Conditions for the restart in 2014, potential performance and limitations LS1 to LS2

Mike Lamont

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

WHAT WE KNOW SO FAR

2011/12

- Successfully wrestled with:
  - Total intensity
  - Bunch spacing
  - Bunch intensity
  - Emittance
  - Beta* & aperture
- (Small) emittance from injectors is important:
  - Tails, losses, performance
  - 50 ns - very good in this regard
- Exploring the effects of high intensity beams:
  - SEUs, beam induced heating, vacuum instabilities…
- Exploring intensity driven instabilities

In general 1/3

- Excellent single beam lifetime – vacuum
- Linear optics: remarkably close to model, beating good and corrected to excellent
- Very good magnetic model – includes dynamic effects
- Excellent correction of orbit through the cycle
- Better than expected aperture (tolerances, alignment)
- Operational robustness
  - Precycle, injection, 450 GeV, ramp & squeeze & collisions routine
  - Very good reproducibility of magnetic machine
- At injection dynamic aperture greater than aperture defined by collimators
  - Excellent field quality, correction of non-linarites
  - Low tune modulation, low power converter ripple
- Low RF noise

In general 2/3

- Head-on beam-beam is not a limitation
- Long range has to be taken seriously
  - See Werner Herr
- Beta* reach (aperture, collimation, optics) established and exploited
- Levelling
  - works in LHCb with transverse separation (issues with Atlas/CMS)
  - first tests of beta* levelling are encouraging
- Availability
  - See Alick – in general – very acceptable
  - Some issues (SEUs, vacuum, cryogenics…) – vigorous follow-up and consolidation performed and planned

In general 3/3

- Unpinned by superb performance of machine protection and associated systems
  - BIS, BLMs, collimators, LBDS…
- Rigorous machine protection follow-up, qualification and monitoring
- **Routine collimation of 110 MJ LHC beams** without a single quench from stored beams.

Machine performing very well, huge amount of experience & understanding, excellent tools – this should be the legacy for post LS1

SYSTEMS AFTER LS1

LS1

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

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

Energy

- Magnets coming from 3-4 do not show degradation of performance
- Our best estimates to train the LHC (with large errors)
  - $\sim$ 30 quenches to reach 6.25 TeV
  - $\sim$ 100 quenches to reach 6.5 TeV
- Two quenches/day $\rightarrow$ 2 to 5 days of training per sector
  - With 100 quenches one expects 400 quench heater firings
- The plan
  - Try to reach 6.5 TeV in four sectors in March 2014
  - Based on that experience, we decide if to go at 6.5 TeV or step back to 6.25 TeV in March 2014

Ezio Todesco – Chamonix 12

Other systems (1/5)

- Cryogenics
  - The first two years of operation were also crucial to identify the weaknesses of the present cryogenic maintenance plan and new issues like SEUs
  - Consolidation plan foreseen during the LS1 to improve the performance in terms of availability and sectorization.
- QPS
  - with respect to radiation to electronics will concern the re-location of equipment and installation of new radiation tolerant hardware.
  - Other upgrades in functionality and supervision
- Energy extraction
  - Installation of snubber capacitors and arc chambers for the main quad circuits will be complete the upgrade of the energy extraction systems.

Other systems (2/5)

- EN-EL – huge program of work
  - consolidation of aging elements of EN/EL infrastructure (part of a 15 years program to substantially increase the reliability and availability of the power distribution network).
  - User requests: the main activities will be the contributions to the R2E project, the BE/BI upgrade projects and the RF upgrade project in SPS (BA3).
- EN-CV
  - upgrade of user's equipment, consolidation work and construction of new plants;
  - Based on experience on the first years of LHC run, adapt installations to new operating parameters.

Other systems (3/5)

- RF (& transverse dampers)
  - Full program of consolidation and improvement
  - The RF can deal with nominal total intensity (2808b, 25 ns, 1.1E11/bunch)
  - For ultimate intensity (2808b, 25 ns, 1.7E11/bunch), the RF must allow for the modulation of the cavity phase by the transient beam loading. First tests should take place before LS1
- Collimation
  - Button pick-ups in tertiaries and some secondaries
  - Refurbishment of TDIs

Other systems (4/5)

- LBDS
  - Install two additional vertical dilution kickers per beam to have the nominal situation of 6 vertical and 4 horizontal dilution kickers per beam
  - Install a third TCDQ absorber and change absorber materials in the existing two TCDQ absorbers
  - Extraction kicker MKD generator isolation along switch to reduce electrical break downs > 5 TeV
  - Extraction kicker MKD GTO switch, change about half the switches, so only have one manufacturer as proven much less sensitive to radiation induced erratic triggering, reducing numbers of asynch beam dumps
  - Change current pick-ups on dilution magnets MKB – less sensitive to beam noise

Jan Uythoven

Other systems (5/5)

- Injection
  - Injection kicker reduction of heating
  - increase number of stripes on ceramic chamber to reduce beam impedance (at least from the present 15 to 19, 24 is ultimate). This also reduces the electrical field inside the chamber which could reduce the number of UFOs.
  - Increase the emissivity of the inside of the injection kicker vacuum tanks
- UFOs
  - Improved cleaning procedure
- E-cloud
  - NEG coated bypass tubes

Jan Uythoven

Vacuum 1/2

- 2011/2012: Dynamic vacuum in the long straight sections (LSS) in presence of high intensity beams:
  - pressures spikes and beam screen temperature oscillations
  - micro-sparking in the RF fingers of the bellows
  - pressure bumps with stimulated desorption by electron cloud, beam losses and/or thermal out gassing stimulated by HOM losses.
- The electron cloud mitigation solutions will be adapted to the different configurations:
  - cold/warm transitions, non-coated surfaces in direct view of beams, photoelectrons, etc.
- Additional pumping and reengineering of components will reduce the sensitivity of the vacuum system to beam losses or HOM inducing out gassing.
- Experimental areas - new Beryllium pipes (ATLAS and CMS)
- Consolidation of vacuum instrumentation, pumping…

Miguel Jimenez

Vacuum 2/2

- When resuming operation with beams, all benefits from 2010-2012 will not be lost.
  - Scrubbing of arcs is expected to be partly kept, measurements in the laboratory and in the SPS have shown that in case the SEY drifts up, the scrubbing will then goes faster (memory effect).
- The 2011 run was the year of electron stimulated desorption in LSS…
- …the 2014-15 run will be dominated by heat loads induced in the arcs and photon stimulated desorption and photo-electrons.

Miguel Jimenez

Quenches after LS1

Quench
⇓
FPA and dump

Yes,
- possibly a few de-training quenches per year.
- several beam-induced quenches.

False triggering
⇓
Quench
⇓
FPA and dump

Yes, <10 per year, due to false triggering of the QPS. Probably none for the 13 kA circuits.

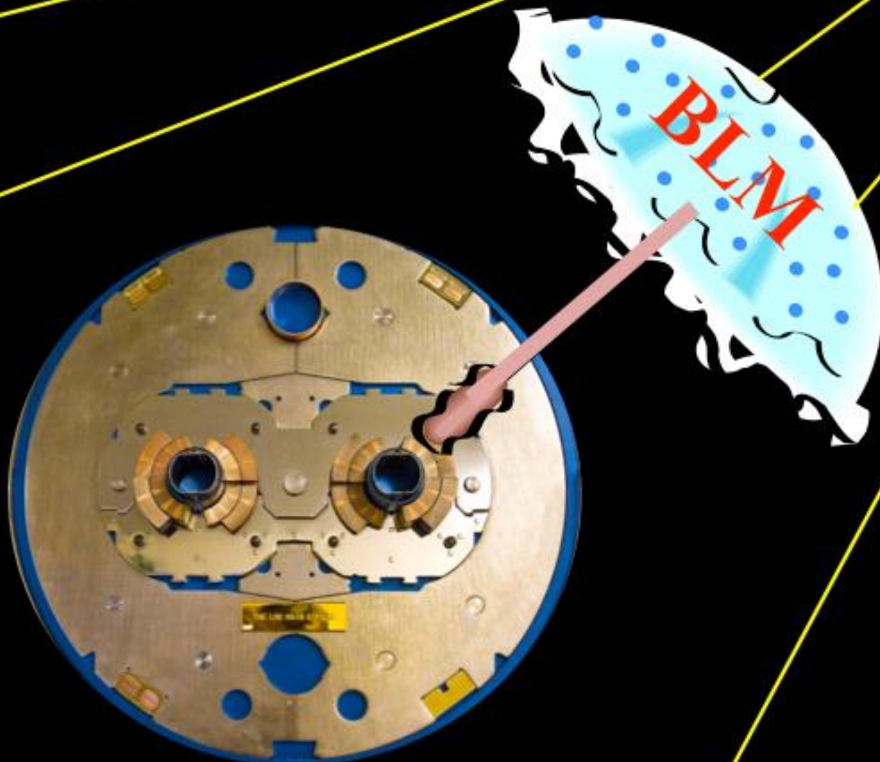
FPA
⇓
Quench

Yes,
- in case of a dipole quench,
- always in certain types of corrector magnets.

FPA
⇓
False triggering
⇓
Quench

To be seen…., but anyhow probably only in the corrector circuits.

The future looks bright



Major R2E consolidation campaign foreseen in LS1

Conclusions 3/3

- **SEE are still expected to be present after LS1**
- However:
  - Mitigation actions (developments/relocation/shielding) will allow to decrease their impact despite higher LHC performances
- Radiation level monitoring requires continuing effort
  - 2nd generation RadMons + BLM team support (!)
- R&D on rad-tol PC critical – perhaps joint with SCLs
- QPS developments in the tunnel critical for operation
- UX45/65 mitigation (other than PLCs) not in R2E baseline

MTBF ≥ 1 week feasible (with continued efforts)

PERFORMANCE

Future performance

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

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; a-C coating in the SPS
- 25 ns has more long-range collisions
  - Increased crossing angle, high beta*
- Total current limit (vacuum; RF) → limit # bunches
- Bunch train current limits in SPS & LHC → limit # bunches
- UFO rate seems to increase for 25 ns spacing
- Ultimately expect to transit to 25 ns spacing because of pile up

MOTIVATION

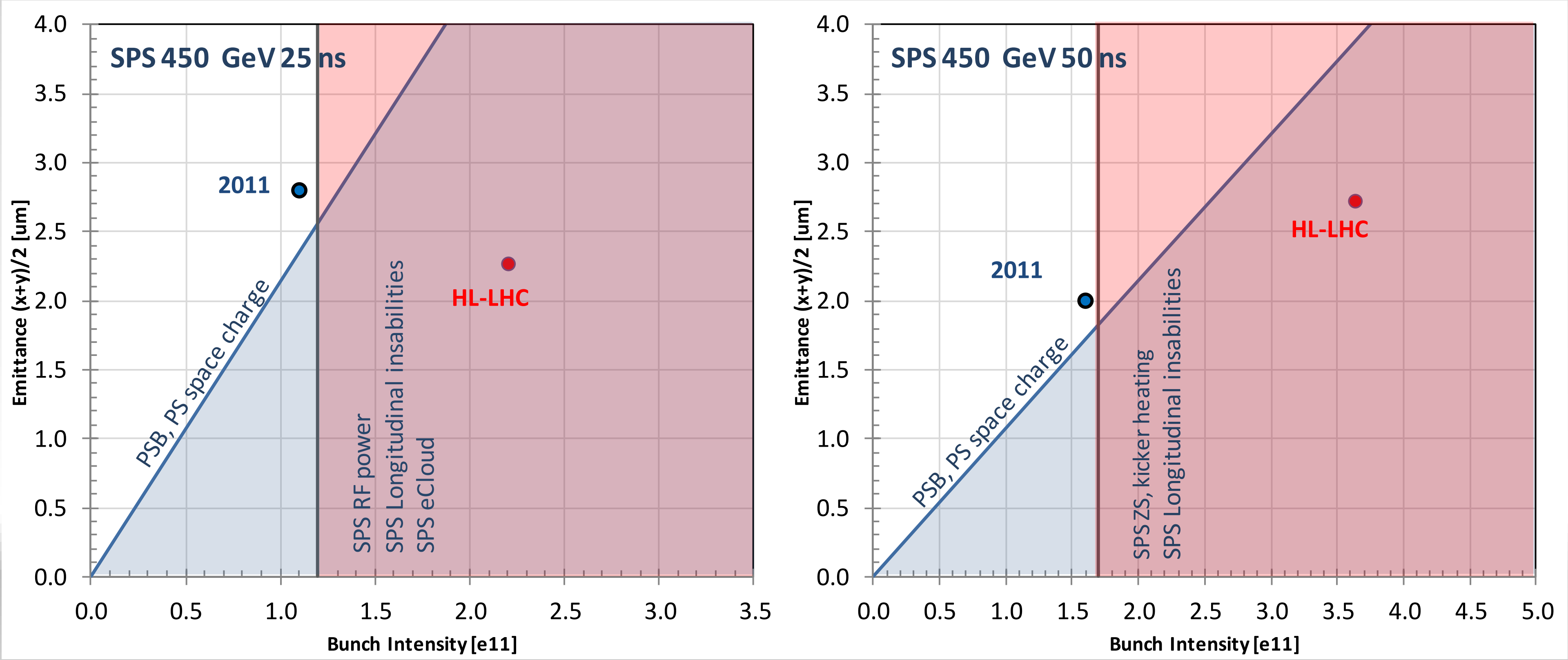
Requirements from HL-LHC

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**

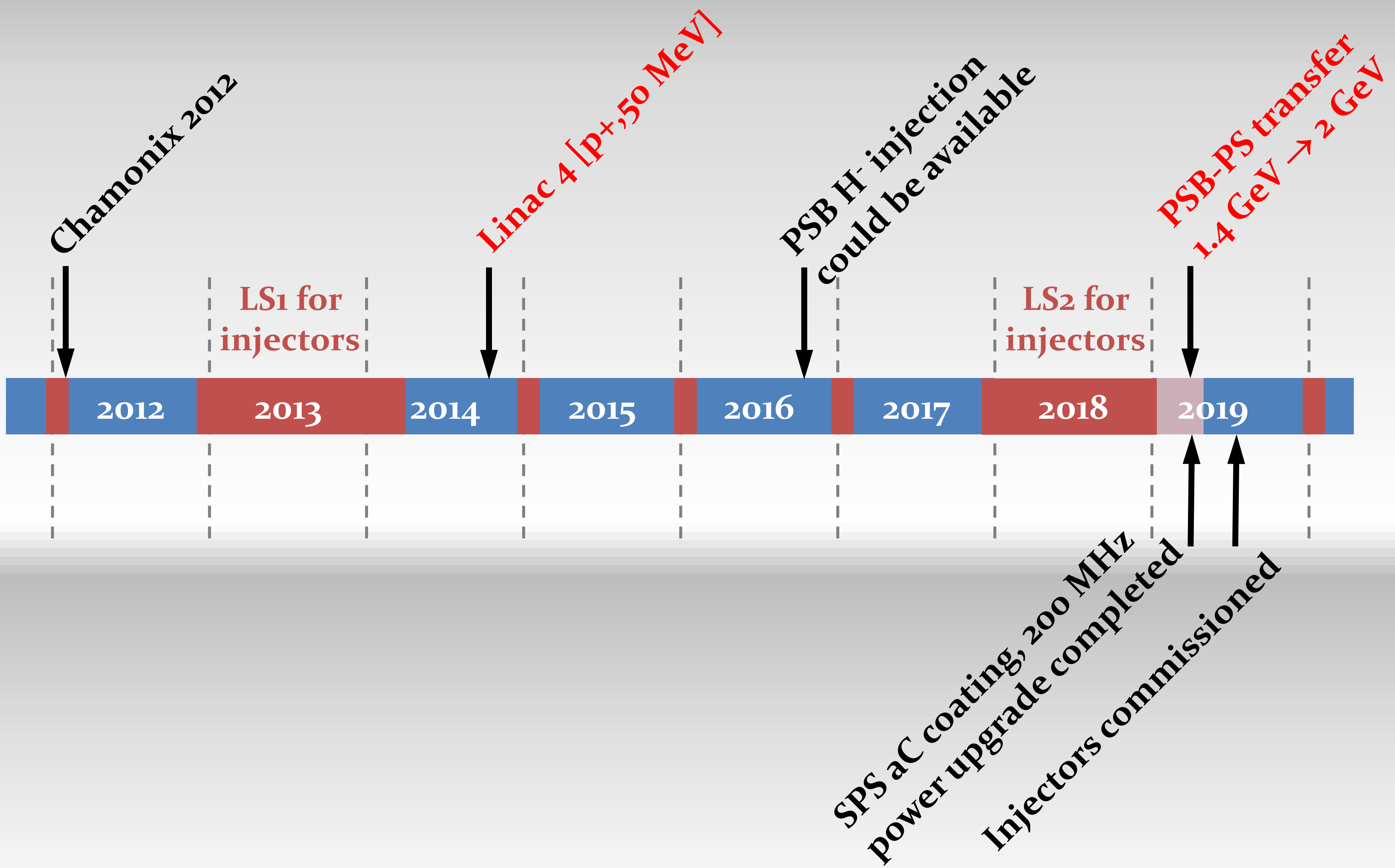
at LHC collision

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



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
  - Injectors unable to exploit LINAC4 before LS2 anyway
- Major upgrades within LIU project, including increase of PSB-PS transfer energy only during LS2

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

Beam from injectors 2/2

Tests with SPS/LHC in 2012		50 ns 32 bunches	50 ns 24 bunches	25 ns 48 bunches
PS injection	Bunch intensity	$0.8 \cdot 10^{12}$ ppb	$0.6 \cdot 10^{12}$ ppb	$0.8 \cdot 10^{12}$ ppb
	Emittance, $\beta\gamma\varepsilon$	~ 1.3 μm	~ 1.0 μm	~ 1.1 μm
	Vert. tune spread, ΔQ_y	-0.26	-0.21	-0.26
PS ejection	Bunch intensity	$1.9 \cdot 10^{11}$ ppb	$1.9 \cdot 10^{11}$ ppb	$1.27 \cdot 10^{11}$ ppb
	Emittance, $\beta\gamma\varepsilon$	~ 1.3 μm	~ 1.1 μm	~ 1.3 μm
	Bunches per batch	32	24	48
Brightness limit PSB			X	
Space charge limit PS		X		X
Coupled-bunch limit PS		X	X	
SPS ejection	Bunch intensity	$1.71 \cdot 10^{11}$ ppb	$1.71 \cdot 10^{11}$ ppb	**$1.15 \cdot 10^{11}$ ppb**
	Emittance, $\beta\gamma\varepsilon$	1.5 μm	1.2 μm	**1.4 μm**
Relative intensity/luminosity in LHC		0.96/1.3	0.92/1.6	**1.2/1.2**

(expected performance, conservative PS space charge limit)

Chamonix 2012, including reduced bunch number in LHC

→ **High intensity 50 ns or moderate intensity high-brightness 25 ns beam**

Beta* & crossing angle

Collimation Scheme		Beta* [cm] 25ns	Half X-angle [microrad] 25 ns	Beta* [cm] 50 ns	Half X-angle [microrad] 50 ns
S1	Same in mm	50	190	40	140
S2	Same in sigma	45	200	35	150
S3	1 sigma retraction	40	210	30	160
S4	Low emittance	40	150	40	120

S1 to S3: courtesy Roderik Bruce

S4: scaling given emittances from Heiko Damerau et al

S1 to S3 give similar performance - geometrical reduction factor bites below 50 cm

Potential performance

All numbers approximate!

	Number of bunches	Ib SPS	Collimator scenario	Emit SPS [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi [fb^{-1}]
25 ns	2800	1.2e11	S1	2.8	1.1e34	23	~30
25 ns low emit	2600	1.15e11	S4	1.4	2.0e34	48	52
50 ns	1380	1.7e11	S1	2.1	1.8e34 level to 0.9e34	81 level to 40	40 – 50*
50 ns low emit	1200	1.71e11	S4	1.5	2.2e34	113	

- 150 days proton physics, HF = 0.2
- 5% beam loss, 10% emittance blow-up in LHC
- 70 mb visible cross-section
- * different operational model - caveat

Potential limitations

- Radiation to electronics – SEU's
- UFOs at higher energy & with 25 ns
  - See previous talk by Tobias Baer
- Electron cloud & high energy & at 25 ns
- Low emittance
  - Risk due to strongly increased energy density
  - Beam dynamics effects: IBS blow-up
  - Noise induced emittance growth can take over → often additive components and not multiplicative.
- Total beam intensity limits in the LHC…

Look to trade off emittance, bunch intensity, number of bunches, total beam intensity

Implications of High Beam Currents

- Higher beam currents generate higher image currents:
  - RF heating of accelerator components
  - Transient beam loading
  - Impedance-induced instabilities
  - Stronger accelerating fields in the beam pipe with impact on electron cloud, UFO's, discharges, …
- Higher beam currents - higher stored energy:
  - More synchrotron photons and therefore more secondary electrons are generated. More heat load to the cryo system.
  - Less tolerance to beam loss and more risk for quenches.
  - More activation of accelerator components.

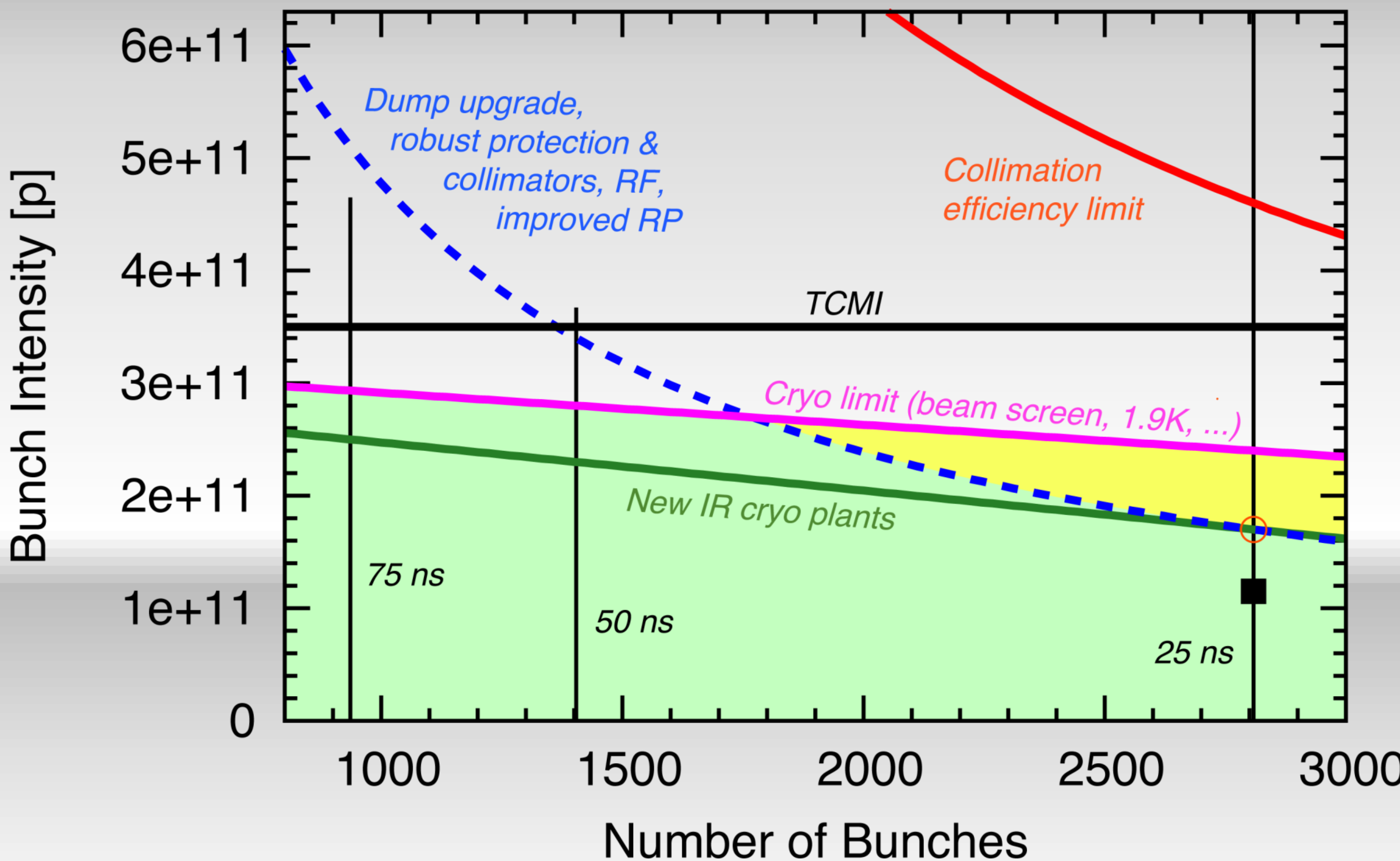
Implications for operational availability and machine protection…

LHC limits

- Encyclopedic run through by Ralph Assmann at Chamonix in view of **HL-LHC**
- Potential limits from:
  - RF, Vacuum, e-cloud, Cryo, Magnets, Injection and Protection, Collimation, SEUs, Radiation Protection, radiation to triplets
- Ultimate intensity seems a reasonable assumption
  - 1.7e11 x 2808

Ralph Assmann

LHC limits



Conclusions

- Carrying forward a wealth of experience from operation at 3.5 and 4 TeV
- Main thrust of LS1 is consolidation of interconnects – accompanied by consolidation and upgrades across the board.
- 6.5 TeV is the target energy for post LS1 operation
- Main LIU performance increases only after LS2
- 25 ns is baseline with low emittance options offering potential go beyond nominal performance
- Levelled 50 ns is an interesting option, particularly if there are total intensity limitations

BACKUP

Cryogenics

- During the LHC operation in 2010 and 2011, the cryogenic system has achieved an availability level fulfilling the overall requirement.
  - Profited from the reduced beam parameters
  - impacts of some failures occurred during the LHC operation were mitigated by using the overcapacity margin, the existing built-in redundancy in between adjacent sector cryogenic plants and the “cannibalization” of spares on two idle cryogenic plants.
- The first two years of operation were also crucial to identify the weaknesses of the present cryogenic maintenance plan and new issues like SEUs.
- After the LS1, nominal beam parameters are expected and the mitigated measures will be less effective or not applicable at all.
- Consolidation plan foreseen during the LS1 to improve the performance of the LHC cryogenic system in terms of availability and sectorization.

QPS

- The upgrade of the LHC Quench Protection System QPS during LS1 with respect to radiation to electronics will concern the re-location of equipment and installation of new radiation tolerant hardware.
- The protection systems for insertion region magnets and inner triplets will be equipped with a dedicated bus-bar splice supervision including some additional modifications in order to improve the EMC immunity.
- Extension of the supervision capabilities
- Installation of snubber capacitors and arc chambers for the main quad circuits will be complete the upgrade of the energy extraction systems.

RF

- Necessary RF consolidation and upgrade is necessary for the next 3-year run period.
- This includes
  - 1) necessary maintenance and consolidation work that could not fit the shorter technical stops during the last years,
  - 2) the upgrade of the SPS 200 MHz system from presently 4 to 6 cavities, which constitutes the present bottle neck for LHC beam current and possibly
  - 3) the replacement of one LHC cavity.

Smaller Emittance versus Higher Intensity

- Transverse energy density depends strongly on beam energy (γ) and is independent of number of protons (N_p^{tot}) over normalized emittance (ε_n):

$$r_E = \gamma^2 \times \frac{N_p^{tot}}{\varepsilon_n} \times C \qquad C = \frac{m_p c^2}{p\sqrt{\beta_x \beta_y}}$$

- Higher intensity or smaller emittance put similar strain on material survival!
- Must be watched carefully to avoid a bad surprise when we have the first abnormal dump with high intensity…
- HiRadMat: Robustness of a spare tungsten collimator will be tested in 2012! Recommend same for TCDQ, …