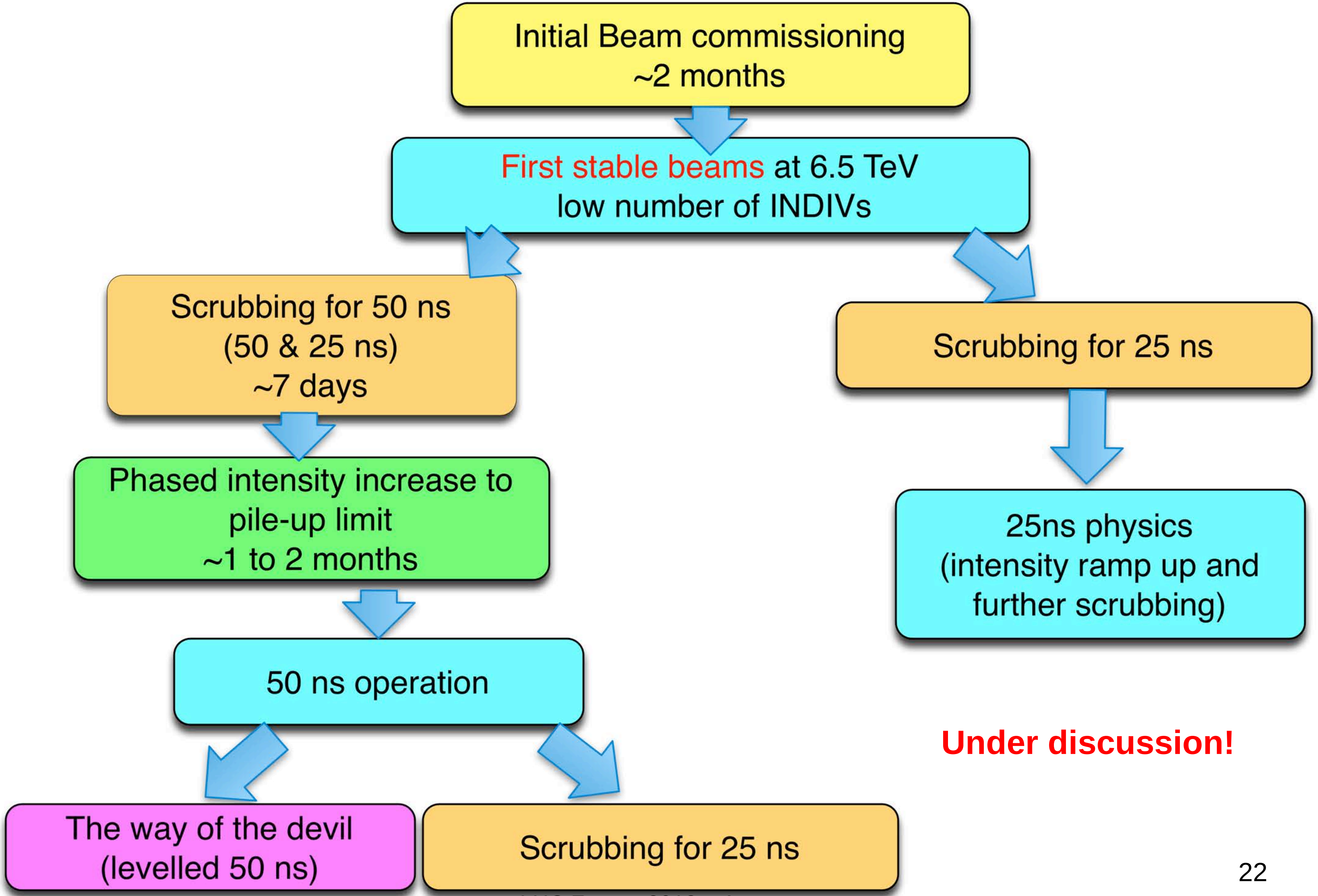
- 6.5 TeV
- 1.1 ns bunch length
- 150 days proton physics
- 85 mb visible cross-section
- * different operational model – caveat - unproven

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 <μ> 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)

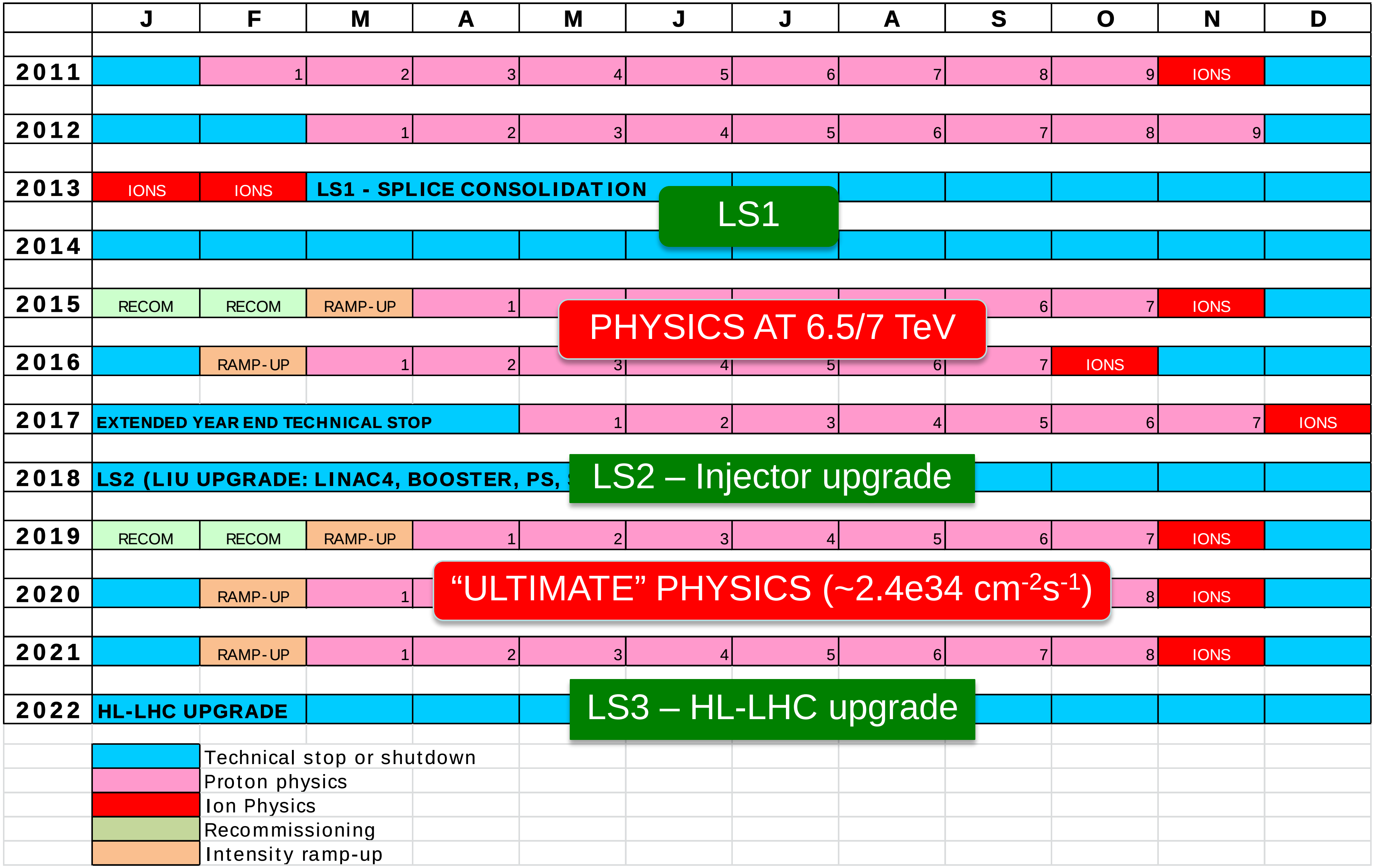
Scrubbing for 25 ns

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					6	7	IONS	
2016		RAMP-UP	1	2	3	4	5	6	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

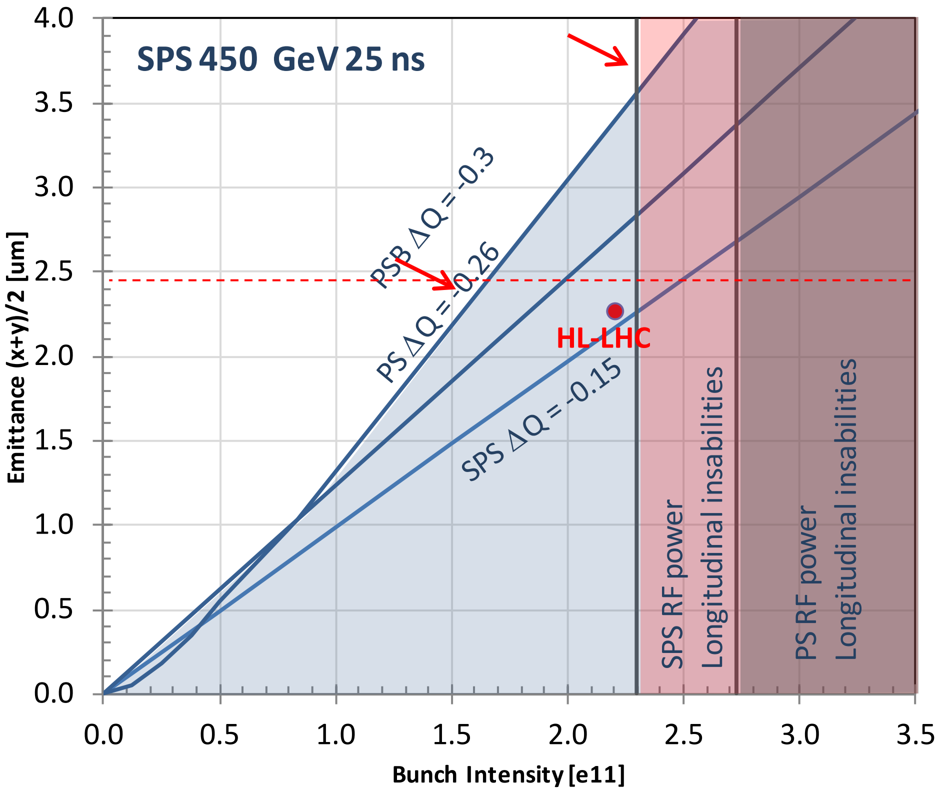
Ion Physics

Recommissioning

Intensity ramp-up

25 ns after LS2 LIU upgrade

- Limit at SPS extraction:
  - 2.3e11 ppb in 3.6 um or 1.6e11 ppb in 2.3 um
  - Fundamental limit: space charge in PS

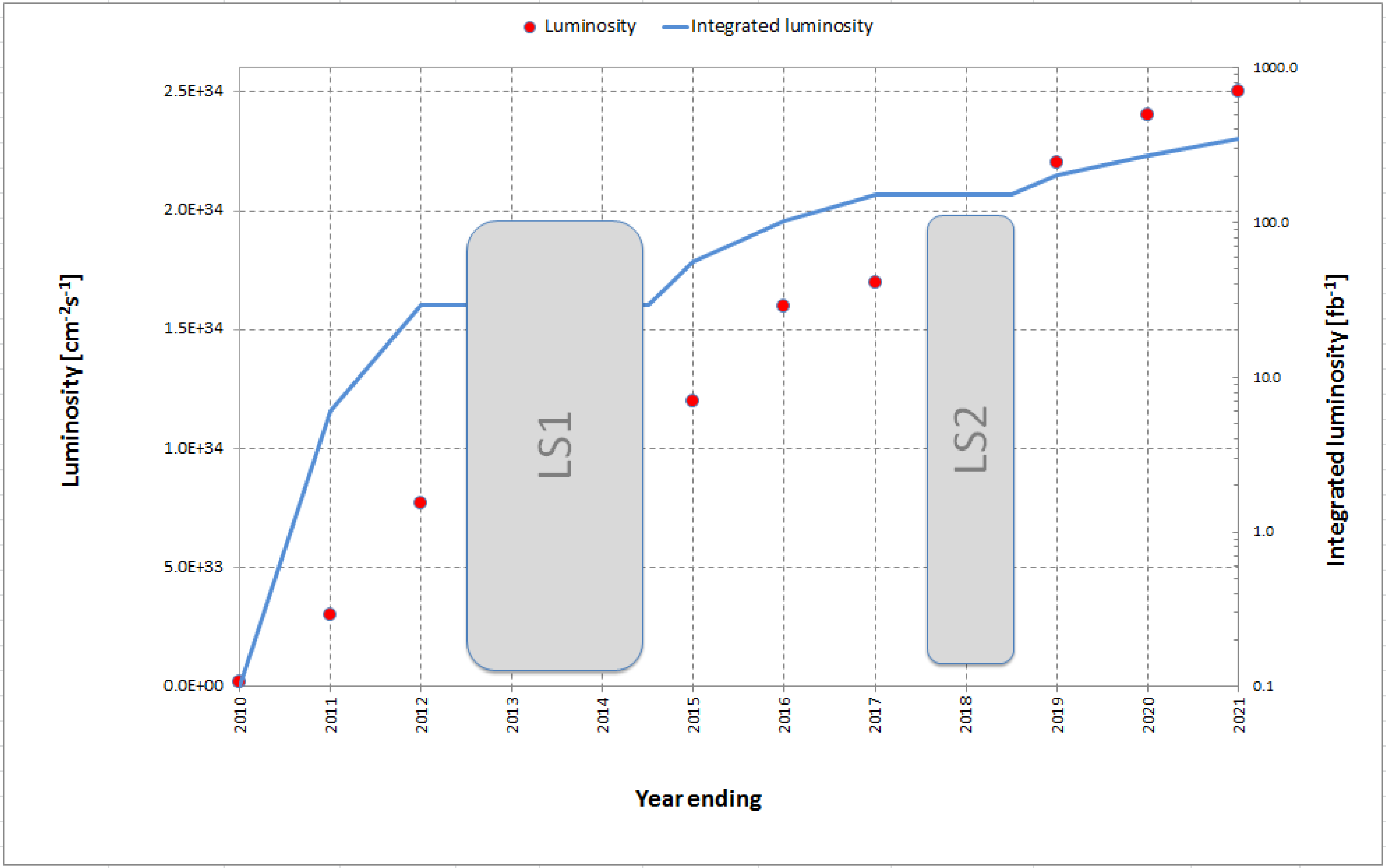


Brennan Goddard at LIU day 2011

LHC limits before LS3

- Encyclopedic run through by Ralph Assmann at Chamonix 2011
- Potential limits from
  - RF, Vacuum, e-cloud, Cryogenics, Magnets, Triplets Injection and Protection, Collimation, SEUs, Radiation Protection
- Ultimate intensity seems a reasonable assumption
  - 1.7e11 ppb x 2808 bunches

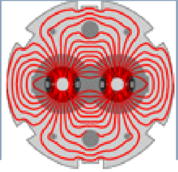
Projected performance to LS3



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

HL-LHC PERFORMANCES

HL-LHC Performance Estimates



🟩 'Stretched' Baseline Parameters following 2^{nd} HL-LHC-LIU:

Parameter	nominal	25ns	50ns
N	1.15E+11	**2.2E+11**	**3.5E+11**
n_b	2808	2808	1404
beam current [A]	0.58	**1.12**	**0.89**
x-ing angle [μrad]	300	590	590
beam separation [σ]	9.9	12.5	11.4
β^* [m]	0.55	**0.15**	**0.15**
ε_n [μm]	3.75	2.5	3.0
ε_L [eVs]	2.51	2.51	2.51
energy spread	1.20E-04	1.20E-04	1.20E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	**18.5**	**17.2**
IBS longitudinal [h]	61 -> 60	**20.4**	**16.1**
Piwinski parameter	0.68	**3.12**	**2.85**
geom. reduction	0.83	**0.305**	**0.331**
beam-beam / IP	3.10E-03	**3.3E-03**	**4.7E-03**
Peak Luminosity	$1\ 10^{34}$	**$7.4\ 10^{34}$**	**$8.5\ 10^{34}$**
Virtual Luminosity	$1.2\ 10^{34}$	**$24\ 10^{34}$**	**$26\ 10^{34}$**
Events /x-ing (peak /leveled)	19/28	207/140	476/140

$6.2\ 10^{14}$ and $4.9\ 10^{14}$ p/beam

➔ Large crossing angle required compensation with crab cavities

Virtual luminosity (25ns) of $L = 7.4 / 0.305\ 10^{34}\ cm^{-2}\ s^{-1}$

$= 24\ 10^{34}\ cm^{-2}\ s^{-1}$ ('k' = 5)

Virtual luminosity (50ns) of $L = 8.5 / 0.331\ 10^{34}\ cm^{-2}\ s^{-1}$

$= 26\ 10^{34}\ cm^{-2}\ s^{-1}$ ('k' = 10)

(Leveled to $5\ 10^{34}\ cm^{-2}\ s^{-1}$ and $2.5\ 10^{34}\ cm^{-2}\ s^{-1}$)

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

2nd HL-LHC General Meeting 13-14 November 2012 Oliver Brüning BE-ABP CERN

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

Goal for integrated annual luminosity:

➔ 250 fb^{-1} per year

Levelling options

- Transverse offsets of the beams at the IP.
  - tested in 2011 with HL-LHC parameters single bunches and in 2012 with present LHC
  - worry about beam-beam: instabilities, emittance growth
- The use of crab cavities for manipulating the beam overlap of the two beams in the luminous region.
- Manipulation of the external crossing angle of the two beams
  - e.g. with the help of partial compensation of the long-range beam-beam interactions in the common vacuum system with the help of wires
- Dynamic change of the beta*
- Bunch length variation

Or combinations of the above

Tatiana Pieloni at BB2013 workshop

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.
- Run II – BCMS – 1.7e34 peak lumi
- Run III – Injector upgrade – ultimate performance