High Energy
High Intensity
Hadron Beams

APD
Accelerator Physics and synchrotron Design

Scenarios for the LHC Upgrade

Walter Scandale & Frank Zimmermann

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Frascati, LNF-INFN

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outline

two scenarios for the beam/IR parameters

- merits and challenges
- impact of β^*
- luminosity evolution
- luminosity leveling
- bunch structures

Injector upgrade

Context, goals and perspectives

Issues for this workshop

LHC challenges

- collimation & machine protection
  - damage, quenches, cleaning efficiency, impedance
- electron cloud
  - heat load, instabilities, emittance growth
- beam-beam interaction
  - head-on, long-range, weak-strong, strong-strong
- multiplicity of the events per crossing

LHC baseline luminosity pushed in competition with SSC
*⇒ **energy versus luminosity race***

Large volume detectors to deal with the large multiplicity per crossing
*⇒ **full separation of the detector / focusing triplet***

parameter	symbol	nominal	ultimate
transverse emittance	ε [μm]	3.75	3.75
protons per bunch	N_b [10^{11}]	1.15	1.7
bunch spacing	Δt [ns]	25	25
beam current	I [A]	0.58	0.86
longitudinal profile		Gauss	Gauss
rms bunch length	σ_z [cm]	7.55	7.55
beta* at IP1&5	$\beta*$ [m]	0.55	0.5
full crossing angle	θ_c [μrad]	285	315
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.64	0.75
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	2.3
peak events per crossing		19	44
initial lumi lifetime	τ_L [h]	22	14
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.46	0.91
	$T_{run,opt}$ [h]	21.2	17.0
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.56	1.15
	$T_{run,opt}$ [h]	15.0	12.0
e-c heat SEY=1.4(1.3)	P [W/m]	1.07 (0.44)	1.04 (0.59)
SR heat load 4.6-20 K	P_{SR} [W/m]	0.17	0.25
image current heat	P_{IC} [W/m]	0.15	0.33
gas-s. 100 h (10 h) τ_b	P_{gas} [W/m]	0.04 (0.38)	0.06 (0.56)
extent luminous region	σ_l [cm]	4.5	4.3

LHC Upgrade

- 10x higher luminosity ~10^{35}cm^{-2} s^{-1} (SLHC)
  - Requires changes of the machine and particularly of the detectors

  ⇒ Upgrade to SLHC mode around 2014-2016

  ⇒ Collect ~1000 fb^{-1}/experiment per year

  ⇒ difficult trade-off in between:
    - collimation & machine protection
    - electron cloud ⇔ heat load
    - beam-beam interaction ⇔ average luminosity - luminosity lifetime
    - multiplicity of the events per crossing ⇔ detector upgrade

- *much later: higher energy? (DLHC)*
  - *LHC can reach $\sqrt{s}$ = 15 TeV with present magnets (9T field)*
  - *$\sqrt{s}$ of 28 (25) TeV needs ~17 (15) T magnets ⇒ R&D needed!*

New upgrade scenarios

parameter	symbol	25 ns, small β^*	50 ns, long
		early separation (ES)	large Piwinski angle (LPA)
transverse emittance	ε [μm]	3.75	3.75
protons per bunch	N_b [10^{11}]	1.7	4.9
bunch spacing	Δt [ns]	25	50
beam current	I [A]	0.86	1.22
longitudinal profile		Gauss	Flat
rms bunch length	σ_z [cm]	7.55	11.8
beta* at IP1&5	β^* [m]	0.08	0.25
full crossing angle	θ_c [μrad]	0	381
Piwinski parameter	$\phi=\theta_c\sigma_z/(2^*\sigma_x^*)$	0	2.0
hourglass reduction		0.86	0.99
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	15.5	10.7
peak events per crossing		294	403
initial lumi lifetime	τ_L [h]	2.2	4.5
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	2.4	2.5
	$T_{run,opt}$ [h]	6.6	9.5
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	3.6	3.5
	$T_{run,opt}$ [h]	4.6	6.7
e-c heat SEY=1.4(1.3)	P [W/m]	1.04 (0.59)	0.36 (0.1)
SR heat load 4.6-20 K	P_{SR} [W/m]	0.25	0.36
image current heat	P_{IC} [W/m]	0.33	0.78
gas-s. 100 h (10 h) τ_b	P_{gas} [W/m]	0.06 (0.56)	0.09 (0.9)
extent luminous region	σ_l [cm]	3.7	5.3
comment		D0 + crab (+ Q0)	wire comp.

challenges

injector upgrade

Crossing with large Piwinski angle

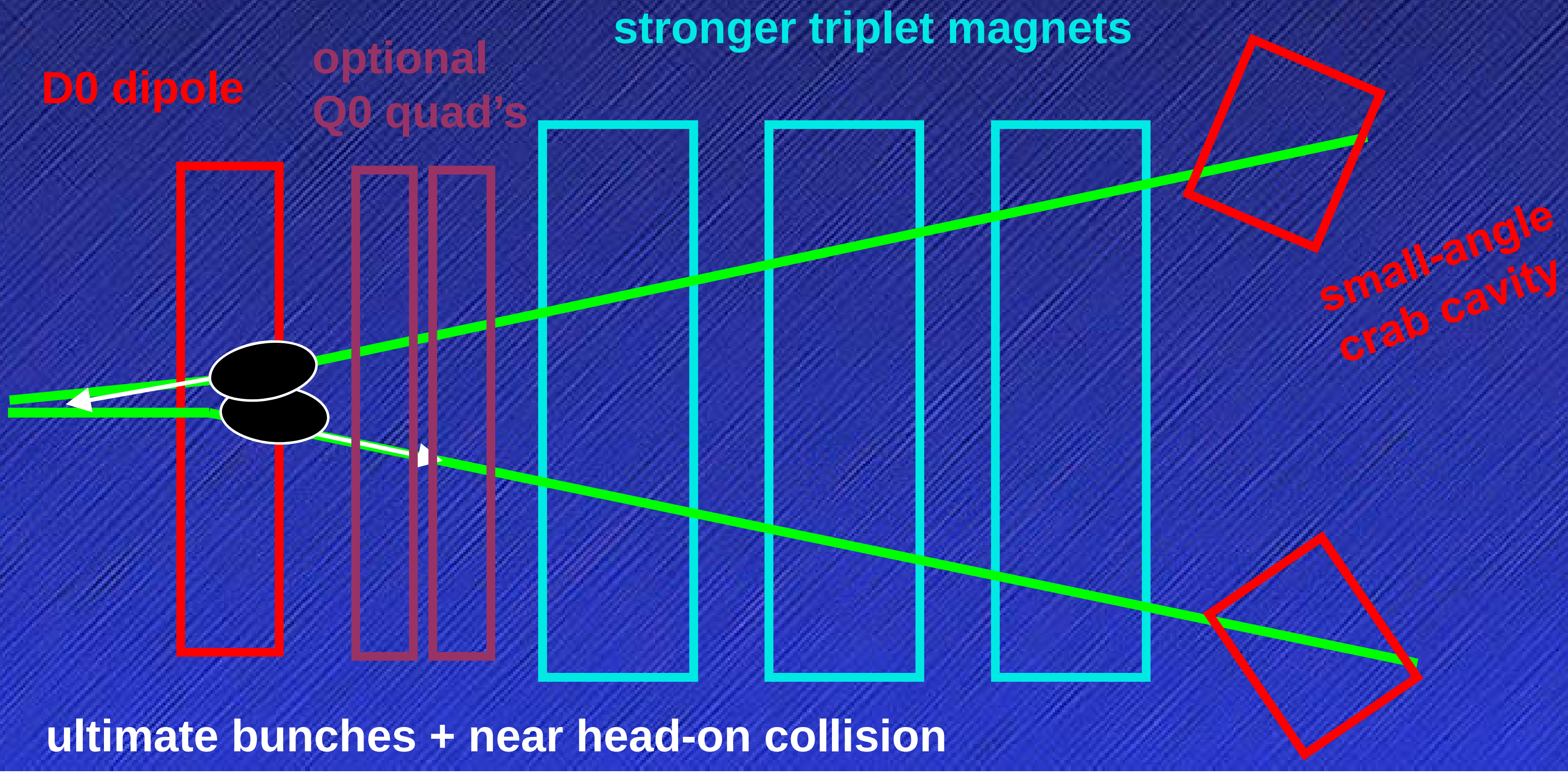
aggressive triplet

compromises between # of pile up events and heat load

LHC upgrade path 1: early separation (ES)

- ultimate LHC beam (1.7×10^{11} protons/bunch, 25 spacing) J.-P. Koutchouk (2005)
- squeeze β^* to ~10 cm in ATLAS & CMS
- add early-separation dipoles in detectors starting at ~ 3 m from IP
- possibly also add quadrupole-doublet inside detector at ~13 m from IP
- and add crab cavities ($\phi_{Piwinski} \sim 0$)

→ new hardware inside ATLAS & CMS detectors, first hadron crab cavities



ES scenario assessment

merits:

most long-range collisions negligible,
no geometric luminosity loss,
no increase in beam current beyond ultimate,
could be adapted to crab waist collisions (LNF/FP7)

challenges:

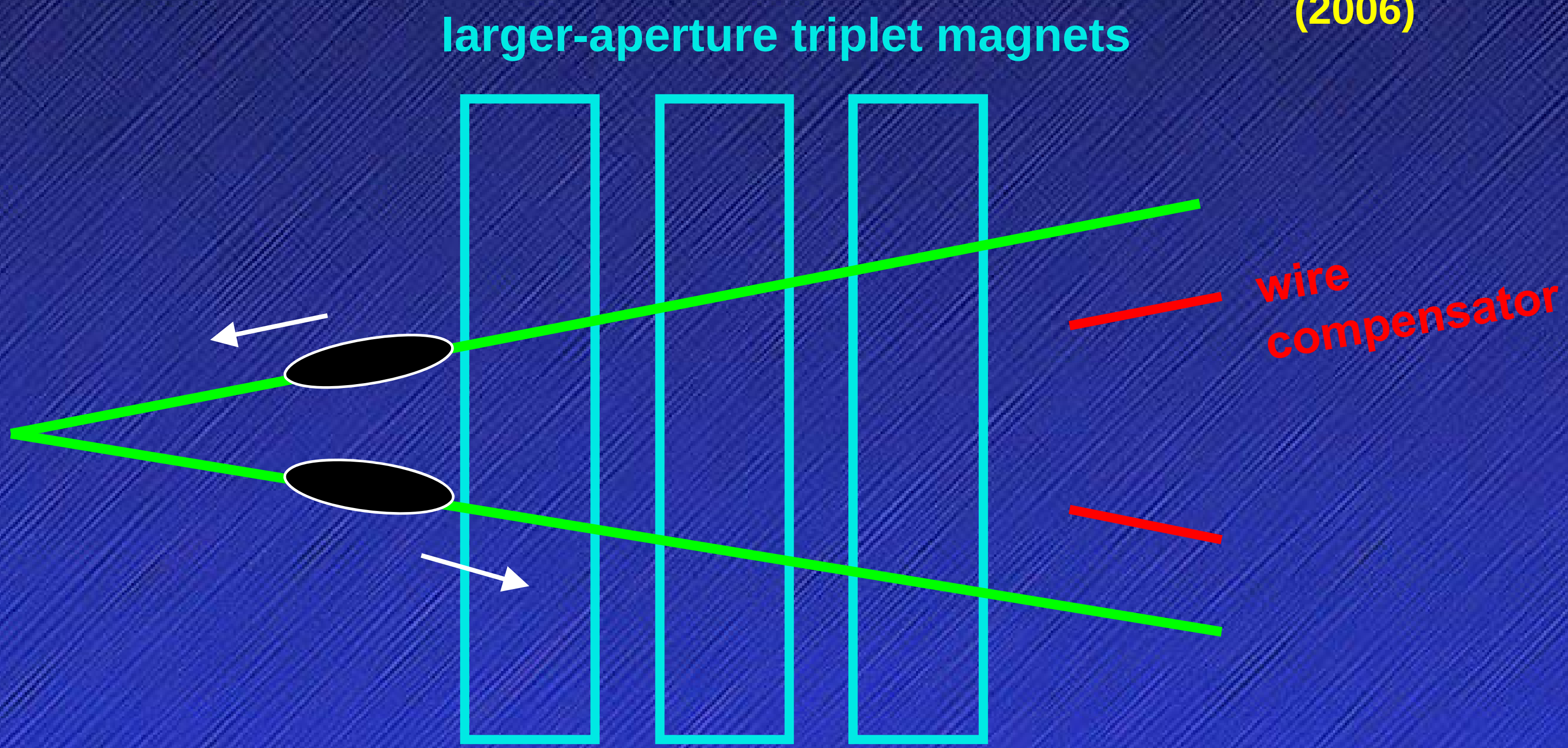
- D0 dipole deep inside detector (~3 m from IP),
- optional Q0 doublet inside detector (~13 m from IP),
- strong large-aperture quadrupoles (Nb_3Sn)
- crab cavity for hadron beams (emittance growth), or shorter bunches (requires much more RF)
- 4 parasitic collisions at 4-5σ separation,
- off-momentum β beating 50% at δ=3x10^{-4} compromising collimation efficiency,
- low beam and luminosity lifetime ~β^*

LHC upgrade path 2: large Piwinski angle (LPA)

- double bunch spacing to 50 ns, longer & more intense bunches with $\phi_{Piwinski} \sim 2$
- β*~25 cm, do not add any elements inside detectors
- long-range beam-beam wire compensation

→ novel operating regime for hadron colliders

F. Ruggiero,
W. Scandale.
F. Zimmermann
(2006)



fewer, long & intense bunches + nonzero crossing angle + wire compensation

LPA scenario assessment

merits:

no elements in detector, no crab cavities,
lower chromaticity,
less demand on IR quadrupoles
(NbTi expected to be possible),
could be adapted to crab waist collisions (LNF/FP7)

challenges:

- operation with large Piwinski parameter unproven for
- hadron beams (except for CERN ISR),
- high bunch charge,
- beam production and acceleration through SPS,
- larger beam current,
- wire compensation (almost established),
- off-momentum β beating ~30% at δ=3x10^{-4}

motivation for flat bunches & LPA

luminosity for Gaussian bunches

$$L^{Gauss} \approx \frac{1}{2} \frac{f_{coll} \gamma}{r_p \beta *} \Delta Q_{tot} N_b$$

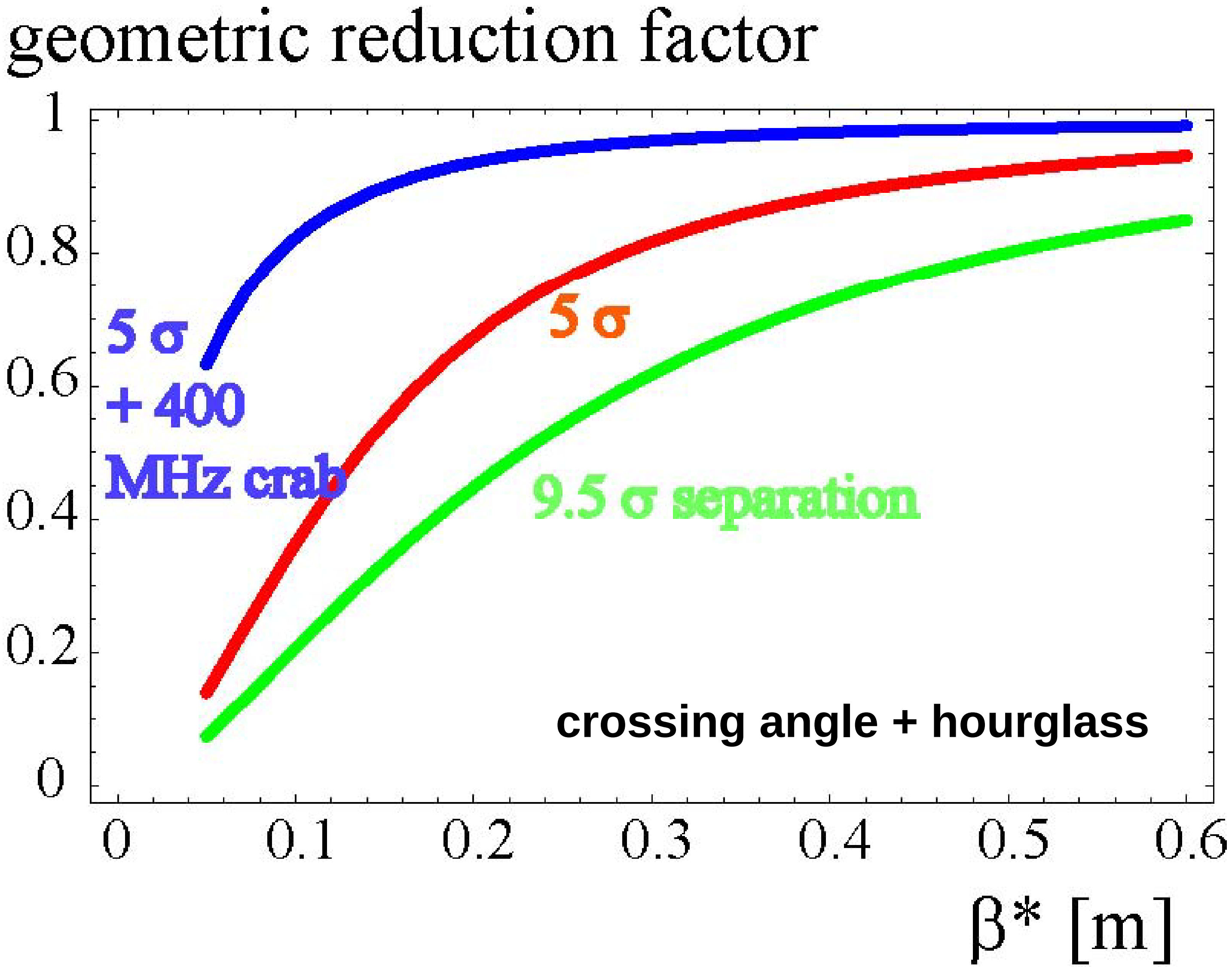
luminosity for "flat" bunches

$$L^{flat} \approx \frac{1}{\sqrt{2}} \frac{f_{coll} \gamma}{r_p \beta *} \Delta Q_{tot} N_b$$

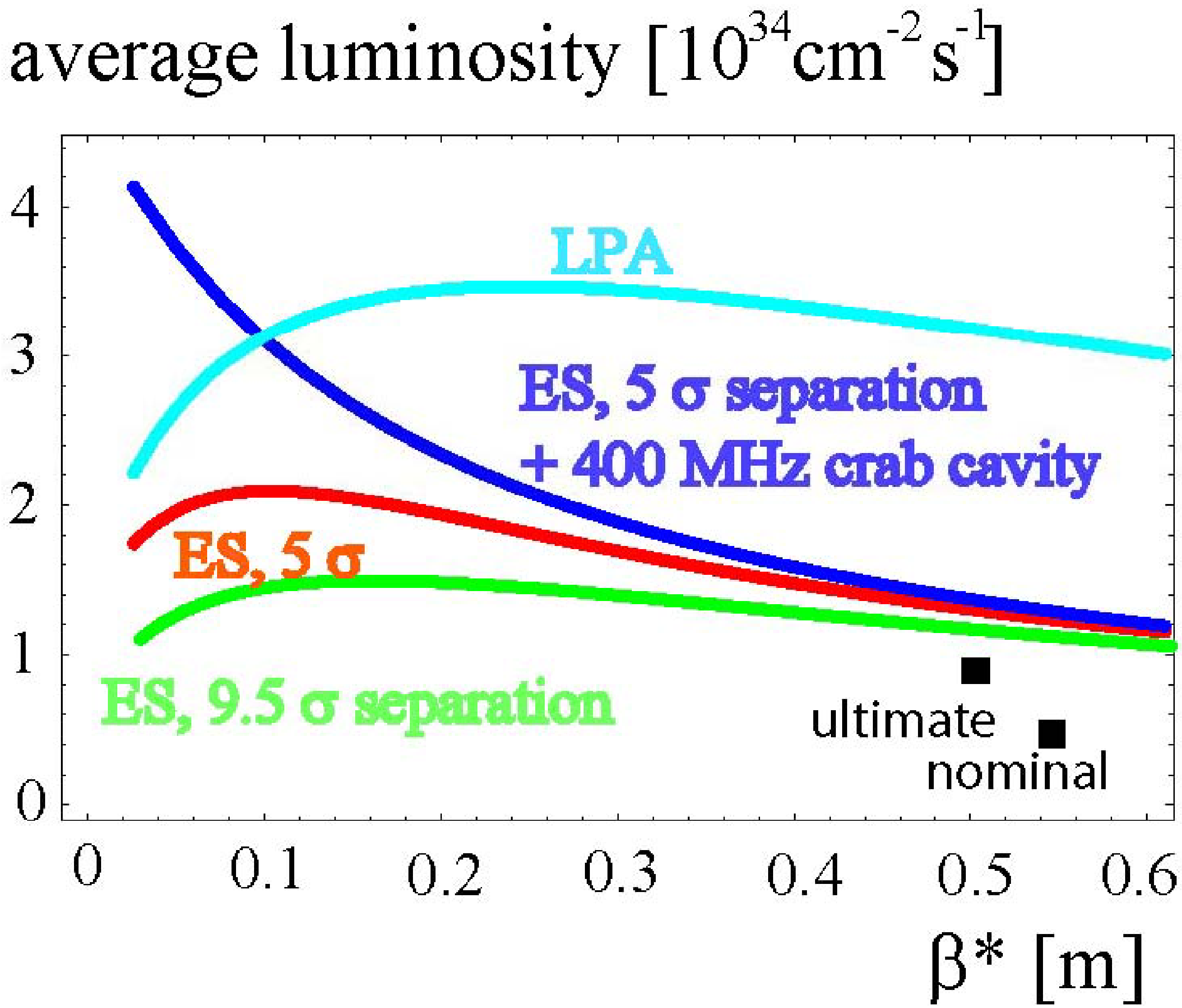
F. Ruggiero, G. Rumolo, F. Zimmermann, Y. Papaphilippou, RPIA2002

- for the same total number of particles and the same total tune shift from two IPs the luminosity will be ~1.4x higher with a "flat" bunch distribution;
- the number of particles N_b can be increased independently of ΔQ_{tot} only in the regime of large Piwinski angle

geometric luminosity reduction vs β*



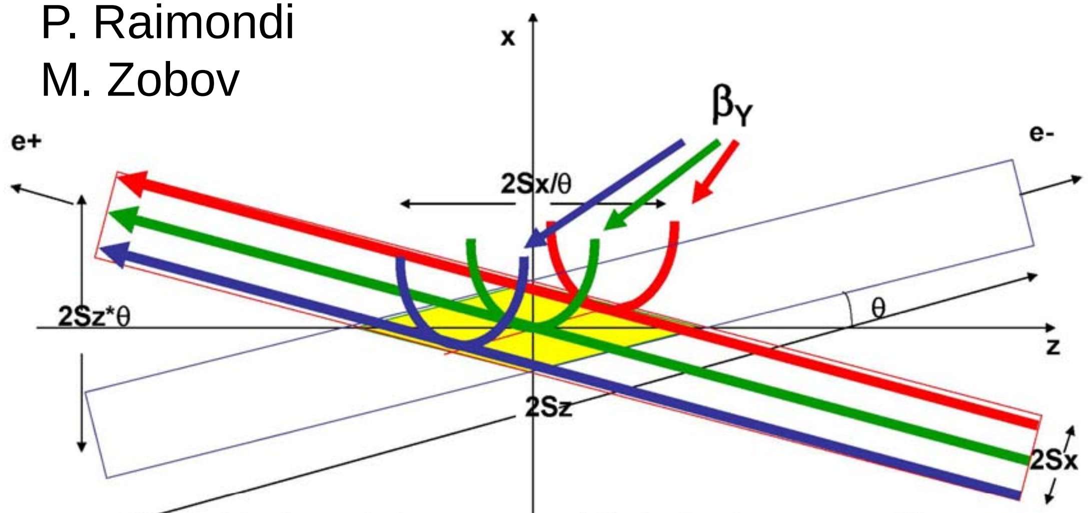
average luminosity vs β*



including crossing angle + hourglass, assuming optimum run time for 5 h turn-around

aside: “crab waist” scheme for LHC?

P. Raimondi
M. Zobov



Crab waist removes bb betratron coupling
Introduced by the crossing angle

Vertical waist has to be a function of x:
Z=0 for particles at $-\sigma_x$ ($-\sigma_x/2\theta$ at low current)
Z= σ_x/θ for particles at $+\sigma_x$ ($\sigma_x/2\theta$ at low current)
Crab waist realized with 2 sextupoles in phase with the IP in X
and at $\pi/2$ in Y

requires:
-flat beams ($\beta_y^* << \beta_x^*$)
-large Piwinski angle
(like LPA)
– $\beta_y^* \sim \sigma_x^*/\theta$
(like ES)
– crab-waist sextupole
transformation

possible approach: go to flat beams, combine ingredients of LPA & ES schemes, add sextupoles

experiments prefer more constant luminosity, less pile up at the start of run, higher luminosity at end

how could we achieve this?

luminosity leveling

Penalty $\Rightarrow$ unavoidable reduction of the average luminosity

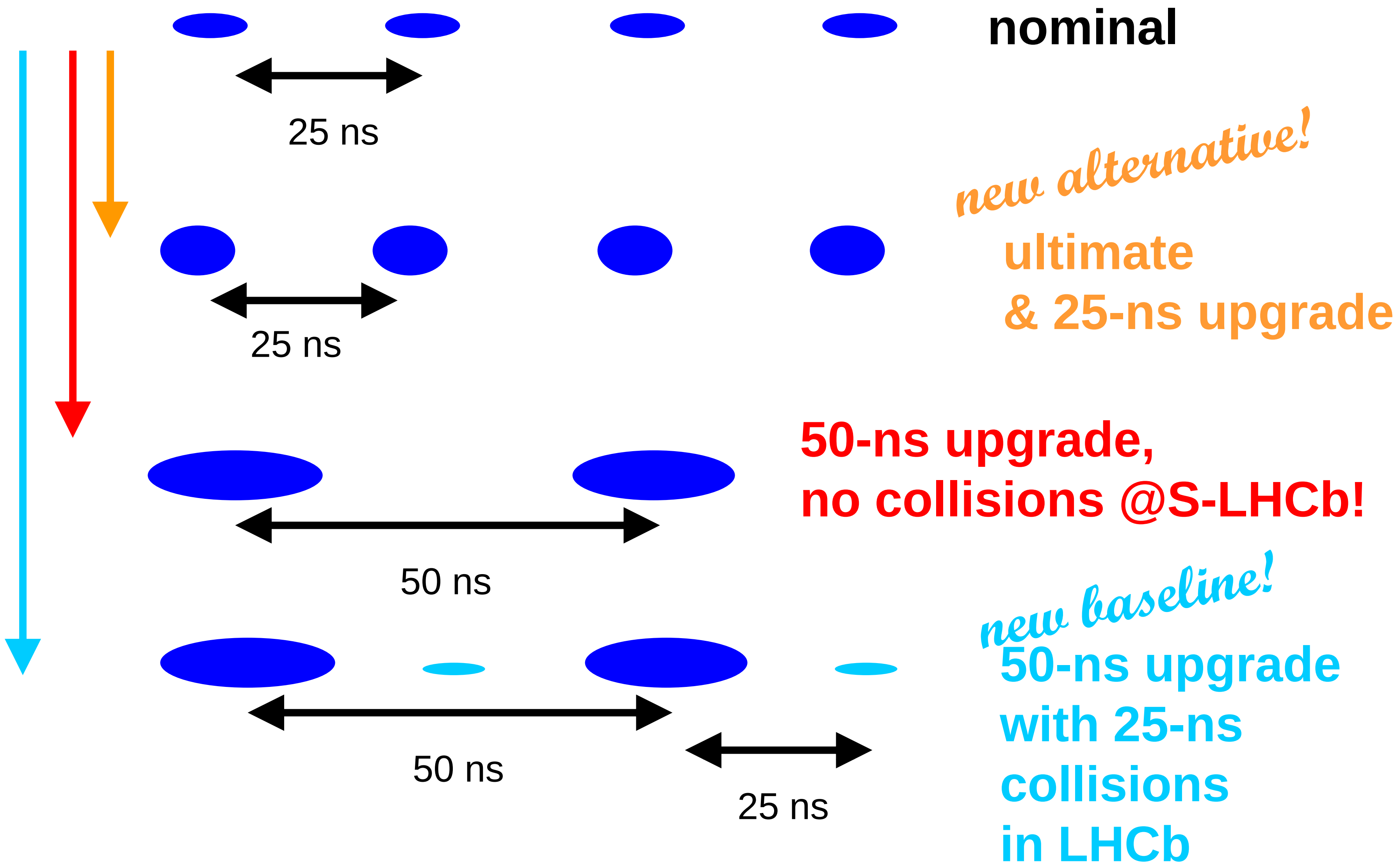
ES:

dynamic β squeeze
dynamic θ change (either IP angle bumps or varying crab voltage)

LPA:

dynamic β squeeze, and/or
dynamic reduction in bunch length

new upgrade bunch structures



Updated needs of SLHC

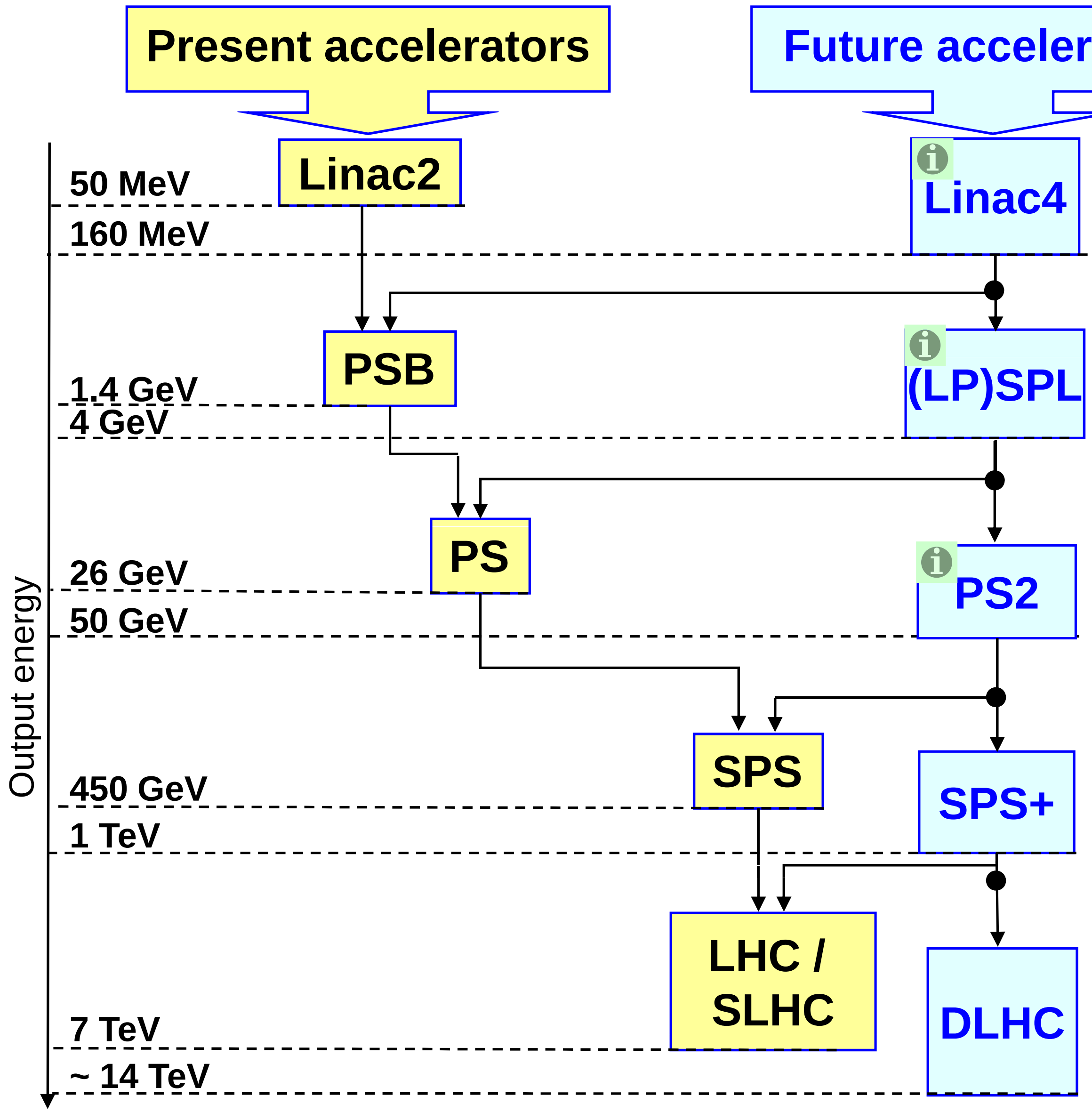
~SLHC option discarded at LUMI'06 in view of image current heat load

Beam parameters [tentative…]	Bunch spacing [ns]	Protons per bunch* [10^{11}]	Transverse emittance in LHC [mm.mrad]	Intensity factor at PS injection*
Nominal	25	1.15 (1.4)	3.75	0.68 (0.81)
Ultimate	25	1.7 (2.1)	3.75	1 (1.2)
2 x ultimate & 25 ns spacing	25	3.4 (4.1)	3.75 (blown-up to 7.5 in LHC)	2 (2.4)
3 x ultimate & 50 ns spacing	50	4.9 (5.9)	3.75	1.44 (1.73)

Proposed maximum goal

* Case of 100 % (80 %) transmission PS to LHC

Updated list of future accelerators



- (LP)SPL is the baseline injector for PS2
- PS2 will use nc magnets
- PS2 size is 15/77 of SPS

(LP)SPL: (Low Power) Superconducting Proton Linac (4-5 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
SLHC: “Superluminosity” LHC (up to 10^{35} $cm^{-2}s^{-1}$)
DLHC: “Double energy” LHC (1 to ~14 TeV)

perspective

- first two or three years of LHC operation will clarify severity of electron cloud, long-range beam-beam collisions, impedance etc.
- first physics results will indicate whether or not magnetic elements can be installed inside the detectors
- these two experiences may decide upgrade path
- crab waist option could be further explored

Issues for discussion

- **ES**
  - **Integrability**
  - **D0 and crab cavity are both are required**
    $\Rightarrow$ ***in alternative use only a crab cavity ?***
  - **Feasibility of β* < 0.15 (chromaticity, dynamic aperture, crossing angle, integrated luminosity,…)**
- **LPA**
  - **Large intensity per bunch**
  - **Multiplicity per crossing**
  - **Flat bunch in the longitudinal phase space**

Once β* is minimized all the hadron colliders have improved the average luminosity through an increase of the circulating intensity