LHC Machine Status & Plans

Frank Zimmermann

ATLAS week 20 June 2011

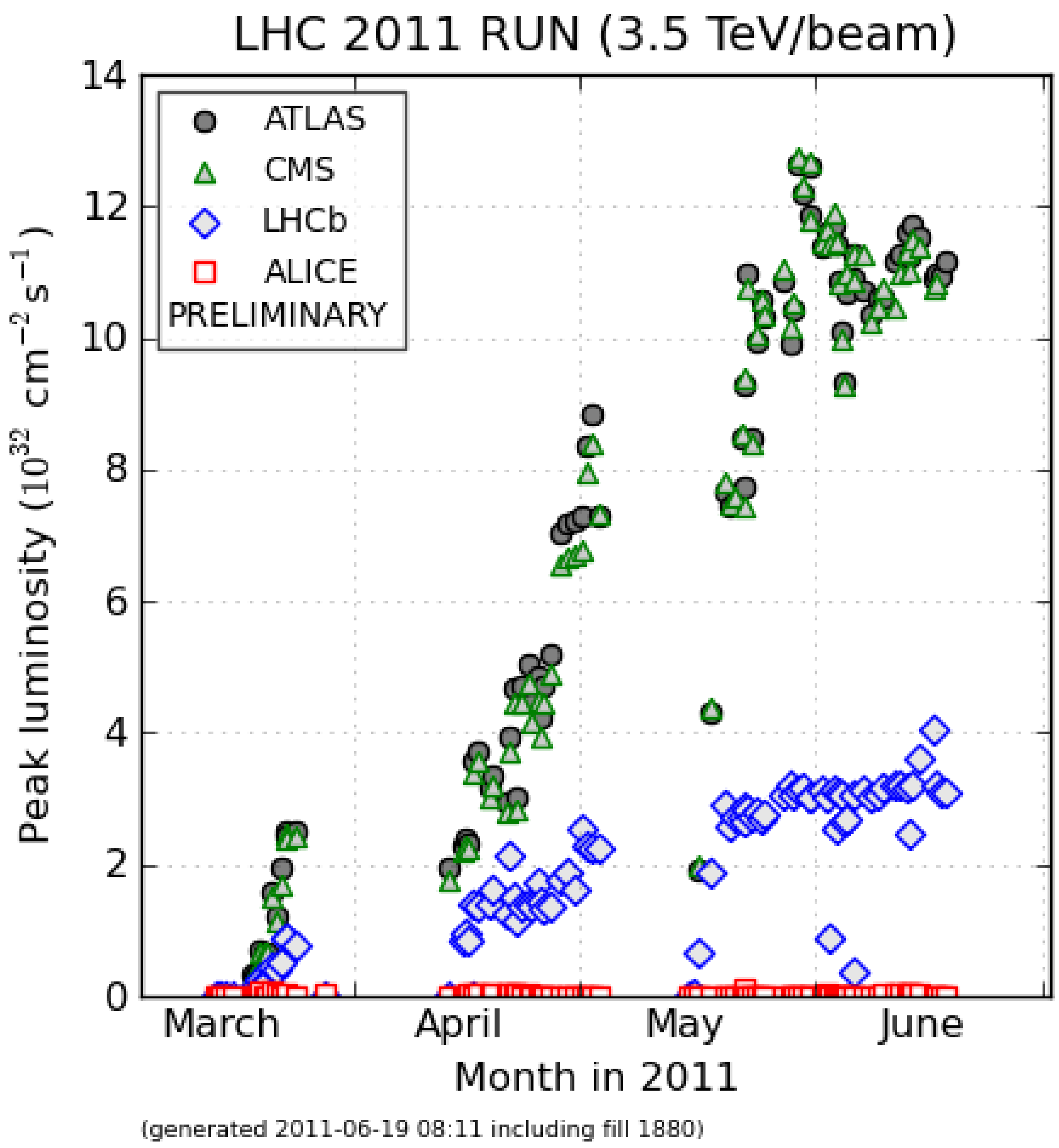
Many thanks to

Ralph Assmann, Hannes Bartosik, Oliver Brüning, Massimiliano Ferro-Luzzi, Klaus Hanke, Humberto Maury, Yannis Papaphilippou, Benoit Salvant, Rende Steerenberg

contents

- status of CERN machines for LHC
- recent LHC and injector MD results
- LHC plans for next months
- LHC plans for next years
- shutdowns
- HL-LHC & LIU projects
- beyond HL-LHC

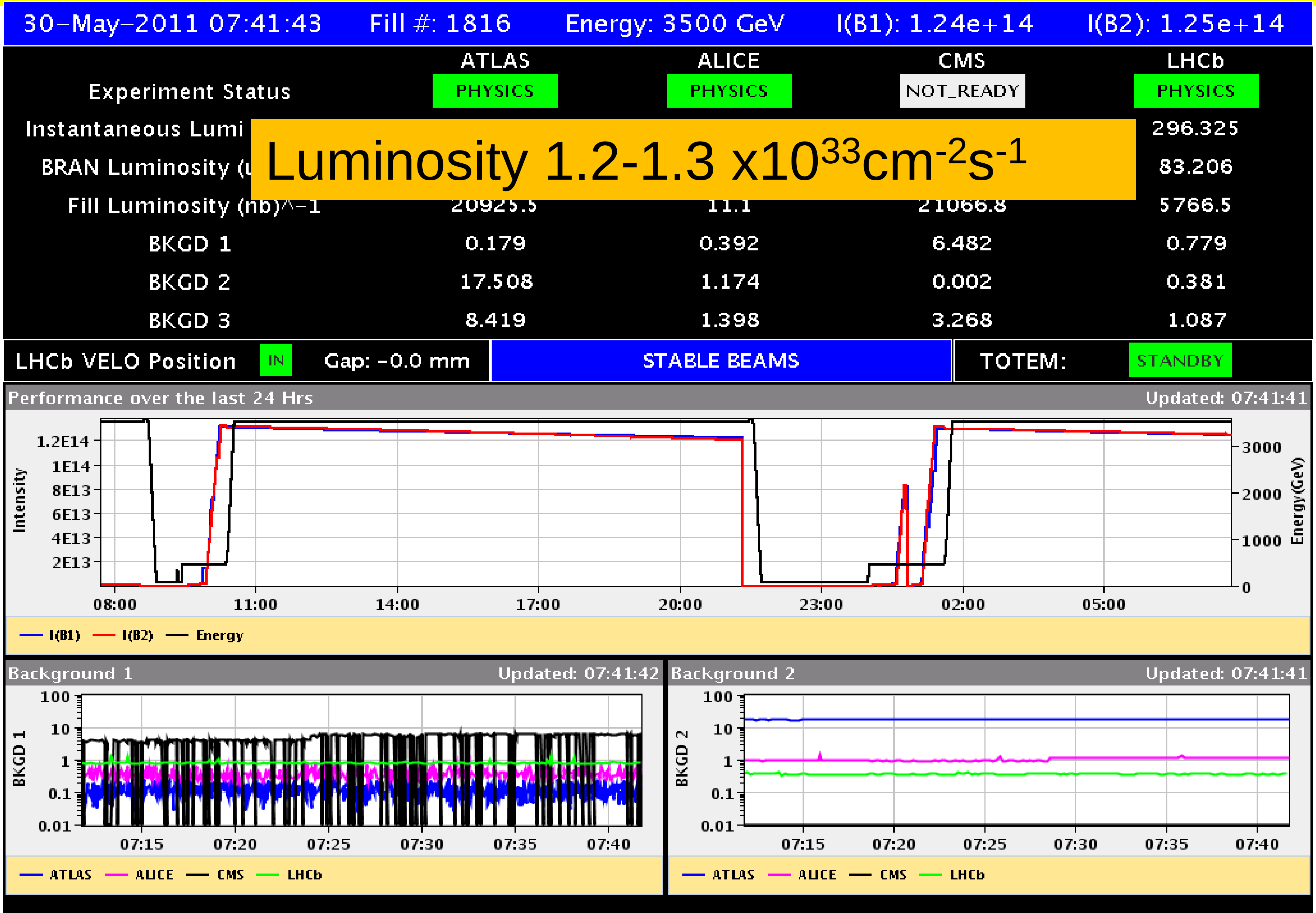
Peak Luminosity



Past Peak Performances

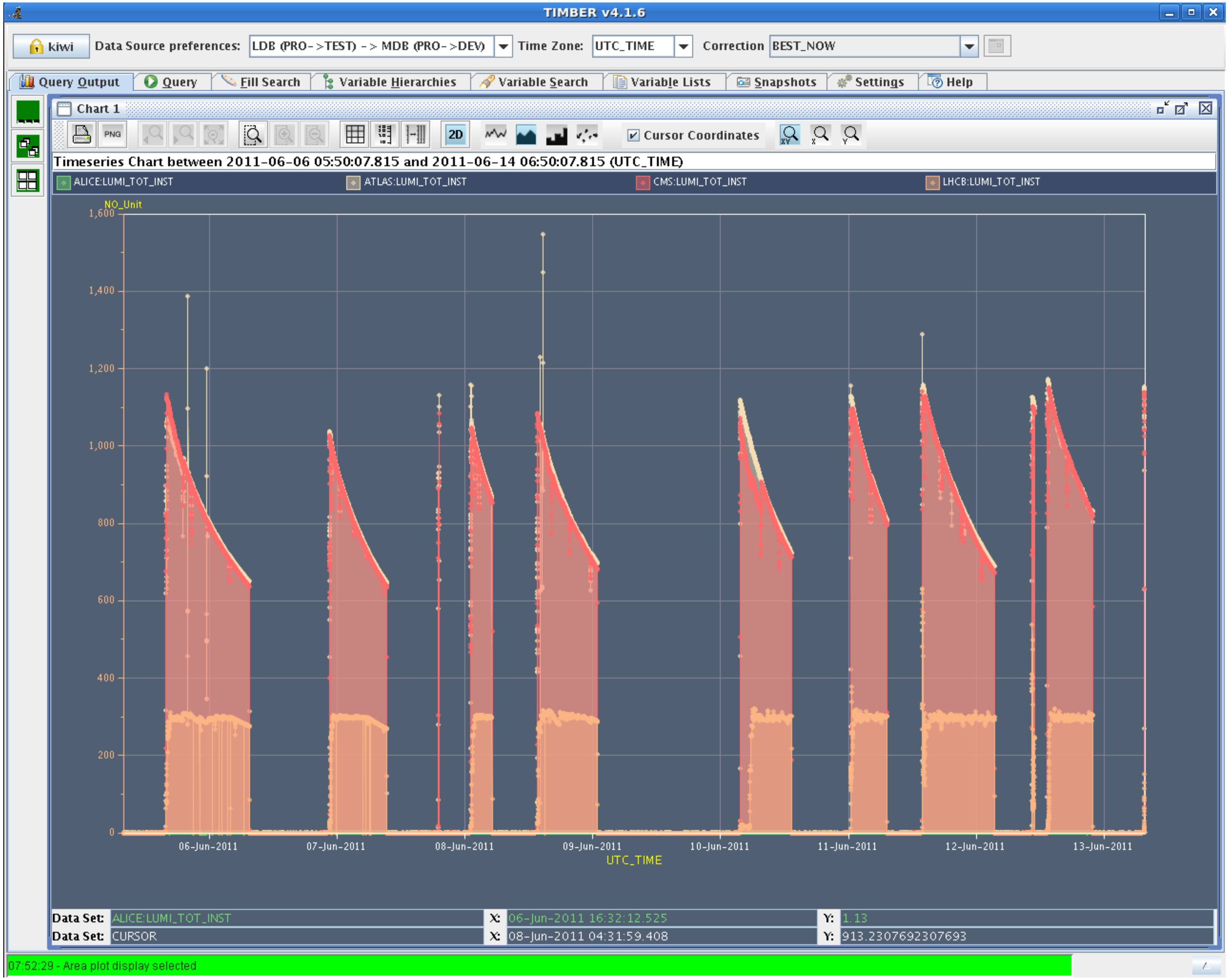
Peak Performances					
Fill Number	Date	Bunch Spacing	Number of Bunches	Peak Luminosity ($10^{33} cm^{-2} s^{-}$	Total Number of protons per beam (10^{14})
1635	18 March 2011	75	32	0.030	0.038
1637	19 March 2011	75	64	0.064	0.074
1644	22 March 2011	75	136	0.167	0.164
1645	22 March 2011	75	200	0.252	0.243
1712	15 April 2011	50	228	0.237	0.285
1716	16 April 2011	50	336	0.353	0.423
1739	26 April 2011	50	480	0.514	0.579
1749	30 April 2011	50	624	0.716	0.756
1755	02 May 2011	50	768	0.826	0.925
1809	27 May 2011	50	912	1.099	1.150
1815	29 May 2011	50	1092	1.268	1.330

back to back fills with 1092 bunches

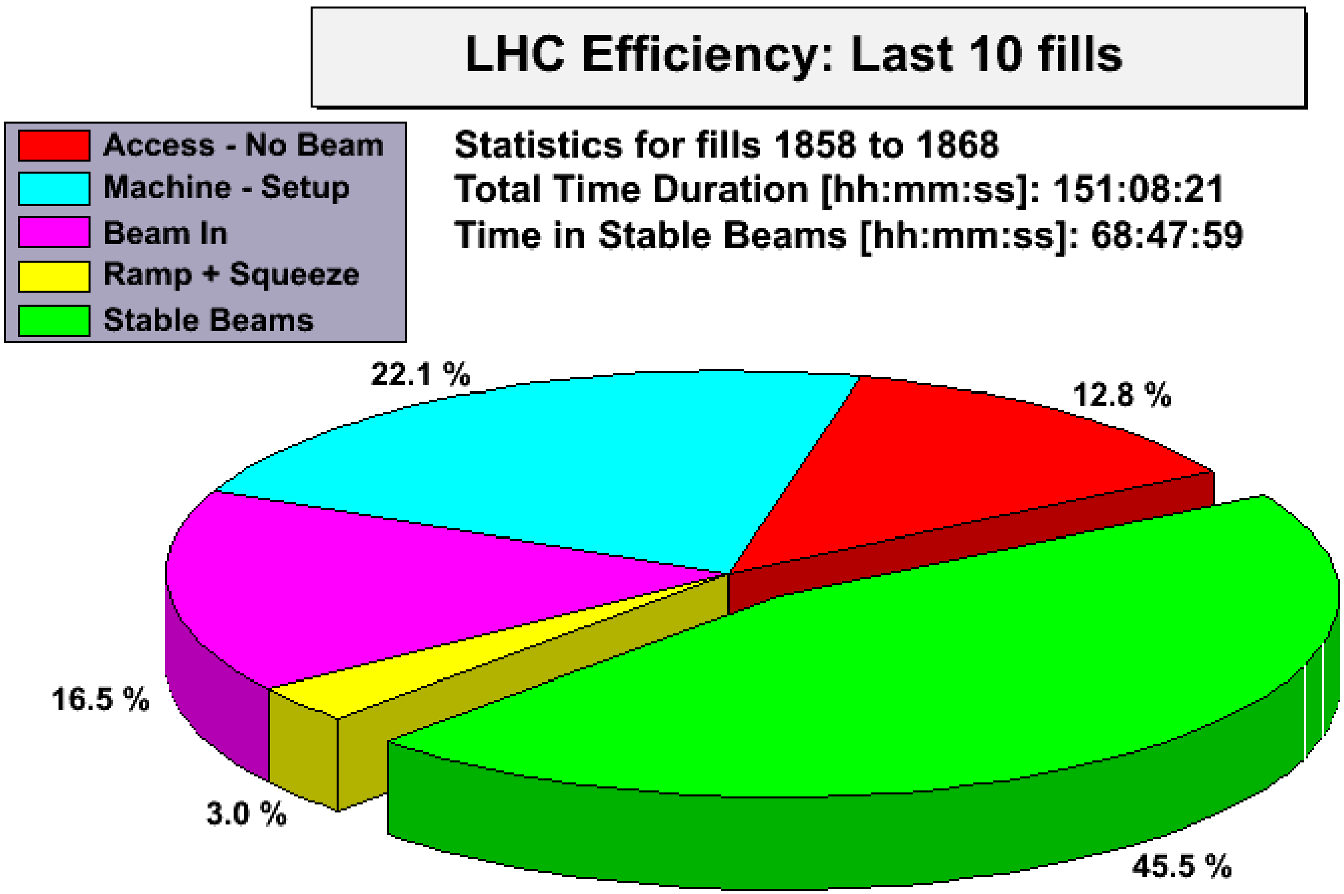


Luminosity 1.2-1.3 x10^{33}cm^{-2}s^{-1}

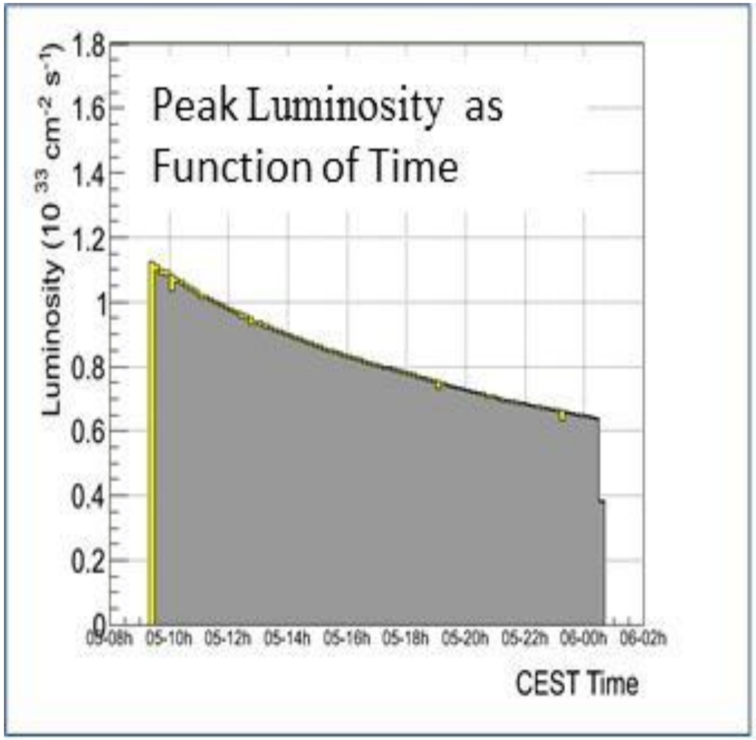
recent LHC week

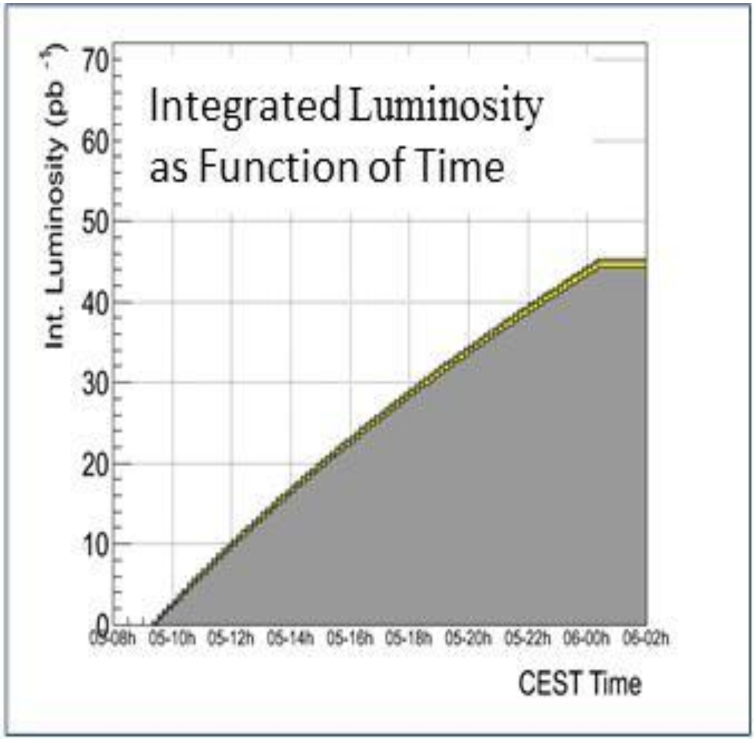


recent LHC 10-fill statistics

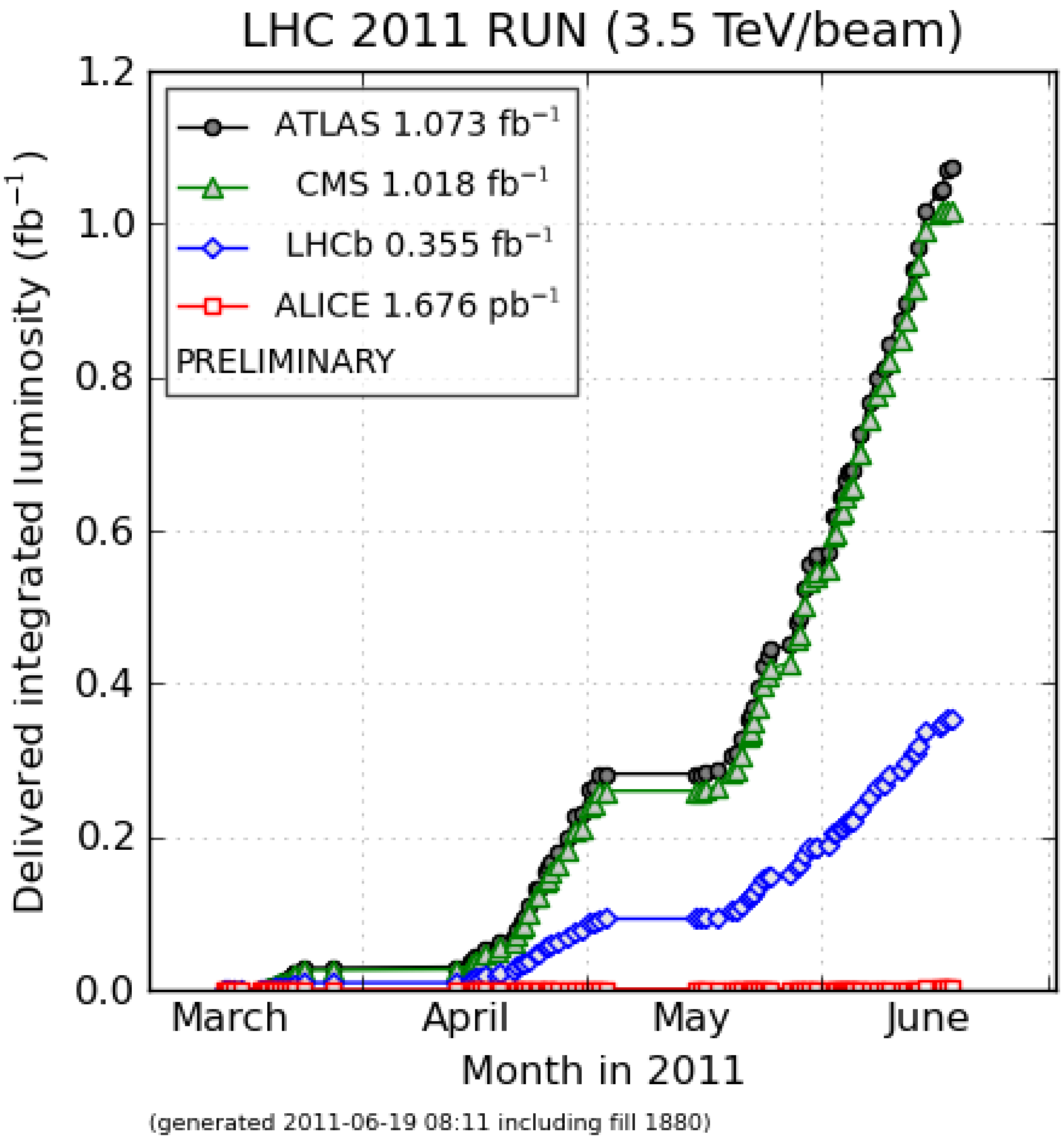


Best Fill as of June14





integrated luminosity



Records

Peak Stable Luminosity	1.26×10^{33}	Fill 1815	11/05/29, 06:41
Max. Luminosity / fill	46.93 pb^{-1}	Fill 1868	11/06/13, 20:00
Max. Luminosity / day	56.33 pb^{-1}	Sunday 12 June, 2011	
Max. Luminosity / 7 days	239.42 pb^{-1}	Wednesday 08 June, 2011 - Tuesday 14 June, 2011	
Max. Colliding Bunches	1042	Fill 1815	11/05/29, 06:41
Max. Peak Events / Bunch Crossing	14.01	Fill 1732	11/04/23, 05:47
Max. Average Events / Bunch Crossing	8.93	Fill 1644	11/03/22, 02:20
Longest Stable Beams / fill	17.9 hours	Fill 1732	11/04/23, 10:25
Longest Stable Beams / day	19.7 hours (82.1%)	Sunday 27 March, 2011	
Longest Stable Beams / 7 days	93.0 hours (55.4%)	Thursday 21 April, 2011 - Wednesday 27 April, 2011	
Fastest Turnaround to Stable Beams	2.4 hours	Fill 1718	11/04/16, 22:56

It is not always easy! A day in June

Cryo S56

Injection preparation for 144b

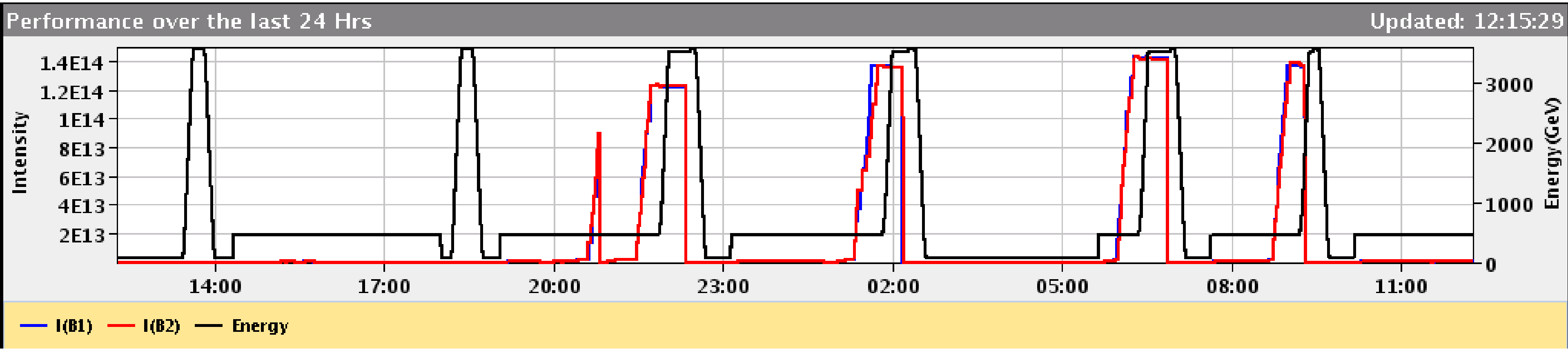
Cryo S34

UFO IR2

QPS noise → quench

RF arc

Collimator temperature



R. Assmann, S. Myers

LHC actual versus design parameters

	design	present	comment
Beam energy	7 TeV	**3.5 TeV**	½ design
transv. norm. emittance	3.75 μm	**2.9 μm**	¾ design!
beta*	0.55 m	1.5 m	3x design
IP beam size	16.7 μm	34 μm	2x design
bunch intensity	1.15×10^{11}	**1.25×10^{11}**	higher than design
luminosity / bunch	3.6×10^{30} $cm^{-2}s^{-1}$	1.1×10^{30} $cm^{-2}s^{-1}$	only factor 3 away (x4 from energy!)
# bunches	2808	1092	approaching ½ design
bunch spacing	25 ns	**50 ns**	
beam current	0.582 A	0.236 A	close to ½ design
rms bunch length	7.55 cm	≥8.7 cm	
crossing angle	285 μrad	240 μrad	
"Piwinski angle"	0.64	≥0.31	
luminosity	10^{34} $cm^{-2}s^{-1}$	1.2×10^{33} $cm^{-2}s^{-1}$	>10% design

luminosity potential of present LHC

how to go further? $$L = \frac{f_{rev} n_b N_b^2}{4\pi\beta^* \varepsilon} \frac{1}{\sqrt{1+\phi_{piw}^2}}$$ $$\phi_{piw} \equiv \frac{\sigma_z \theta_c}{2\sigma_{x,y}^*}$$

50 ns spacing:

n_b: 1092 → 1380, N_b: 1.2x10^{11}→1.7x10^{11} (double batch inj.)

β*: 1.5 →1.0 m

total gain ~ factor 4 → **5x10^{33} cm^{-2}s^{-1} at 3.5 TeV**

25 ns spacing (e- cloud in SPS & LHC!?):

n_b: 1092 → 2808, N_b: 1.2x10^{11}

β*: 1.5 →1.0 m, γε: 3 μm → 4 μm

total gain ~ factor 3 → **4x10^{33} cm^{-2}s^{-1} at 3.5 TeV**

another factor 4 from going to ~7 TeV (&β*~0.5 m)

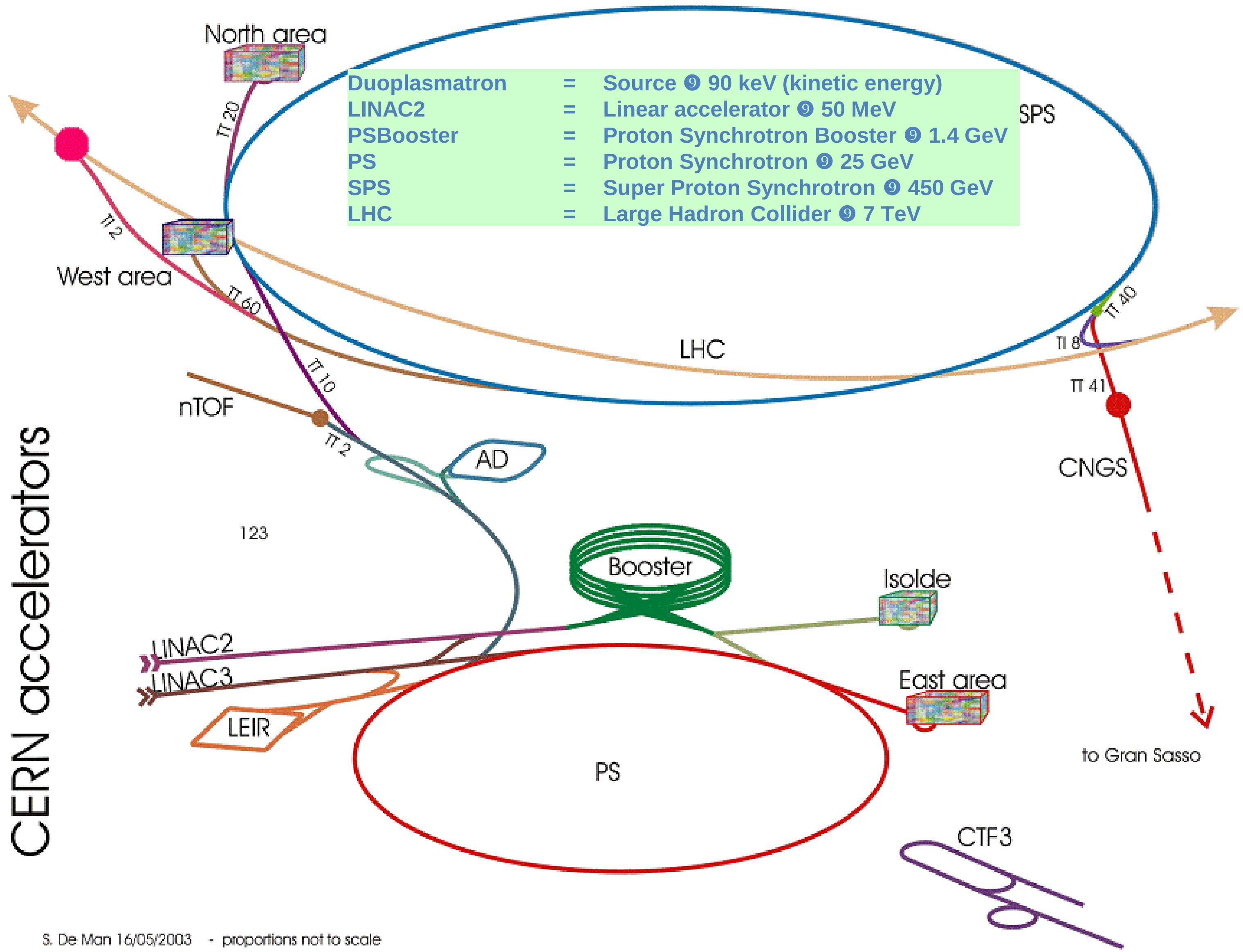
2x10^{34} cm^{-2}s^{-1} at ~7 TeV does not appear impossible

some possible concerns

- radiation to electronics – SEU’s
- UFOs
- longitudinal instability: “dancing bunches”
- electron cloud at 25 ns
- long-range beam-beam effects
- emittance growth in physics (all IBS?)
- …

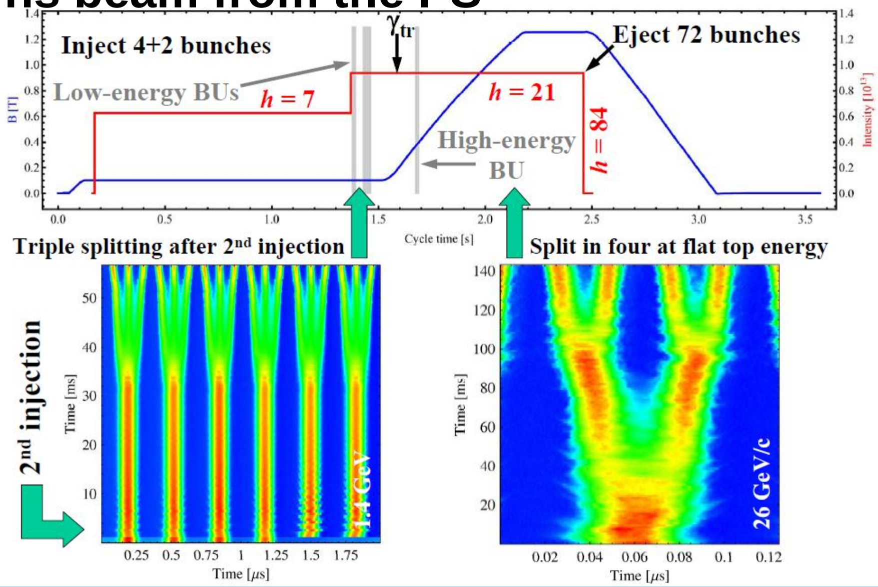
LHC injector complex

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



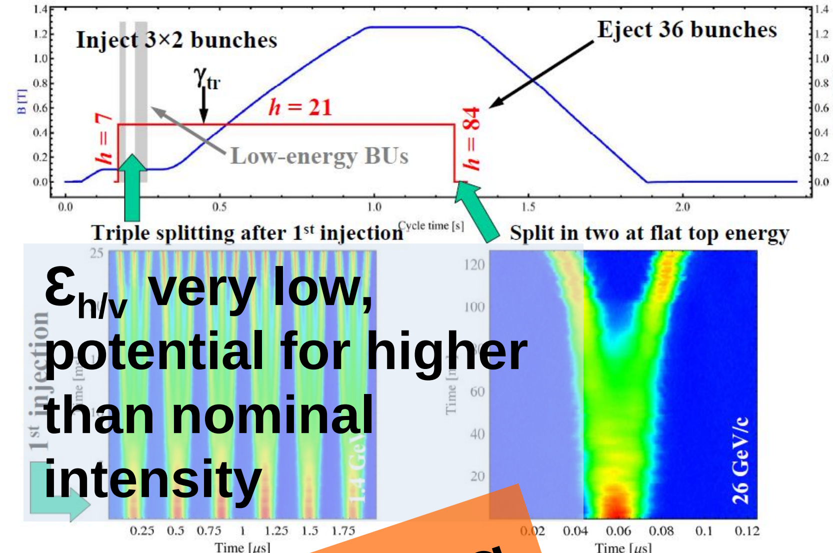
3 LHC *p* beams from the CERN PS

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



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

Rende Steerenberg Chamonix 2011

machine experiments ongoing

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 (now) → LHC 50 DB (lower emittance) or LHC25 DB (more bunches)

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

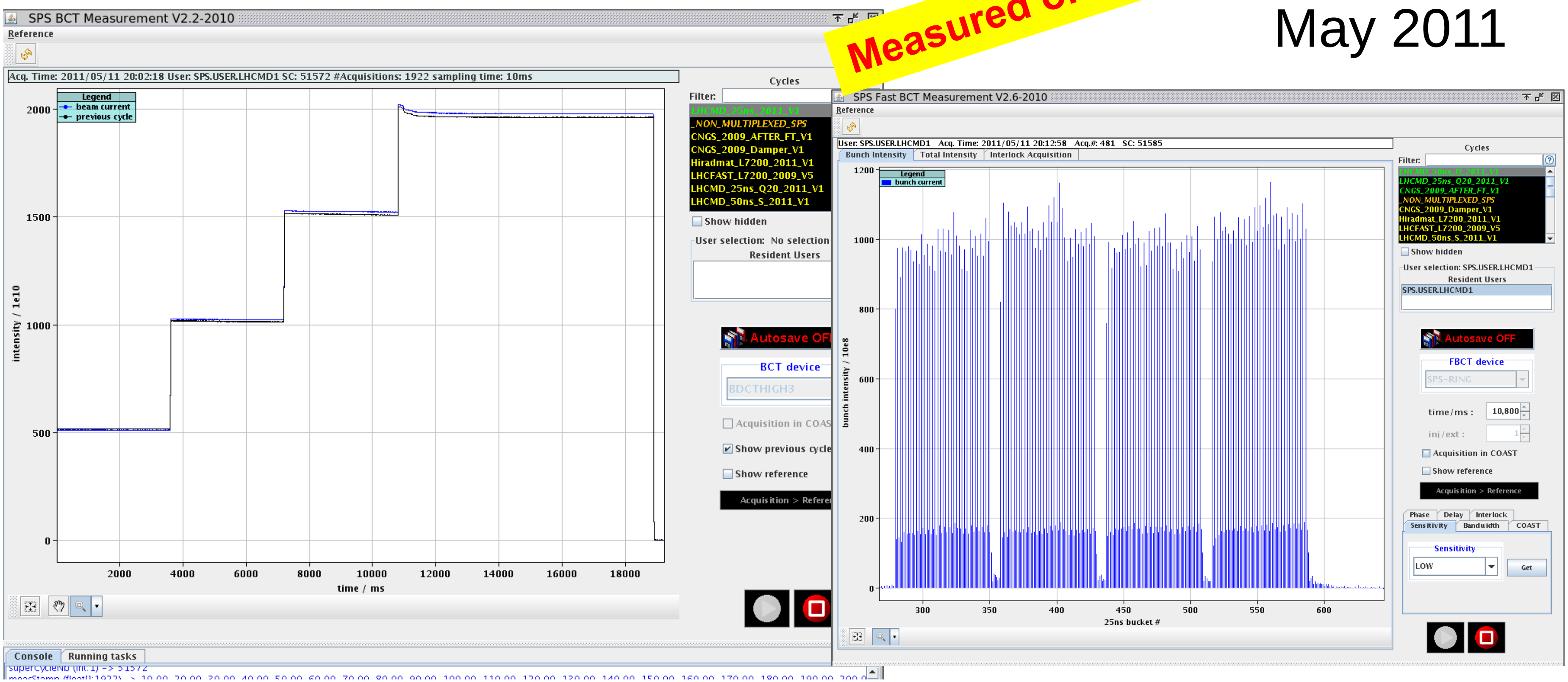
SPS: 50ns bunch train – Double PSB batch

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

- 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)

Measured on 1st batch – to be confirmed

May 2011



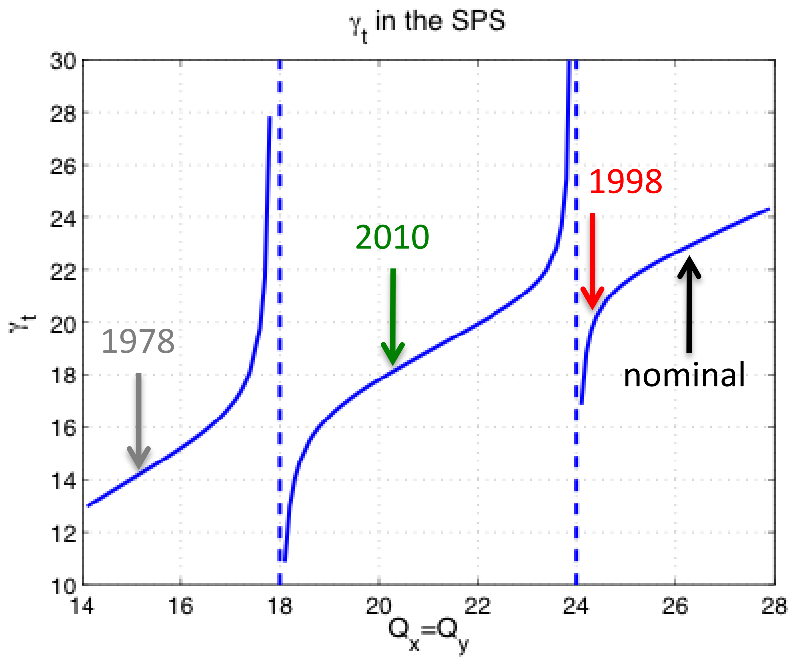
new optics for SPS (low γ_t or "Q20")

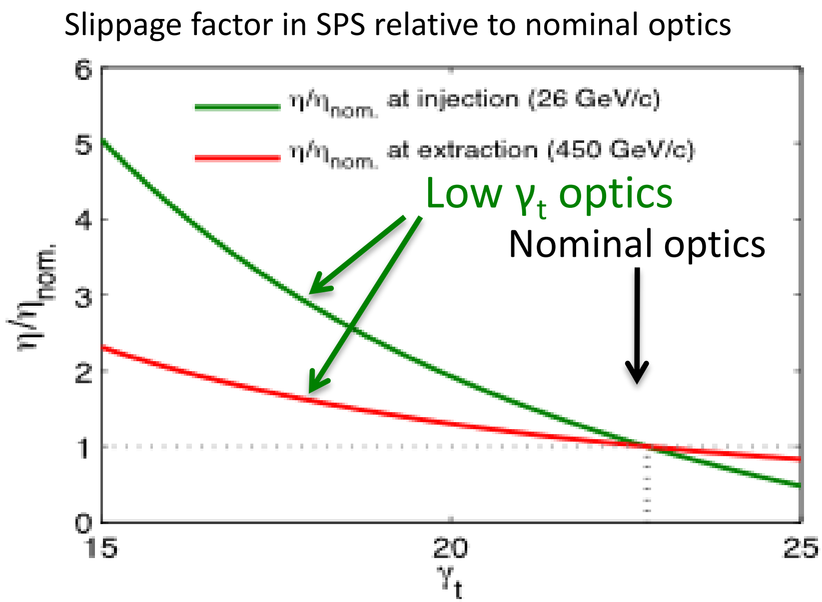
H. Bartosik, Y. Papaphilippou

- 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

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

- 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)

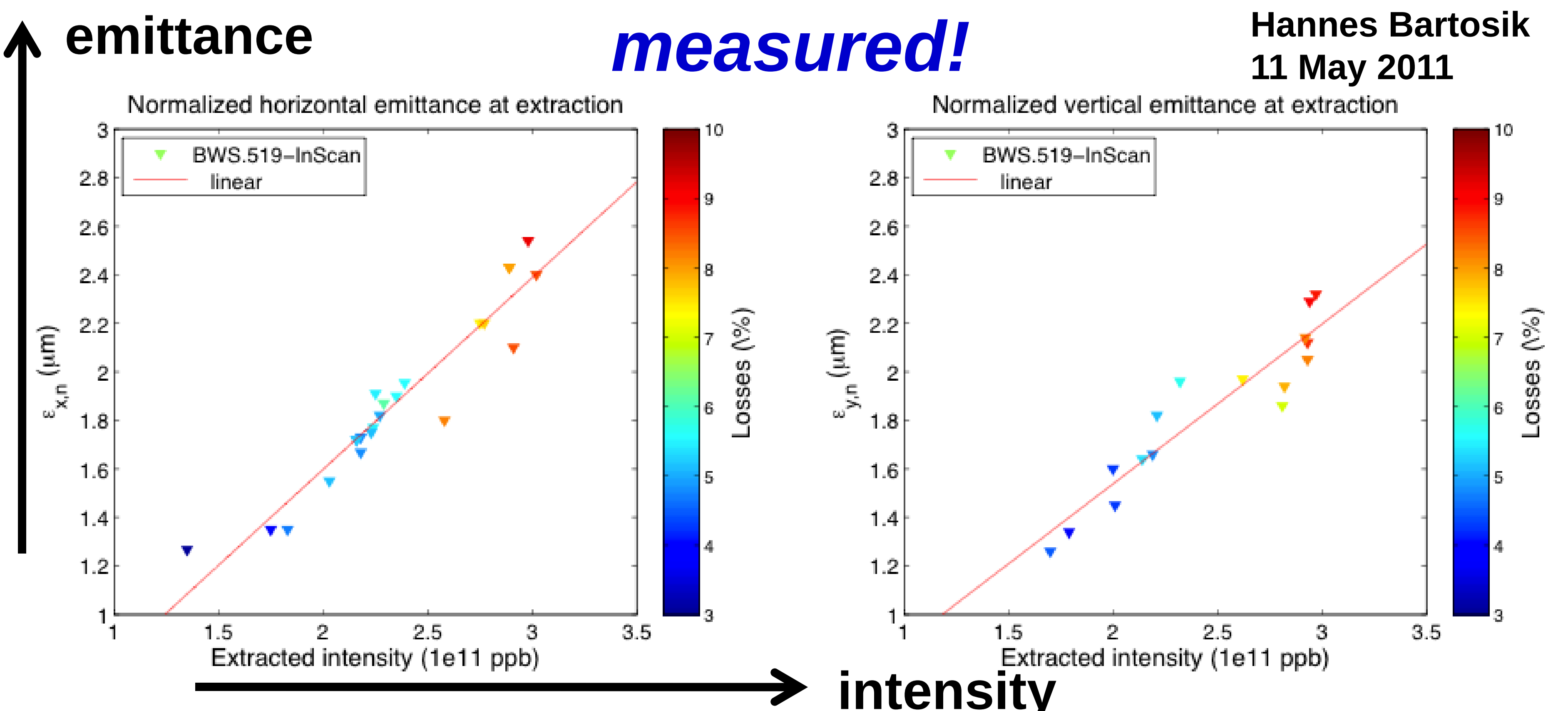
chromaticity Q’/Q	0.0	0.07
old Q26 optics	$1.7\text{x}10^{11}$	$2.2\ \text{x}10^{11}$
new Q20 optics	$2.8\text{x}10^{11}$	$3.8\ \text{x}10^{11}$

>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 γε~2.5 μm (2/3 LHC design!)**



LHC: days for physics in 2011

Phase	Days	Comment
Commissioning	21	
Scrubbing run	10	
5 MDs	22	4.5 days per slot
6 Technical stops	30	5 days (4 days TS plus 1 day recovery with beam)
Special requests	10	TOTEM/ALPHA Intermediate energy run Luminosity scans
Intensity ramp up	~39	
Total high intensity	**~130**	
Ion setup	4	
Ion physics	24	
TOTAL	**290**	

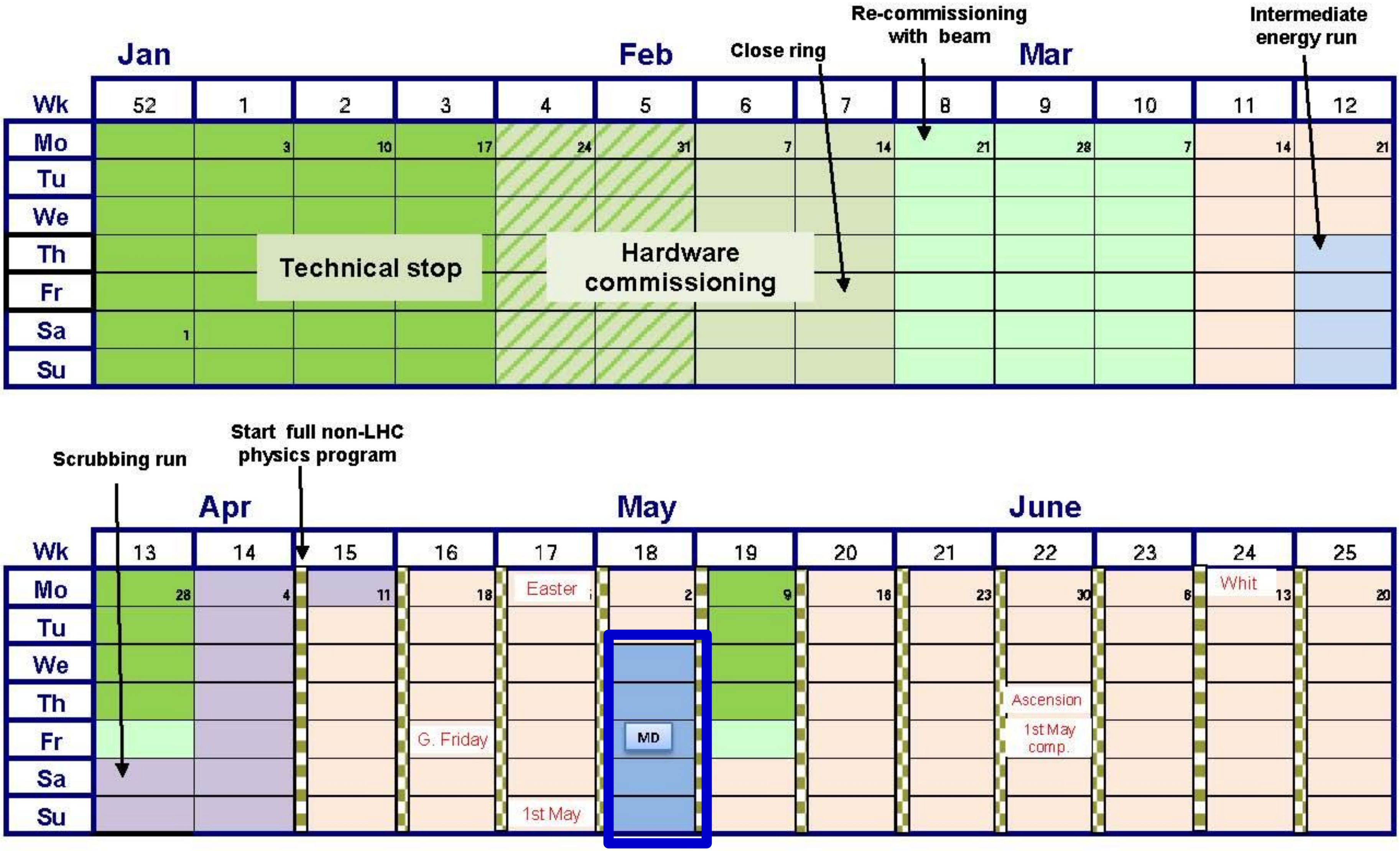
M. Lamont March 2011

ML

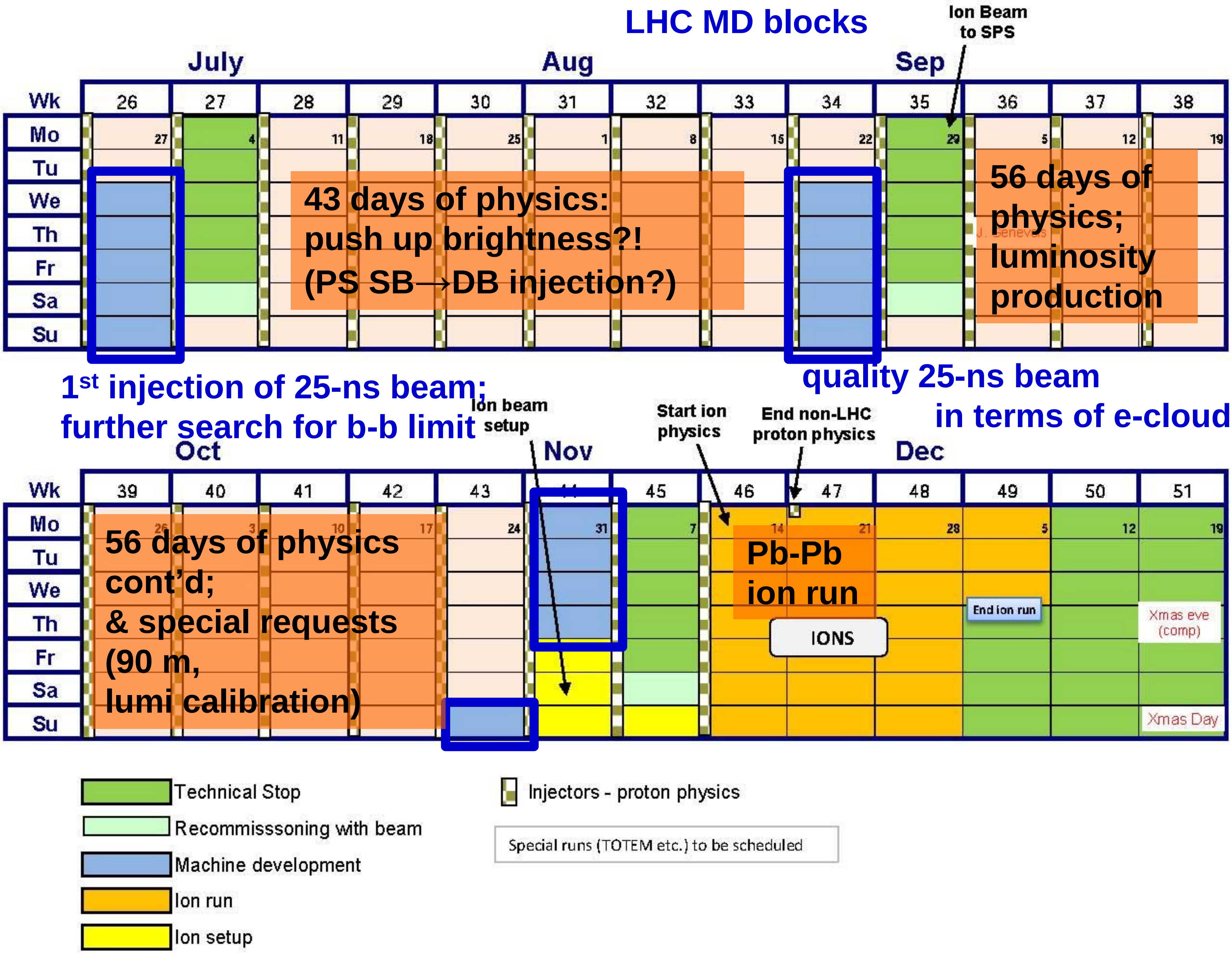
26/5/2011
V3.0

2011 LHC Schedule

Approved by the Research Board, December 2010



1st LHC MD block; bb studies, ATS optics,…



LHC MD blocks
Ion Beam to SPS
July
Aug
Sep
Wk
26
27
28
29
30
31
32
33
34
35
36
37
38
Mo
Tu
We
Th
Fr
Sa
Su
43 days of physics:
push up brightness?!
(PS SB→DB injection?)
56 days of physics;
luminosity production
1st injection of 25-ns beam;
further search for b-b limit
quality 25-ns beam
in terms of e-cloud
Ion beam setup
Start ion physics
End non-LHC proton physics
Oct
Nov
Dec
39
40
41
42
43
44
45
46
47
48
49
50
51
56 days of physics cont'd;
& special requests
(90 m,
lumi calibration)
Pb-Pb ion run
IONS
End ion run
Xmas eve (comp)
Xmas Day
Technical Stop
Recommisssoning with beam
Machine development
Ion run
Ion setup
Injectors - proton physics
Special runs (TOTEM etc.) to be scheduled

several **“special” runs already done**:

- **1.38 TeV run** (ALICE request),
- **VdM fills** at 3.5 TeV (ATLAS),
- **90 m MD** (ALFA/TOTEM),
- **RP TOTEM-220 m & ALFA setting-up for squeezed physics**

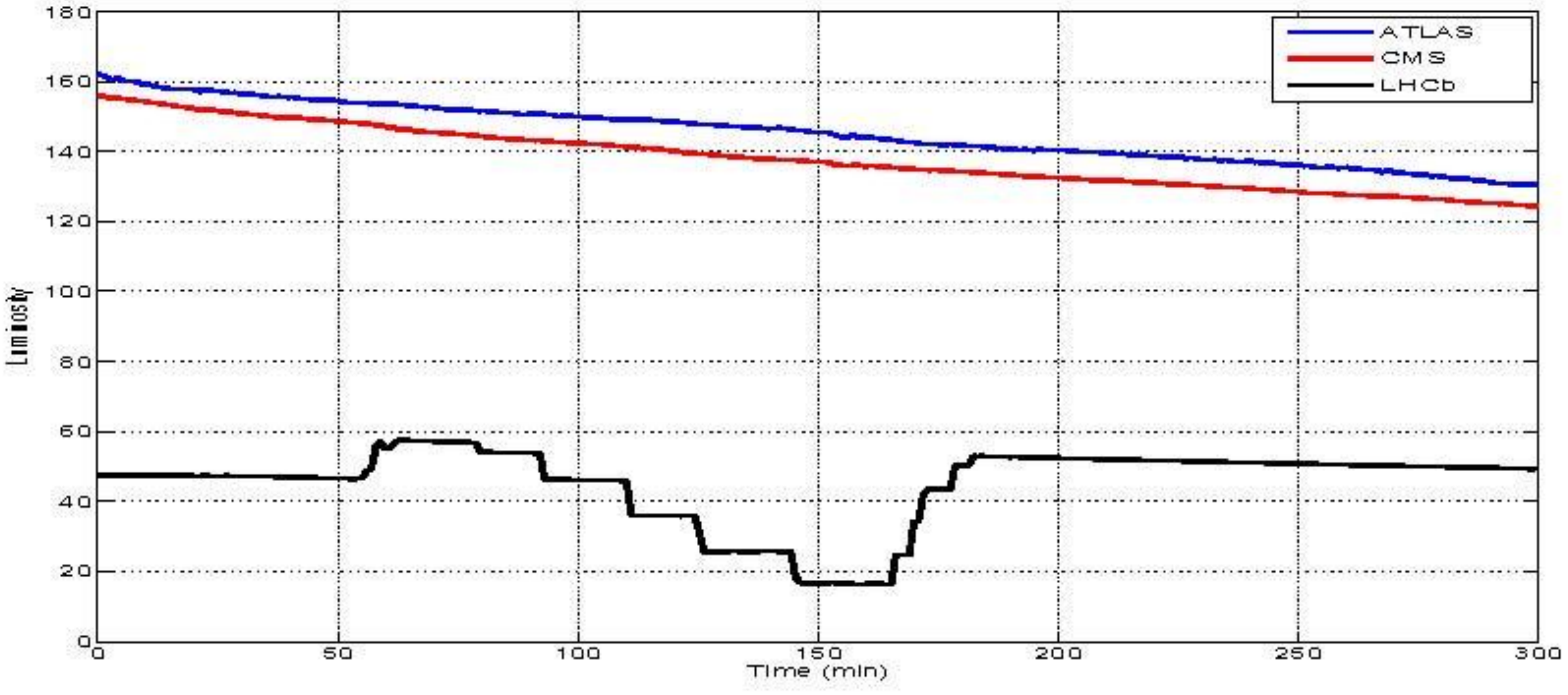
still on the **wish list (for September):**

- **90 m physics** (several short fills)
- **ultimate luminosity calibration**

regular polarity reversals for LHCb (every 1-2 months) and ALICE (less transparent)

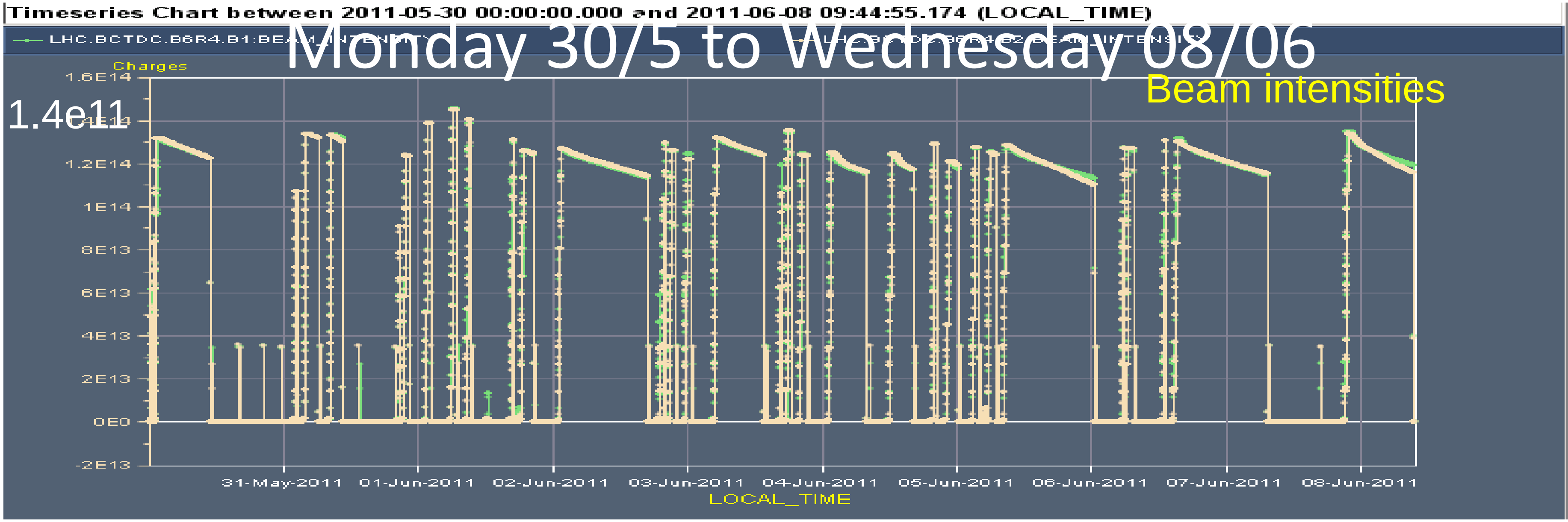
offset leveling test

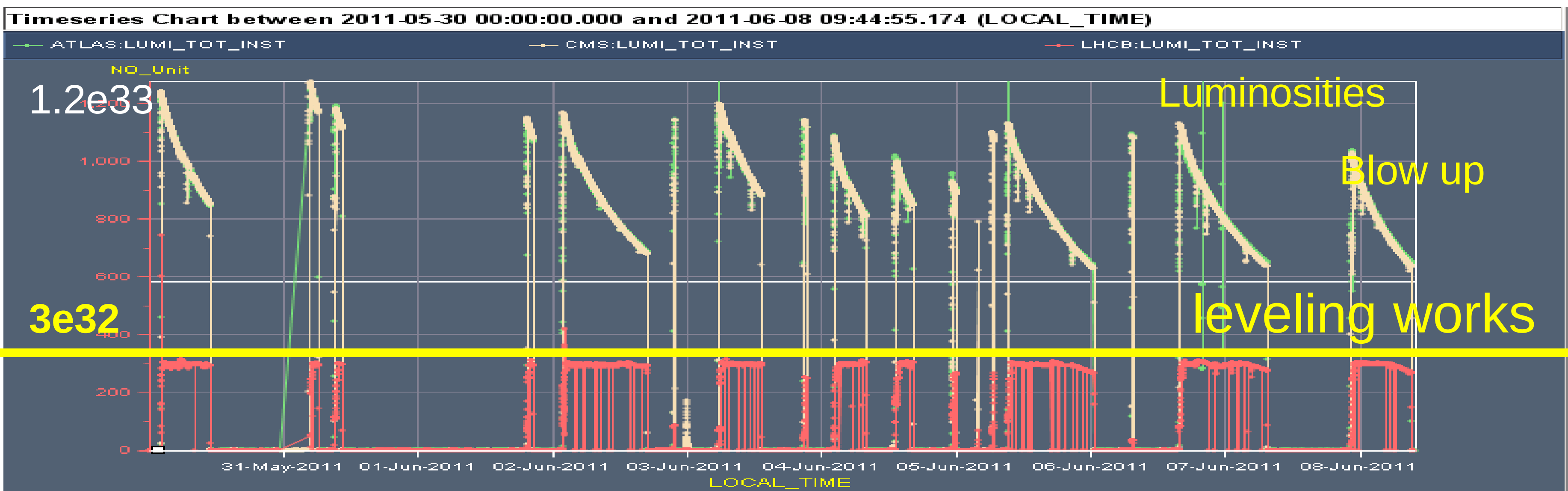
W. Herr et al,
March 2011



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)

routine leveling in IP2 & 8!

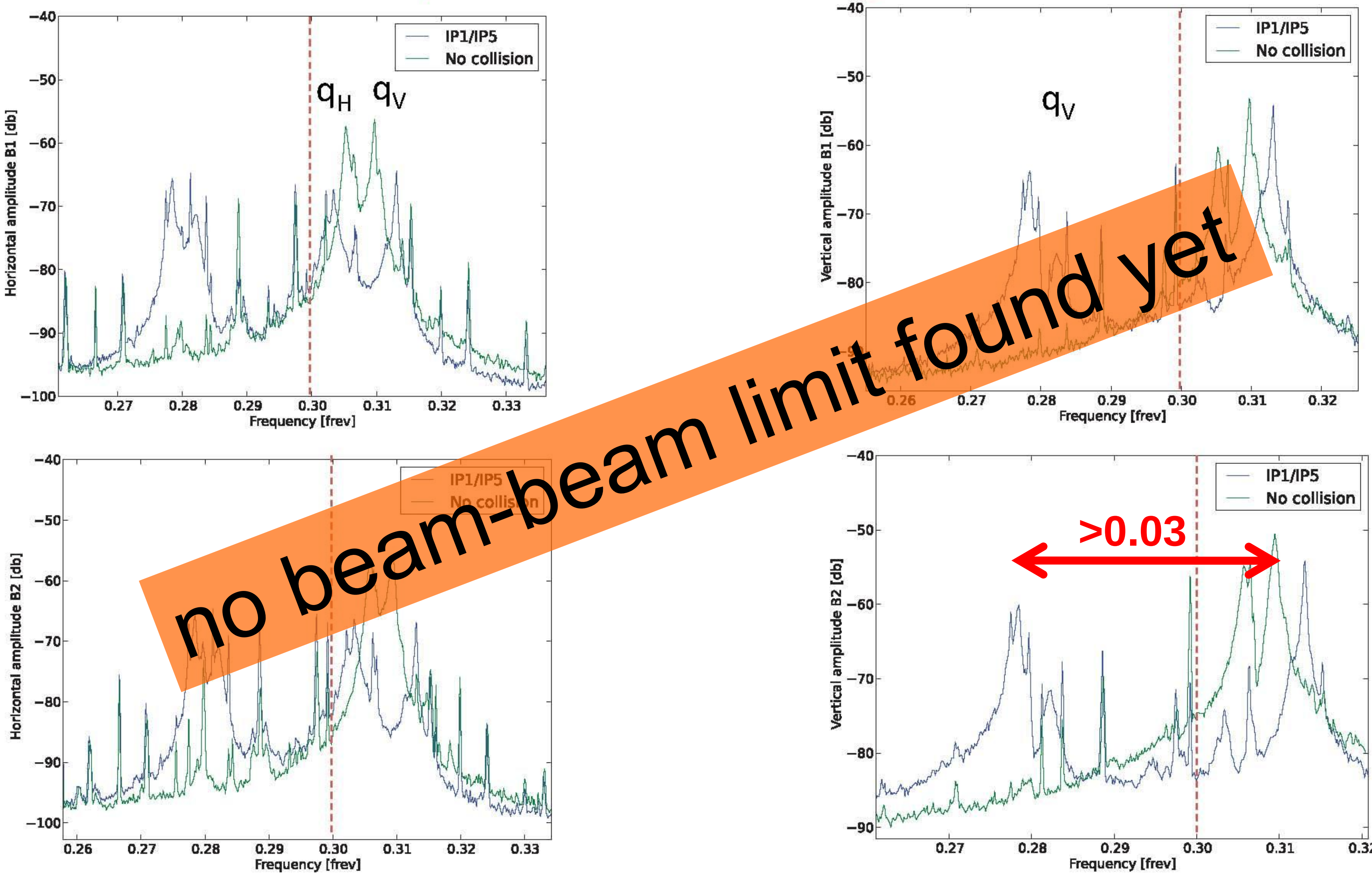




Wk 3

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

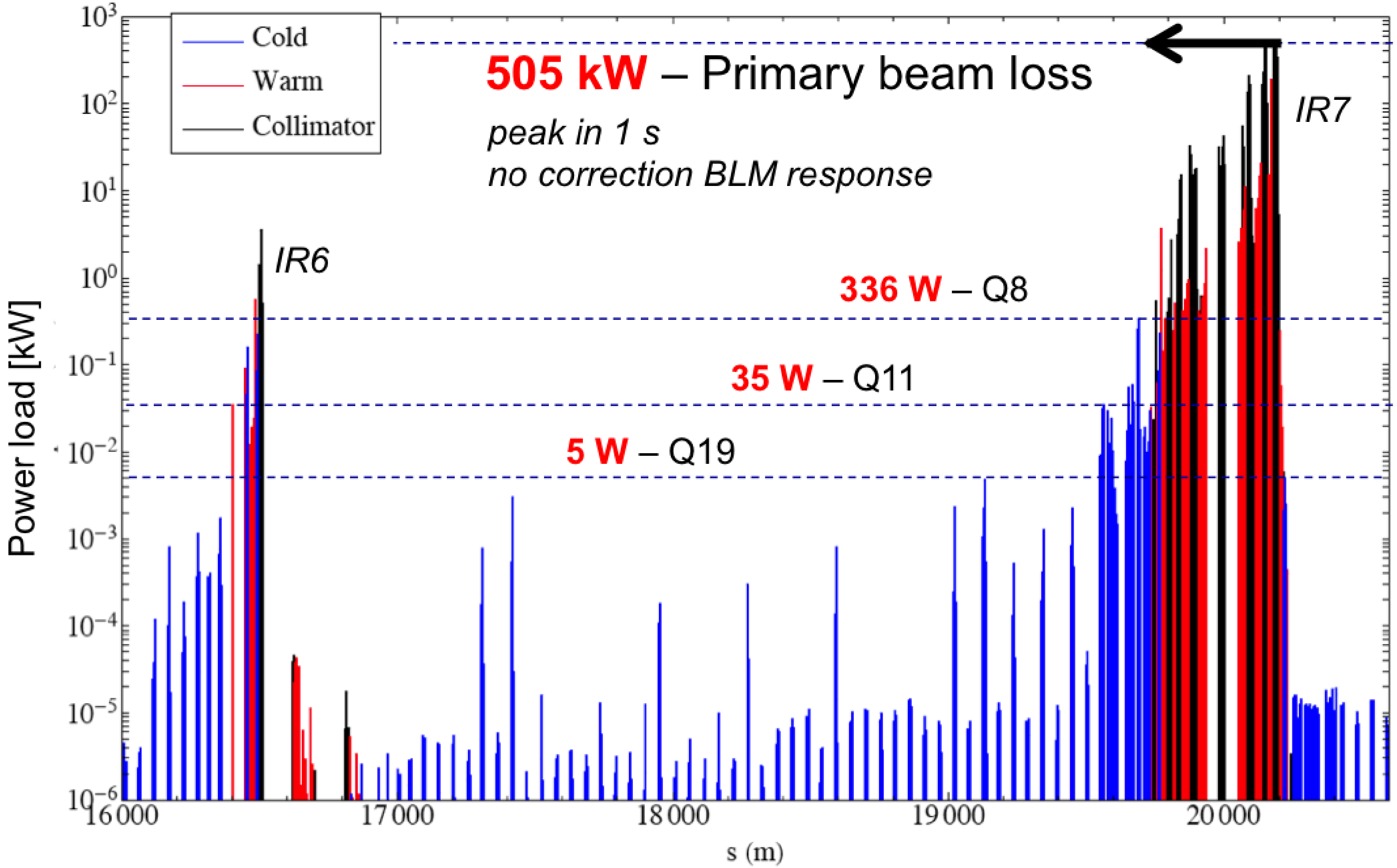
tune spectra colliding IP1 & IP5



beam parameters investigated **beyond nominal LHC (N_b = 1.8-1.95x10^{11}, ε =1.2-1.4 μm);** 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*****!**

collimation MD#1 May 2011

intentional large loss on primary collimator to see margins



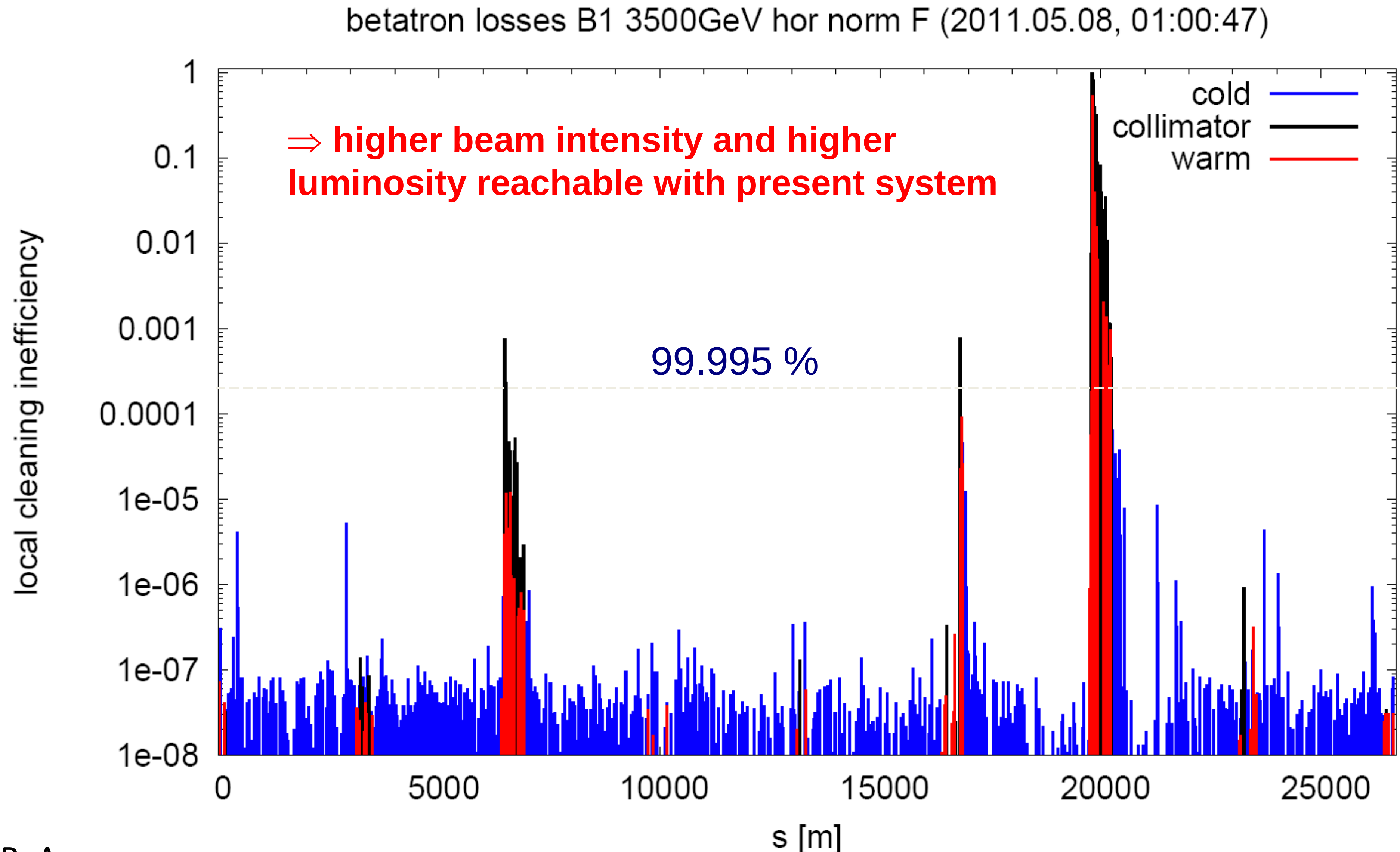
3.5 TeV operational collimator settings (not best possible)

No quench of any magnet!

R. Assmann

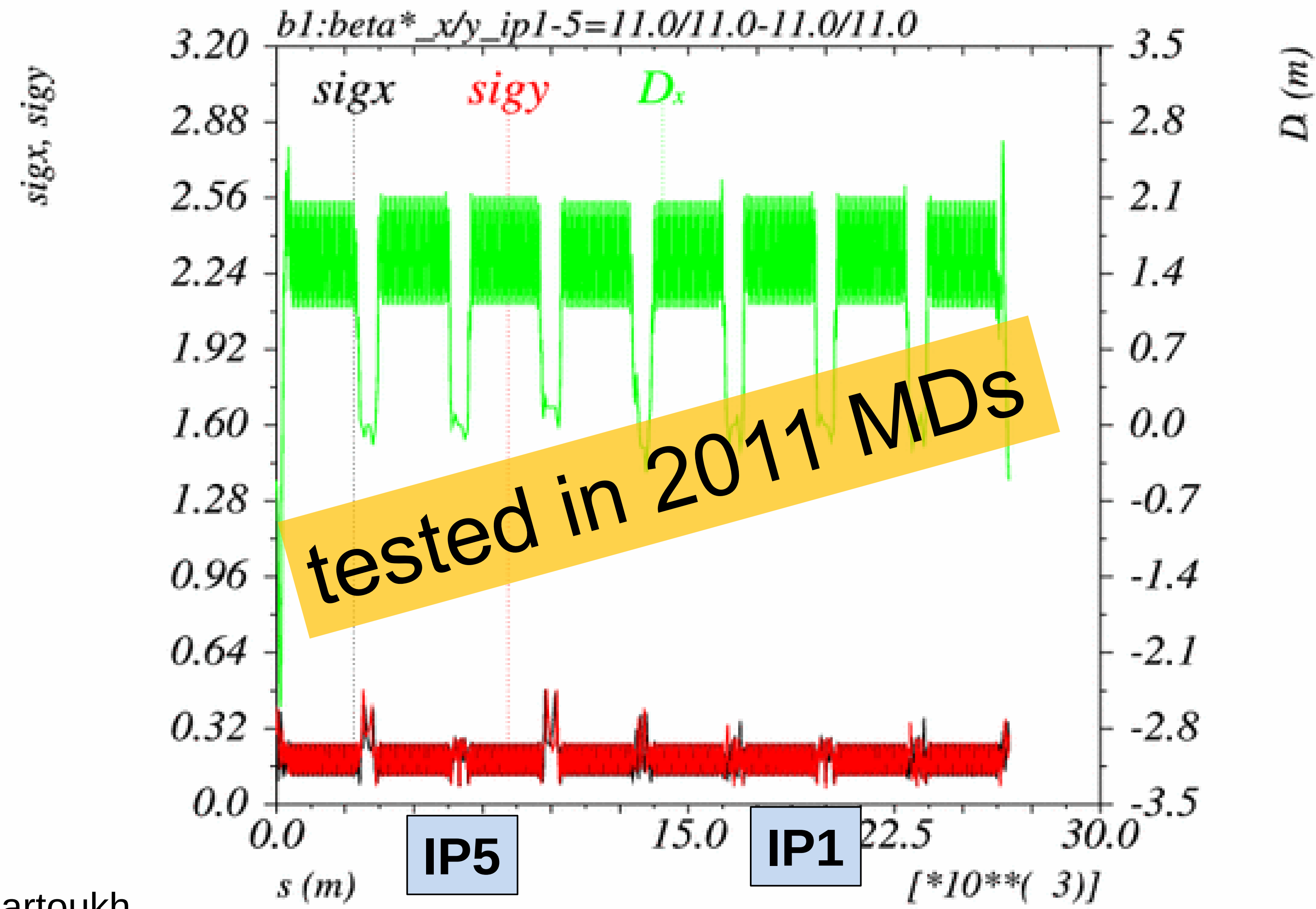
collimation MD#2 May 2011

cleaning efficiency with tighter collimator settings



R. Assmann

LHC “ATS” optics: squeezing IP1 to 10 cm

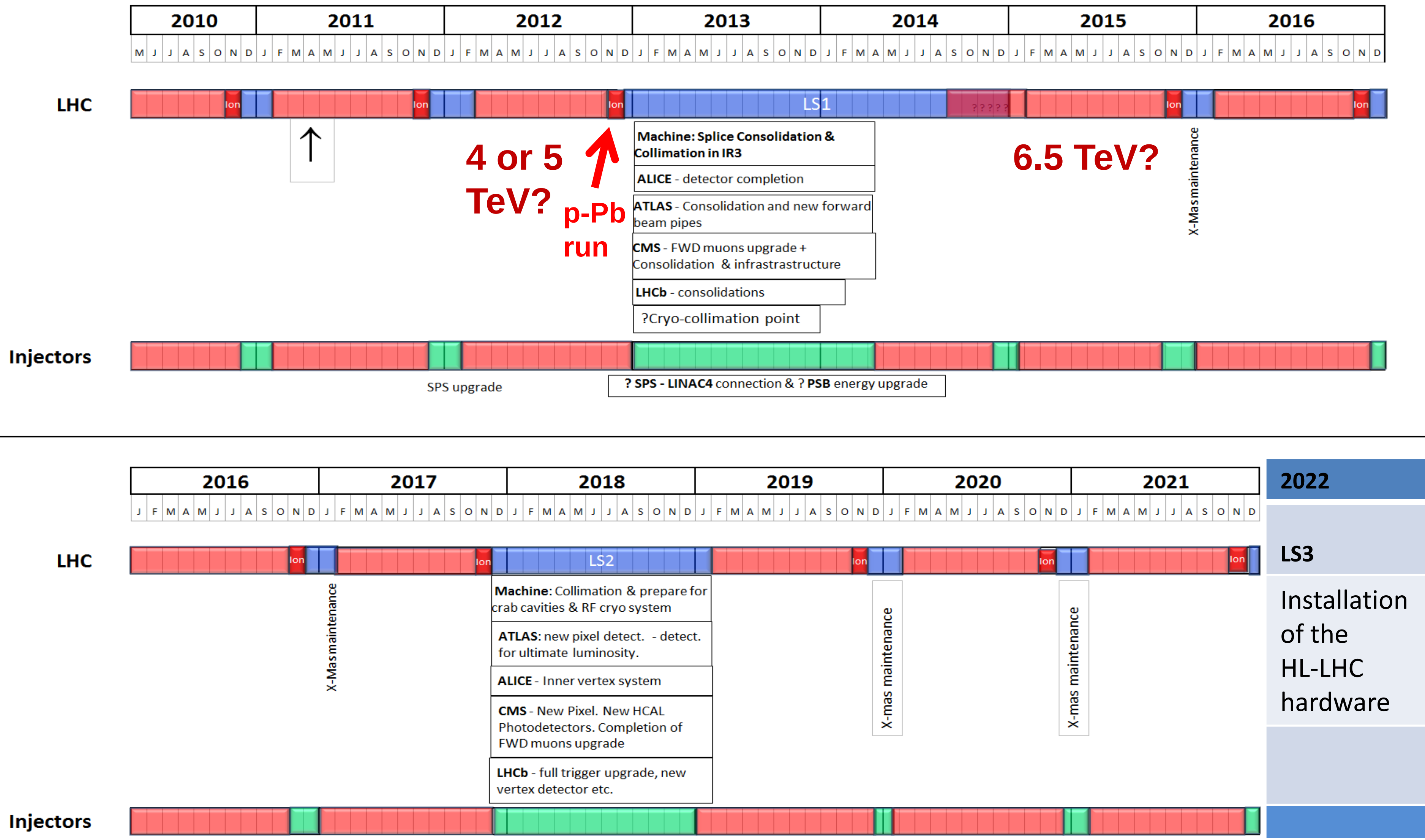


S. Fartoukh

Beam sizes @ 3.5 TeV [mm] and Dispersion [m]

New rough draft 10 year plan

Not yet approved!



(long) shutdowns

Xmas stop 2011

thermal amplifier test to determine beam energy for 2012

LS1: 2013-2014

machine splice consolidation for 7 TeV (14 months)

ATLAS (19 m.), CMS (17m), ALICE (12-17m), LHCb (12m)

upgrades; LINAC4 connection, PSB upgrade (?)

2013-2017:

collimation upgrade (BPM jaws), 4 x design current

LS2: 2018

collimation upgrade (dispersion suppressors)

preparation for crab cavities & RF cryosystem

detector upgrades

LS3: 2022

major HL-LHC hardware (IR, cryo, crab cavities)

major detector upgrades

future beam energy

quench propagation test during May TS:

encouraging results - to be confirmed

“thermal amplifier” measurement over XMAS break

to determine beam energy for 2012 (4 or 5 TeV?);

qualification tool to qualify maximum current
a sector can safely withstand

after **interconnect splice consolidation in LS1**

retraining of magnets (to reach 6.5 TeV?)

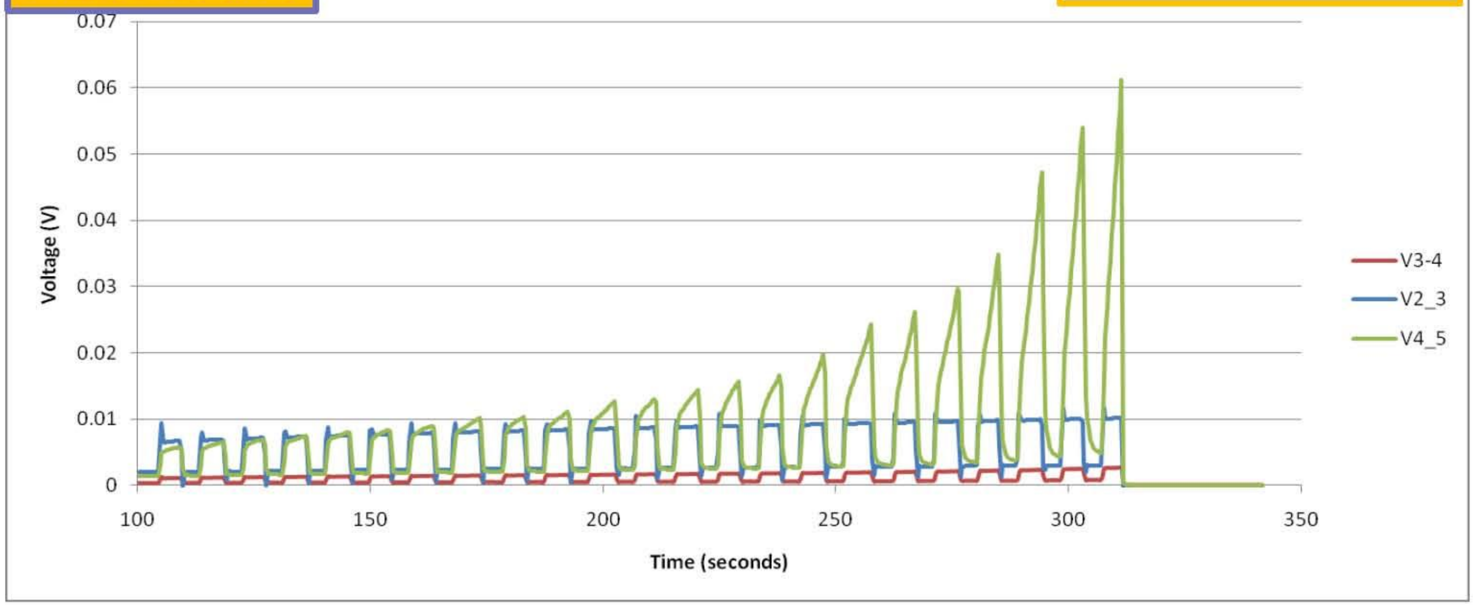
thermal amplifier

M. Koratzinos
Chamonix 2011

- The thermal amplifier uses a pulse of high current (order 3000A) to selectively warm up bad splices in a sector.
- Current flows through the diodes, so very little energy is stored in the circuit (= safe).
- It is a direct measurement of a thermal runaway at the exact conditions of a joint.
- Temperature of operation: around 40K

RB: a typical bad joint has excess resistance of 2% - if we warm it up, its resistance grows by ~200 times – easy to detect!

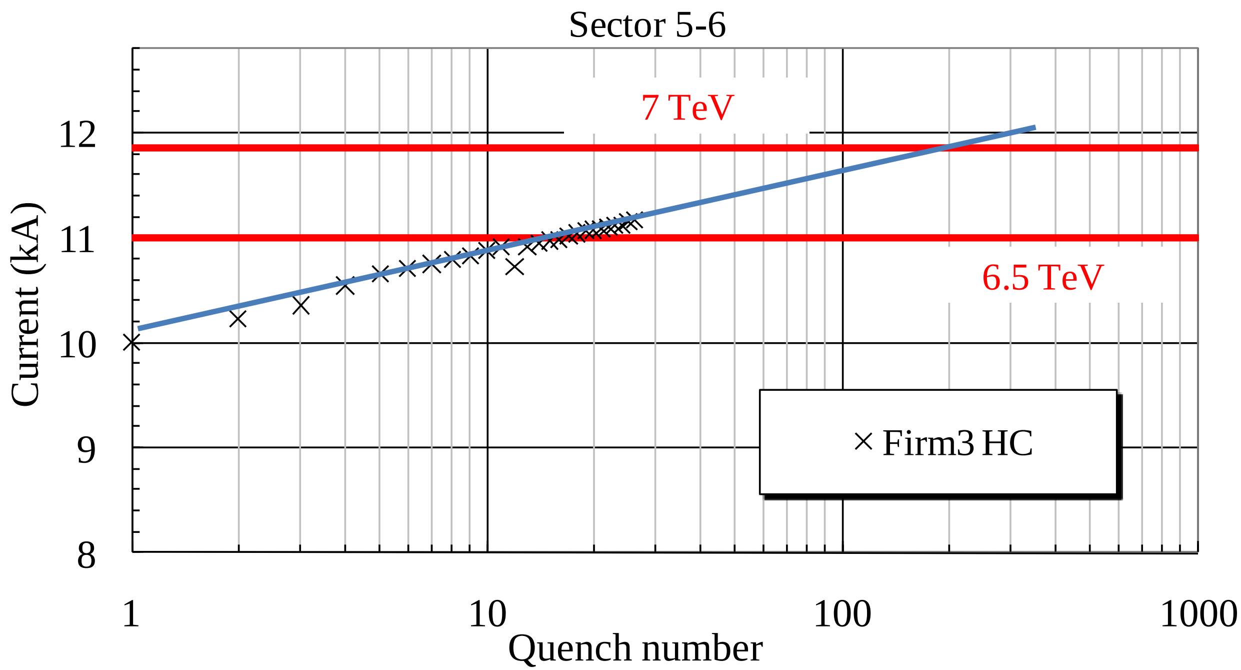
REAL DATA



The **GREEN** voltage contains a 50uOhm defect. The **BLUE** and **RED** voltages are across perfect joints

magnet retraining: quenches vs. energy

empirical extrapolation of hardware commissioning data based on exponential fit



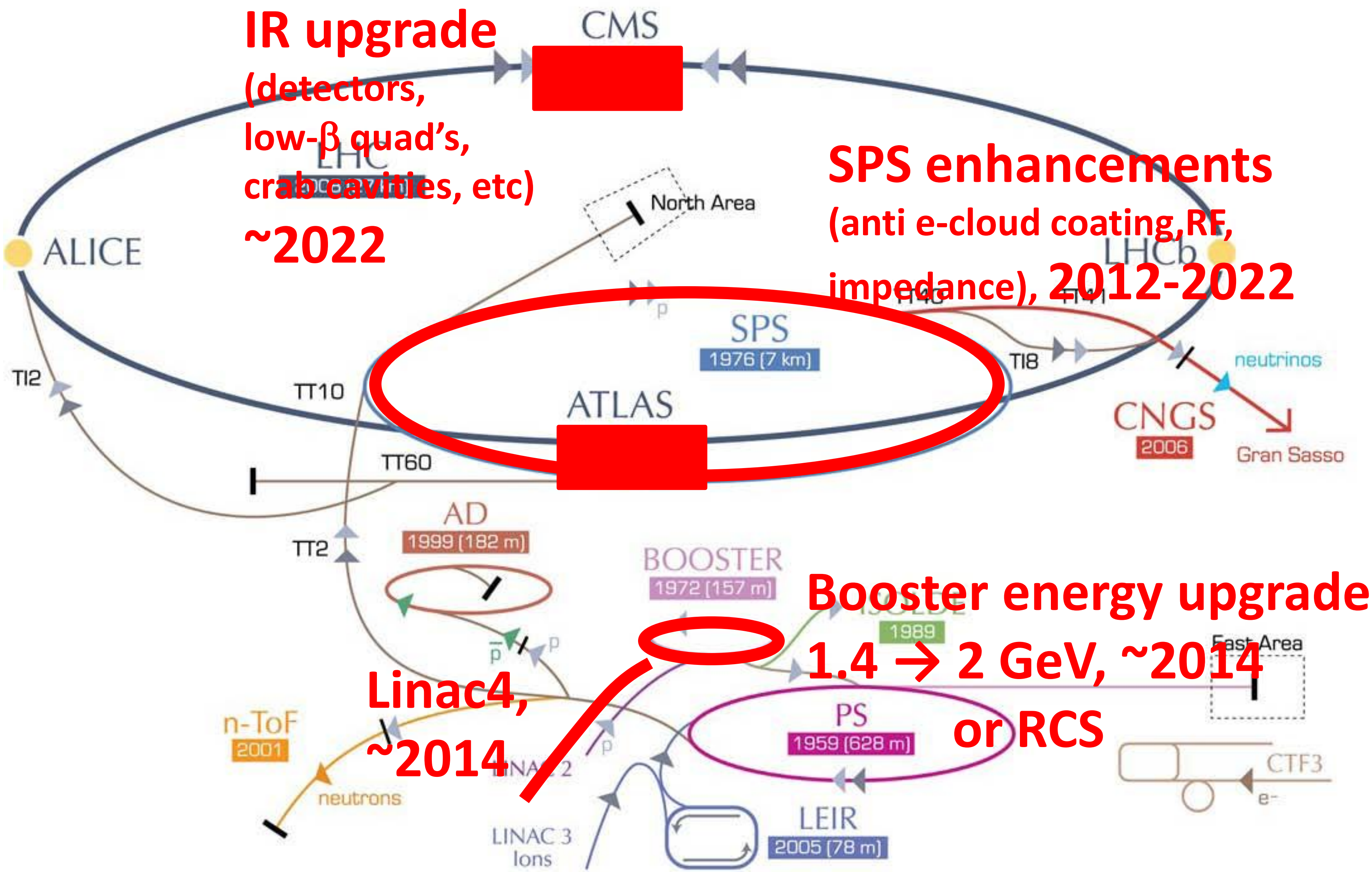
– ~200 quenches per sector 5-6

– For generic sector having 33% of Firm3: 110±35 quenches per octant to reach nominal

[A. Verweij, Chamonix 2009]

E. Todesco

HL-LHC – LHC modifications



HL-LHC goals

- Leveled peak luminosity: $L = 5\ 10^{34}\ cm^{-2}\ s^{-1}$
- Virtual peak luminosity: $L = 10\ 10^{34}\ cm^{-2}\ s^{-1}$
- Integrated luminosity: 200 fb^{-1} to 300 fb^{-1} per year
- Total integrated luminosity: ca. 3000 fb^{-1} by 2030

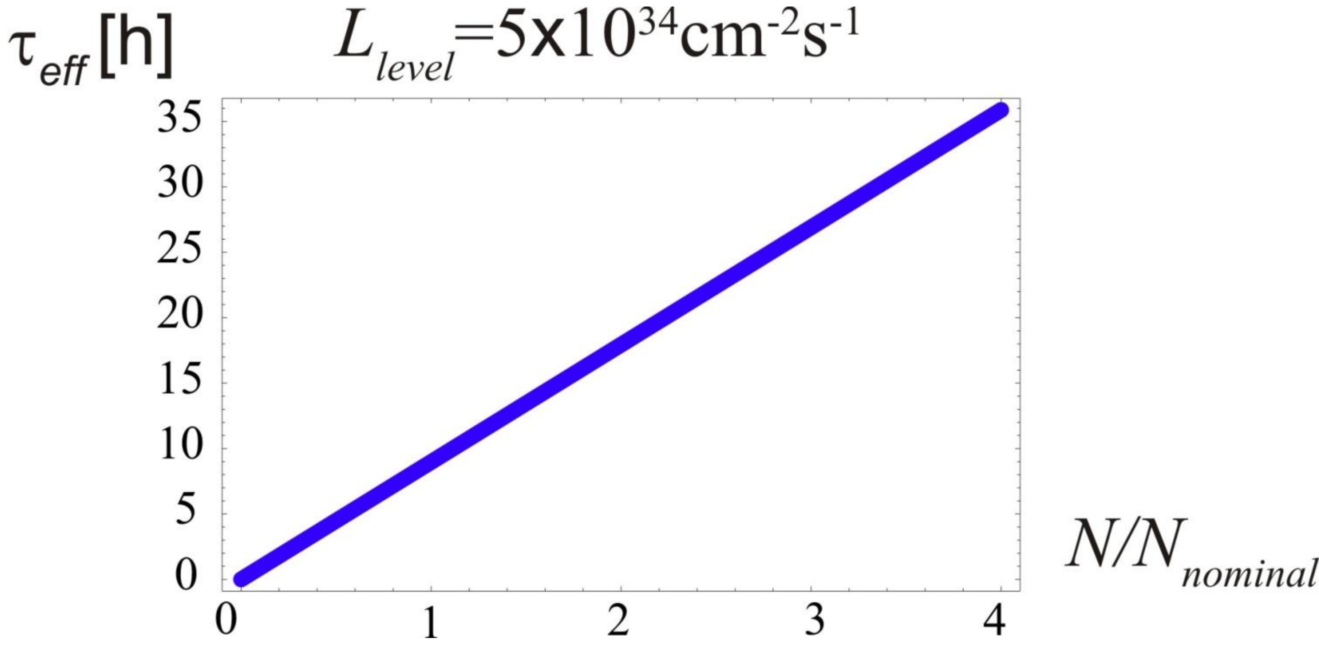
effective beam lifetime

for given luminosity

τ_{eff} scales with total beam current

$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_{eff}} = -n_{IP}\sigma L_{lev} \quad (\sigma=100 \text{ mbarn})$$

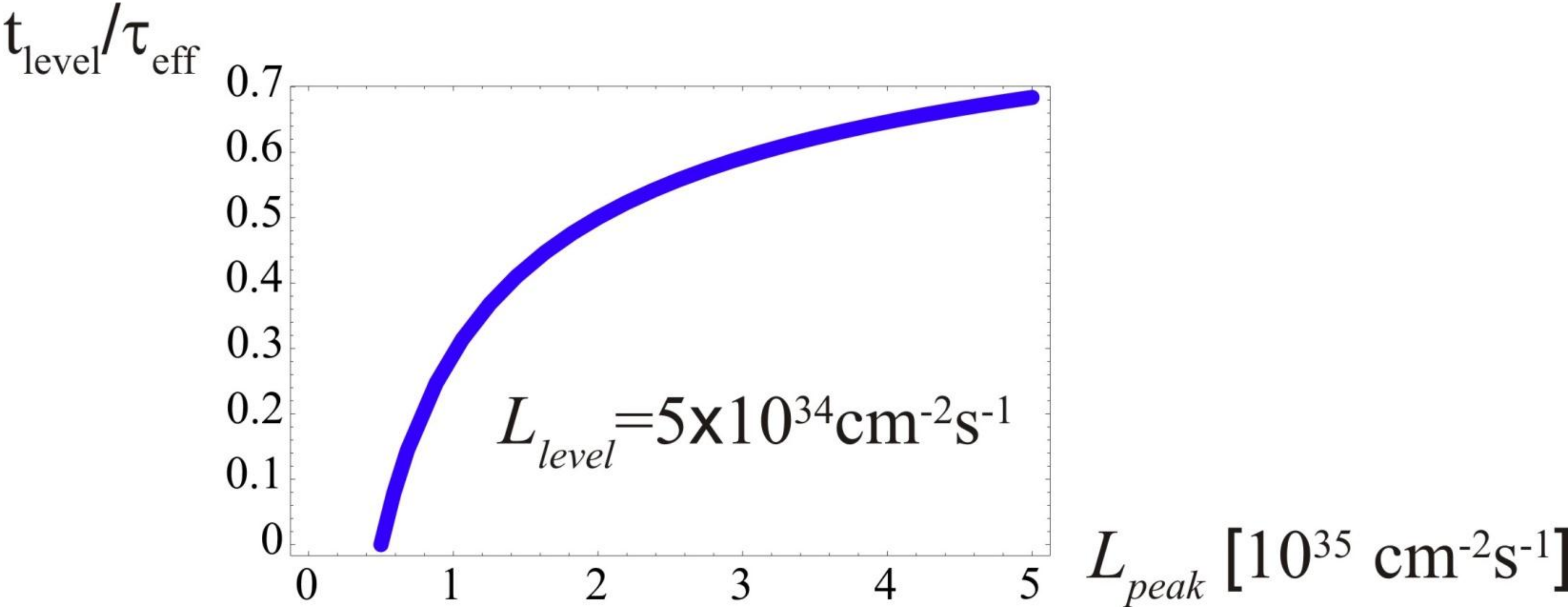
$$\tau_{eff} = \frac{N_{tot}}{n_{IP}\sigma L_{lev}}$$



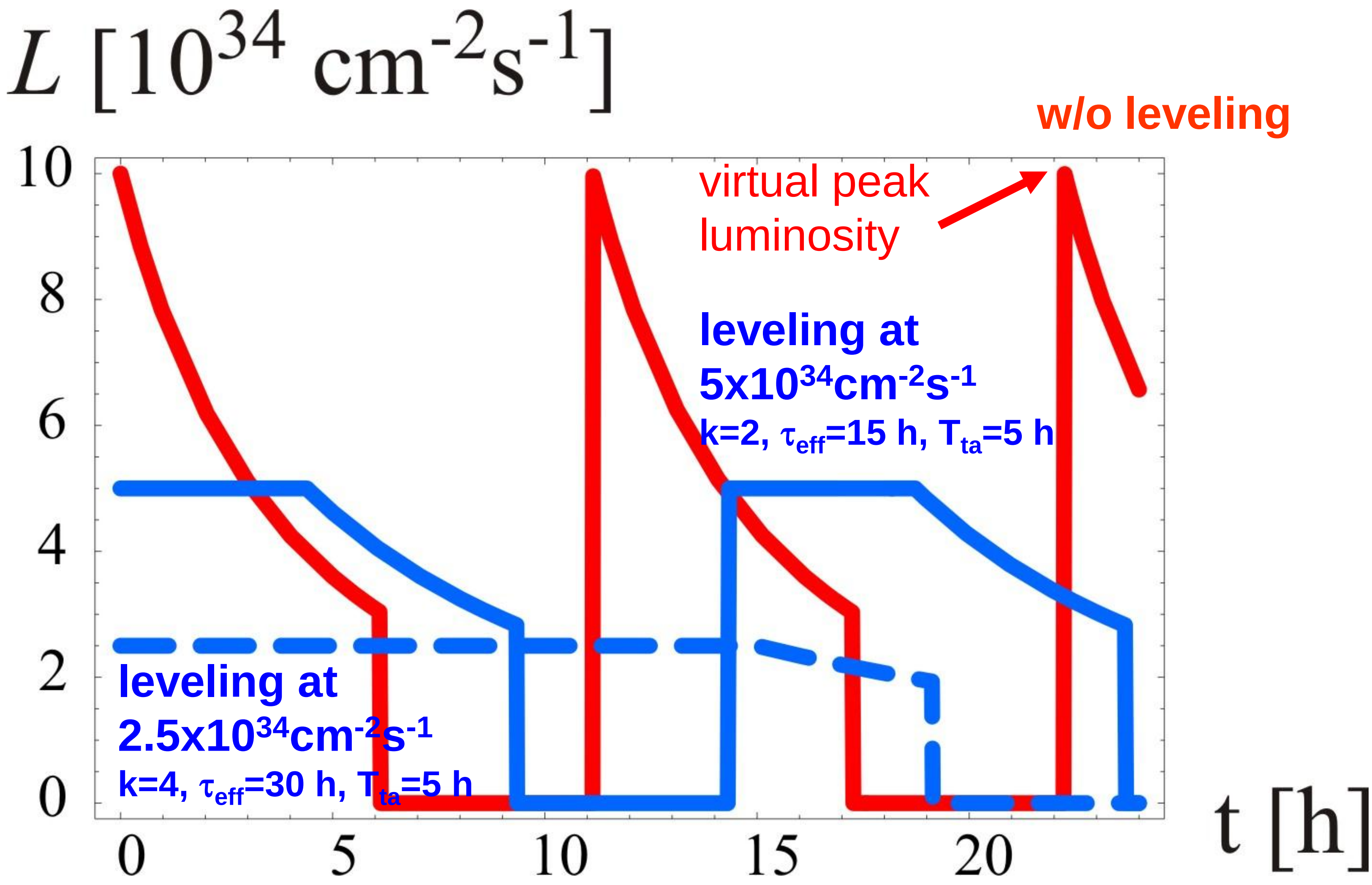
maximum leveling time

$\hat{L} = kL_{lev}$ virtual peak luminosity

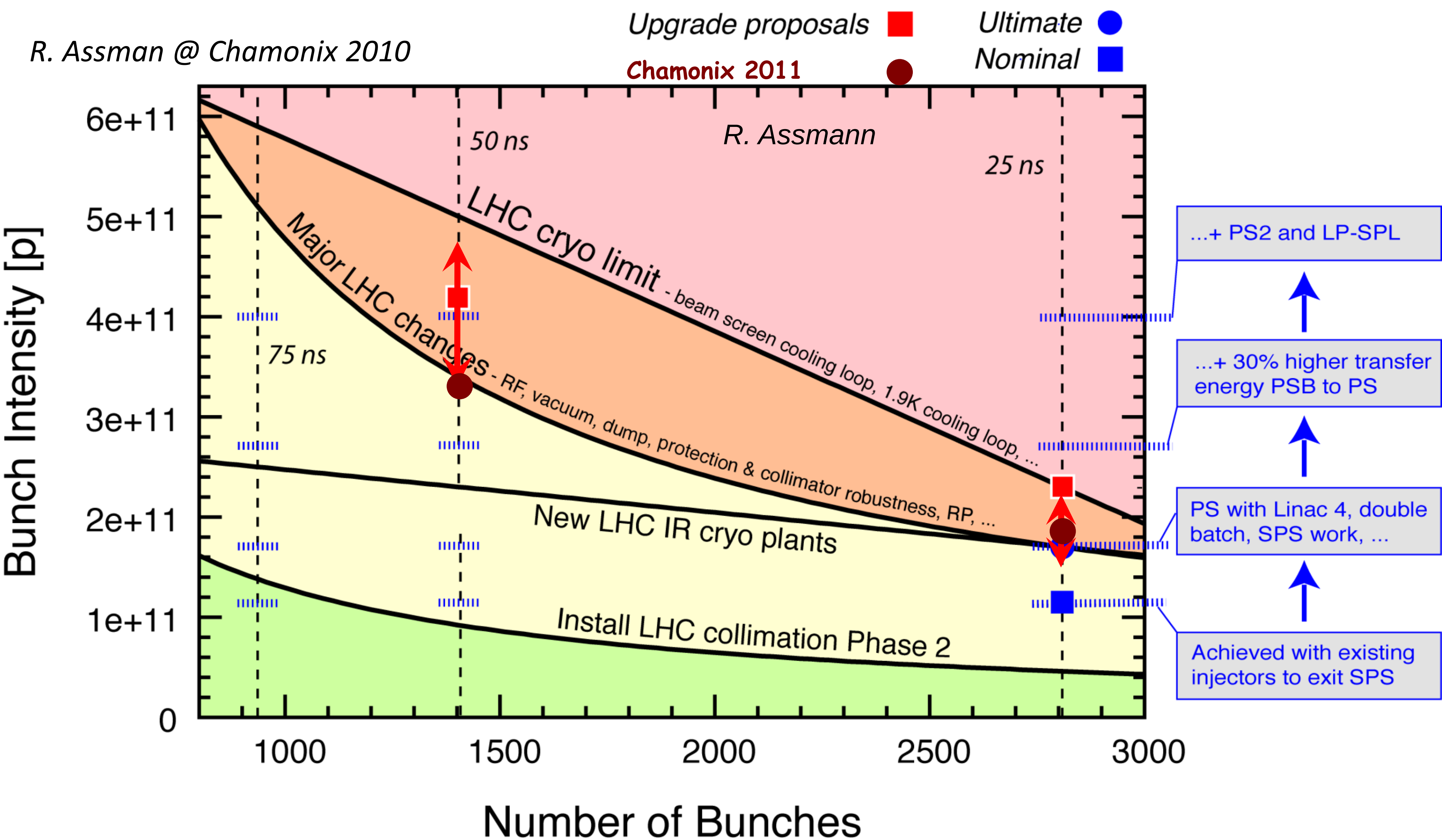
$$t_{lev} = \tau_{eff}\left(1 - \frac{1}{\sqrt{k}}\right)$$



luminosity leveling at the HL-LHC



LHC Intensity Limits (7 TeV)

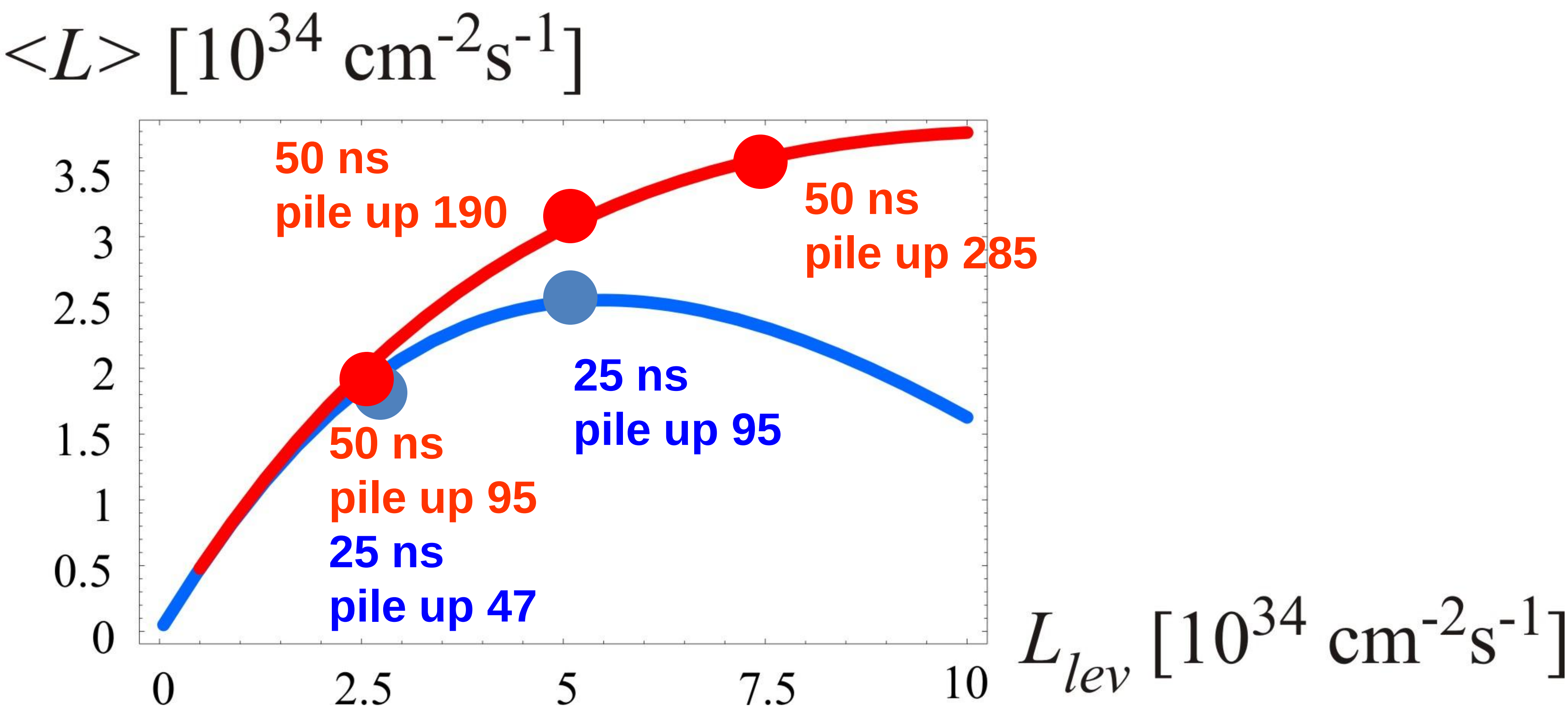


Ideal scenario: no imperfections included! Note: Some assumptions and conditions apply…

example HL-LHC parameters

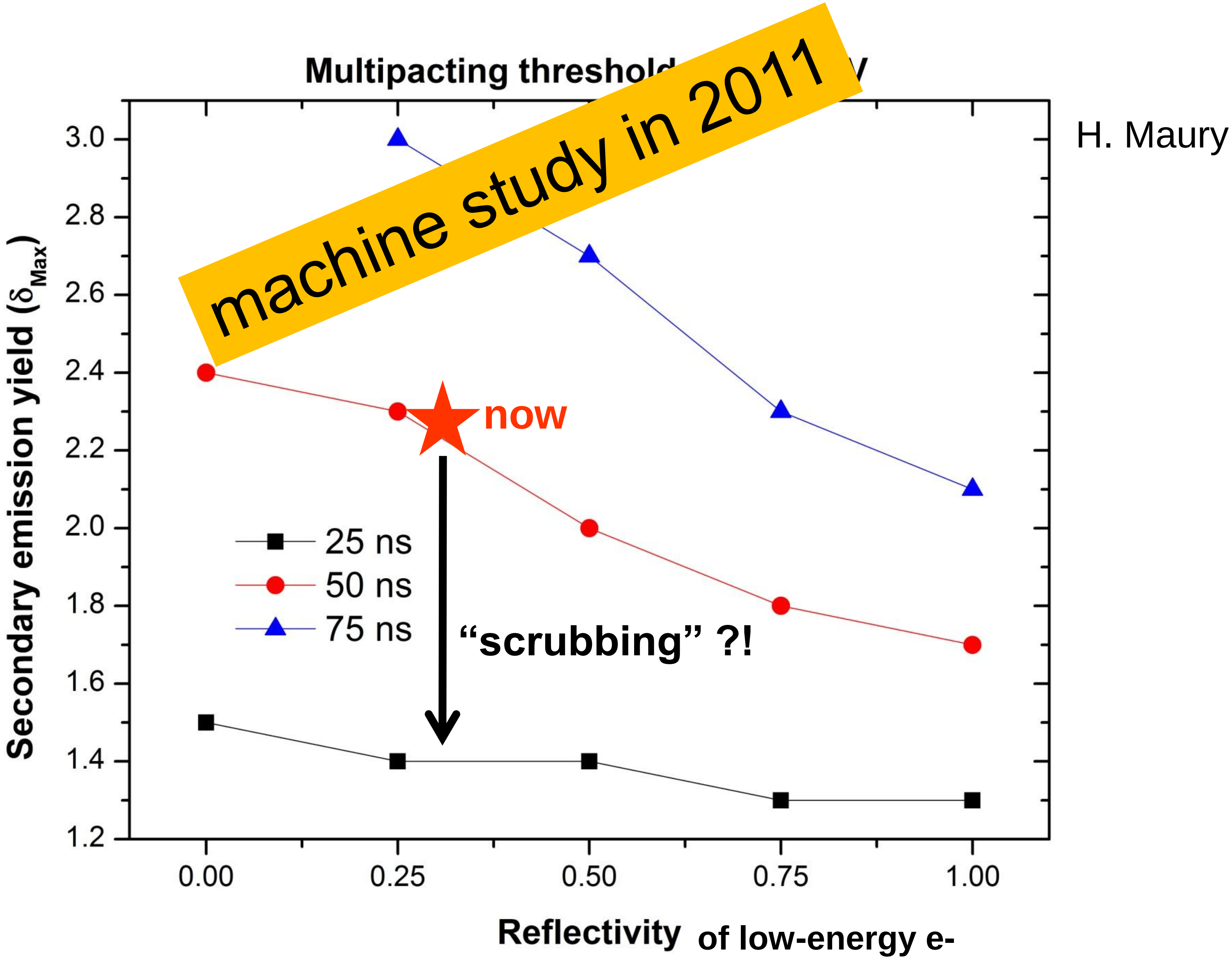
parameter	symbol	**nom.**	nom.*	**25 ns, crab, lrc**	**50 ns, crab, lrc**
protons per bunch	N_b [10^{11}]	**1.15**	1.7	**1.7**	**3.4**
bunch spacing	Δt [ns]	**25**	50	**25**	**50**
beam current	I [A]	**0.58**	0.43	**0.86**	**0.86**
rms bunch length	σ_z [cm]	**7.55**	7.55	**7.55**	**7.55**
beta* at IP1&5	β^* [m]	**0.55**	0.55	**0.15**	**0.15**
full crossing angle	θ_c [μrad]	**285**	285	**425**	**425**
normalized mittance	$\gamma\varepsilon$ [μm]	**3.75**	3.75	**2.8**	**2.8**
Piwinski parameter	$\phi=\theta_c\sigma_z/(2^*\sigma_x^*)$	**0.65**	0.65	**2.13**	**2.13**
tune shift	ΔQ_{tot}	**0.009**	0.0136	**0.006-0.011**	**0.012-0.015**
potential pk luminosity	L [10^{34} cm^{-2}s^{-1}]	**1**	1.1	**9.6**	**19.3**
actual (leveled) pk luminosity	L_{lev} [10^{34} cm^{-2}s^{-1}]	**1**	1.1	**5**	**5 (2.5)**
events per #ing		**19**	40	**95**	**190 (95)**
effective lifetime	τ_{eff} [h]	**44.9**	30	**13.3**	**13.3 (26.6)**
level time / run time	$t_{level,run}$ [h]	**15.2**	12.2	**3.7 / 8.6**	**6.5 / 10.1 (16.4)**
e-c heat SEY=1.2	P [W/m]	**0.2**	0.1	**0.4**	**0.3**
SR+IC heat 4.6-20 K	P_{SR+IC} [W/m]	**0.32**	0.30	**0.58**	**0.91**
IBS ε rise time (*z*, *x*)	$\tau_{IBS,z/x}$ [h]	**58, 104**	39, 70	**71, 60**	**36, 30**
annual luminosity	L_{int}[fb^{-1}]	**57**	58	**259**	**317 (204)**

trade off: integrated lumi ↔ pile up



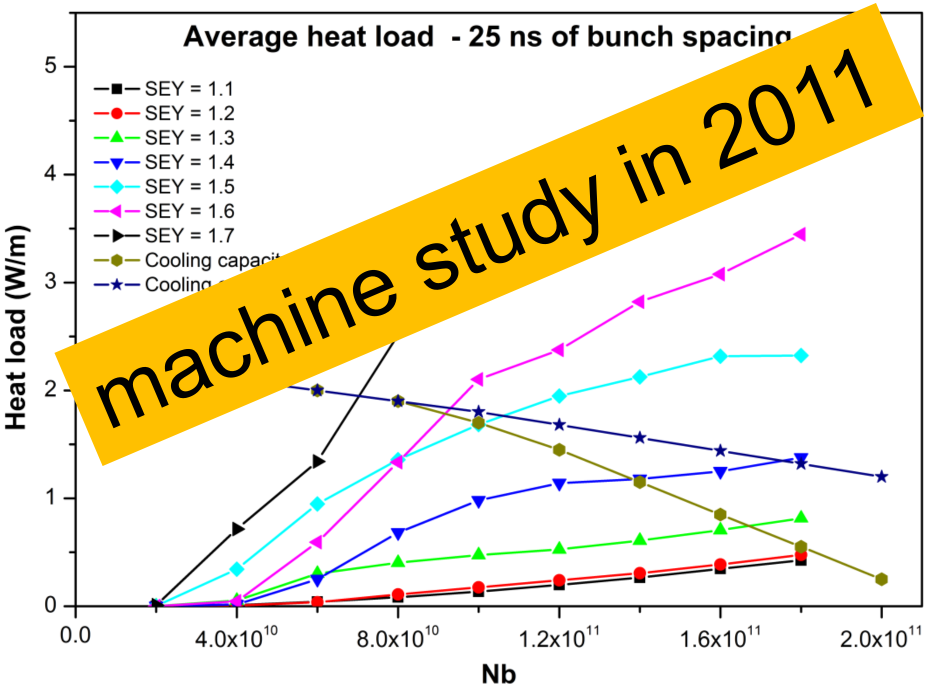
roughly for 2 times more integrated luminosity 4 times the pile up

electron cloud build up at 3.5 TeV

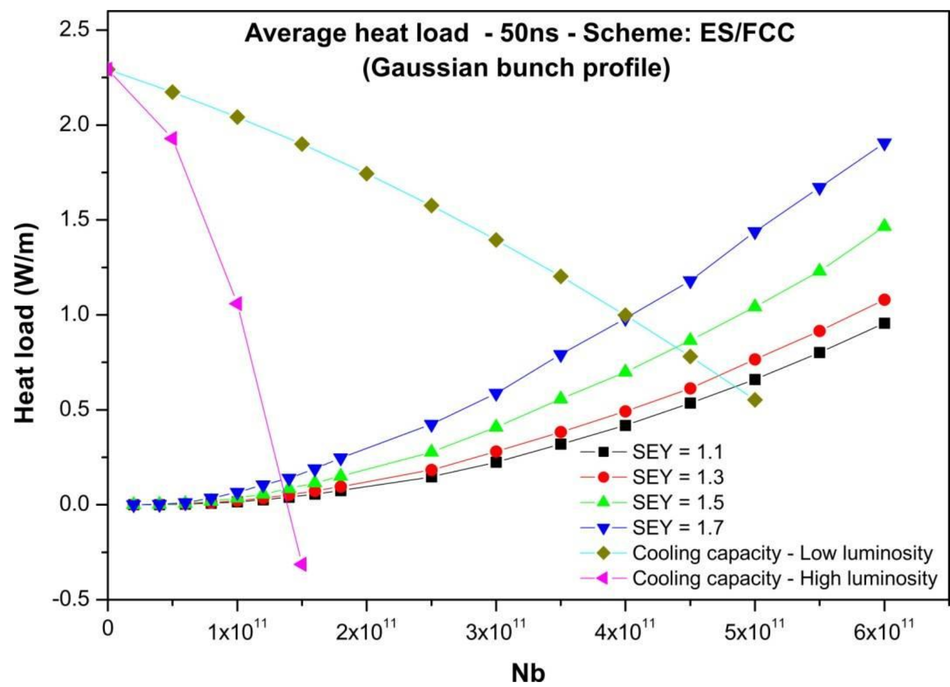


electron-cloud heat load (at 7 TeV)

25-ns bunch spacing



50-ns bunch spacing



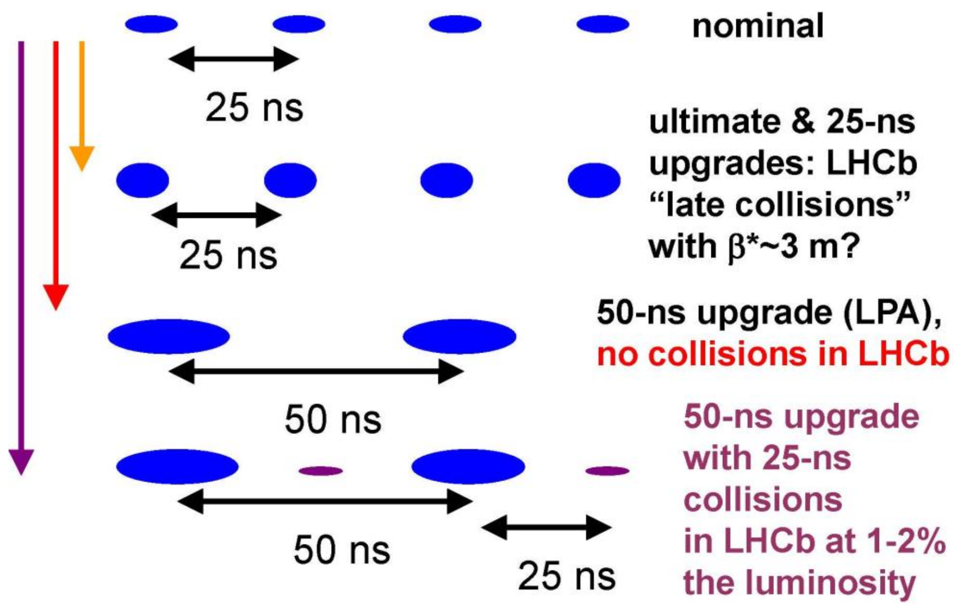
H. Maury
L. Tavian

dedicated IR cryo plants needed;

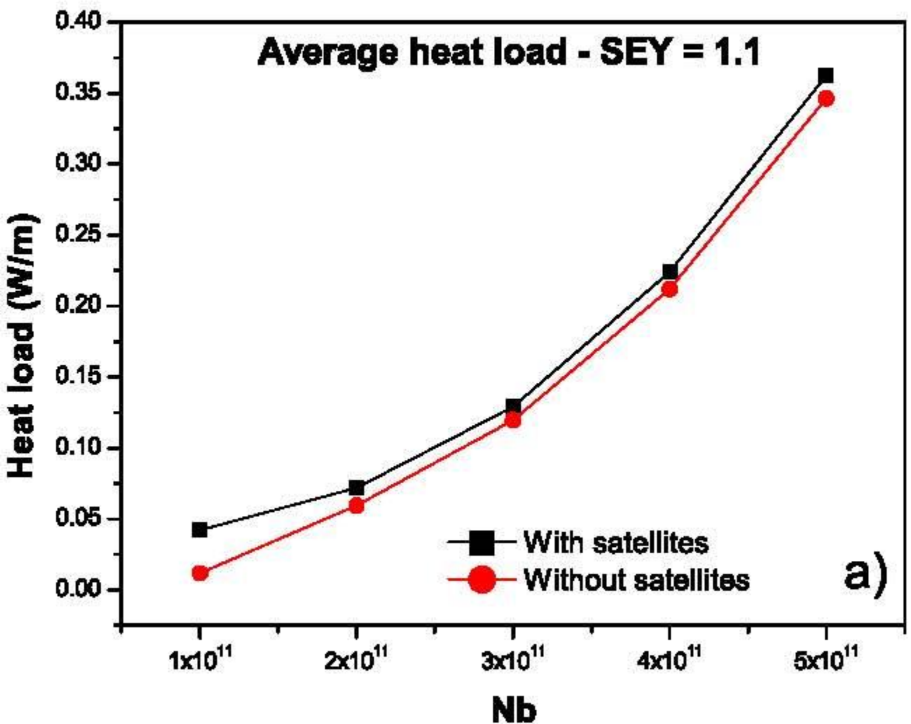
50 ns much easier than 25 ns;

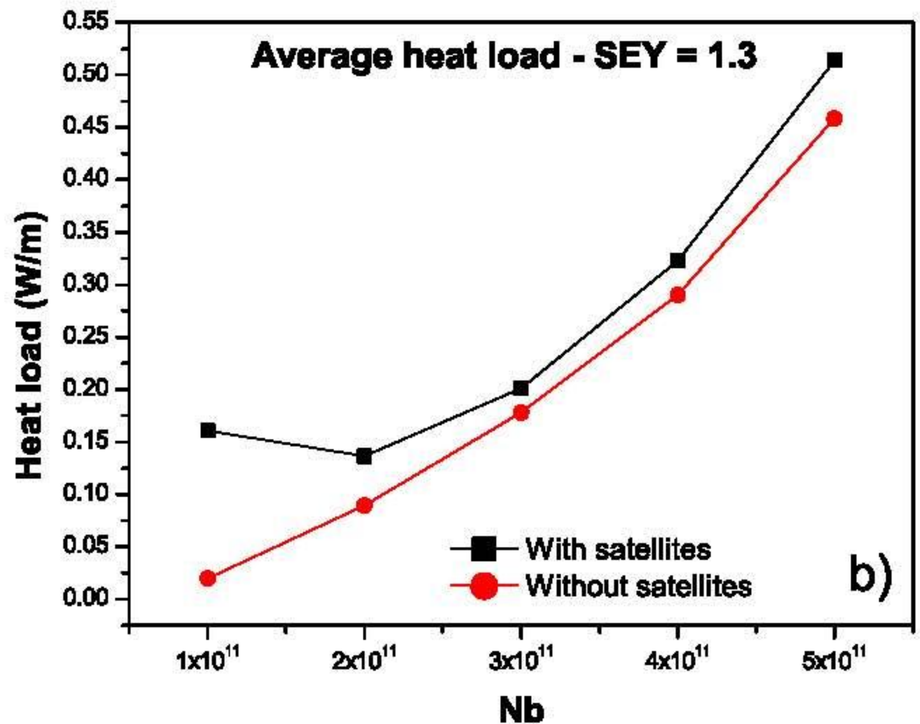
at 25 ns electron cloud contribution acceptable if $\delta_{max} \leq 1.2$

e-cloud heat load also OK for 50 ns spacing plus "LHCb satellites"



H. Maury

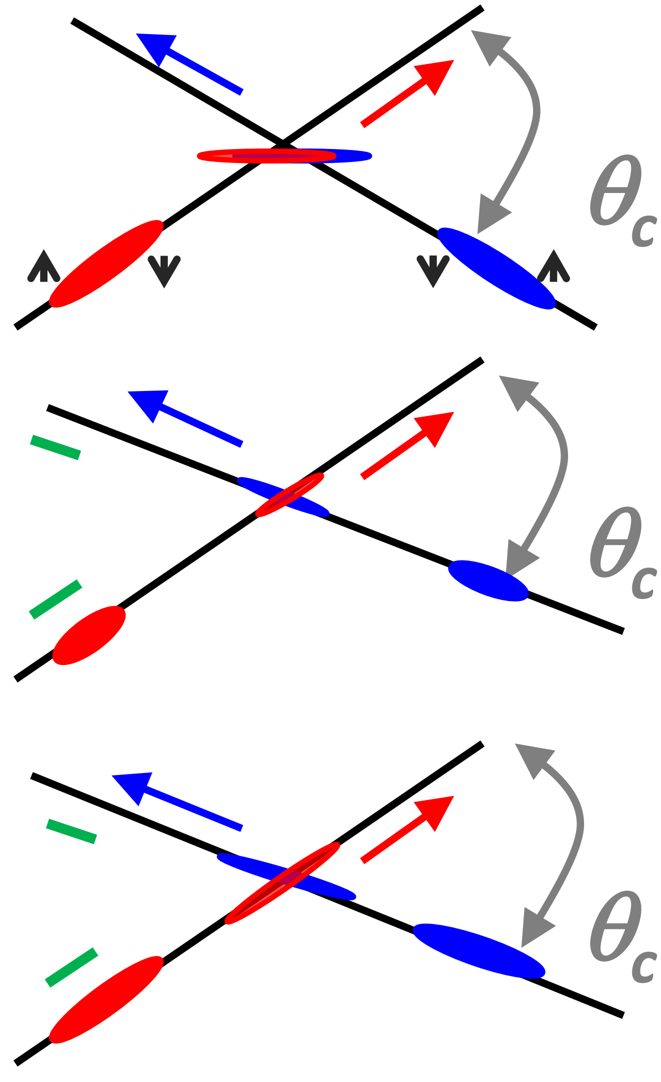




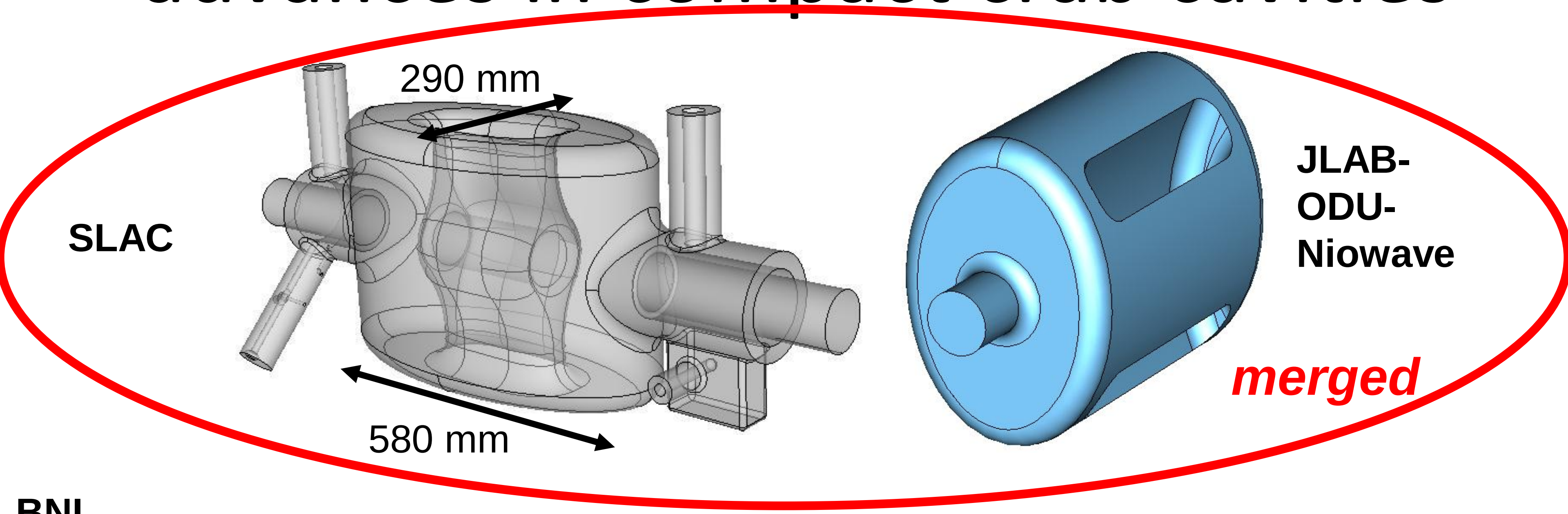
approaches to boost LHC luminosity

- low β* & crab cavities (80 MV)
- low β* & higher harmonic RF (7.5 MV @800 MHz) + LR
  compensation
- large Piwinski angle + LR-BB
  compensation

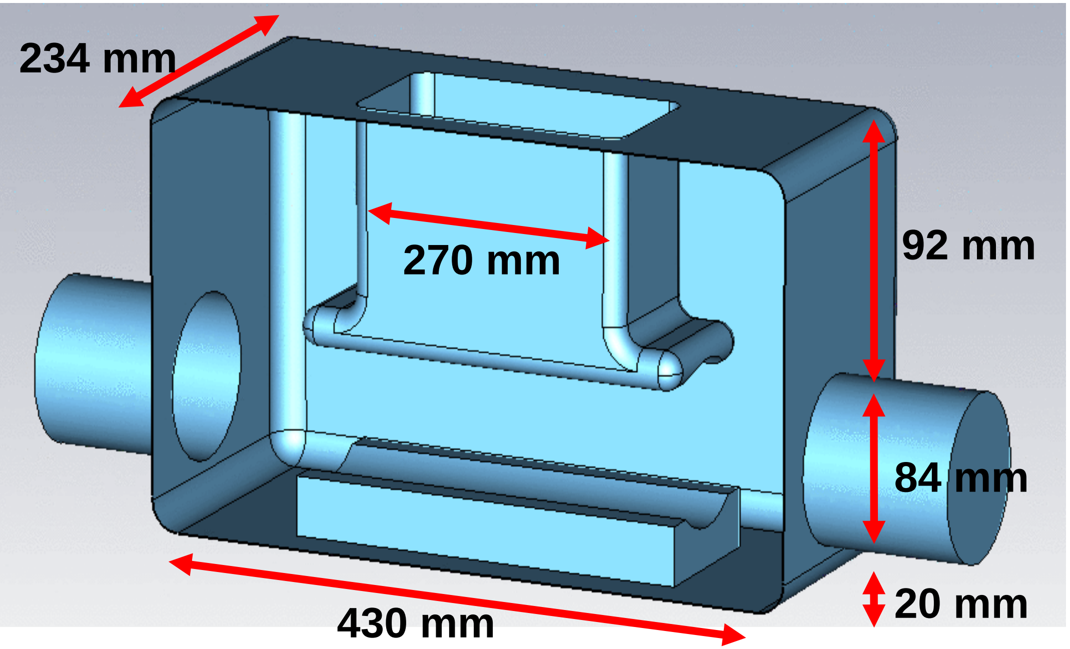
always pushing intensity to "limit"



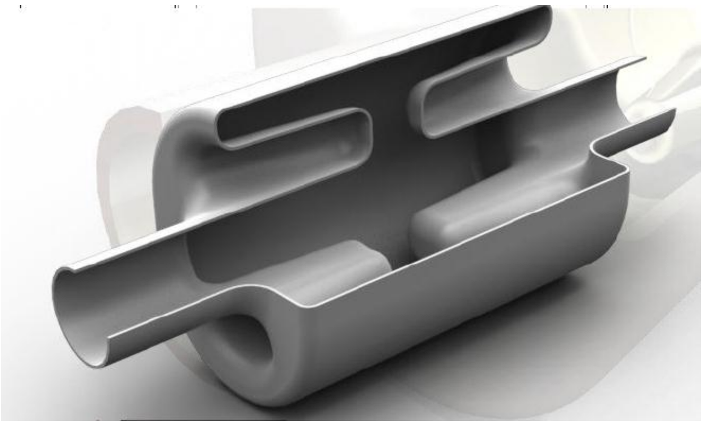
advances in compact crab cavities



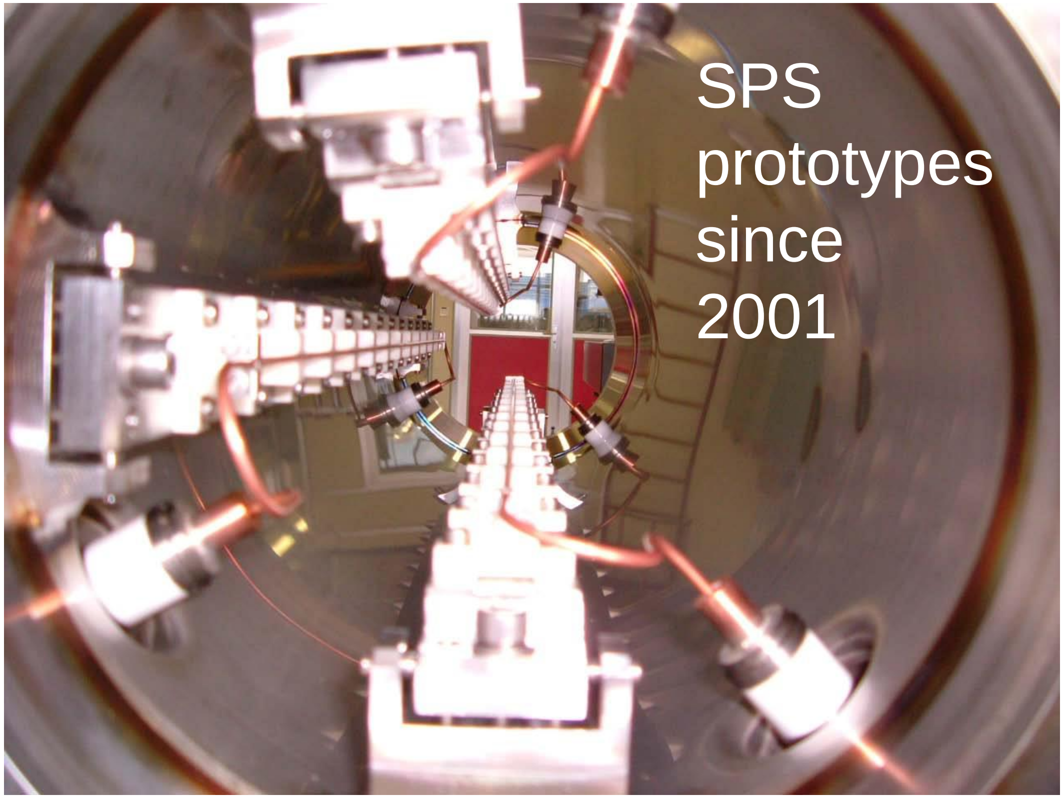
BNL



Cockcroft Institute & EuCARD



long-range beam-beam compensator



after Chamonix 2011
launch of BE-BI project

concept: integrate wire inside "collimator" like copper block, with Integrated BPMs; diamond insulation

goal:
install two LHC Prototypes during LS1

CERN
CH-1211 Geneva 23
Switzerland

the
Large Hadron Collider
project

LHC Project Document No. **LHC-BBC-EC-0001**
EDMS Document No. **503722**
Engineering Change requested by (Name & Div./Grp.) : **C.Fischer AB/BDI**

Date: 2004-10-27

Engineering Change Order – Class I

RESERVATIONS FOR BEAM-BEAM COMPENSATORS IN IR1 AND IR5

Brief description of the proposed change(s) :

Reservations on the vacuum chamber in IR1 and IR5 for beam-beam compensator monitors.
We propose to include these modifications in the next v.6.5 machine layout version.

Equipment concerned :	***Drawings concerned :***	***Documents concerned :***
BBC	**LHCLSX—0001** **LHCLSX—0002** **LHCLSX—0009** **LHCLSX—0010**	

PE in charge of the item :	***PE in charge of parent item in PBS :***
J.P. Koutchouk AT/MAS	**C. Rathjen AT/VAC**

Decision of the Project Engineer :	***Decision of the PLO for Class I changes :***
☐ Rejected. ☐ Accepted by Project Engineer, no impact on other items. *Actions identified by Project Engineer* ☑ Accepted by Project Engineer, but impact on other items. *Comments from other Project Engineers required* *Final decision & actions by Project Management*	☐ Not requested. ☐ Rejected. ☑ Accepted by the Project Leader Office. *Actions identified by Project Leader Office*
Date of Approval : 2004-10-27	***Date of Approval :*** 2004-10-27

Actions to be undertaken :
Modify the drawings and Equipment codes concerned to reflect the changes described in this ECO.

Date of Completion : 2004-10-27	***Visa of QA Officer :***

*Note : when approved, an **Engineering Change Request** becomes an **Engineering Change Order/Notification**.*

for future LHC
LR beam-beam
compensators,
3-m long sections
have been reserved
in LHC at 104.93 m
(center position)
on either side of
IP1 & IP5

higher harmonic RF cavity

LHC Project Note 394

2007-02-16

Trevor.Linnecar@cern.ch

An RF System for Landau Damping in the LHC

T. Linnecar and E. Shaposhnikova / AB-RF

Keywords: RF Systems, Landau Damping, Longitudinal Beam Stability

800-MHz system; stability gain > factor 3;
e.g. lower longitudinal emittance (no blow up in LHC), short bunches, higher intensity

Summary

A Landau system in the LHC could significantly increase the longitudinal stability of the LHC beams in the absence of wide-band longitudinal feedback and provide more freedom to define the bunch parameters even during the initial stages of LHC operation. This technique for stabilizing beams, used already in many accelerators, has proven to be very useful in the SPS, raising the instability thresholds by a factor five. One of the luminosity upgrade paths for LHC requires an RF system at 1.2 GHz with ~ 60 MV per beam for bunch shortening. A much smaller RF system at this frequency with ~3 MV per beam would be sufficient to provide Landau damping. This Note analyses the possible benefits and recommends that an R & D programme, leading to one prototype cryostat per ring to be installed in the LHC machine, be launched as soon as possible.

High Energy-LHC (HE-LHC)

ATS working group since April 2010

EuCARD AccNet workshop HE-LHC'10 , 14-16 October 2010

key topics

beam energy 16.5 TeV; 20-T magnets

cryogenics: **synchrotron-radiation heat**

radiation damping & emittance control

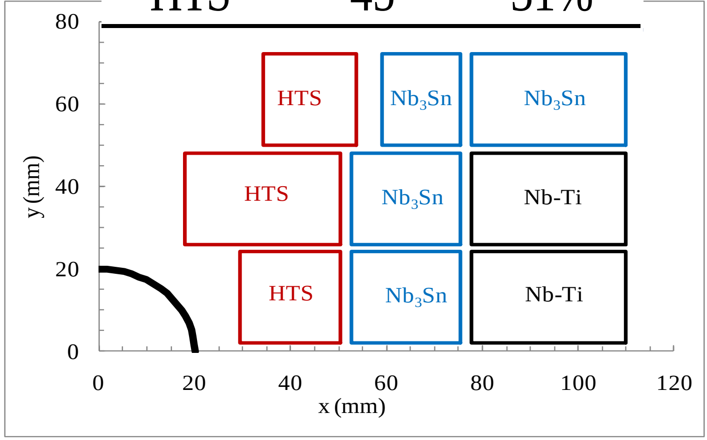
vacuum system: synchrotron radiation

new injector: energy > 1 TeV

parameters

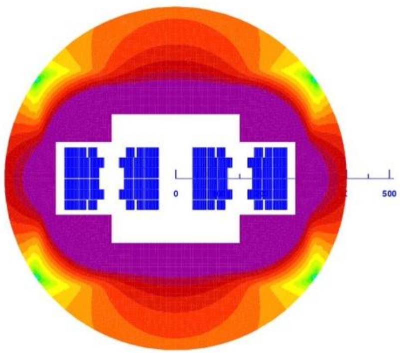
	LHC	HE-LHC
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40
#bunches	2808	1404
IP beta function [m]	0.55	1 (x), 0.43 (y)
number of IPs	3	2
beam current [A]	0.584	0.328
SR power per ring [kW]	3.6	65.7
arc SR heat load dW/ds [W/m/ap]	0.21	2.8
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0
events per crossing	19	76

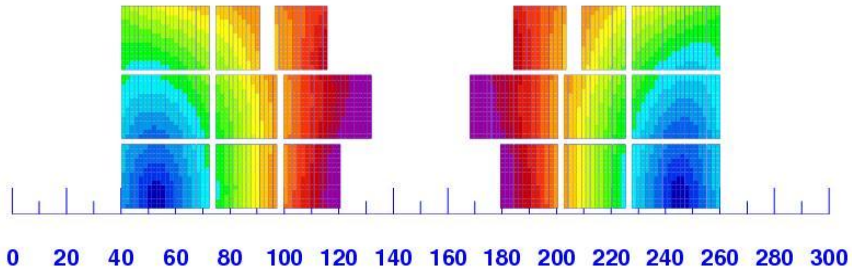
	Turns	%
Nb-Ti	40	28%
Nb_3Sn	58	41%
HTS	45	31%



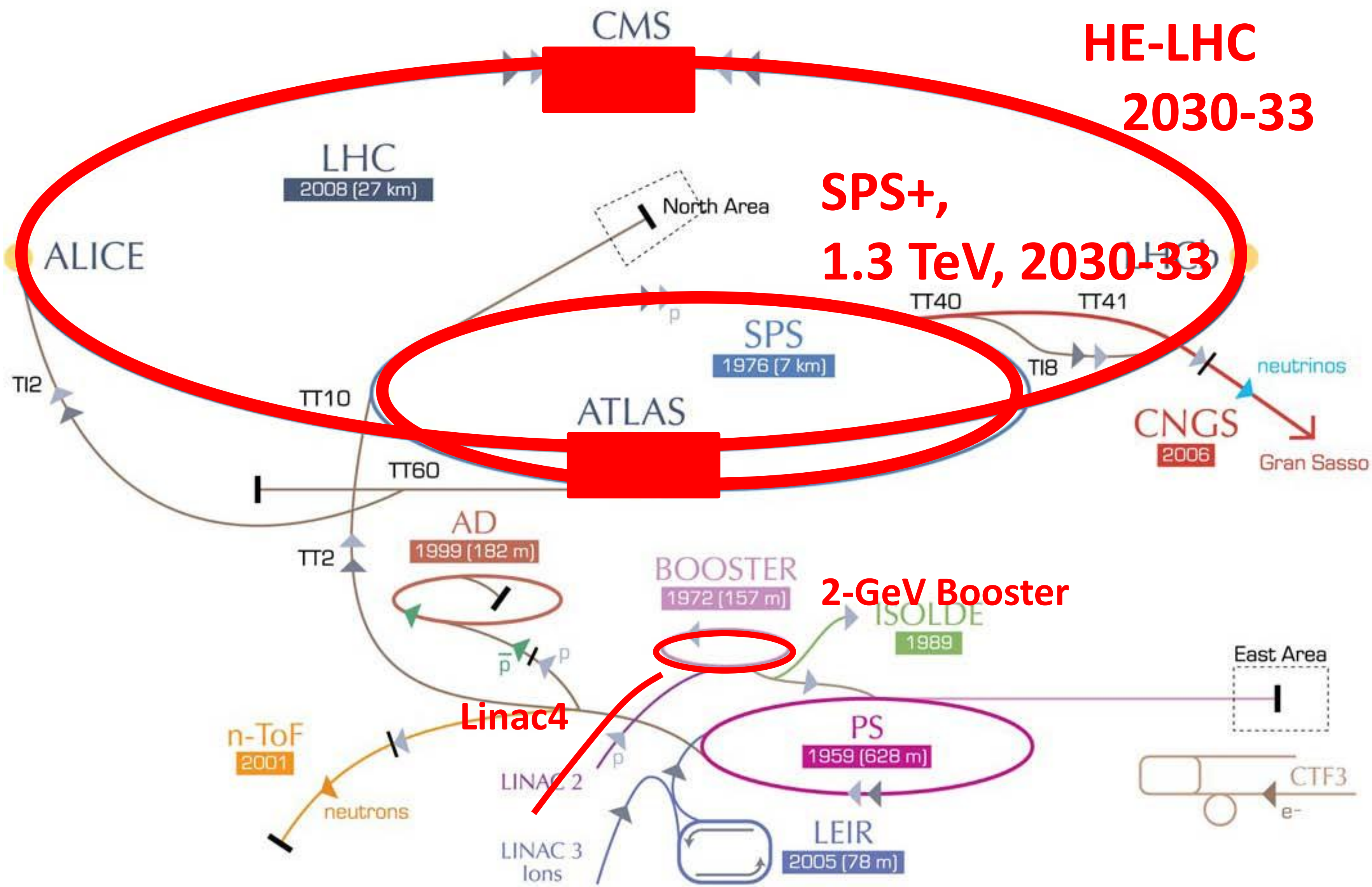
E. Todesco

hybrid magnet





HE-LHC – LHC modifications



EuCARD Newsletter article

European Coordination for Accelerator Research and Development Newsletter

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EuCARD >> News >> Newsletters >> Issue 8 >> Article 2

Proposed increase in energy takes LHC even further into the future

Accelerator scientists from around the world came together in Malta in October to discuss the possibility of increasing the energy of the present LHC. Organised by AccNet within EuCARD, the High Energy (HE) LHC workshop was convened to discuss the possible future LHC upgrade to a 16.5 TeV beam machine.

Participants in the HE-LHC'10 workshop. *Image courtesy of Kazuhito Ohmi. Thumbnail image on main page courtesy of CERN.*

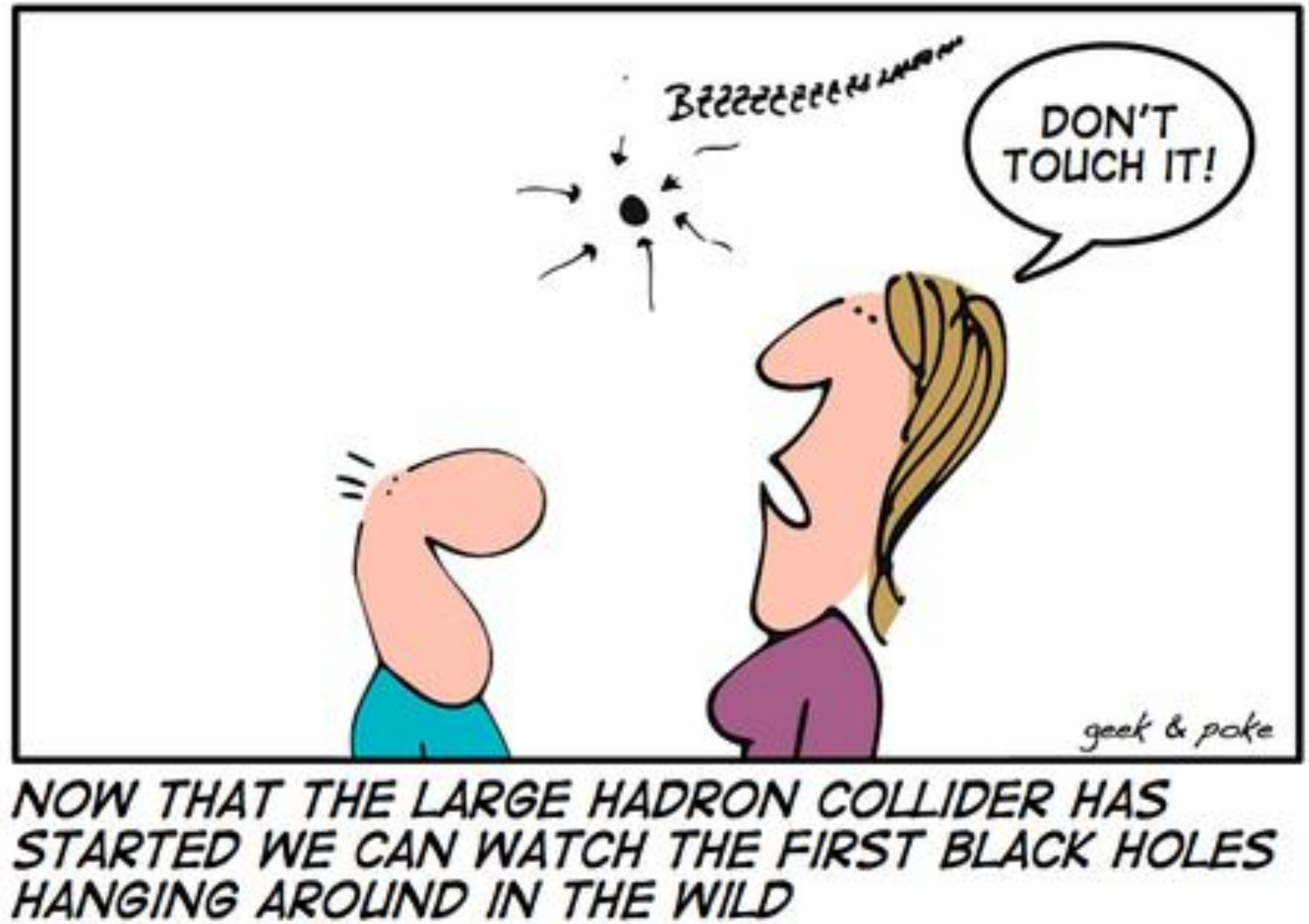
summary

- LHC **luminosity leveling works**
- **beam-beam tune shift 3x design**
  - beam parameters now constrained by acceptable detector pile up?!
- injectors send beam w **higher bunch charge and lower emittance than design** (and still improving)

- finally 25 ns or 50 ns beam ?!
- LS1 length determined by ATLAS

conclusions

- LHC **rapid & safe increase in beam intensity & luminosity**; transition to physics operation with a few **dedicated MD periods** / year
- **LHC & injector performances exceed expectations** (intensity, emittance, aperture, beam-beam effects,...)
- it should be possible to surpass design parameters in various ways
- **upgrade strategy** for the next 20 years



thank you for your attention!