Machine plans

O. Brüning BE-ABP

Upgrade Studies and Taskforces

- The Chamonix 2010 discussions led to five new task forces:

  -Planning for a long shut down in 2012 for splice consolidation

  -Long term consolidation planning for the injector complex

  -SPS upgrade task force

  ➔ accelerated program for SPS upgrade

  -PSB upgrade and its implications for the PS (e.g. radiation etc)

  -LHC High Luminosity project

  ➔ investigate planning for ONE upgrade by 2018-2020

- Launch of a dedicated study for doubling the beam energy in the LHC ➔ HE-LHC

New Project Structure at CERN

- High Luminosity LHC Projects: L. Rossi
  - ➔ prepare for operation at 5 10^{34} cm^{-2} sec^{-1}
  - ➔ prepare for integrated luminosity of 3000 fb^{-1} (200 fb^{-1} to 300 fb^{-1} / y)
  - ➔ Ready for implementation by 2020

- LHC Injector Upgrade Project: R. Garoby
  - ➔ remove bottlenecks in the PS and SPS
  - ➔ investigate options for PSB upgrade (energy)

- LHC Consolidation Project: S. Baird
  - ➔ have to consolidate existing injector complex for at least 15+ years

- Linear Collider Project: Steinar Stapnes

Chamonix 2010 Scenario A:

- Two years at 3.5 TeV
- 2010: should peak at 10^{32} and yield up to 0.5 fb^{-1}
- 2011: ~1 fb^{-1} at 3.5 TeV
- 2012: splice consolidation (and cryo collimator prep.)
- 2013: 6.5 TeV - 25% nominal intensity
- 2014: 7 TeV – 50% nominal intensity

(2013–2014: Aggressive)

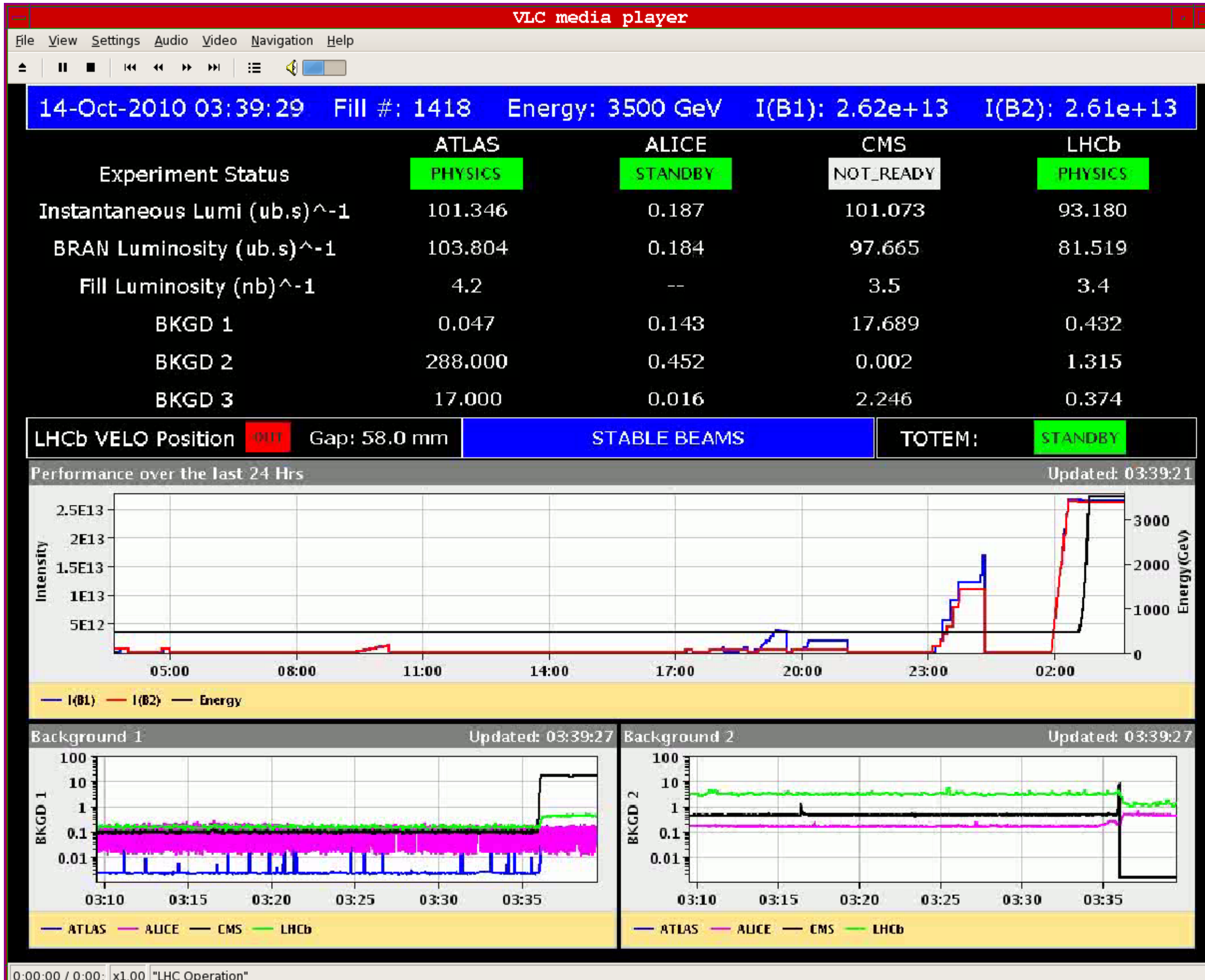
Year	Months	energy	beta	ib	nb	Peak Lumi	Lumi per month	Int Lumi Year	Int Lumi Cul
2010	8	3.5	2.5	7 e10	720	1.2 e32	-	0.2	0.2
2011	8	3.5	2.5	7 e10	720	1.2 e32	0.1	0.8	1.0
2012									
2013	6	6.5	1	1.1 e11	720	1.4 e33	1.1	7	8
2014	7	7	1	1.1 e11	1404	3.0 e33	2.3	16	24

M. Lamont @ Cahmonix 2010

LHC protons 2010: mission accomplished

250 bunches with ca. 2.6 10^{13} ppb

$L_0 > 10^{32}$ cm^{-2} s^{-1} ➔ Emittance in collision < 3 μm



Operation Experience in 2010:

- **Aperture** → measured aperture better than expected
  → allows further reduction of β^* → $\beta^* = 1.5$m

- **Emittance** → able to operate the LHC with 50% smaller than nominal beam emittances (aperture & brightness)

- **beam-beam:** → able to collide beams with larger than nominal beam-beam parameters

→ ability to exceed the luminosity target from Chamonix 2010
→ potential for achieving > 5 fb^{-1} @ 3.5 TeV within 2 years

Estimated Peak and Integrated Luminosity

$\beta^* = 1.5m$

days	H.F	Comm with	Fills with	kb	Nb e11	ε μm	ξ/IP	L Hz/cm^2	Stored energy MJ	L Int fb^{-1} 4 TeV	L Int fb^{-1} 3.5 TeV
160	0.3	150 ns	150 ns	368	1.2	2.5	0.006	~5.2e32	~30	~2.1	~1.9
135	**0.2**	**75 ns**	**75 ns**	**936**	**1.2**	**2.5** **2** **1.8**	**0.006** **0.007** **0.008**	**~1.3e33** **~1.6e33** **~1.8e33**	**~75**	**~3** **~3.8** **~4.2**	**~2.7** **~3.3** **~3.7**
125	0.15	50 ns	50 ns	1404	1.2	2.5	0.006	~2e33	~110	~3.2	~2.8

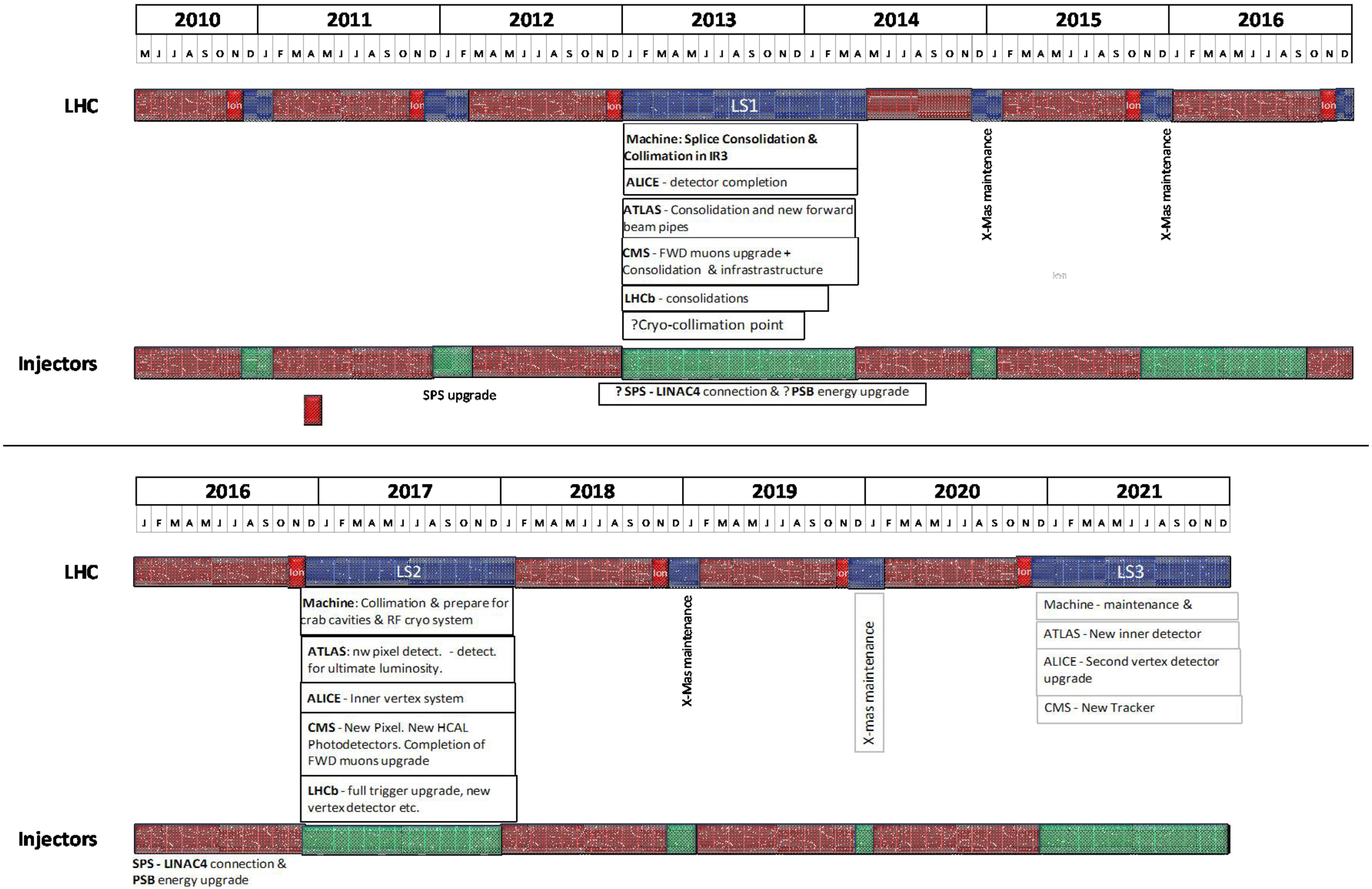
M. Meddahi @ Cahmonix 2011

Chamonix 2011 decisions:

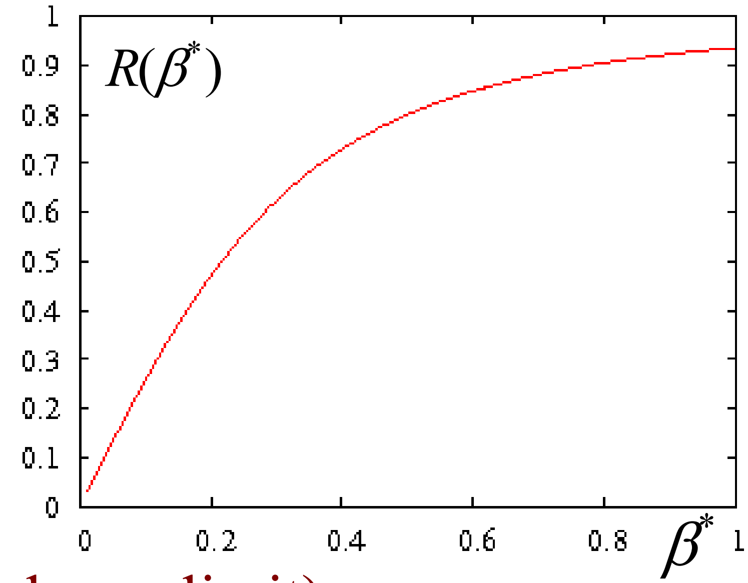
- LHC running in 2012 to benefit from potential for reaching more than 5 fb^{-1} before first long shut down.
- Remain at 3.5 TeV beam energy due to unacceptably high risks for machine operation at beam energies above 3.5 TeV
- Prepare for 18 month long shutdown in 2013 – 2014
- Commissioning and operation at 7 TeV in 2015 and 2016
- Upgrade LHC in 2017 to be compatible with operation with above nominal beam intensities (LINAC4 & Collimation upgrade)

Draft 10 year plan

[Outcome Chamonix 2011 presented @ LMC 81 - draft]



Performance optimization for the LHC



- Luminosity – performance:

$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot f_{rev}}{A} \cdot R(\phi, \beta^*, \varepsilon_n, \sigma_s)$$

➔1) maximize bunch intensity (beam-beam limit)
➔2) minimize beam size (constant beam power)
➔3) maximize number of bunches

- Operation at beam-beam limit
  ➔ use R for performance optimization – leveling: LPS, SE, CC

➔ What is the beam-beam limit in the LHC?!

Maximum bunch intensity:

- Single bunch limitations from collective effects:
  -TMCI: ➔ ca. 3.5 10^{11} particles per bunch

- Beam-beam limitations given by brightness (N/ε), head-on and long range collisions:
  -Limit for total tune spread: ➔ $\Delta Q = 0.02$ to 0.03
  $\Delta Q = 0.0235$ achieved in 2010 operation without long range
  $\Delta Q = 0.02$ during routine operation in Tevatron

- Long range beam-beam effects:
  ➔ LHC is the first machine with large number of long-range beam-beam interactions that can be controlled by a crossing angle

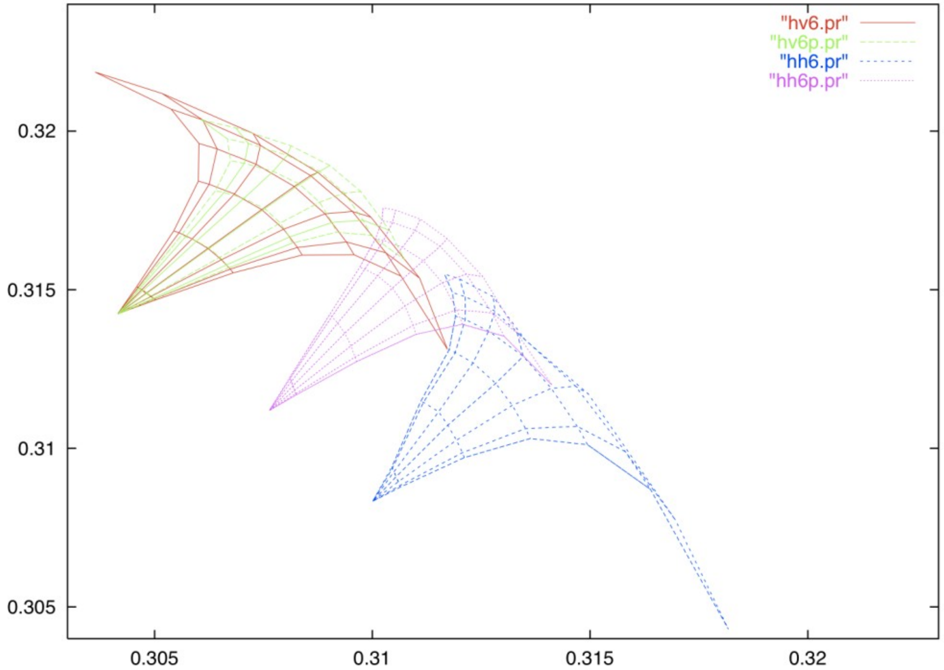
➔ maximum bunch intensity depends on minimum emittance

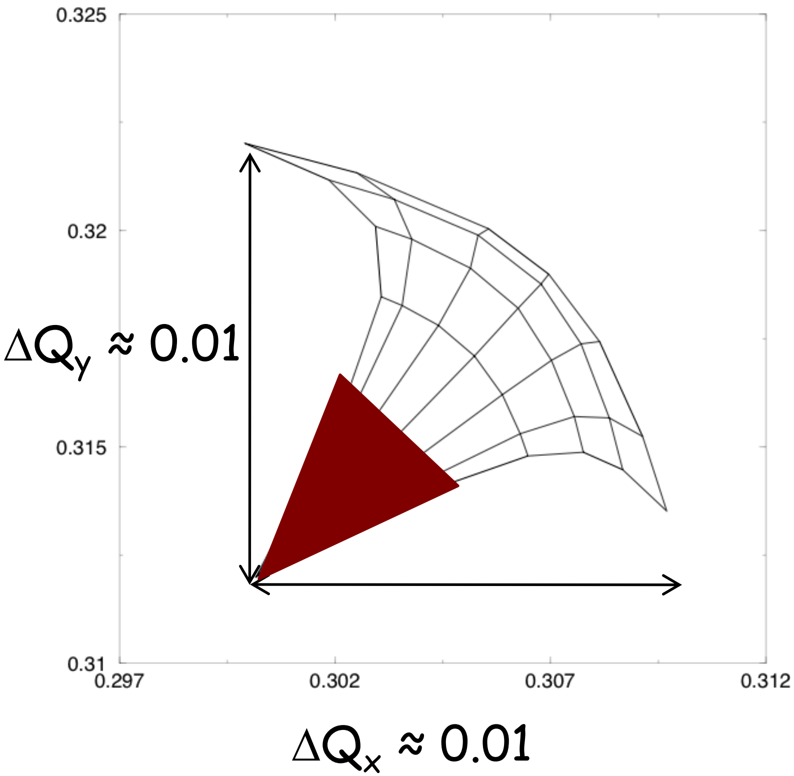
LHC Challenges: Beam-Beam Interaction

- Tune Footprint:

Pacman bunches
alternating crossing planes

nominal beams
all insertions
Head-on &
Long range



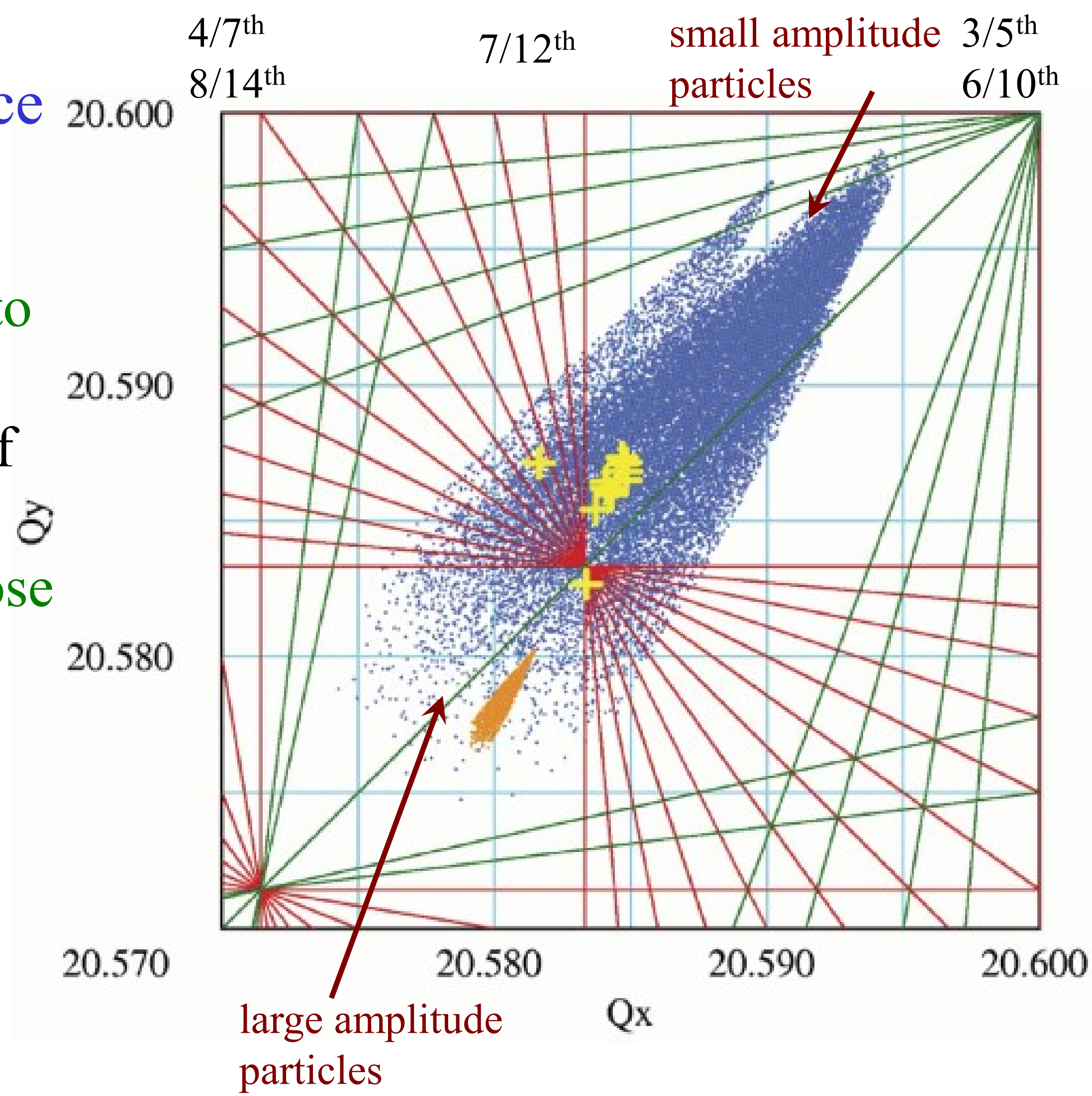


Werner Herr

Expected Beam-Beam limit for the LHC

Tevatron Run2 experience

1)Vertical ε blow up largest if small amplitude particles close to 3/5th or 7/12th.
2)Horizontal ε blow up largest if tune close to 7/12th.
3)Halo particles lost faster if close to 7/12th.
4)Tune shift depends on bunch position in train ➔ 'scallops'
5)'Scallops' only developed for large b-b parameters (≥ 0.02)



PRST, A&B 8, 2005

Minimum β^* values:

- Minimum β^* at 7 TeV for existing triplet:
  -β^* of 0.3m to 0.4 based on measured aperture and nominal settings

- HL LHC Upgrade: New scheme (ATS) for optics
  S. Fartoukh
  -β^* of 0.15m accessible for round beams @ 7 TeV
  -β^* of 0.3m / 0.075m accessible for flat beams @ 7 TeV

- Long range b-b can be alleviated by β^* increase ('soft landing'):
  ➔ assume 20% larger β^* as quoted for normal operation

  ➔ β^* of 0.5m accessible for round beams @ 7 TeV with nom
  ➔ β^* of 0.2m accessible for round beams @ 7 TeV with HL

Maximum number of bunches:

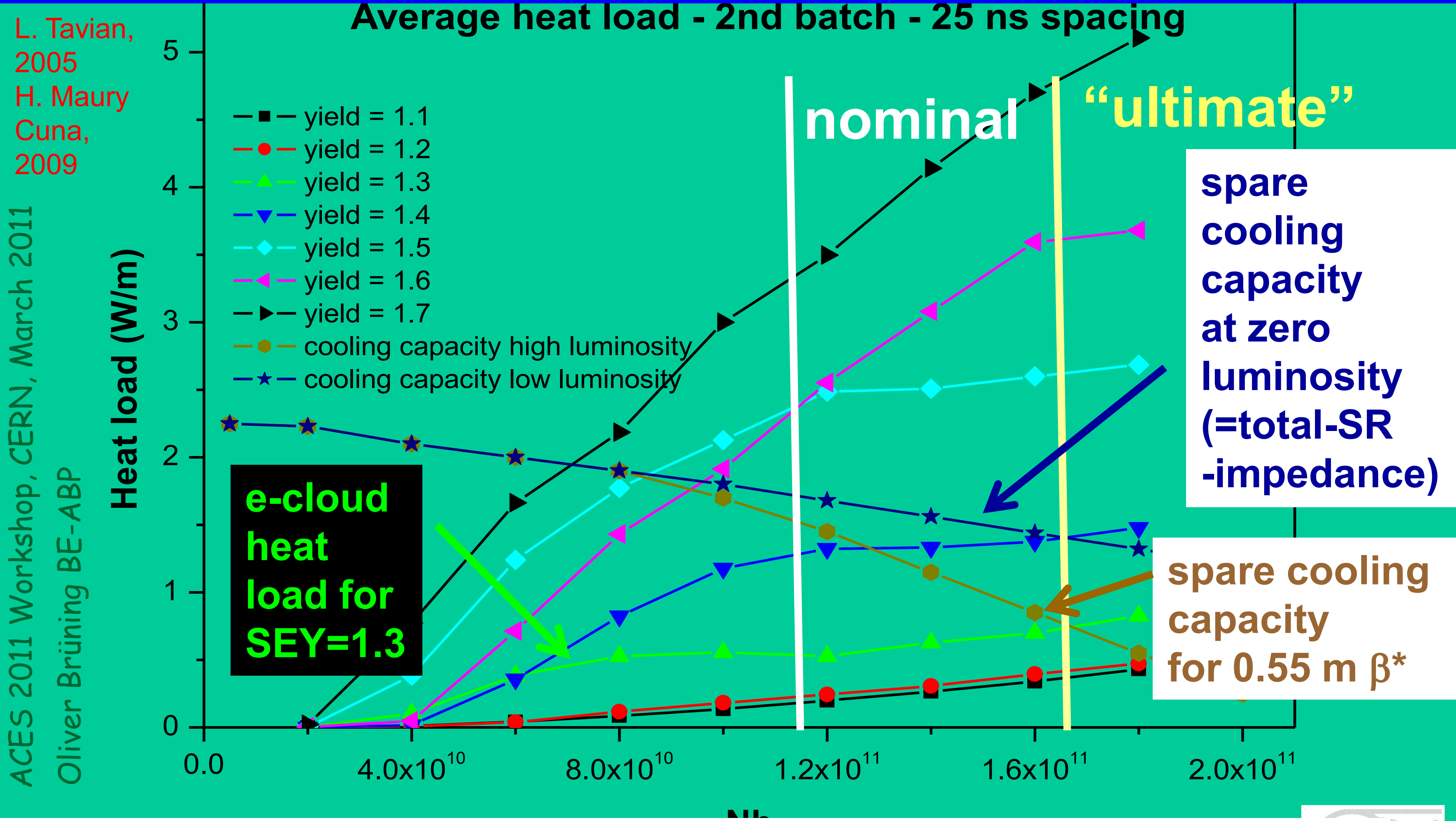
- Limited by total beam power:
  Current estimates of the hardware limitations from the nominal machine indicate a limit of 0.85 A (ultimate bunch current).

- Might be limited by cleaning inefficiency and minimum lifetime:
  Existing collimation system good for ca. 0.4 A for minimum beam lifetimes of 0.2 hours
  Might also be limited by impedance issues & collective effects

  → Upgrade of the LHC collimation system under preparation

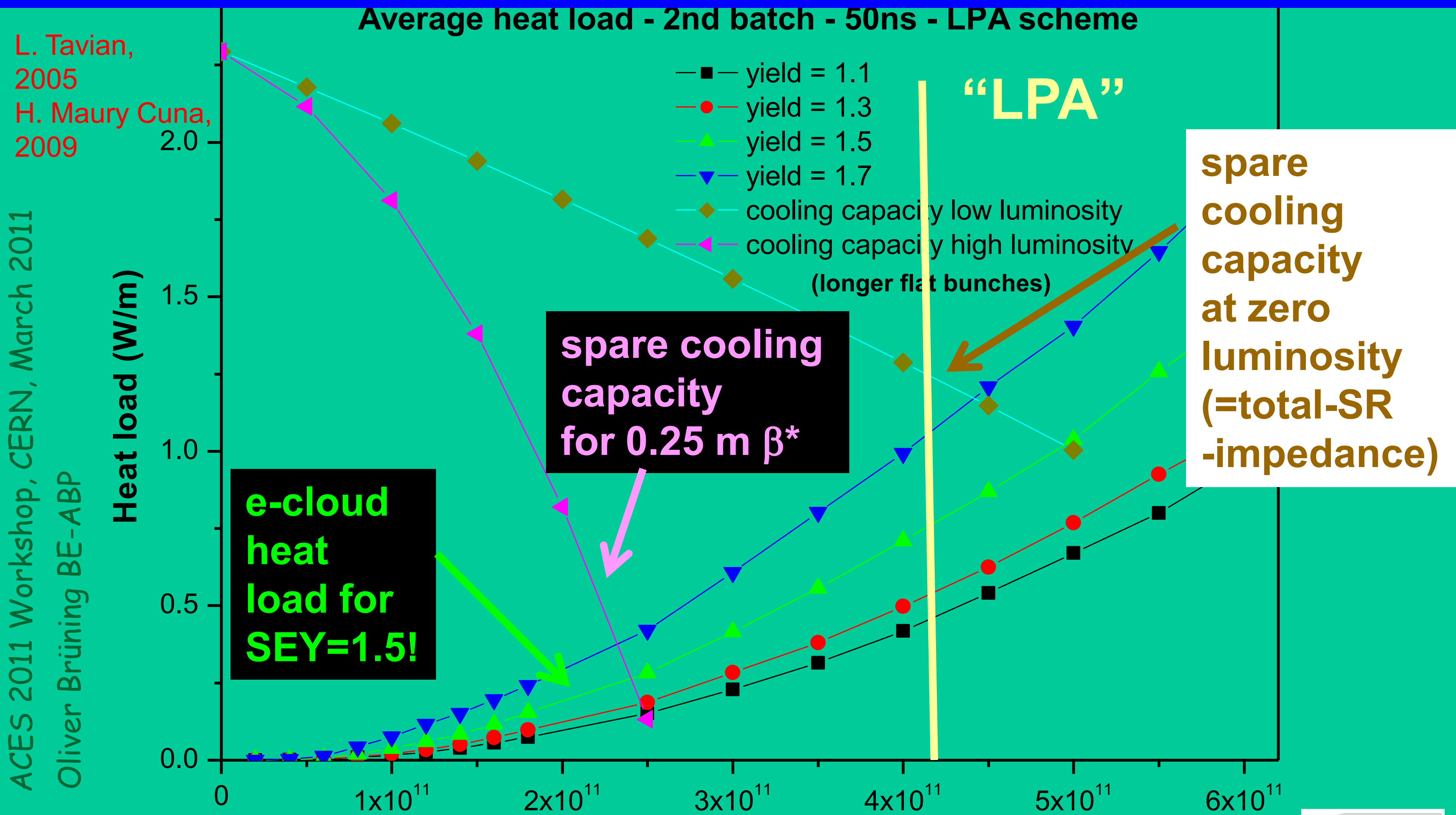
- Electron cloud effects: Heat load and instabilities
  → $N > 1.7\ 10^{11}$ not obvious at 25 ns bunch spacing (SEY < 1.3)
  → $N > 4\ 10^{11}$ possible for 50 ns bunch spacing and SEY $= 1.7$
  → instabilities in the SPS @ 25ns (ca. ultimate intensity & emittance)

cooling & e- heat for 25 ns spacing



going above N_b=1.7x10^{11} & ultimate luminosity requires dedicated IR cryo plants; limit then becomes N_b~2.3x10^{11}

cooling & e- heat for 50 ns spacing



going above N_b=2.3x10^{11} & ultimate luminosity requires dedicated IR cryo plants; limit then becomes N_b~5.0x10^{11}

LHC Performance Estimates

Performance reach for LINAC4 + LIU + HL triplet:

		small β*		'large' β*	
Parameter	**nominal**	**25ns**	**50ns**	**25ns**	**50ns**
N	1.15E+11	**2.0E+11**	**3.3E+11**	**2.0E+11**	**3.3 E+11**
n_b	2808	2808	1404	2808	1404
beam current [A]	0.58	**1.02**	**0.84**	**1.02**	**0.84**
x-ing angle [μrad]	300	**420**	**520**	**270**	**320**
beam separation [σ]	10	10	10	10	10
β* [m]	0.55	**0.2**	**0.2**	**0.5**	**0.5**
ε_n [μm]	3.75	**2.5**	**3.75**	**2.5**	**3.75**
ε_L [eVs]	2.51	2.5	2.5	2.5	2.5
energy spread	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	**25**	**37**	**25**	**37**
IBS longitudinal [h]	61 -> 60	**21**	**21**	**21**	**21**
Piwinski parameter	0.68	**1.92**	**1.95**	**0.78**	**0.76**
geom. reduction	0.83	**0.46**	**0.46**	**0.79**	**0.80**
beam-beam / IP	3.10E-03	**4.5E-03**	**4.9E-03**	**7.7E-3**	**8.6E-3**
Peak Luminosity	$1\ 10^{34}$	**$7.0\ 10^{34}$**	**$6.3\ 10^{34}$**	**$4.8\ 10^{34}$**	**$4.4\ 10^{34}$**
Events / crossing	19	**133**	**239**	**91**	**167**

LHC Performance Estimates

Performance reach for LINAC4 + LIU + HL triplet: long bunch

		small β*		'large' β*	
Parameter	**nominal**	**25ns**	**50ns**	**25ns**	**50ns**
N	1.15E+11	**2.0E+11**	**3.3E+11**	**2.0E+11**	**3.3 E+11**
n_b	2808	2808	1404	2808	1404
beam current [A]	0.58	**1.02**	**0.84**	**1.02**	**0.84**
x-ing angle [μrad]	300	**420**	**520**	**270**	**320**
beam separation [σ]	10	10	10	10	10
β* [m]	0.55	0.2	0.2	0.5	0.5
ε_n [μm]	3.75	2.5	3.75	2.5	3.75
ε_L [eVs]	2.51	**3.0**	**3.0**	**3.0**	**3.0**
energy spread	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04
bunch length [m]	7.50E-02	**0.1**	**0.1**	**0.1**	**0.1**
IBS horizontal [h]	80 -> 106	**39**	**56**	**39**	**56**
IBS longitudinal [h]	61 -> 60	**58**	**56**	**58**	**56**
Piwinski parameter	0.68	**2.57**	**2.59**	**1.04**	**1.00**
geom. reduction	0.83	**0.36**	**0.36**	**0.69**	**0.70**
beam-beam / IP	3.10E-03	**3.6E-03**	**4.9E-03**	**6.8E-3**	**7.6E-3**
Peak Luminosity	$1\ 10^{34}$	**$5.5\ 10^{34}$**	**$4.9\ 10^{34}$**	**$4.2\ 10^{34}$**	**$3.9\ 10^{34}$**
Events / crossing	19	**105**	**186**	**80**	**148**

Summary Performance Reach:

Performance Reach of the LHC

-Existing LHC & injectors can reach nominal performance with 25ns and 50ns beams: $L = 1\ 10^{34}\ cm^{-2}\ sec^{-1}$

-Small emittance option with 50ns operation can reach:
$L = 1.7\ 10^{34}\ cm^{-2}\ sec^{-1}$

@ half nominal total beam current for 50ns beam option

-Nominal machine with LINAC4 and 50ns operation can reach:
$L = 2.5\ 10^{34}\ cm^{-2}\ sec^{-1}$

with approximately nominal total beam current

-Full upgrade can reach:
$L \geq 5\ 10^{34}\ cm^{-2}\ sec^{-1}$

with geometric reduction factor!

➔ CC & LRBB wires are ideal tool for leveling!

Options for Leveling:

- CRAB cavities

  -New technology not yet demonstrated for hadron storage rings

- Wires for long range beam-beam compensation:

  -New technology not yet demonstrated for hadron storage rings with long range beam-beam interactions

- Operation with offsets at the IP:

  -Has been difficult in other machines

- Dynamic optics change during physics collisions:

  -Has never been done so far in a collider plus complication of crossing angle in common beam pipes for the LHC

Spare Transparencies

LHC Challenges: Beam-Beam Interaction

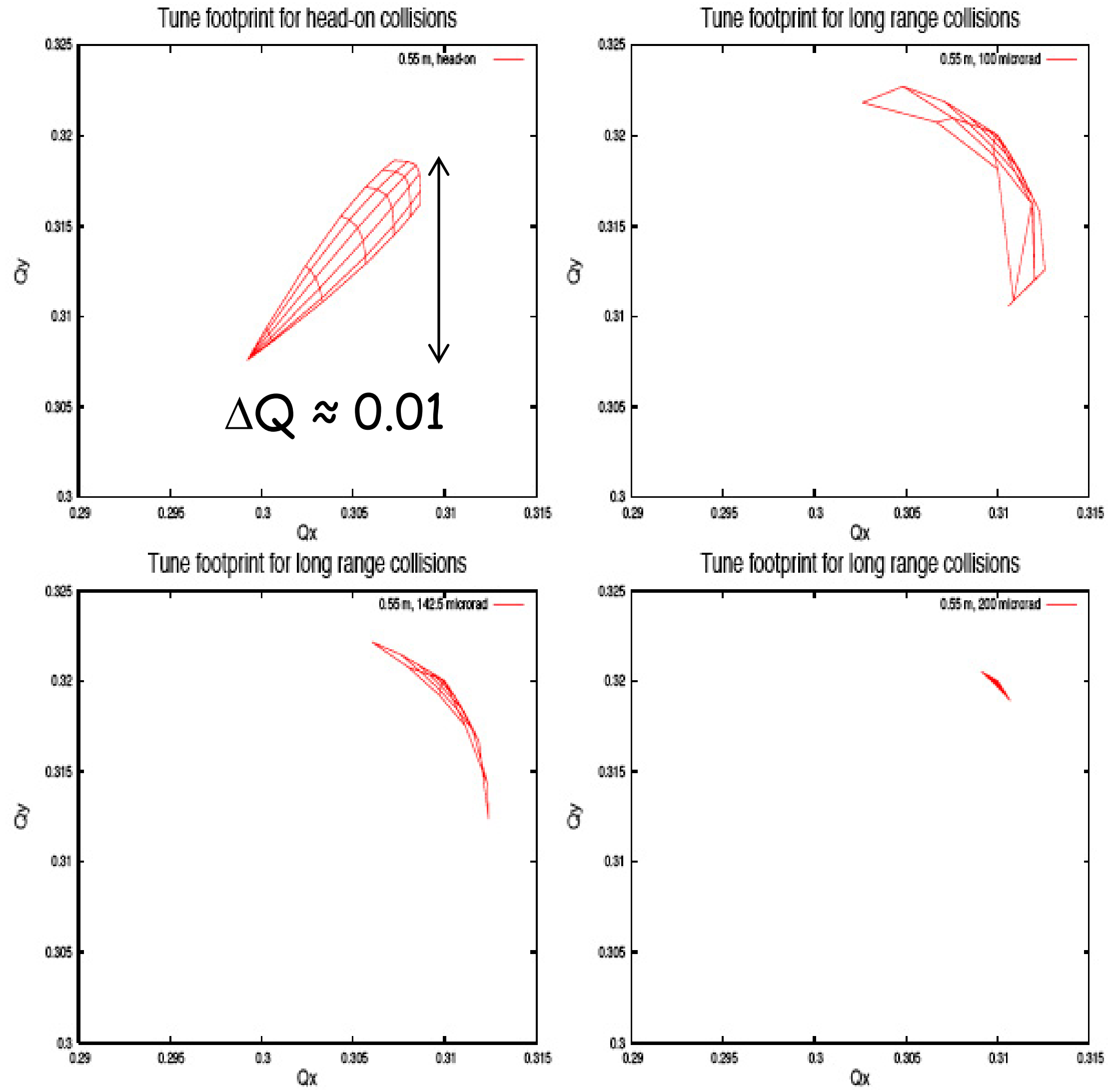
- Tune spread due to head-on beam-beam interaction wo x-ing:

$$\xi_{beam-beam} = \frac{r_p}{4\pi} \cdot \frac{N_b}{\varepsilon_n}$$

- Long range interactions:

Crossing angle configurations:

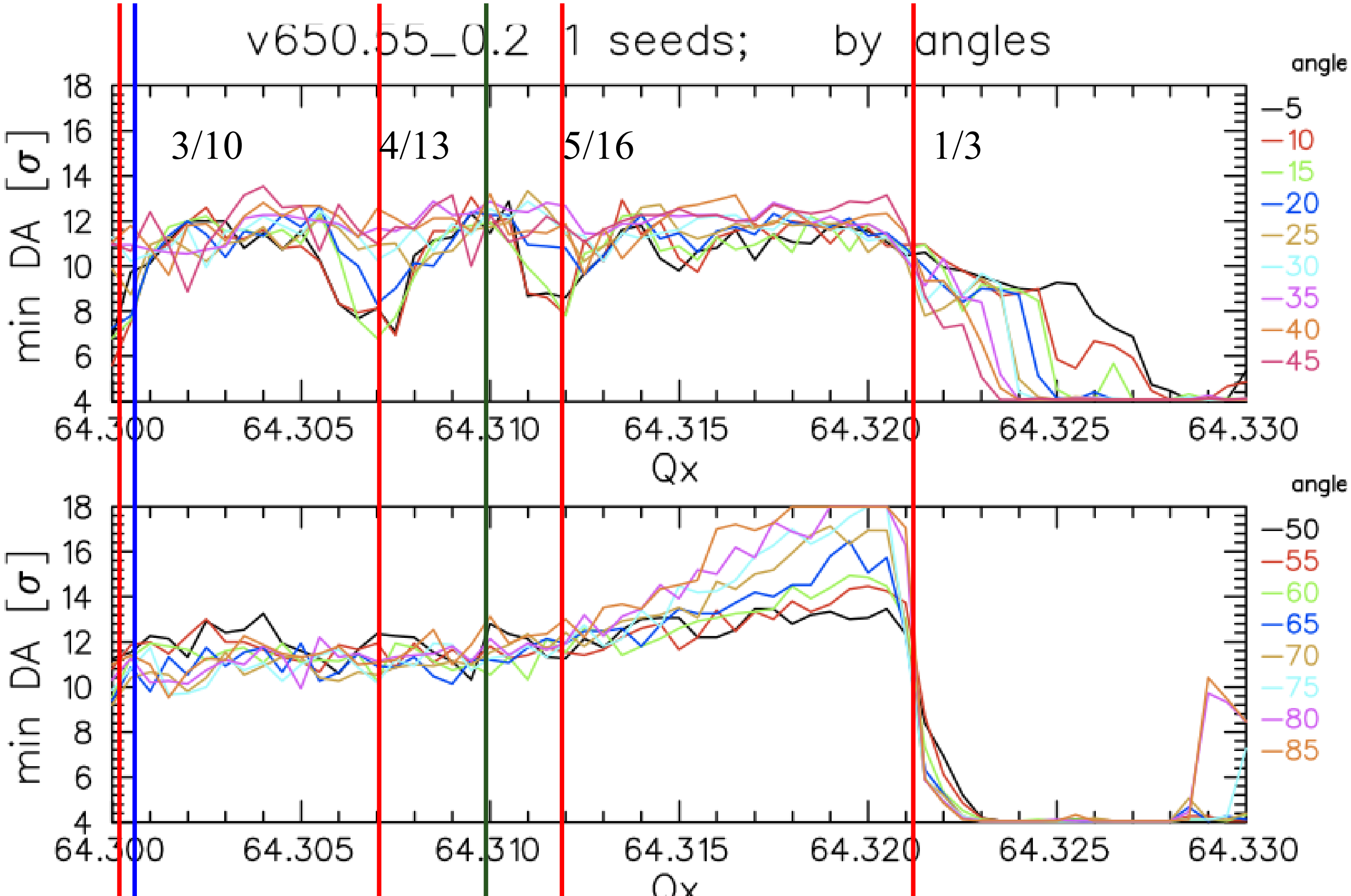
Top Left:	only head-on
Top right:	= 200µrad (≈ 7σ)
Bottom left:	= 285µrad (≈ 10σ)
Bottom right	= 400µrad (≈ 13σ)



Werner Herr et al, LPN 416

LHC Challenges: Beam-Beam Interaction

Werner Herr &



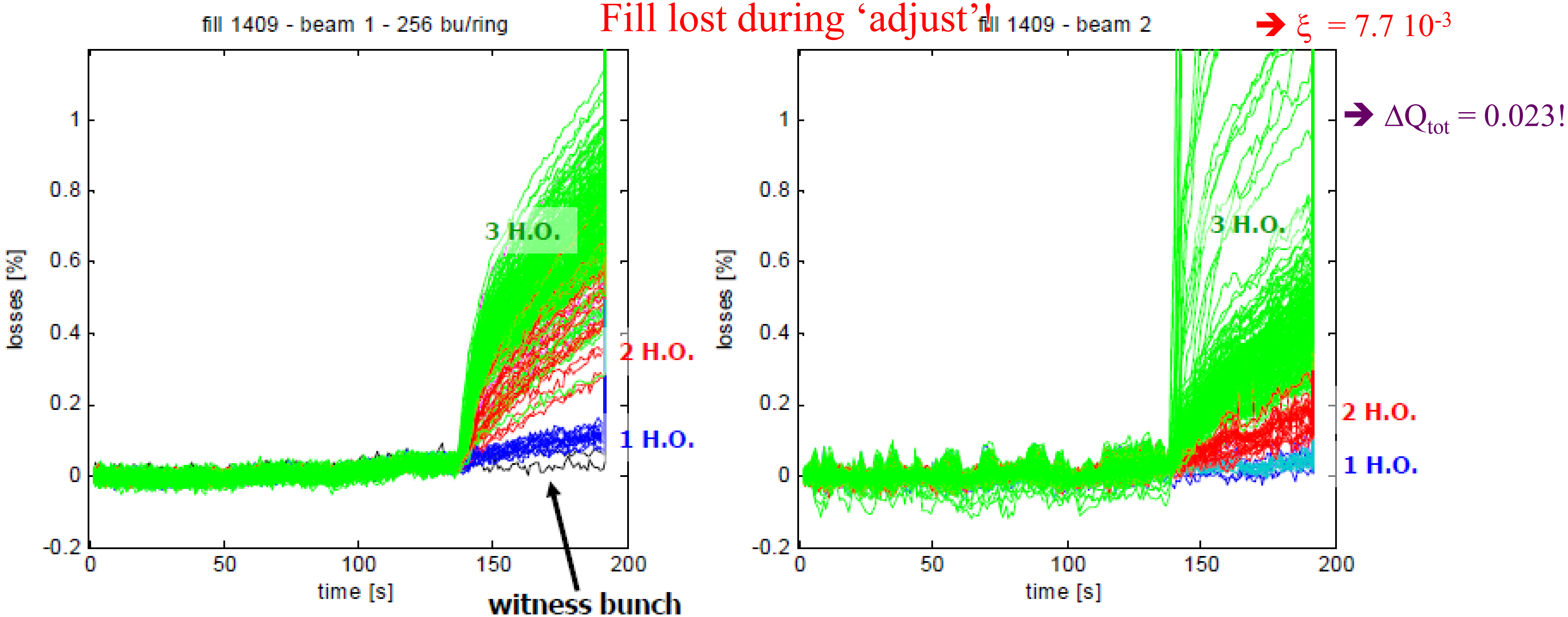
with b-b and ΔQ_{tot} = 0.01 nominal tune

$\xi_{bb} = 3.3\ 10^{-3}$

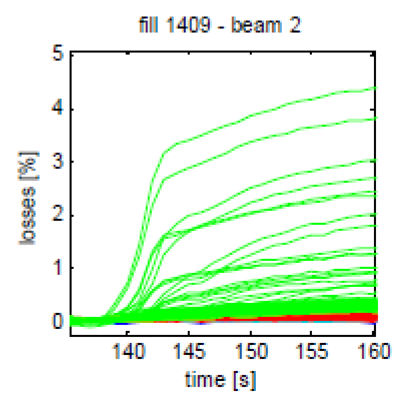
Beam-Beam: Bunch by bunch

Fill 1409: 12.10.2010

$\varepsilon_n = 1.6\ \mu m$; $N_b = 10^{11}$; 256 bunches



- beams dumped right after colliding (~1 minute)
- clear dependence of losses on number of H.O. collisions
- some bunches b2 lose up to 5% in the first few seconds
  - 12 out of 14 biggest losers from first 3 16-bunch injections
    - 10^{th} 11^{th} 12^{th} 13^{th} in the 16-bunch train

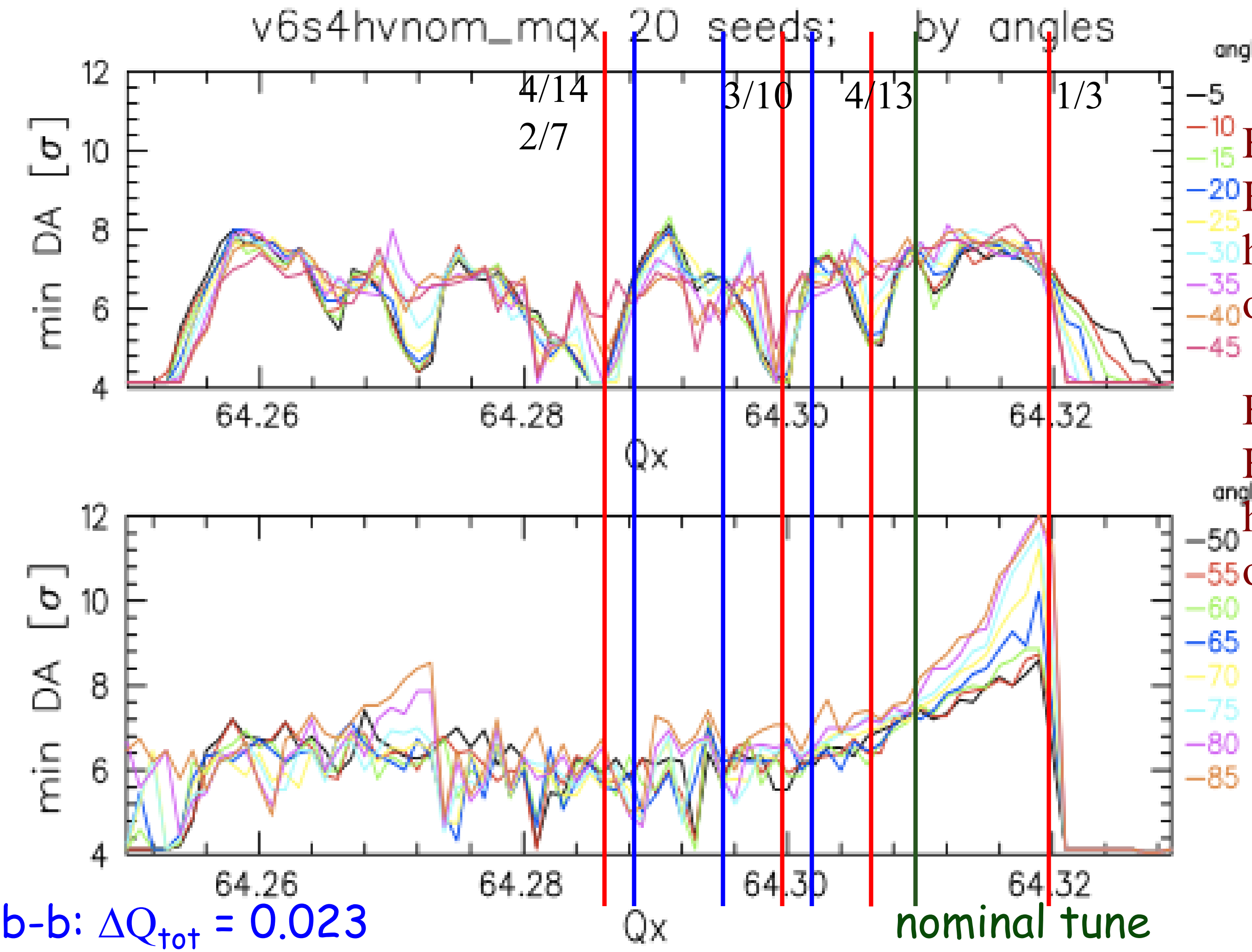


IPs: 1 5 2 8 - 1 5 8 - 1 5 2 - 1 5 - 2 8 - 8 - 2

giulia papotti (BE/OP/LHC)

LHC Challenges: Beam-Beam Interaction

Werner Herr & Itchev



Bunches with 2 HO collisions have 1 σ particles on 3/10th resonance!

Bunches with 3 HO collisions have 2 σ particles on 3/10th resonance!

with 3 b-b: $\Delta Q_{tot} = 0.023$

$\xi_{bb} = 7.7\ 10^{-3}$

Assumptions on Injector Performance I:

PAC'07;
CERN-AB-2007-037

- Existing injector performance:

-50ns: 1.2 10^{11} ppb; ε_n = 2.5µm to 3 µm (SB injection into PS)
-50ns: 1.2 10^{11} ppb; ε_n = 1.5 µm (DB 2008 MD [EM])
-50ns: 1.7 10^{11} ppb; ε_n = 3µm to 4 µm (SB injection into PS)
➔ limited by SPS single bunch

➔ 1.7 10^{11} ppb; ε_n = 1.8µm to 2.5µm with DB?!?

-25ns: 1.2 10^{11} ppb; ε_n = 3µm to 4 µm (GA)
-25ns: 1.4 10^{11} ppb; ε_n = 4µm to 10µm (limited by SPS instabilities [EC])

- Existing injector performance with LINAC4:

-50ns: 2.5 10^{11} ppb; ε_n = 3.5 µm (if not limited by e-cloud; scaled from 2008 MD and relying on lower γ-t SPS lattice)
-25ns: 1.4 10^{11} ppb; ε_n =3.5µm – 10µm (single batch [MV 2010& EC])

Assumptions on Injector Performance II:

- Injector performance with LINAC4 and upgrades (PSB):

-50ns: 2.7 10^{11} <-> 3.5 10^{11} ppb; ε_n = 1.1 μm <-> ε_n = 1.5 μm
(SG, MG and HD assuming a Laslett space charge limit of ΔQ = -0.3)

-25ns: 1.7 10^{11} <-> 2.0 10^{11} ppb; ε_n = 1.5 μm <-> ε_n = 1.8 μm
(SG, MG and HD assuming a Laslett space charge limit of ΔQ = -0.3)

- Injector performance with LINAC4 and upgrades: SPS SC limit

-50ns: 3.3 10^{11} ppb; ε_n = 3.75 μm (SPS space charge EC: ΔQ = -0.13)

-25ns: 2.0 10^{11} ppb; ε_n = 2.5 μm (SPS space charge EC: ΔQ = -0.13)

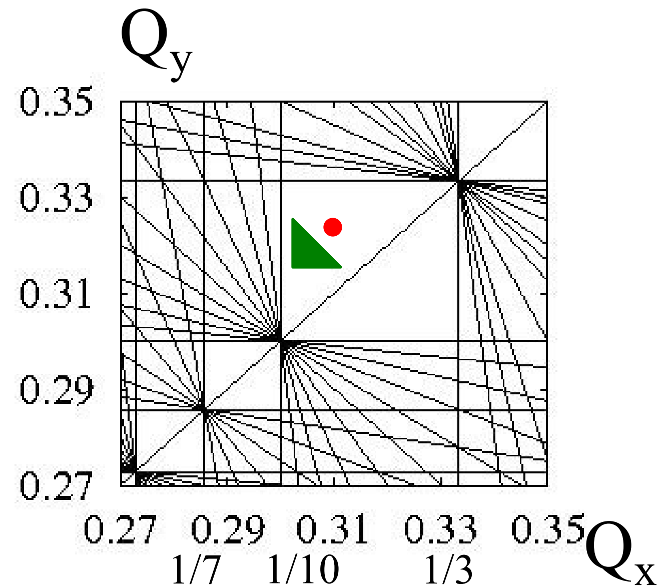
Other Potential Performance Limitations

- electron cloud effects ➔ vacuum & beam instabilities
  ➔ cryogenic load (in the LHC)
  ➔ bunch spacing (50ns) ➔ beam scrubbing
- UFOs ➔ fill abort and overall efficiency
  ➔ beam scrubbing?
- collective effects: ➔ TMCI threshold of 3.5 10^{11}ppb (Q' = 0)
  ➔ coupled bunch limit might be smaller
  for modified cleaning insertions
- faults and overall efficiency: ➔ average turnaround time
  & (R2E) ➔ statistics (Evian: ca. 25%)

LHC Challenges: Beam-Beam Interaction

- LHC working point: n+m < 12

➔ $Q_x = 64.31; Q_y = 59.32$
total tune spread must be
smaller than 0.018 (SppS experience)
keep $\delta Q = 8\ 10^{-3}$ for operation tolerances
and coupling!



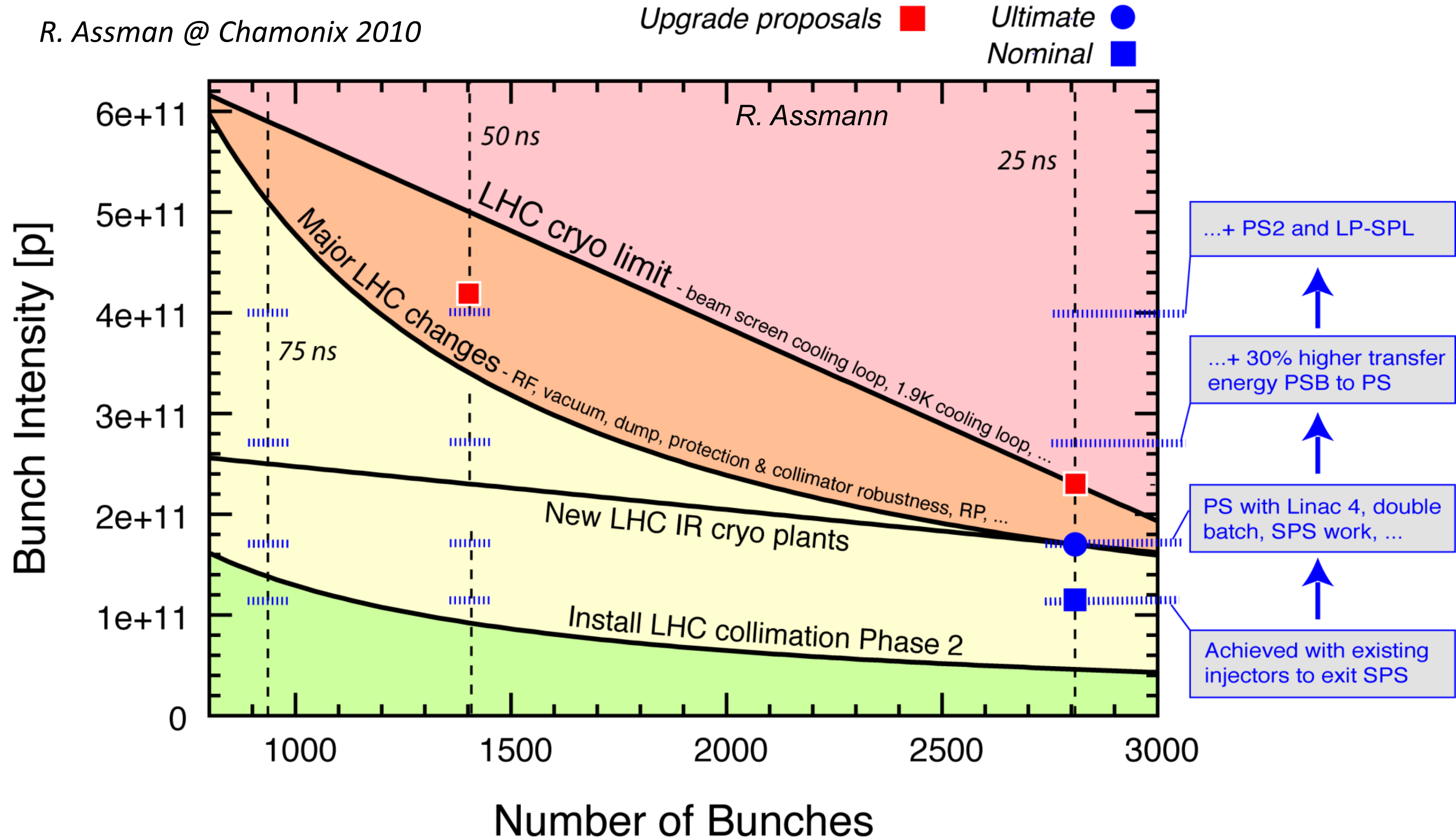
- bunch intensity limited by beam-beam force:

3 head-on/bunch ➔ $\xi_{beam\text{-}beam} < 3.3\ 10^{-3}$ ➔ $N < 1.2\ 10^{11}$

2 head-on/bunch ➔ $\xi_{beam\text{-}beam} < 5\ 10^{-3}$ ➔ $N < 1.7\ 10^{11}$

Summary of LHC Intensity Limits (7 TeV)

R. Assman @ Chamonix 2010



Ideal scenario: no imperfections included!

Note: Some assumptions and conditions apply…

2011

3.5 TeV: run flat out at ~100 pb^{-1} per month

5 TeV:

- start with optimistic end of 2010 level
- tight collimator settings and limits given by Ralph & Werner

	No. bunches	**ppb**	**Total Intensity**	**beta***	**Peak Lumi**	**Int Lumi [pb^{-1}]**
50 ns	432	7 e10	3 e13	2	1.3 e32	~85
Pushing intensity limit	720	7 e10	5.1 e13	2	2.2 e32	~140
Pushing bunch current limit	432	11 e10	4.8 e13	2	3.3 e32	~209

Either way should be able to deliver around 1 fb^{-1}

Collisions in 2010:

Fill	# bunch	N bunch [10^{11} p]	$\varepsilon_{H/V}$ B1 @inj [μm]	$\varepsilon_{H/V}$ B2 @inj [μm]	L_{peak} [10^{32} $cm^{-2}s^{-1}$]	$\varepsilon_{H/V}$ @coll. from lumi [μm]	Stable beams [h]	L_{int} [pb^{-1}]	Reason for dump	$\varepsilon_{H/V}$ @end of coast (from Lumi scan) [μm]
1408	248	1.02	-	-	0.94	2.5	9.5	>2.4	Prog.	3.8/3.9
1410	256	1.04	1.5/1.3	1.4/1.6	1.3	1.8	0	0	BLM on MQW	-
1418	248	1.04	1.7/1.6	2.1/2.2	1.03	2.4	8.5	>2.4	PC IT.R1	-
1422	16	0.78	2.4/2.6	2.6/3.2	0.018	3.9	5.5	0.03	LBDS	-
1424	312	1.13	2.0/1.9	2.2/2.4	1.35	2.6	1	0.4	UFO LHCb BCM	-
1427	312	0.89	2.0/1.8	2.2/2.4	0.86	2.6	9.5	2.3	Prog.	3.2/3.1
1430	312	1.15	-	-	1.48	2.4	0.6	0.3	UFO Pt.4	-

- Typical emittances in collision 2.5 μm

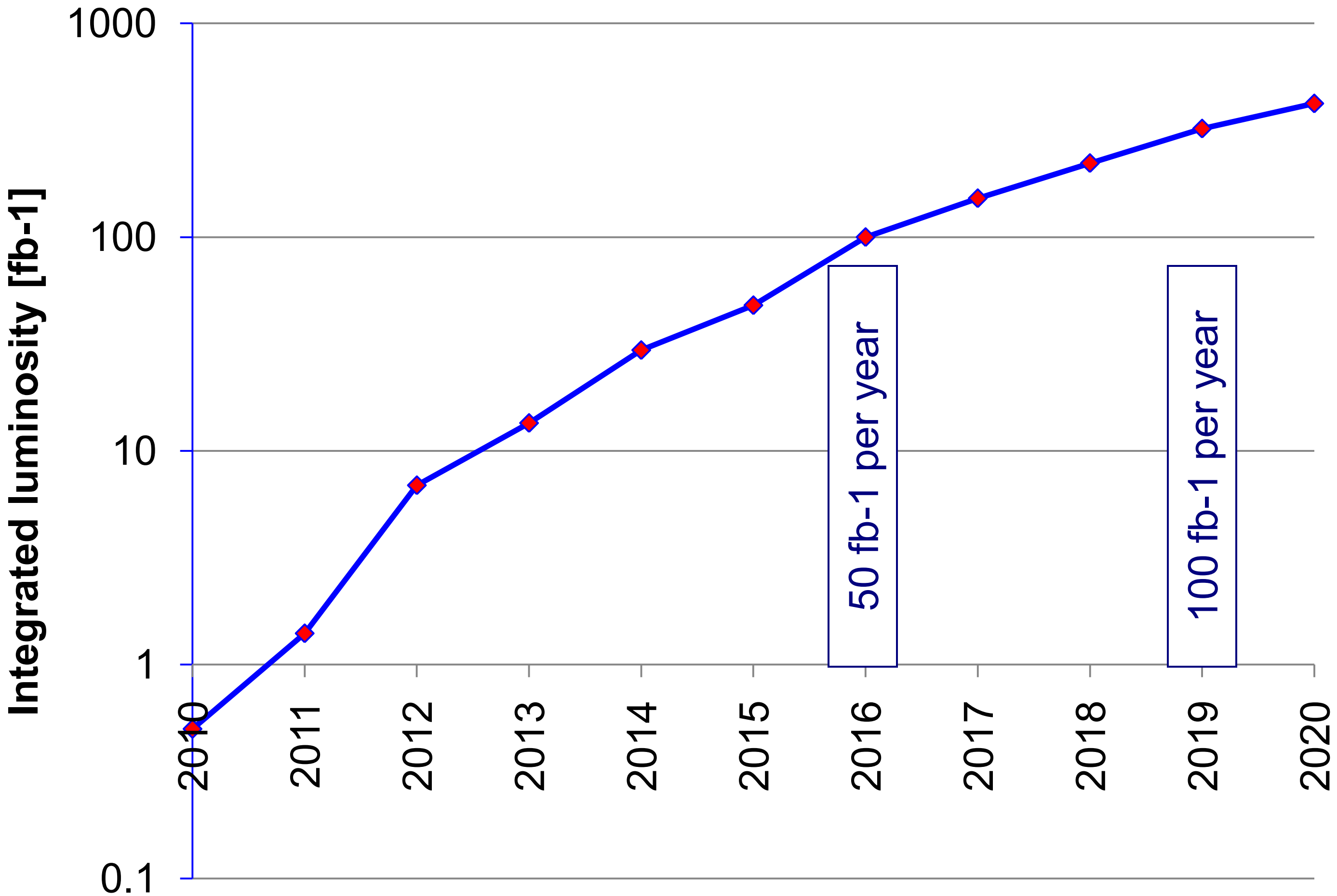
  ➔ ca. 50% higher than nominal beam-beam parameter!!!

Projecting

M. Lamont @ Chamonix 2010

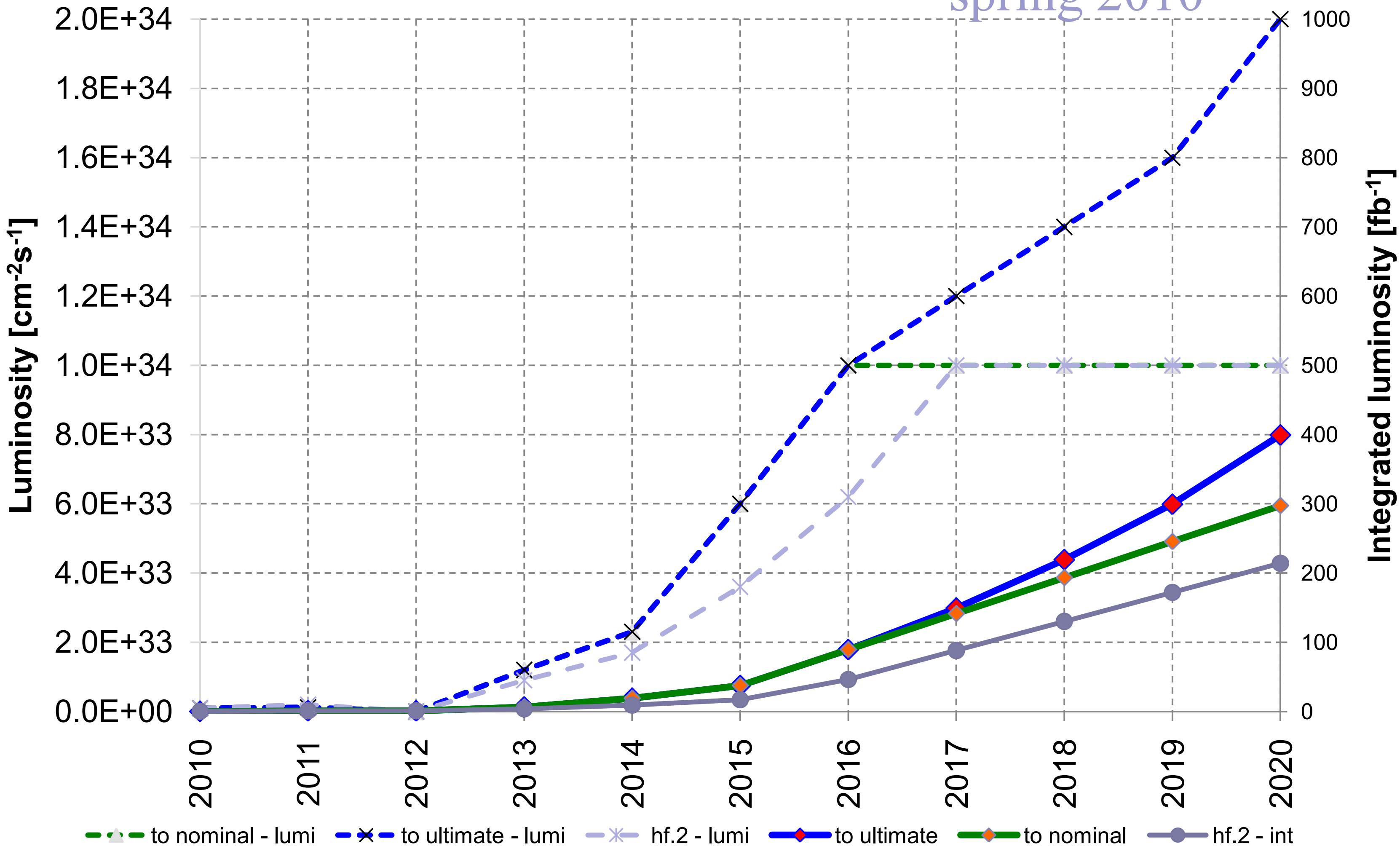
Pushing to nominal in 2016 and taking a couple of years to get to get to ultimate

[potential to push phase 1 upgrade not included]



Updated LHC lumi vs. (end of) year

Courtesy of M. Lamont, spring 2010



3.5 TeV: run flat out at ~100 pb^{-1} per month

	Nb	ppb	Total Intensity	MJ	beta*	Peak Lumi	Int Lumi per month [pb^{-1}]
50 ns	432	7 e10	3 e13	17	2.5	7.4 e31	~63 (34)
Pushing intensity limit	796	7 e10	5.1 e13	31	2.5	1.4 e32	~116 (63)

16% nominal

Should be able to deliver around 1 fb^{-1}