“Phase-2” Scenarios

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LHCC Upgrade Review

February 2010

input from 2001 LHC Upgrade Feasibility Study and from numerous CARE-HHH and EuCARD-AccNet workshops

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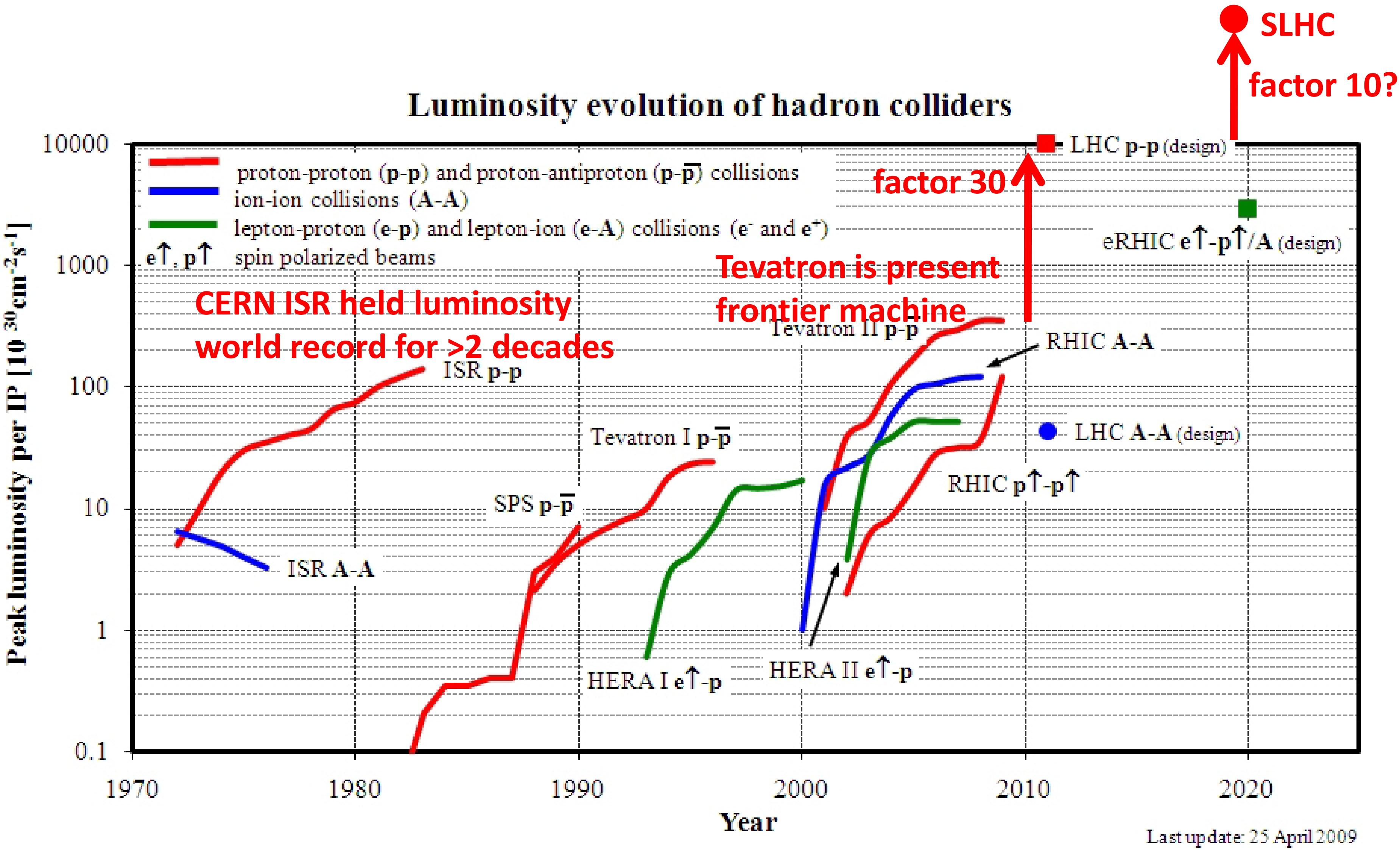


Courtesy W. Fischer

disclaimer

LHC upgrade plans & schedule under review at:

- LHC Machine Committee (weekly)
- special "brainstorming" meetings
- directorate retreat mid-November
- Chamonix 2010 workshop (Jan. '10)
- CERN MAC (1st mtg. 26 October)
- LHC "lumi up" task force (next week)

previous assumptions & schedules are likely to change significantly

plans, scenarios & time scales being revised…

contents of this presentation

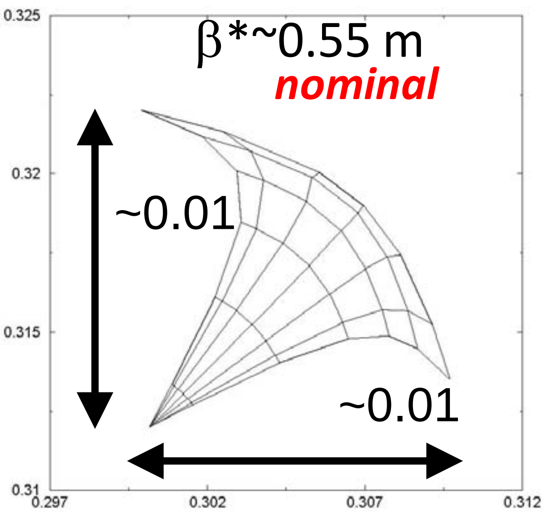
1) parameters
2) the original plan; LHCb & ALICE?
3) few words about phase-I
4) constraints & collision schemes
5) recent progress (CC, LPA, e-cloud)
6) example scenarios
7) luminosity leveling
8) turnaround time, β^*, intensity
9) conclusions & questions

parameters

- β^* - IP beta function
- β_x^*/β_y^* - ratio of IP beta functions
- θ_c – (full) crossing angle
- ε_N – normalized transverse emittance
- N_b – bunch intensity
- n_b – number of bunches ($\rightarrow s_b$ - bunch spacing)
- longitudinal bunch profile (“flat” vs “Gaussian”)
- number of collision points (IP’s)
- T_{ta} – turn-around time

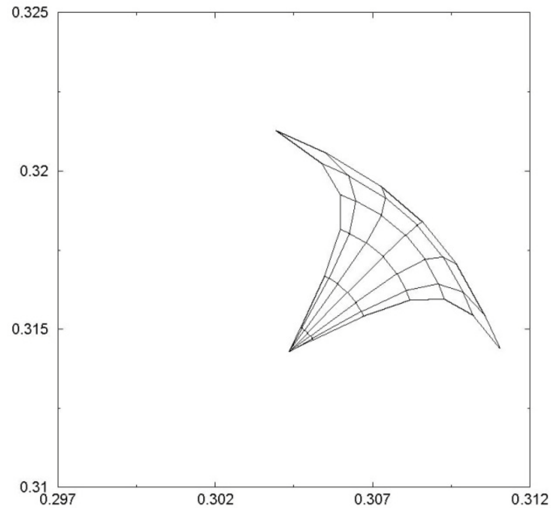
#IP's : the original plan – "phase 0"

J.Gareyte, F. Ruggiero *et al*, e.g. LHC'99 workshop, LHC Project Report 626

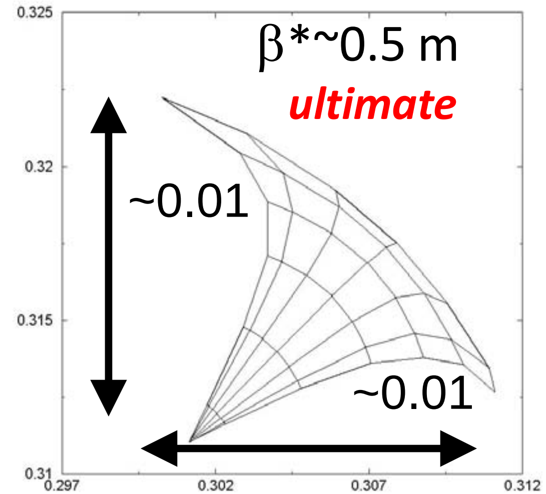


nominal tune footprint up to 6σ with 4 IPs & nom. intensity N_b=1.15x10^{11}

L=10^{34} cm^{-2}s^{-1}



tune footprint up to 6σ with nominal intensity and 2 IPs

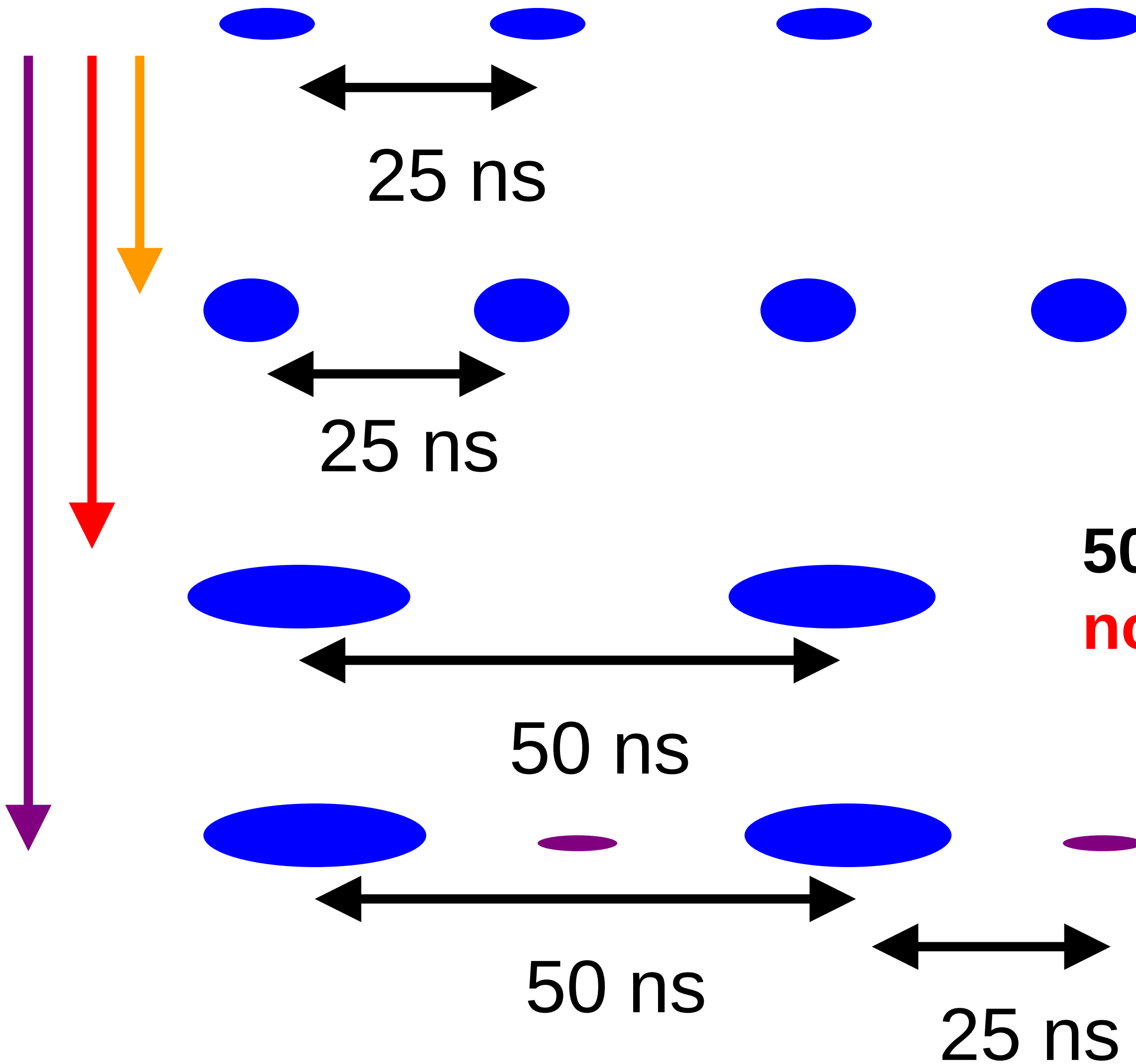


tune footprint up to 6σ with 2 IPs at ultimate intensity N_b=1.7x10^{11}

L=2.3x10^{34} cm^{-2}s^{-1}

"going from 4 to 2 IPs ATLAS & CMS luminosity can be increased by factor 2.3 - further, increasing crossing angle to 340 μrad, bunch length (x2), & bunch charge to N_b=2.6x10^{11} would yield L=3.6x10^{34} cm^{-2}s^{-1} [β*=0.5 m]"

what about LHCb? – bunch patterns



nominal

ultimate & 25-ns upgrades: LHCb “late collisions” with β*~3 m?

50-ns upgrade (LPA), no collisions in LHCb

50-ns upgrade with 25-ns collisions in LHCb at 1-2% the luminosity

50 ns: much reduced e- cloud! LHCb transparent

LHC-IR “phase-I”: merits & concerns

+ $\beta*$ reduction by up to a factor of 2

+ larger aperture in triplet

- **potential loss in optics flexibility**

- **higher chromaticity & chromatic aberrations**

- **more parasitic long-range beam-beam collisions**

- about 1 year downtime

upgrade constraints

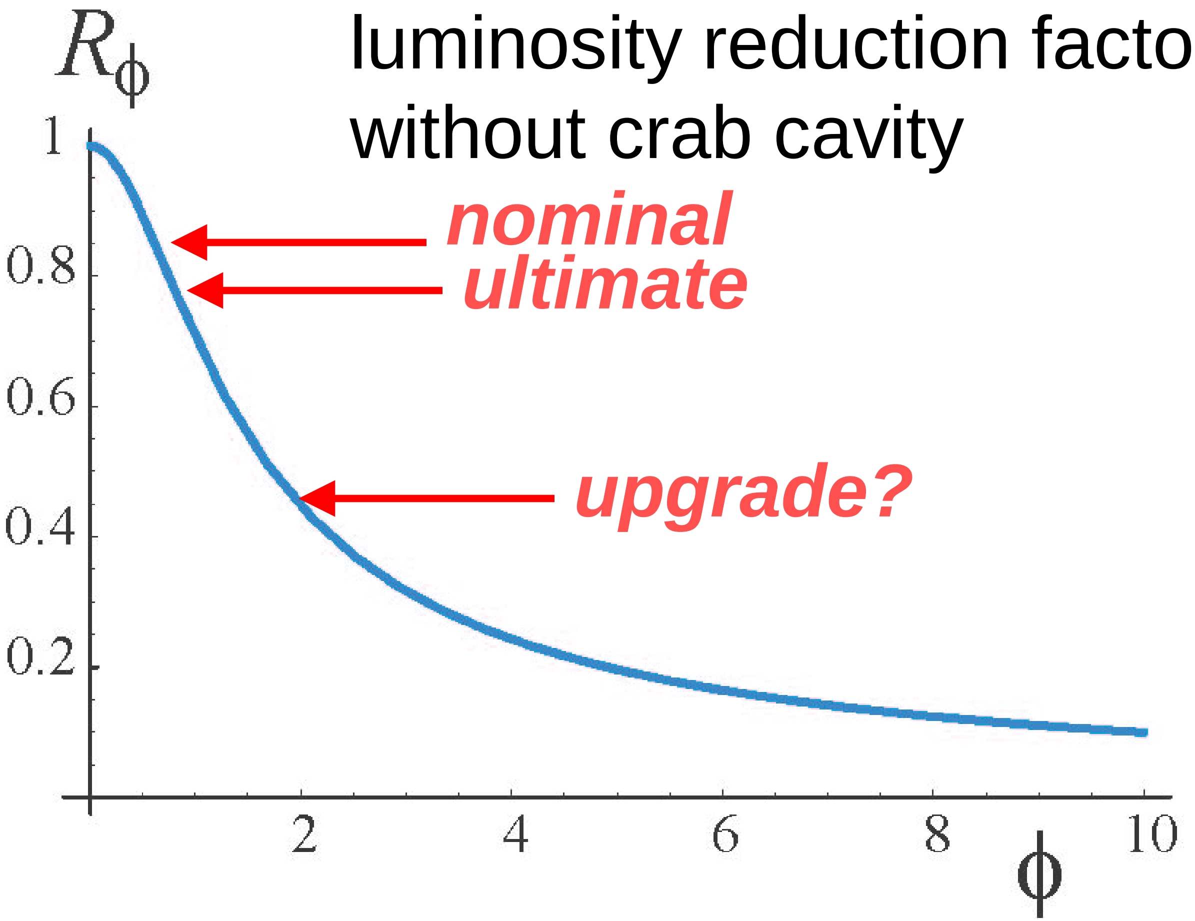
- **total beam-beam tune shift ≤0.01**
  - SPS p-pbar experience
- long-range beam-beam → **crossing angle ≥9σ**
- **arc cooling capacity**
  - global & local limitations, cooling shares with IR
  - heat load from SR, image currents, & e-cloud
- IR layout & optics → β^*
- **event pile up** in the detectors (≤300, ≤150?)
- **luminosity lifetime** (≥ 5h?)

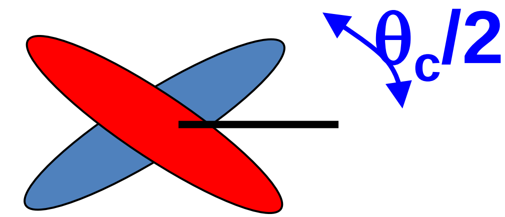
constraint - crossing angle

$$R_\phi = \frac{1}{\sqrt{1+\phi^2}}; \quad \phi \equiv \frac{\theta_c \sigma_z}{2\sigma_x^*}$$

"Piwinski angle"

luminosity reduction factor without crab cavity





effective beam size $\sigma \rightarrow \sigma / R_\phi$

range - *f*(triplet, β*):

285 μrad (nominal)
315 μrad (ultimate)
till~410 μrad "phase I"
→500 μrad "phase II"?

b-b tune shift, ϕ & luminosity

$$\Delta Q_{bb} = \frac{N_b}{\gamma\varepsilon}\frac{r_p}{2\pi}\frac{1}{\sqrt{1+\phi_{piw}^2}}\frac{1}{F_{profile}}$$

total b-b tune shift for two IP's with alternating crossing

$$L = \frac{1}{4\pi} f_{rev} n_b \gamma \frac{1}{\beta^*(\gamma\varepsilon)} N_b^2 \frac{1}{\sqrt{1+\phi_{piw}^2}}$$

at the b-b limit, larger Piwinski angle &/or larger emittance increase luminosity!

$$= \frac{\pi}{r_p^2} f_{rev} n_b \gamma \frac{(\gamma\varepsilon)}{\beta^*} \Delta Q_{bb}^2 F_{profile}^2 \sqrt{1+\phi_{piw}^2}$$

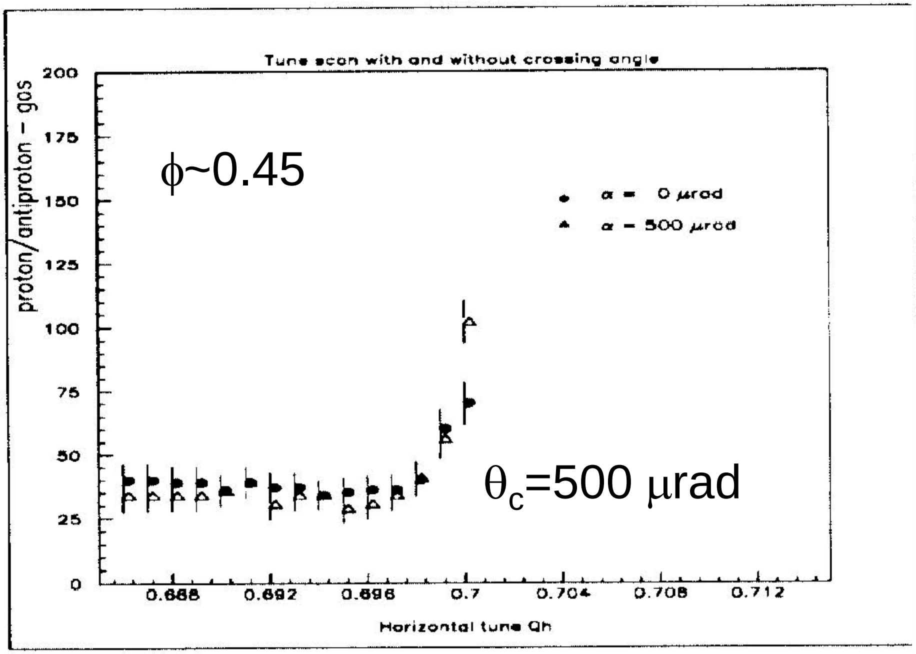
<u>optimization strategies:</u>

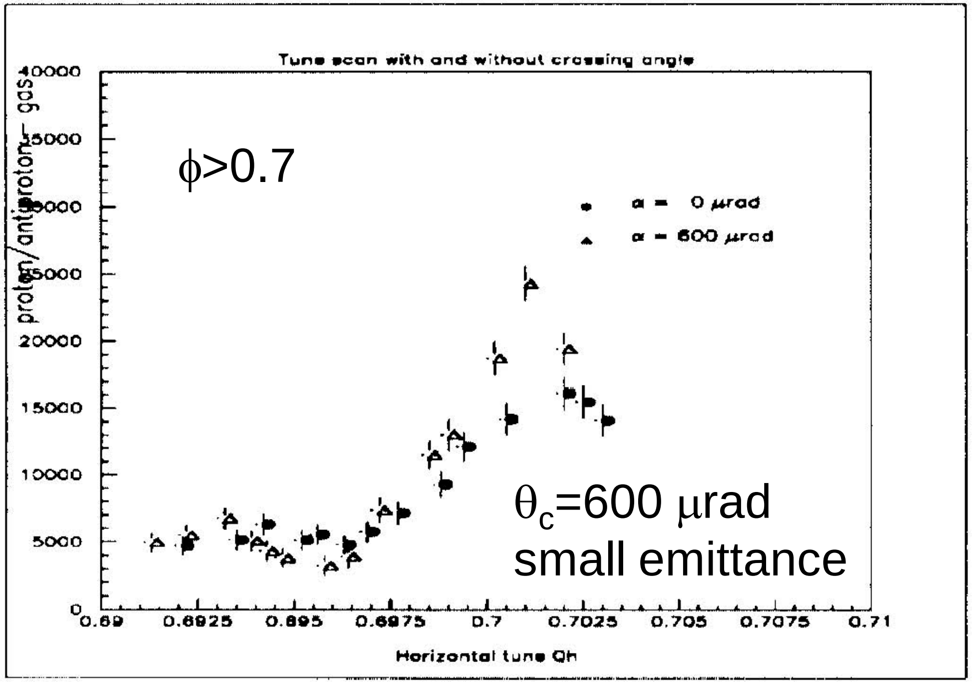
1) increase N_b with ε (e.g. controlled ε blow up at top energy)
2) increase N_b with $1/R_\phi$ & "flat" bunch $F_{profile}$~1.4 ("LPA")
3) vary ε as $1/R_\phi$ ("small emittance")
4) set $1/R_\phi$=1 at IP and minimize β^* (e.g. crab crossing)

beam-beam limit – θ_c dependence?

in lepton colliders crossing angle has reduced the beam-beam limit (DORIS-I, KEKB,…)

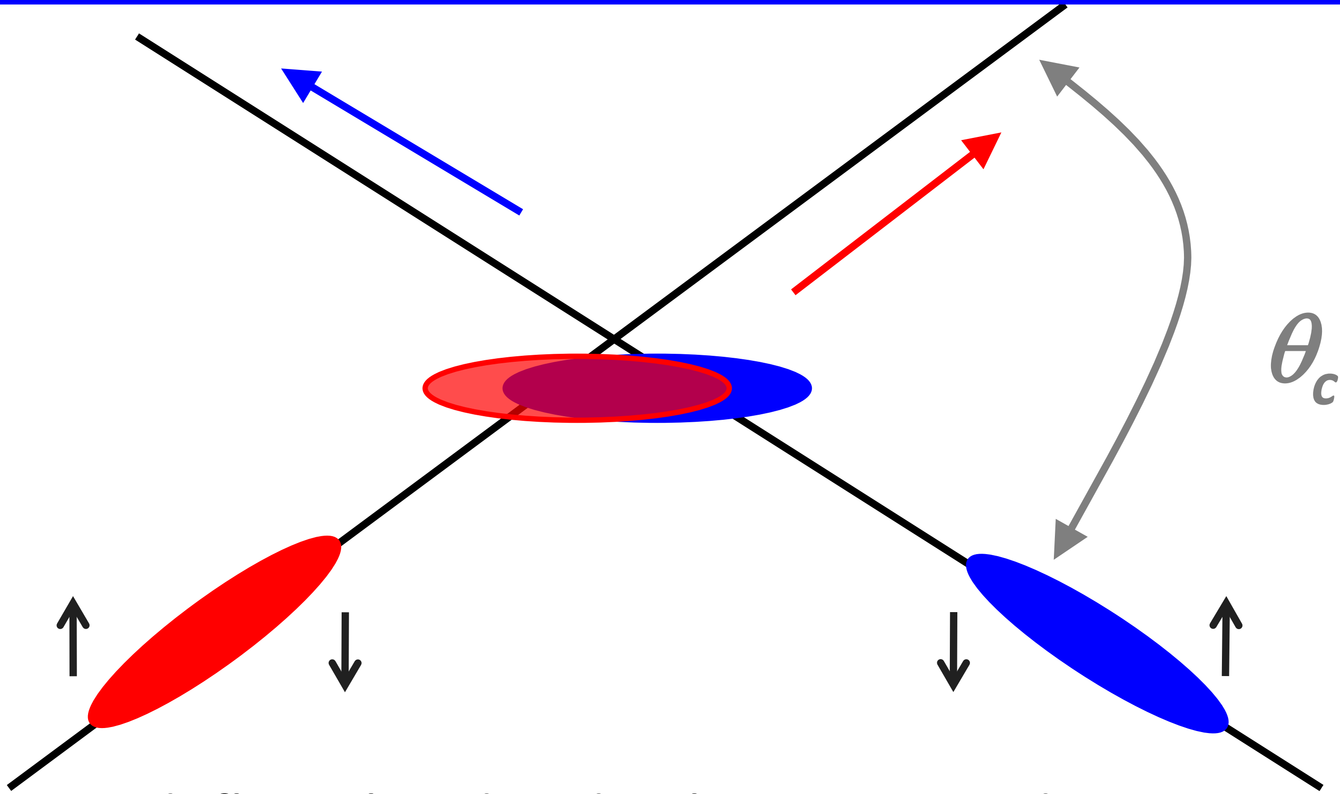
for hadrons, one historical experiment at the SPS
K. Cornelis, W. Herr, M. Meddahi, PAC91 San Francisco





(almost) no additional beam-beam effect, but ϕ was much smaller than considered for SLHC

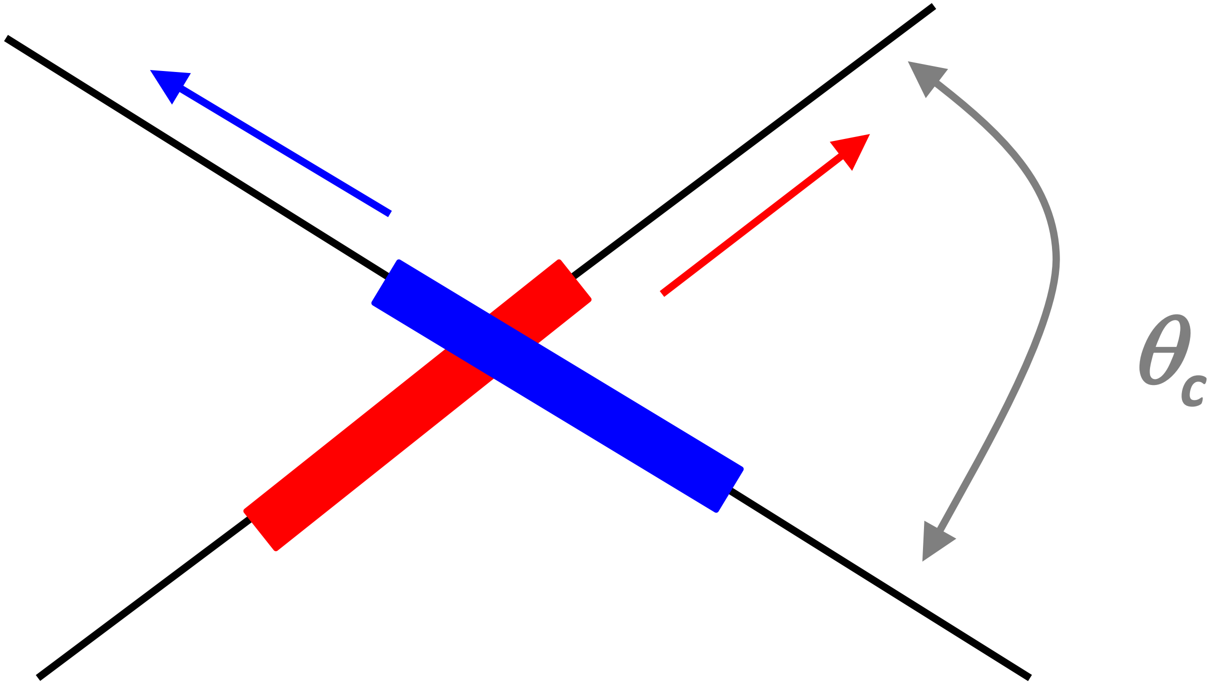
crab crossing



- RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" for luminosity and tune shift
- bunch centroids still cross at an angle (easy separation)
- 1st proposed in 1988, in operation at KEKB since 2007

<u>advantages:</u> higher geometric luminosity, easy leveling, potentially higher beam-beam tune shift

large Piwinski angle – “LPA”



1) large Piwinski angle $\theta_c \sigma_z \gg 2\, \sigma_x{}^*$
2) longitudinally flat profile

→ **reduced tune shift, higher bunch charge (& 50 ns spacing for e-cloud)**

recent progress on “phase-II” schemes

efforts focus on crab crossing & LPA scheme:

✓ crab cavities

✓ generation & stability of long flat bunches

✓ electron cloud simulations

LHC-CC09 workshop

LHC Crab Cavity Workshop, jointly organized by CERN, EuCARD-ACCNET, US-LARP, KEK, & Daresbury Lab/Cockcroft Institute CERN, 16-18 September 2009

~50 participants, LHC Crab Cavity Advisory Board established

CERN statement (Steve Myers) on LHC crab cavities issued after AccNet LHC-CC09 workshop

DG-DAT-2009-012 1 October 2009

Statements on Crab Cavities from CERN

(Steve Myers, Director of Accelerators and Technology)

1. Following the success of KEKB, CERN must pursue the use of crab cavities for the LHC, since the potential luminosity increase is significant.

2. A final crab-cavity implementation for the LHC has not yet been settled. Both "local" and "global" crabbing schemes are still under consideration for the LHC upgrade phase II. Future R & D should focus on compact cavities which are suitable for both schemes.

3. One possible show-stopper has been highlighted: machine protection, which is critical for LHC. The effect of fast cavity changes needs to be looked at with high priority. Mitigation schemes such as raising the Q value of the cavity to ~10^6 (from ~10^5 at KEK) will be studied.

4. Another important issue is the impedance. Since the LHC revolution frequency changes during acceleration, the detuning of the cavity may be more difficult than was the case for KEKB, and other measures (like strong damping of the dipole mode) need to be examined.

5. High reliability of the crab cavities is essential; the trip rate should be low enough not to perturb LHC beam operation.

6. Validation cavity tests in the LHC itself are not deemed essential. It is considered plausible to install a new system in the LHC without having tested a prototype in the LHC beforehand. As in all new colliders, this has been done with many other components.

7. Demonstration experiments should focus on the differences between electrons and protons (e.g. effect of crab-cavity noise with beam-beam tune spread; impedance; beam loading) and on reliability & machine protection which are critical for the LHC.

8. A beam test with a KEKB crab cavity in another proton machine is considered useful, meaningful and sufficient (for deciding on a full crab-cavity implementation in LHC) if it addresses the differences between protons and electrons.

9. Possible modifications of LHC Interaction Region 4 during the 2013/14 shutdown should be studied to evaluate the feasibility of installing and testing crab-cavity prototypes, and of accommodating a possible global crab-cavity scheme.

10. The timing of the crab-cavity implementation should be matched to the short and long-term goals and to the overall CERN schedule, and be in phase with the experiment upgrades.

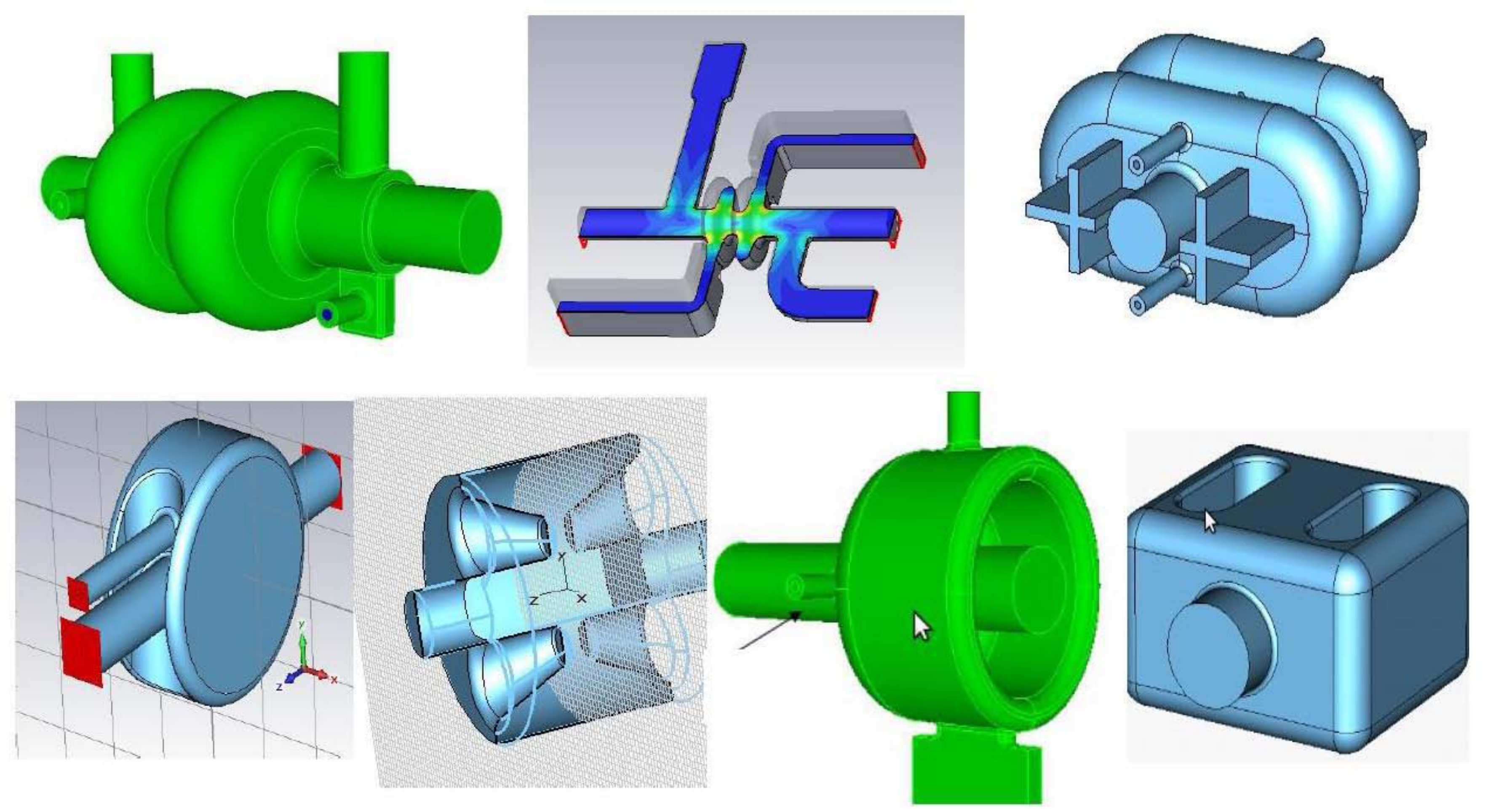
11. **The crab-cavity infrastructure should be included in all other LHC upgrades scenarios.**

12. **Crab cavities can increase the LHC luminosity without an accompanying increase in beam intensity, thereby avoiding negative side effects associated with high intensity and high stored beam energy. This opinion has been endorsed by the general-purpose high-luminosity experiments.**

CERN statements (excerpts)

1. **KEKB success … CERN must pursue crab cavities for LHC**
2. **…** Future R&D should focus on **compact cavities … suitable for both [local and global] schemes**
7. **Demonstration experiments should focus on differences between electrons and protons** (e.g. effect of crab-cavity noise with beam-beam, impedance, beam loading) and on reliability & machine protection which are critical for LHC
8. **A beam test with KEKB crab cavity in another proton machine …** useful, meaningful and sufficient …
9. **Possible modifications of Interaction Region 4** during the 2013/14 shutdown
11. Crab cavity infrastructure … **be included in all … LHC upgrades**
12. **Crab cavities can increase luminosity w/o accompanying increase in beam intensity, thereby avoiding negative side effects**

CC designs presented at LHC-CC09



further crab cavity progress

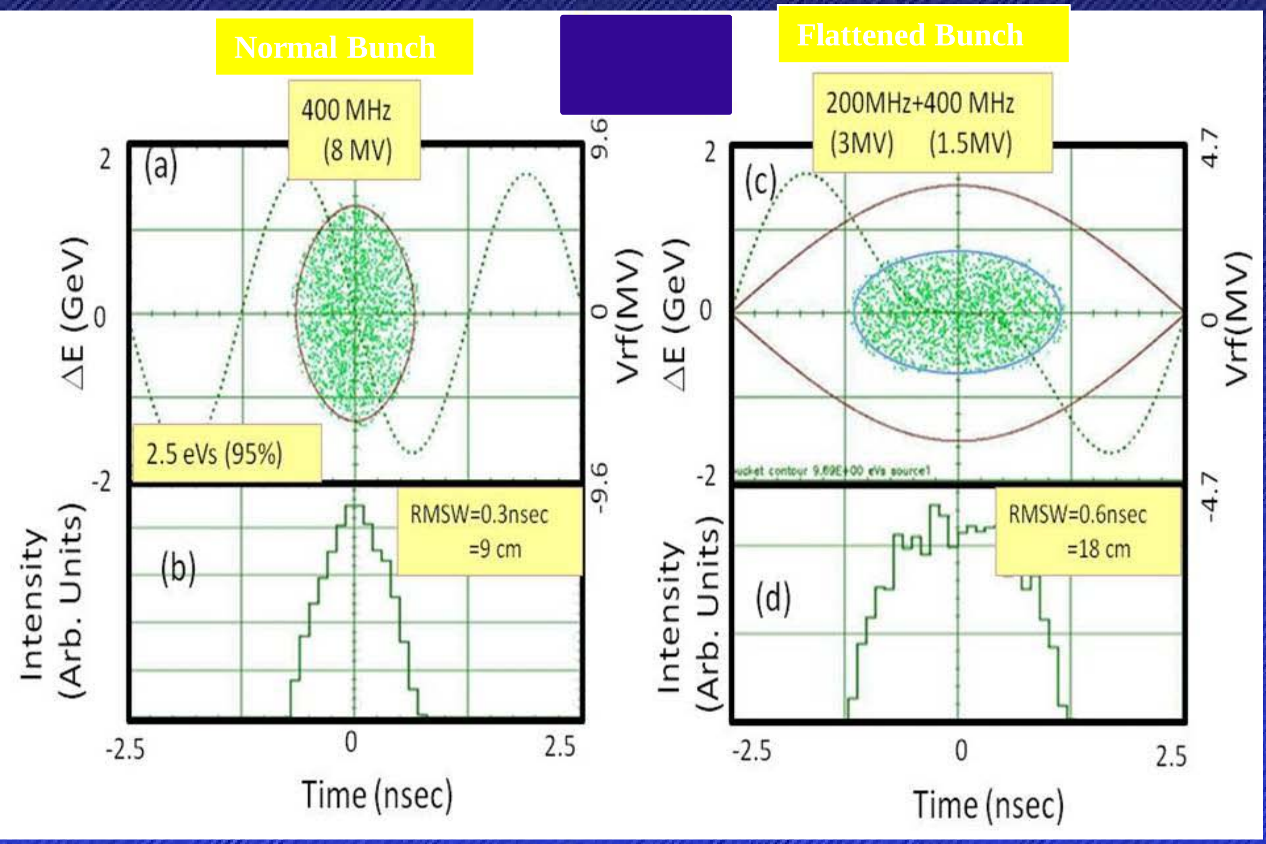
30 October 2009:
launch of CERN working group on feasibility of KEKB crab cavity test in SPS

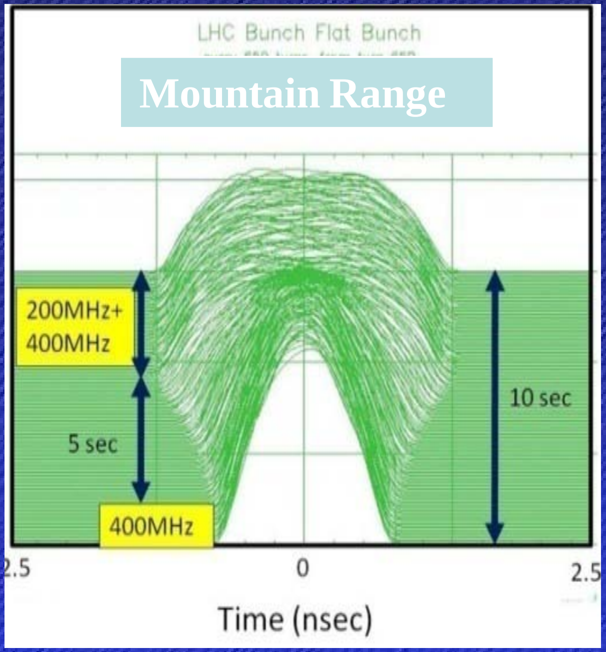
WG conclusions on 18 December 2009:
no real showstoppers; KEKB crab cavity could be used/tested at SPS in 2012; best location found (space & available cryogenics);
SPS beam test including LHC collimators;
effect of RF noise; trip rates; proposal of bypass (i.e. 2 movable beam pipes w Y)

LPA progress

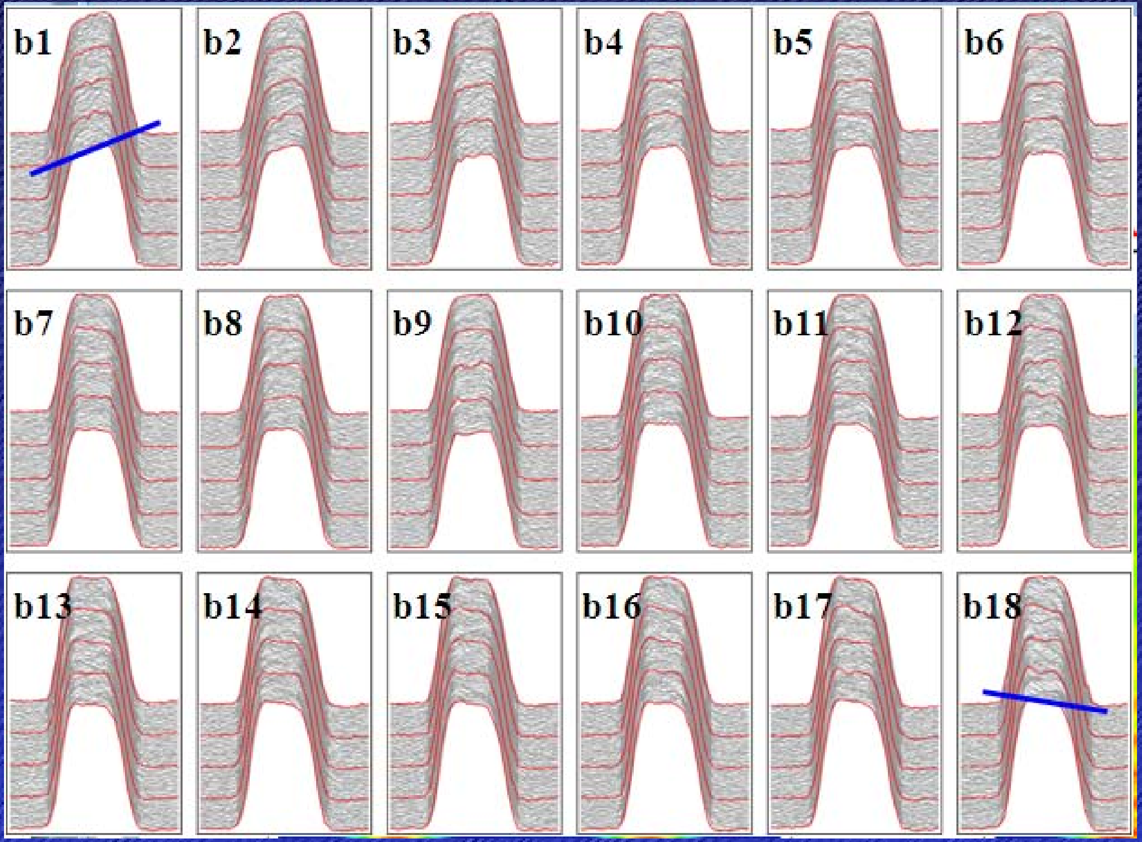
simulation studies and experiments on LPA beam generation & stability by Chandra Bhat (US-LARP/FNAL)

Example: Bunch Flattening of the LHC Beam at 7 TeV
with 400MHz and 200MHz RF systems





LPA experiments in PS & SPS



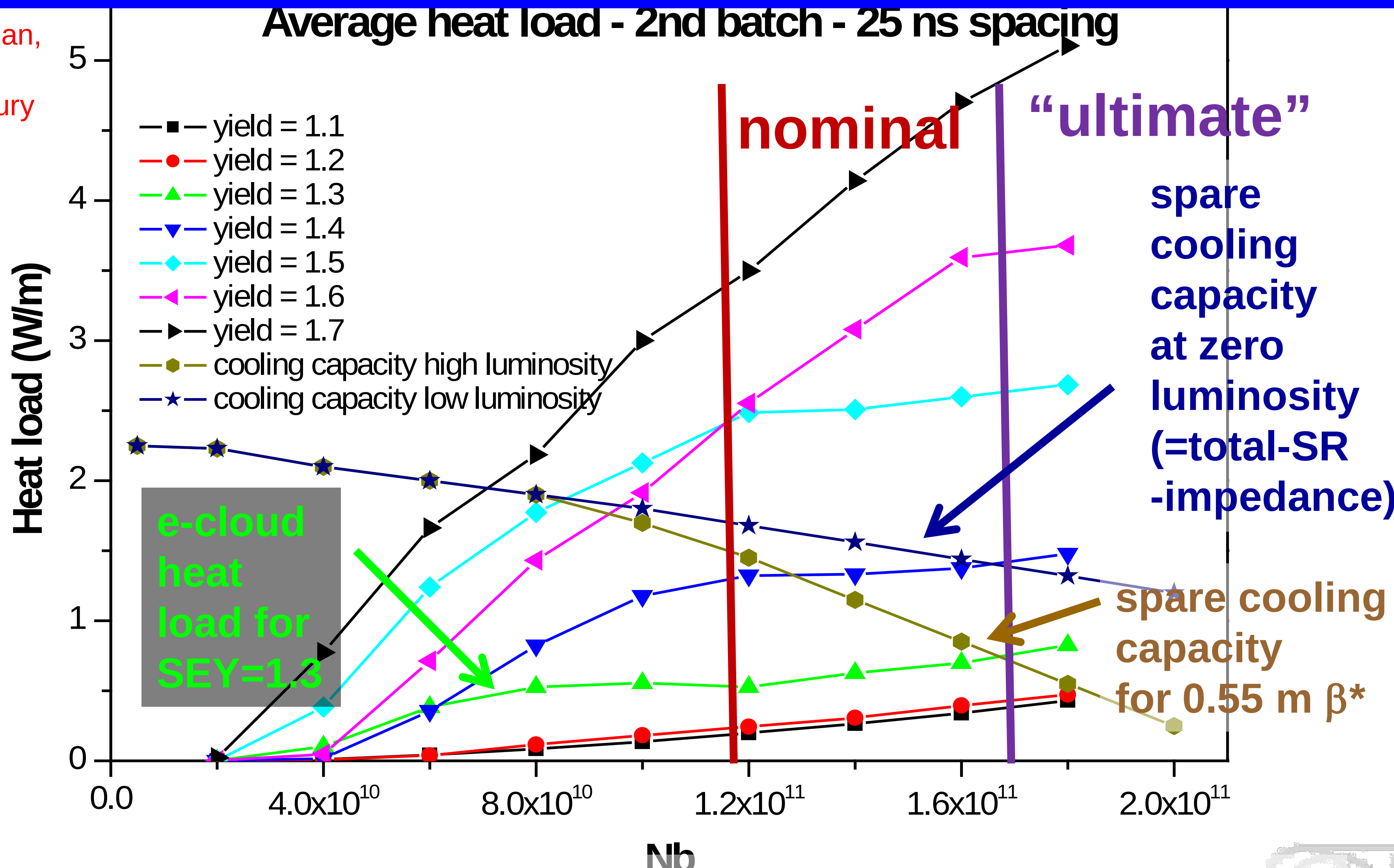
flatness along the PS batch

Chandra Bhat,
Heiko Damerau,
et al.

transient beam loading compensation may be required

cooling & e- heat for 25 ns spacing

L. Tavian, 2005
H. Maury Cuna, 2009

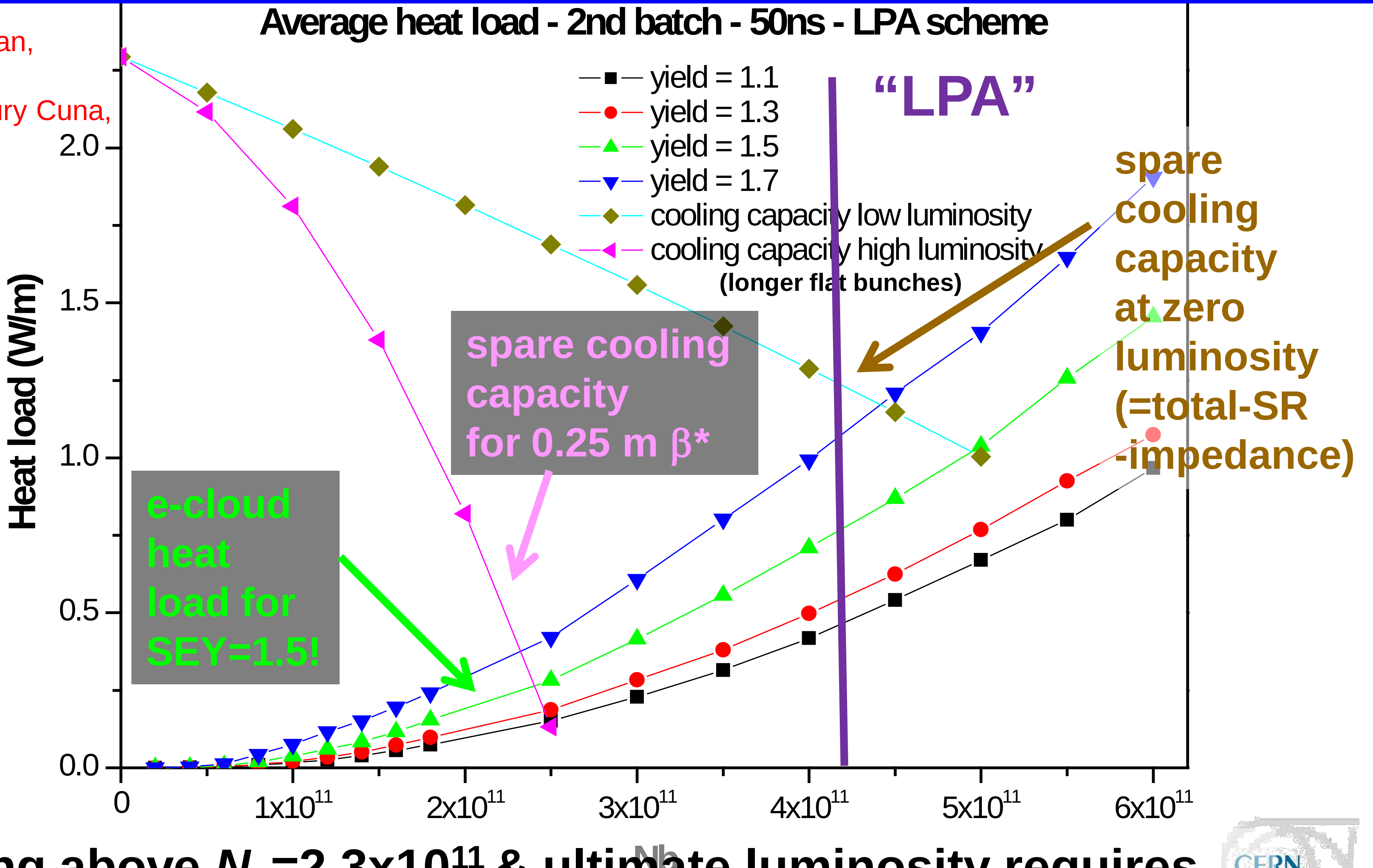


going above N_b=1.7x10^{11} & ultimate luminosity requires dedicated IR cryo plants; limit then becomes N_b~2.3x10^{11}

CERN

cooling & e- heat for 50 ns spacing

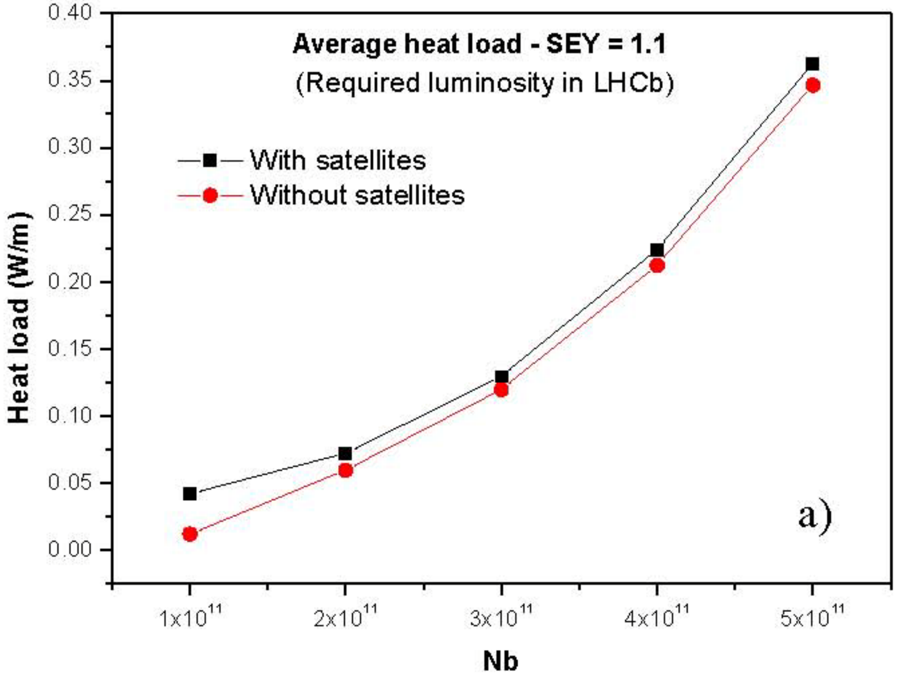
L. Tavian, 2005
H. Maury Cuna, 2009

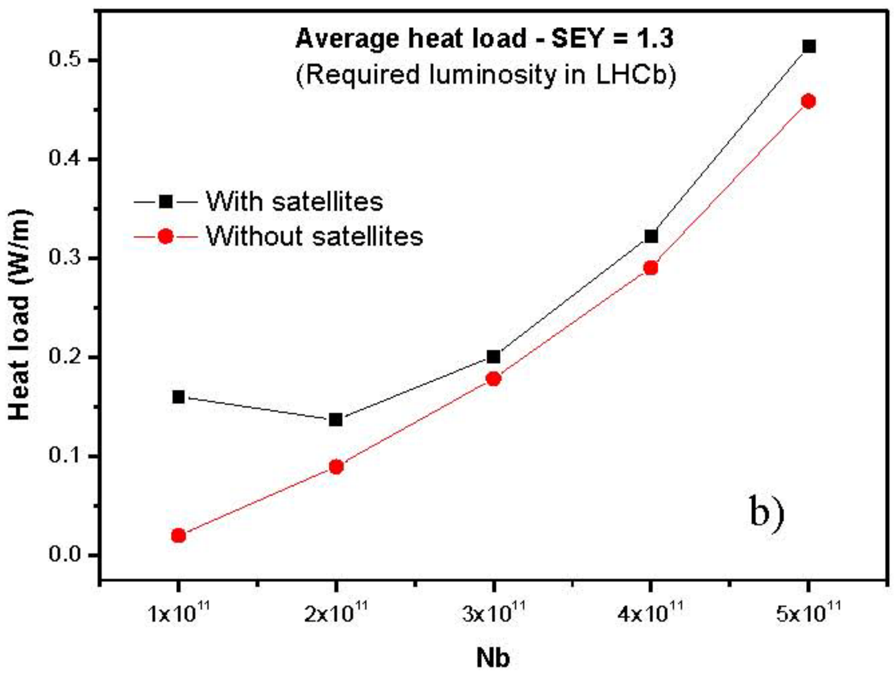


going above N_b=2.3x10^{11} & ultimate luminosity requires dedicated IR cryo plants; limit then becomes N_b~5.0x10^{11}

e- heat with LHCb satellite

H. Maury Cuna, 2009





satellite intensity is varied as the inverse of main-bunch intensity to yield target luminosity of 2×10^{33} $cm^{-2}s^{-1}$ in (S)LHCb

“LHCb satellite” has small effect on 50-ns heat load

constraints - N_b range

- **beam-beam tune shift** of "head-on" collision
  - ✓ is the limit for crab crossing;
  - ✓ going beyond ultimate N_b requires large Piwinski angle or large emittance;
  - ✓ even larger crossing angle than for LR-BB may be needed in some scenarios
- **arc cooling capacity** (global & **local limits**)
- **collimation efficiency** & **machine protection**
- **injectors**

N_b constraint: collimator damage

- studied in simulations & experiments, small beam size
- **critical failure mode**: one dump kicker module pre-fires asynchronously & kicks bunches onto collimators
- **collimator damage limit in kJ/mm^2:**
  - Cu: 50 kJ/mm^2
  - **CFC: 5 MJ/mm^2 (collimators – 2 MJ/mm^2 tested in TT40)**
- typical location: σ_r = 0.2 mm ➔ A_b = 0.13 mm^2 (nominal emittance, without dilution from showers).
- stored energy & transverse energy density:
  - nominal bunch: **130 kJ ➔ 1.0 MJ/mm^2**
  - ultimate bunch: **190 kJ ➔ 1.5 MJ/mm^2**
  - 2 x ultimate bunch: **380 kJ ➔ 3.0 MJ/mm^2**
- single bunch > 5.1e11 *p* exceeds damage limit of primary & secondary collimators; **damage limit depends only on total beam intensity**

constraint - beam brightness

- transverse energy density rises strongly with beam energy (γ); it also scales with number of protons (N_p^{tot}) over normalized emittance (ε_n):

$$\rho_E = \gamma^2 \cdot \frac{N_p^{tot}}{\varepsilon_n} \cdot C \qquad\qquad C = \frac{m_p c^2}{\pi \sqrt{\beta_x \beta_y}}$$

- **higher intensity or smaller emittance put similar strain on material survival!**
- → "low emittance" upgrade options are no magic bullet; they solve some issues (RF, radiation, …), but do not address damage limit
- **constraint** from machine robustness:

$$\frac{N_p^{tot}}{\varepsilon_n} \leq 1.3 \times 10^{20} \ \frac{\text{protons}}{\text{m rad}}$$

constraint – β* range

0.55 m nominal

0.50 m ultimate

0.40 m
0.30 m
0.25 m

IR "phase I" ,
larger aperture NbTi quad's +…

0.22 m
…
0.14 m

IR "phase II"
Nb_3Sn quad's + …

hard limit from linear chromatic correction

constraint – pile up

bunch collision rate
= #bunches/beam x revolution frequency

#events per bunch crossing
= cross section x luminosity / bunch collision rate

nominal #events/crossing in the detector
= $6\text{x}10^{-26}$ cm^2 10^{34} cm^{-2}s^{-1} / (32 x10^6 s^{-1})
= 19

inelastic cross section

e.g. 10 times higher luminosity at same #bunches
→ ~200 events per crossing (*detector upgrade!*)

luminosity decay & lifetime

fast decay of beam intensity and luminosity (few hours) dominated by proton burn off

$$L(t) = \frac{\hat{L}}{\left(1 + t/\tau_{eff}\right)^2}$$

with

$$\tau_{eff} = \frac{N_b n_b}{n_{IP} \hat{L} \sigma_{tot}}$$

algebraic (≠exponential) decay!

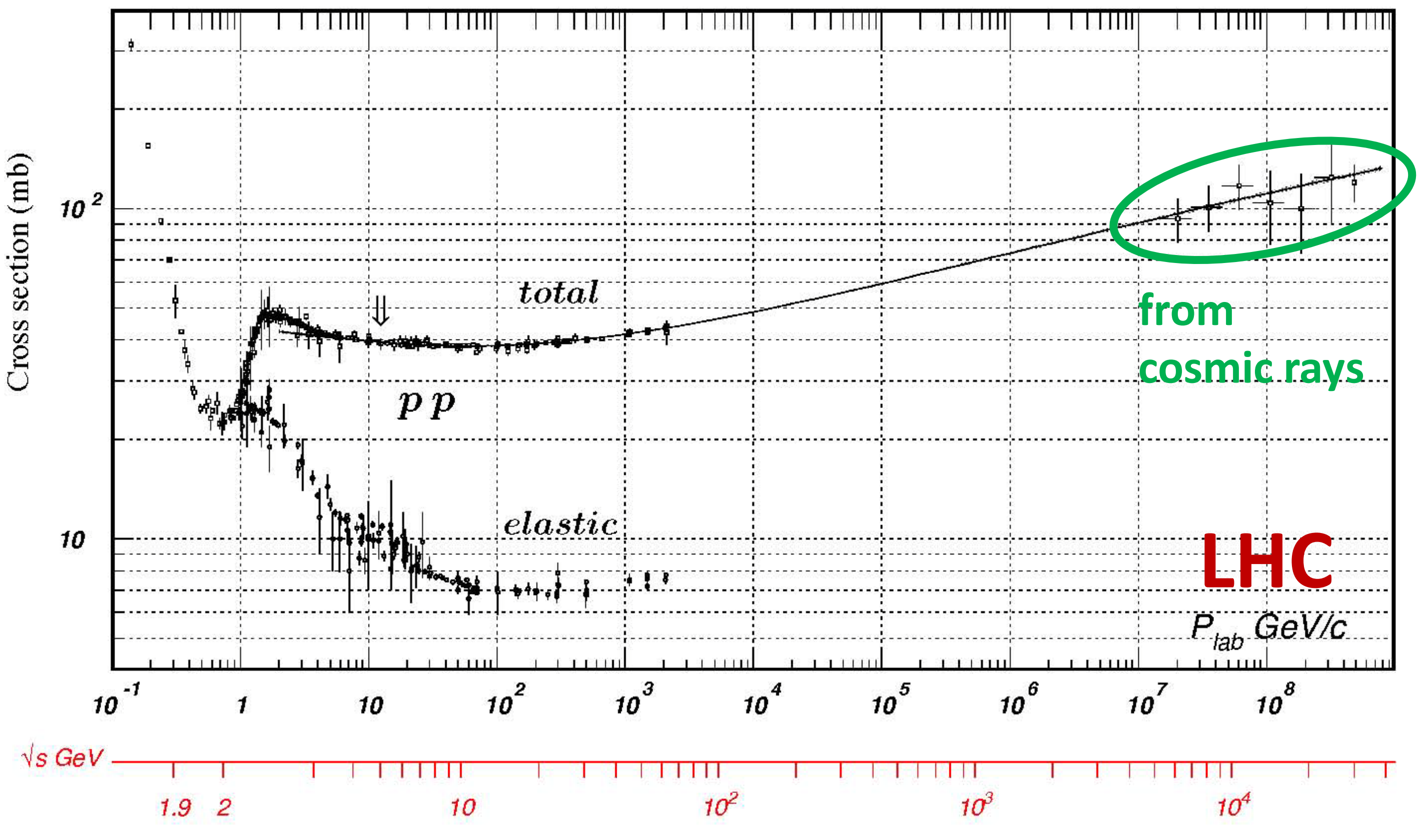
(gas scattering and IBS add negligible contributions [F.Z. ABP-RLC 23.09.05] , which are not exponential either)

$$\tau_{lumi} \propto \frac{\text{total beam intensity}}{\text{luminosity}}$$

for a given luminosity value, the luminosity lifetime depends only on total beam current [w/o leveling]

cross sections

C. Amsler *et al.,* Physics Letters **B667**, 1 (2008)



σ_{tot}~ 100 mbarn ~ 10^{-25} cm^2

$\sigma_{inelastic}$~ 60 mbarn~ 6×10^{-26} cm^2

total cross section for LHC c.m. energy from cosmic ray experiments

example scenarios

(1) nominal, N_b=1.15x10^{11} ,β^*=0.55 m, θ_c=285 μrad

(2) ultimate , N_b=1.7x10^{11} ,β^*=0.50 m, θ_c=315 μrad

(3) "phase I+", N_b=2.3x10^{11} ,β^*=0.30 m, θ_c=348 μrad

(4) "phase I w crab", N_b=1.6x10^{11} ,β^*=0.30 m (θ_c=348 μrad)

(5) "phase II+", N_b=2.3x10^{11} ,β^*=0.14 m, θ_c=509 μrad

(6) "phase II w crab", N_b=1.6x10^{11} ,β^*=0.14 m

(θ_c=509 μrad) [also same case w/o crab]

(7) "LPA-50", 50 ns, N_b=4.2x10^{11} , β^*=0.25 m, θ_c=381 μrad

(8) "LPA-25", 25 ns, N_b=2.6x10^{11} , β^*=0.50 m, θ_c=339 μrad

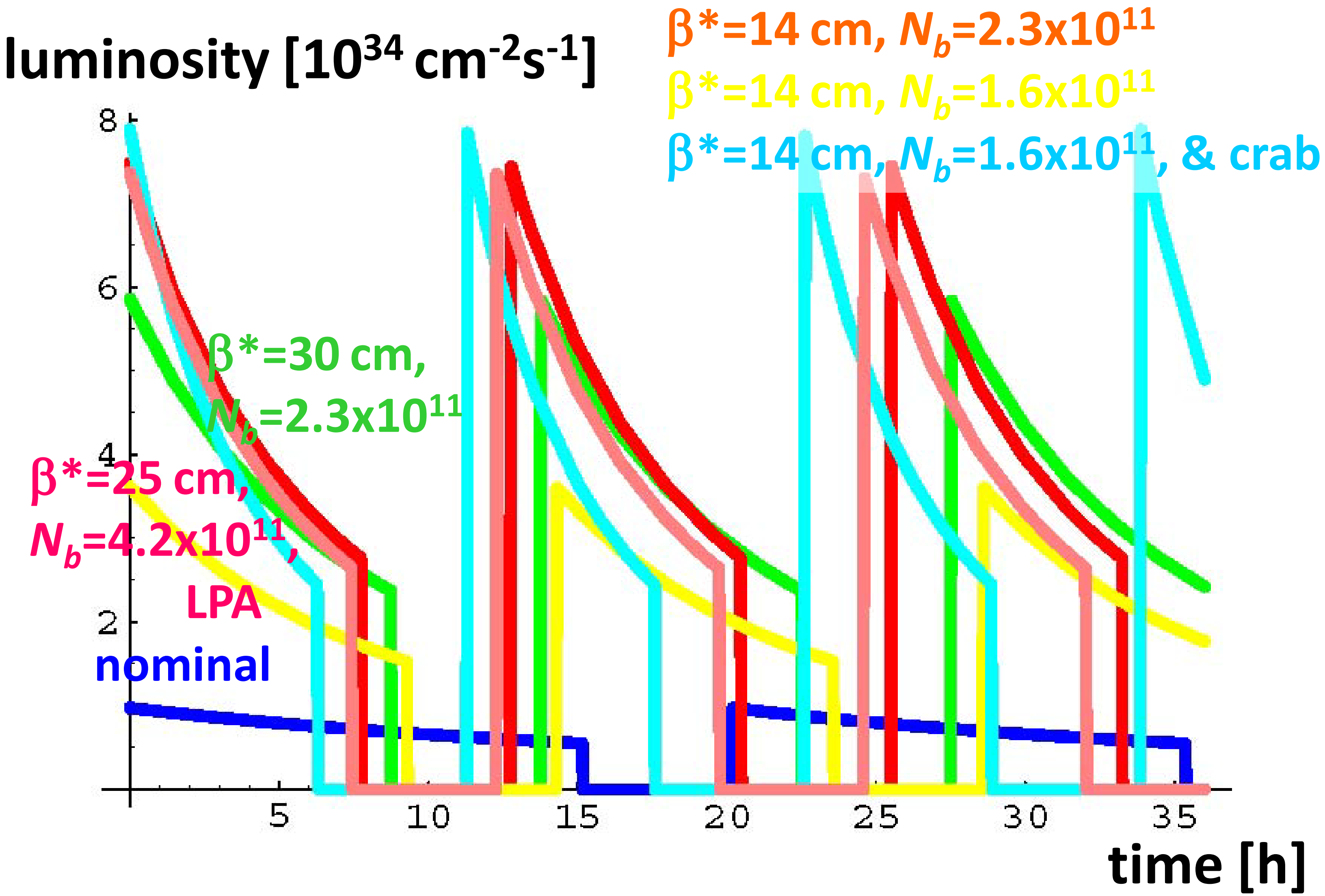
parameter	symbol	nom.	ult.	β*=30 cm, HI	β*=30, cm , CC	β*=14, cm HI	β*=14 cm, CC	LPA – 25	LPA – 50
transverse emittance	ε [μm]	3.75	3.75	**3.75**	**3.75**	**3.75**	**3.75**	**3.75**	**3.75**
protons per bunch	N_b [10^{11}]	1.15	1.7	**2.3**	**1.6**	**2.3**	**1.6**	**2.6**	**4.2**
bunch spacing	Δt [ns]	25	25	**25**	**25**	**25**	**25**	**25**	**50**
beam current	I [A]	0.58	0.86	**1.16**	**0.81**	**1.16**	**0.81**	**1.32**	**1.06**
longitudinal profile		Gauss	Gauss	**Gauss**	**Gauss**	**Gauss**	**Gauss**	**Flat**	**Flat**
rms bunch length	σ_z [cm]	7.55	7.55	**7.55**	**7.55**	**7.55**	**7.55**	**11.8**	**11.8**
beta* at IP1&5	β* [m]	0.55	0.5	[illegible]	**0.30**	**0.14**	**0.14**	**0.50**	**0.25**
full crossing angle	θ_c [μrad]	285	315	[illegible]	**(348)**	**509**	**(509)**	**339**	**381**
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.65	[illegible]	[illegible]	**0.0**	**2.3**	**0.0**	**2.0**	**2.0**
tune shift	ΔQ_{tot}	[illegible]	[illegible]	[illegible]	**0.01**	**0.006**	**0.01**	**0.01**	**0.01**
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	[illegible]	**5.9**	**4.0**	**7.5**	**7.9**	**4.0**	**7.4**
peak events per #ing	[illegible]	[illegible]	[illegible]	**111**	**76**	**142**	[illegible]	**75**	**280**
initial lumi lifetime	[illegible] [h]	23	15	**7.7**	[illegible]	[illegible]	[illegible]	**12.4**	**5.3**
effective luminosity ($T_{turnaround}$=[illegible] h)	L_{eff}[10^{34} cm^{-2}s^{-1}]	0.45	0.90	**1.8**	[illegible]	[illegible]	**1.7**	**1.5**	**1.9**
	$T_{run,opt}$ [h]	21.5	[illegible]	[illegible]	[illegible]	**11.0**	**8.9**	**16.0**	**10.5**
effective luminosity ($T_{turnaround}$=2 h)	L_{eff}[10^{34} cm^{-2}s^{-1}]	[illegible]	[illegible]	**3.2**	**2.2**	**3.8**	**3.5**	**2.4**	**3.6**
	$T_{run,opt}$ [illegible]	[illegible]	7.7	**5.5**	**5.6**	**4.9**	**4.0**	**7.2**	**4.7**
e-c heat SEY=1.3	P [illegible]	0.4	0.6	**1.3**	**0.7**	**1.3**	**0.7**	**1.4**	**0.8**
SR heat 4.6-20 K	P_{SR} [illegible]	0.17	0.25	**0.34**	**0.24**	**0.34**	**0.24**	**0.38**	**0.31**
image current heat	[illegible] [W/m]	0.15	0.33	**0.60**	**0.29**	**0.60**	**0.29**	**0.39**	**0.51**
gas-s. 100 h τ_b	[illegible] [W/m]	0.04	0.06	**0.08**	**0.05**	**0.08**	**0.05**	**0.09**	**0.07**
luminous region	σ_l [cm]	4.5	4.3	**3.7**	**5.3**	**2.2**	**5.3**	**5.2**	**3.8**
annual luminosity	L_{int}[fb^{-1}]	57	116	**245**	**169**	**286**	**253**	**198**	**274**

example parameters

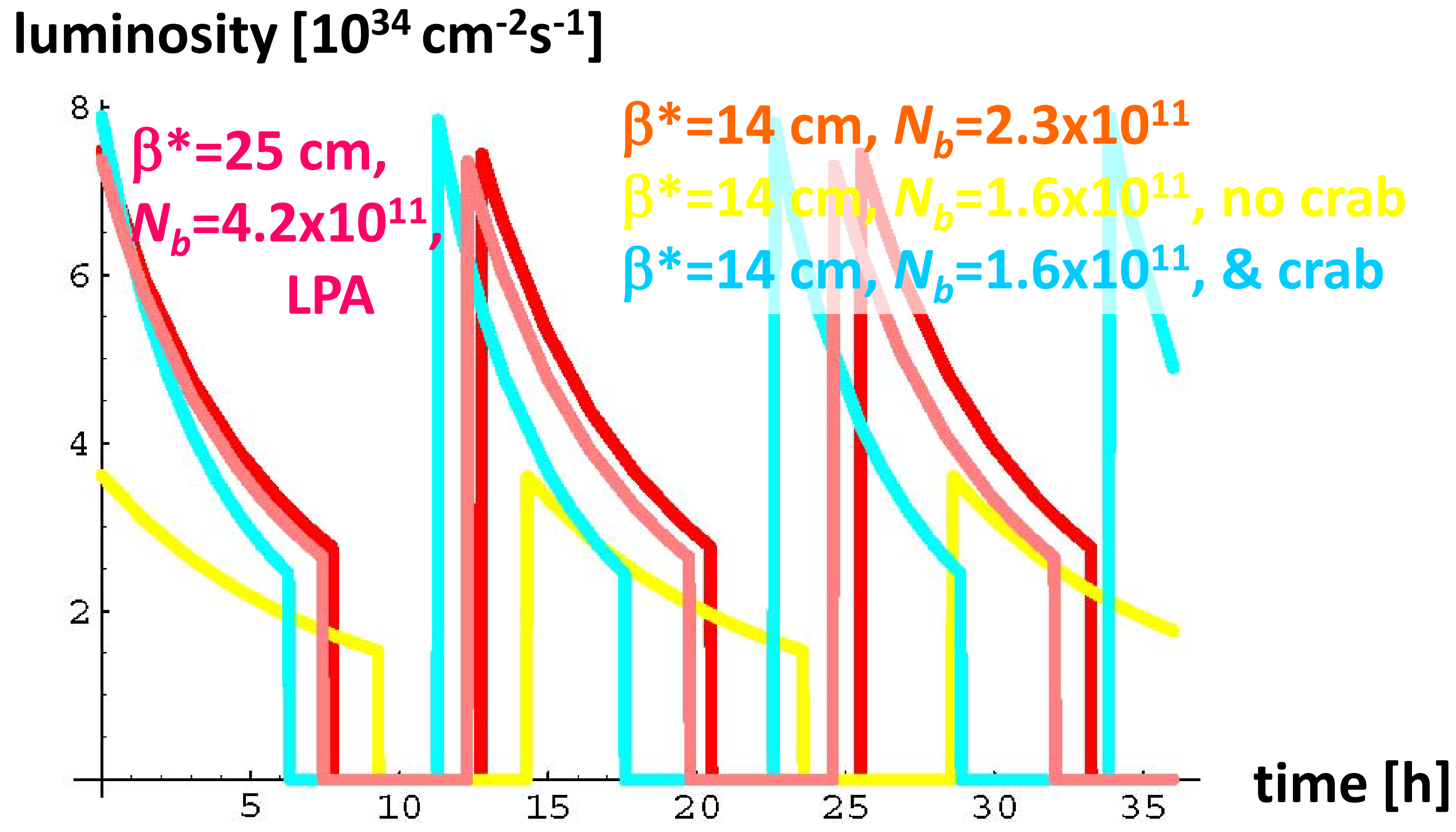
parameter highlights

parameter	symbol	nom.	ult.	β*=30	β*=30 (crab)	β*=14	β*=14 (crab)	LPA(50 ns, flat)
ppb	N_b [10^{11}]	1.15	1.7	**2.3**	**1.6**	**2.3**	**1.6**	**4.2**
beta* at IP1&5	β* [m]	0.55	0.5	**0.30**	**0.30**	**0.14**	**0.14**	**0.25**
Piwinski angle		0.65	0.75	**1.1**	**0.0**	**2.3**	**0.0**	**2.0**
tune shift	ΔQ_{tot}	0.009	0.009	**0.01**	**0.01**	**0.006**	**0.01**	**0.01**
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	2.3	**5.9**	**4.0**	**7.5**	**7.9**	**7.4**
peak evt's / #ing		19	44	**111**	**76**	**142**	**150**	**280**
lumi lifetime	τ_L [h]	23	15	**7.7**	**7.8**	**6.0**	**4.0**	**5.3**
average ($T_{turnaround}$=5 h)	L_{eff}[10^{34} cm^{-2}s^{-1}]	0.55	1.12	**2.4**	**1.6**	**2.8**	**2.4**	**2.6**
	$T_{run,opt}$ [h]	15.2	12.2	**8.7**	**8.8**	**7.7**	**6.3**	**7.5**
annual luminosity (200 days, 60% availability)	L_{int}[fb^{-1}]	57	116	**245**	**168**	**286**	**253**	**274**

luminosity evolution - examples

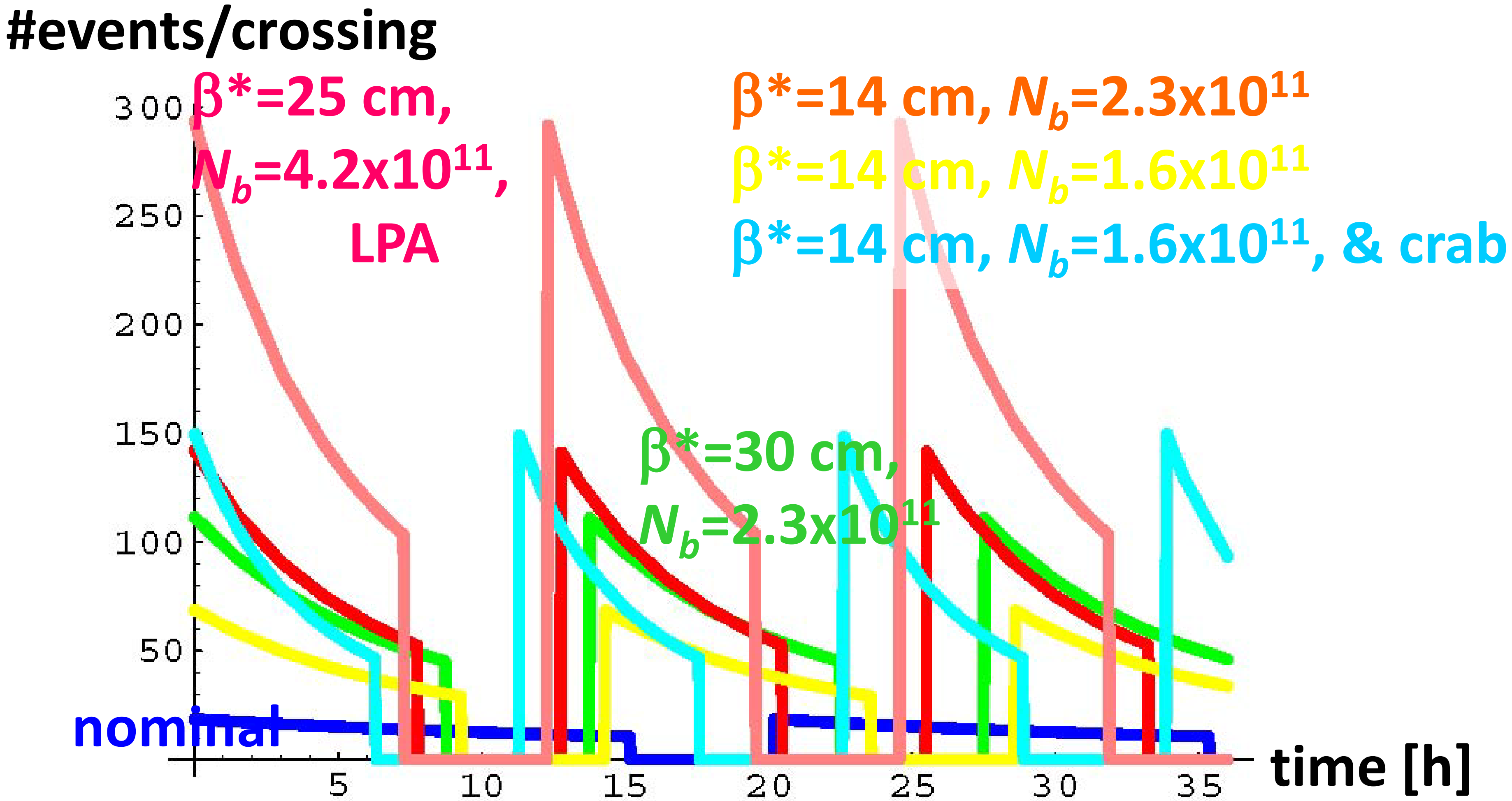


luminosity evolution – selected cases



β*=14 cm & N_b=2.3x10^{11} has very similar performance to β*=14 cm,& N_b~1.6x10^{11} and crab, and to β*=25 cm & N_b=4.2x10^{11} & 50 ns spacing

events/crossing evolution



all scenarios give peak #events/#ing ~100-150, except for LPA ~300

luminosity leveling

changing θ_c, β^* or σ_z during the store in order to
$\rightarrow$ **reduce event pile up & IR peak power deposition**
$\rightarrow$ **maximize integrated luminosity**

leveling with crossing angle has two advantages:
increased average luminosity, operational simplicity

natural option for early separation or crab cavities,
leveling may first be tested in LHC heavy-ion collisions

two leveling strategies:
(1) constant luminosity
(2) constant beam-beam tune shift

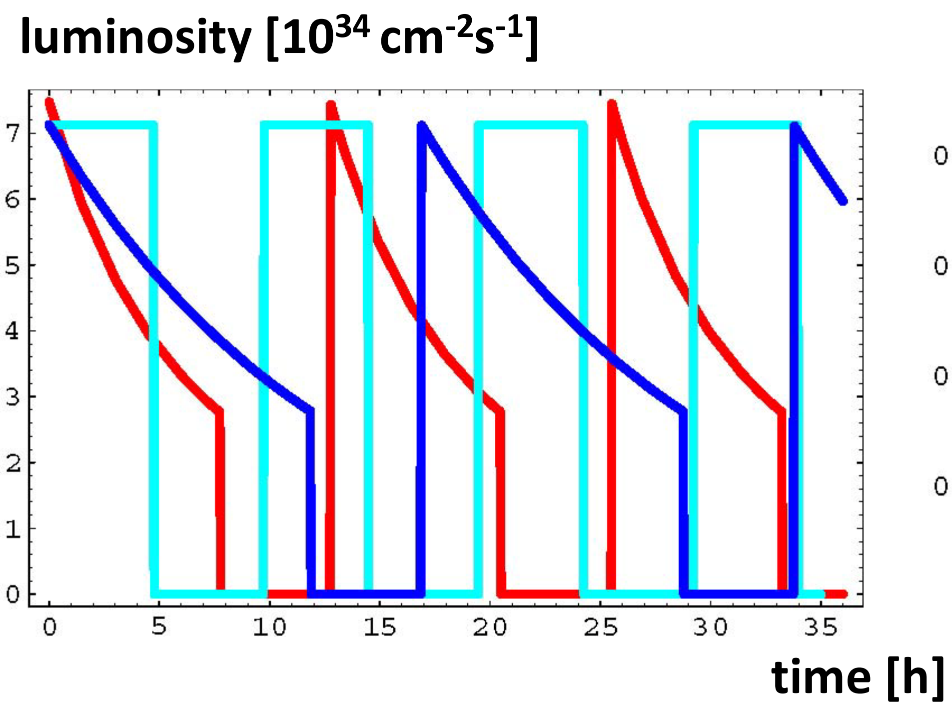
optimum run time & av. luminosity

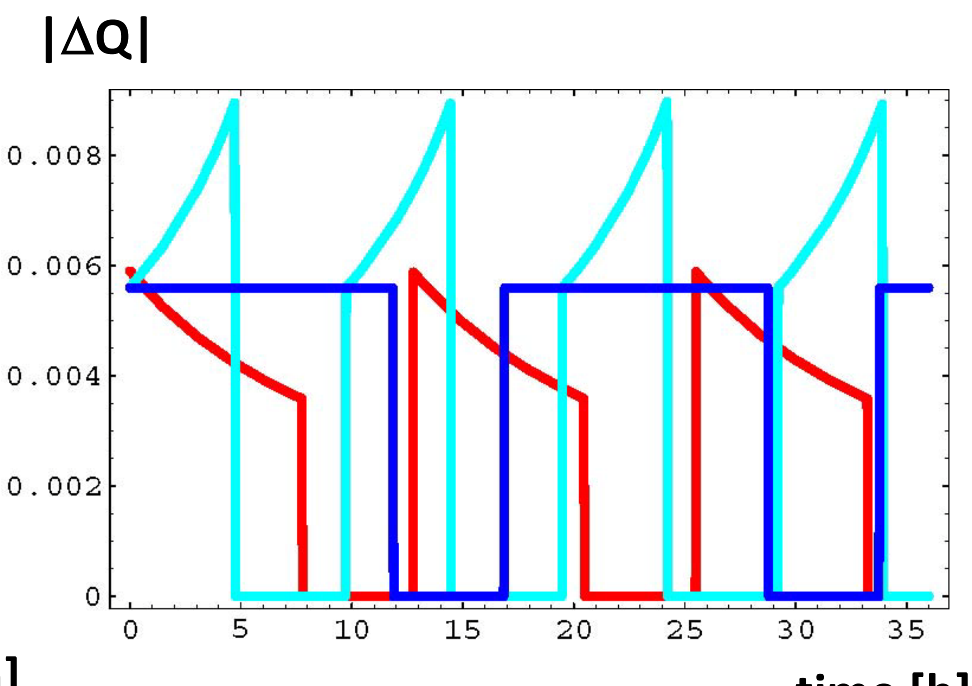
	w/o leveling	L=const	ΔQ_{bb}=const
luminosity evolution	$L(t)=\frac{\hat{L}}{\left(1+t/\tau_{eff}\right)^2}$	$L = L_0 \approx const$	$L(t)=\hat{L}\exp\left(-t/\tau_{eff}\right)$
beam current evolution	$N(t)=\frac{N_0}{\left(1+t/\tau_{eff}\right)}$	$N = N_0 - \frac{N_0}{\tau_{eff}}t$	$N(t)=$ $N(0)\exp\left(-t/\tau_{eff}\right)$
optimum run time	$T_{run}=\sqrt{\tau_{eff}T_{ta}}$	$T_{run}=\frac{\Delta N_{max}\tau_{eff}}{N_0}$	$T_{run}=\tau_{eff}$ $\min\left[\ln\left(\sqrt{1+\phi_{piw}(0)^2}\right),\right.$ $\left.\ln\left(\left(T_{ta}+T_{run}+\tau_{eff}\right)/\tau_{eff}\right)\right]$
average luminosity	$L_{ave}=\hat{L}\frac{\tau_{eff}}{\left(\tau_{eff}^{1/2}+T_{ta}^{1/2}\right)^2}$	$L_{ave}=\frac{L_0}{1+\frac{L_0\sigma_{tot}n_{IP}}{\Delta N_{max}n_b}T_{ta}}$	$L_{ave}=\frac{\tau_{eff}}{T_{ta}+T_{run}}\left(1-e^{-T_{run}/\tau_{eff}}\right)$

leveling 2 → exponential *L* decay, w decay time τ_{eff} (not $\tau_{eff}/2$)

leveling – example evolution

β^*=14 cm, N_b=2.3x10^{11}, T_{ta}=5 h





no leveling
ΔQ=const
L=const

no leveling
ΔQ=const
L=const

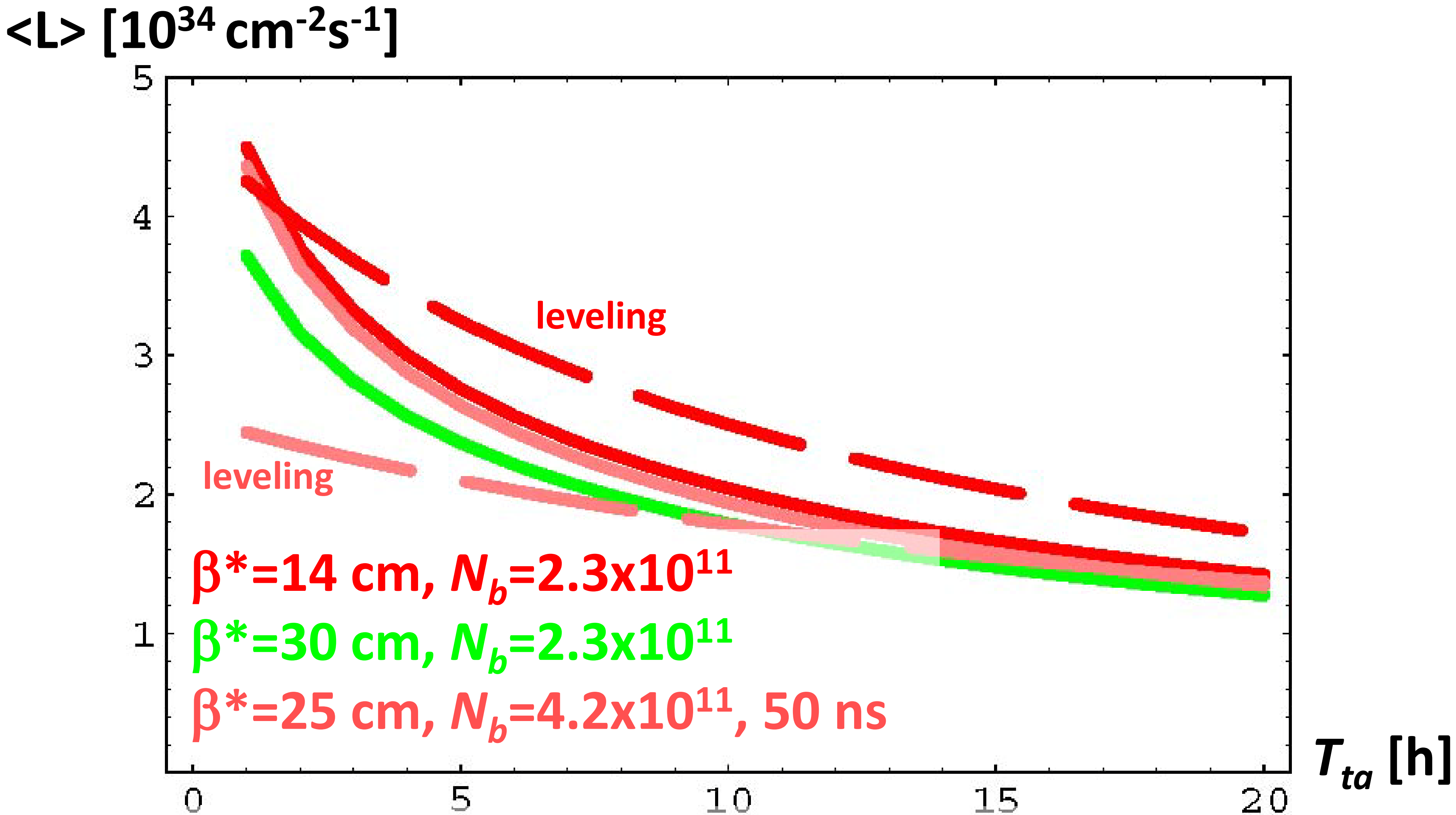
leveling – example numbers

	β*=14 cm, 25 ns spacing, T_{ta}=5 h			
	no leveling	***L*=const**	**ΔQ_{bb}=const**	
$N_b(0)$ [10^{11}]	2.3	2.3	2.3	2.3
$L(0)[10^{34}cm^{-2}s^{-1}]$	7.5	7.1	12.3	7.1
$\|\Delta Q_{bb}(0)\|$	0.0059	0.0056	0.01	0.0056
$\|\Delta Q_{bb}(T_{run})\|$	0.0036	0.0090	0.01	0.0056
$\theta_c(0)$ [μrad]	50[illegible]	539	239	[illegible]39
run time T_{run} [h]	7.74	4.74	2.72	11.9
$<L>[10^{34}cm^{-2}s^{-1}]$	2.8	3.5	3.6	3.2
events/#ing (0)	14[illegible]	135	234	[illegible]35

leveling – other example numbers

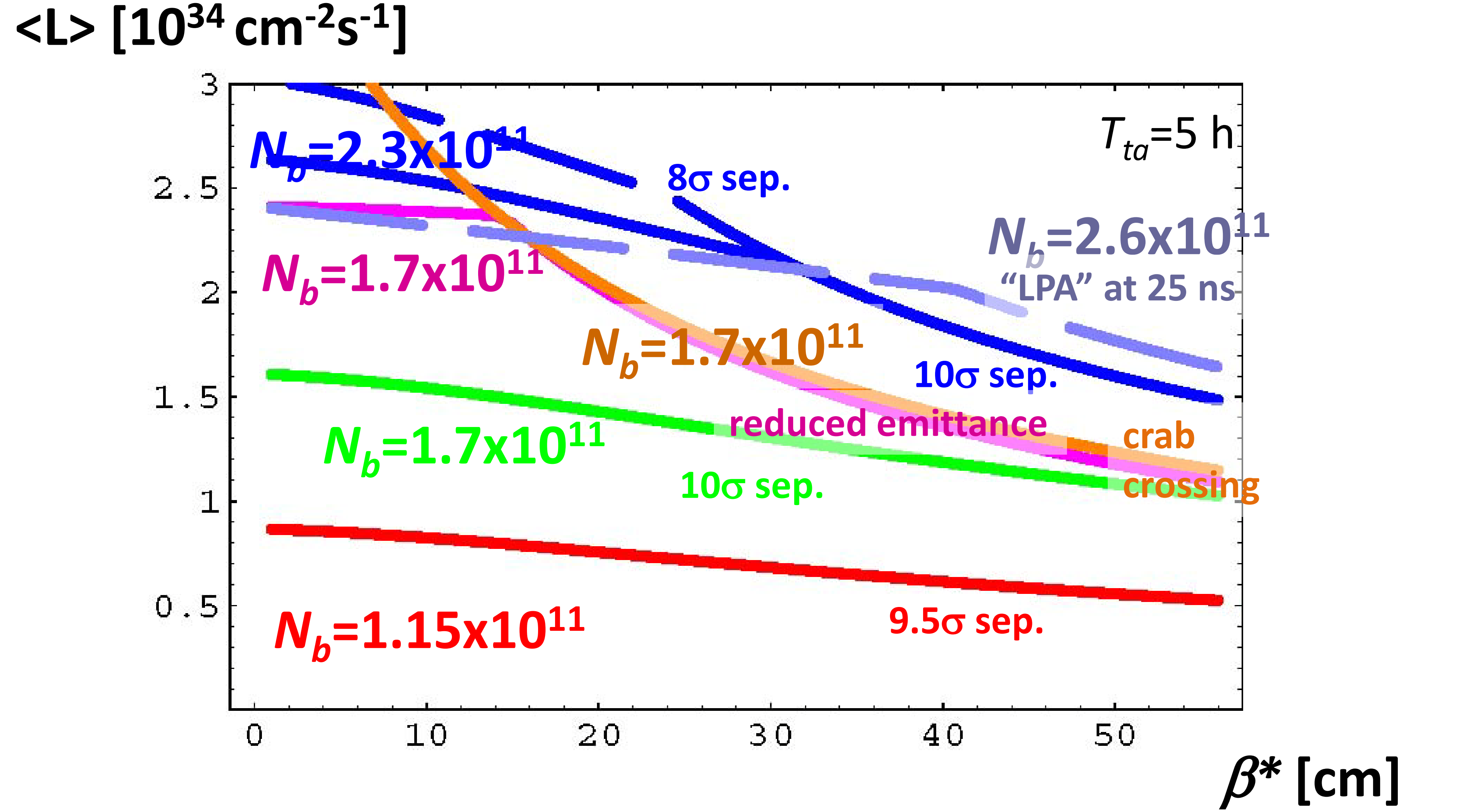
	β^*=25 cm, 50 ns spac., "LPA" T_{ta}=5 h		
	no leveling	L=const	ΔQ_{bb}=const
$N_b(0)$ [10^{11}]	4.2	4.2	4.2
$L(0)$[10^{34}cm^{-2}s^{-1}]	7.4	4.5	4.5
$\lvert\Delta Q_{bb}(0)\rvert$	0.010	0.0056	0.0056
$\lvert\Delta Q_{bb}(T_{run})\rvert$	0.006	0.010	0.0056
$\theta_c(0)$ [μrad]	231	672	672
run time T_{run} [h]	7.45	6.0	23.2
<L>[10^{34}cm^{-2}s^{-1}]	[illegible].6	2.5	2.1
events/#ing (0)	280	172	172

<*L*> vs. turnaround time



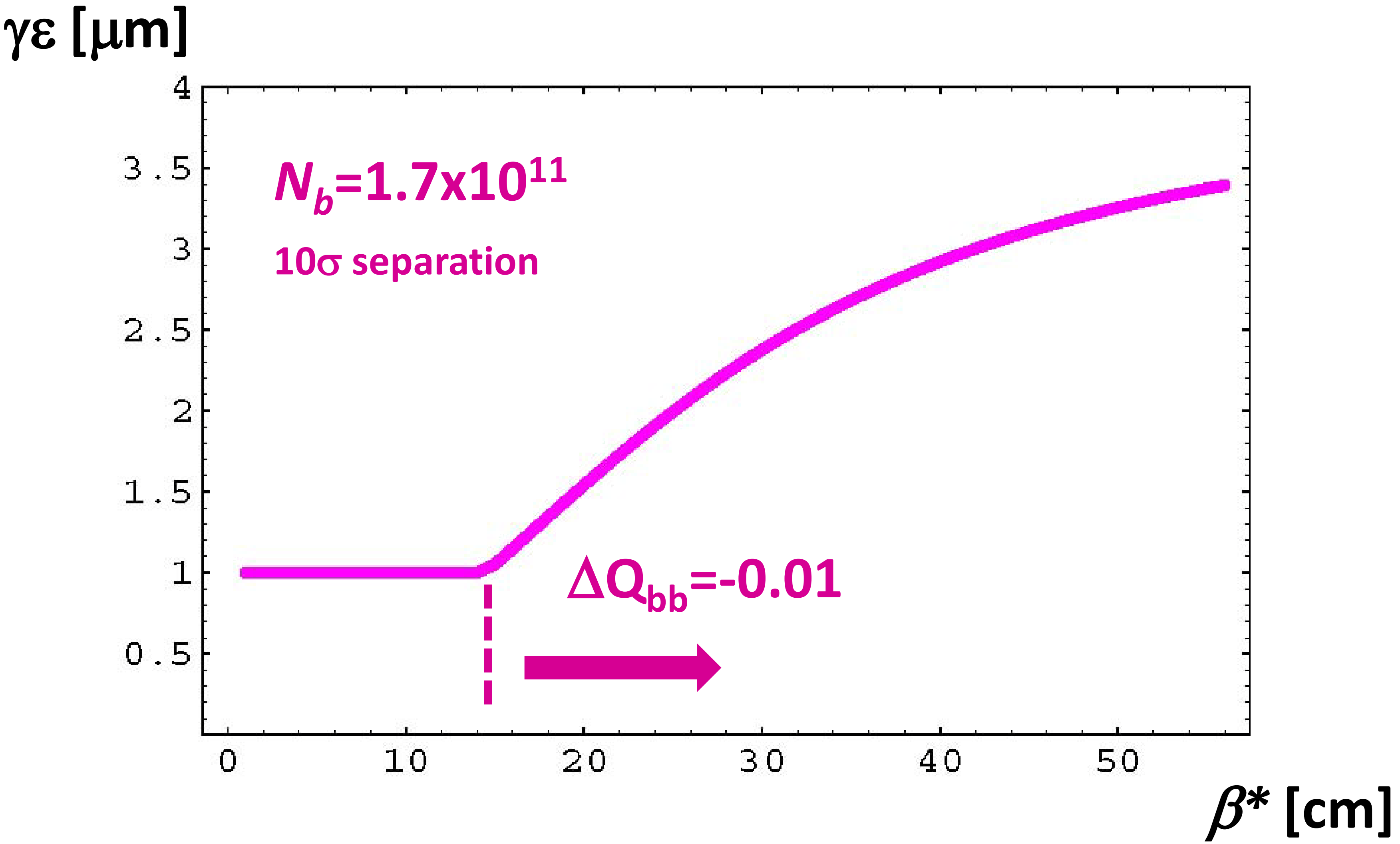
reducing T_{ta} from 10 to 2 h increases <*L*> about 2x, similar average luminosity for all 3 scenarios

<L> vs. β* - the KEY PLOT



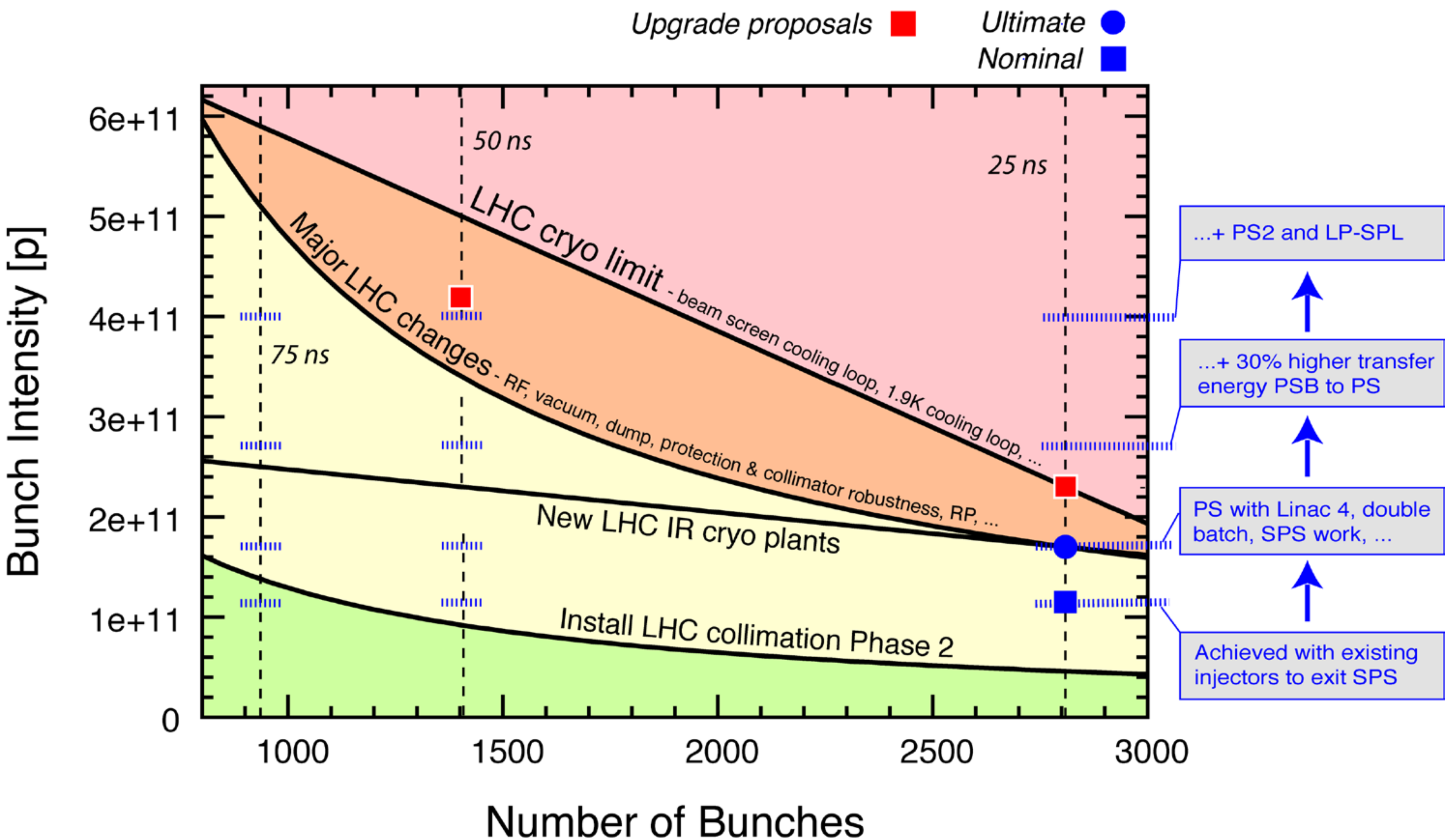
beam intensity is much more important than *β, reducing *β** only helps with crab cavities or with smaller emittance**

ε vs. β* - for low-emittance scheme



emittance for the low-emittance scheme determined by ΔQ

LHC intensity limits at 7 TeV



Ralph Assmann, LMC 03.02.2010

note: some assumptions and conditions

conclusions

- **several upgrade scenarios w. 25 or 50-ns spacing**
- annual luminosities of 150-300 fb^{-1}
- **collimation phase 2 essential**
- **beyond ultimate: separate cryoplants for IR1, 5 & 4**
- **maximum N_b ~$2.3x10^{11}$ at 25 ns, ~$5.0x10^{11}$ at 50 ns**
  limited by arc beam-screen cooling capacity
- T_{ta} - 10→2 h: 2x higher <*L*>
- β^* : factor 2 reduction → 10-20% higher <*L*>, unless
  accompanied by crab cavities or smaller ε
- **N_b: factor 2 increase → 3 times higher <*L*>!**
- crab crossing: 10-100% higher <*L*> ; crab cavities
  also provide easy leveling & increase flexibility

more conclusions

- **leveling with (effective) crossing angle:**
  →1.5-3 x higher T_{run}, →40% lower peak pile up
  →(or) increase <L> by ~15%
- present luminosity optimization assumes collisions in two IPs, LHCb collisions compatible with 50-ns spacing by adding less-intense satellite bunches
- recommended **R&D focus**:

- understanding and **mitigating intensity limits**
- **minimization of turnaround time** (3 h → ~1 h?)
- new **interaction-region design with (much) smaller** β^* together **with crab cavities and/or smaller-emittance beams**

questions

- **how much event pile up is acceptable?**
  - is there a clear upper limit and which?
- is #events per crossing the relevant number, or e.g. #events per 50 ns?
  - or in other words, **is pile up limit / crossing the same for 25-ns and 50-ns spacing?**
- is there an **official policy or guideline for LHCb and ALICE running at the time of SLHC?**; will the 4 experiments always run together? present upgrade scenarios are optimized for high luminosity in two IPs; additional collisions will contribute to ΔQ_{bb}

thank you for your attention!