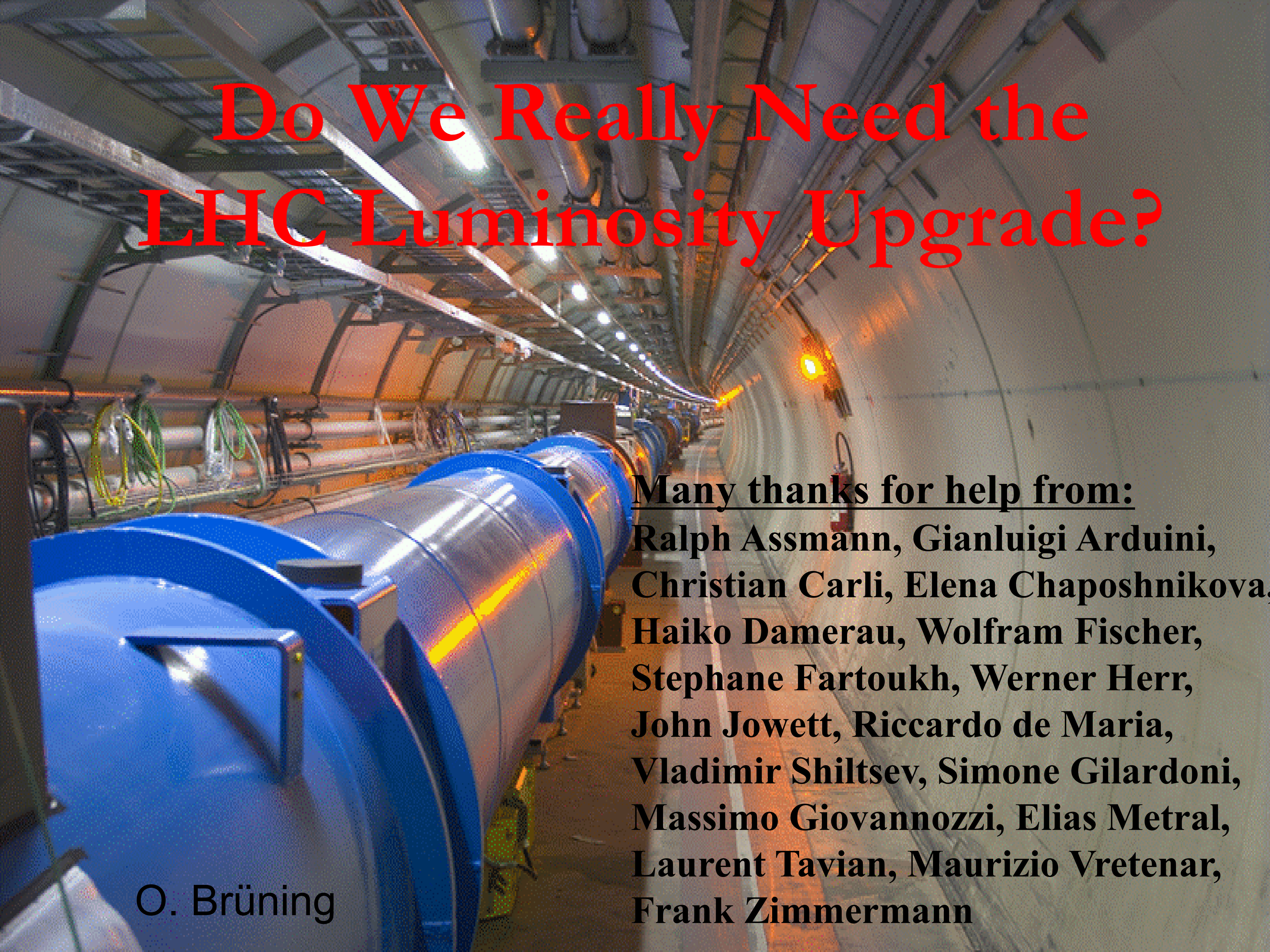
Do We Really Need the LHC Luminosity Upgrade?



Many thanks for help from:

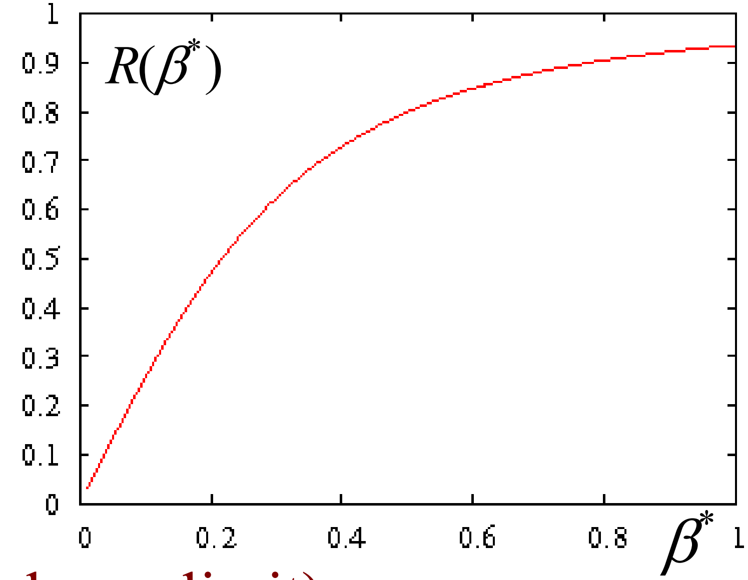
Ralph Assmann, Gianluigi Arduini, Christian Carli, Elena Chaposhnikova, Haiko Damerau, Wolfram Fischer, Stephane Fartoukh, Werner Herr, John Jowett, Riccardo de Maria, Vladimir Shiltsev, Simone Gilardoni, Massimo Giovannozzi, Elias Metral, Laurent Tavian, Maurizio Vretenar, Frank Zimmermann

O. Brüning

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

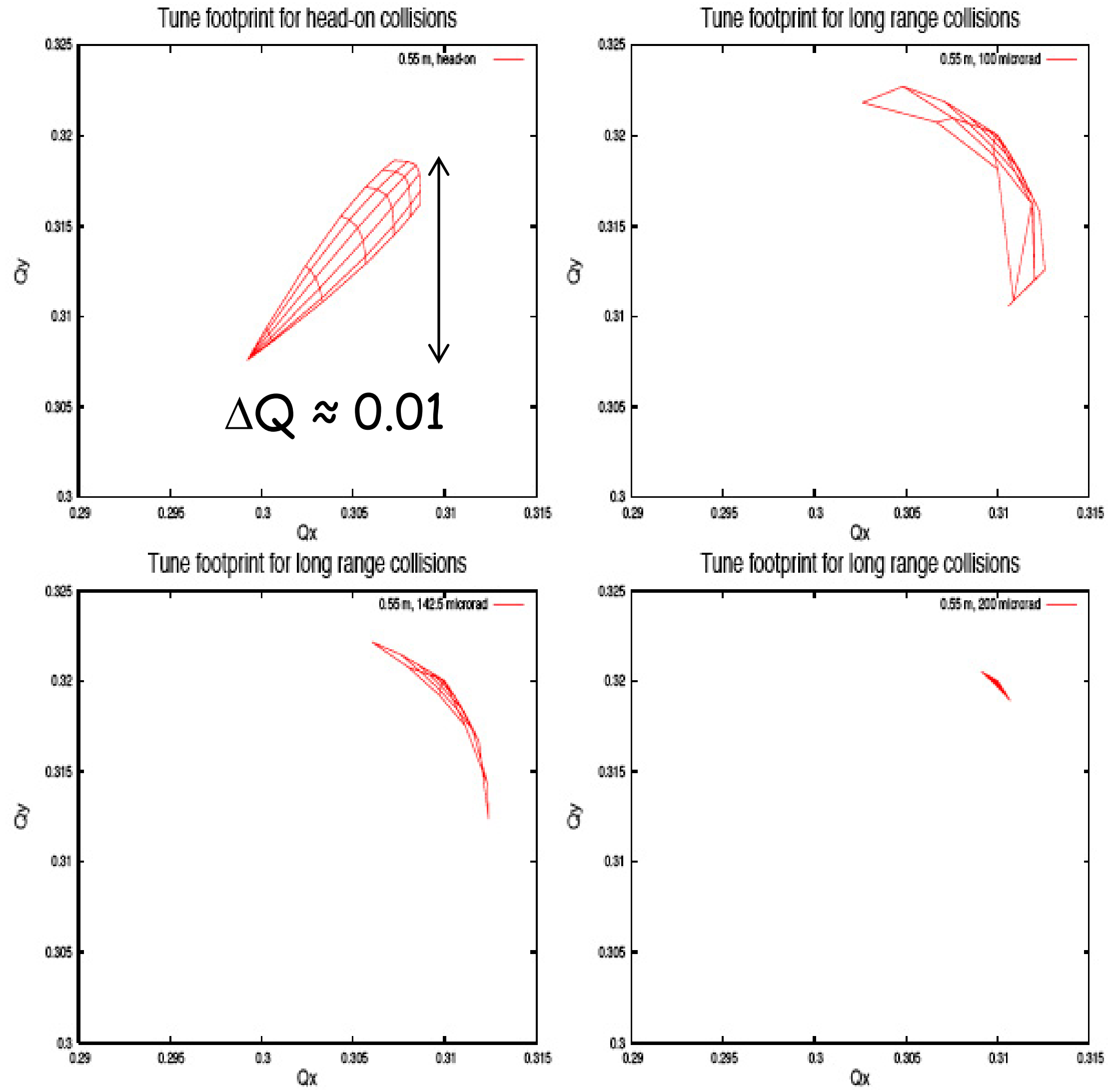
➔ What is the beam-beam limit in the LHC?!

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)

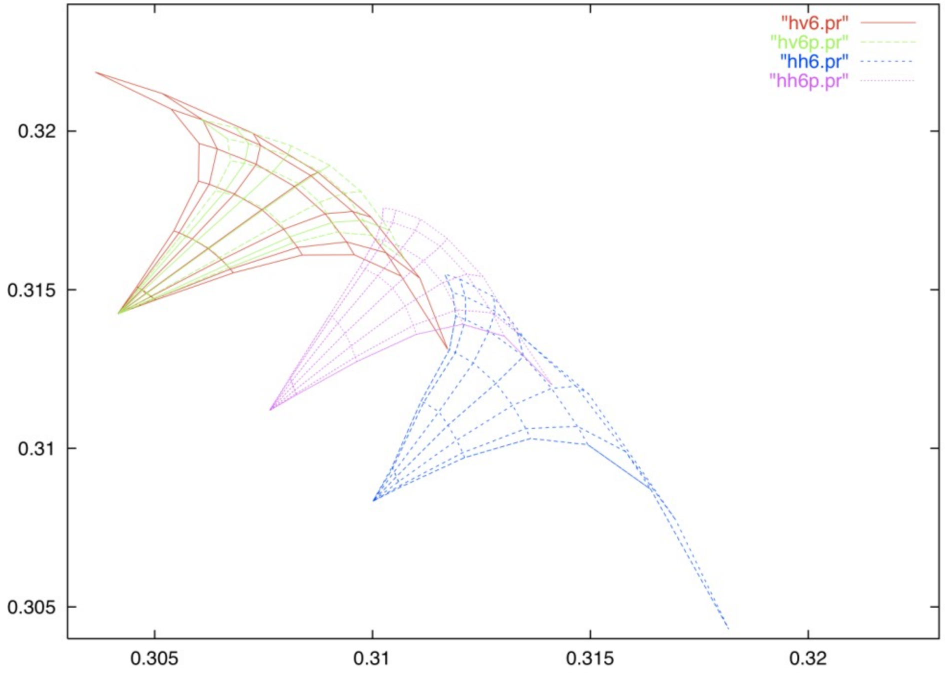
Werner Herr et al, LPN 416

LHC Challenges: Beam-Beam Interaction

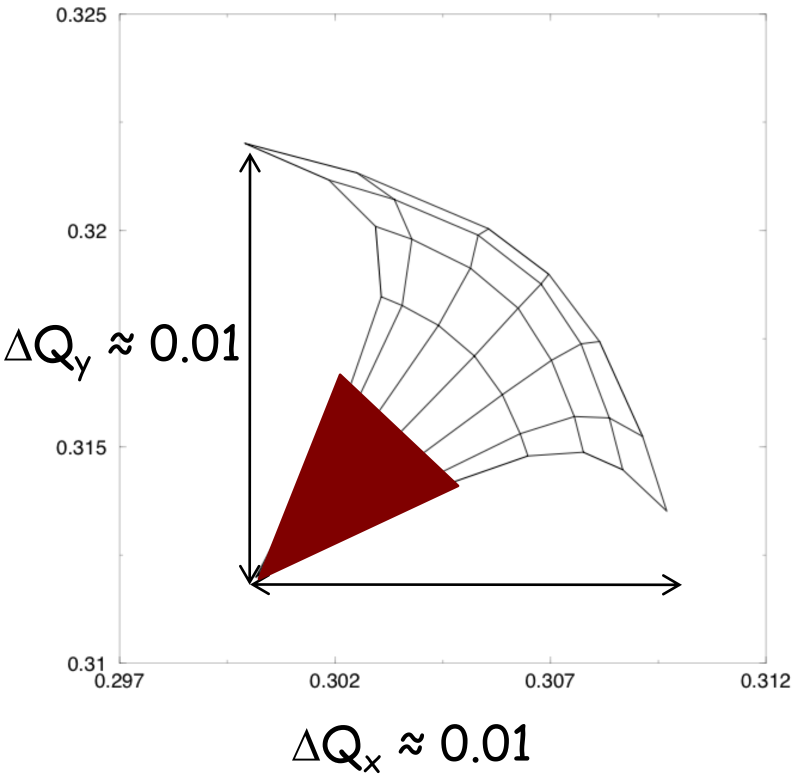
- Tune Footprint:

Pacman bunches
alternating crossing planes

nominal beams
all insertions
Head-on &
Long range



Werner Herr



Expected Beam-Beam limit for the LHC

- Experience from other machines:

1)SppS: $\xi = 0.006$ with 3 IPs ➔ $\Delta Q = 0.018$

Jacques Gareyte
@ LHC'99

2)Tevatron: $\xi = 0.01$ with 2 IPs ➔ $\Delta Q = 0.02$

V. Shiltsev &
PRST, A&B 8, 2005

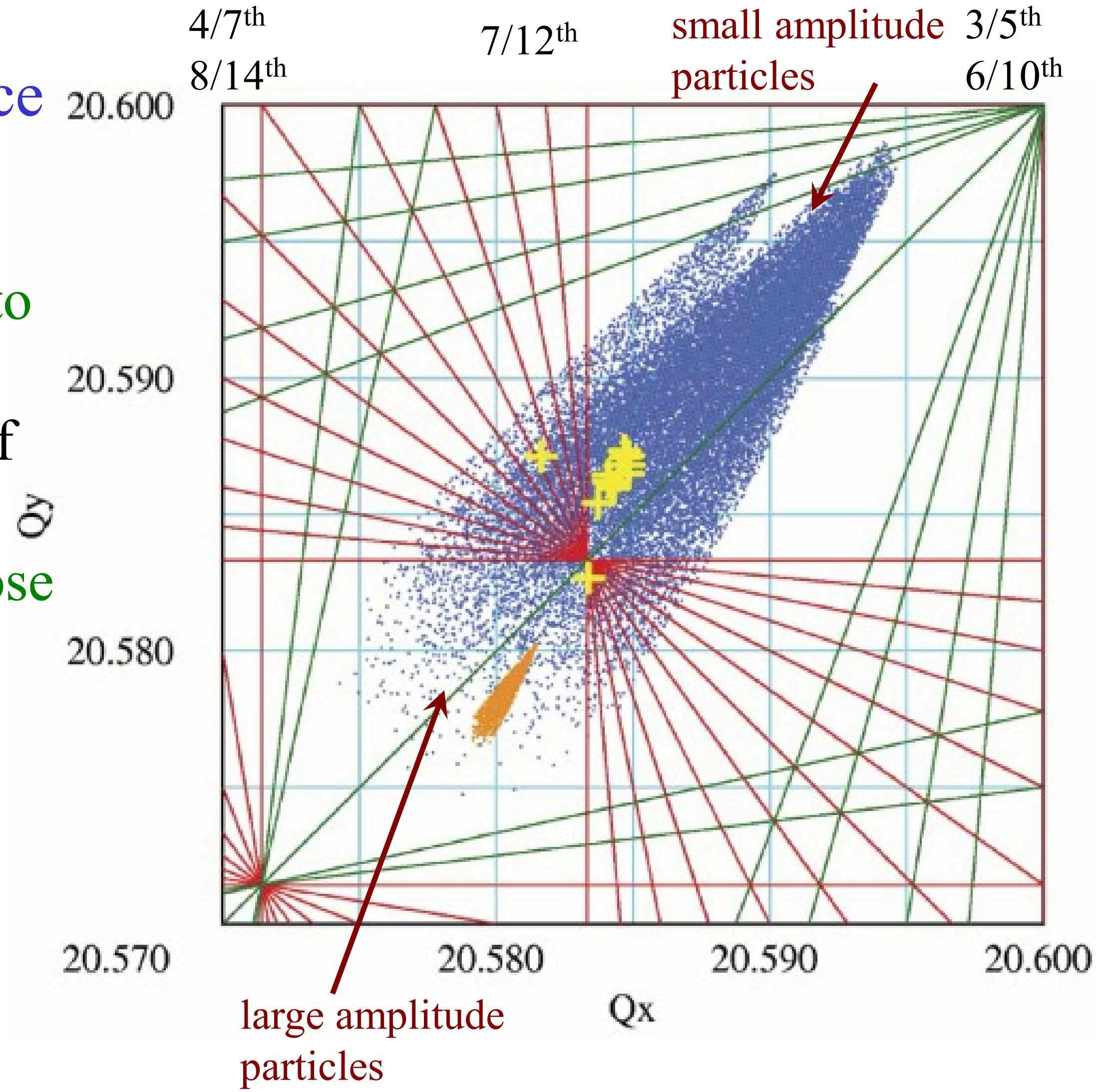
3)The performance in both colliders is limited by resonances and the b-b tune spread: avoid resonance of order 12 or lower! ➔ the tune is sandwiched between a low order resonance driven by lattice non-linearity and a high order resonance driven by beam-beam

4)Higher b-b tune shifts are possible but with degraded performance (luminosity lifetime and background – not yet a problem in the LHC)

Expected Beam-Beam limit for the LHC

- Tevatron Run2 experience

1)Vertical ε blow up largest if small amplitude particles close to $3/5^{th}$ or $7/12^{th}$.
2)Horizontal ε blow up largest if tune close to $7/12^{th}$.
3)Halo particles lost faster if close to $7/12^{th}$.
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

Expected Beam-Beam limit for the LHC

- Nominal LHC configuration and design report assumption:

Jacques Gareyte @ LHC'99

1)Place the tunes between 10th and 3rd order resonances: $Q_x = 64.31$; $Q_y = 59.32$ (SppS equivalent below the half integer)

2)Assuming that coupling will be bigger in the LHC than in the SppS, the LHC tunes are separated by $\delta Q = 0.01$ ➔

➔ total space available in tune diagram: $\Delta Q = 0.01$

➔ can go to $\Delta Q = 0.015$ if coupling is small and $\delta Q = 0.005$.

3)Use alternate crossing planes to minimize overall tune foot print with long-range beam-beam.

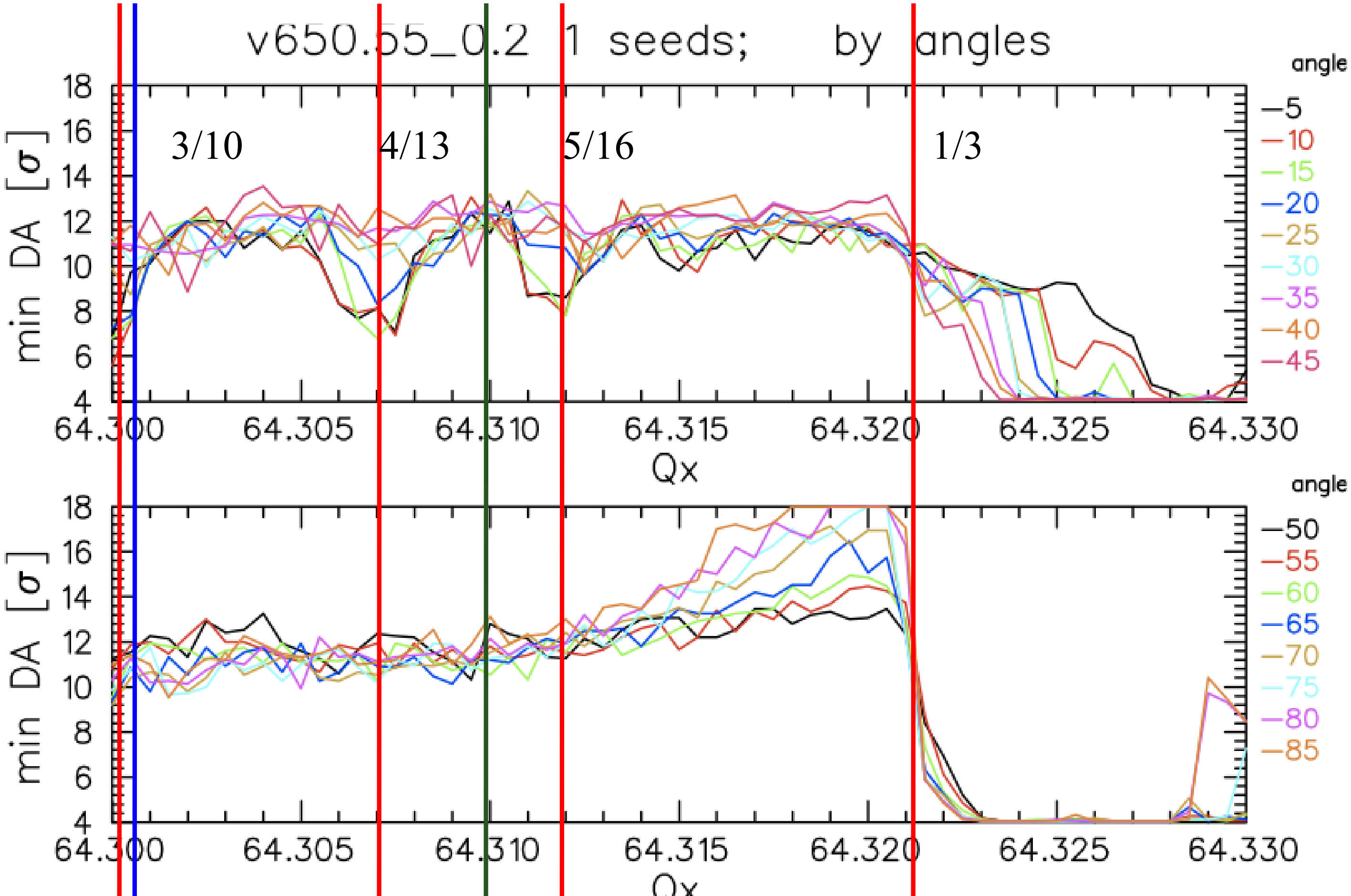
Jacques Gareyte @ LHC'99

3)Use β^* to control long-range beam-beam (soft landing)

LHC Challenges: Beam-Beam Interaction

DA from simulations:

Werner Herr &
Dobrin Kaltchev



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

ξ_{bb} = 3.3 10^{-3}

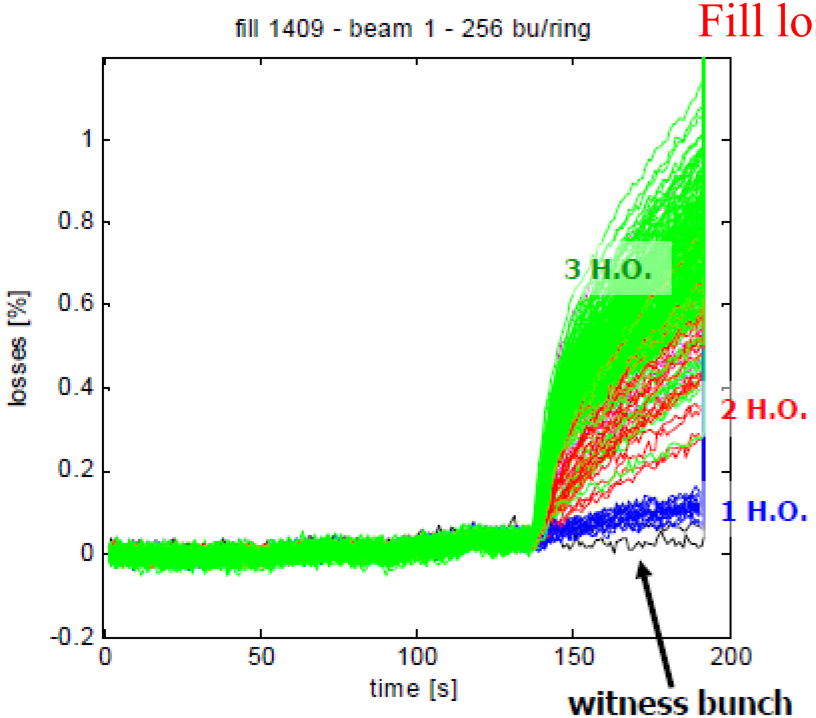
Beam-Beam: Bunch by bunch

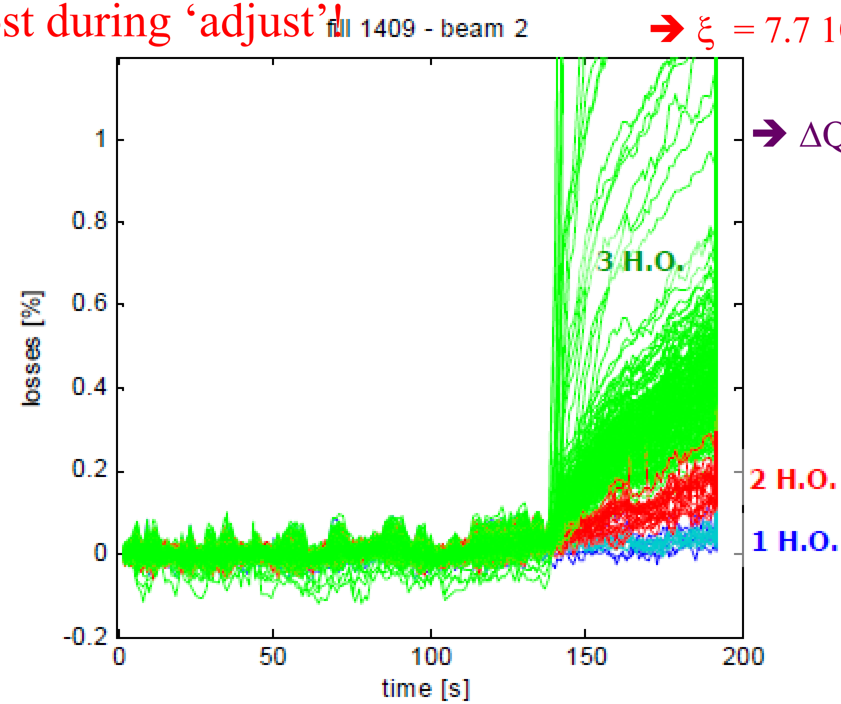
Fill 1409: 12.10.2010
$\varepsilon_n = 1.6\ \mu m$; $N_b = 10^{11}$; 256 bunches

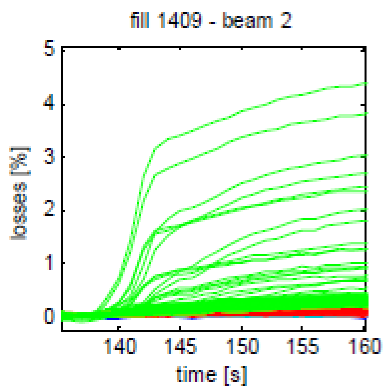
Fill lost during 'adjust'!

→ $\xi = 7.7\ 10^{-3}$

→ $\Delta Q_{tot} = 0.023$!!







- 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
    - 10th 11th 12th 13th in the 16-bunch train

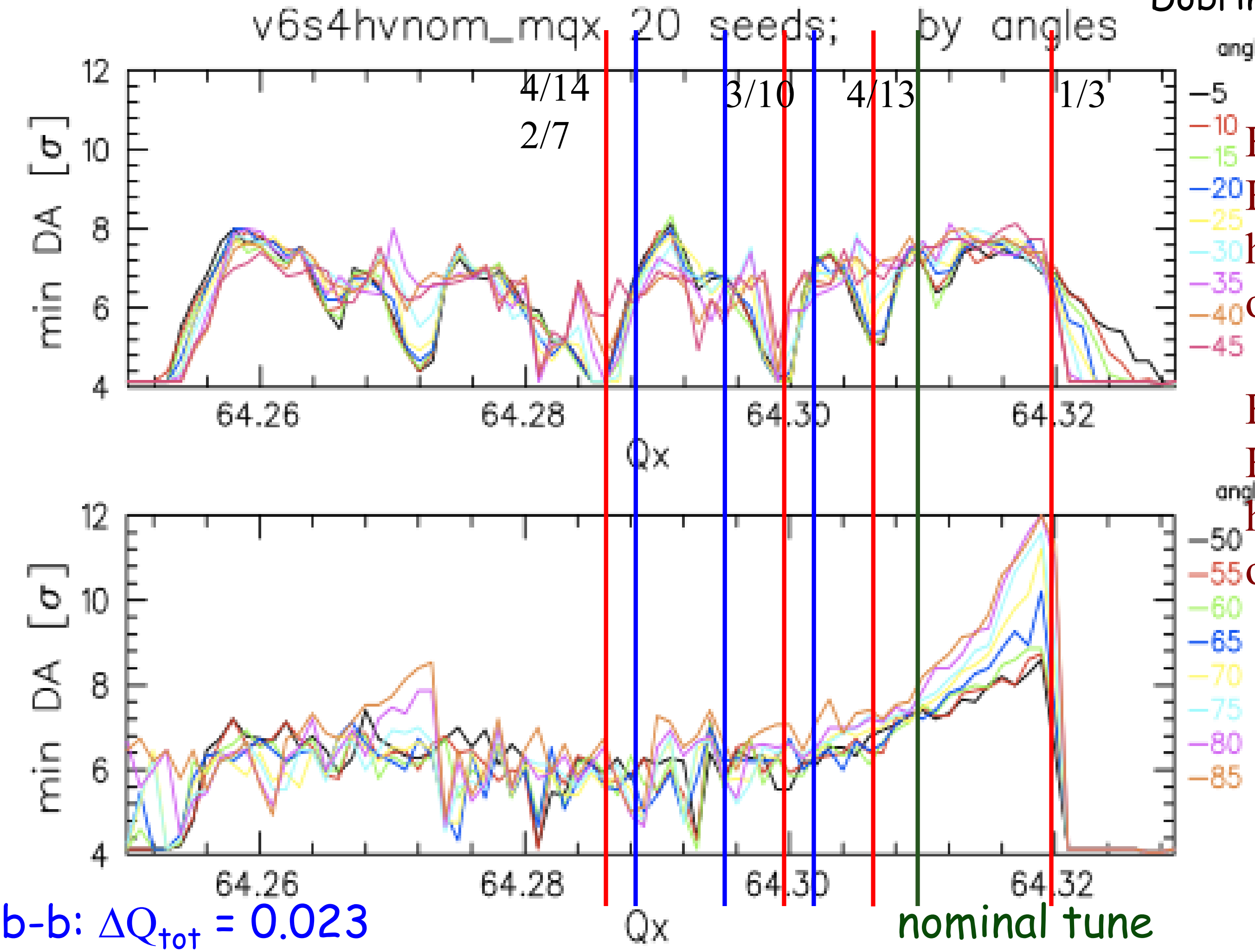
IPs: 1 5 2 8 - 1 5 8 - 1 5 2 - 1 5 - 2 8 - 8 - 2

giulia papotti (BE/OP/LHC)

LHC Challenges: Beam-Beam Interaction

DA from simulations:

Werner Herr &
Dobrin Kaltchev



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: $\Delta Q_{tot} = 0.023$

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

Expected Beam-Beam limit for the LHC

Modified LHC configuration:

1)Avoid small amplitude particles close to resonance clusters. Halo particles are also faster lost if close to resonance but impact on luminosity should be small

Tevatron

1)Divide the bunches in 3 groups: 1, 2 and 3 head on collisions

2)Adjust pre collision tune such that all tunes are below 1/3rd resonance and low amplitude particles for each group are above a strong resonance cluster:

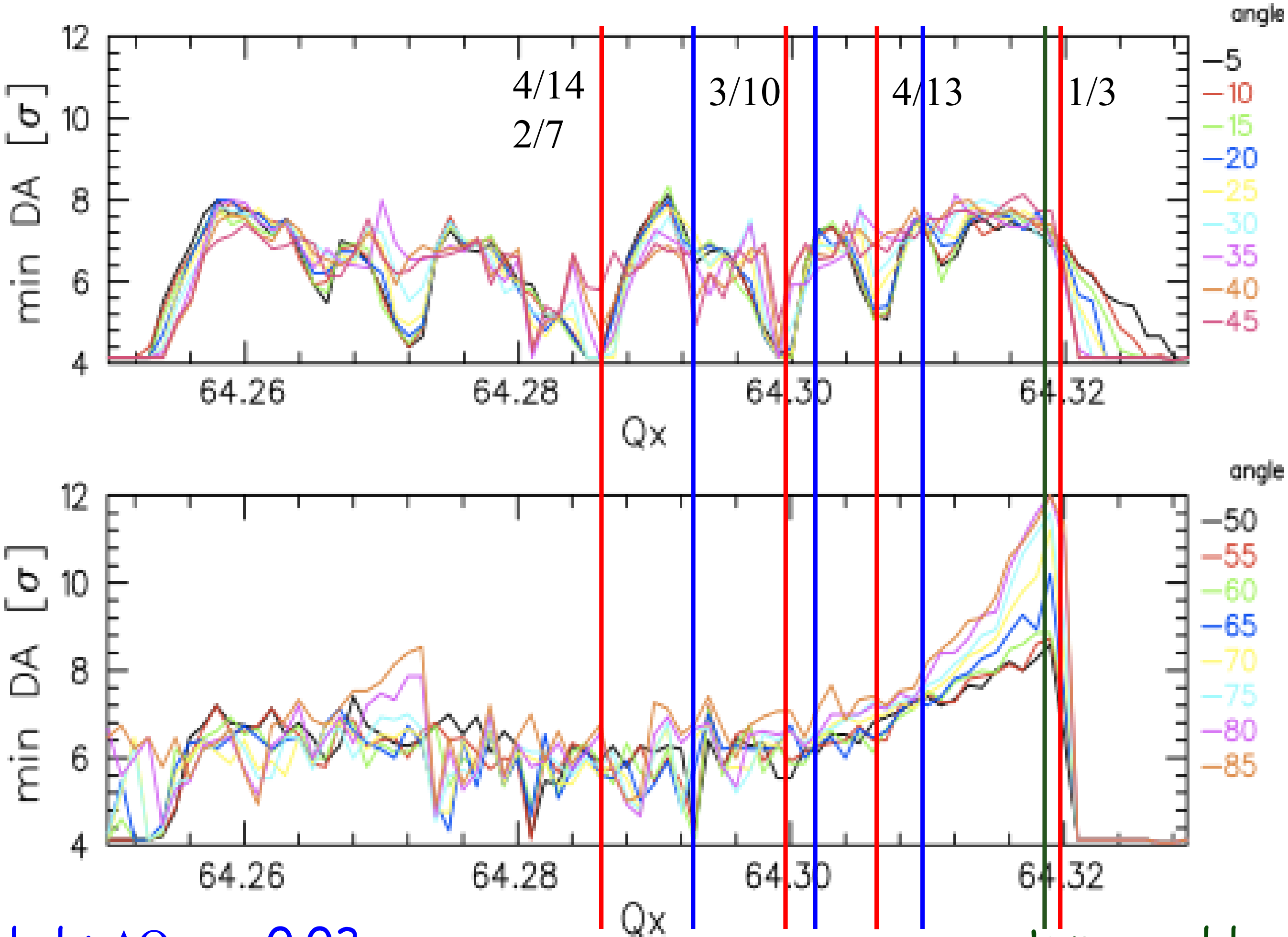
- One group above 4/13th
- One group above 3/10th
- One group above 2/7th

LHC Challenges: Beam-Beam Interaction

Werner Herr & Dobrin Kaltchev

Simulation @ injection

- DA from simulations:



Assume in the following:

$\Delta Q_{tot} = 0.02$

and

$\xi_{bb} = 0.007$

with 3 b-b: $\Delta Q_{tot} = 0.03$
$\xi_{bb} = 10\ 10^{-3}$

Performance estimates in terms of β^* :

- 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:
  -β^* of 0.15m accessible for round beams @ 7 TeV
  -β^* of 0.3m / 0.075m accessible for flat beams @ 7 TeV

S. Fartoukh

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

J. Gareyte

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

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])

LHC Performance Estimates

Performance reach for existing machines @ 7 TeV:

Parameter	nominal	nominal emittance 25ns	nominal emittance 50ns	small emittance 50ns
N	1.15E+11	1.2E+11	1.7E+11	1.7E+11
n_b	2808	2808	1404	1404
beam current [A]	0.58	0.61	**0.43**	**0.43**
x-ing angle [μrad]	300	**320**	**320**	**270**
beam separation [σ]	10	10	10	10
β^* [m]	0.55	**0.5**	**0.5**	**0.5**
ε_n [μm]	3.75	3.75	3.75	2.5
ε_L [eVs]	2.51	2.5	2.5	2.5
energy spread	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
IBS horizontal [h]	80 -> 106	101	71	**29**
IBS longitudinal [h]	61 -> 60	58	41	**25**
Piwinski parameter	0.68	0.76	0.76	0.78
geom. reduction	0.83	0.80	0.80	0.79
beam-beam / IP	3.10E-03	**3.1E-03**	**4.4E-03**	**6.6E-03**
Peak Luminosity	$1\ 10^{34}$	**$1.0\ 10^{34}$**	**$1.2\ 10^{34}$**	**$1.7\ 10^{34}$**

Radiation damping:
hor: 26h
ver: 13h

LHC Performance Estimates

Performance reach for existing machines + LINAC4:

Parameter	nominal	nominal emittance 25ns	nominal emittance 50ns
N	1.15E+11	**1.4E+11**	**2.5E+11**
n_b	2808	2808	1404
beam current [A]	0.58	0.71	0.64
x-ing angle [μrad]	300	**320**	**320**
beam separation [σ]	10	10	10
β^* [m]	0.55	**0.5**	**0.5**
ε_n [μm]	3.75	3.75	3.75
ε_L [eVs]	2.51	2.2	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	80	45
IBS longitudinal [h]	61 -> 60	41	23
Piwinski parameter	0.68	0.76	0.76
geom. reduction	0.83	0.80	0.80
beam-beam / IP	3.10E-03	**3.64E-03**	**6.5E-03**
Peak Luminosity	$1\ 10^{34}$	**$1.6\ 10^{34}$**	**$2.5\ 10^{34}$**

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)

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	$1\ 10^{34}$	**$7.0\ 10^{34}$**	**$6.3\ 10^{34}$**	**$4.8\ 10^{34}$**	**$4.4\ 10^{34}$**

LHC Performance Estimates

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

Parameter	nominal	small β* 25ns	small β* 50ns	'large' β* 25ns	'large' β* 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	**>40**	**56**	**>40**	**56**
IBS longitudinal [h]	61 -> 60	**>40**	**56**	**>40**	**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	$1\ 10^{34}$	**$5.5\ 10^{34}$**	**$4.9\ 10^{34}$**	**$4.2\ 10^{34}$**	**$3.9\ 10^{34}$**

Summary Performance Reach:

- Do we really need the LHC luminosity upgrade? Yes

-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!

Summary Performance Reach:

- Beam-beam limit:

-Assuming a beam-beam limit of 0.02 and alternating crossing for round beams (geometric reduction of ξ_{b-b}) LHC reaches b-b limit only with all upgrade options, 50ns beams and $\beta^* = 0.5$m.

-The beam-beam limit can also be reached with other upgrade configurations if:

-LRBB compensation is implemented
(➔ can operate with smaller crossing angle ➔ larger 'R')

-With the Crab cavity operation (➔ larger 'R')

➔ LRBB wire compensation and Crab cavities are ideal tools for luminosity leveling and maximizing integrated luminosity

Summary Performance Reach:

Beam-beam limit:

-Actual beam-beam limit in the LHC is vital input for LHC upgrade strategy (HL and LIU [e.g ε vs intensity optimization])

➔ Should give measurement of maximum attainable beam-beam parameter a high priority in 2011 operation (as function of number of long-range collisions and separation!)
($\xi_{b\text{-}b}$ = 0.008 in reach @ 3.5 TeV with 50ns, 1.7 10^{11}, ε = 2.5μm)

➔ Should also address the importance of lifetime degradation of tail particles above 3 σ.

➔ Should test operational procedures for tune adjustments during luminosity fill to compensate for tune changes as beam intensity drops over a fill!

Summary Performance Reach:

- General limit:

-Total beam current of ca. 0.8 A at limit of LHC cryo system [Laurent Tavian] + limits from other major LHC components (R. Assmann in Chamonix 2010)

➔ Assuming the performance of the injector complex is limited by brightness [e.g. space charge] it would be interesting to reduce the beam emittance at constant brightness

➔ 50ns bunch operation attractive option to minimize total current and e-cloud (but: larger pile up in experiments!)

Summary Performance Reach for small ε:

- Injector performance when optimized for small ε:
  -What is the smallest emittance we can generate for nominal and ultimate intensities at 25ns and 50ns? ➔ MD studies

- Injector performance when optimized for ε = 2.5 μm or 3.75 μm:
  -What is the maximum bunch intensity we can generate for a given normalized emittance at 25ns and 50ns? ➔ MD studies
  (space charge limit in the SPS – measurements with low γ-t lattice)

Other Potential Performance Limitations

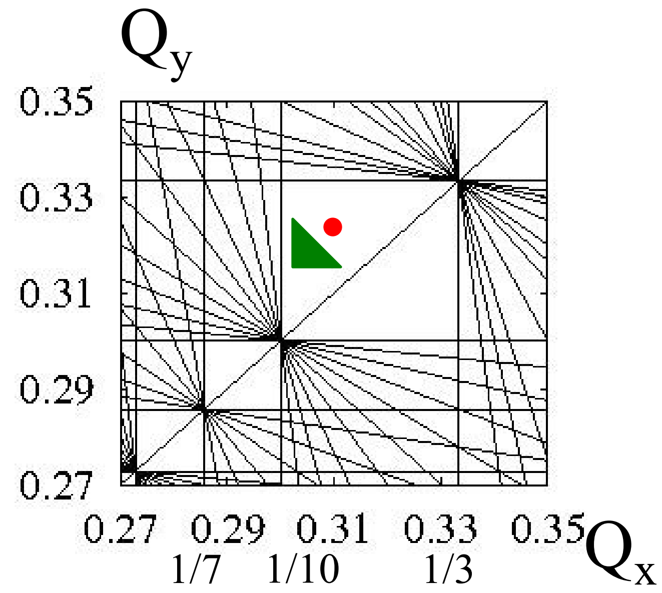
- electron cloud effects → vacuum & beam instabilities
  → cryogenic load (in the LHC)
  → bunch spacing (50ns) → beam scrubbing
- UFOs → fill abort and overall efficiency
  → beam scrubbing?
- collective effects: → TMCI threshold of 3.5 10^{11}ppb (Q' = 0)
  → coupled bunch limit might be smaller
 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

Spare Transparencies

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:

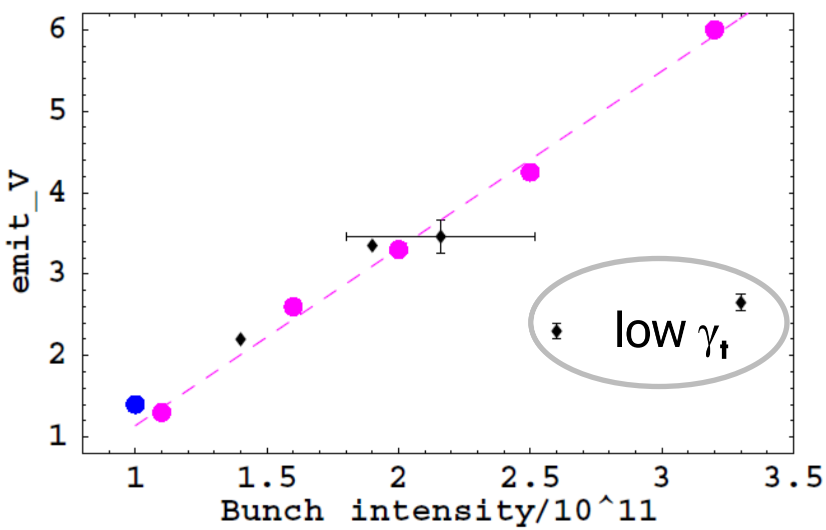
3 head-on/bunch → $\xi_{beam-beam} < 3.3\ 10^{-3}$ → $N < 1.2\ 10^{11}$

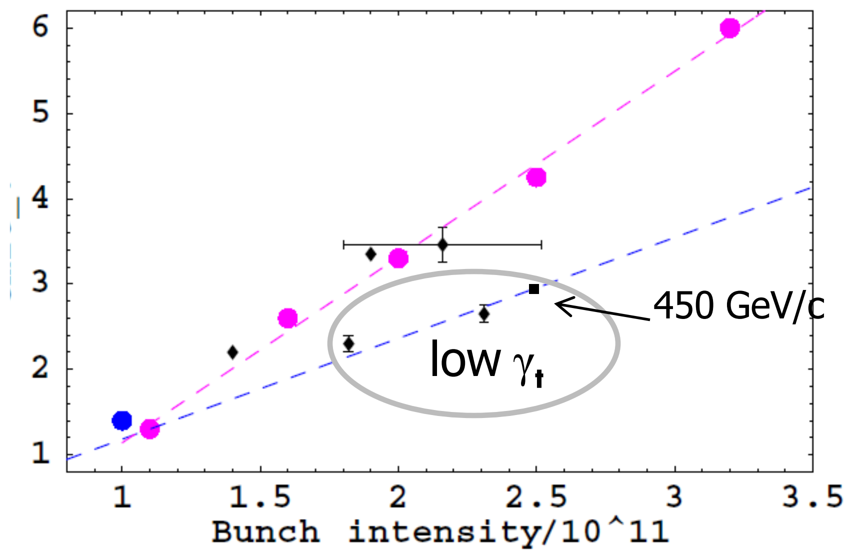
2 head-on/bunch → $\xi_{beam-beam} < 5\ 10^{-3}$ → $N < 1.7\ 10^{11}$

What is SPS space charge limit at 26 GeV/c?

Single bunch data
with nominal (γ_t =22.8)
and "low γ_t" optics (γ_t=18)

"Low γ_t" data scaled by 30% in intensity (for low V and losses)
linear fit: ε= 1.4 (N/10^{11})
→ space charge limit $\Delta Q_{sch} \sim$ 0.13
(nominal LHC beam ΔQ =0.05)





→ preliminary results, accurate measurements in 2011

Assumptions on Injector Performance III:

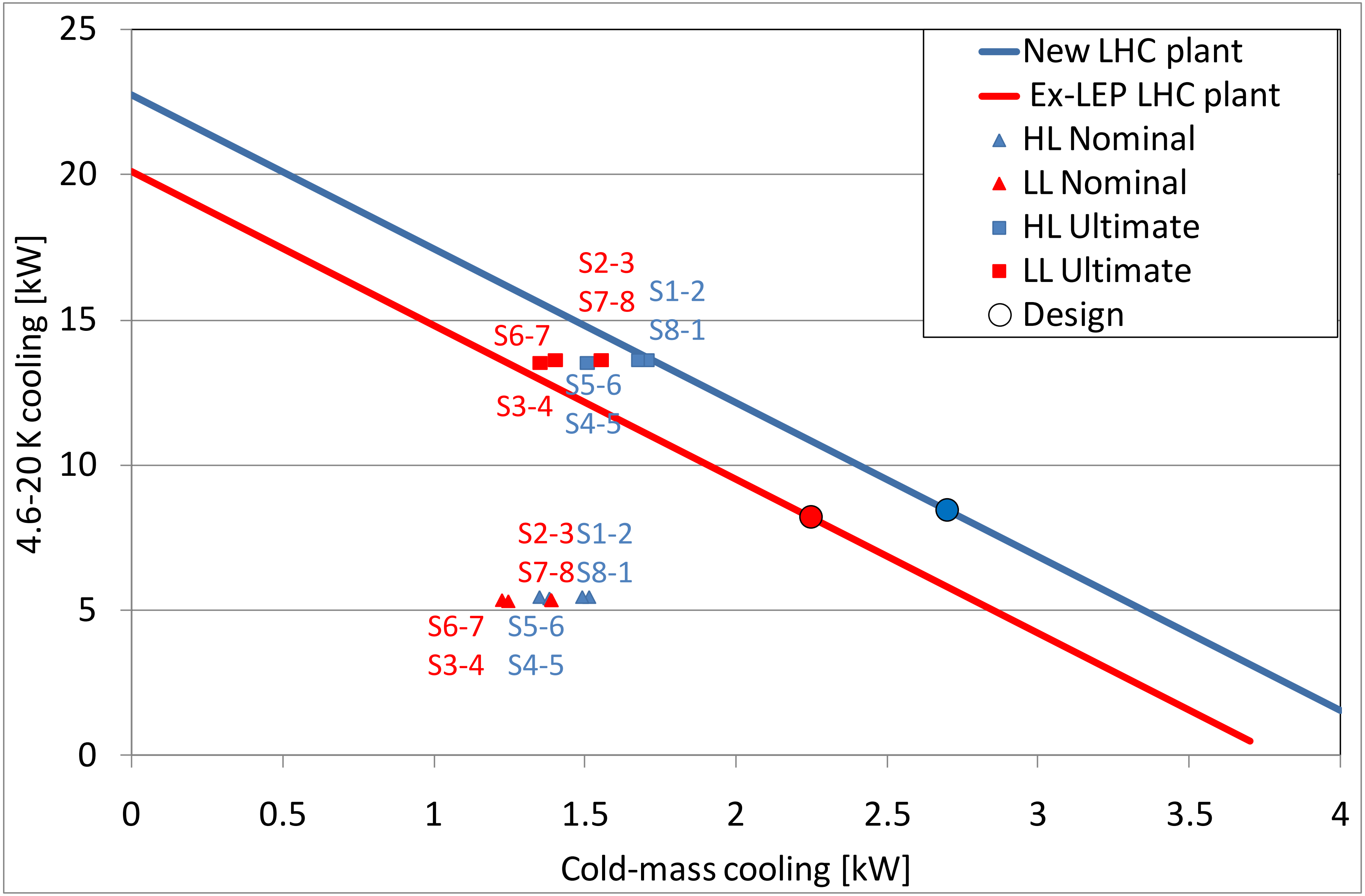
- Special filling scheme using 64 bunches per PS (SB!): [Christian Carli]

-25ns: 2.2 10^{11} ppb; $\varepsilon_n = 2.5$ μm (at exit PS) ➔ nom. emittance in LHC?
with 2688 bunches in the LHC

-50ns: 2.5 10^{11} <-> 5 10^{11} ppb; $\varepsilon_n = 2.5$ μm (at exit PS)
with 1344 bunches in the LHC

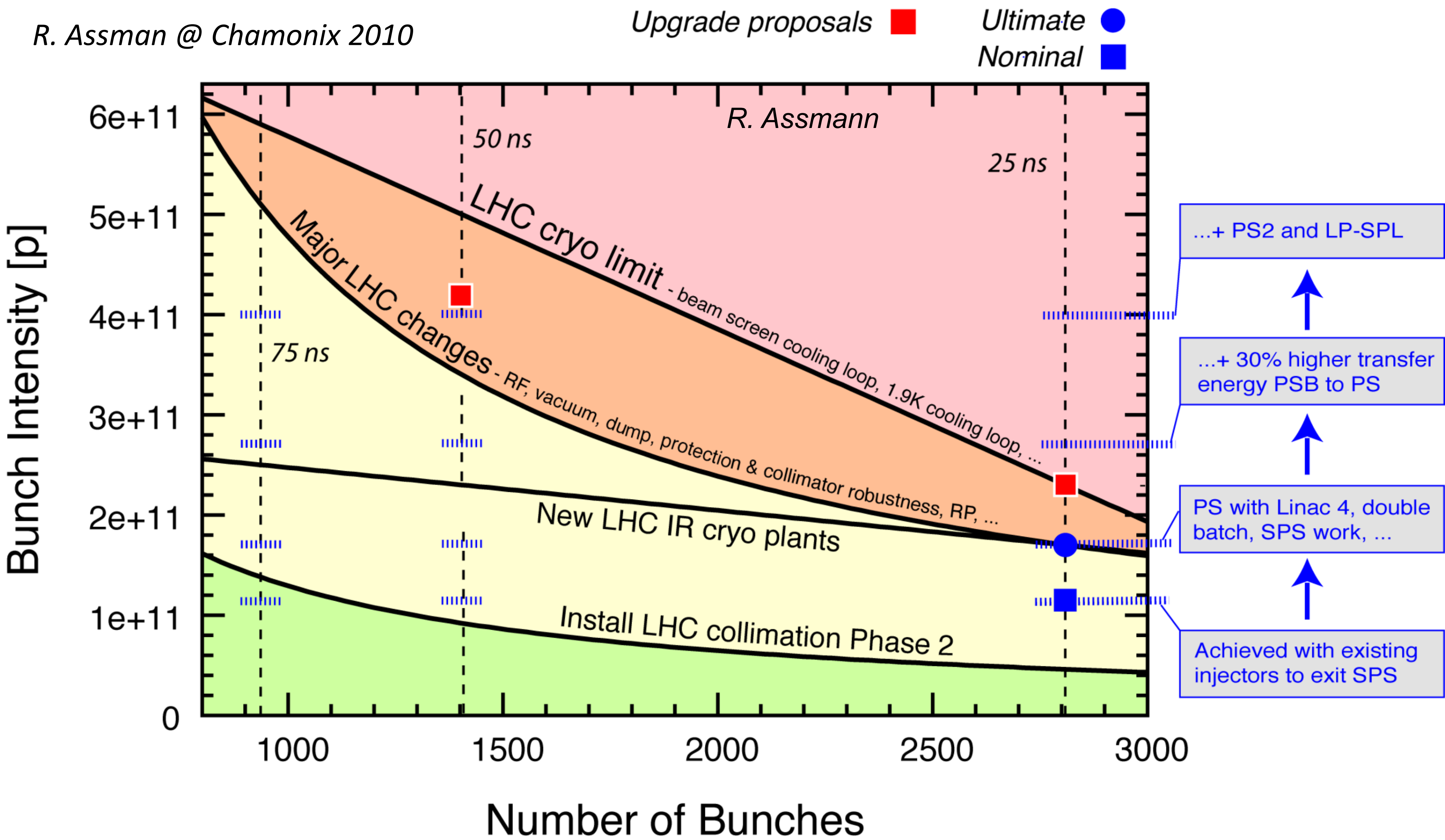
LHC following upgrade @ P1 & P5 (2021)

(New cryoplants for ITs cooling)



Summary of LHC Intensity Limits (7 TeV)

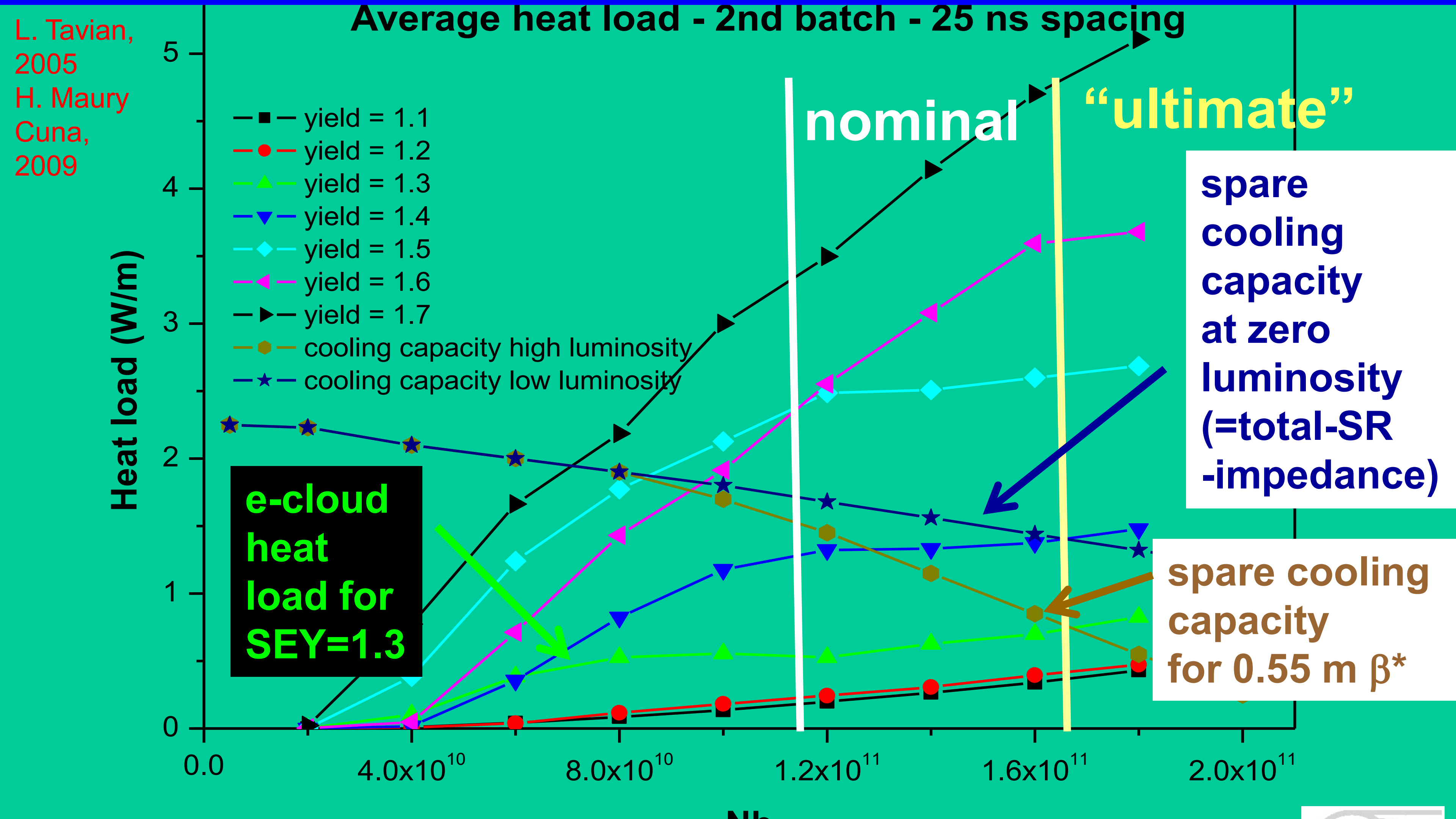
R. Assman @ Chamonix 2010



Ideal scenario: no imperfections included!

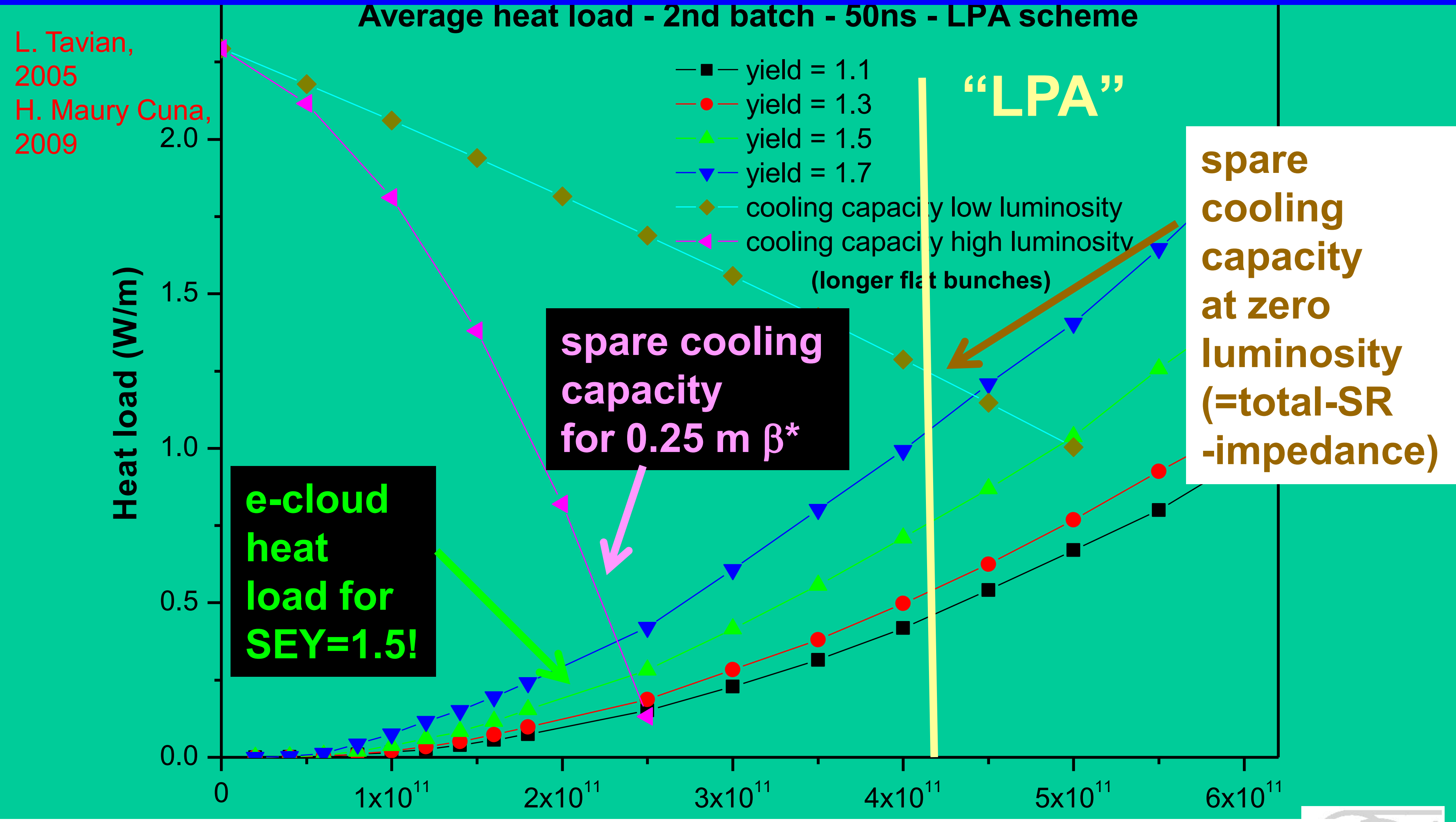
Note: Some assumptions and conditions apply…

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}

Operation at the Beam-Beam Limit

Options for maximizing luminosity at the beam-beam limit:

$$L \propto \Delta Q_{bb} \cdot \frac{N_b}{\beta^*} \qquad \Delta Q_{bb} \propto \frac{N_b}{\varepsilon} \cdot R(\beta^*)$$

(for alternating crossing)

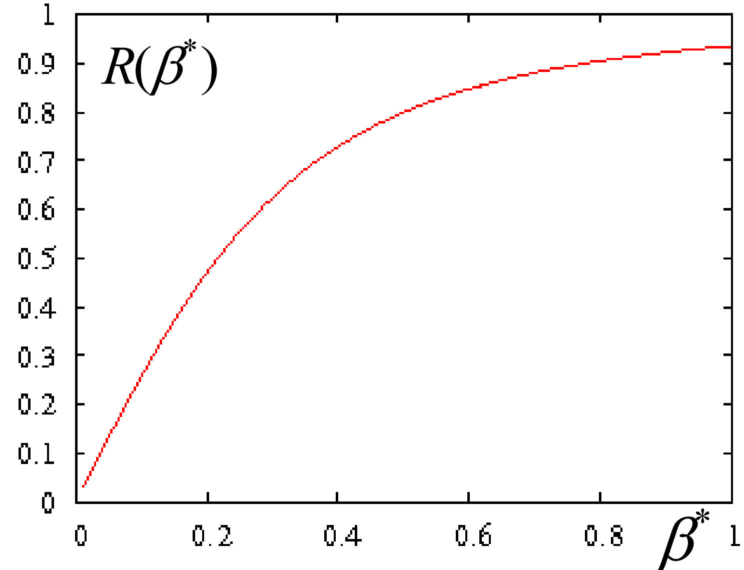
1) keep β* and N/ε constant

increase current at constant brightness

$\varepsilon_n > 3.75\ 10^{-6}$ μm requires controlled ε blow up at top energy

2) keep ε_n constant and increase N with 1/R (LPA)

➔ 1) and 2) imply larger than ultimate beam currents; 2) requires larger than ultimate brightness!



3) keep N constant and vary ε as R

(referred to as small emittance scheme)

➔ requires smaller than nominal emittance

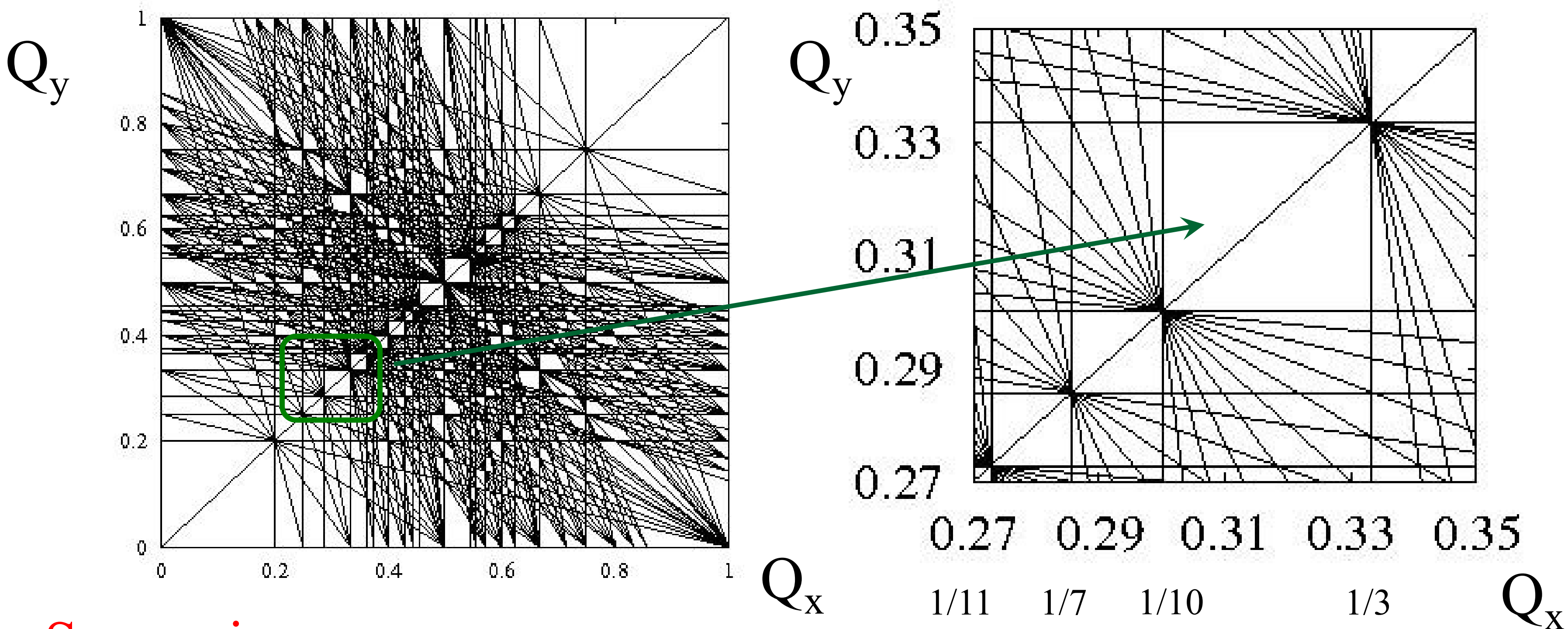
➔ leveling via aperture or Crab Cavities

4) compensate R at IP and minimize β^*

➔ is compatible with ultimate beam parameters; requires Crab Cavities

LHC Challenges: Single Particle Stability

- tune: Q = number of oscillations per revolution
- resonances: $n\,Q_x + m\,Q_y + r\,Q_s = p$; "order" = n+m+r



SppS experience:

➔ working point must stay clear of resonances of order 10 or lower!

Performance estimates in terms of β^* :

- Minimum β^* at 3.5 TeV:
  - β^* of 0.8m based on measured aperture and nominal settings
  - β^* of < 2m accessible for measured aperture and emittance
  - β^* = 1.1m based on nominal machine scaled by energy

  ➔ β^* = 1.1m used as reference in the following

- HL LHC Upgrade:
  - β^* of 0.15m accessible for round beams @ 7 TeV
  - β^* of 0.3m / 0.075m accessible for flat beams @ 7 TeV

  S. Fartoukh

  J. Gareyte

- Long range b-b can be alleviated by β^* increase ('soft landing'):

  ➔ assume 10% larger β^* as quoted for normal operation

Summary Assumptions for Performance Estimates:

- Beam-beam parameter of 0.02 to 0.03 accessible

- β^* (optimistic estimates with 10% margin for beam-b):
  - β^* of 1.5m for round beams with nom. triplet @ 3.5 TeV
  - β^* of 0.6m for round beams with nom. triplet @ 7 TeV
  - β^* of 0.2m for round beams with HL upgrade

- bunch intensity and brightness:
  - 50ns: 10^{11} ppb @ ε_n = 1.5 μm to 2 μm
  - 50ns: 1.7 10^{11} to 5.4 10^{11} ppb @ nominal emittance ε_n = 3.75μm
  - 25ns: 10^{11} to 2.7 10^{11} ppb @ < nominal emittance ε_n = 3.75μm

- LHC limitations at 7 TeV operation:
  - Cooling power: ca. 1.4 A / beam
  - Cleaning inefficiency and impedance: lifetime? efficiency

LHC Performance Estimates

Performance reach for existing machines @ 7 TeV:

Parameter	nominal	nominal emittance 25ns	nominal emittance 50ns	small emittance 50ns
N	1.15E+11	1.2E+11	1.7E+11	1.7E+11
n_b	2808	2808	1404	1404
beam current [A]	0.58	0.61	**0.43**	**0.43**
x-ing angle [μrad]	300	**320**	**320**	**270**
beam separation [σ]	10	10	10	10
β^* [m]	0.55	**0.5**	**0.5**	**0.5**
ε_n [μm]	3.75	3.75	3.75	2.5
ε_L [eVs]	2.51	2.5	2.5	2.5
energy spread	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
IBS horizontal [h]	80	72	51	20
IBS longitudinal [h]	61	43	30	18
Piwinski parameter	0.68	0.76	0.76	0.78
geom. reduction	0.83	0.80	0.80	0.79
beam-beam / IP	3.10E-03	**3.1E-03**	**4.4E-03**	**6.6E-03**
Peak Luminosity	$1\ 10^{34}$	**$1.0\ 10^{34}$**	**$1.2\ 10^{34}$**	**$1.7\ 10^{34}$**

LHC Performance Estimates

Performance reach for existing machines + LINAC4:

Parameter	nominal	nominal emittance 25ns	nominal emittance 50ns
N	1.15E+11	**1.4E+11**	**2.5E+11**
n_b	2808	2808	1404
beam current [A]	0.58	0.71	0.64
x-ing angle [μrad]	300	**320**	**320**
beam separation [σ]	10	10	10
β^* [m]	0.55	**0.5**	**0.5**
ε_n [μm]	3.75	3.75	3.75
ε_L [eVs]	2.51	2.2	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	62	35
IBS longitudinal [h]	61	37	21
Piwinski parameter	0.68	0.76	0.76
geom. reduction	0.83	0.80	0.80
beam-beam / IP	3.10E-03	**3.64E-03**	**6.5E-03**
Peak Luminosity	$1\ 10^{34}$	**$1.6\ 10^{34}$**	**$2.5\ 10^{34}$**

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	**16**	**26**	**16**	**26**
IBS longitudinal [h]	61	**17**	**16**	**17**	**16**
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	$1\ 10^{34}$	**$7.0\ 10^{34}$**	**$6.3\ 10^{34}$**	**$4.8\ 10^{34}$**	**$4.4\ 10^{34}$**

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	**23**	**35**	**23**	**35**
IBS longitudinal [h]	61	**21**	**21**	**21**	**21**
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	$1\ 10^{34}$	**$5.5\ 10^{34}$**	**$4.9\ 10^{34}$**	**$4.2\ 10^{34}$**	**$3.9\ 10^{34}$**