“LHC: the status, the projections for this year, and the possibilities for the near and far future..”

LHC Accelerator Prospects

Mike Lamont
for the LHC team

Acknowledgements: Brennan Goddard, Heiko Damerau, Frank Zimmermann, Werner Herr

2011 – A QUICK LOOK BACK

2011

- Successfully wrestled with:
  - Total intensity
  - Bunch spacing
  - Bunch intensity
  - Emittance
  - Beta* & aperture

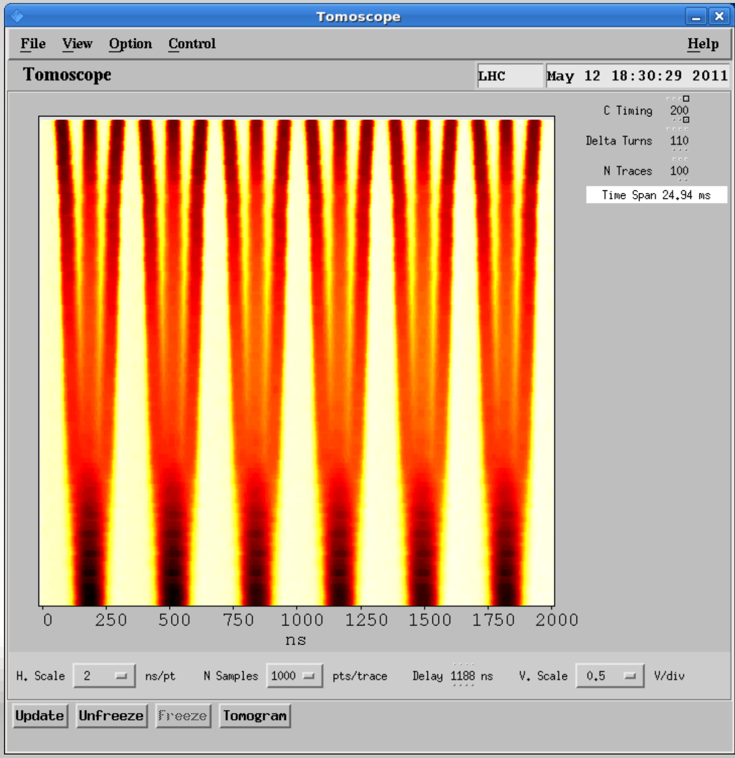
- Good performance from working on all available parameters
- Definitely exploring the effects of high intensity beams:
  - SEUs, beam induced heating, vacuum instabilities…
  - Operational efficiency suffering as a result

Of note

- Operational robustness
  - Precycle, injection, 450 GeV, ramp & squeeze & collisions routine
- Machine protection
  - Unpinned by superb performance of machine protection and associated systems
  - Rigorous machine protection follow-up, qualification and monitoring
- **Routine collimation of 110 MJ LHC beams** without a single quench from stored beams.

Beam from injectors

Excellent performance – years in the preparation



Best in 2011 with 50 ns:

- ~1.45 x 10^{11} ppb
- ~2.3 microns into collision

Design with 25 ns:

- **1.15 x 10^{11} ppb**
- **Normalized emittance 3.75 microns**

IR1 and IR5 aperture at 3.5 TeV

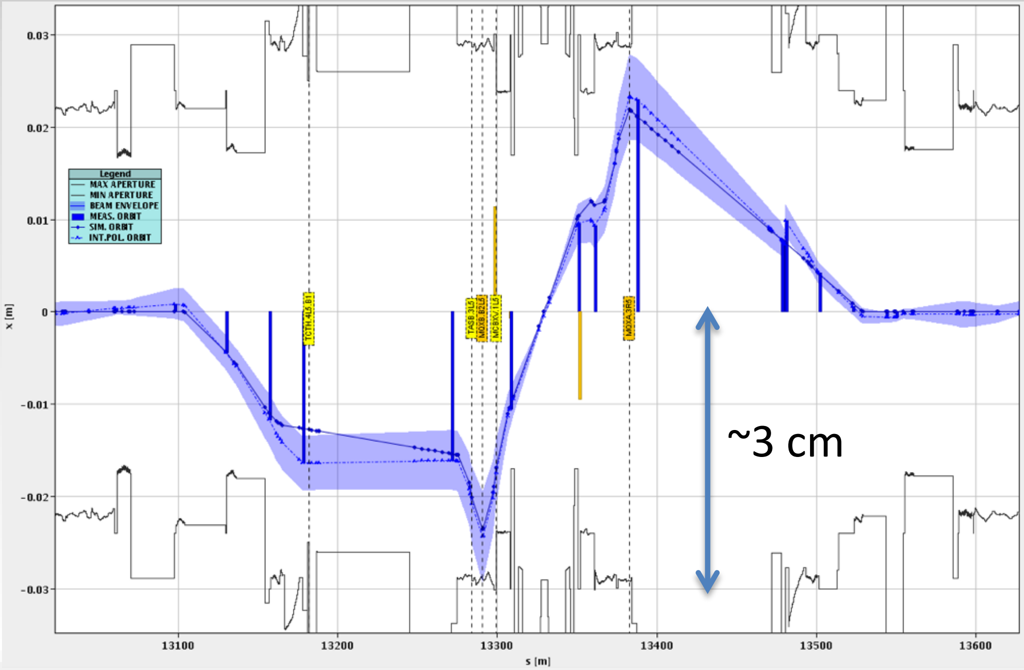
2011's "platinum mine"

IR	Plane	Type of bump in standard optics	Aperture [σ]
1	H	Separation	19.8 – 20.3
1	V	Crossing	18.3 – 18.8
5	H	Crossing	19.8 – 20.3
5	V	Separation	> 20.3

*We got **4-6 sigmas** more than the expected 14 sigma*

Triplet aperture compatible with a well-aligned machine, a well centred orbit and a ~ design mechanical aperture

CMS



Stefano Redaelli

~600 m

Additional margin allowed squeeze to beta* = 60 cm in 2012

– big success – 6e33 $cm^{-2}s^{-1}$

2011 to 2012

- Well organized, productive Xmas technical stop
  - Lot of R2E related work
  - Plus consolidation and improvements of many systems
- Vacuum consolidation to address successfully diagnosed causes of instabilities in 2011
- Injection collimators issues diagnosed and understood - spare in preparation - fingers crossed in the meantime
- Cool-down of machine exactly on schedule
- Very smooth hardware commissioning including careful quench-less commissioning of main circuits to 4 TeV
- Well oiled Machine checkout final tests and preparation for beam

2012

2012 run configuration

- Energy – 4 TeV
  - Low number of quenches (as in 2011) assumed
- Bunch spacing - 50 ns
- Tight collimator settings
  - Now proven operationally
- Atlas and CMS beta* - 60 cm
- Alice and LHCb beta* - 3 m
  - Natural satellites versus main bunches in Alice
  - Tilted crossing in LHCb

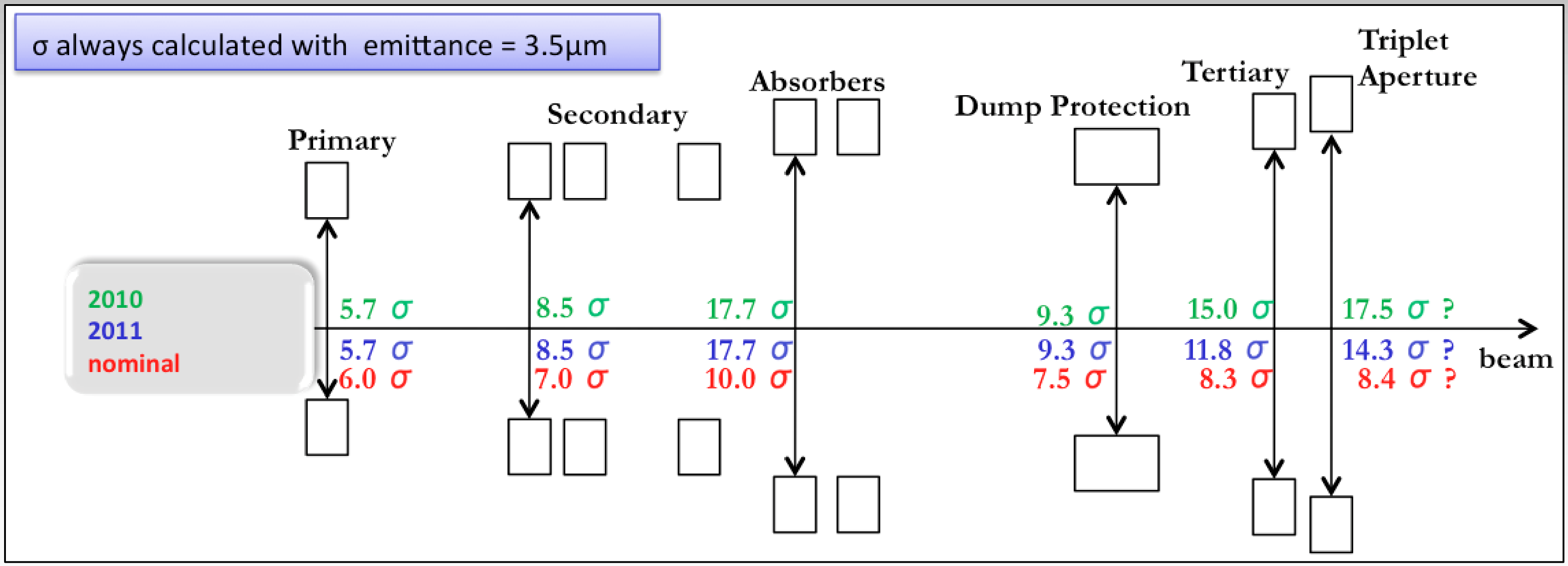
Bunch spacing

Performance from injectors

Bunch spacing	From Booster	Protons per bunch (ppb)	Emittance H&V [mm.mrad]
150	Single batch	1.1×10^{11}	1.6
75	Single batch	1.2×10^{11}	2.0
50	Single batch	1.45×10^{11}	3.5
50	Double batch	1.6×10^{11}	2.0
25	Double batch	1.2×10^{11}	2.7

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

Collimator settings 2012



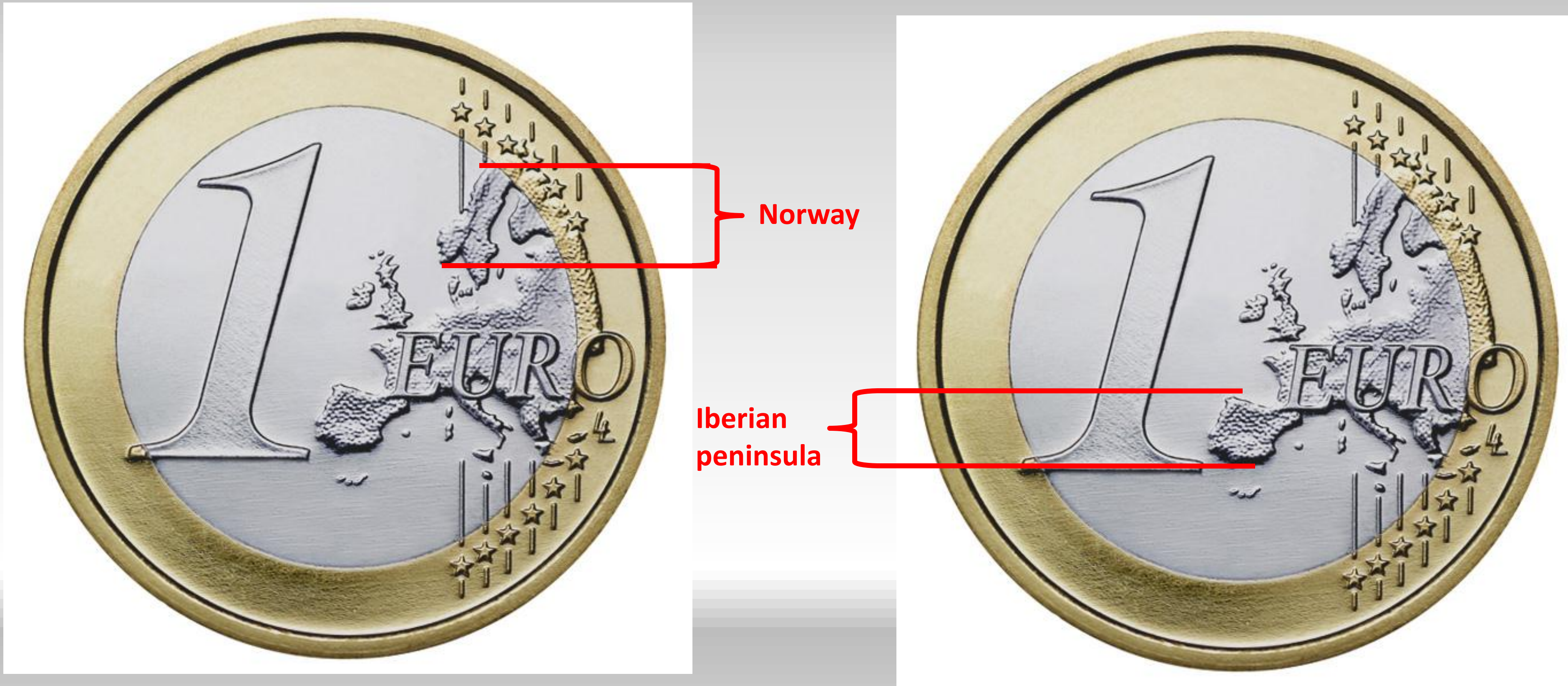
Collimation hierarchy has to be respected in order to achieve satisfactory protection and cleaning.

Aperture plus tight settings allows us to squeeze to 60 cm

2012: tight settings

	σ
TCP 7	4.3
TCSG 7	6.3
TCLA 7	8.3
TCSG 6	7.1
TCDQ 6	7.6
TCT	9.0
Aperture	10.5

How tight?



Intermediate settings (2011):
~3.1 mm gap at
primary collimator

Tight settings (2012):
~2.2 mm gap at
primary collimator

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

L(mm) MDC		PRS R(mm)
	IP1	
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

BETATRON_HOR BETATRON_VER OFFMOMENTUM_POS_DP OFFMOMENTUM_NEG_DP

2012 – canonical (long) year

	Days
Machine check-out	2
Commissioning with beam	21
Machine development	22
Technical stops	20
Scrubbing (25 ns)	3
Technical stop recovery	6
Initial intensity ramp-up	~21
Proton running	~126
Special runs	~8
Ion setup	4
Ion run	24

~150 days

50 ns performance estimate

from Moriond

4 TeV, 50 ns, 1380 bunches, 1.6e11, 2.5 microns
150 days of proton physics (assuming similar efficiencies to 2011)

Beta* [cm]	Collimators	Peak Lumi [$cm^{-2}s^{-1}$]	Int. Lumi [fb^{-1}]	Pile-up	Increase in peak
90	Intermediate	5.1e33	12.1 – 14.5	26	
70	Tight	6.2e33	14.7 – 17.6	31	+22%
60	Tight	6.8e33	16.2 – 19.3	35	+10%

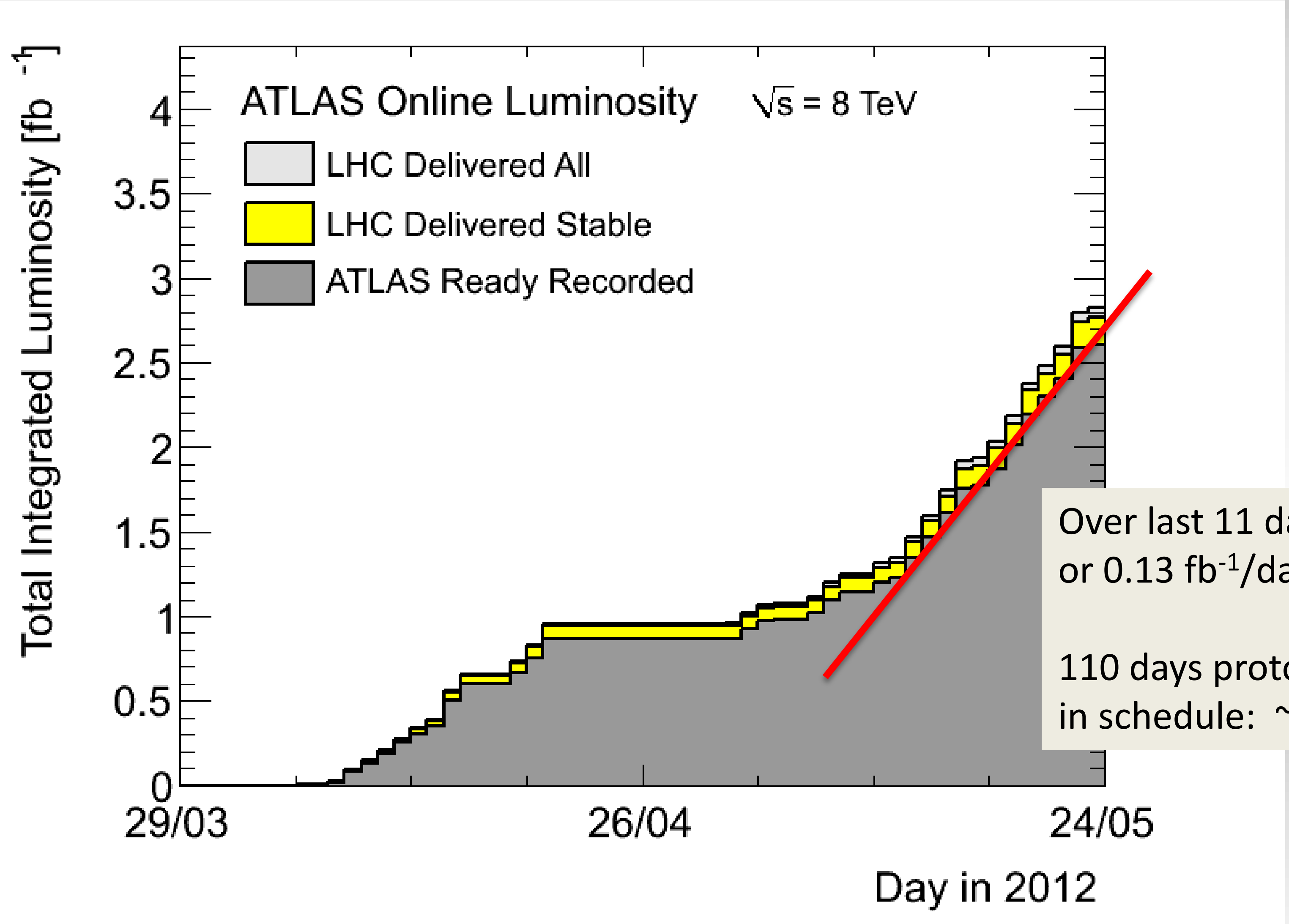
2012 so far

Date	Milestone
Thu 15.03	Both beams captured, orbit and Q adjusted
Fri 16.03	**Both beams at 4 TeV**
Sun 18.03	**Both beams squeezed to 0.6 m**
Thu 5th April	First stable beams – 3 bunches
Wed 18th April	1380 bunches per beam - peak luminosity ~5.5e33 $cm^{-2}s^{-1}$
20-22 April	Machine development
23-27 April	Technical stop
to 10 May	Struggled back up to 1380 ~4.3e33 $cm^{-2}s^{-1}$
Last weekend	~6e33 $cm^{-2}s^{-1}$ and ~190 fb^{-1} in one fill… production running

2012 so far

- Smooth re-commissioning
- Tight collimator setting operational
- Squeeze to 60 cm OK
- Excellent peak performance
  - Peak/delivery rates
- Luminosity production hampered by
  - Injector beam quality (some foot shooting)
  - Machine availability – in particular cryogenics issues
  - Some fun with beam-beam instabilities, LHCb's tilted crossing angle….
  - Now settling down

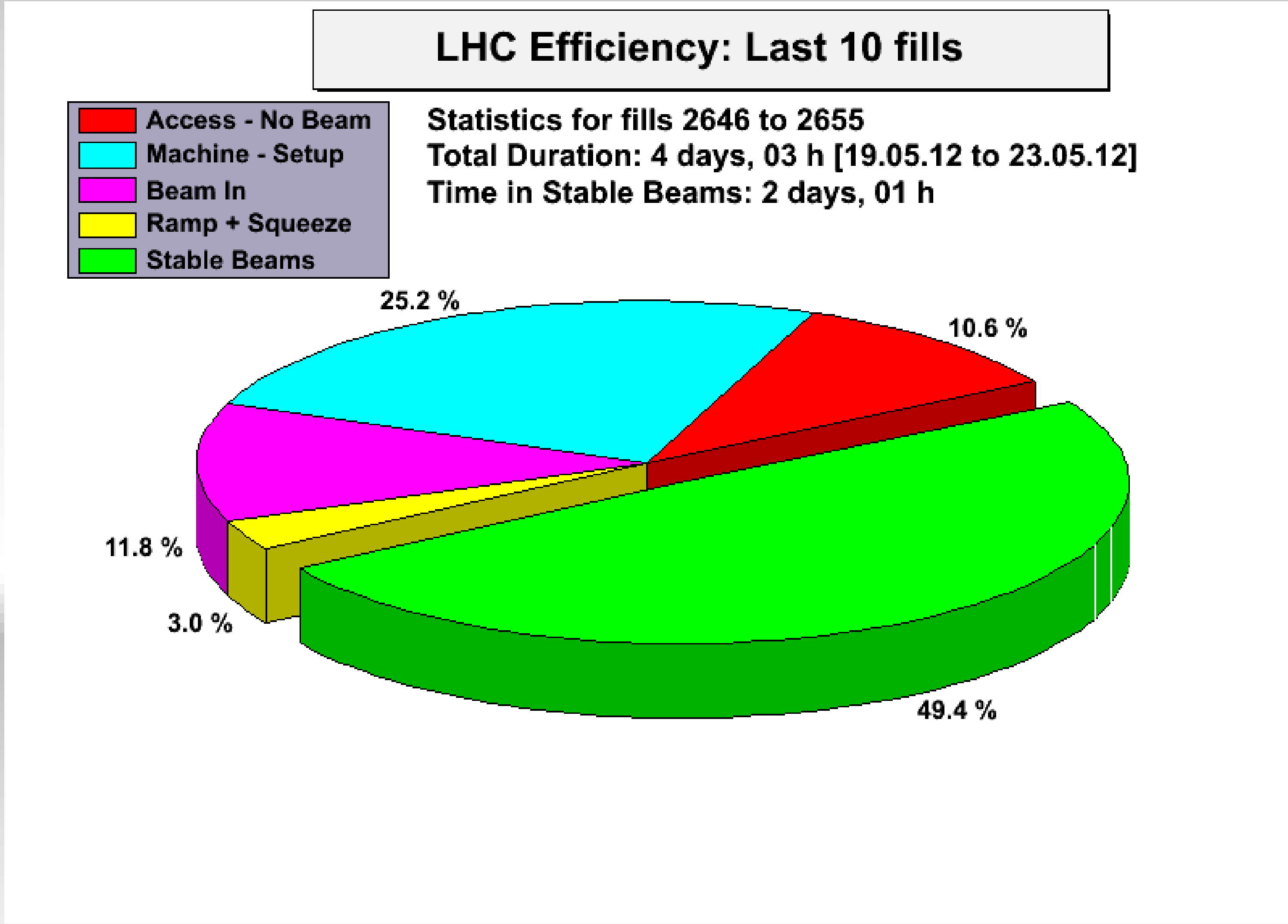
Production running



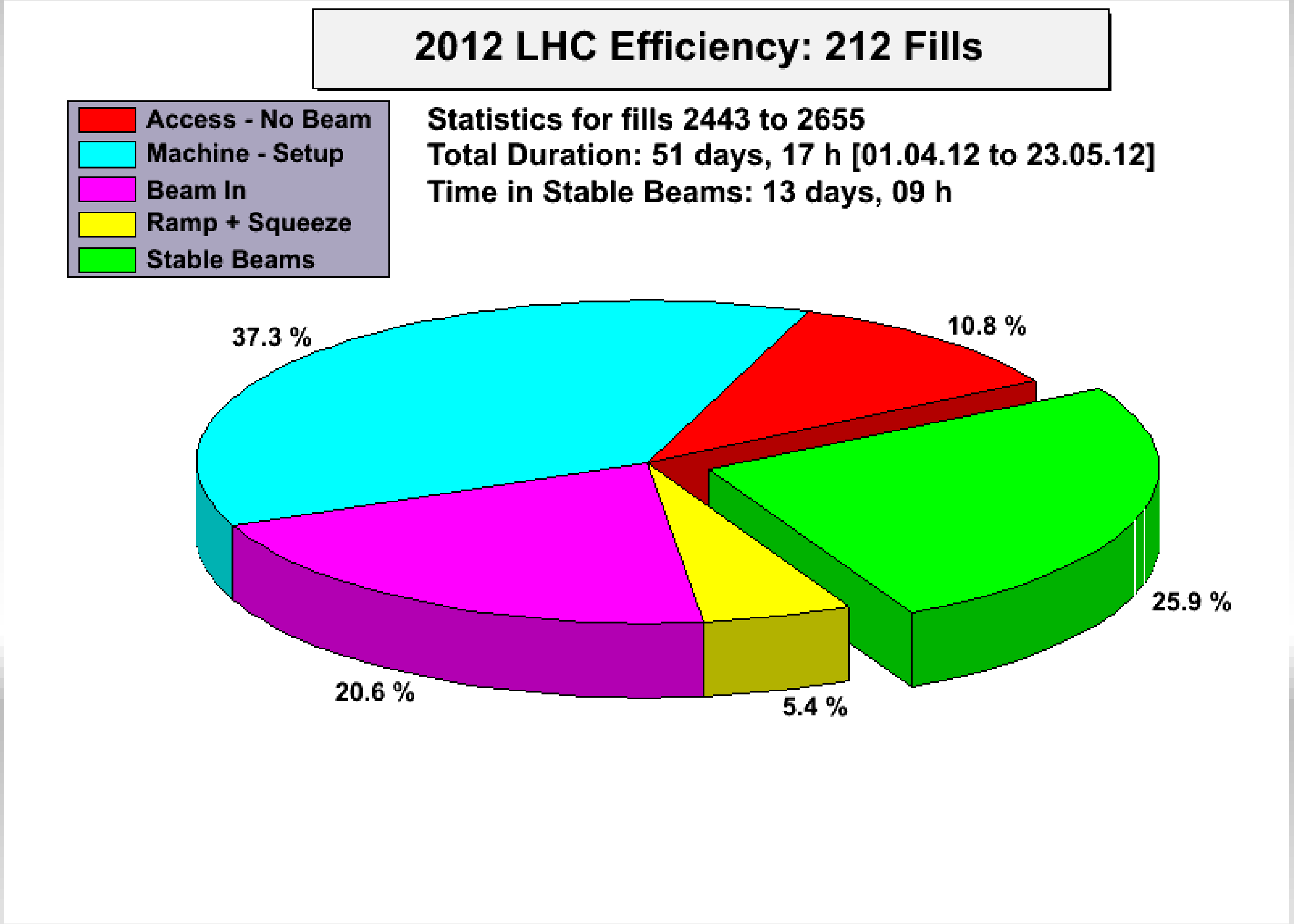
Over last 11 days: ~1.45 fb^{-1} or 0.13 fb^{-1}/day

110 days proton physics left in schedule: ~14 fb^{-1}

Recent operational efficiency



This year


2012 LHC Efficiency: 212 Fills
Access - No Beam
Machine - Setup
Beam In
Ramp + Squeeze
Stable Beams
Statistics for fills 2443 to 2655
Total Duration: 51 days, 17 h [01.04.12 to 23.05.12]
Time in Stable Beams: 13 days, 09 h
37.3 %
10.8 %
25.9 %
20.6 %
5.4 %

Lessons for the future

- Head-on beam-beam is not a limitation
- Long range has to be taken seriously
  - Need separation (otherwise bad lifetime and beam loss)
  - Small as possible emittances are good
  - Require separation established (10 to 12 sigma) and thus the crossing angle (important because our F is going to bite at lower beta)
- beta* reach (aperture, collimation, optics) established
- Levelling tested – it works in LHCb!
- Availability issues (SEUs, vacuum, cryogenics…) – vigorous follow-up and consolidation

50 versus 25 ns

- 50-ns beam: smaller emittance from the PS
  - less splittings in the PS; i.e. less charge in the PSB
  - ~2 vs ~3.5 micron at LHC injection
- 25-ns beam: emittance growth due to e-cloud in the SPS and LHC
  - to be improved by scrubbing in the LHC, and a-C coating in the SPS
- 25-ns has more long-range collisions
- Total current limit (by vacuum; RF) → limit # bunches
- Bunch train current limits in SPS & LHC → limit # bunches
- UFO rate seems to greatly increase for 25-ns spacing
- Ultimately we will (try to) transit to 25-ns spacing because of pile up

TOWARDS EXPLOITING THE ‘NOMINAL’ AND ‘ULTIMATE’ PARAMETER SET OF THE LHC

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	IONS	
2013	LS1 - SPLICE CONSOLIDATION											
2014									RECOM	RECOM	1	2
2015	1	2	3	4	5	6	7	8	9	10	IONS	
2016		1	2	3					8	9	IONS	
2017		1	2	3	4	5	6	7	8	9	IONS	
2018	LS2											
2019		1	2	3	4	5	6	7	8	9	IONS	
2020		1	2	3					8	9	IONS	
2021		1	2	3	4	5	6	7	8	9	IONS	
2022	HL-LHC upgrade											

LS1

PHYSICS AT 6.5/7 TeV

LS2

“ULTIMATE” PHYSICS

LS3

HL-LHC

- Technical stop or shutdown
- Proton physics
- Ion Physics
- Recommissioning

NB: not yet approved

LSs

2013 – 2014: Long Shutdown 1 (LS1) consolidate for 6.5 / 7TeV

- Measure all splices and repair the defective
- Consolidate interconnects with new design (clamp, shunt)
- Finish installation of pressure release valves (DN200)
- Magnet consolidation
- Measures to further reduce SEE (R2E): relocation, redesign, …
- Install collimators with integrated button BPMs (tertiary collimators and a few secondary collimators)
- Experiments consolidation/upgrades

2018: LS2 to prepare for 'ultimate LHC' parameter set:

- Phase II collimation upgrade
- Major injectors upgrade (LINAC4, 2GeV PS Booster, SPS coating, …)
- Prepare for crab cavities (for HL-LHC)

Future performance

- What can the injectors deliver?
- What can the LHC take?
  - RF, cryo, MP, e-cloud…
- What can the LHC do with it?
  - Squeeze, pile-up…
- Scheduled time
- Machine availability & operational robustness

INJECTORS

MOTIVATION

Requirements from HL-LHC

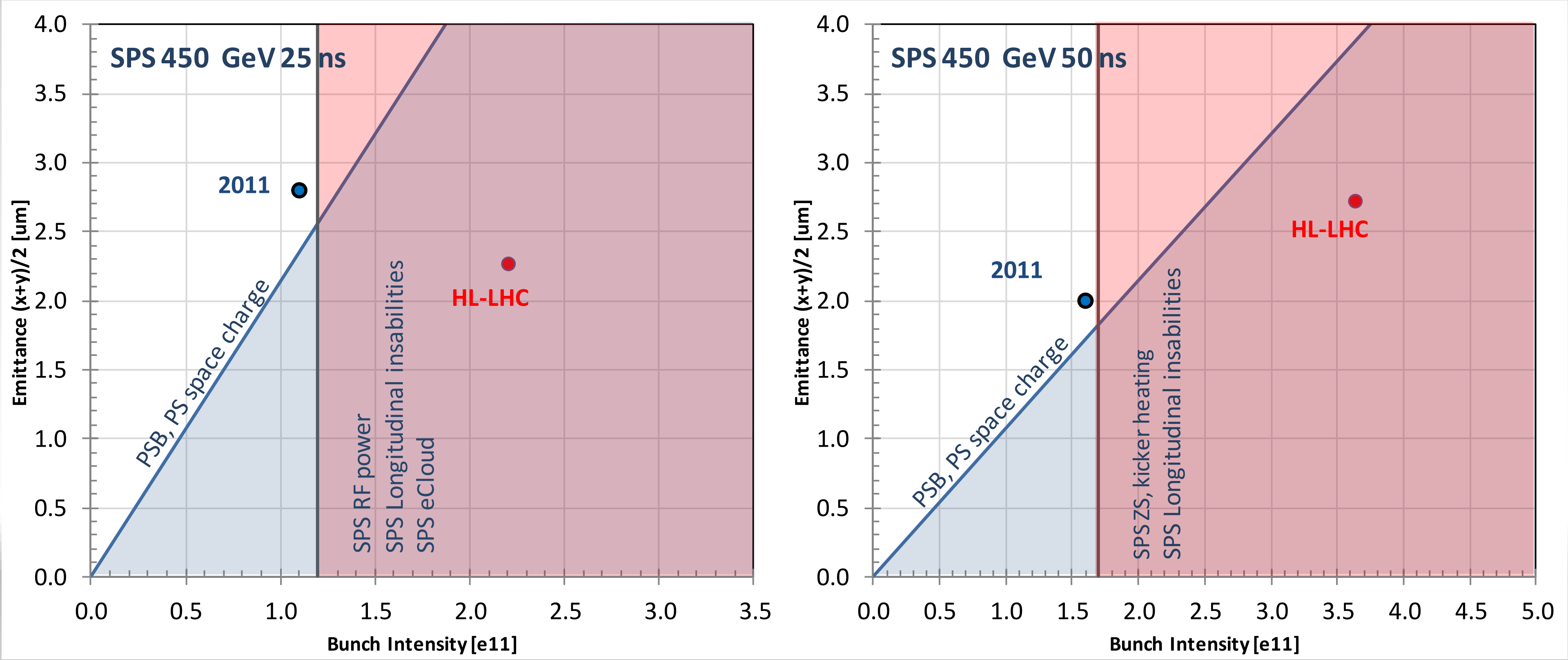
Target: 250-300 fb^{-1} per year

Parameter	nominal	minimum β* 25ns	minimum β* 50ns
N	1.15E+11	**2.0E+11**	**3.3E+11**
n_b	2808	2808	1404
beam current [A]	0.58	**1.02**	**0.84**
x-ing angle [μrad]	300	475	520
beam separation [σ]	10	10	10
β^* [m]	0.55	**0.15**	**0.15**
ε_n [μm]	3.75	2.5	3.0
ε_L [eVs]	2.51	2.5	2.5
energy spread	1.00E-04	1.00E-04	1.00E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	**25**	**17**
IBS longitudinal [h]	61 -> 60	**21**	**16**
Piwinski parameter	0.68	**2.5**	**2.5**
geom. reduction	0.83	**0.37**	**0.37**
beam-beam / IP	3.10E-03	**3.9E-03**	**5.0E-03**
Peak Luminosity	$1\ 10^{34}$	**$7.4\ 10^{34}$**	**$8.4\ 10^{34}$**
Events / crossing	19	**141**	**257**

at LHC collision

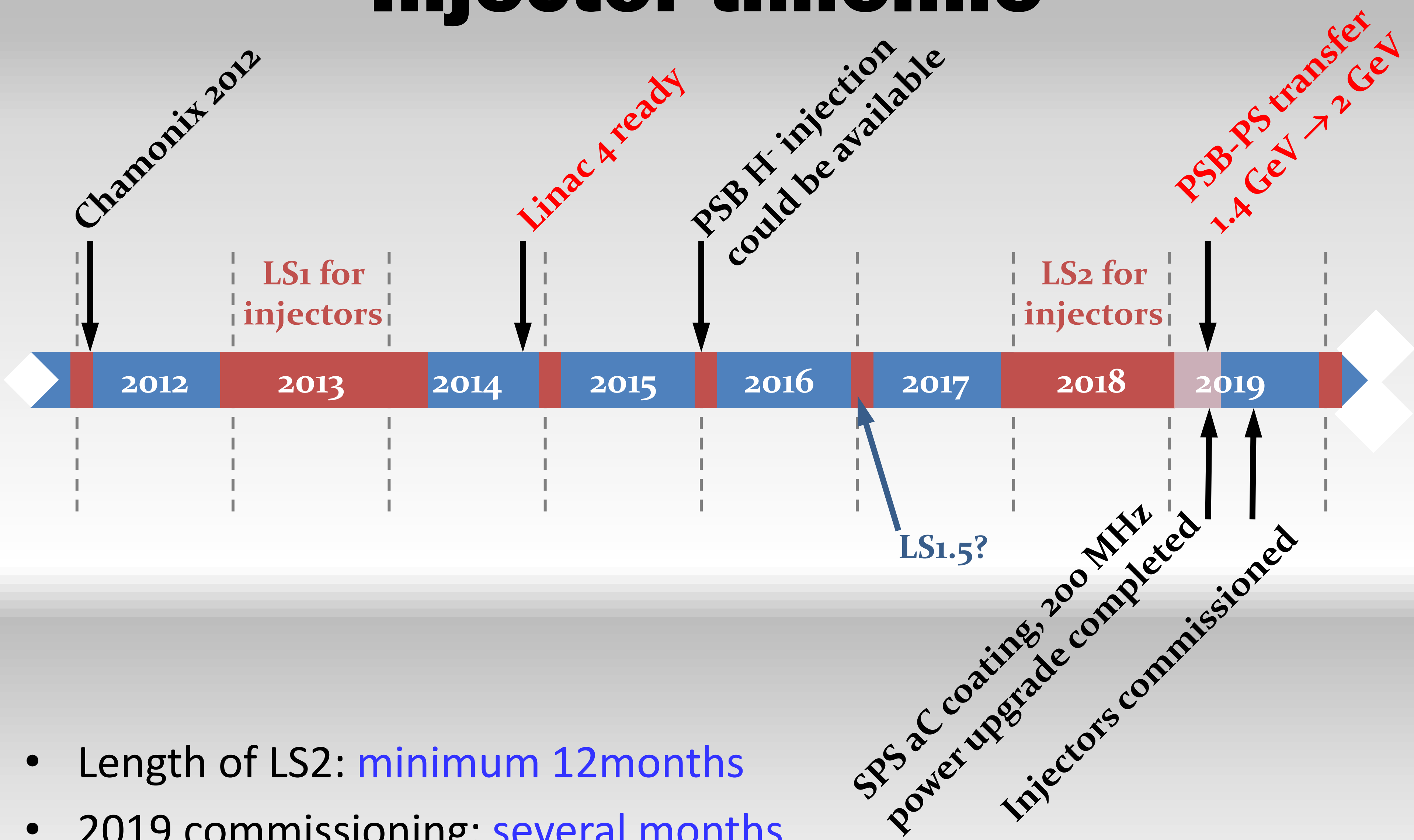
O.Brüning, HI-LUMI event 16-18 November 2011

2011 to post-LS2



- 2011 was excellent: 1.5e11 with 2.5 um for 50 ns (at LHC flat-top)
  - Around 1.1 e11 with 2.8 um for 25 ns, extracted from SPS
- Large improvement is required for either 25 or 50 ns beam!

Injector timeline



- Length of LS2: minimum 12months
- 2019 commissioning: several months

Injector plans - summary

- Situation at the end of 'injector LS1' (03/2014)
  - Linac4 being commissioned, proton operation possible from 2014
  - PSB injection for H- not yet available (baseline: Q4/2015)
  - PSB PS transfer energy: 1.4 GeV
- Some potential improvements after LS1
  - Low emittance beams – to be tested Q3/2012
  - SPS improvements (optics, RF, impedance)
- LINAC4 connection baseline is now LS2
  - (with a weakening option for LS1.5)
  - Injectors unable to exploit LINAC4 before LS2 anyway
- Major upgrades within LIU project, including increase of PSB-PS transfer energy only during LS2
- After LS2 towards HL-LHC beam available from injectors
  - LHC will only be able partially exploit this beam

AFTER LS1

Beam from injectors 1/2

Operational production scheme		25 ns ~nominal	50 ns (CBI-limit)
PS injection	Bunch intensity, ×10[11] p/b	16	12
	Emittance, $\beta\gamma\varepsilon$	2.4 µm	1.8 µm
	Vert. tune spread, ΔQ_y	-0.26	-0.25
PS ejection	Bunch intensity, ×10[11] p/b	1.27	1.90
	Emittance, $\beta\gamma\varepsilon$	2.5 µm	1.9 µm
	Bunches per batch	72	36
Brightness limit PSB		X	X
Space charge limit PS		X	X
Coupled-bunch limit PS			X
SPS ejection: expected (achieved)	Bunch intensity, ×10[11] p/b	**1.15**	**1.7**
	Emittance, $\beta\gamma\varepsilon$	**2.8 µm**	**2.1 µm**
Relative beam quality factor, q_{ib}		1.2	1.7

H. Damerau – Chamonix2012

Potential for nominal luminosity in LHC…

Beam from injectors 2/2

First PS studies in 2012		25 ns low $\varepsilon_x/\varepsilon_y$	25 ns ultra-bright
PS injection	Bunch intensity	$0.8\cdot10^{12}$ ppb	$0.65\cdot10^{12}$ ppb
	Emittance, $\beta\gamma\varepsilon$	1.2 μm	1.0 μm
	Vert. tune spread, ΔQ_y	-0.24/-0.26	-0.26
PS ejection	Bunch intensity	$1.27\cdot10^{11}$ ppb	$1.54\cdot10^{11}$ ppb
	Emittance, $\beta\gamma\varepsilon$	1.3 μm	1.1 μm
	Bunches per batch	36/**48**	32
Brightness limit PSB		X/-	X
Space charge limit PS		-/X	X
Coupled-bunch limit PS			
SPS ejection	Bunch intensity	**$1.15\cdot10^{11}$ ppb**	**Beyond SPS reach**
	Emittance, $\beta\gamma\varepsilon$	**1.4 μm**	
Relative beam quality factor, q_{ib}		**2.2**	

Potential for ~twice the nominal luminosity in LHC…

LHC after LS1

- Energy 6.5 TeV (in 2015)
- Aperture not worse than now
- Bunch spacing 25 ns or 50 ns
- Understand (and control) emittance increase
- Pile-up – assume acceptable mean mu of ~40
  - This will constrain the utility of 50 ns
- Beta* ~0.5 m
  - of limited utility to squeeze further

Potential limitations

Performance could be impacted by:

- Radiation to electronics – SEU’s
- UFOs at higher energy & with 25 ns
- Electron cloud & high energy & at 25 ns
- Emittance growth in physics
- Total beam intensity limits in the LHC…

Potential performance

	Beta* [cm]	Ib SPS	Emit SPS [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi [fb^{-1}]
25 ns	50	1.2e11	2.8	1.2e34	28	32
25 ns low emit	50	1.2e11	1.4	2.2e34	46	57
50 ns level	50	1.7e11	2.1	1.7e34 level 0.9e34	76 level 40	40 – 50*

All numbers approximate!

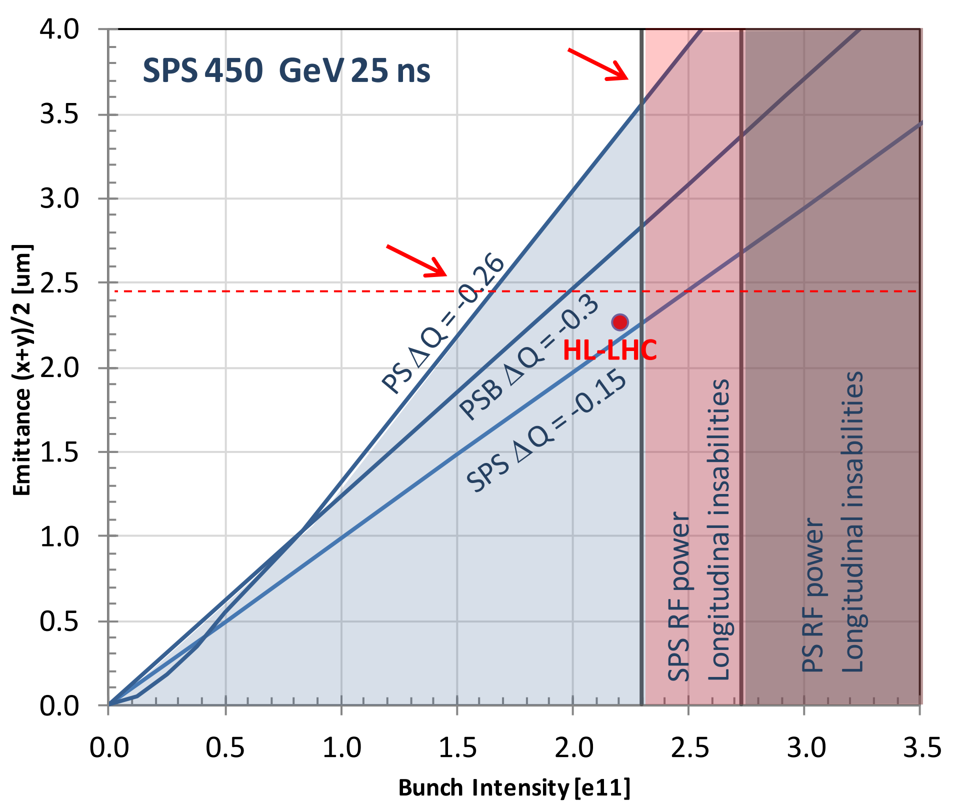
- 150 days proton physics
- 5% beam loss, 10% emittance blow-up in LHC
- 10 sigma separation
- 70 mb visible cross-section
- * different operational model - caveat

HL-LHC like beams available

AFTER LS2

25 ns after LIU upgrade

- Limit is 2.3e11 p+/b in 3.6 um at SPS extraction (1.6e11 in 2.3 um)

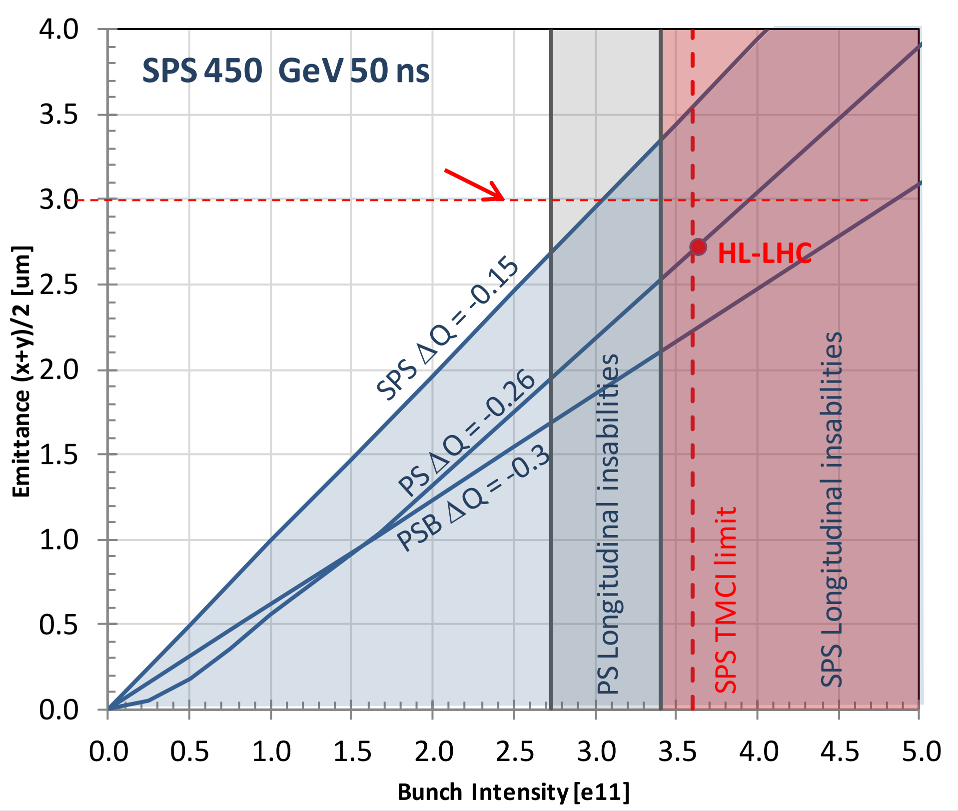


- Fundamental limit: space charge in PS

Brennan Goddard

50 ns after LIU upgrade

- Limit is 2.7e11 p+/b in 2.7 um at SPS extraction (closer to HL-LHC requirement)



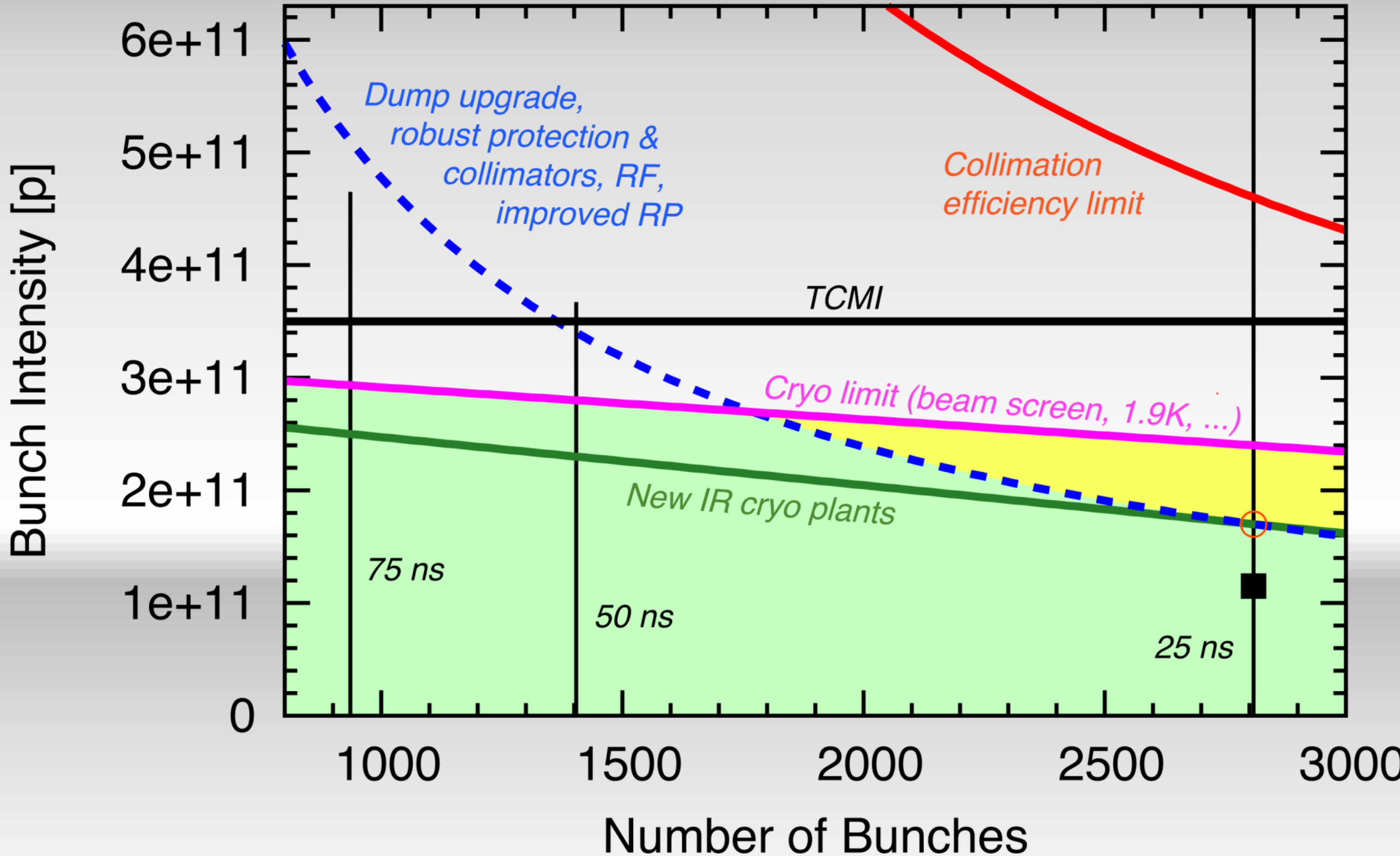
- Limited by longitudinal instabilities in PS and SPS, and by brightness in SPS

Brennan Goddard

LHC limits

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

LHC limits


Bunch Intensity [p]
6e+11
5e+11
4e+11
3e+11
2e+11
1e+11
0
1000
1500
2000
2500
3000
Number of Bunches
Dump upgrade,
robust protection &
collimators, RF,
improved RP
Collimation
efficiency limit
TCMI
Cryo limit (beam screen, 1.9K, ...)
New IR cryo plants
75 ns
50 ns
25 ns

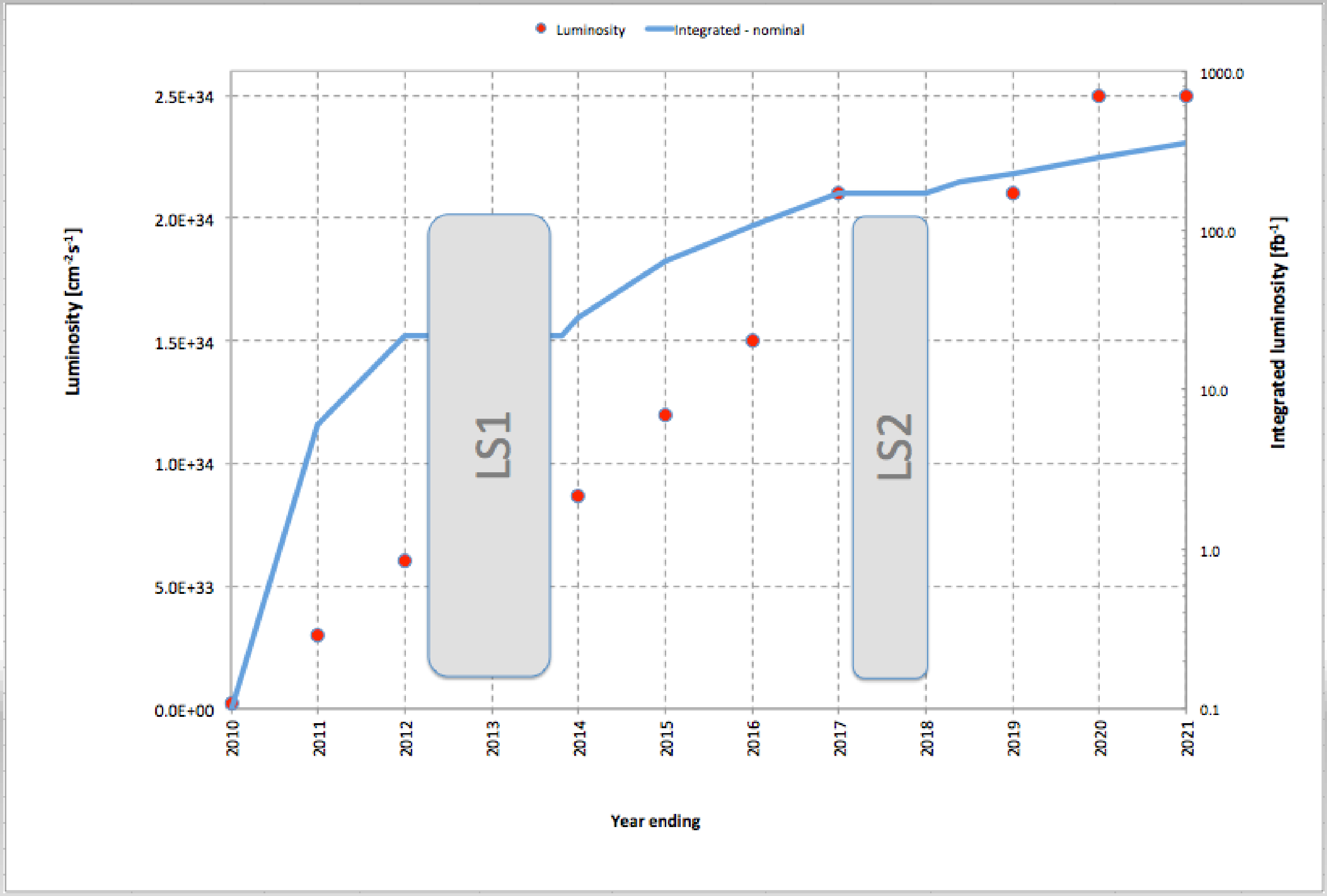
Performance estimate

- 7 TeV
- 150 days of proton physics
- Hübner Factor = 0.2 for 25 ns
- Different OP model for 50 ns levelled

	Beta* [cm]	Ib (SPS)	Emit (SPS) um	Peak Lumi [$cm^{-2}s^{-1}$]	Pile-up	Int. Lumi [fb^{-1}]
25 ns	50	1.6e11	2.3	2.5e34	56	~65
50 ns	50	2.7e11	2.7	2.8e34 level 0.9e34	125 level 40	~50

Neglecting low emittance option
All numbers approximate!

Projection



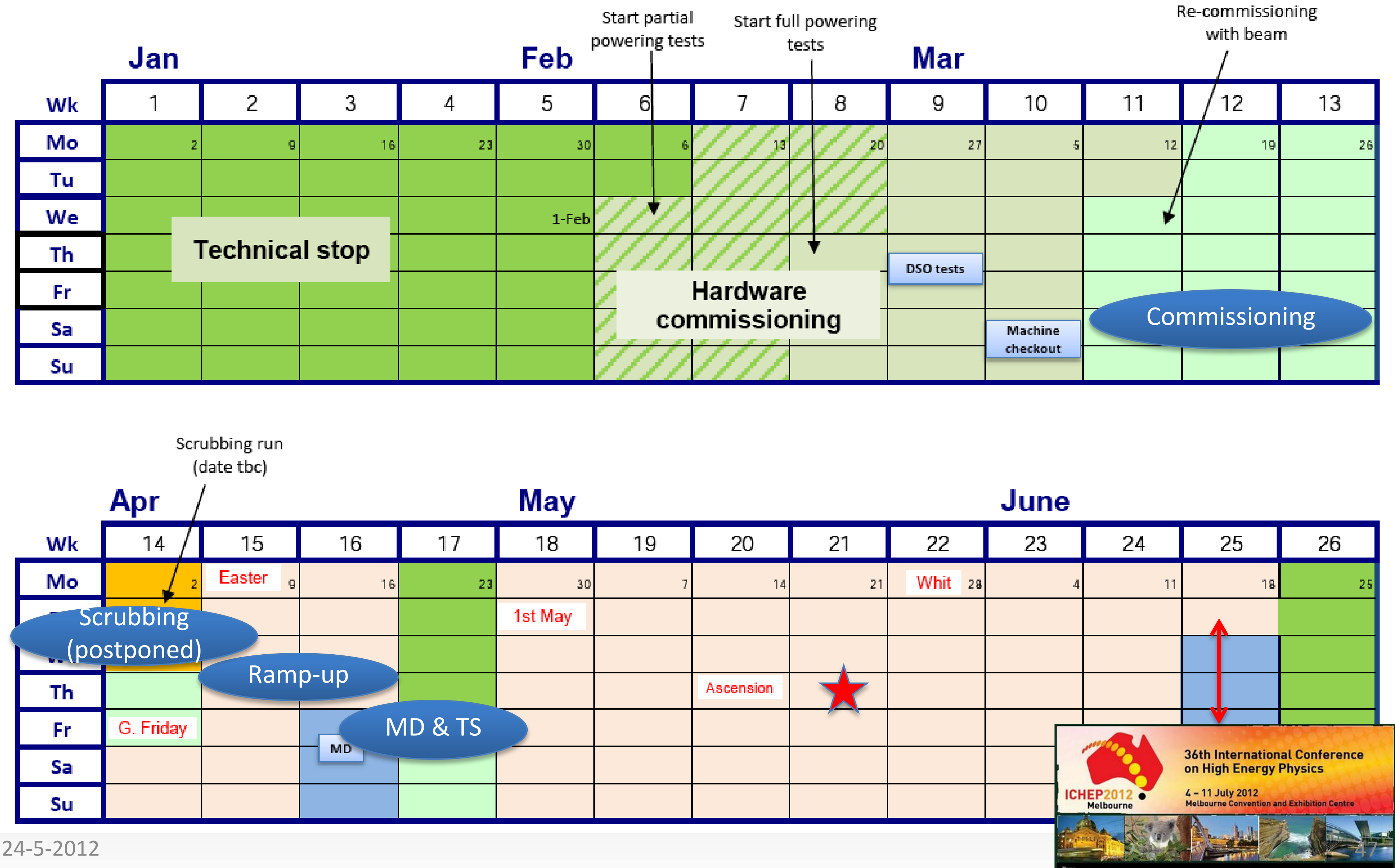
- 25 ns
- Low emittance option viable between LS1 & LS2
- Usual warnings apply

Conclusions

- 2012 performance, after some more experience, is looking encouraging, goals for year credible
- Injector planning stabilizing
  - LINAC4 connection, LIU upgrades not until LS2
  - Interesting improvement possible before
  - Towards HL-LHC beams after
- 25 ns is baseline with potential to reach ultimate luminosity certainly after, possibly before, LS1
- Levelled 50 ns is an interesting option, particularly if there are total intensity limitations
  - Certainly not yet given

SPARE

2012 LHC schedule Q1/Q2



2012 LHC schedule Q3/Q4