Accelerators Options for the LHC Luminosity Upgrade: Status after LUMI06

Upgrade Beam Parameters & Integrated Luminosity

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topics

- LUMI'06 conclusions
- possible LHC+ bunch structures
- heat load & cooling capacity
- integrated luminosity
- 12.5 ns at lower bunch charge

APD workshop 'LUMI 06' (70 participants)

Towards a Roadmap for the Upgrade of the LHC and GSI Accelerator Complex

IFIC, Valencia (Spain), 16-20 October 2006

→ strong synergy with US-LARP mini collaboration meeting 25-27 Oct. 2006

IR scheme, beam parameters, injector upgrade

LUMI'06 Conclusions

IR upgrade & beam parameters:

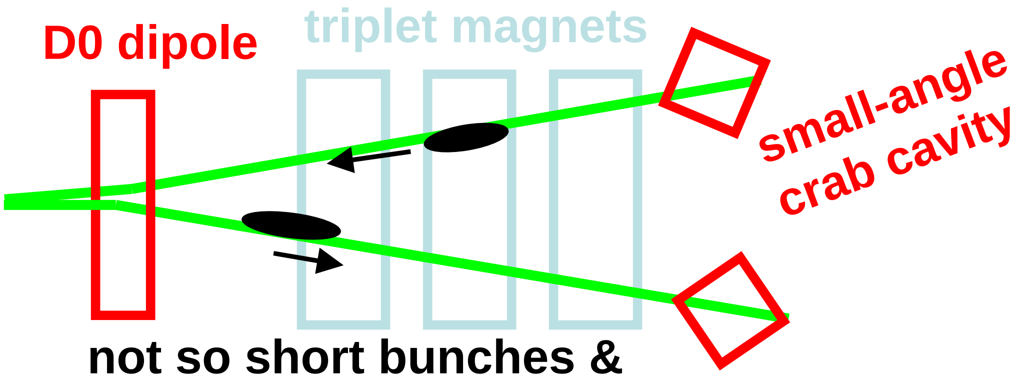
1) quadrupole 1st preferred over dipole 1st
2) pushed NbTi or Nb3Sn still pursued, or hybrid solution ***- new***
3) slim magnets inside detector ("D0 and Q0") ***– new***
4) wire compensation almost established, electron lens ***– new***
5) crab cavities: large angle rejected; small-angle ***– new***
6) 12.5 ns strongly deprecated
7) e-cloud/pile-up compromise:
   25-ns w $\beta^{*}\sim 10$ cm, or 50-ns spacing long bunches ***– new***

injector upgrade:

1) linac4/SPL & n.c. PS2 endorsed
2) SPS enhancements
3) s.c. PS2+ challenged; e.g., e-cloud could be serious problem for injectors ***- new***

Example IR Layouts

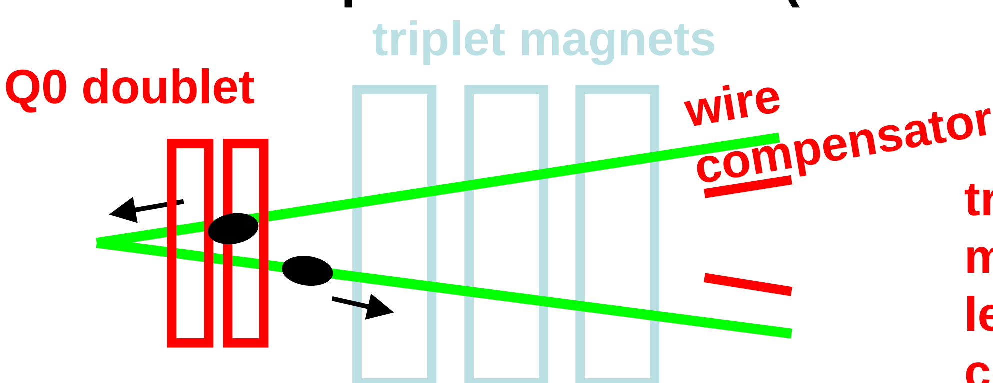
D0 dipole deep inside detector (e.g., ~3 m from IP)



not so short bunches & near head-on collision

less LR collisions. no geometric lumi. loss

Q0 doublet deep inside detector (7.5 or 13 m from IP)



short bunches & "minimum" crossing angle & wire

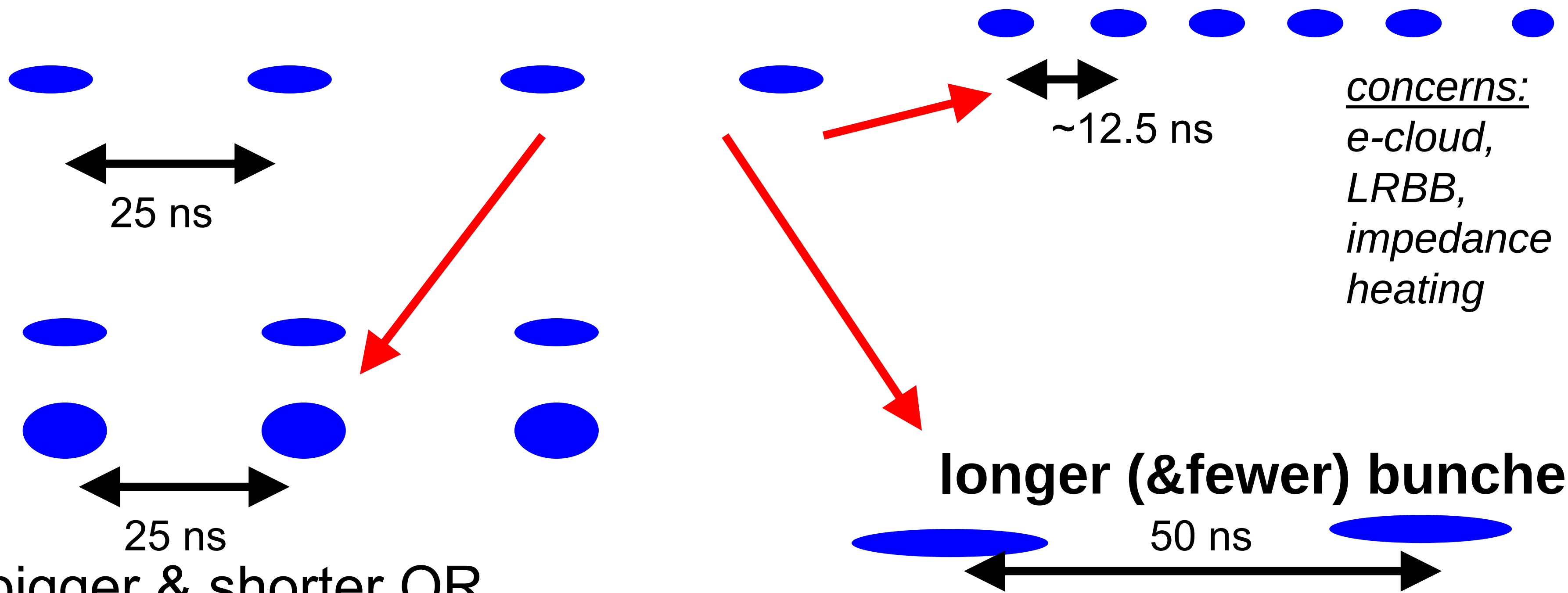
triplet quads much easier, less Q', could be combined with D0

bunch structures

plus:
can use crab cavities
event pile up tolerable

nominal & ultimate LHC

more & shorter bunches



concerns:
e-cloud,
LRBB,
impedance
heating

longer (&fewer) bunches

plus:
no e-cloud?
less current

concerns:
event pile up
impedance

bigger & shorter OR
more focused bunches

plus:
limited e-cloud
limited pile up

concerns:
impedance heating,
LR compensation,
aberrations

transitions by bunch merging or splitting;
new rf systems required for cases 1 and 3

LUMI'05 parameters

parameter	symbol	nominal	ultimate	12.5 ns spac., short	75 ns spacing, long
transverse emittance	ε [μm]	3.75	3.75	3.75	3.75
protons per bunch	N_b [10^{11}]	1.15	1.7	1.7	6
bunch spacing	Δt [ns]	25	25	12.5	75
beam current	I [A]	0.58	0.86	1.72	1
longitudinal profile		Gauss	Gauss	Gauss	flat
rms bunch length	σ_z [cm]	7.55	7.55	3.78	14.4
beta* at IP1&5	β* [m]	0.55	0.5	0.25	0.25
full crossing angle	θ_c [murad]	285	315	445	430
Piwinski parameter	$\theta_c \sigma_z/(2\sigma_x)$	0.64	0.75	0.75	2.8
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	2.3	9.2	8.9
events per crossing		19	44	88	510
initial lumi lifetime	τ_L [h]	22	14	7.2	4.5
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.46	0.91	2.7	2.1
	$T_{run,opt}$ [h]	21.2	17.0	12.0	9.4
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.56	1.15	3.6	2.9
	$T_{run,opt}$ [h]	15.0	12.0	8.5	6.6
e-c heat SEY=1.4(1.3)	P [W/m]	1.07 (0.44)	1.04 (0.6)	13.34 (7.85)	0.26
SR heat load 4.6-20 K	P_{SR} [W/m]	0.17	0.25	0.5	0.29
image current heat	P_{IC} [W/m]	0.15	0.33	1.87	0.96
gas-s. 100 h (10 h) τ_b	P_{gas} [W/m]	0.04 (0.38)	0.06 (0.6)	0.113 (1.13)	0.07 (0.7)
comment				partial wire c.	

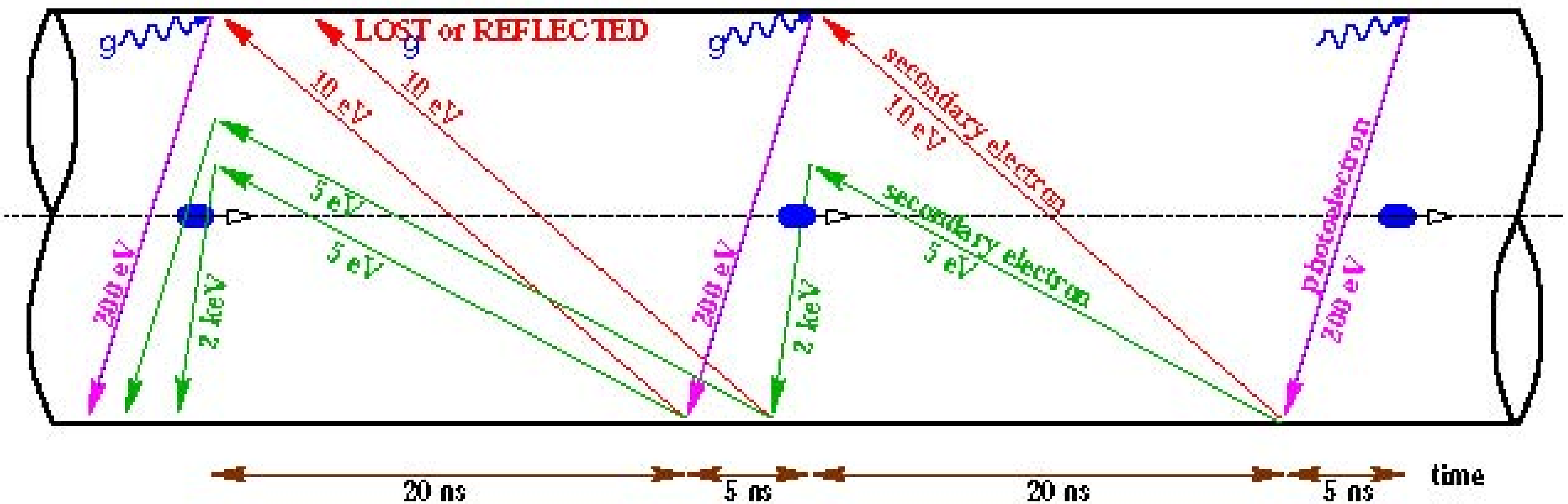
old upgrade parameters

LUMI'06 parameters

parameter	symbol	ultimate	25 ns, smaller β*	25 ns, large ε	50 ns, long
transverse emittance	ε [μm]	3.75	3.75	7.5	3.75
protons per bunch	N_b [10^{11}]	1.7	1.7	3.4	4.9
bunch spacing	Δt [ns]	25	25		50
beam current	I [A]	0.86	0.86	1.72	1.22
longitudinal profile		Gauss	Gauss	Gauss	Flat
rms bunch length	σ_z [cm]	7.55	7.55	3.78	14.4
beta* at IP1&5	β* [m]	0.5	0.08	0.25	0.25
full crossing angle	θ_c [murad]	315	100	539	381
Piwinski parameter	$\theta_c\sigma_z/(2\sigma_x^*)$	0.75	0.60	0.64	2.5
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	2.3	15.5	9.7	8.9
events per crossing		44	296		340
initial lumi lifetime	τ_L [h]	14	2.1	6.8	5.3
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.91	2.4	2.7	2.3
	$T_{run,opt}$ [h]	17.0	6.5	12.0	10.3
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	1.15	3.6	3.6	3.1
	$T_{run,opt}$ [h]	12.0	4.6	8.5	7.3
e-c heat SEY=1.4(1.3)	P [W/m]	1.04 (0.59)	1.04 (0.59)	2.56 (2.1)	0.36 (0.1)
SR heat load 4.6-20 K	P_{SR} [W/m]	0.25	0.25	0.5	0.36
image current heat	P_{IC} [W/m]	0.33	0.33	3.74	0.78
gas-s. 100 h (10 h) τ_b	P_{gas} [W/m]	0.06 (0.56)	0.06 (0.56)	0.11 (1.13)	0.09 (0.9)
comment			D0 + crab	wire comp.	wire comp.

new upgrade parameters

electron cloud in the LHC



schematic of e- cloud build up in the arc beam pipe, due to **photoemission** and **secondary emission;** **electrons transfer energy from beam to chamber wall**

[Courtesy F. Ruggiero]

zoom on heat load

parameter	symbol	nominal	ultimate	12.5 ns	25 ns, smaller β*	50 ns, long
SR heat load 4.6-20 K	P_{SR} [W/m]	0.17	0.25	0.5	0.25	0.36
image current heat	P_{IC} [W/m]	0.15	0.33	1.87	0.33	0.78
total BS heat load w/o e-cloud	$P_{SR} + P_{IC}$ [W/m]	0.32	0.58	2.37	0.58	1.14
local cooling limit*	P_{cool} [W/m]	2.4	2.4	2.4	2.4	2.4
cooling remaining for e-cloud	$P_{cool, rest}$ [W/m]	2.08	1.82	0.03	1.82	1.26
simulated e-c heat for SEY=1.4 (1.3)	P [W/m]	1.07 (0.44)	1.04 (0.6)	13.34 (7.85)	1.04 (0.59)	0.36 (0.1)

* L. Tavian, LUMI'06

Not feasible **OK**

run time & integrated luminosity

$$\frac{1}{N_b}\frac{\Delta N_b}{\Delta t} = n_{IP} L \sigma \frac{1}{n_b}\frac{1}{N_b} + c\left(\frac{N}{V}\right)_{vac} \sigma_{vac}$$ collisions, gas scattering

$$N_b \approx \frac{N_b^0}{1 + n_{IP} L \sigma N_b^0 t / n_b} \equiv \frac{N_b^0}{1 + t/\tau}$$ intensity evolution for collisions only

$$\frac{1}{\varepsilon_x}\frac{\Delta \varepsilon_x}{\Delta t} = \frac{1}{\tau_{IBS}(N_b, \varepsilon_x, \varepsilon_y, \sigma_z, \sigma_\delta, \ldots)} \propto N_b^2$$ intrabeam scattering (IBS) growth

burn-off collision lifetime with σ~100 mbarn, n_{IP}~2:

$L_{peak}=10^{34}$ cm^{-2}s^{-1} in 2808 bunches, N_b~1.15x10^{11}:
τ~45 h (luminosity lifetime 22 h)

$L_{peak}=10^{35}$ cm^{-2}s^{-1} in 5616 bunches, N_b~1.7x10^{11}:
τ~14 h (luminosity lifetime 7 h)

τ_{gas} > 100 h (luminosity lifetime 50 h)

τ_{IBS}~105 h (horizontal emittance growth time;
luminosity lifetime 210 h)

burn-off dominates over gas scattering and IBS

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

luminosity time evolution

$$L_{ave} = \frac{\hat{L}\,\tau_{eff} T_{run}}{\left(\tau_{eff} + T_{run}\right)\left(T_{run} + T_{turnaround}\right)}$$

average luminosity

$$\rightarrow \quad T_{run,optimum} = \sqrt{\tau_{eff} T_{turnaround}}$$

opt. run time

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

opt. av. luminosity

effective decay time

$$\tau_{eff} = \frac{4\pi\beta^*\varepsilon}{n_{IP} N_b \sigma}$$

L_{peak} [$cm^{-2}\,s^{-1}$]	beam lifetime τ_{eff} [h]	$T_{turnaround}$ [h]	T_{run} [h]	Int L over 200 days [fb^{-1}]
10^{34}	45	10	21	79
10^{34}	45	5	15	6x 97
10^{35}	14	10	12	473
10^{35}	14	5	8	8x 629

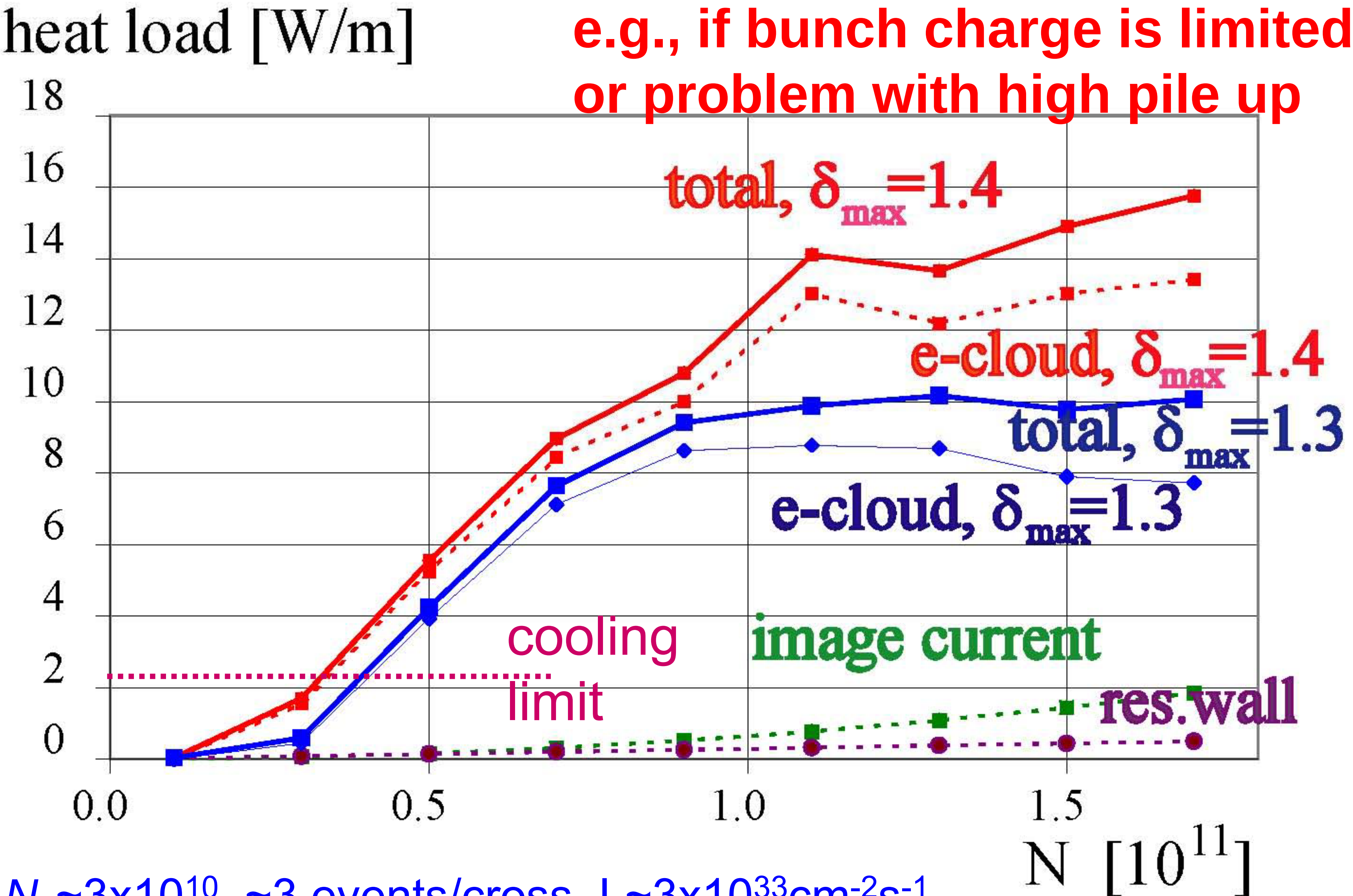
smaller β* allows for lower beam current in LHC, but increases events/crossing & it reduces the beam & luminosity lifetimes

zoom on decay time & integrated luminosity for various options

parameter	symbol	nominal	ultimate	12.5 ns	25 ns, smaller β^*	50 ns, long
max. # events / crossing		19	44	88	296	340
peak luminosity	L [1e34 cm-2s-1]	1	2.3	9.2	14.4	8.9
effective beam decay time	τ_{eff} [h]	45	29	14.4	4.6	10.7
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} $cm^{-2}s^{-1}$]	0.46	0.91	2.7	2.4	2.3
	$T_{run,opt}$ [h]	21.2	17.0	12.0	6.5	10.3
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} $cm^{-2}s^{-1}$]	0.56	1.15	3.6	3.6	3.1
	$T_{run,opt}$ [h]	15.0	12.0	8.5	4.6	7.3

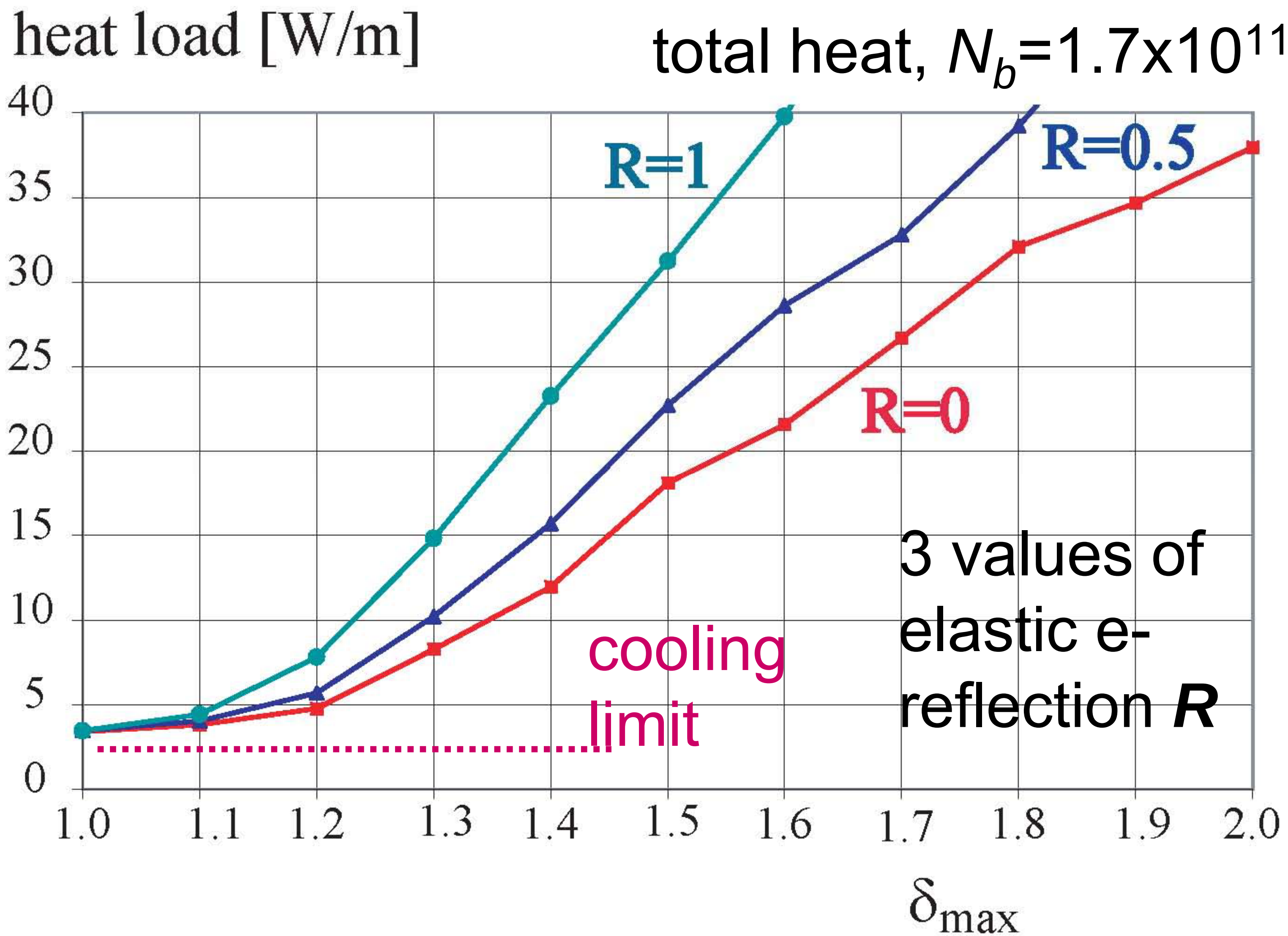
could 12.5 ns at lower bunch charge be of interest?

e.g., if bunch charge is limited or problem with high pile up



N_b~$3x10^{10}$, ~3 events/cross.,L~$3x10^{33}cm^{-2}s^{-1}$

could 12.5 ns become possible for smaller δ_{max} ?



No! Heat above cooling limit even at δ_{max}=1.0, for any R

appendix

- luminosity formulae & constraints
- luminous region

luminosity

$$L \approx \frac{n_b N_b^2 f_{rev}}{4\pi\beta^* \varepsilon} \frac{F_{profile}}{\sqrt{1+\phi^2}}$$

parameters that enter:

$\phi \equiv \frac{\theta_c \sigma_z}{2\sigma^*_{x,y}}$: Piwinski angle

N_b : # protons per bunch

σ_z : rms bunch length

f_{rev} : revolution frequency

n_b : # bunches per beam

θ_c : full crossing angle

ε : (geometric) transverse emittance

β^* : beta function at collision point

$\sigma^*_{x,y} = \sqrt{\beta^* \varepsilon}$: rms transverse spot size at collision point

$$F_{profile} = \begin{cases} 1 & \text{for Gaussian bunch} \\ \sim 1.42 & \text{for long uniform bunch} \end{cases}$$

there are many parameter constraints, for example

ε limited by arc aperture and field quality at injection

β^* limited by final triplet aperture & crossing angle

& long-range beam-beam & collimation

& chromatic correction (& beam lifetime)

θ_c limited by geometric luminosity loss & long-range

collisions & triplet aperture & triplet field errors

$n_b N_b$ ~ total current, limited by collimation, machine

protection, beam dump

n_b limited by electron cloud heating

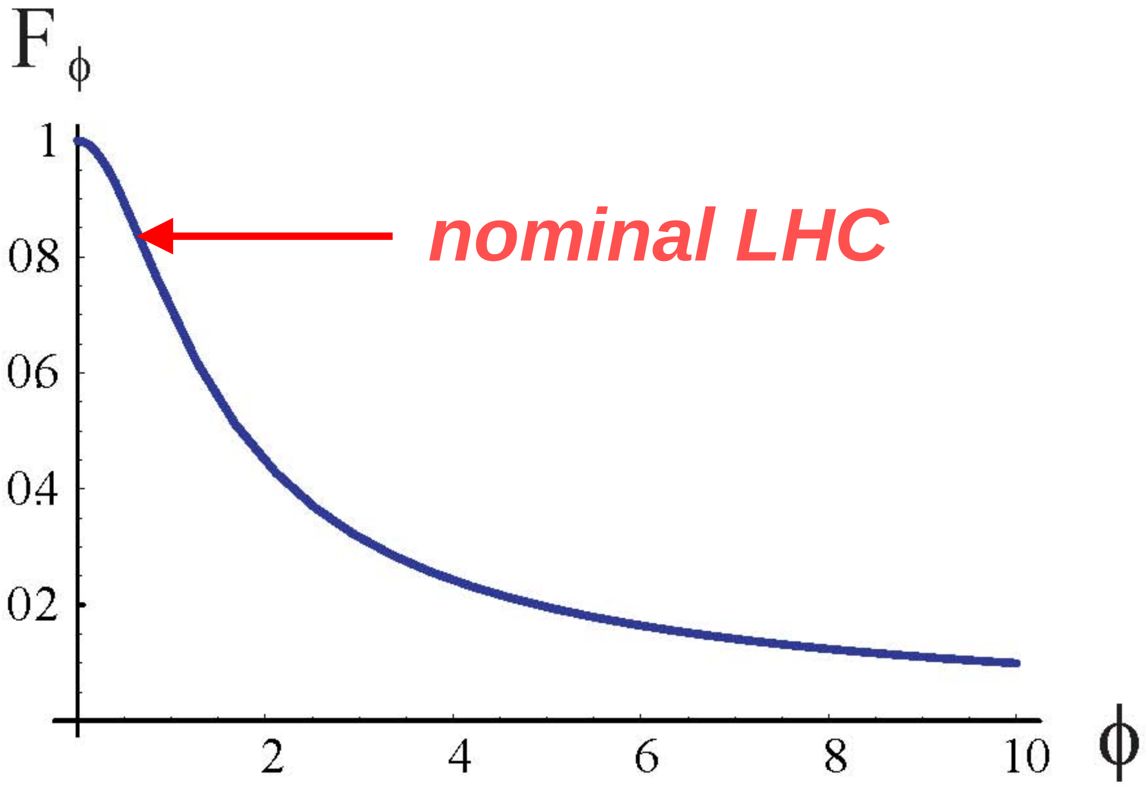
N_b limited by image-current heating & collimation &

pile-up events

nominal crossing angle "at the edge"

$$F_\phi = \frac{1}{\sqrt{1+\phi^2}}; \quad \phi \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$ Piwinski angle

luminosity reduction factor



another important constraint is the (head-on) beam-beam tune shift

$$\Delta Q_{bb} \approx \frac{N_b r_p}{2\pi\gamma\varepsilon}\sqrt{1+\phi^2}$$

total beam-beam tune shift at two IPs with alternating crossing

$\Delta Q_{bb} < 0.01 - 0.015$, beam-beam limit for hadron colliders (from $Sp\bar{p}S$ experience) for operation at the beam-beam limit luminosity equation can be rewritten as

injector upgrade

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

LHC + injector changes

IR upgrade

LHC+ injector changes

due to the crossing angle, colliding long bunches does not mean the events are spread out over a large area

rms length of luminous region $$\frac{1}{\sigma_l^2} \approx \left(\frac{2}{\sigma_z^2} + \frac{\theta_c^2}{2\sigma^{*2}_{x,y}} \right)$$

	nominal	ultimate	12.5 ns	25 ns, low β^*	50 ns
σ_l [cm]	4.5	4.3	2.1	2.5	3.5

luminous region is largest for nominal LHC