Machine Progress Towards Higher Luminosity

Frank Zimmermann

CMS Upgrade Meeting

FNAL, Chicago, 7 November 2011 (via EVO)

Thanks to Martin Aleksa, Gianluigi Arduini, Ralph Assmann, Hannes Bartosik, Oliver Brüning, Massimiliano Ferro-Luzzi, Jordan Nash, Yannis Papaphilippou, Anders Ryd, Benoit Salvant

CERN

BE Beams Department

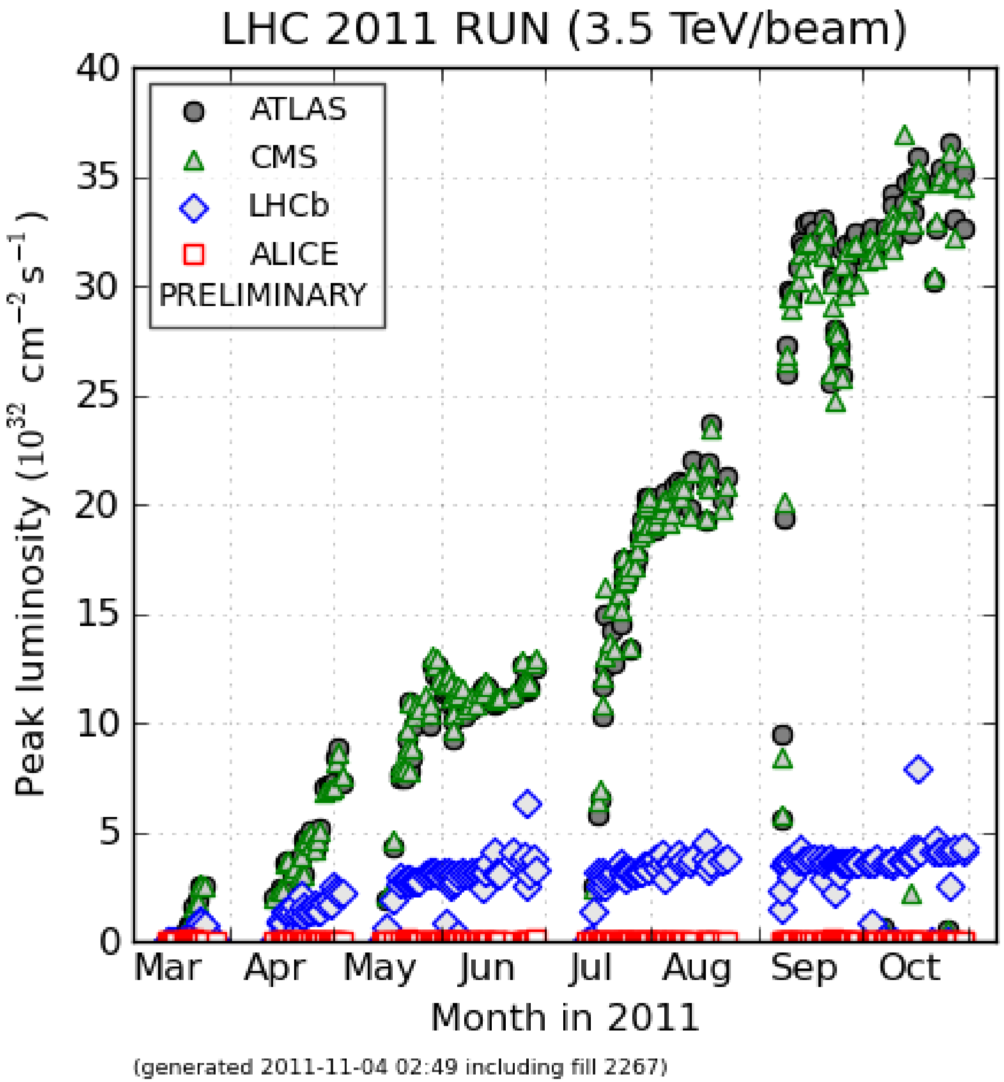
EuCARD

ACCNET

topics

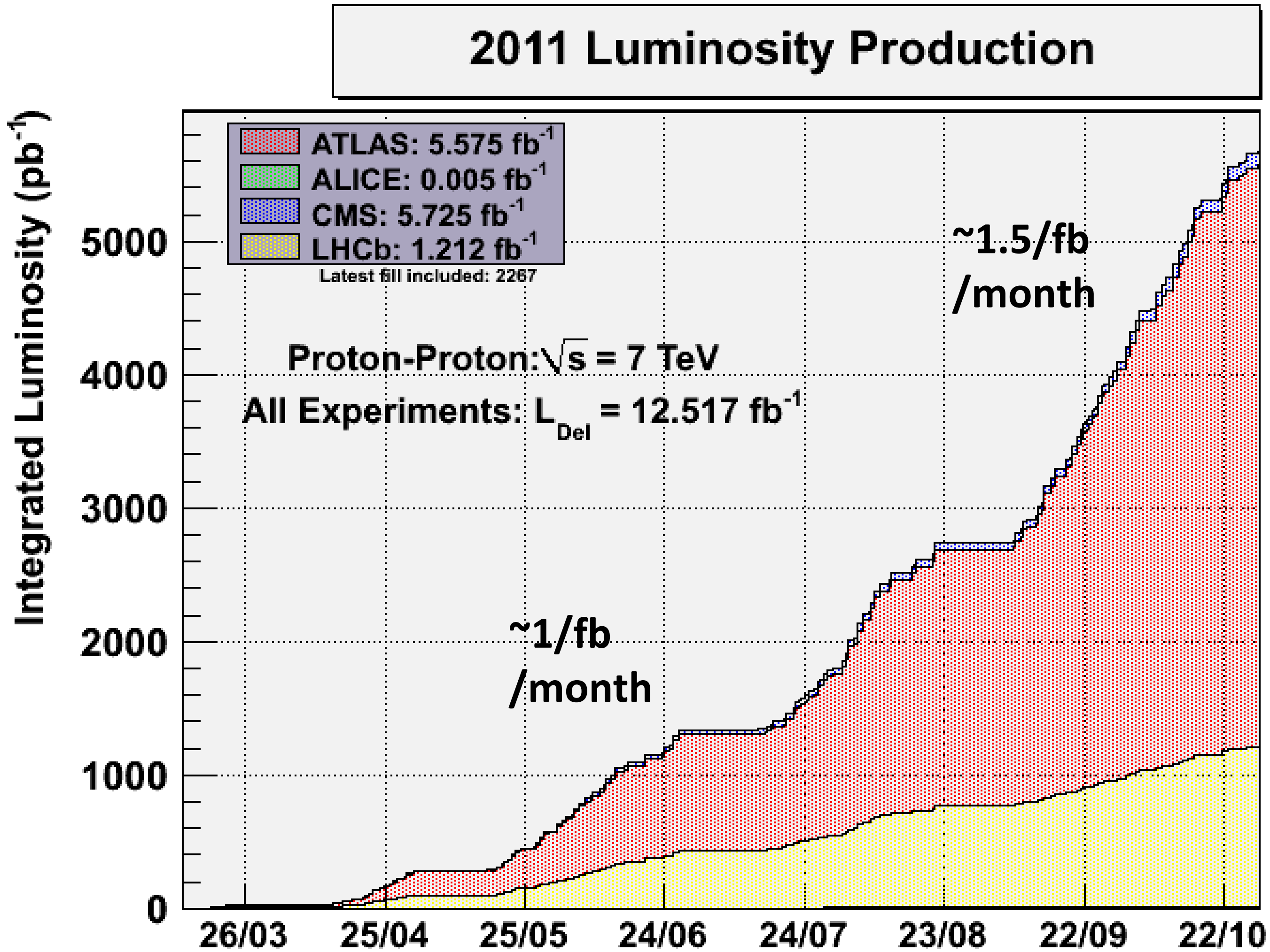
- luminosity evolution over next few years
  in light of 2011 experience
    - beam-beam limits
    - β^* reach (aperture, collimation, optics)
    - leveling, pile up
- 50-ns vs 25-ns running
    - electron cloud
    - enhanced satellites w 50 ns spacing
- before/after Linac4 & other upgrades
- how to reach highest luminosity?

2011 peak luminosity evolution



peak luminosity increased almost linearly over the year (adding more bunches, increasing bunch intensity, reducing β^*) – now near the limit

2011 integrated luminosity evolution

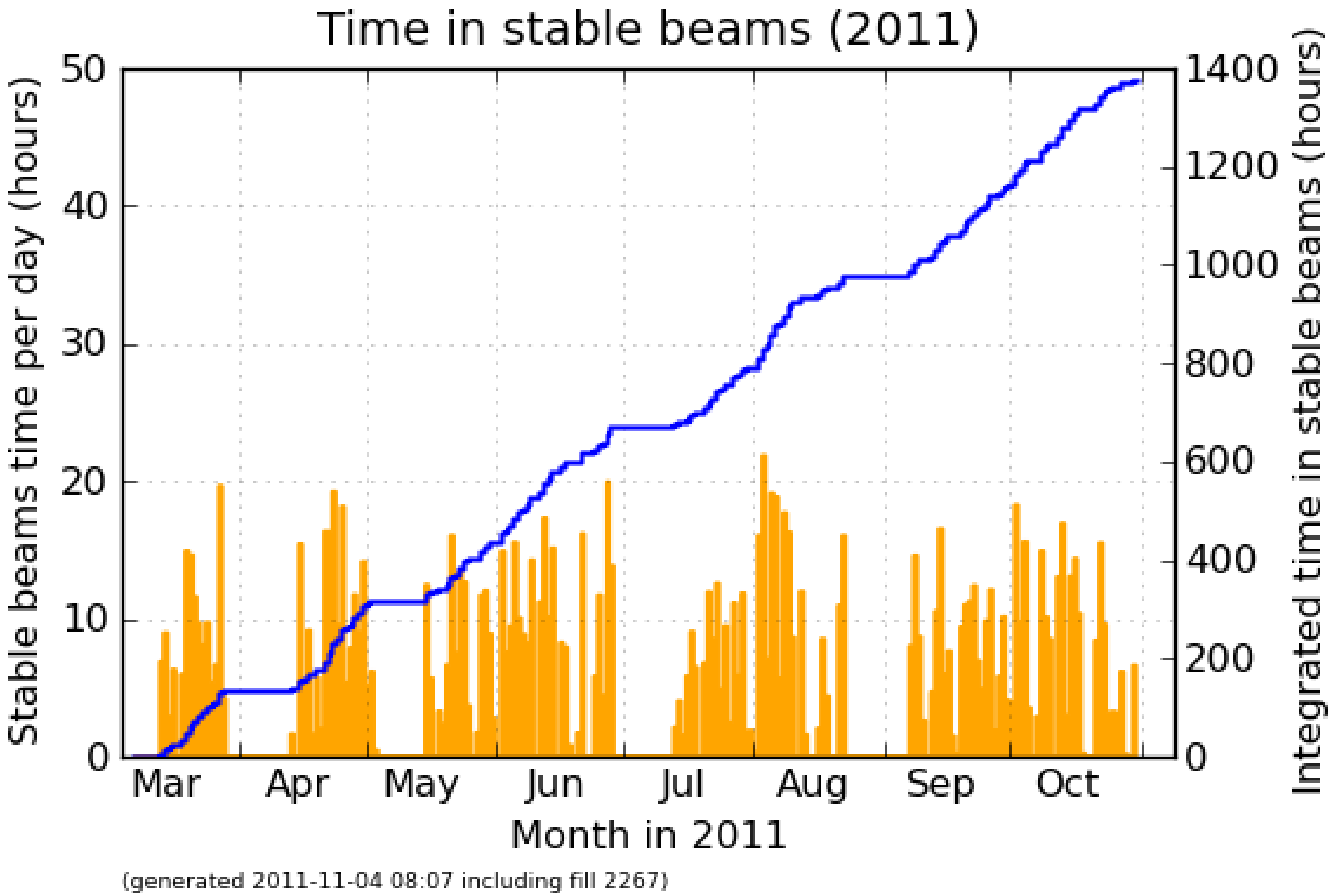


9 months with ~26 days each & peak luminosity of $3.6x10^{33}$ $cm^{-2}s^{-1}$ (at the end) and 5.5/fb in total gives a “Hübner factor” of ~0.08

2011 LHC records

	CMS	ATLAS
peak stable luminosity delivered	3.55×10^{33} cm^{-2} s^{-1}	3.65×10^{33} cm^{-2} s^{-1}
maximum luminosity in on fill	123.13 pb^{-1}	122.44 pb^{-1}
maximum luminosity in one day	135.65 pb^{-1}	135.45 pb^{-1}
maximum luminosity in 7 days	537.9 pb^{-1}	583.5 pb^{-1}
maximum luminosity in 1 month	1614.99 pb^{-1}	
maximum colliding bunches (w/o satellites)	1331	1331
maximum peak #events /crossing		23.8 (33.96)
maximum (av.) #events / bunch crossing	19.94	17.5 (32.21)
longest time in stable beams for one fill	26 h	26 h
longest time in stable beams for one day	19.9 h (82.9%)	21.9 h (91.2%)
longest time in stable beams for one week	107.1 h (63.7%)?	107.1 h (63.7%)
longest time in stable beams for one month	232.2 h	232.2 h?
fastest turnaround to stable beams	2.1 h	2.1 h

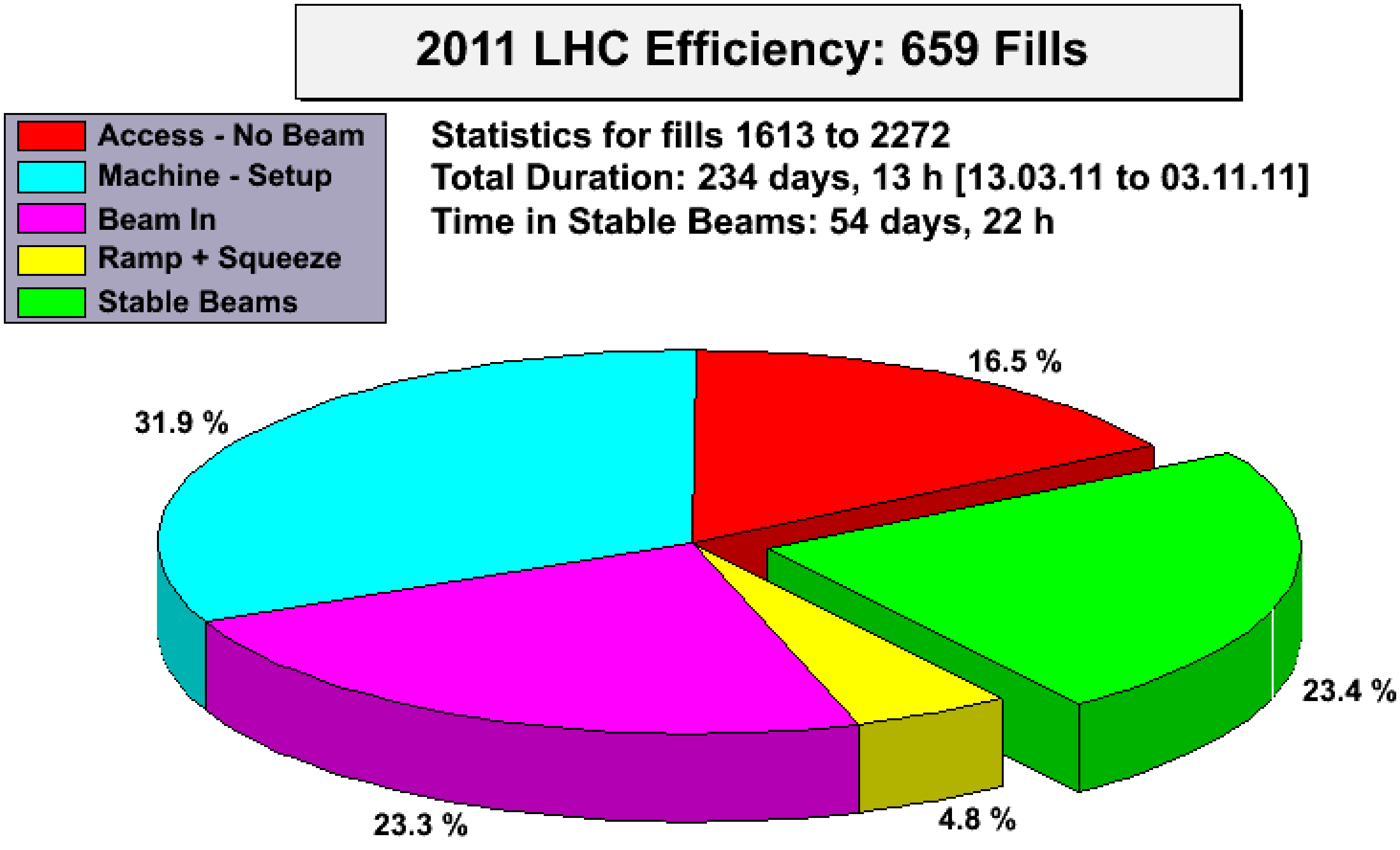
2011 time spent in physics



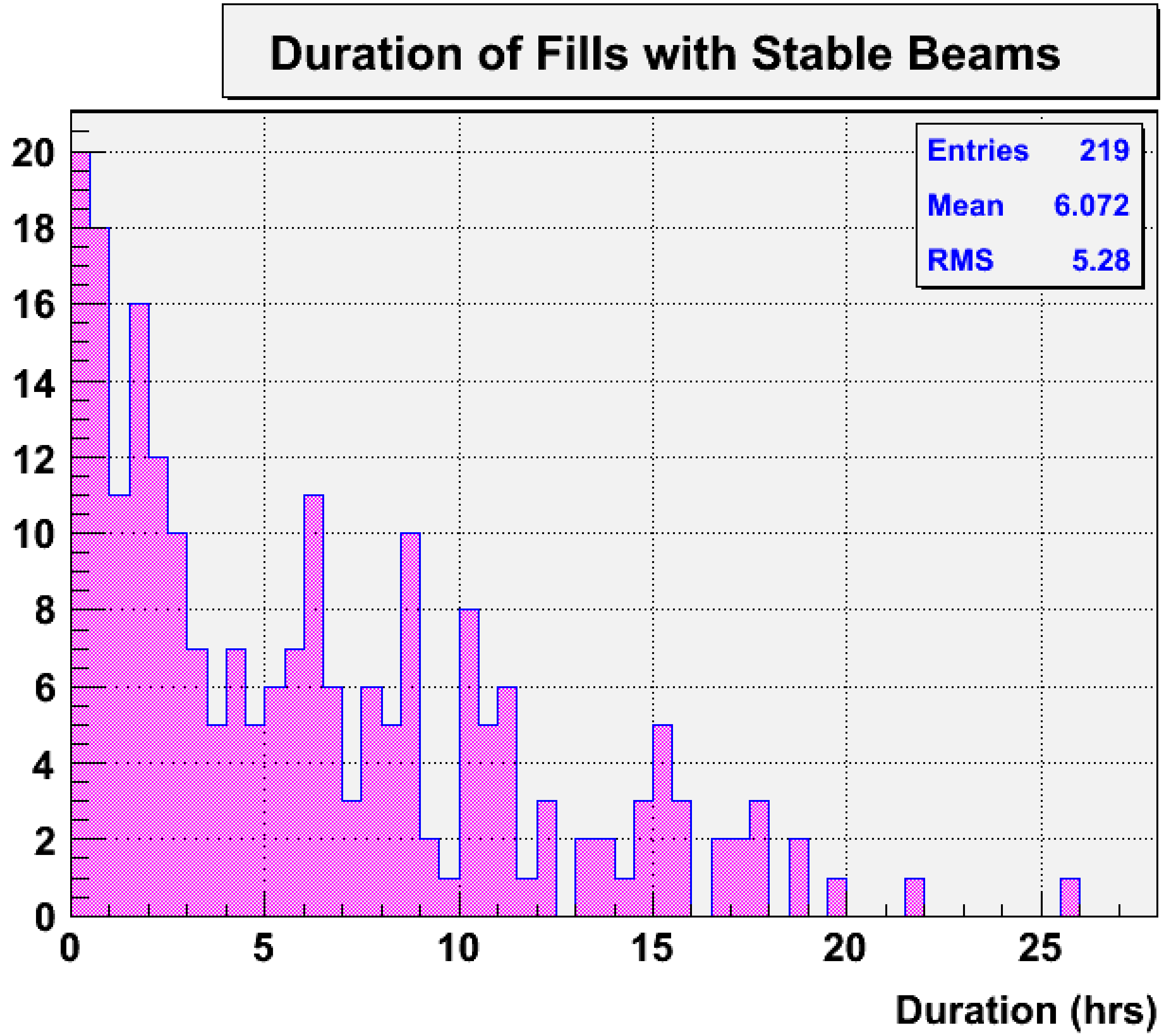
1400/(31 24 8) ~23.5% of the total,

+ lumi decay + lumi ramp up → consistent with Hübner factor 0.08

2011 time spent in physics



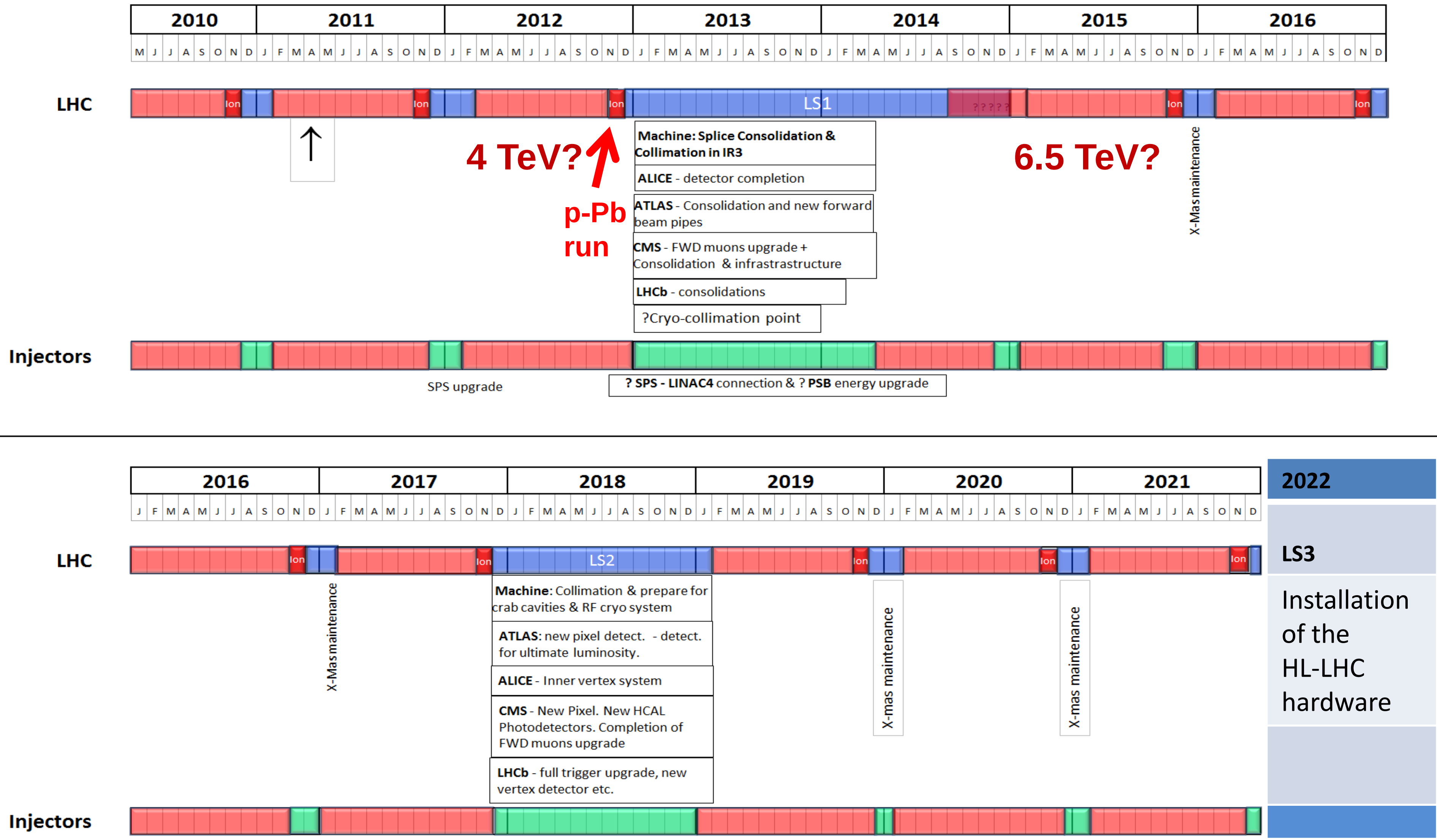
2011 length of physics fills



10 year plan 2011-2021

from early 2011

New rough draft 10 year plan

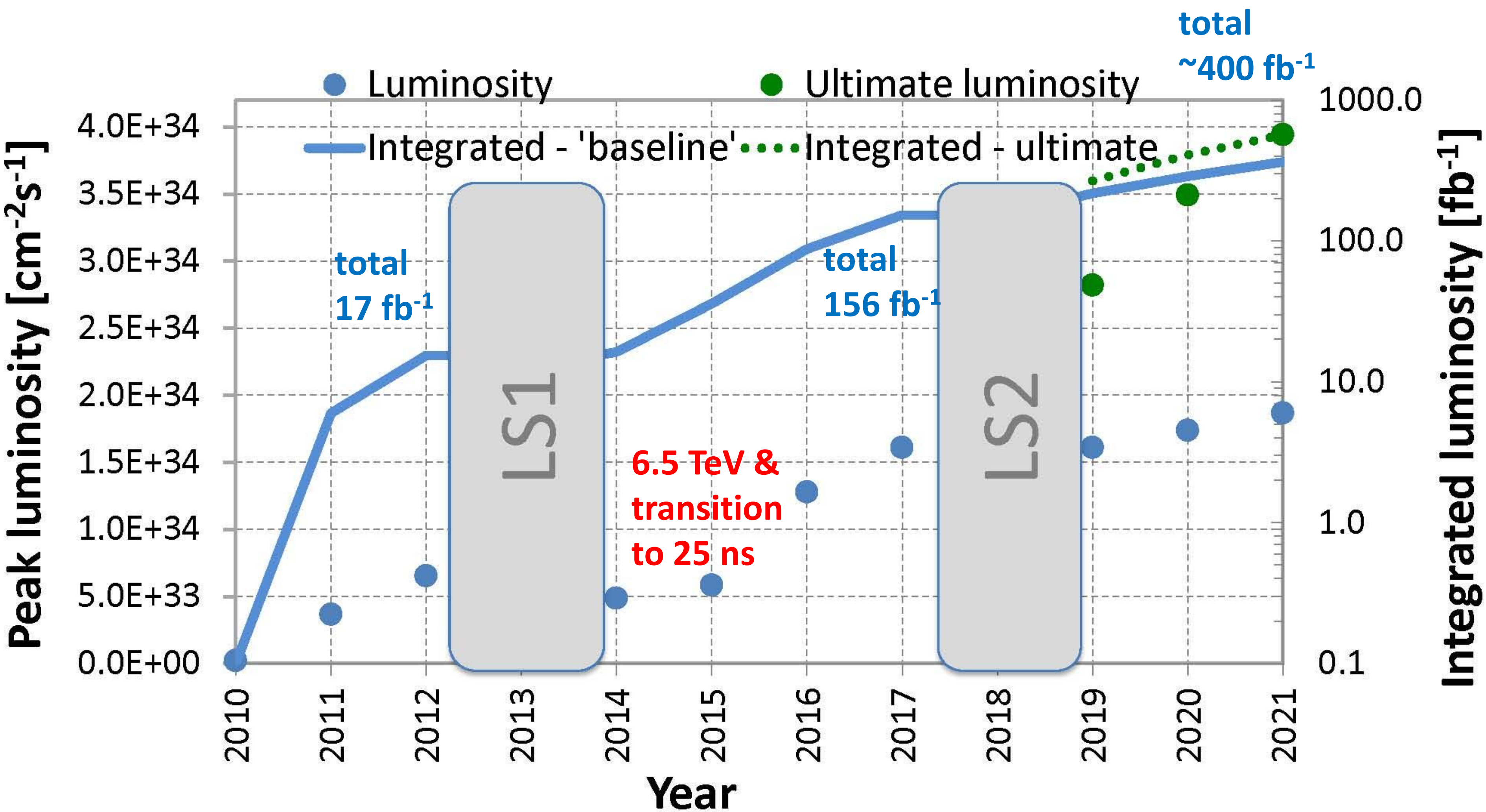


LHC beam parameters

	design	October 2011	end 2012 ?	2016 ??
Beam energy	7 TeV	**3.5 TeV**	**4 TeV**	**6.5 TeV**
transv. norm. emittance	3.75 μm	**2.5 μm**	**2.5 μm**	**3.5 μm**
beta*	0.55 m	1.0 m	0.7 m	0.5 m
IP beam size	16.7 μm	24 μm	19 μm	17 μm
bunch intensity	1.15×10^{11}	**1.5×10^{11}**	**1.6×10^{11}**	**1.2×10^{11}**
# colliding bunches	2808	1331	1350	2800
bunch spacing	25 ns	**50 ns**	**50 ns**	25 ns
beam current	0.582 A	0.335 A	0.388 A	0.604 A
rms bunch length	7.55 cm	9 cm	9 cm	7.6 cm
full crossing angle	285 μrad	240 μrad	240 μrad	260 μrad
“Piwinski angle”	0.64	0.37	0.51	0.61
peak luminosity	10^{34} cm^{-2}s^{-1}	**3.6×10^{33} cm^{-2}s^{-1}**	**7.4×10^{33} cm^{-2}s^{-1}**	**1.3×10^{34} cm^{-2}s^{-1}**
average peak pile up*	25	**18**	**36**	**30**

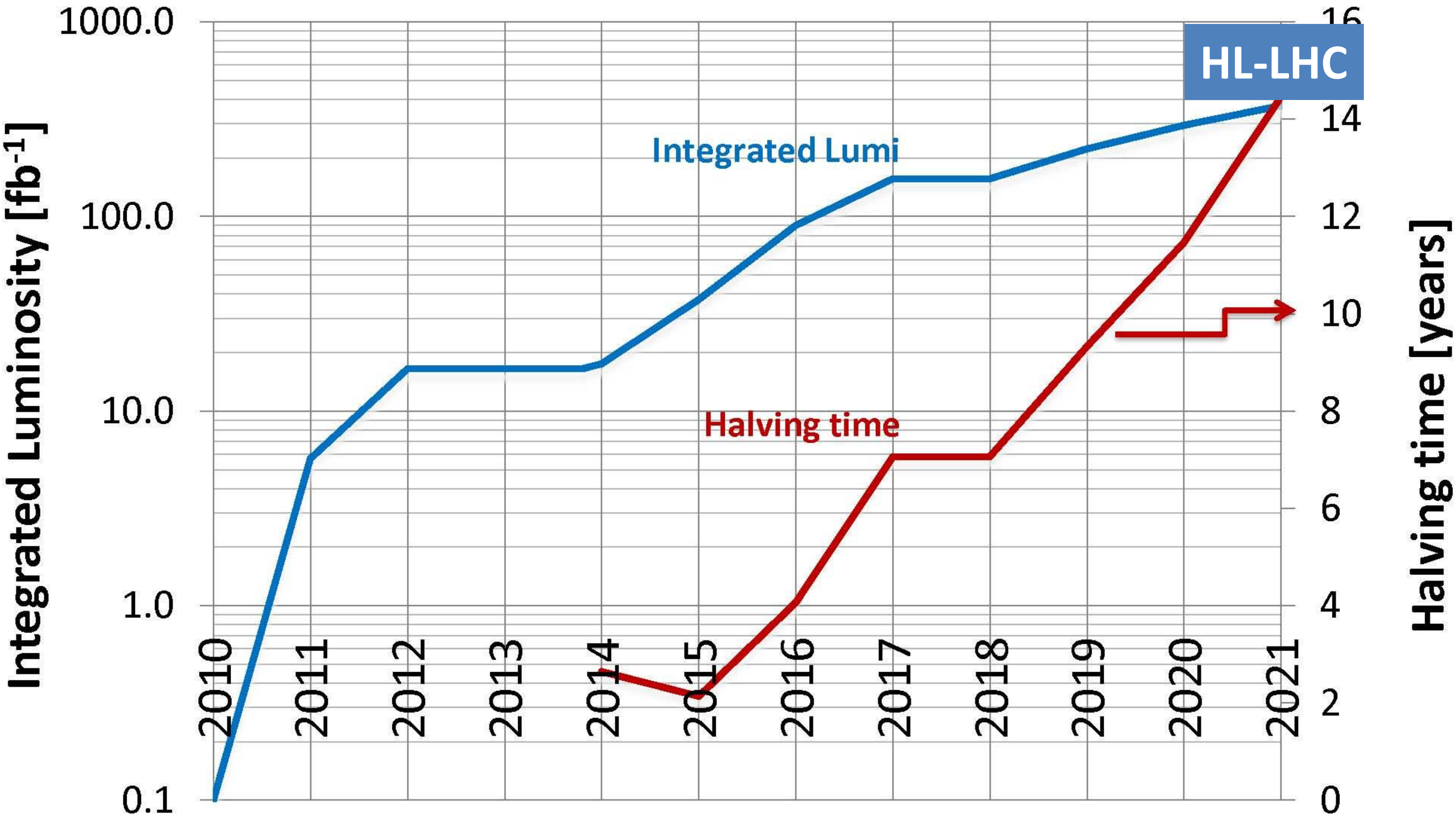
* with σ~80 mbarn

10-year luminosity forecast



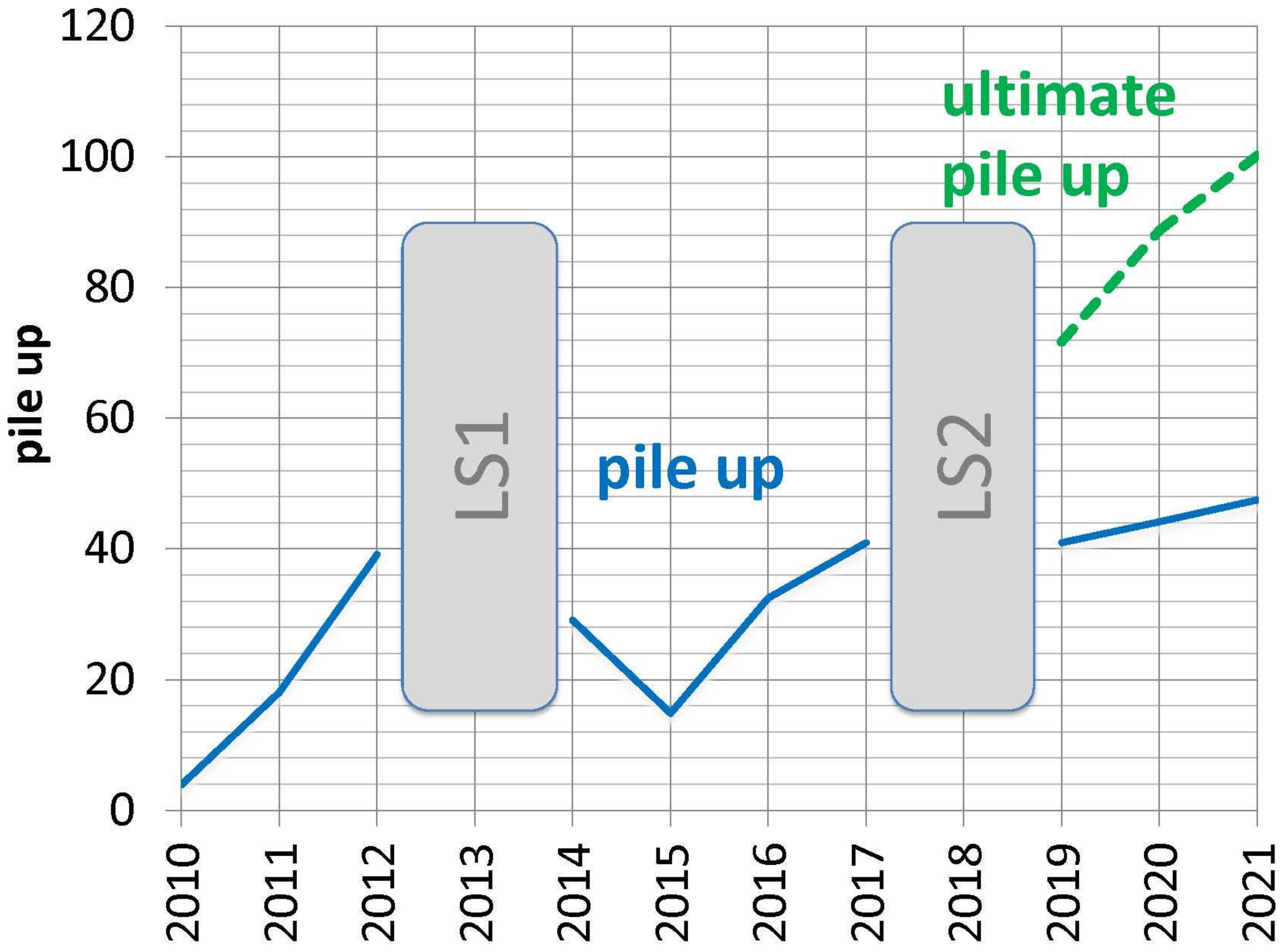
modified from O. Brüning, M. Lamont, L. Rossi

10-year luminosity forecast



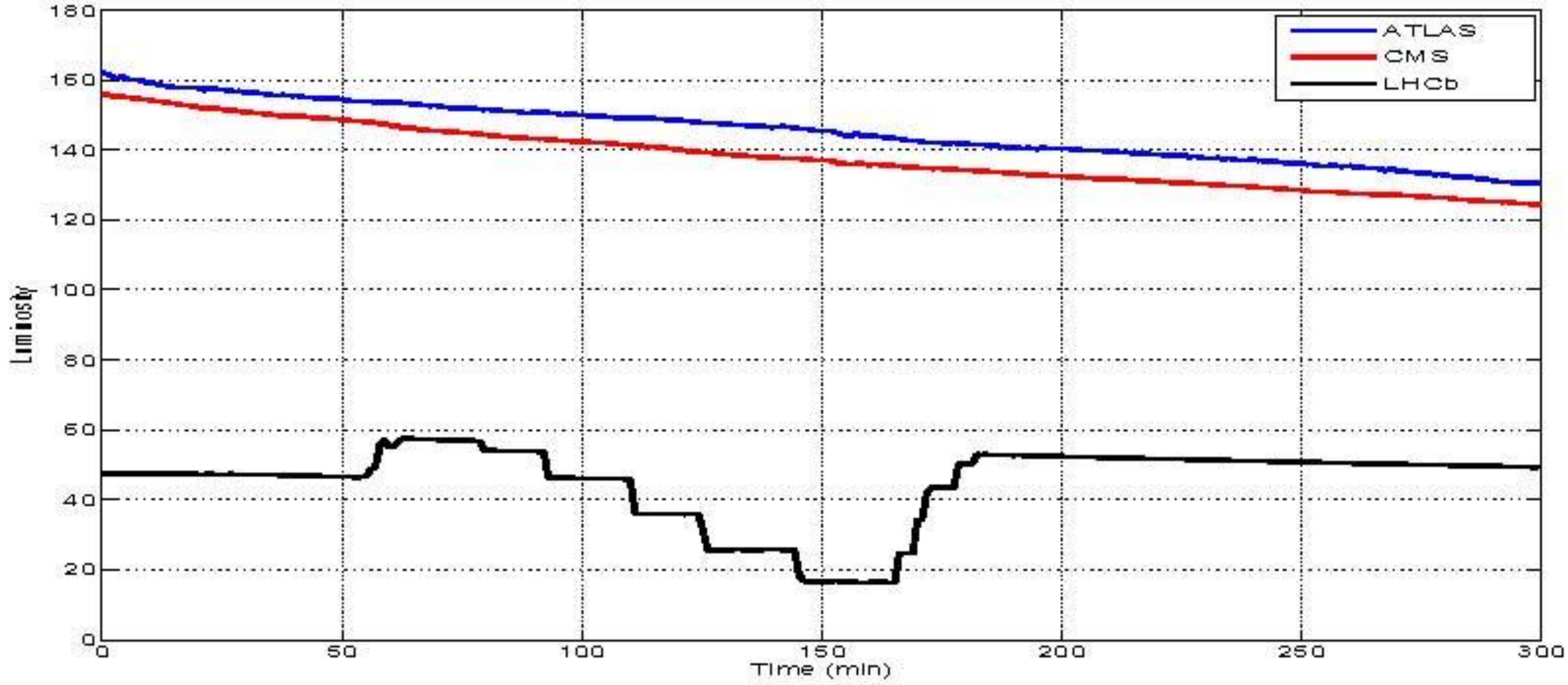
modified from O. Brüning, M. Lamont, L. Rossi

10-year pile-up forecast



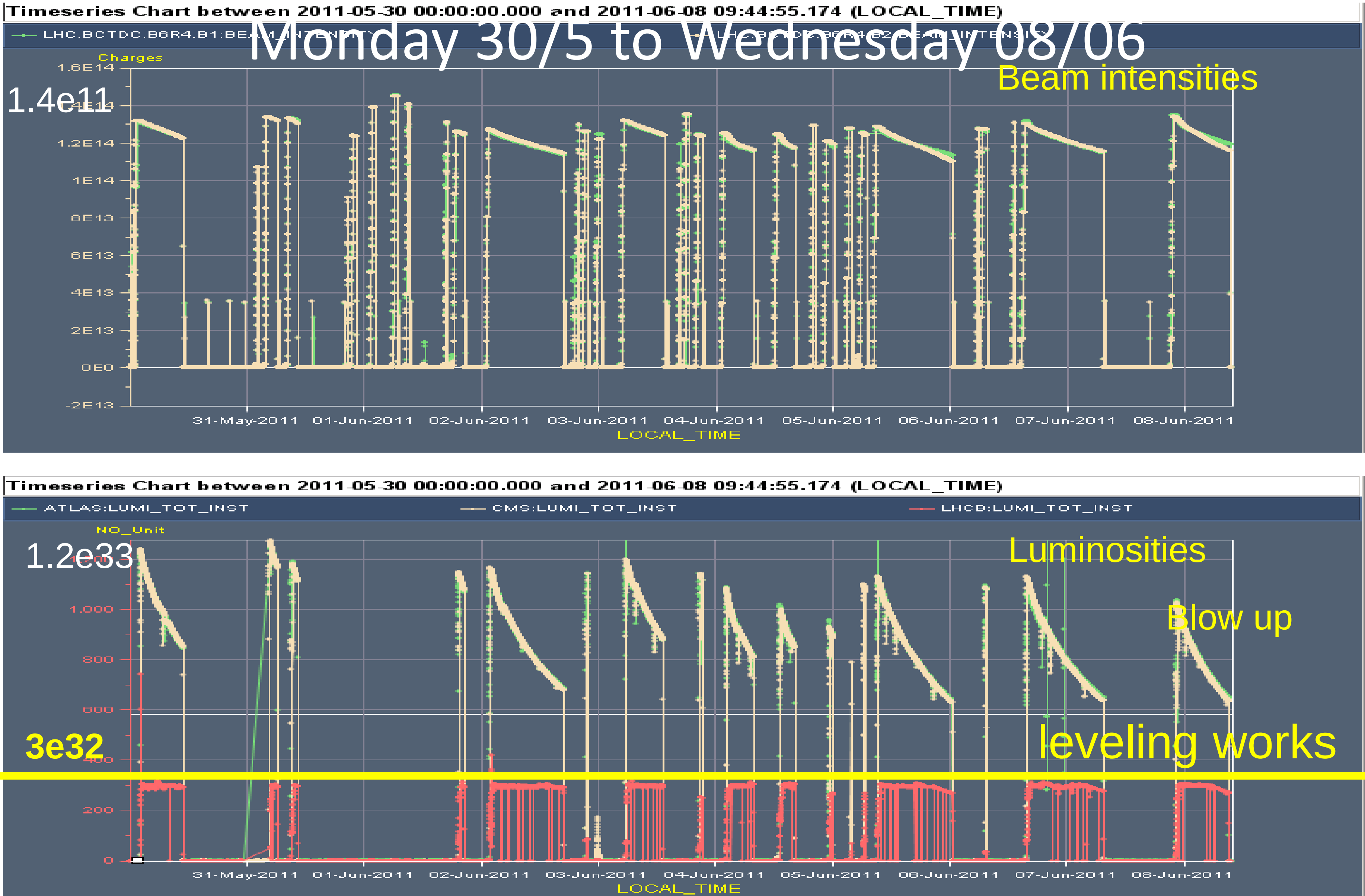
2011: offset leveling test

W. Herr et al, March 2011



conclusion: the luminosity can be successfully leveled using transverse offsets between 0 and a few σ (here at IP8) without significant effects on the beam or the performance of the other experiments (IP1&5)

2011: routine leveling in IP2 & 8



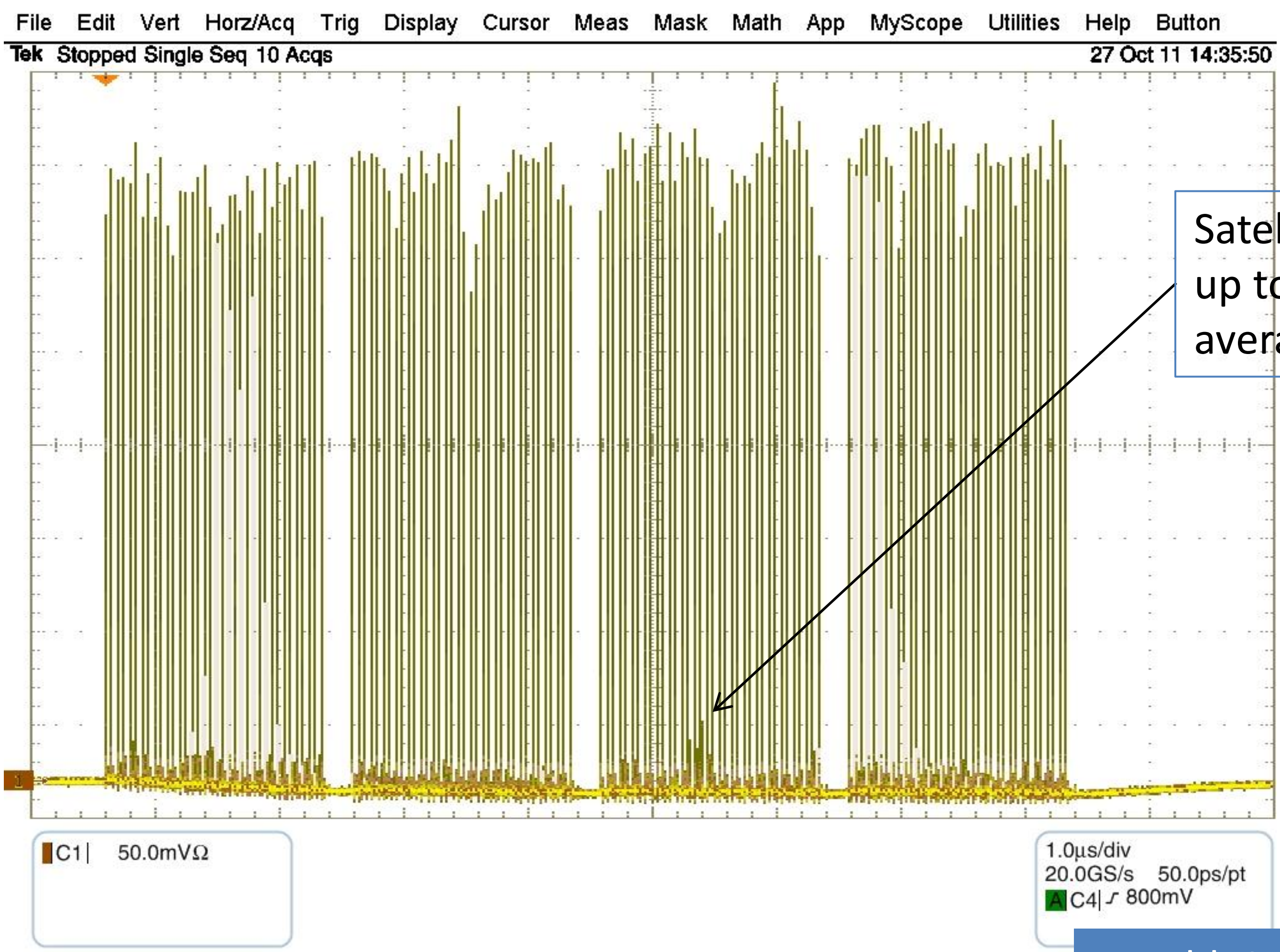
Wk 3

enhanced satellites for ALICE

- wall current profile SPS beam
- average over sequential 10 turns, 20 ms before extraction
- 144 bunches with satellites

test in week 43

enhanced satellites are produced by RF gymnastics in the PS (S. Hancock)



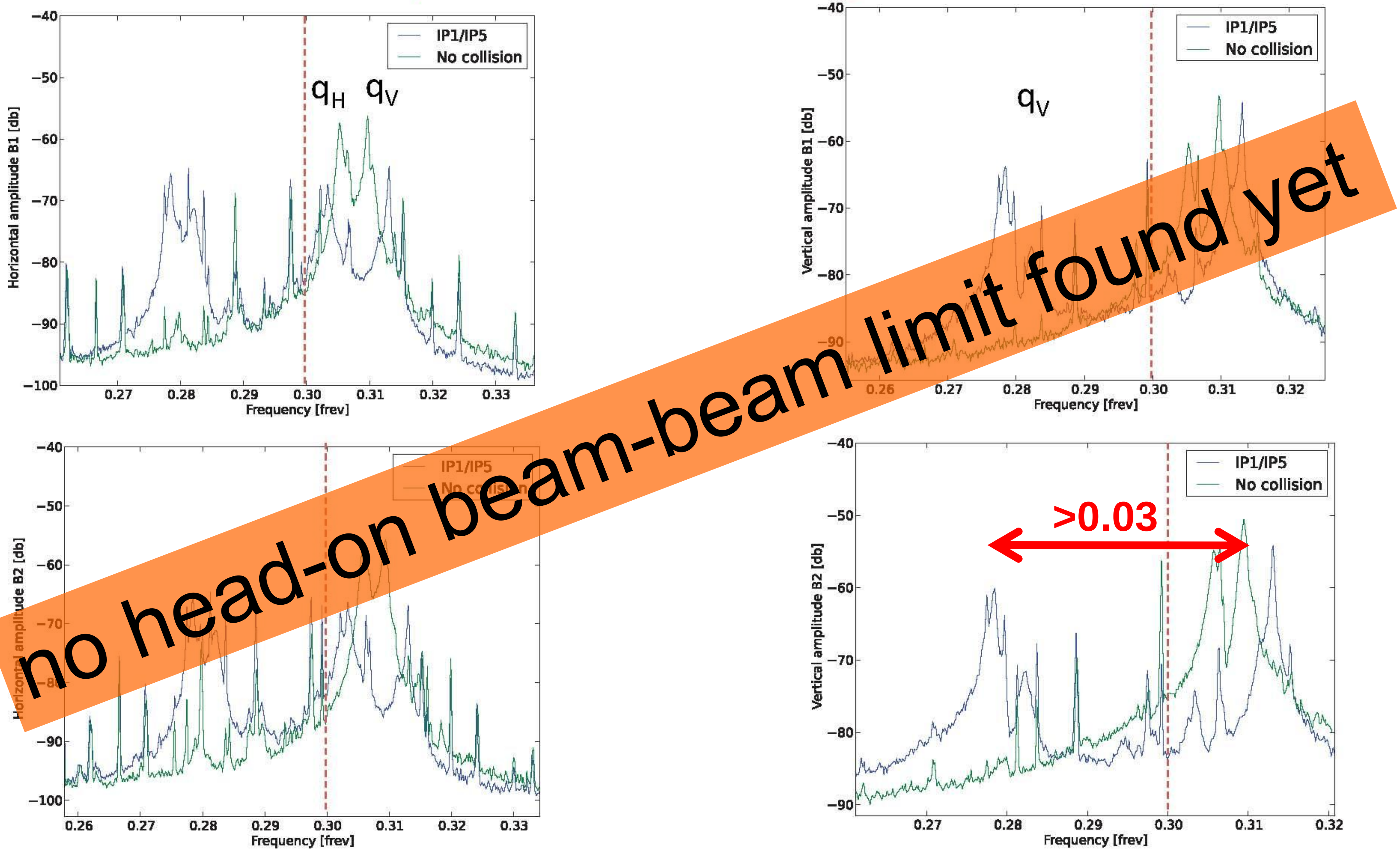
Satellites going up to about 8 %, average of few %

T.Bohl, S.Hancock

R. Assmann, LMC

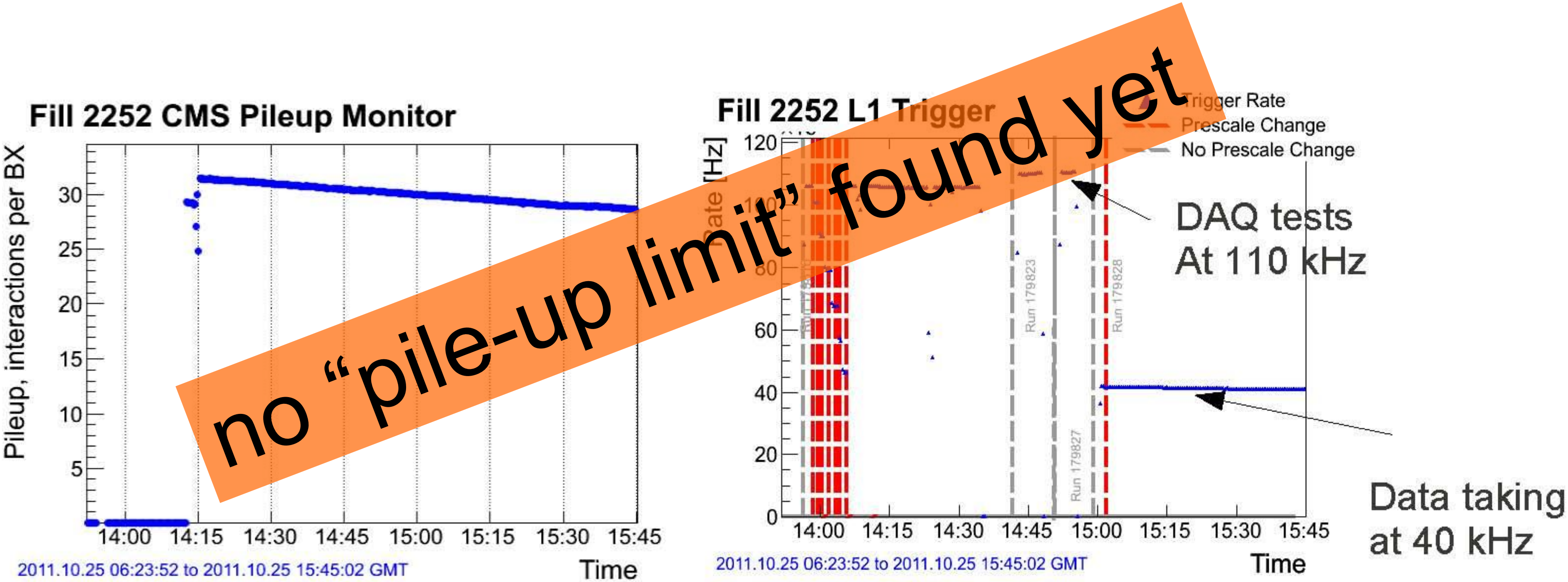
T. Pieloni, W. Herr et al, May 2011

tune spectra colliding IP1 & IP5



beam parameters investigated **beyond nominal LHC (N_b = 1.8-1.95x10^{11},** ε **=1.2-1.4** μ**m);** no significant beam losses nor emittance effects observed with linear head-on parameter of **ξ_{bb}= 0.02 /IP** and **ξ_{bb}=0.034 (total)** ***– more than 3x above design*****!**

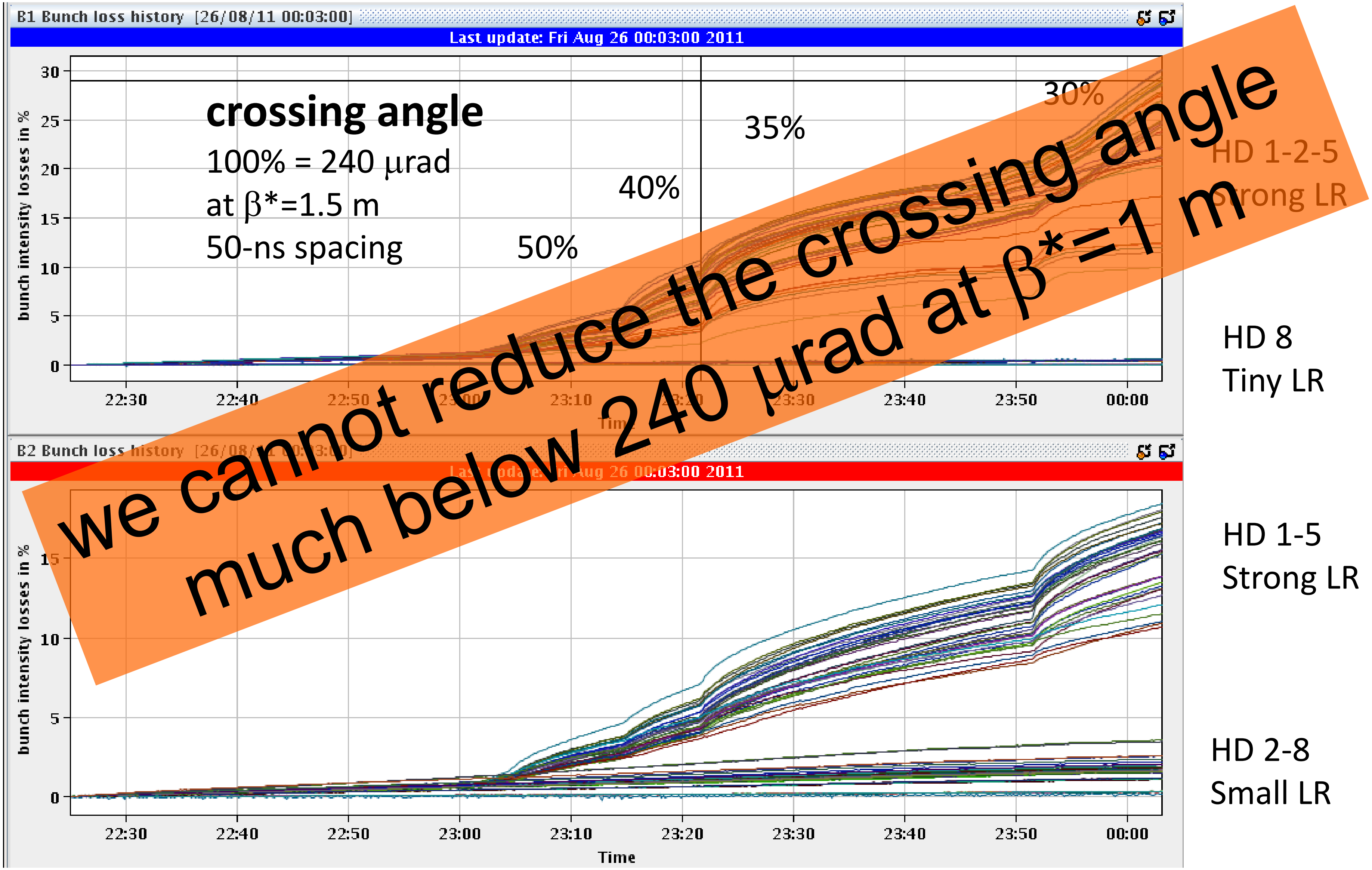
high pile-up test – CMS results



- With a PU of >30 at the start of the fill we ran at 110 kHz L1 trigger rate – no limitation seen by the DAQ bandwidth.
- Without modifications to the readout we can operate at 7e33 Hz/cm2 with 50 ns bunch spacing.

W. Herr et al, August 2011

long-range beam-beam effect

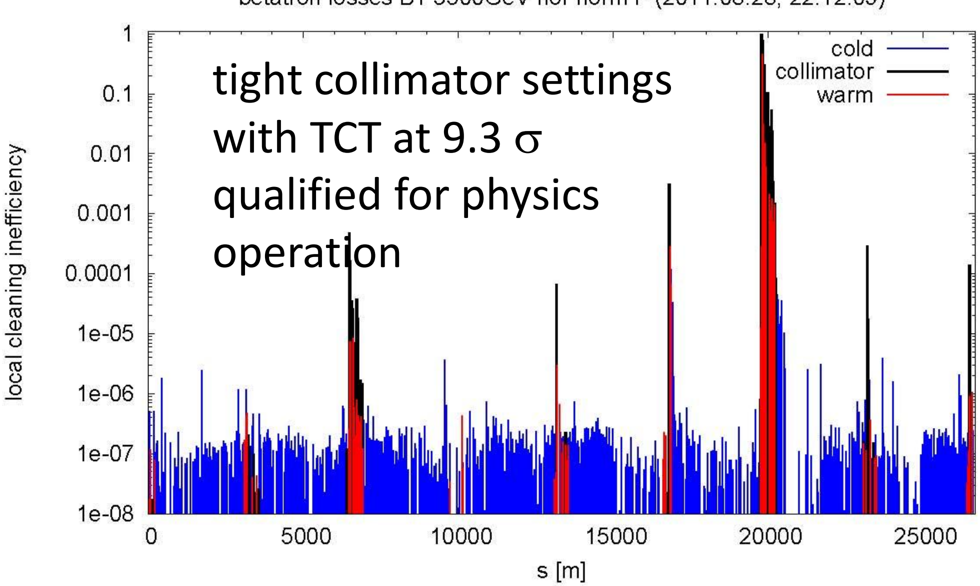


β* reach from 2011 MDs

tight collimator settings tested in MD block2

Table 1: Collimator half opening, in units of σ, at top energy and squeezed optics for tight settings and relaxed settings.

Collimators	Relaxed setting (σ)	Tight setting (σ)
TCP IR7	5.7	4.0
TCS IR7	8.5	6.0
TCL IR7	17.7	8.0
TCP IR3	12.0	12.0
TCS IR3	15.6	15.6
TCL IR3	17.6	17.6
TCT	11.8	9.3
TCS IR6	9.3	6.8
TCDQ IR6	9.8	7.3



R. Assmann et al, CERN-ATS-Note-2011-079 MD

"We found a good **IR aperture** in both planes and IPs. So good that we want to take more time to see if we overlooked something. Had to open the TCT aperture to the following values before seeing primary losses at the triplet:"

IR1 - V -> 18.3 - 18.8 σ (at β*=1.5 m)

IR1 - H -> 19.8 - 20.3 σ

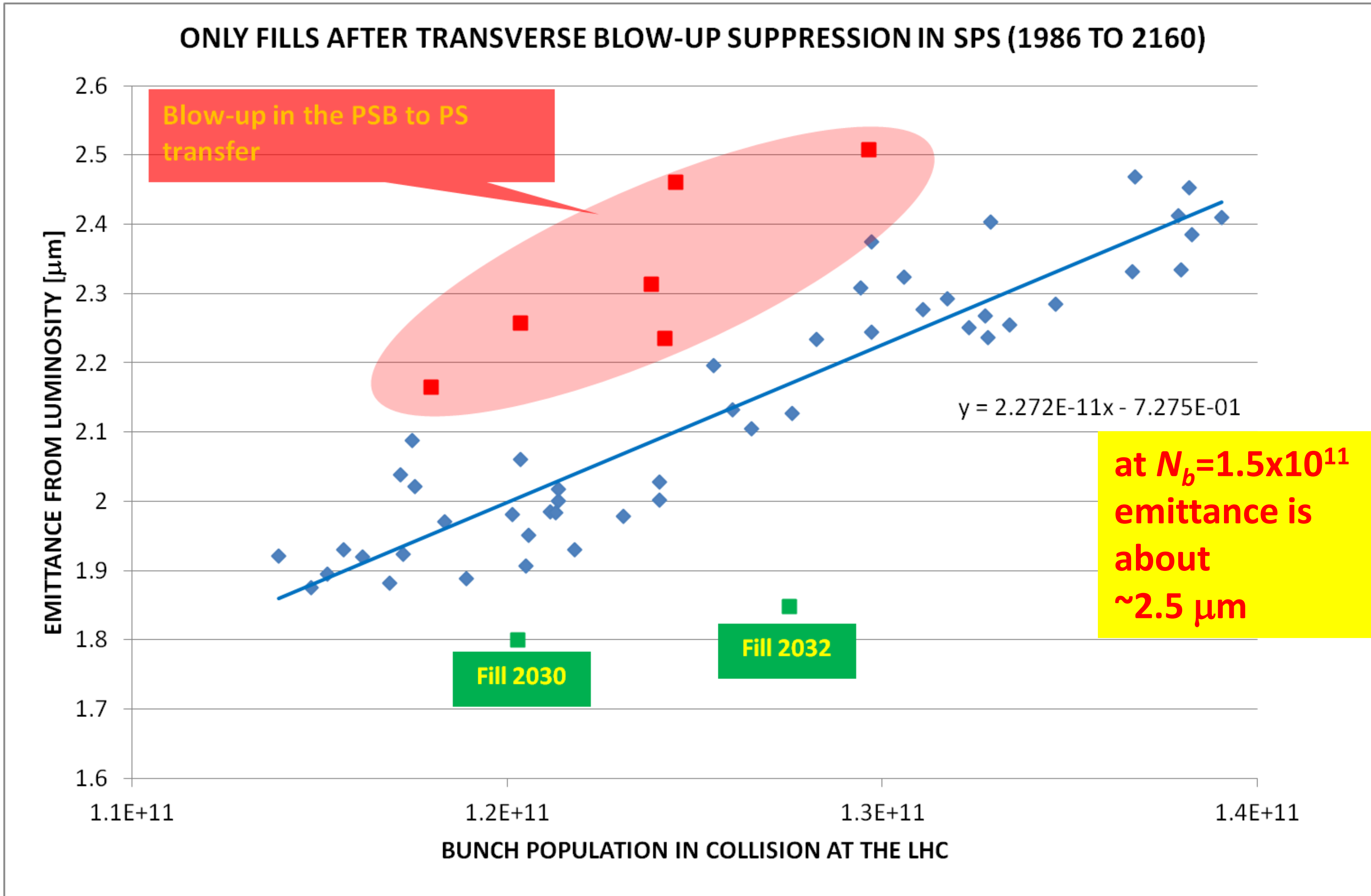
IR5 - V -> ≥ 20.3 σ (corrector limit reached)

IR5 - H -> 19.8 - 20.3 σ

S. Redaelli, M. Giovannozzi et al
LHC MD block 3

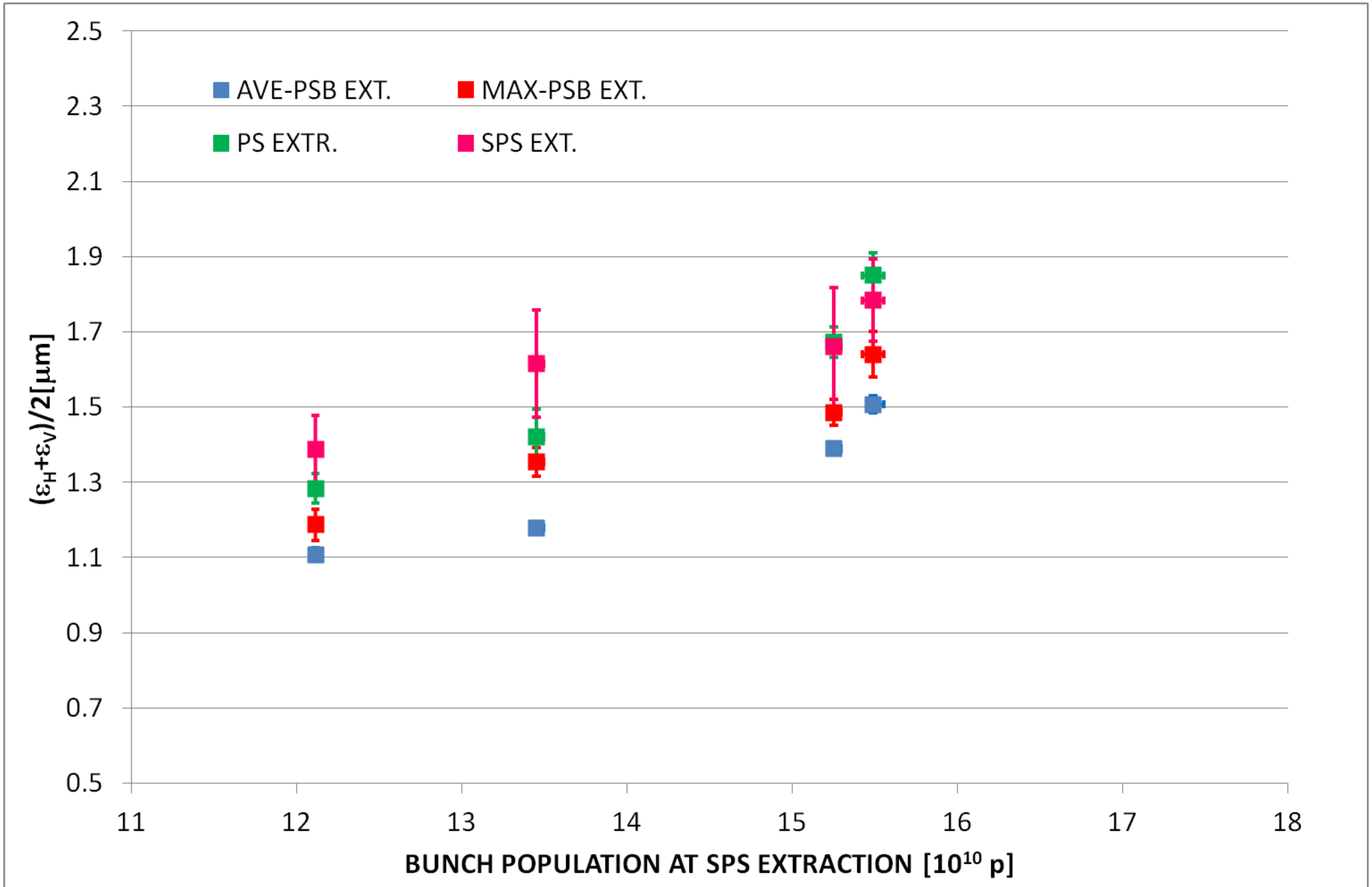
at present TCTs at 11.8 σ at β*=1 m; this could be reduced to 9.3 σ (β*<0.7 m)

2011: LHC emittance vs bunch intensity with 50 ns spacing



G. Arduini, LMC110

2011: injector emittance vs equivalent LHC bunch intensity (w/o losses)



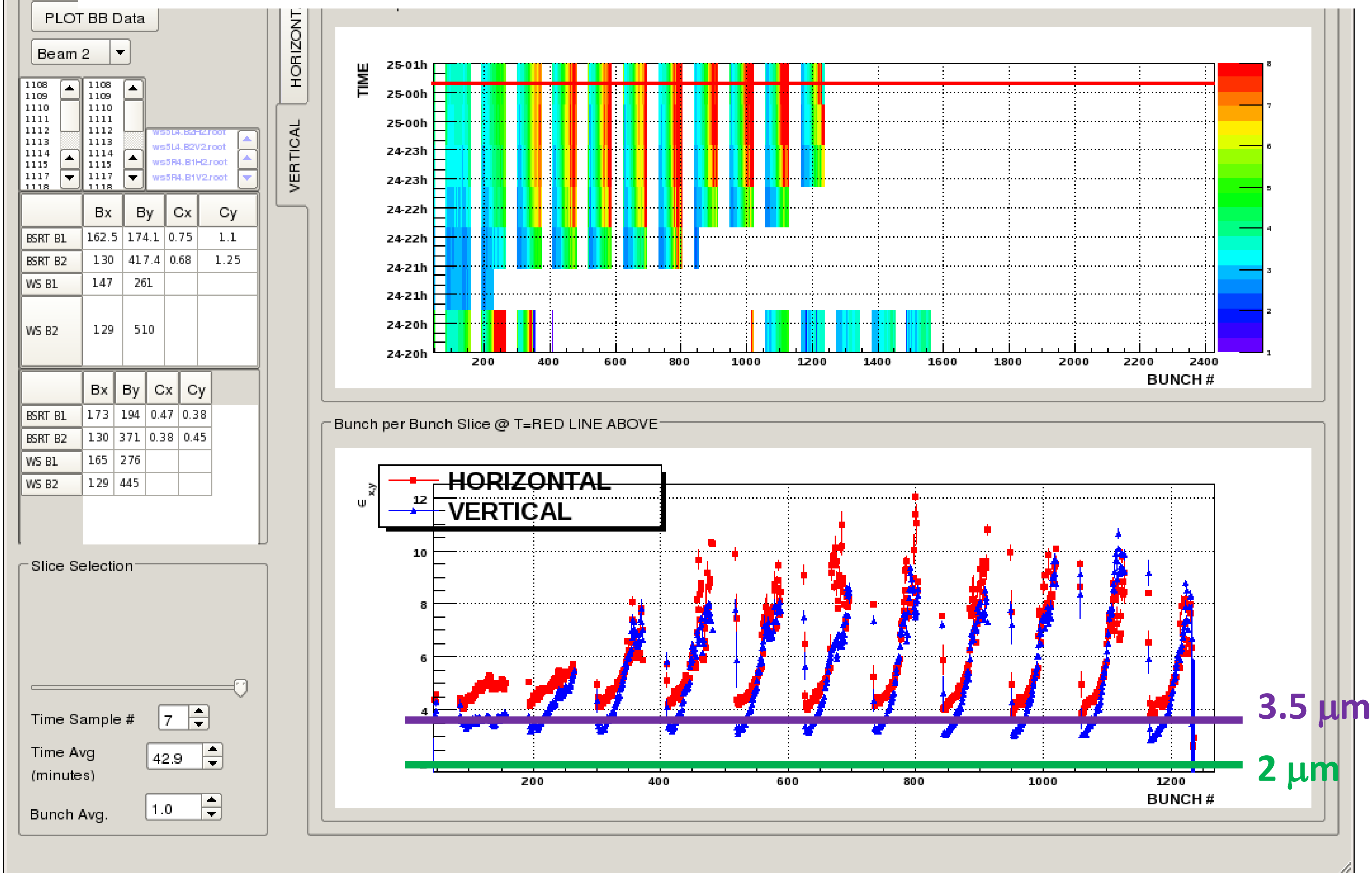
G. Arduini, LMC110

50 ns vs 25 ns

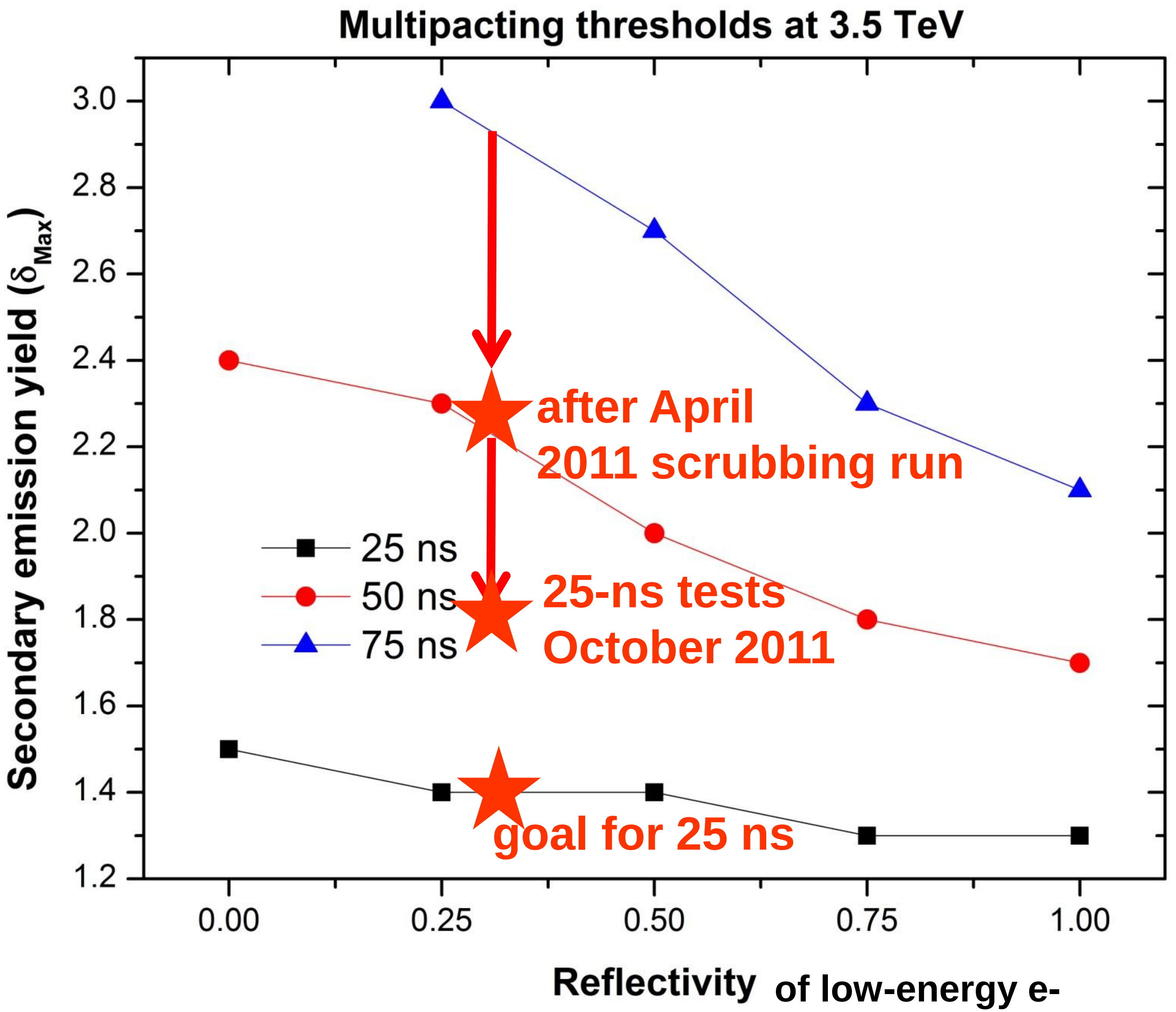
- **50-ns beam: smaller emittance from the PS** (less splittings in the PS; i.e. less charge in the PSB); ~2 μm vs ~3.5 μm at LHC injection
- **25-ns beam: emittance growth due to e-cloud in the SPS and LHC** (to be improved by scrubbing in the LHC, and a-C coating in the SPS)
- 25-ns has more **long-range 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 (2014?) we must (try to) transit to 25-ns spacing** because of pile up
- also there are the possibilities to **alternate high-luminosity high-pile-up 50-ns running and lower-luminosity 25-ns running with reduced pile up** (?); **or to use ALICE enhanced satellites to get both high and low pile up events at the same time** – preferences of experiments?

e-cloud emittance blow up with 25 ns

MD October 2011



electron cloud scrubbing – LHC arcs



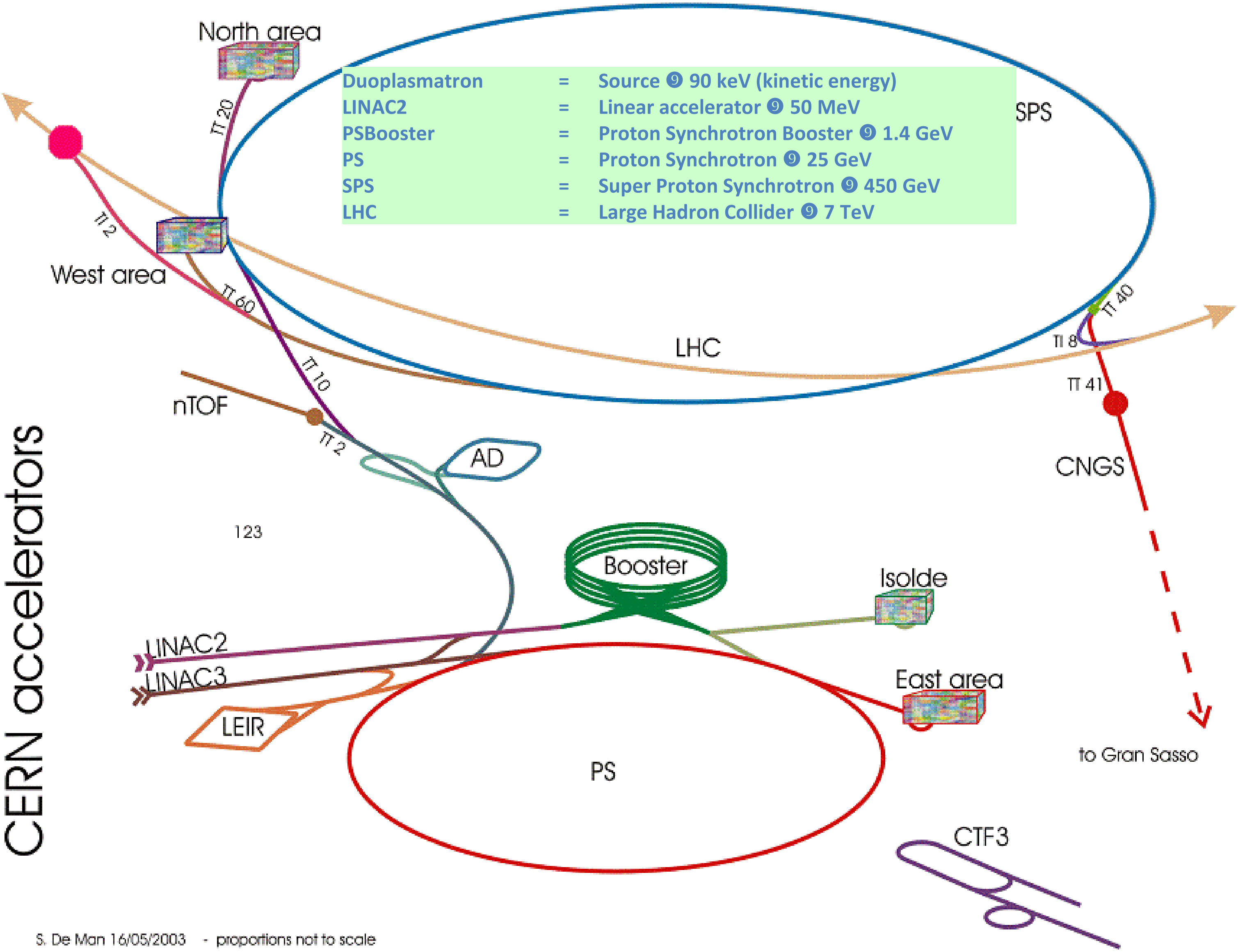
H. Maury

possible concerns for 2014/15

- radiation to electronics – SEU’s
- UFOs at higher energy & with 25 ns
- electron cloud & high energy & at 25 ns
- emittance growth in physics
- …

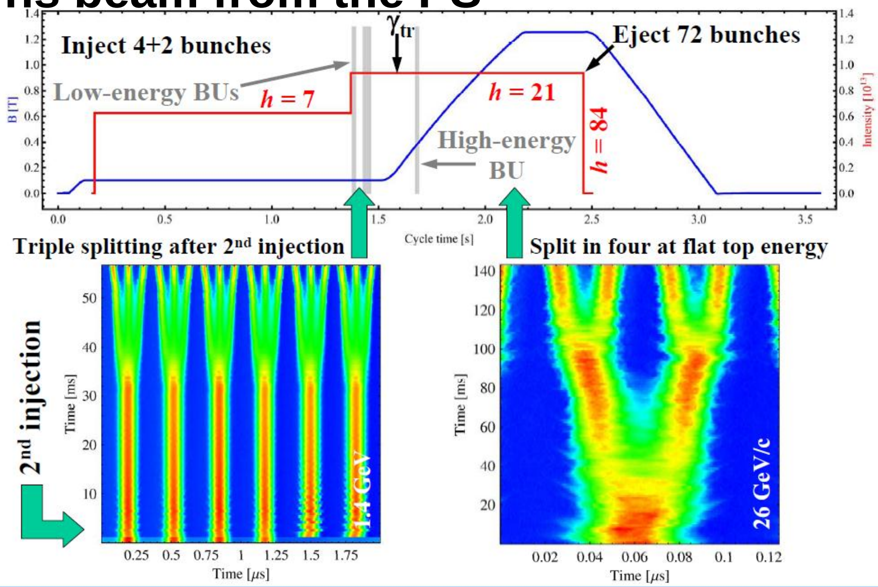
LHC injector complex

Duoplasmatron	=	Source ❾ 90 keV (kinetic energy)
LINAC2	=	Linear accelerator ❾ 50 MeV
PSBooster	=	Proton Synchrotron Booster ❾ 1.4 GeV
PS	=	Proton Synchrotron ❾ 25 GeV
SPS	=	Super Proton Synchrotron ❾ 450 GeV
LHC	=	Large Hadron Collider ❾ 7 TeV



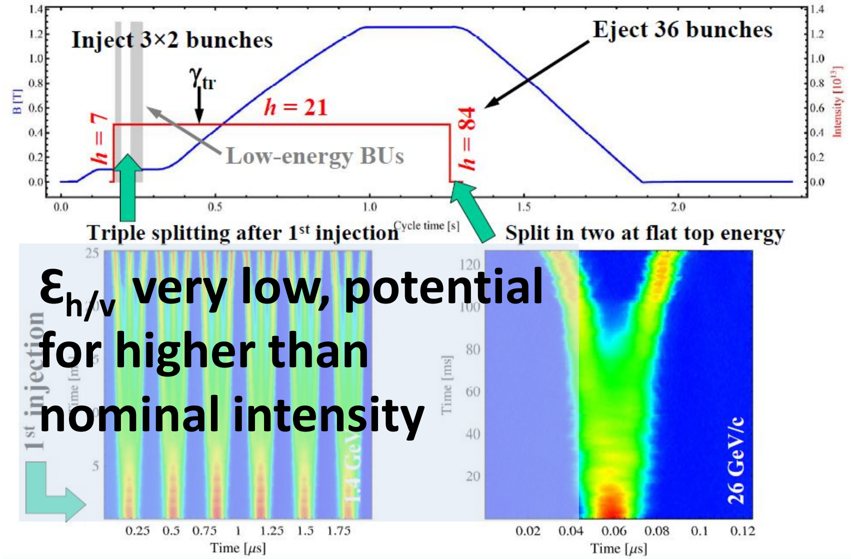
3 LHC *p* beams from the CERN PS

25 ns beam from the PS



→ Each bunch from the Booster divided by 6 → 6 × 3 × 2 × 2 = 72

50 ns beam from the PS



$\varepsilon_{h/v}$ very low, potential for higher than nominal intensity

→ Each bunch from the Booster divided by 6 → 6 × 3 × 2 = 36

Rende Steerenberg
Chamonix 2011

Possible Characteristics 2011

	PSB extraction				**PS extraction**			**SPS extraction**			
	Ip / ring [x10^{11}]	**ε_h and ε_v [mm · mrad] 1σ, norm.**	**nb batches**	**nb bunches**	**Ip / bunch [x10^{11}]**	**ε_h and ε_v [mm · mrad] 1σ, norm.**	**nb bunches**	**Ip / bunch [x10^{11}]**	**ε_h and ε_v [mm · mrad] 1σ, norm.**	**ε_{longit} [eVs]**	**nb bunches**
LHC25 (DB)	16	2.5	2	4 + 2	1.3	2.5	72	**1.15**	**3.6**	0.7	4 x 72
LHC50 (SB)	24	3.5	1	3 x 2	1.75	3.5	36	**1.45**	**<3.5**	≤ 0.8	4 x 36
LHC50 (DB)	8	1.2	2	4 + 2	1.3	1.3	36	**1.15 (?)**	**1.5 (?)**	≤ 0.8	4 x 36

LHC50 SB (2010) → **LHC 50 DB (low emittance, 2011)** **or** **LHC25 DB (more bunches)**

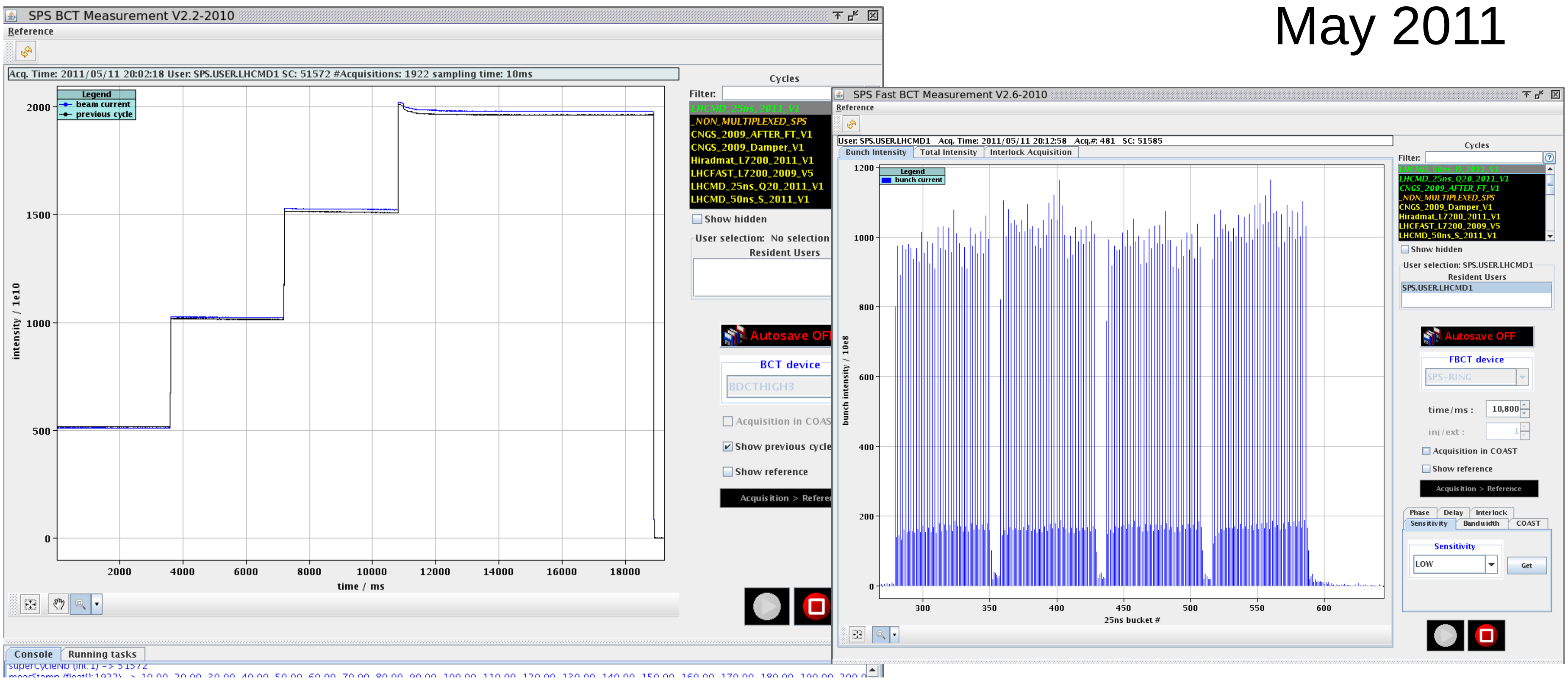
+ future PS “**batch compression**” to (further) boost the brightness?

SPS: 50ns bunch train – Double PSB batch

Intensity **1.65 10^{11} p/b reached !**

- Up to 4 batches injected
- **Very low losses** along the cycle (reproducible 3%)
- **ε_x=2.0 μm and ε_y=1.9 μm** at flat top (sum 3.9)

May 2011



new optics for SPS (low γ_t or "Q20")

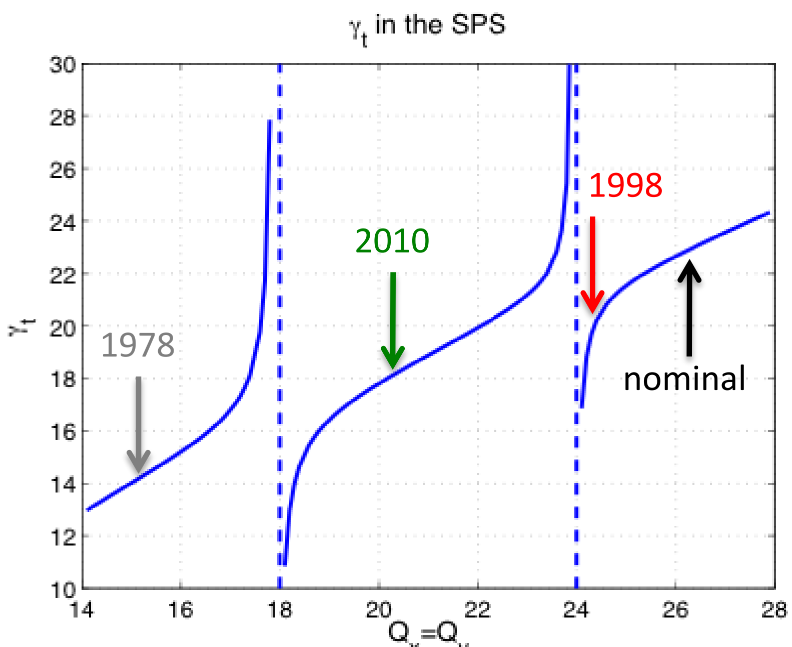
not yet fully commissioned for LHC

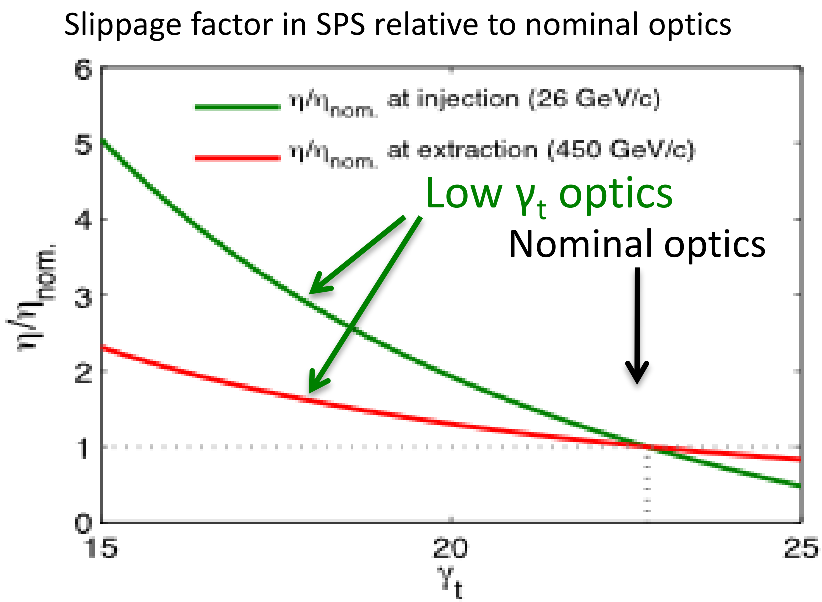
H. Bartosik, Y. Papaphilippou

N_{th} … Instability threshold
ε … longitudinal emittance
τ … bunch length
η … slippage factor

- SPS intensity limitations for LHC p beams in SPS
  - TMCI due to transverse impedance, $N_{th} \sim \eta$
  - Loss of longitudinal Landau damping), $N_{th} \sim \varepsilon^2\tau\eta$
  - Longitudinal coupled bunch instabilities, $N_{th} \sim \eta\varepsilon^2/\tau$
  - Electron cloud instability
- Slippage factor η defined by optics through transition energy (γ_t):

$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$





→ **Increase in instability thresholds** N_{th} for higher slippage factor η due to faster synchrotron motion ($\Omega_s \propto \sqrt{|\eta| V_{RF}}$) and faster damping of instabilities

SPS single-bunch intensity limits

(units of protons/bunch)

chromaticity Q'/Q	**0.0**	**0.07**
old Q26 optics	1.7×10^{11}	2.2×10^{11}
new Q20 optics	2.8×10^{11}	3.8×10^{11}

>2 x LHC ultimate

Benoit Salvant

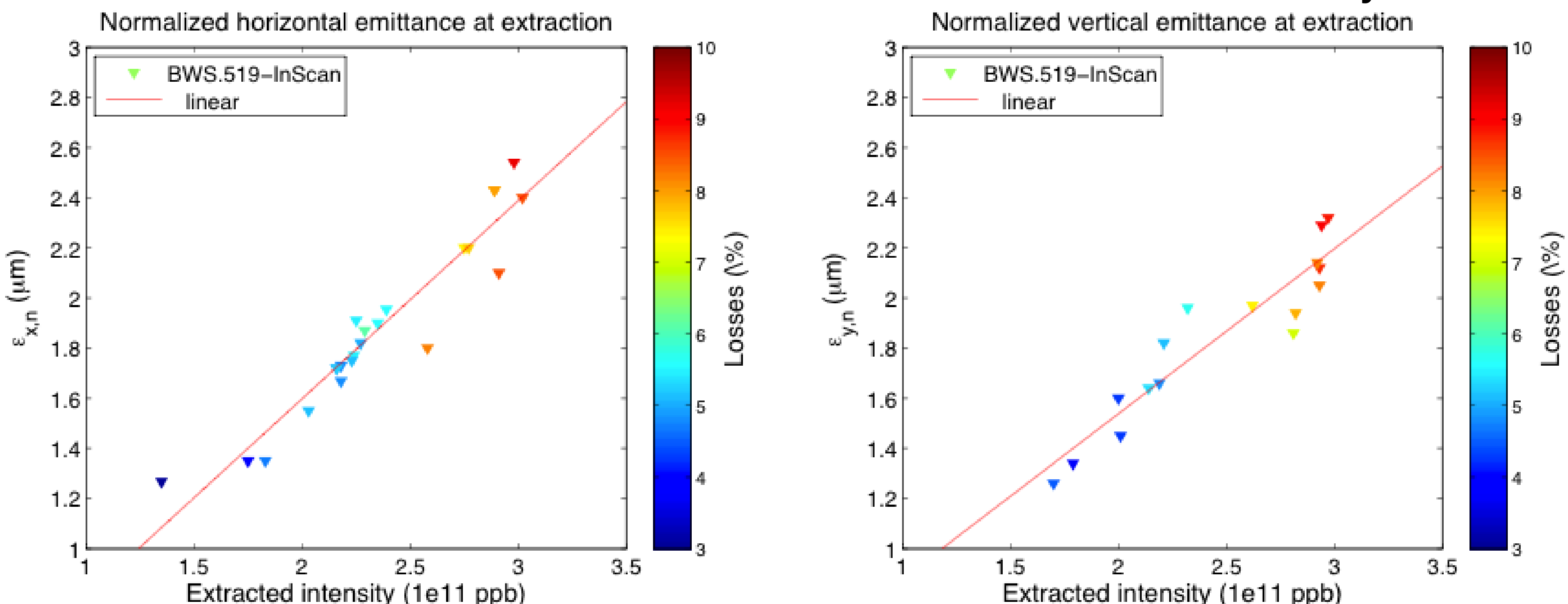
N_b & ε with SPS Q20 low-γ_t optics (1 bunch)

- extracted intensity together with total losses along the cycle
- overestimation of horizontal emittance and its slope (dependence of dp/p on intensity)
- PSB emittances: ~ 1μm < 1.5e11p / ~ 1.1μm @ 2e11p / ~ 1.3μm @ 3e11p
- bunch length slightly increasing with intensity
- **up to N_b~3x10^{11} (~3x LHC at 450 GeV with $\gamma\varepsilon$~2.5 μm (2/3 LHC design!)**

emittance

measured!

Hannes Bartosik
11 May 2011



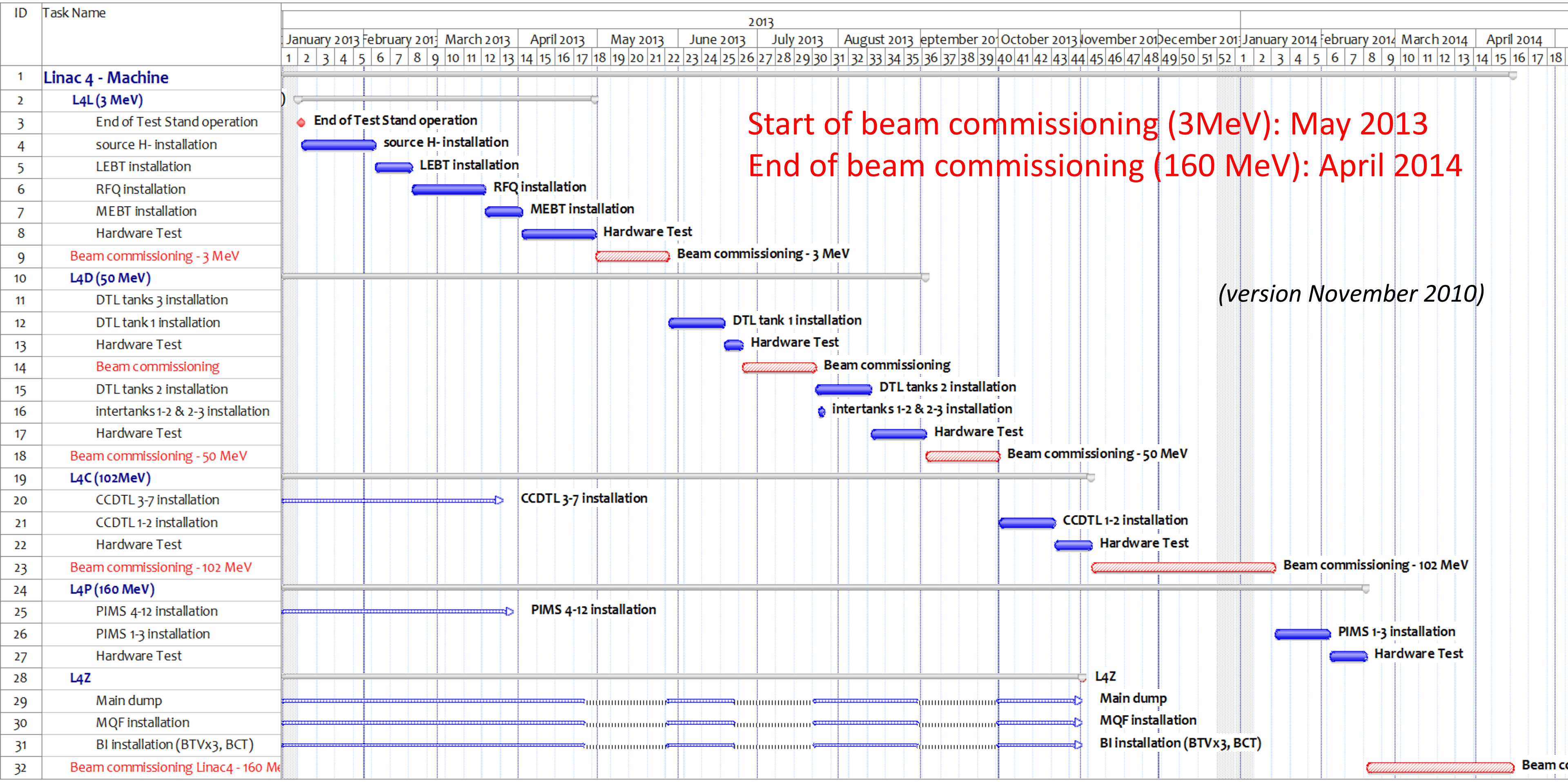
intensity

Overall LHC Injector Upgrade Planning

	Linac4	PS injector, PS and SPS	Beam characteristics at LHC injection
2011 - 2012	Continuation of construction…	• Beam studies § simulations • Investigation of RCS option • Hardware prototyping • Design § construction of some equipment • TDR	25 ns, 1.2 10^{11}p/b, **~2.5 mm.mrad** 50 ns, 1.7 10^{11}p/b, **~2.2 mm.mrad** 75 ns, 1.2 10^{11} p/b, $\leq$ 2 mm.mrad
2013 – 2014 (Long Shutdown 1)	**• Linac4 beam commissioning** **• Connection to PSB ?**	• PSB modification (H^- injection) ? • PSB beam commissioning ? • Modifications and installation of prototypes in PS and SPS	
2015 - 2017	• Progressive increase of Linac4 beam current	• If Linac4 connected: progressive increase of PSB brightness • Some improvement of PS beam (Injection still at 1.4 GeV) • Equipment design § construction for PS injector, PS and SPS • Beam studies	• Limited gain at LHC injection (pending PSB (or RCS), PS and SPS hardware upgrades)
2018 (Long Shutdown 2)		**• Extensive installations in PS injector, PS and SPS** **• Beam commissioning**	
2019 –2021			**After ~1 year of operation: beam characteristics for HL-LHC…**

R. Garoby, 24 June 2011

Linac4 commissioning schedule



5 commissioning stages:
(on intermediate dumps)

3 MeV 10 MeV 50 MeV 100 MeV 160 MeV

Linac4 ready : April 2014

Baseline scenario: LINAC4 connection in LS2

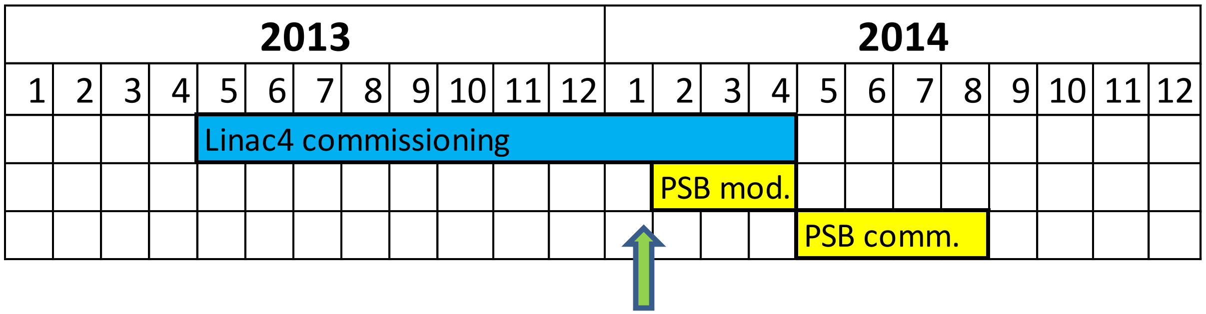
1. Keep Linac4 commissioning schedule (April 2014)
2. Schedule connection to the PSB only in LS2 → minimum risk; but need to operate in parallel Linac2 and Linac4 for some years;
3. In case of problems with Linac2, be ready from 2015 to an "emergency" connection of Linac4, with 2 possible options:

   a) with **H-** & full performance after 7-month shutdown;

   b) with **protons at 50 MeV** after a few days shutdown but with reduced PSB performance.

alternative LINAC4 connection scenarios for LS1 (NOT baseline)

A.

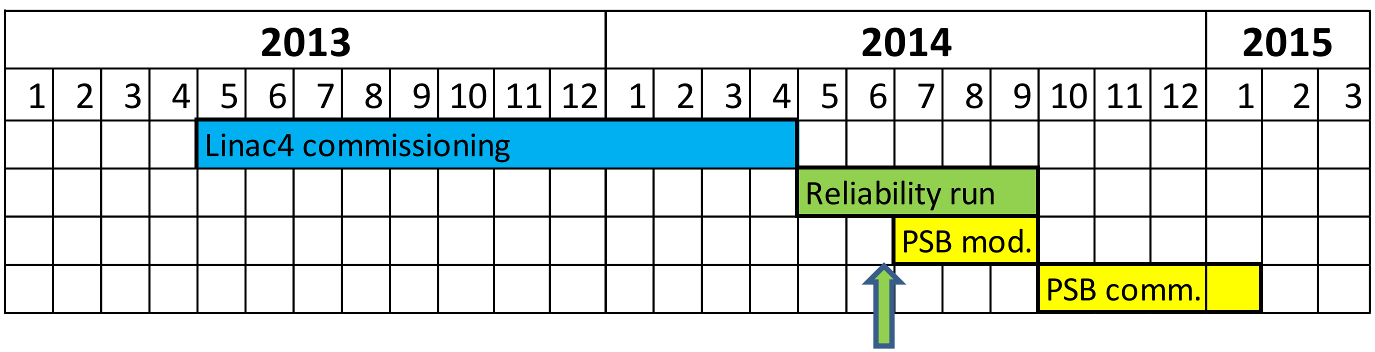


"green light" Jan. 2014, Linac4 commissioned only to 100 MeV

+ : *Linac4 + PSB available from 2015 (PSB performance + mitigate risk of Linac2 failure)*

- : a) *Risk of reliability/performance issues appearing in the last phase of commissioning*
b) *Injectors have to stop in 2014.*

B.



"green light" June 2015, Linac4 commissioned + 5 months reliability run

+ : *Linac4 + PSB available from 2015 (PSB performance + mitigate risk of Linac2 failure)*

- : a) *Start LHC only in 2015*
b) *Injectors have to stop in 2014.*

M. Vretenar, CERN MAC, August 2011

would there be any benefit for LHC from Linac4 alone?

- For 25 ns spacing it is very difficult to go beyond what is done today without RF & e-cloud improvements in the SPS & PSB energy upgrade (all planned in LS2)
- With 50 ns bunch spacing one might gain up to a factor of 2 in intensity at the SPS from LINAC4

potential 50-ns luminosity reach with LINAC4 (*my estimate*)

- $\gamma\varepsilon$ ~2.5 μm
- N_b ~2.5x10^{11}

E= 4 TeV, β^*~0.7 m:

L~1.6x10^{34} cm^{-2}s^{-1}, pile up ~74

E = 6.5 TeV, β^*~0.45 m :

L~3.7x10^{34} cm^{-2}s^{-1}, pile up ~170

a few conclusions

- in 2012 may expect addtitonal 10/fb at 4 TeV with ~36 maximum pile up at 50 ns spacing
- from 2014 run with 25 ns spacing at 6.5 TeV
- by 2017 may have ~150/fb and by 2021 ~400/fb with maximum pile up <50
- early connection of LINAC4 might (only) help for 50-ns operation, but could then give highest luminosity & with high maximum pile up (70-170)
- maximum luminosity is determined by acceptable pile up (no head-on beam-beam limit!)
- leveling could also be applied for CMS to limit the pile up
- enhanced satellites would give low & high pile up events
- LHC will exceed design luminosity; 2021: time for HL-LHC

thank you for your attention