Machine Plans for Upgrades
"SLHC"type luminosities - issues and solutions

Frank Zimmermann

CMS Upgrade Week

29 April 2010

Input from 2001 LHC Upgrade Feasibility Study and from numerous CARE-HHH and EuCARD-AccNet workshops, LMC's, Chamonix2010, CERN MAC, etc.

Special thanks to R. Bailey, C. Bhat, O. Brüning, R. Calaga, H. Damerau, O. Dominguez, L. Evans, S. Fartoukh, R. Garoby, J.-P. Koutchouk, H. Maury Cuna, S. Myers, R. Ostojic, L. Rossi, F. Ruggiero, W. Scandale, G. Sterbini, L. Tavian, T. Taylor, E. Todesco, R. Tomas,…

contents

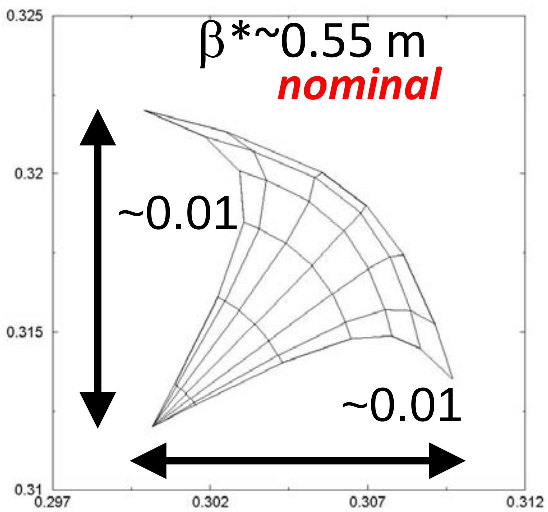
- **parameters available**
- **relationship, constraints and challenges**
- **possible parameter ranges**
- **different optimization strategies**
- **high luminosity scenarios**
- **upgrade time lines**

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

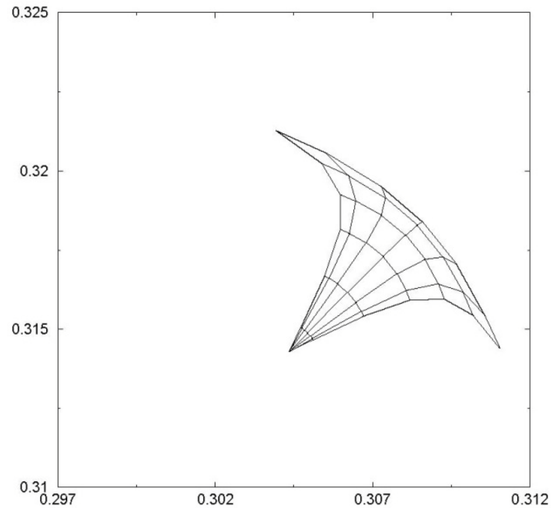
#IP's : the original plan – "phase 0"

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

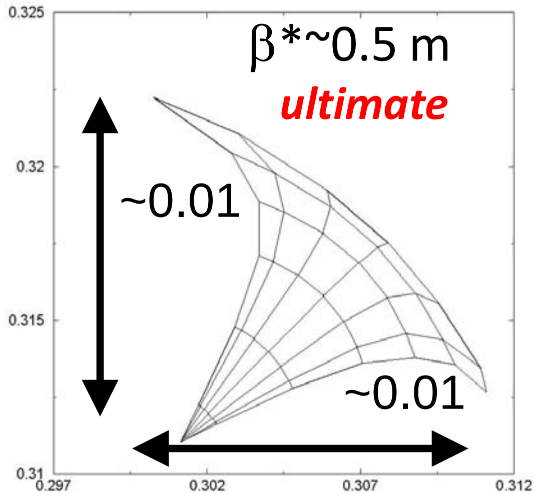


nominal tune footprint up to 6σ with 4 IPs & nom. intensity N_b=1.15x10^{11}

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



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

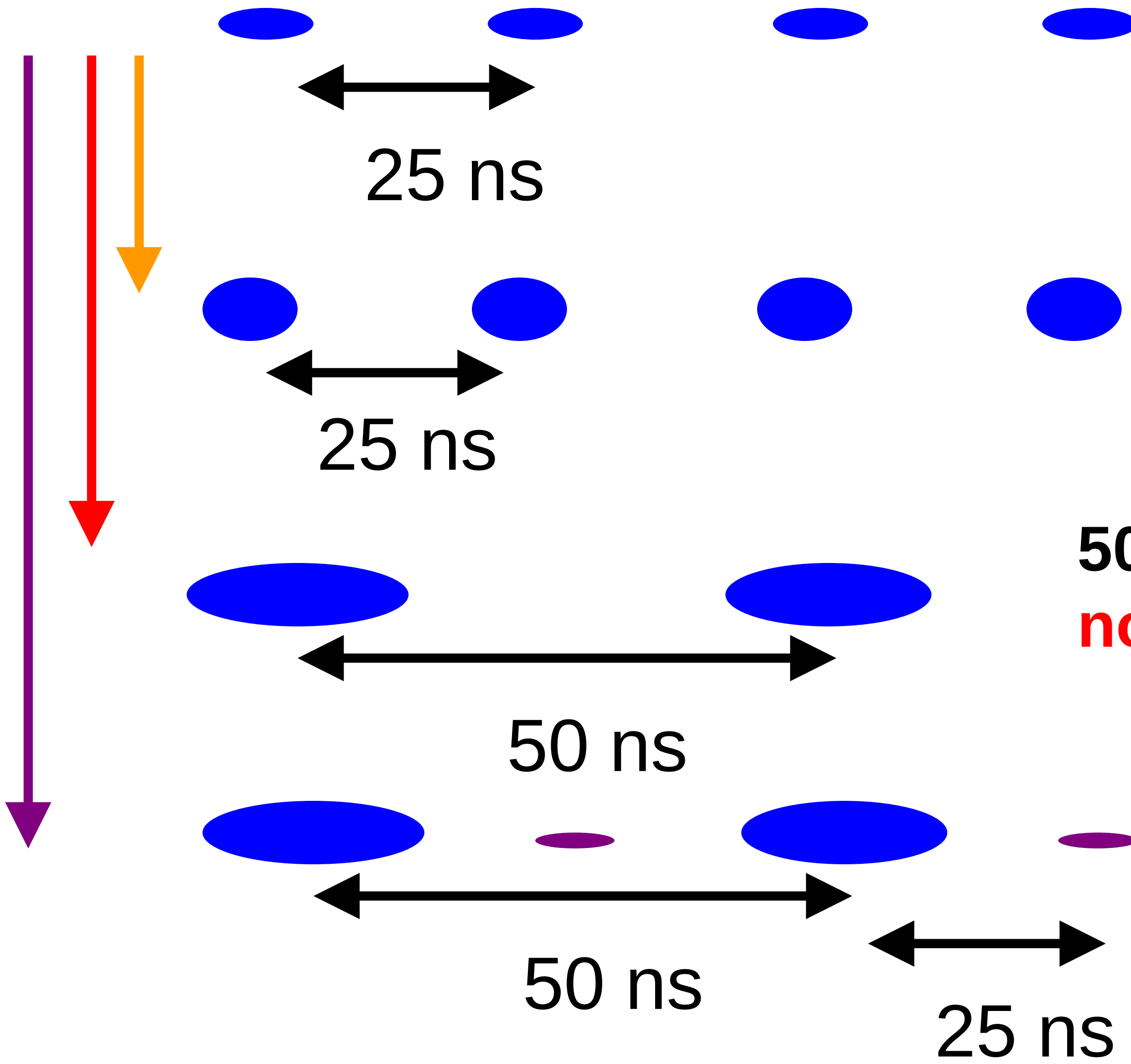


tune footprint up to 6σ with 2 IPs at ultimate intensity N_b=1.7x10^{11}

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

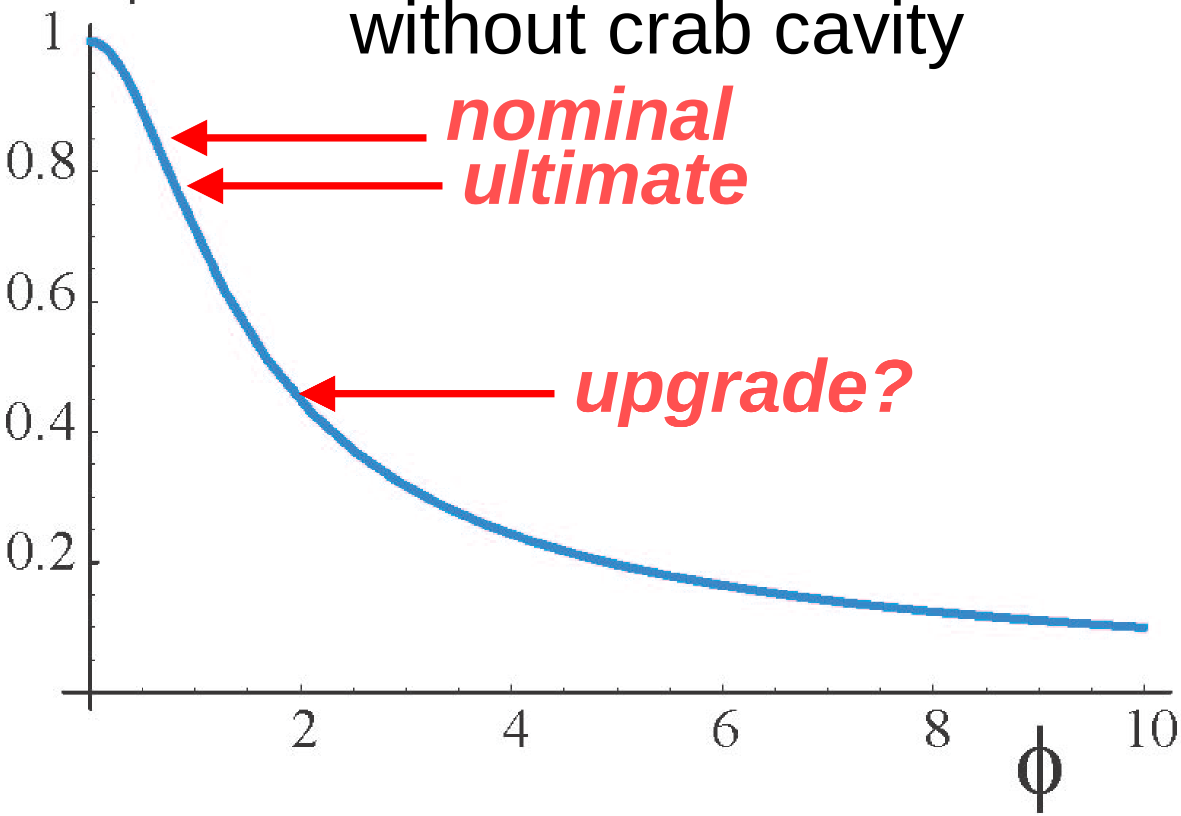
constraints

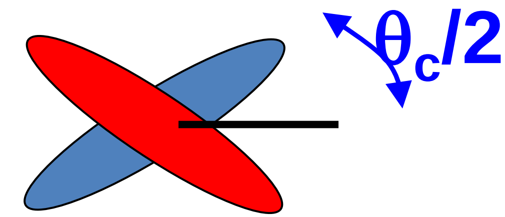
- **total beam-beam tune shift ≤0.01**
  - SPS p-pbar experience
- long-range beam-beam → **crossing angle ≥9σ**
- **arc cooling capacity**
  - global & local limitations, cooling shares with IR
  - heat load from SR, image currents, & e-cloud
- IR layout & optics → β^*
- **event pile up** in the detectors (≤300, ≤200?)
- **luminosity lifetime** (≥ 2h? ≥ 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"?

beam-beam 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>

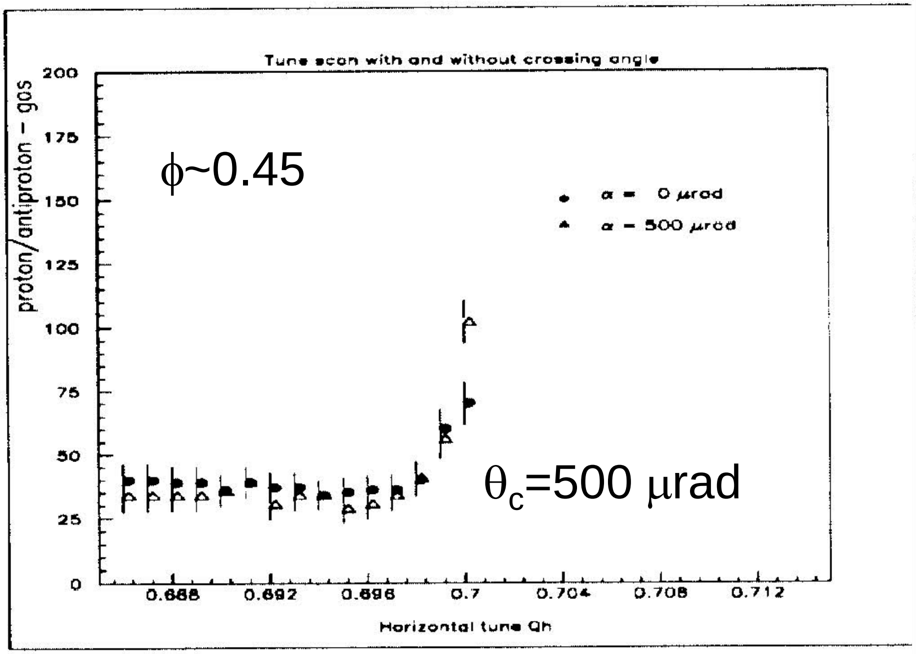
1) increase N_b with ε (e.g. controlled ε blow up at top energy)
2) increase N_b with $1/R_\phi$ & "flat" bunch $F_{profile}$~1.4 ("LPA")
3) vary ε as $1/R_\phi$ ("small emittance")
4) set $1/R_\phi$=1 at IP and minimize β^* (e.g. crab crossing)

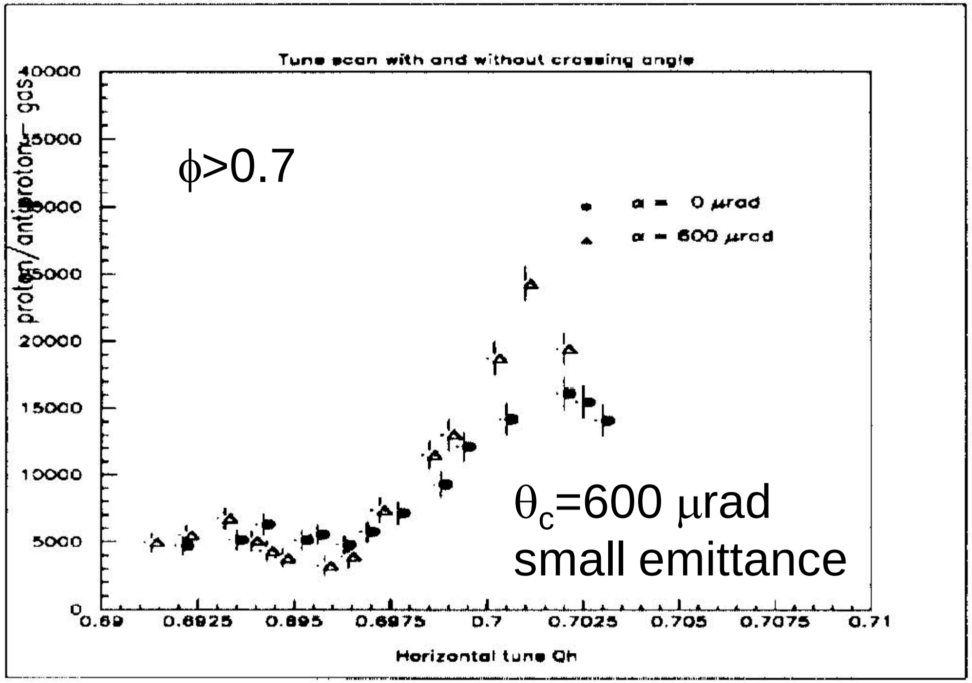
beam-beam limit – θ_c dependence?

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

for hadrons, one historical experiment at the SPS

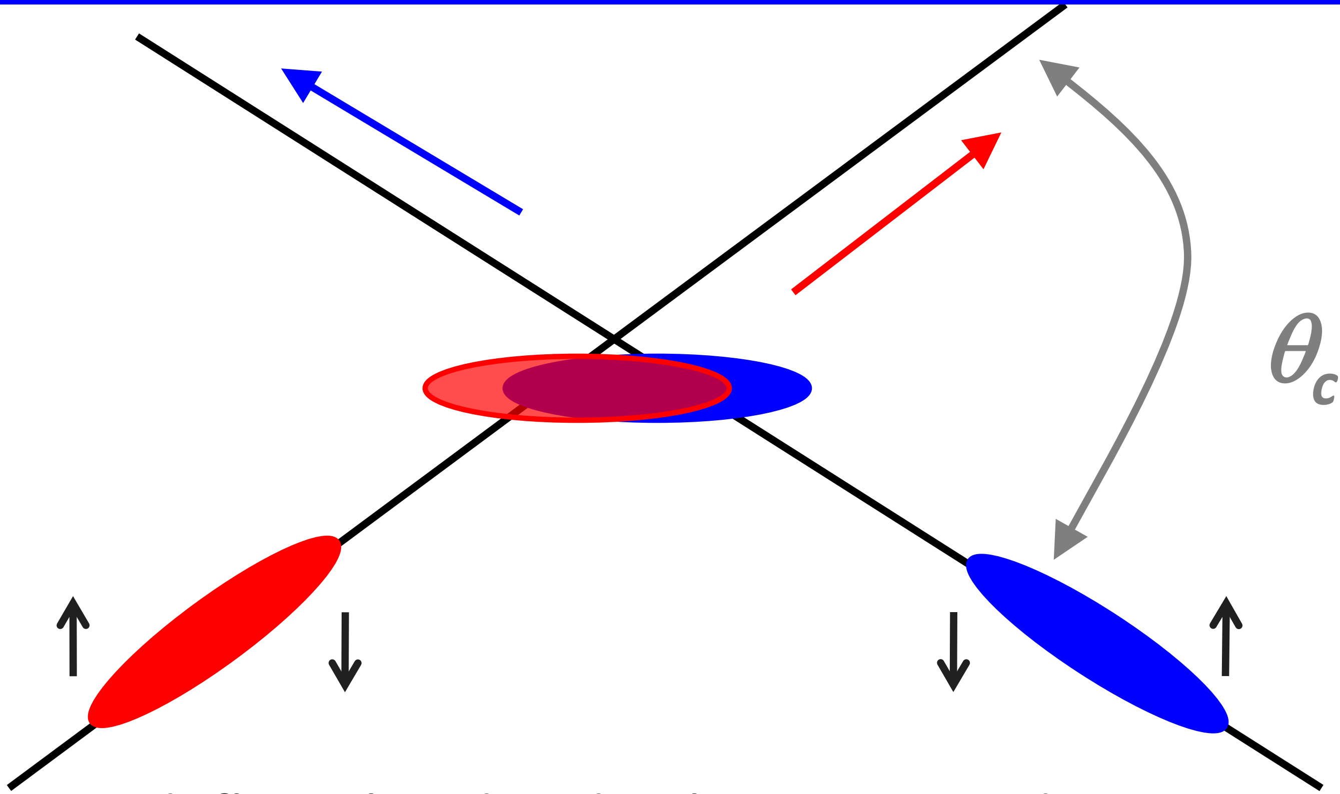
K. Cornelis, W. Herr, M. Meddahi, PAC91 San Francisco





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

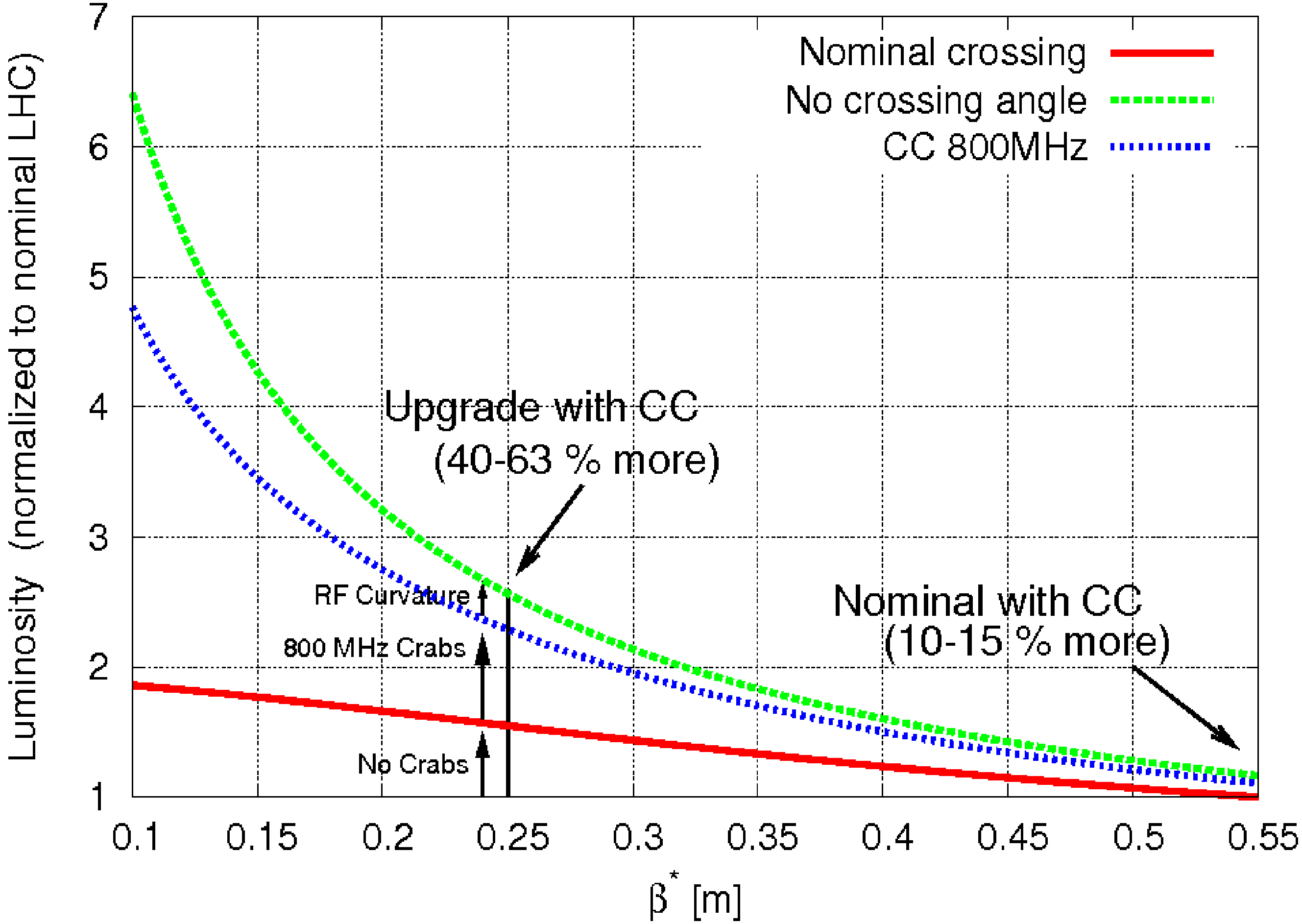
crab crossing



- 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

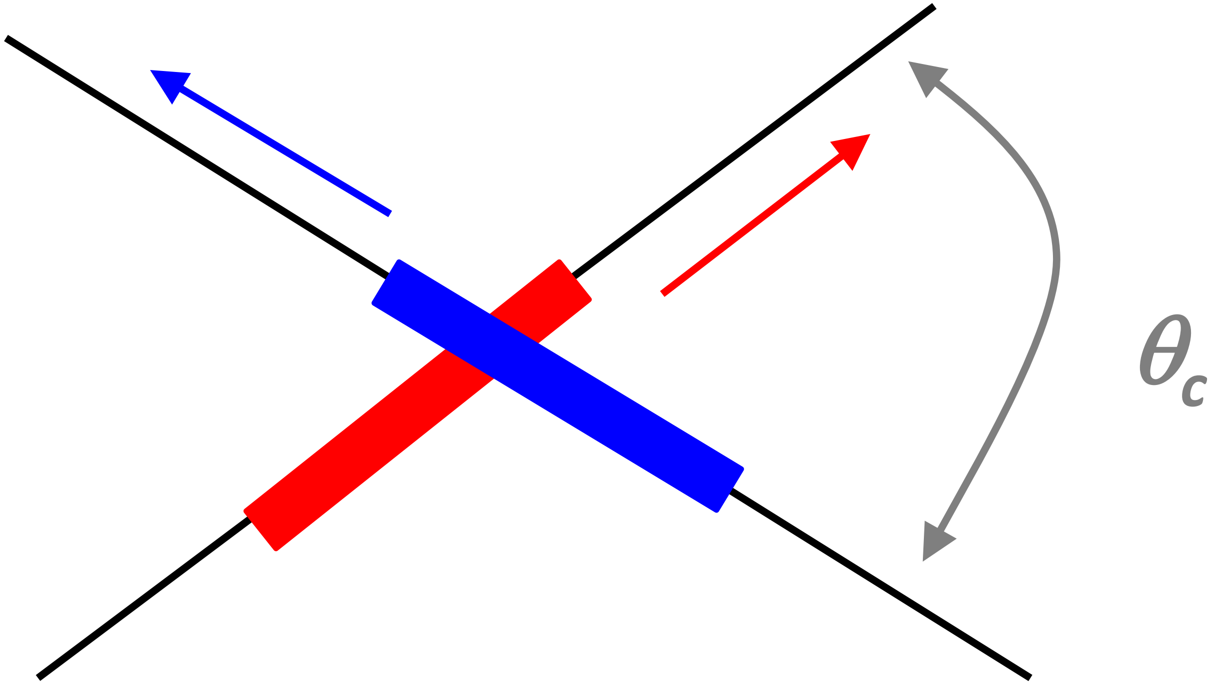
peak luminosity gain w crab cavities



R. Calaga

crab cavities are important & effective for small β*

large Piwinski angle – “LPA”



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

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

constraints - N_b range

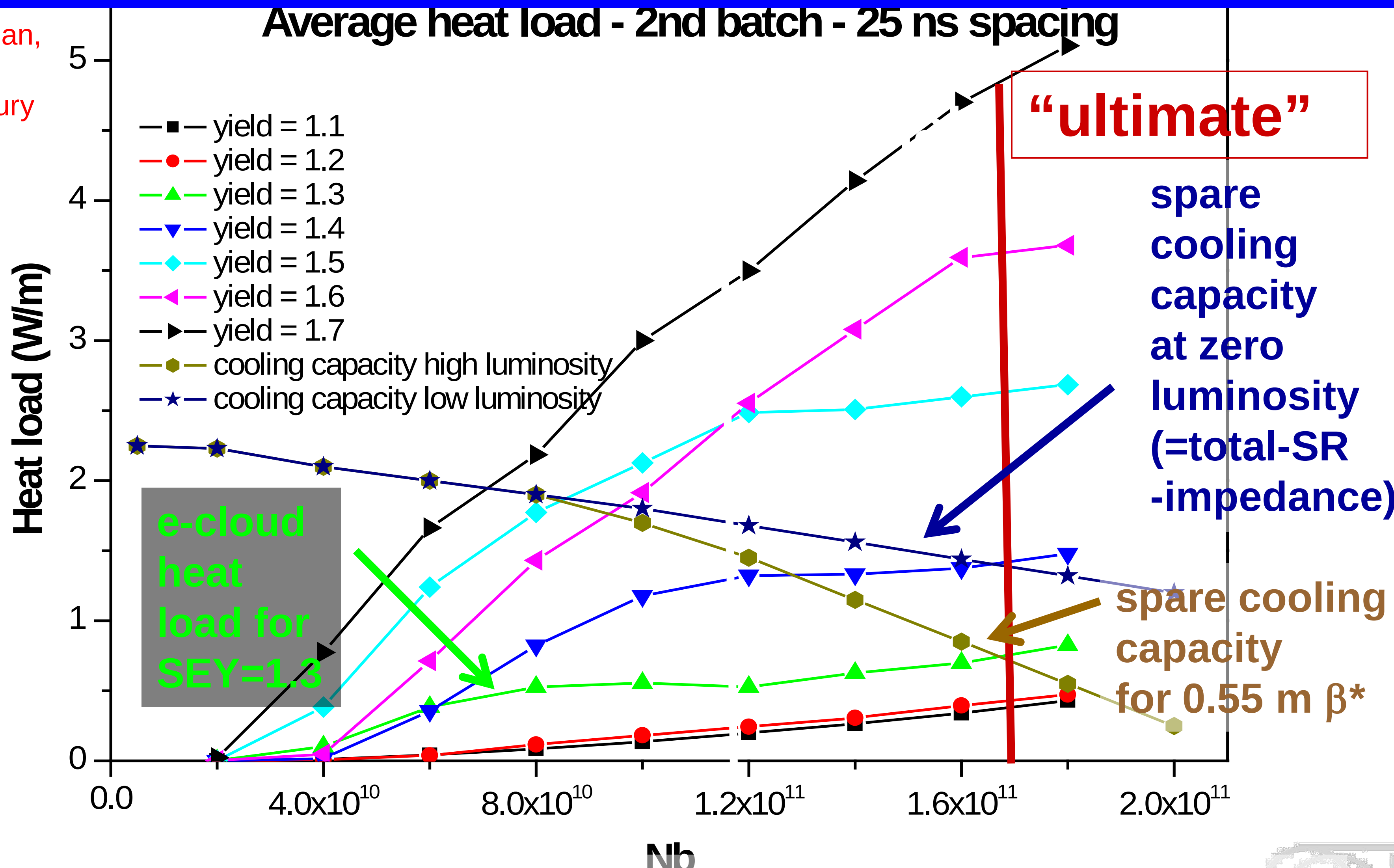
- **beam-beam tune shift** of "head-on" collision
  - ✓ is the limit for crab crossing;
  - ✓ going beyond ultimate N_b requires large Piwinski angle or large emittance;
  - ✓ even larger crossing angle than for LR-BB may be needed

- **arc cooling capacity**

- **injectors**, **collimation**, machine protection,…

cooling & e- heat for 25 ns spacing

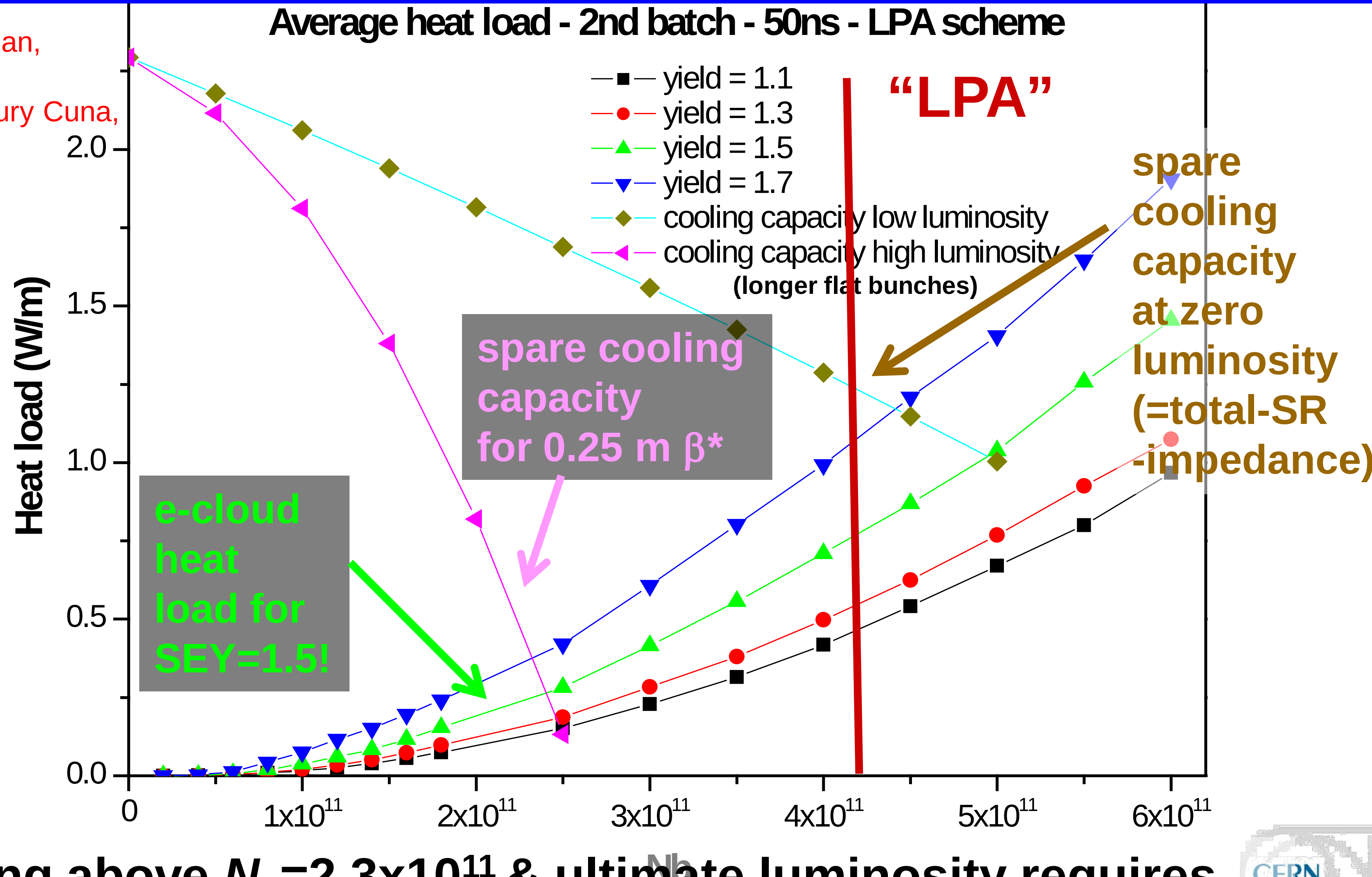
L. Tavian, 2005
H. Maury Cuna, 2009



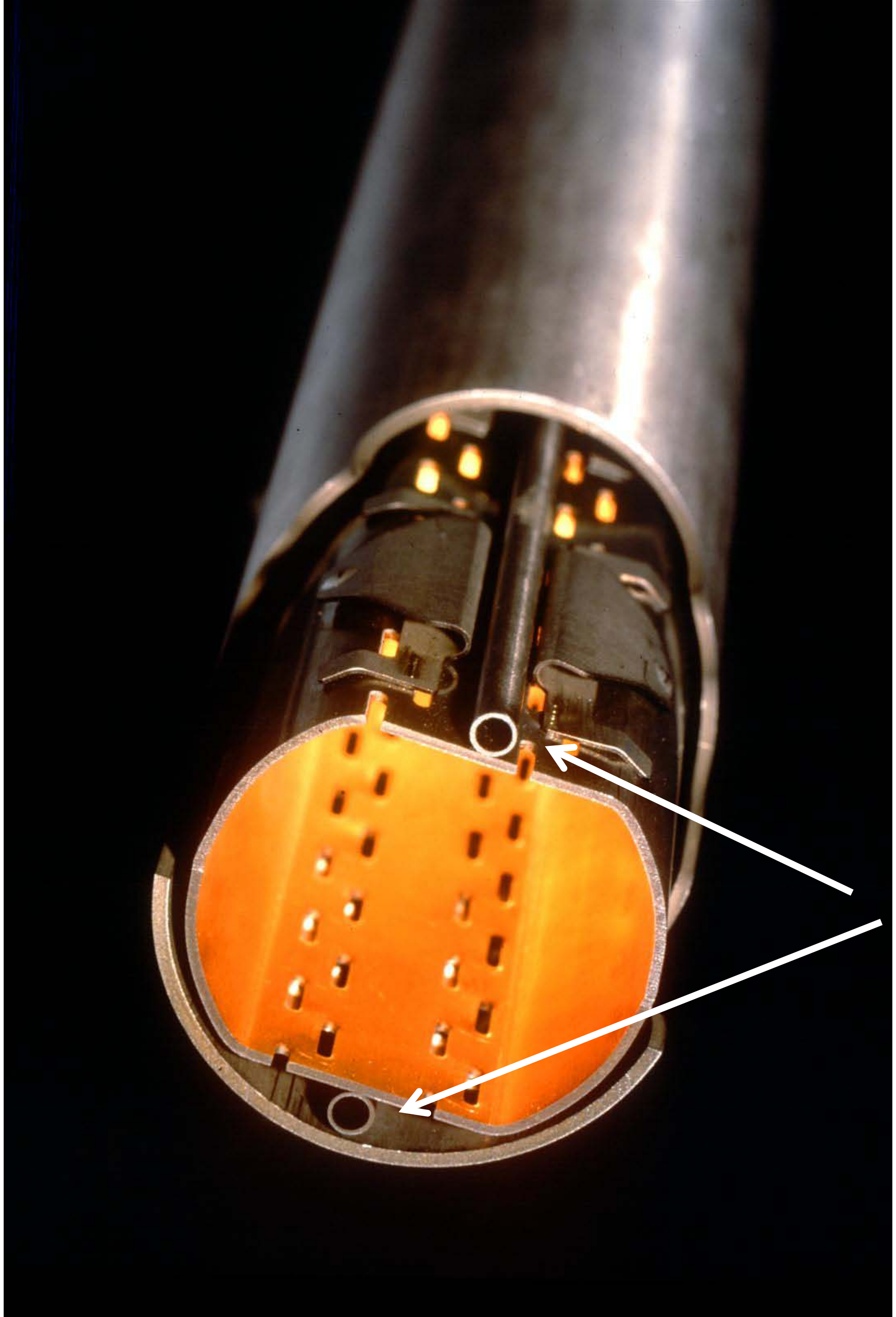
going above N_b=1.7x10^{11} & ultimate luminosity requires dedicated IR cryo plants; limit then becomes N_b~2.3x10^{11}

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}

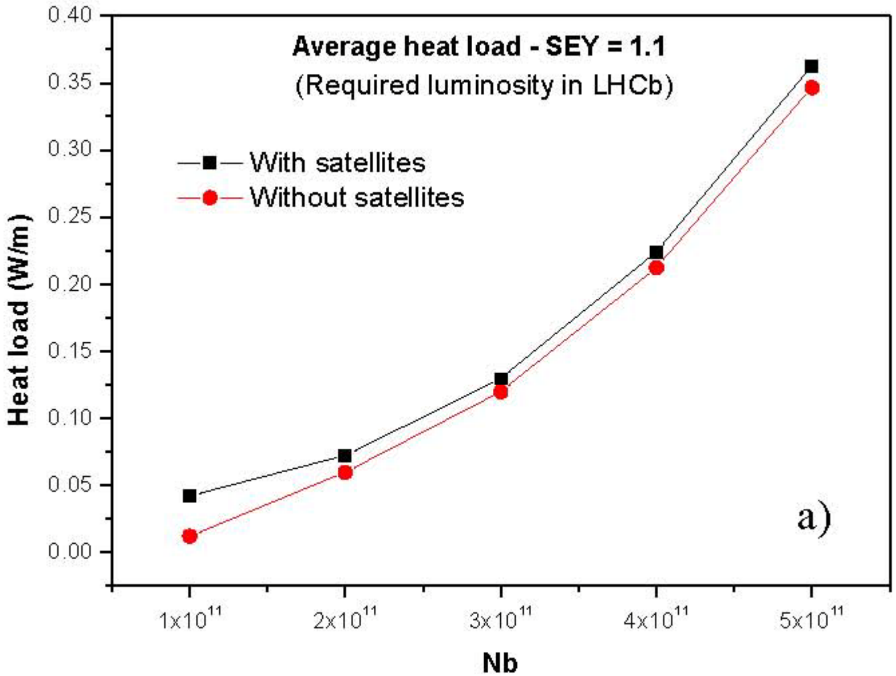


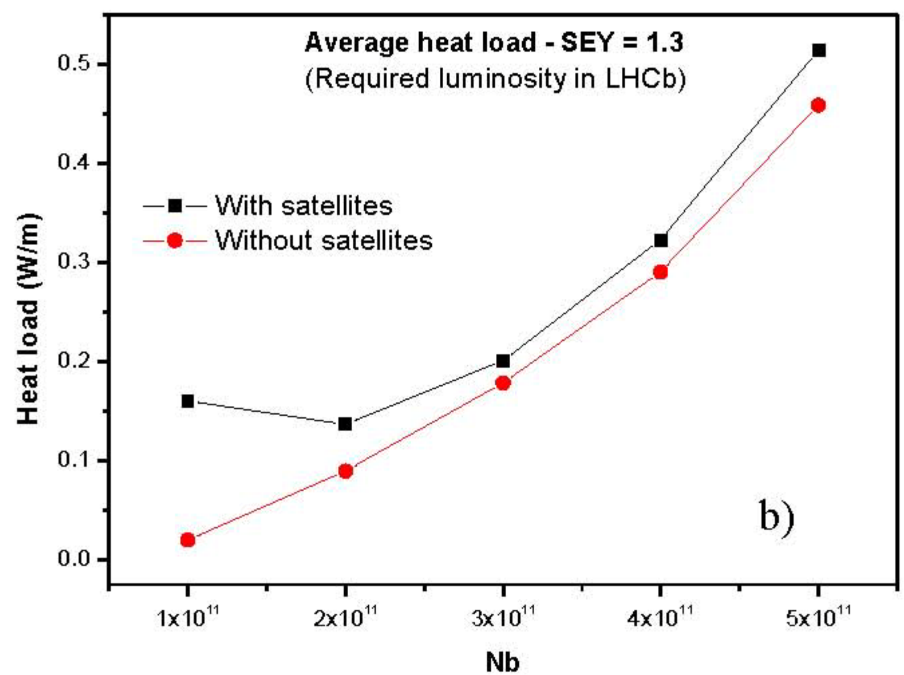
with separate
IR cryoplants,

the local arc
cooling capacity is
limited by hydraulic
impedance (i.e. the
diameter) of the
cooling capillaries
on the arc
beam screens

e- heat with LHCb satellite: OK

H. Maury Cuna, 2009

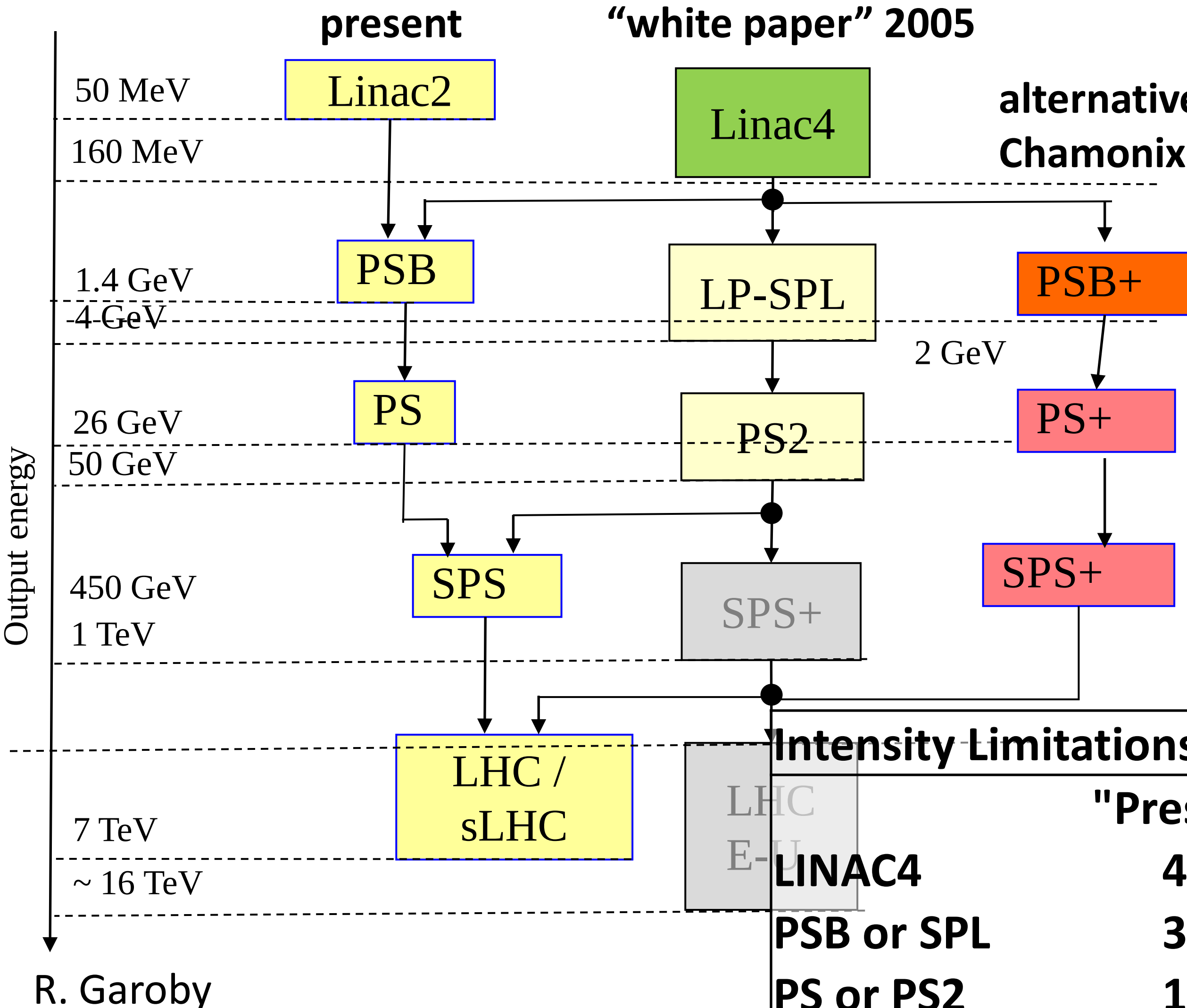




satellite intensity is varied as the inverse of main-bunch intensity to yield target luminosity of 2×10^{33} cm^{-2}s^{-1} in (S)LHCb

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

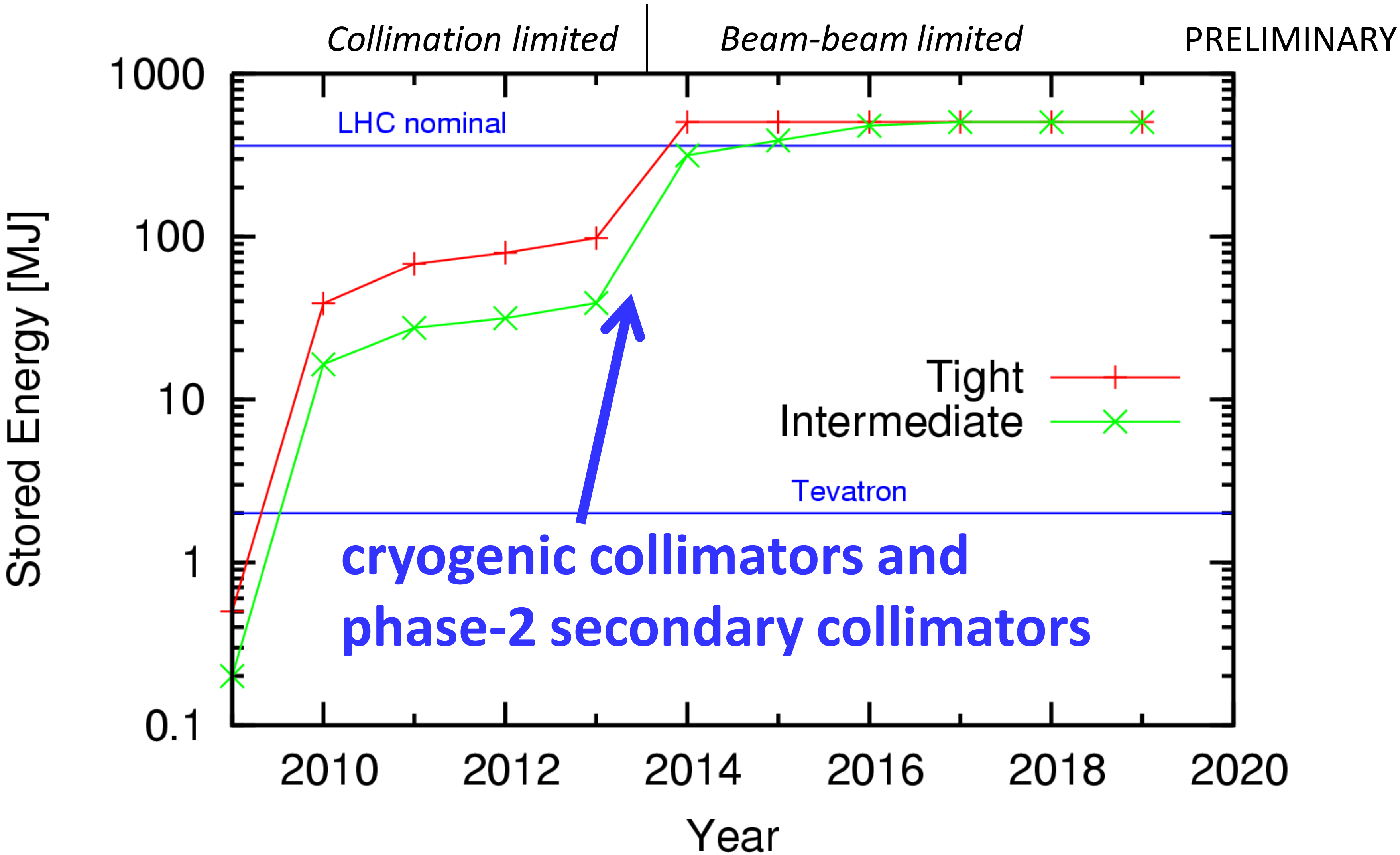
injector upgrade & intensity limits



S. Myers

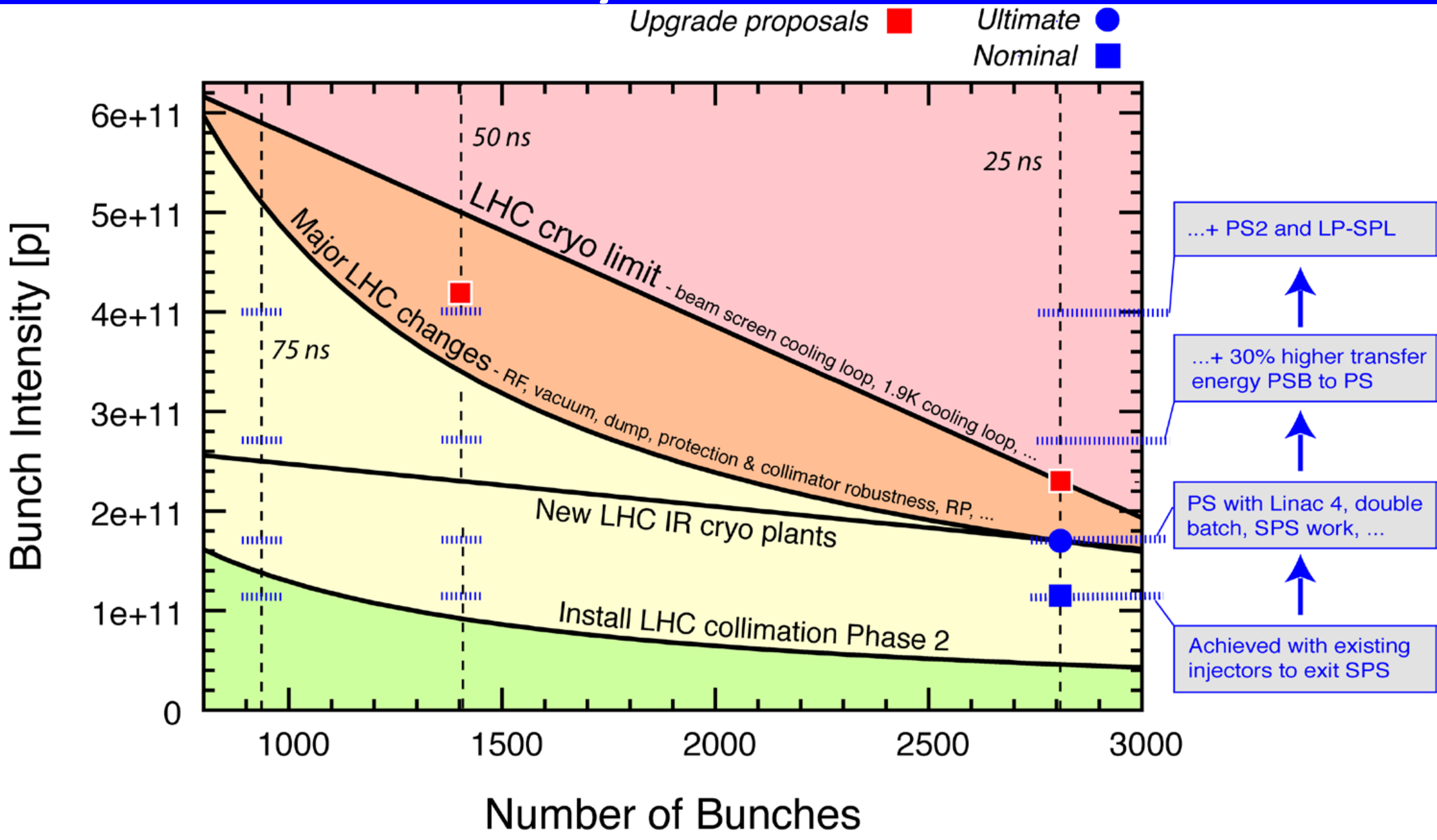
Intensity Limitations (10^{11} protons per bunch)	"Present"	SPL-PS2	2GeV in PS
LINAC4	4.0	4.0	4.0
PSB or SPL	3.6	4.0	3.6
PS or PS2	1.7	4.0	3.0
SPS	1.2	>1.7?	>1.7?
LHC	1.7-2.3?	1.7-2.3?	1.7-2.3?

collimation intensity limits



R. Assmann, C. Bracco, LHCC Upgrade Review, Sept. 2009

LHC intensity limits - schematic



R. Assmann, LMC, 03.02.2010

Note: Some assumptions and conditions apply…

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 + …

…

0.07 m?!

novel Q' correction schemes

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
= 6×10^{-26} cm^2 10^{34} cm^{-2}s^{-1} / (32 $\times 10^6$ 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

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

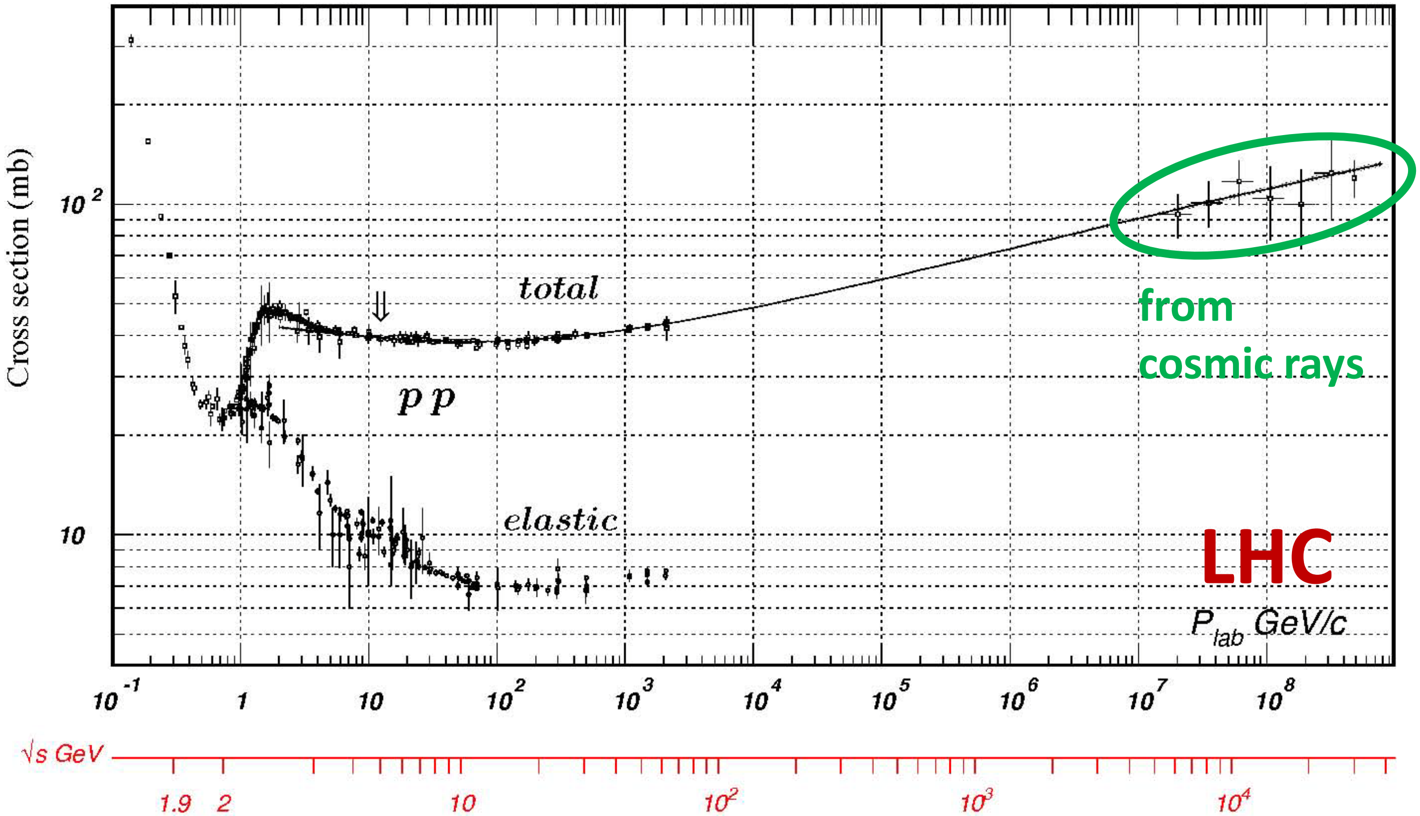
algebraic (≠exponential) decay

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

for given luminosity, 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~ $6x10^{-26}$ 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) nominal*, N_b=1.7x10^{11} ,β*=0.55 m, θ_c=285 μrad, 50 ns

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

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

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

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

(7) "phase II w (&w/o) crab", N_b=1.6x10^{11} ,β*=0.14 m, 509 μrad

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

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

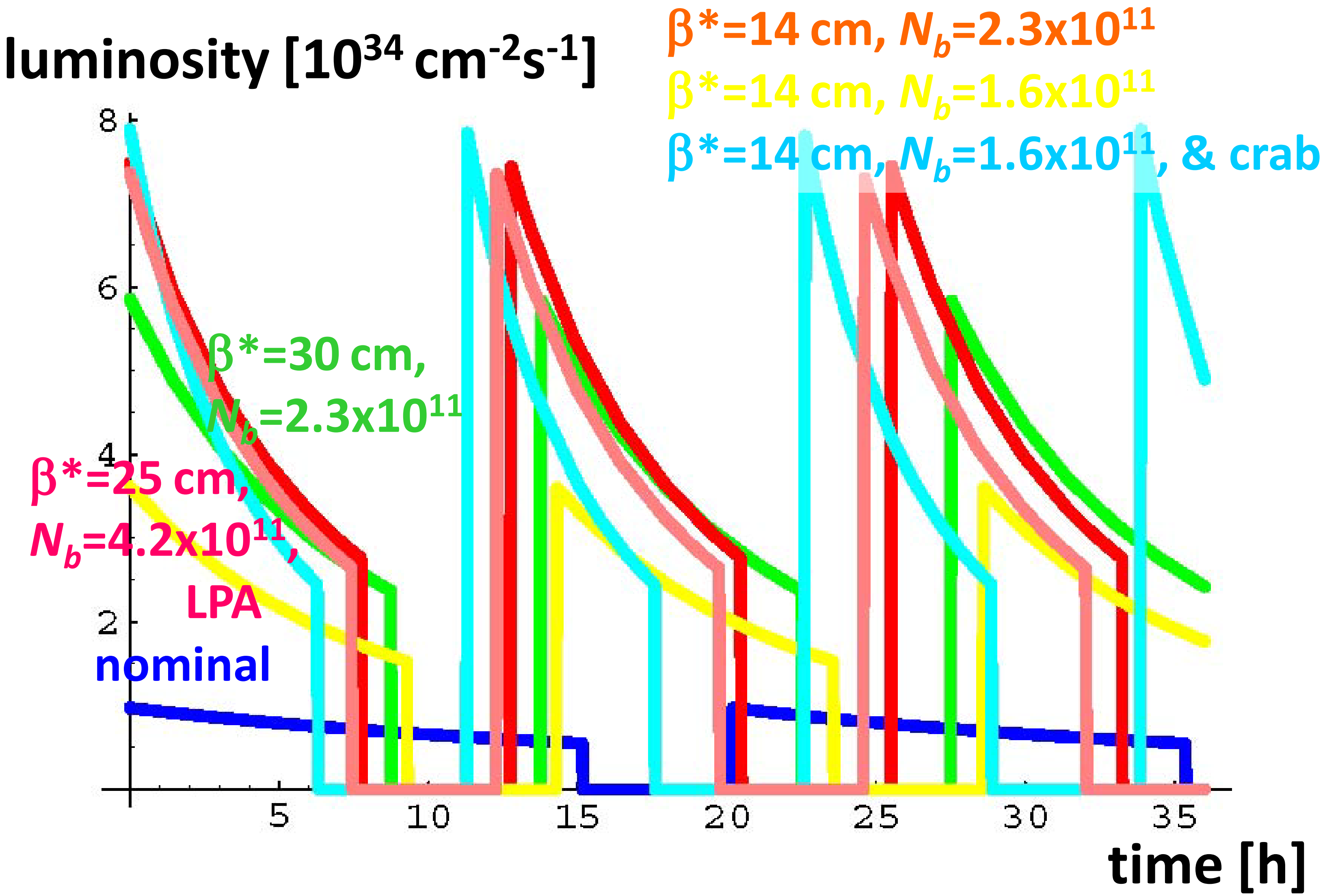
parameter	symbol	nom.	nom.*	ult.	β*=30 cm, HI	β*=30,cm , CC	β*=14, cm HI	β*=14 cm, CC	LPA – 25	LPA – 50
transverse emittance	ε [μm]	3.75	3.75	3.75	**3.75**	**3.75**	**3.75**	**3.75**	**3.75**	**3.75**
protons per bunch	N_b [10^{11}]	1.15	1.7	1.7	**2.3**	**1.6**	**2.3**	**1.6**	**2.6**	**4.2**
bunch spacing	Δt [ns]	25	50	25	**25**	**25**	**25**	**25**	**25**	**50**
beam current	I [A]	0.58	0.43	0.86	**1.16**	**0.81**	**1.16**	**0.81**	**1.32**	**1.06**
longitudinal profile		Gauss	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**	**7.55**	**11.8**	**11.8**
beta* at IP1&5	β* [m]	0.55	0.55	0.5	**0.30**	**0.30**	**0.14**	**0.14**	**0.50**	**0.25**
full crossing angle	θ_c [μrad]	285	285	315	**348**	**(348)**	**509**	**(509)**	**339**	**381**
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.65	0.65	0.75	**1.1**	**0.0**	**2.3**	**0.0**	**2.0**	**2.0**
tune shift	ΔQ_{tot}	0.009	0.0136	0.009	**0.01**	**0.01**	**0.006**	**0.01**	**0.01**	**0.01**
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	1.1	2.3	**5.9**	**4.0**	**7.5**	**7.9**	**4.0**	**7.4**
peak events per #ing		19	40	44	**111**	**76**	**142**	**150**	**75**	**280**
initial lumi lifetime	τ_L [h]	23	16	15	**7.7**	**7.8**	**6.0**	**4.0**	**12.4**	**5.3**
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.45	0.43	0.90	**1.8**	**1.2**	**2.0**	**1.7**	**1.5**	**1.9**
	$T_{run,opt}$ [h]	21.5	17.7	17.2	**12.4**	**12.5**	**11.0**	**8.9**	**16.0**	**10.5**
effective luminosity ($T_{turnaround}$=2 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.67	0.68	1.41	**3.2**	**2.2**	**3.8**	**3.5**	**2.4**	**3.6**
	$T_{run,opt}$ [h]	9.6	7.9	7.7	**5.5**	**5.6**	**4.9**	**4.0**	**7.2**	**4.7**
e-c heat SEY=1.3	P [W/m]	0.4	0.1	0.6	**1.3**	**0.7**	**1.3**	**0.7**	**1.4**	**0.8**
SR heat 4.6-20 K	P_{SR} [W/m]	0.17	0.13	0.25	**0.34**	**0.24**	**0.34**	**0.24**	**0.38**	**0.31**
image current heat	P_{IC} [W/m]	0.15	0.17	0.33	**0.60**	**0.29**	**0.60**	**0.29**	**0.39**	**0.51**
gas-s. 100 h τ_b	P_{gas} [W/m]	0.04	0.03	0.06	**0.08**	**0.05**	**0.08**	**0.05**	**0.09**	**0.07**
luminous region	σ_l [cm]	4.5	4.5	4.3	**3.7**	**5.3**	**2.2**	**5.3**	**5.2**	**3.8**
annual luminosity	L_{int}[fb^{-1}]	57	56	116	**245**	**169**	**286**	**253**	**198**	**274**

example parameters

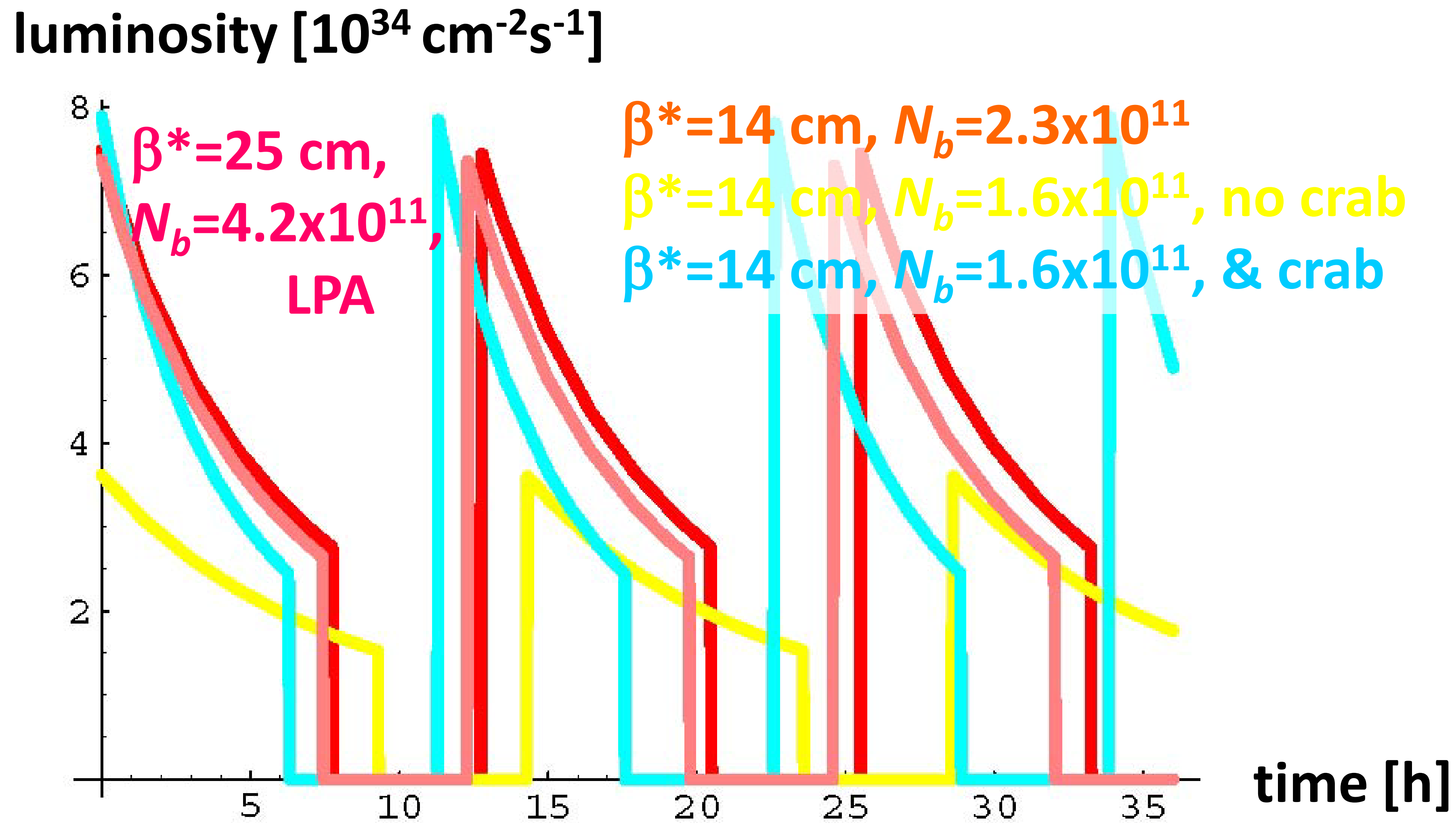
parameter highlights

parameter	symbol	nom.	nom.* (50 ns).	ult.	β*=30 (crab)	β*=14	β*=14 (crab)	LPA(50 ns, flat)
ppb	N_b [10^{11}]	1.15	1.7	1.7	**1.6**	**2.3**	**1.6**	**4.2**
beta* at IP1&5	β* [m]	0.55	0.55	0.5	**0.30**	**0.14**	**0.14**	**0.25**
Piwinski angle		0.65	0.65	0.75	**0.0**	**2.3**	**0.0**	**2.0**
tune shift	ΔQ_{tot}	0.009	0.0136	0.009	**0.01**	**0.006**	**0.01**	**0.01**
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	1.1	2.3	**4.0**	**7.5**	**7.9**	**7.4**
peak evt's / #ing		19	40	44	**76**	**142**	**150**	**280**
lumi lifetime	τ_L [h]	23	16	15	**7.8**	**6.0**	**4.0**	**5.3**
average ($T_{turnaround}$=5 h)	L_{eff}[10^{34} cm^{-2}s^{-1}]	0.55	0.54	1.12	**1.6**	**2.8**	**2.4**	**2.6**
	$T_{run,opt}$ [h]	15.2	7.9	12.2	**8.8**	**7.7**	**6.3**	**7.5**
annual lum. (200 days, 60% availability)	L_{int}[fb^{-1}]	57	56	116	**168**	**286**	**253**	**274**

luminosity evolution - examples

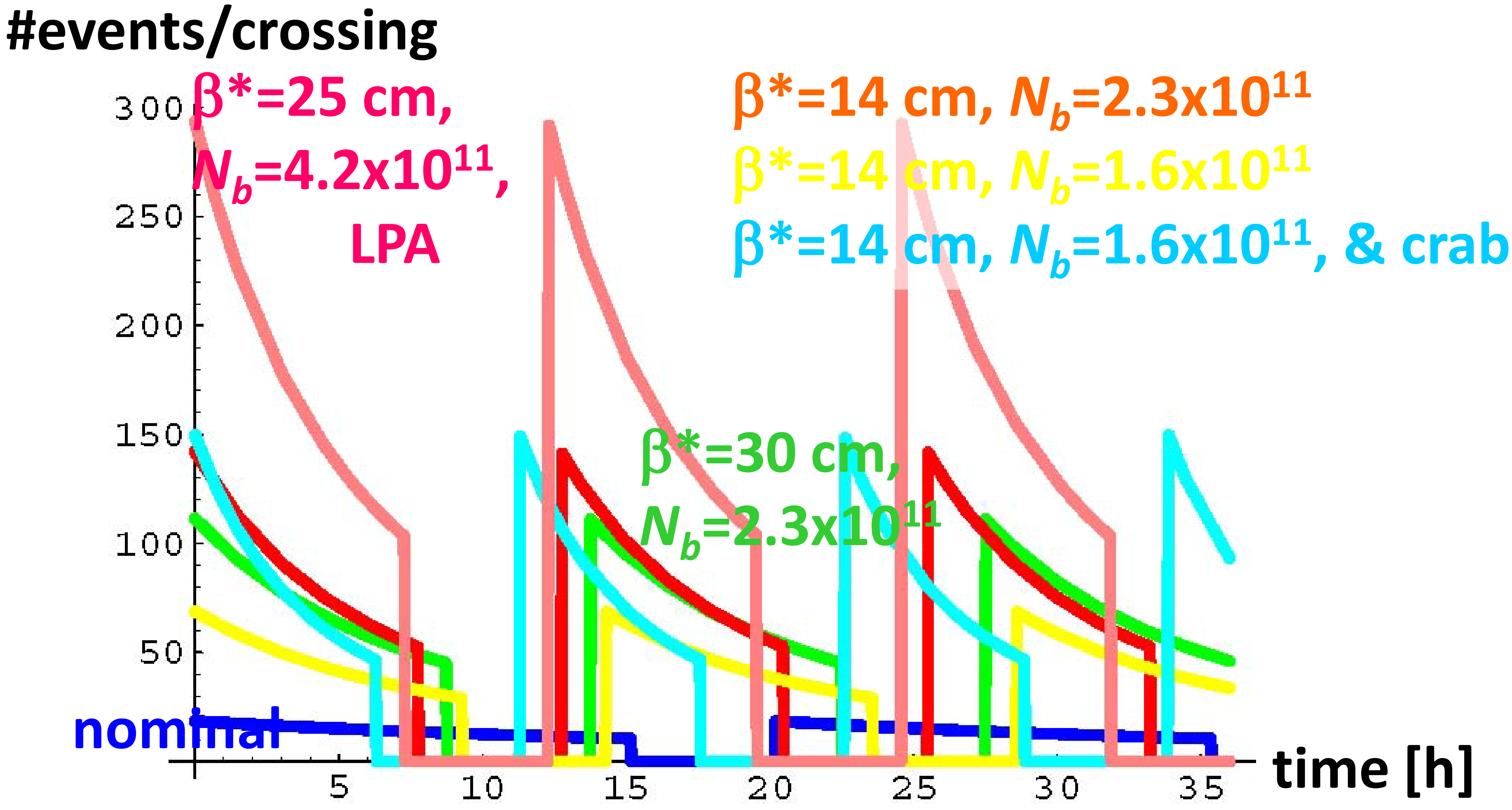


luminosity evolution – selected cases



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

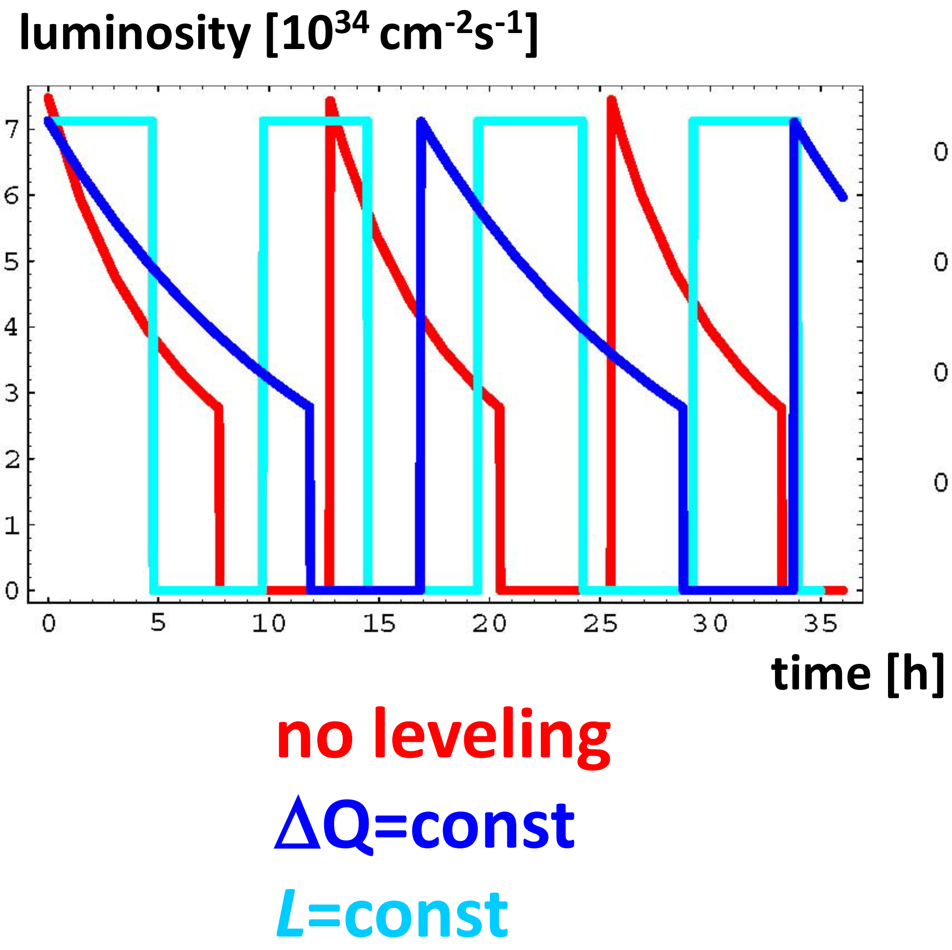
optimum run time & av. luminosity

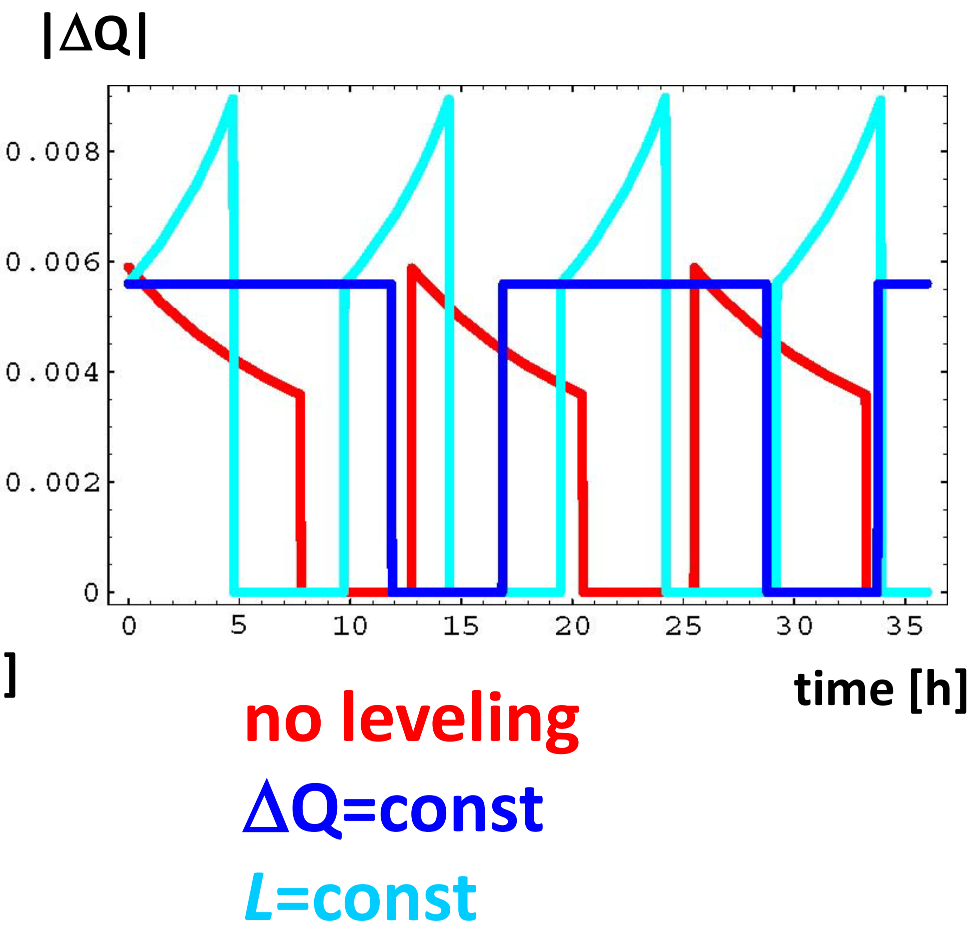
	w/o leveling	L=const	ΔQ_{bb}=const
luminosity evolution	$L(t)=\frac{\hat{L}}{\left(1+t/\tau_{eff}\right)^2}$	$L=L_0\approx const$	$L(t)=\hat{L}\exp\left(-t/\tau_{eff}\right)$
beam current evolution	$N(t)=\frac{N_0}{\left(1+t/\tau_{eff}\right)}$	$N=N_0-\frac{N_0}{\tau_{eff}}t$	$N(t)=$ $N(0)\exp\left(-t/\tau_{eff}\right)$
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





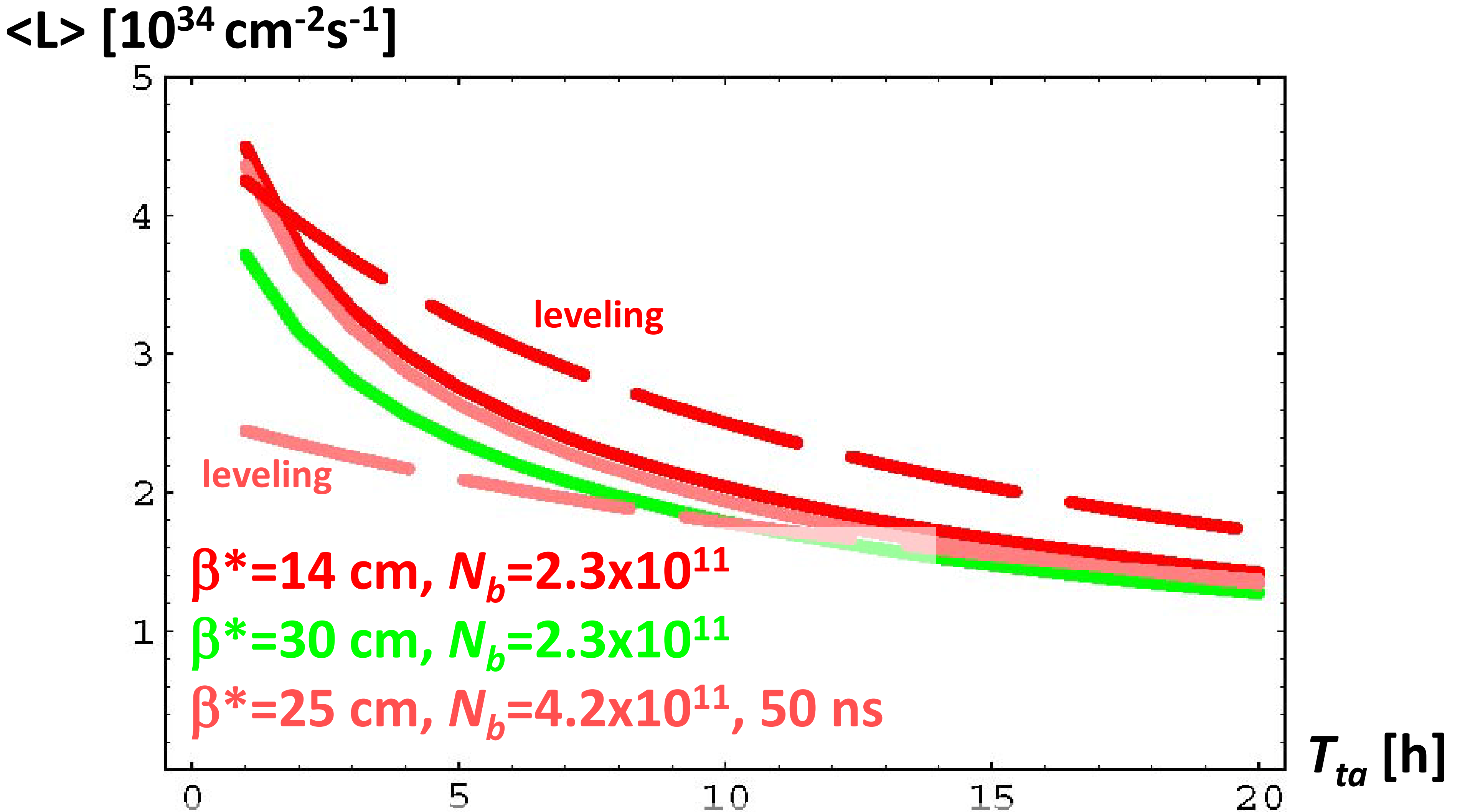
leveling – example numbers

	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	539
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	135

leveling – other example numbers

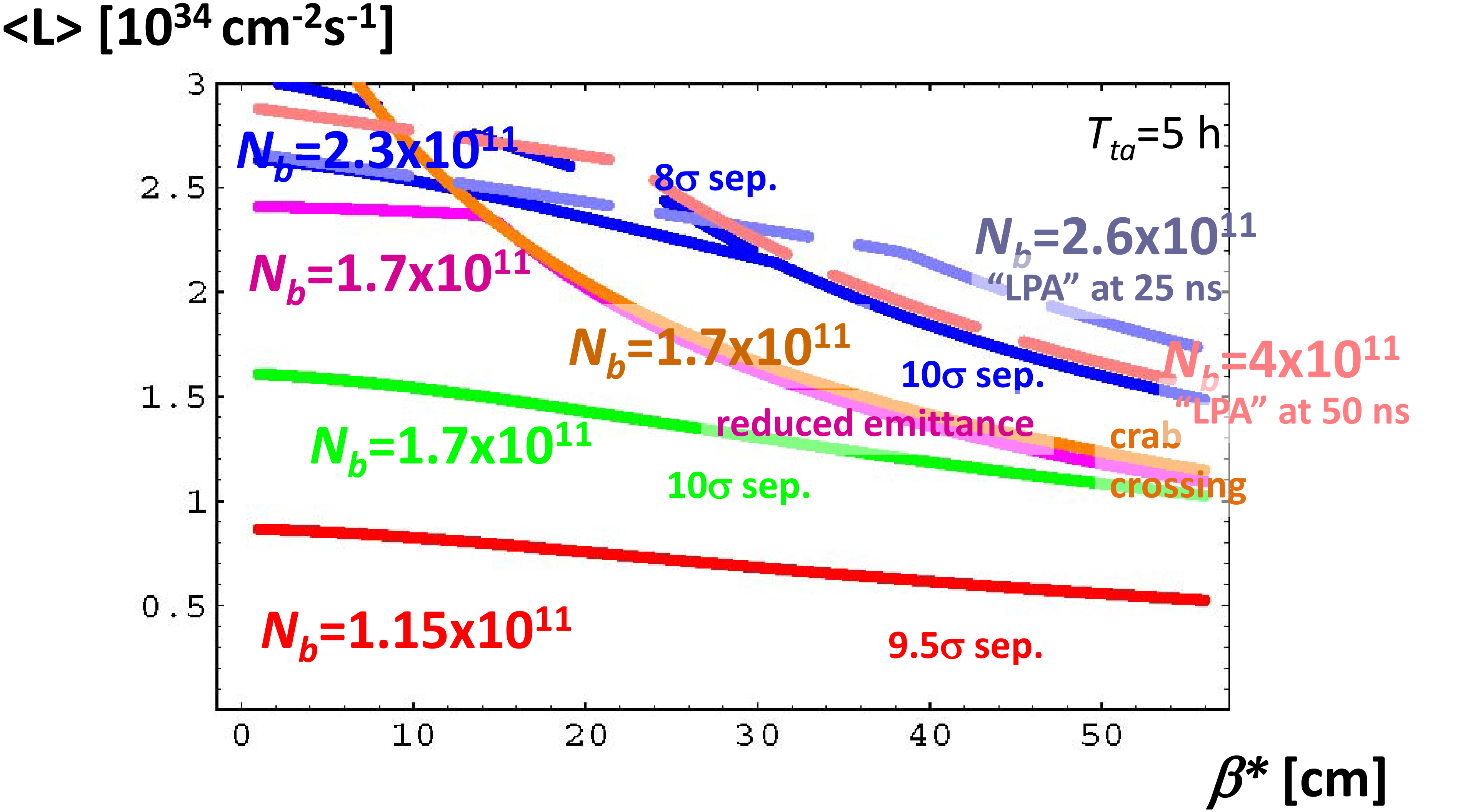
	β^*=25 cm, 50 ns spac., "LPA" T_{ta}=5 h		
	no leveling	L=const	ΔQ_{bb}=const
$N_b(0)$ [10^{11}]	4.2	4.2	4.2
$L(0)$[10^{34}cm^{-2}s^{-1}]	7.4	4.5	4.5
$\|\Delta Q_{bb}(0)\|$	0.010	0.0056	0.0056
$\|\Delta Q_{bb}(T_{run})\|$	0.006	0.010	0.0056
$\theta_c(0)$ [μrad]	231	672	672
run time T_{run} [h]	7.45	6.0	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 in the presence of crab cavities**

conclusions

- upgrade scenarios with 25 & 50 ns spacing
- maximum N_b ~2.3x10^{11} at 25 ns, ~5.0x10^{11} at 50 ns
- T_{ta} - 10→2 h: 2x higher <*L*>
- β^* : factor 2 reduction → 10-20% higher <*L*>
- **N_b: factor 2 increase → 3 times higher <*L*>!**
- crab crossing: 20-100% higher <*L*>
- luminosity optimization assumes two IPs;
  needs/policy for ALICE & LHCb?
- θ_c leveling can increase run time by factor 1.5-3,
  & reduce pile up, at ~ constant <*L*>
- annual luminosities of 150-300 fb^{-1}
- put emphasis on N_b (!!), T_{ta} (!) and crab crossing

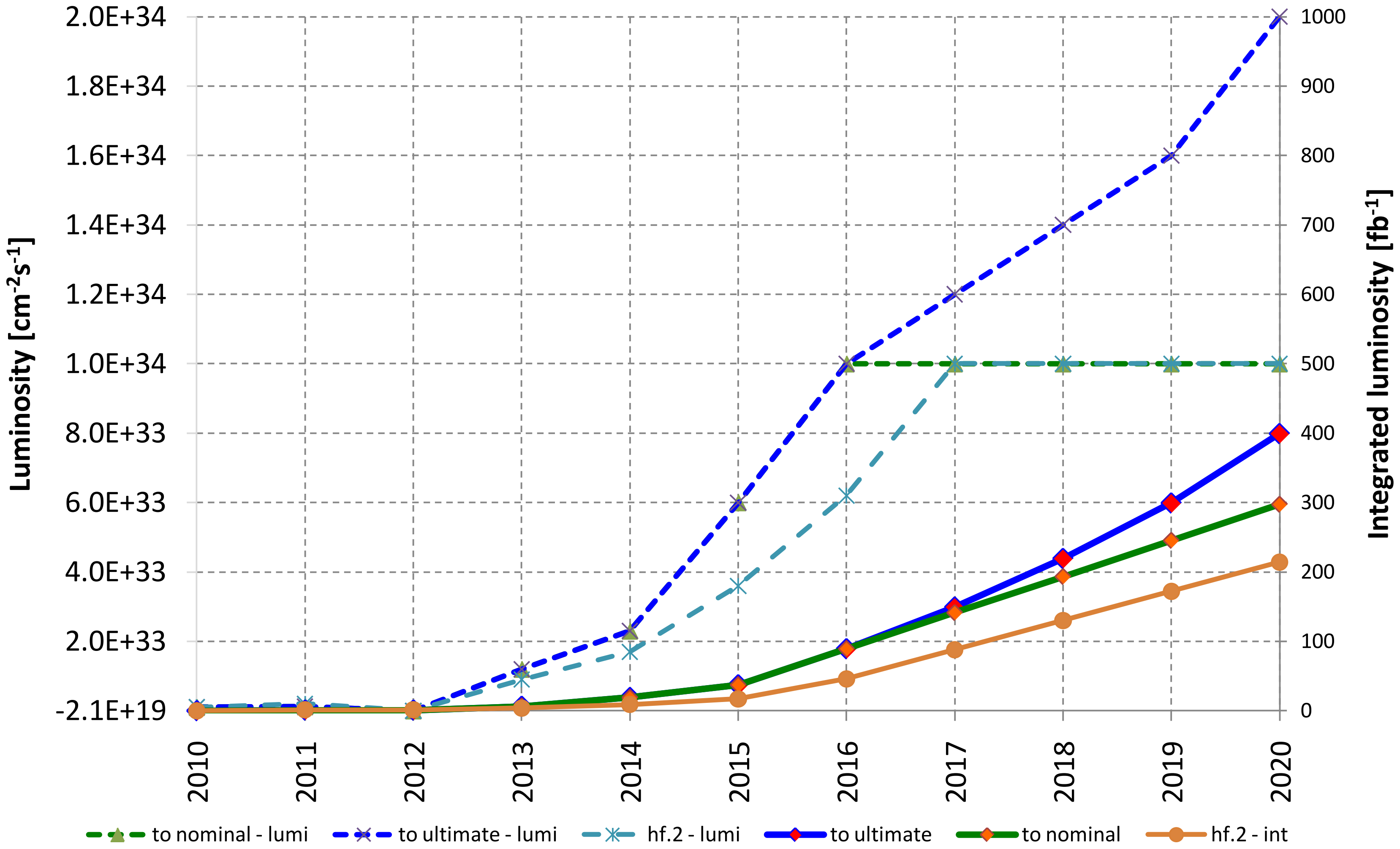
upgrade time lines

- **collimation** upgrade 2013-2015

- parallel R&D on Nb-Ti and Nb_3Sn **IR quadrupoles**
  technology choice by 2014
- parallel R&D on compact and global **crab cavities**
  choice by 2014

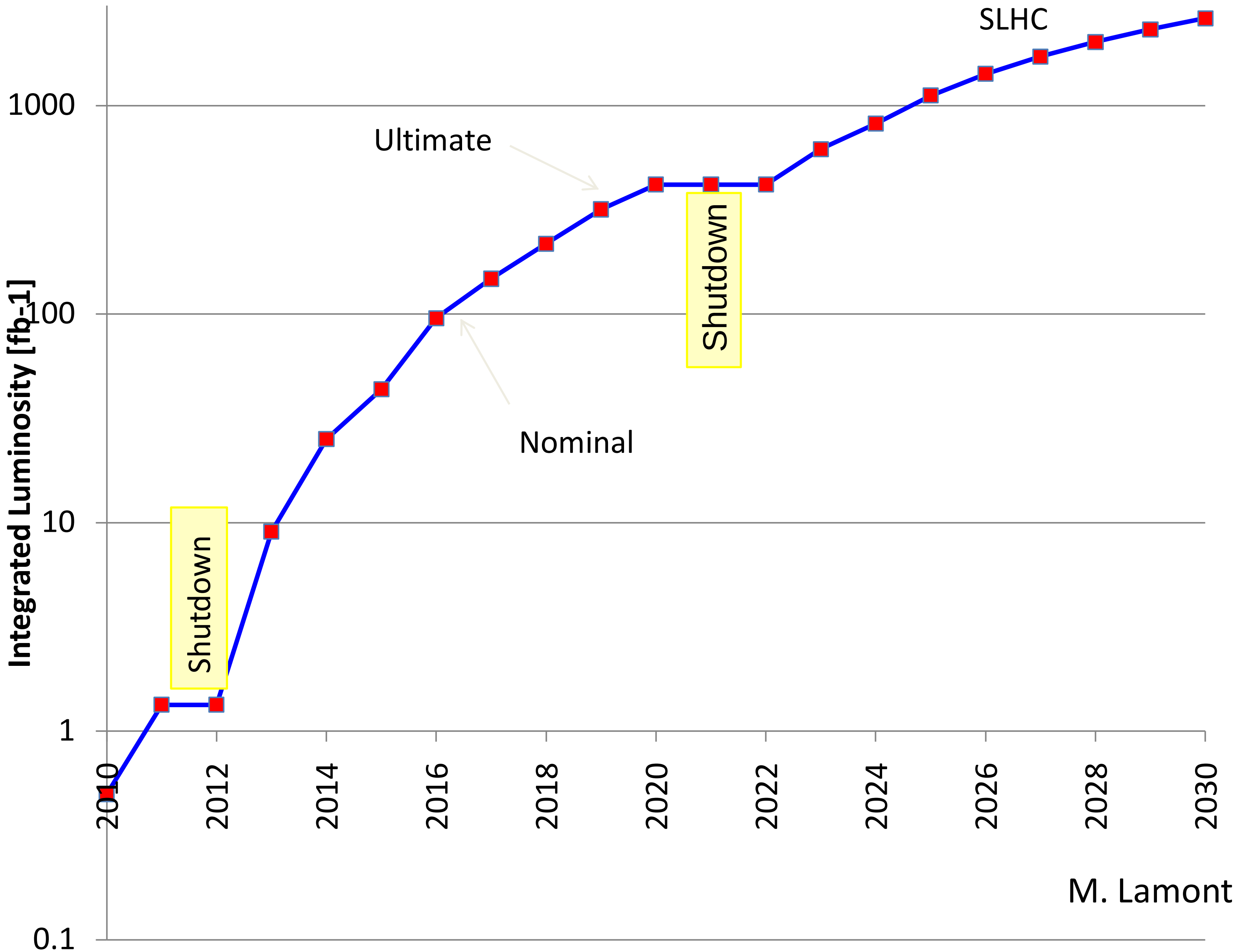
- **LINAC4** connection 2014-15
- **injector** upgrades & consolidation (PSB, PS, SPS)
  completed by ~2015
- production & installation of **new IRs** ~2018-22
- production & installation of **crab cavities** ~2018-22

possible luminosity evolution → 2020



M. Lamont, L. Rossi

possible luminosity evolution → 2030



thank you for your attention!