LHC Upgrade

Frank Zimmermann
on behalf of many people,
LHCC review, 16 February 2009

constraints from beam dynamics & collimation, parameter choices, and upgrade scenarios

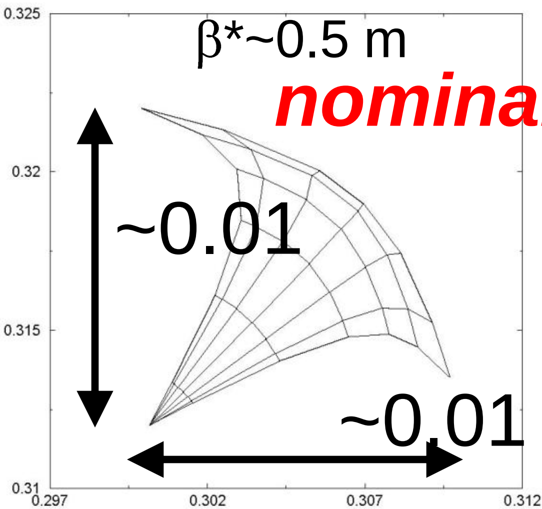
We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395)

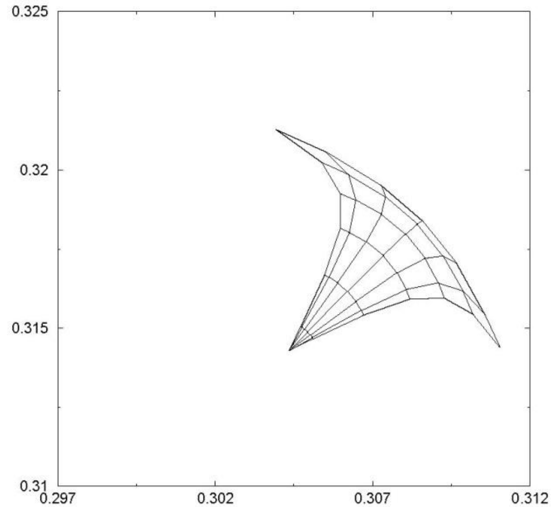
key upgrade drivers:

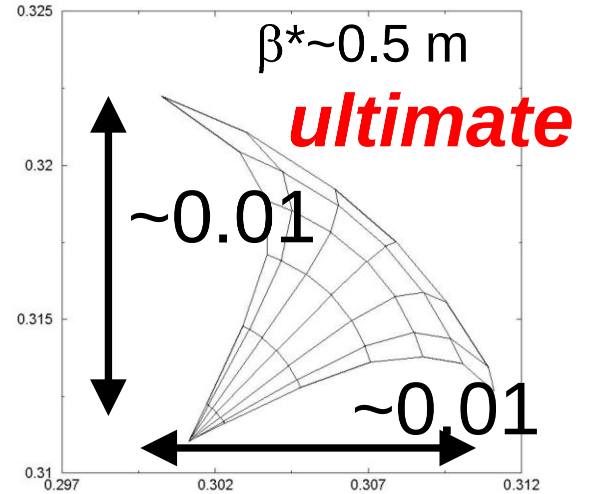
- head-on beam-beam limit
- detector pile up
- long-range beam-beam effects
- crossing angle
- collimation & machine protection
- beam from injectors
- heat load (SR, impedance, e-cloud)

head-on beam-beam limit

from 2001 upgrade feasibility study, 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}

$L=2.3\times10^{34}$ cm^{-2}s^{-1}

SPS: beam-beam limit ↔ total tune shift ΔQ~0.01 (Tevatron: 0.02?!)

going from 4 to 2 IPs ATLAS & CMS luminosity can be increased by factor 2.3

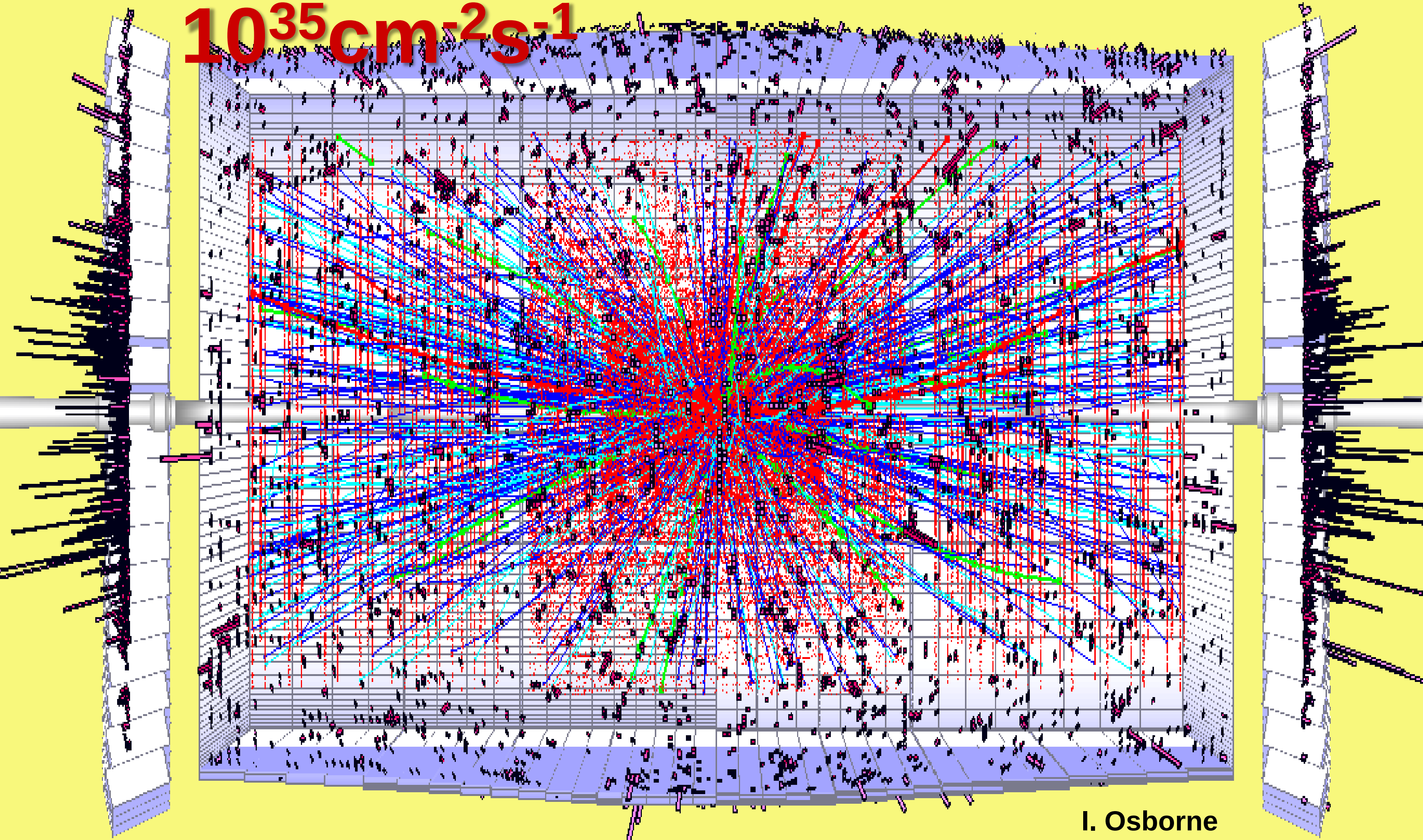
further, increasing crossing angle to 340 μrad, bunch length (x2), & bunch charge to N_b=2.6x10^{11} would yield $L=3.6\times10^{34}$ cm^{-2}s^{-1} (β*=0.5 m still)

beam-beam limit ↔ bunch charge!

detector pile up

< 200-300 events/#ing!?

$10^{35} cm^{-2} s^{-1}$



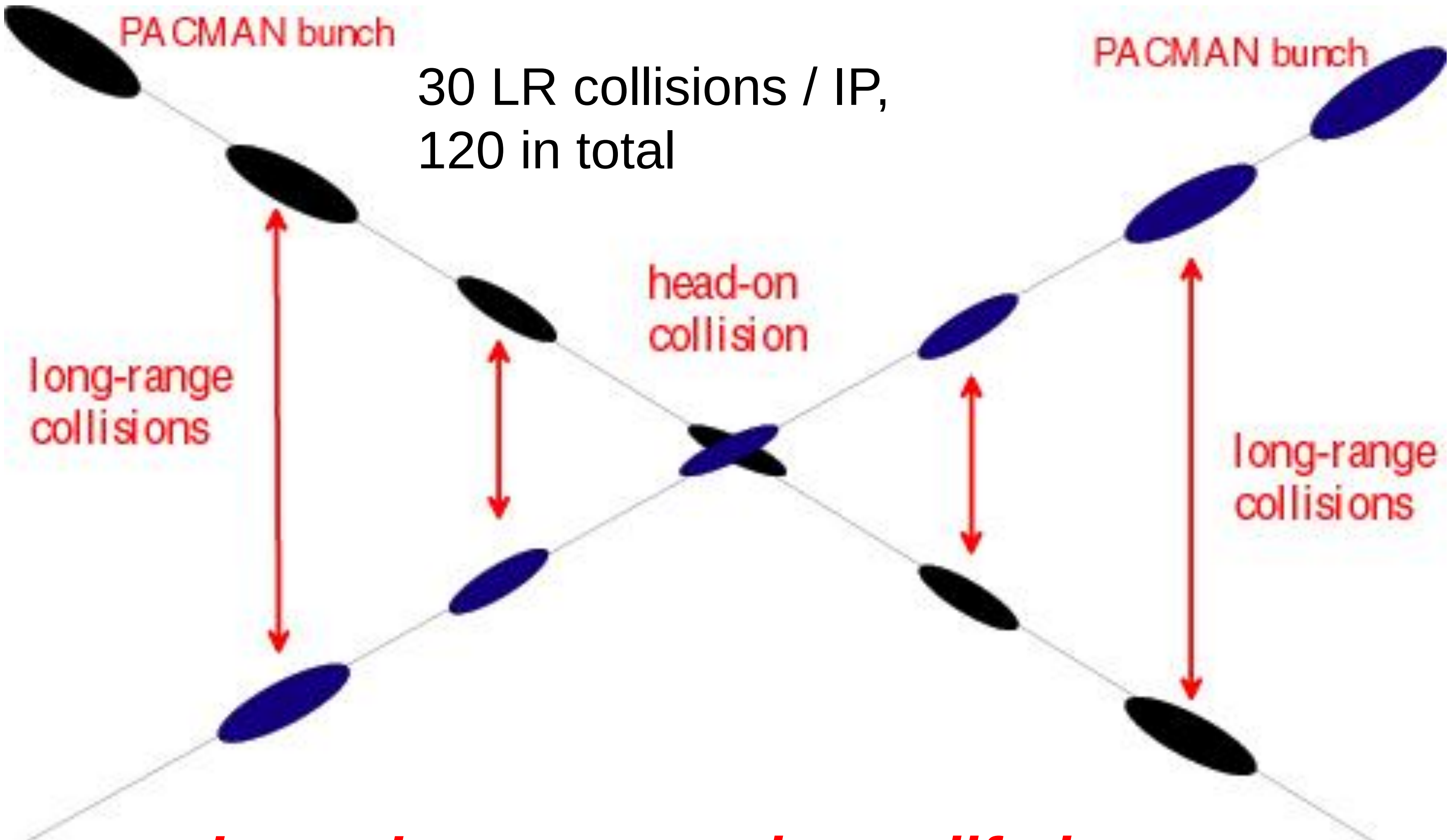
I. Osborne

↔ bunch spacing!

generated tracks per crossing,
p_t > 1 GeV/c cut, i.e. soft tracks removed!

long-range (LR) beam-beam

30 LR collisions / IP,
120 in total



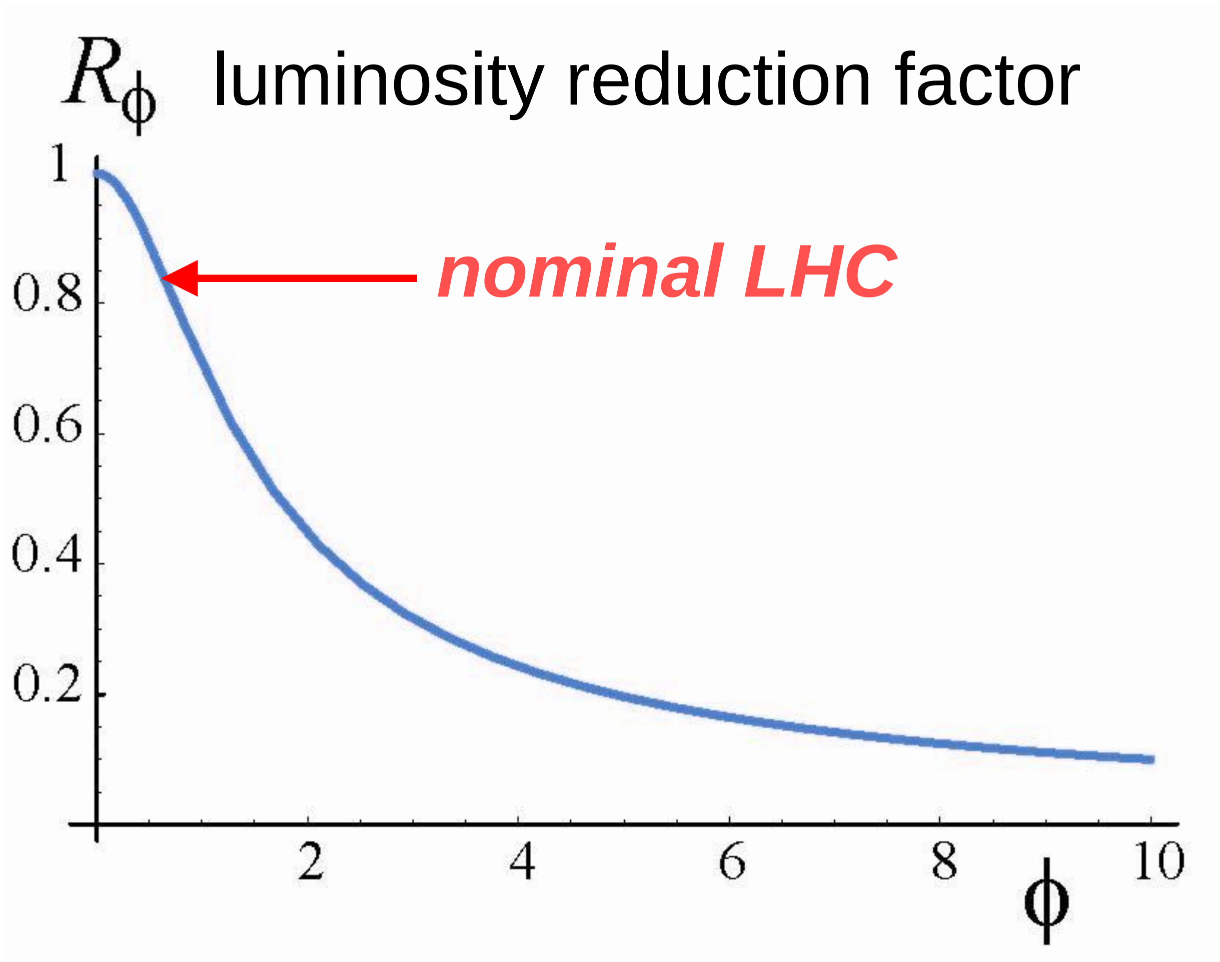
→ beam losses, poor beam lifetime

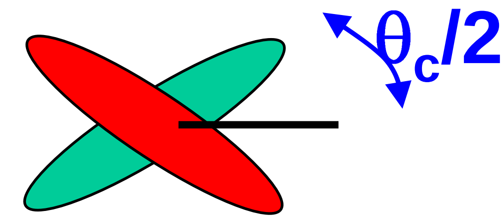
↔ minimum crossing angle & β, aperture!*

crossing angle

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

"Piwinski angle"





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

→ luminosity loss, poor beam lifetime

↔ bunch length, β*, crab cavities, emittance, early separation scheme!

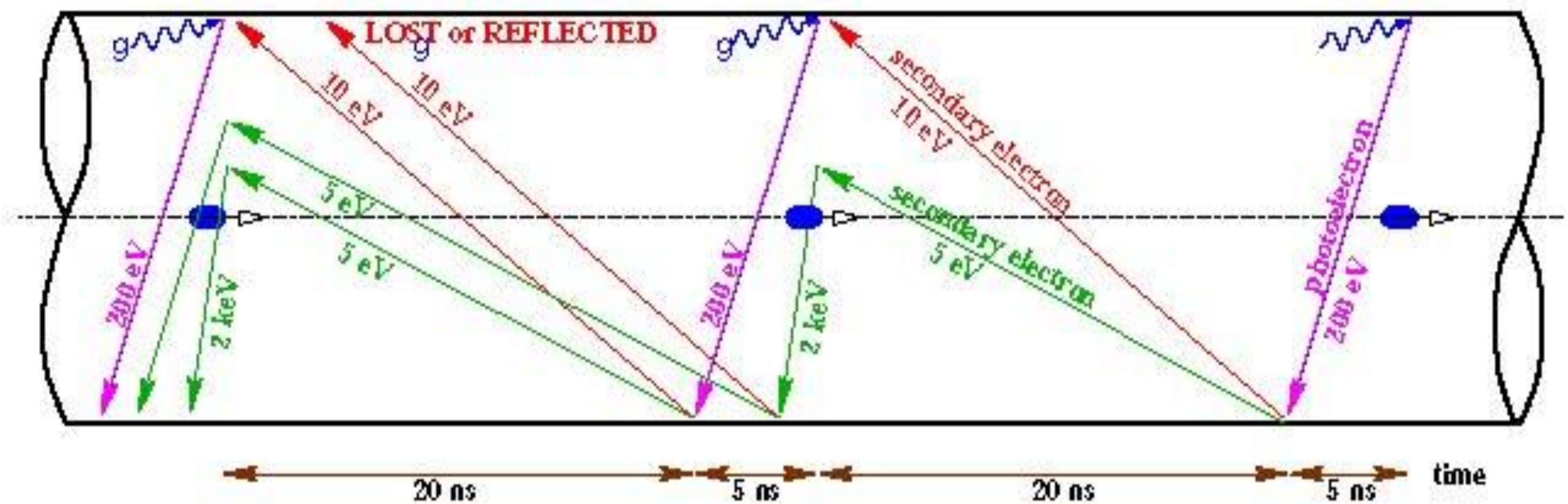
collimation

R. Assmann, HHH-2008

- main task: **quench protection**: 1% beam loss in 10 s at 7 TeV ~ 500 kW energy ; quench limit = 8.5 W/m!
- simulated **cleaning efficiency w. errors allows only ~5% of nominal intensity** for assumed loss rate
- **IR upgrade will not improve intensity limit**
- **"phase-II" collimation** with **(sacrificial or consumable?) Cu & cryogenic collimators** under study ; predicted factor 30 improvement in cleaning efficiency: **99.997 %/m** → **99.99992 %/m** ; **ready for nominal and higher intensity in 2012?!**

electron cloud

[F. Ruggiero]



schematic of e- cloud build up in LHC beam pipe, due to **photoemission** and **secondary emission**

→ ***heat load (→ quenches), instabilities, emittance growth, poor beam lifetime***

also synchrotron radiation & beam image currents add to heat load

↔ ***bunch spacing, bunch charge & bunch length!***

injector limitations

- **nominal LHC beam ~ present performance limit**
- **ultimate LHC beam out of reach**
- **component aging & reliability problems**
- important limiting mechanisms like space charge, & aperture are common to all injectors and will "profit" from an **injection energy increase**; in particular the PSB will profit from new LINAC4
- TMCI is a major limitation for PS and SPS and an **increase in $|\eta|$** is necessary (avoid transition crossing and $\gamma_{inj} >> \gamma_{tr}$)

G. Arduini, BEAM'07

development of scenarios

2001/02 feasibility study (LHC Project Report 626):

"phase 0" – no HW changes
"phase 1" – IR upgrade, 12.5 ns or superbunches
"phase 2" – major HW changes; injector upgrade

32 workshops
156 documents

CARE
HHH
CARE – HHH 2004 - 2008
High energy High intensity Hadron beams

HHH-2004: superbunches †
LUMI'05: IR upgrade w. NbTi and β^*=0.25 m, "LPA" scheme; "early separation"
LUMI'06: 12.5 ns †
"dipole first schemes" †
BEAM'07: beam production; luminosity leveling; "full crab crossing"
HHH-2008: "low emittance"

LHC upgrade stages

"phase 1" 2013, 2x10^{34} cm^{-2}s^{-1}:

new NbTi triplets, D1, TAS,
β^*~0.25-0.3 m in IP1 & 5,
beam from new Linac4

+ injector upgrade

"phase 2" 2017, ~10^{35} cm^{-2}s^{-1} :

possibly Nb_3Sn triplet & β^*~0.15 m

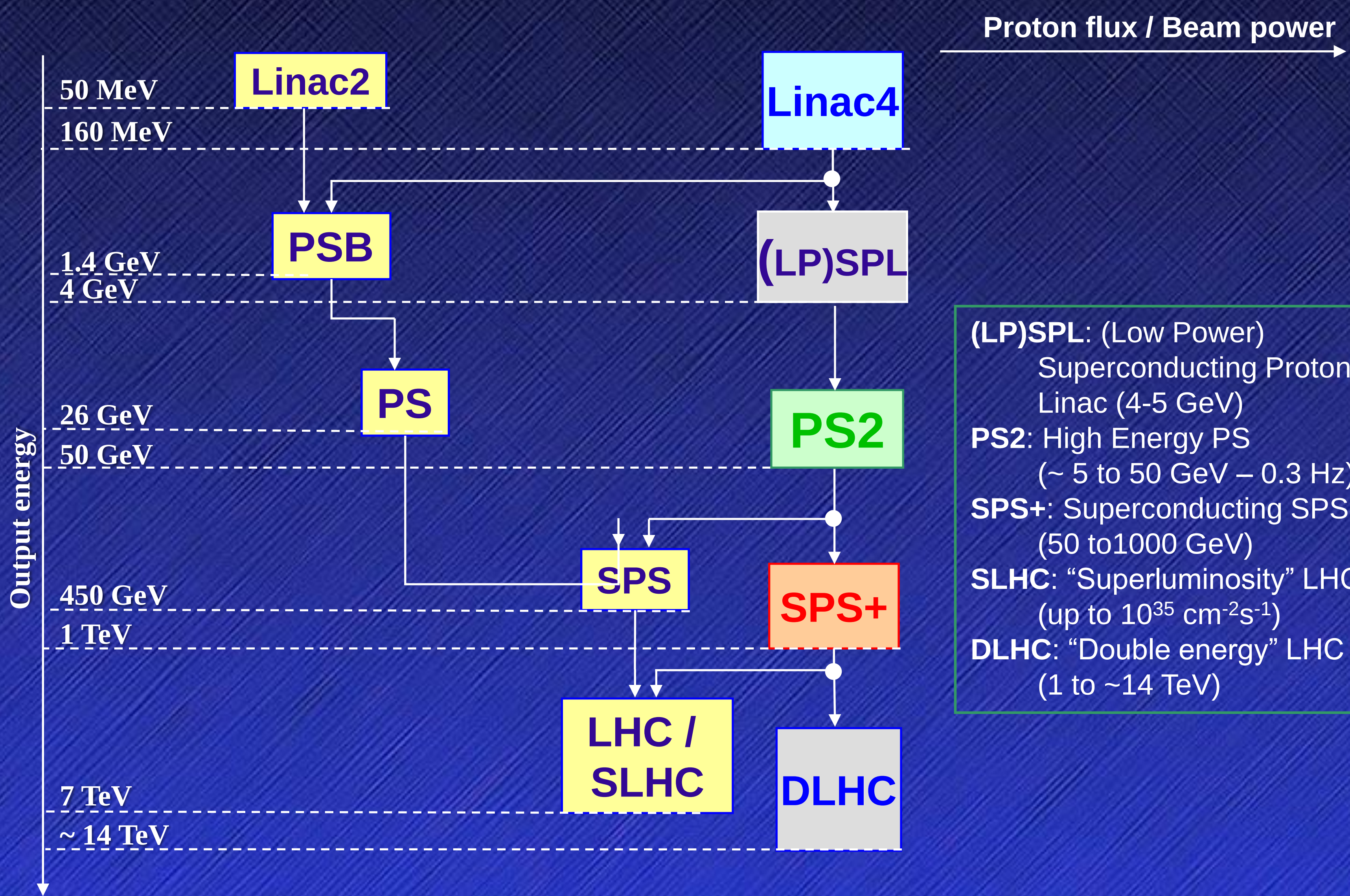
complementary measures 2010-2017:

e.g. long-range beam-beam compensation,
crab cavities, advanced collimators, crab waist?
[, coherent e- cooling??, e- lenses??]

phase-2 might be just phase 1 plus complementary measures

longer term (2020?): energy upgrade, LHeC,…

present and future injectors



(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)

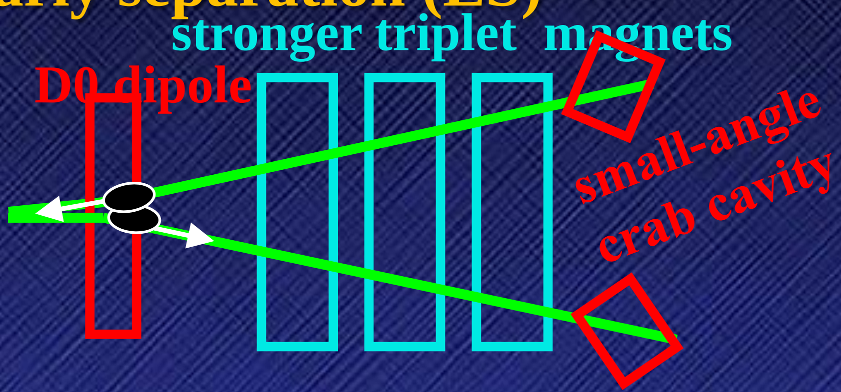
LHC "phase-2" scenarios

- early separation (ES)
  - β^*~0.1 m, 25 ns, N_b=1.7x10^{11}, detector embedded dipoles
- full crab crossing (FCC)
  - β^*~0.1 m, 25 ns, N_b=1.7x10^{11}, local and/or global crab cavities
- large Piwinski angle (LPA)
  - β^*~0.25 m, 50 ns, N_b=4.9x10^{11}, "flat" intense bunches
- low emittance (LE)
  - β^*~0.1 m, 25 ns, $\gamma\varepsilon$~1-2 μm, N_b=1.7x10^{11}

“phase-2” IR layouts

early separation (ES)

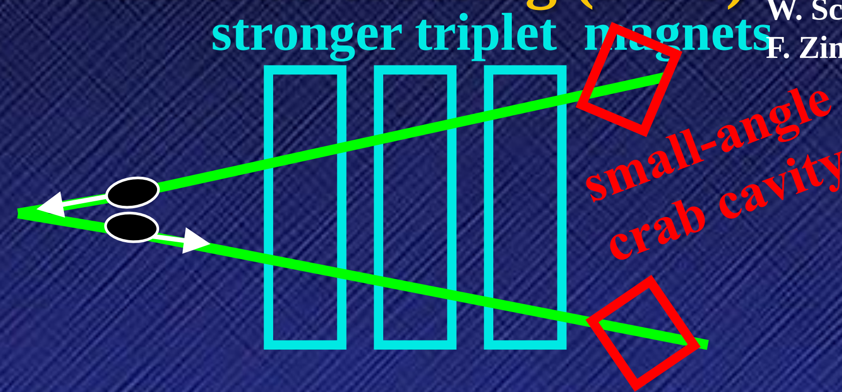
J.-P. Koutchouk



- early-separation dipoles in side detectors , crab cavities
  → hardware inside ATLAS & CMS detectors,
  first hadron crab cavities; off-δ β

full crab crossing (FCC)

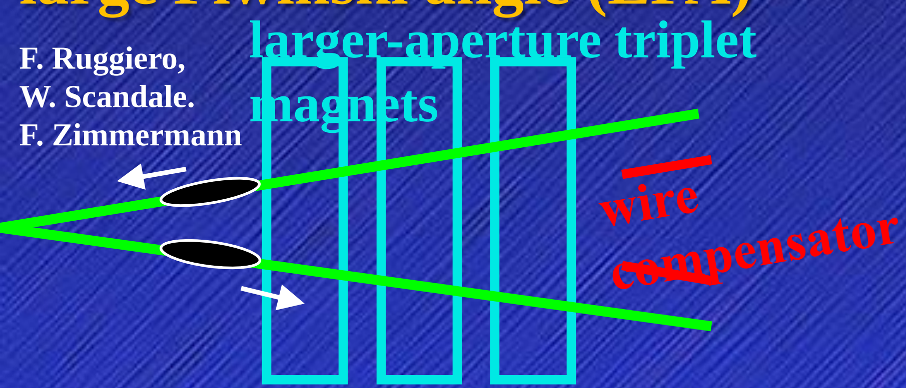
L. Evans,
W. Scandale,
F. Zimmermann



- crab cavities with 60% higher voltage
  → first hadron crab cavities, off-δ β-beat

large Piwinski angle (LPA)

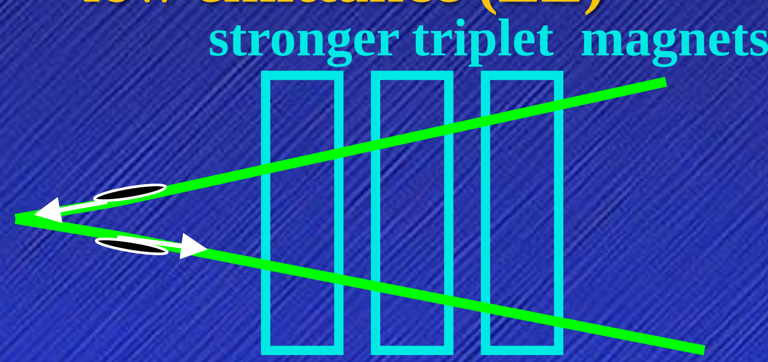
F. Ruggiero,
W. Scandale.
F. Zimmermann



- long-range beam-beam wire compensation
  → novel operating regime for hadron colliders,
  beam generation

low emittance (LE)

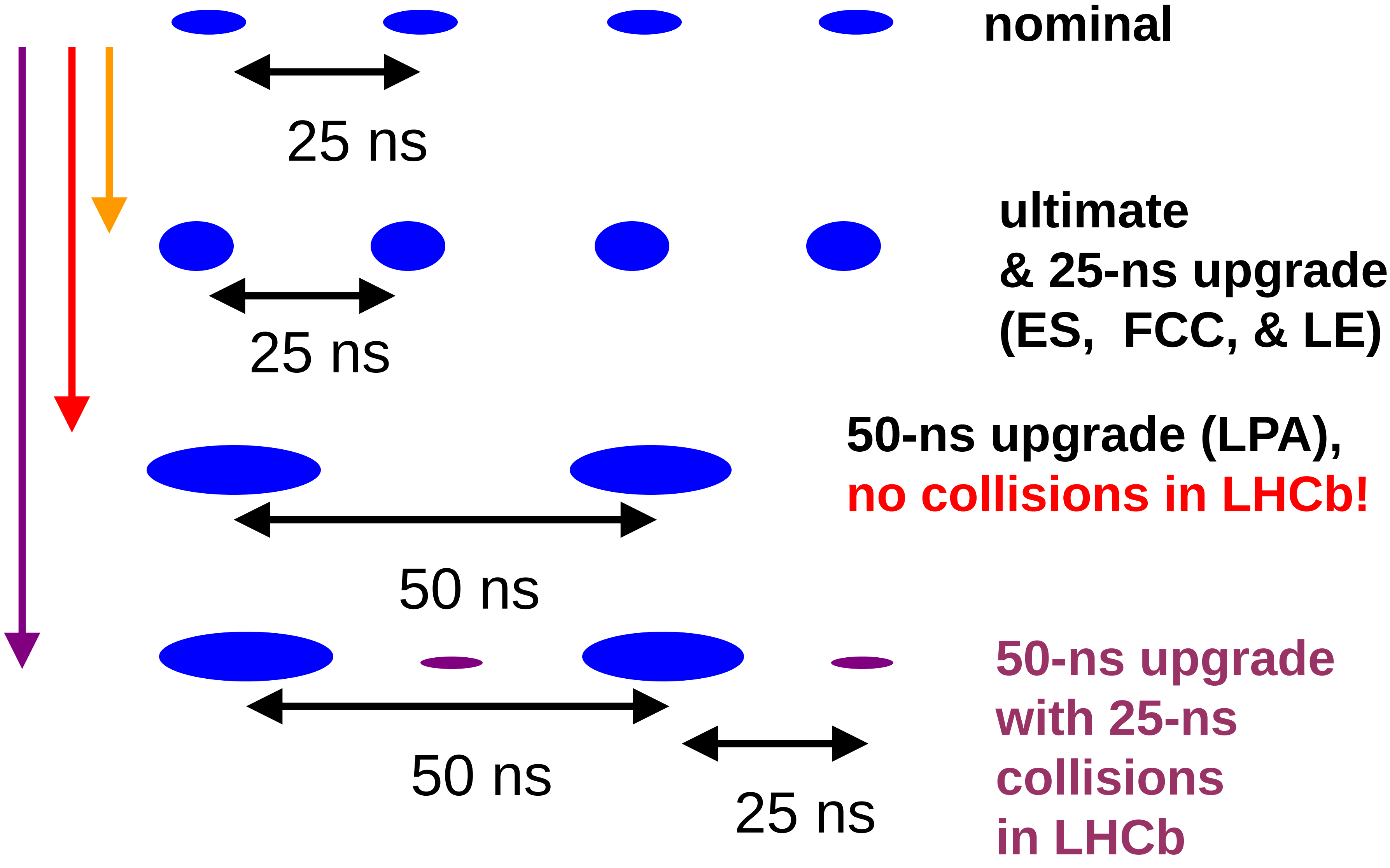
R. Garoby



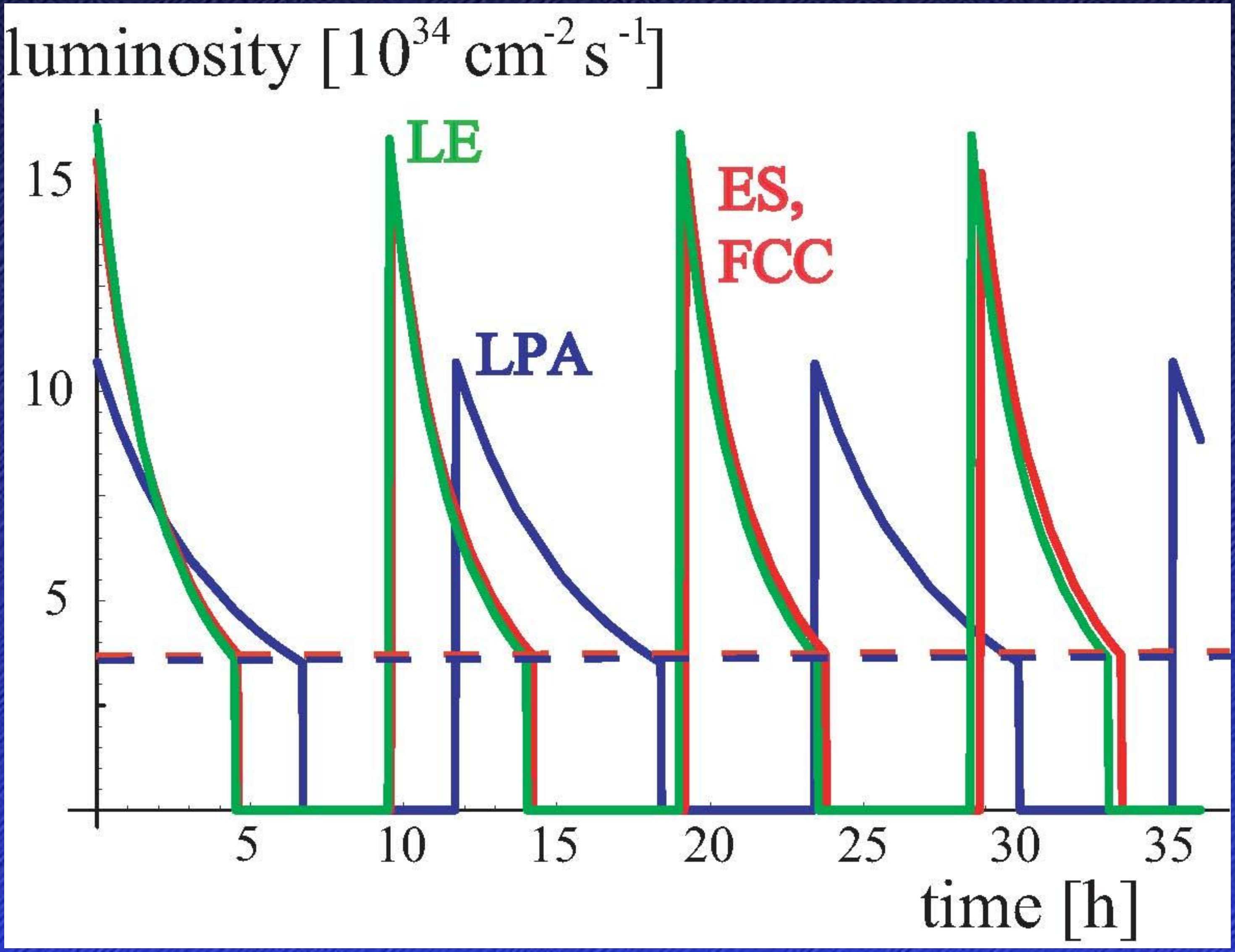
- smaller transverse emittance
  → constraint on new injectors, off-δ β-beat

parameter	symbol	nominal	ultimate	ES	FCC	LE	LPA
transverse emittance	ε [μm]	3.75	3.75	**3.75**	**3.75**	**1.0**	**3.75**
protons per bunch	N_b [10^{11}]	1.15	1.7	**1.7**	**1.7**	**1.7**	**4.9**
bunch spacing	Δt [ns]	25	25	**25**	**25**	**25**	**50**
beam current	I [A]	0.58	0.86	**0.86**	**0.86**	**0..86**	**1.22**
longitudinal profile		Gauss	Gauss	**Gauss**	**Gauss**	**Gauss**	**Flat**
rms bunch length	σ_z [cm]	7.55	7.55	**7.55**	**7.55**	**7.55**	**11.8**
beta* at IP1&5	$\beta*$ [m]	0.55	0.5	**0.08**	**0.08**	**0.1**	**0.25**
full crossing angle	θ_c [μrad]	285	315	**0**	**0**	**311**	**381**
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.64	0.75	**0**	**0**	**3.2**	**2.0**
geometric reduction		1.0	1.0	**0.86**	**0.86**	**0.30**	**0.99**
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	2.3	**15.5**	**15.5**	**16.3**	**10.7**
peak events per #ing		19	44	**294**	**294**	**309**	**403**
initial lumi lifetime	τ_L [h]	22	14	**2.2**	**2.2**	**2.0**	**4.5**
effective luminosity ($T_{turnaround}$=10 h)	L_{eff}[10^{34} cm^{-2}s^{-1}]	0.46	0.91	**2.4**	**2.4**	**2.5**	**2.5**
	$T_{run,opt}$ [h]	21.2	17.0	**6.6**	**6.6**	**6.4**	**9.5**
effective luminosity ($T_{turnaround}$=5 h)	L_{eff}[10^{34} cm^{-2}s^{-1}]	0.56	1.15	**3.6**	**3.6**	**3.7**	**3.5**
	$T_{run,opt}$ [h]	15.0	12.0	**4.6**	**4.6**	**4.5**	**6.7**
e-c heat SEY=1.4(1.3)	P [W/m]	1.1 (0.4)	1.04(0.6)	**1.0 (0.6)**	**1.0 (0.6)**	**1.0 (0.6)**	**0.4 (0.1)**
SR heat load 4.6-20 K	P_{SR} [W/m]	0.17	0.25	**0.25**	**0.25**	**0.25**	**0.36**
image current heat	P_{IC} [W/m]	0.15	0.33	**0.33**	**0.33**	**0.33**	**0.78**
gas-s. 100 h (10 h) τ_b	P_{gas} [W/m]	0.04 (0.4)	0.06 (0.6)	**0.06 (0.56)**	**0.06 (0.56)**	**0.06 (0.56)**	**0.09 (0.9)**
extent luminous region	σ_l [cm]	4.5	4.3	**3.7**	**3.7**	**1.5**	**5.3**
comment		nominal	ultimate	**D0 + crab**	**crab**		**wire comp.**

upgrade bunch patterns

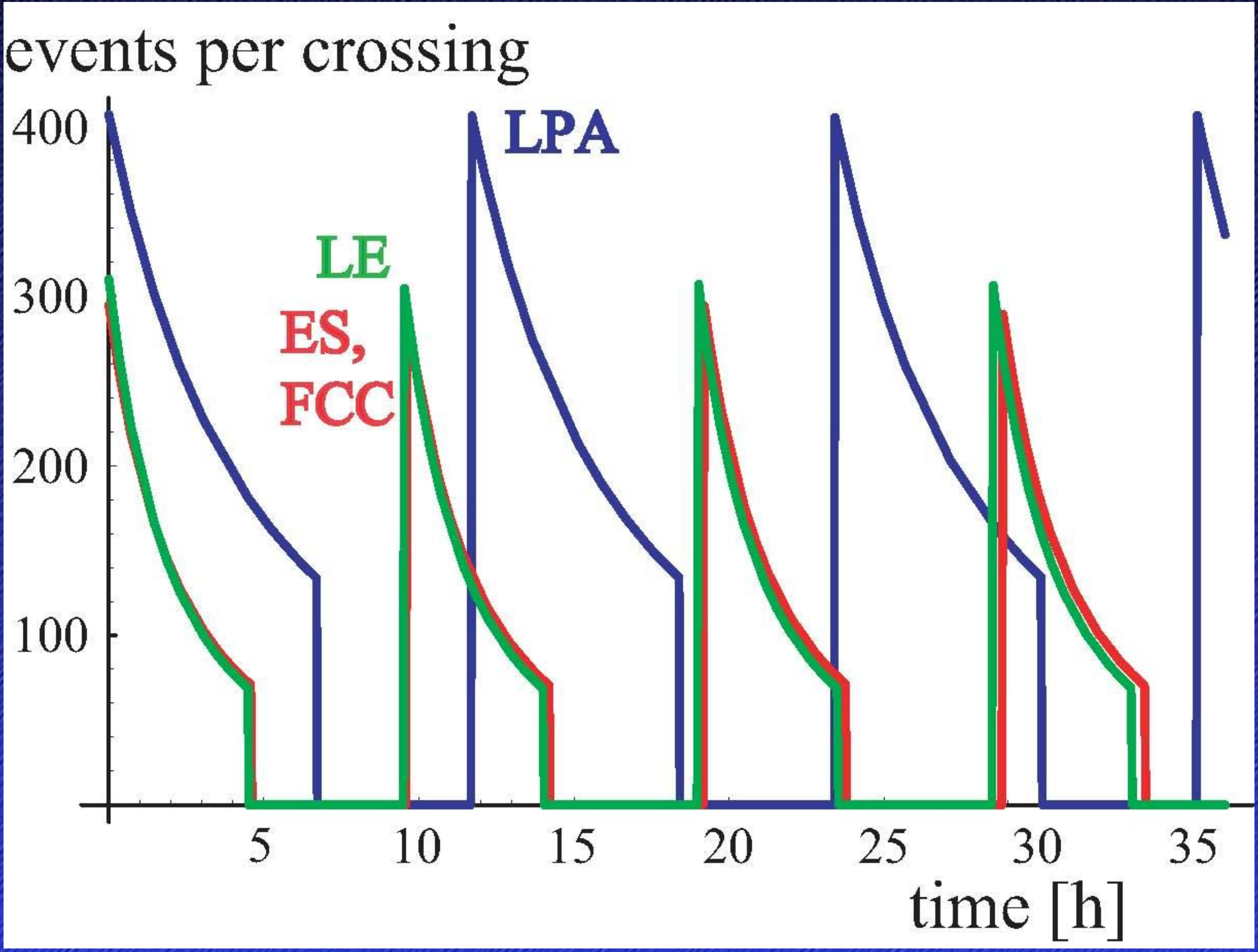


luminosity evolution



average luminosity

event pile up



b.-b. ΔQ & peak luminosity

$$\Delta Q_{bb} = \frac{N_b}{\gamma\varepsilon}\frac{r_p}{2\pi}\frac{1}{\sqrt{1+\phi_{piw}^2}}\frac{1}{F_{profile}} \qquad \phi_{piw} \equiv \frac{\sigma_z \theta_c}{2\sigma_{x,y}^*}$$

Piwinski angle

total beam-beam tune shift at 2 IPs with alternating crossing;

we increase charge N_b until limit ΔQ_{bb} is reached; to go further we must increase ϕ_{piw}, and/or ε and/or $F_{profile}$ (~$2^{1/2}$ for flat bunches)

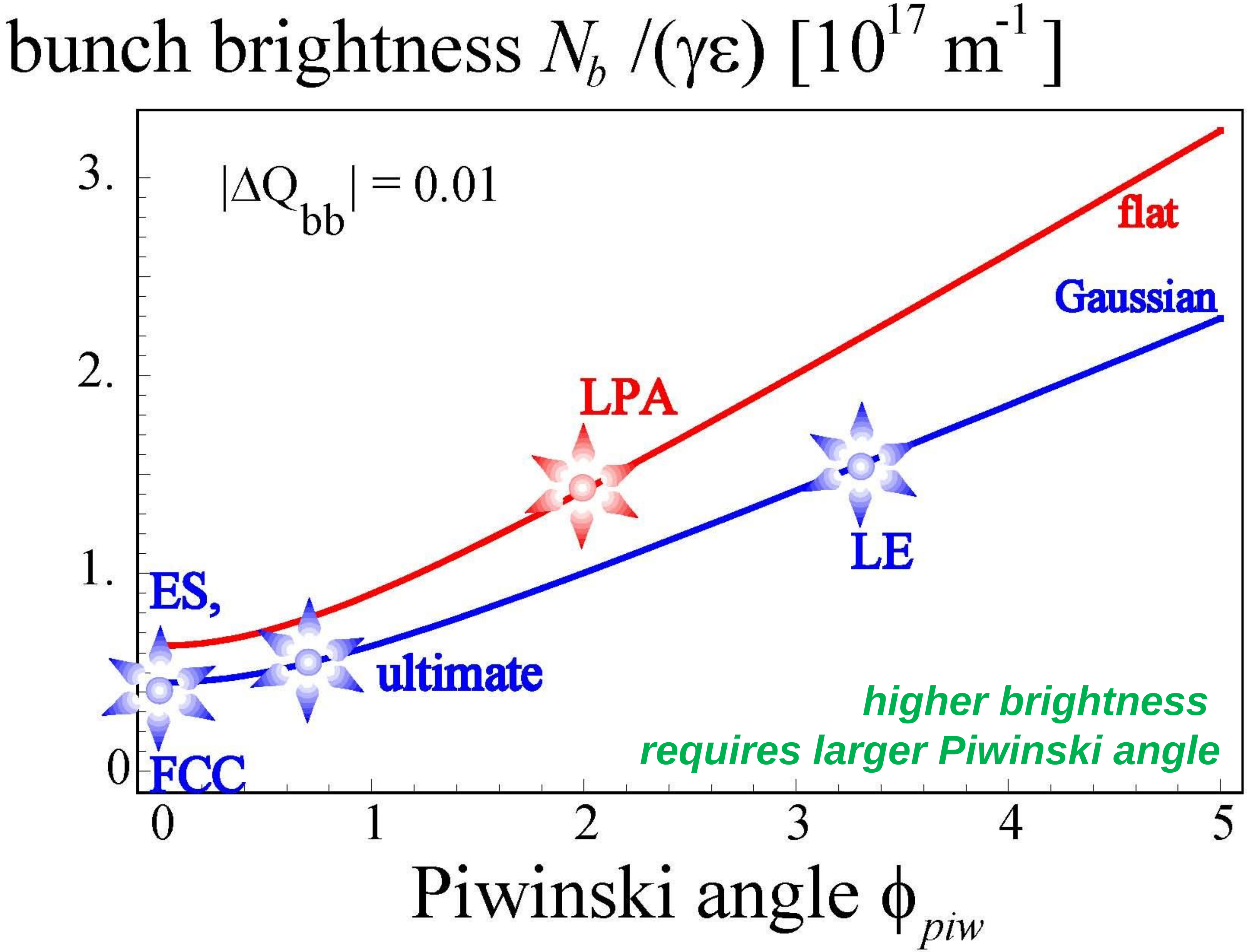
$$L = \frac{1}{4\pi} f_{rev} n_b \gamma \frac{1}{\beta^* (\gamma\varepsilon)} N_b^2 F_{hg} \frac{1}{\sqrt{1+\phi_{piw}^2}}$$

$$= \frac{1}{2r_p} f_{rev} n_b \gamma \frac{1}{\beta^*} N_b \Delta Q_{bb} F_{profile} F_{hg}$$

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

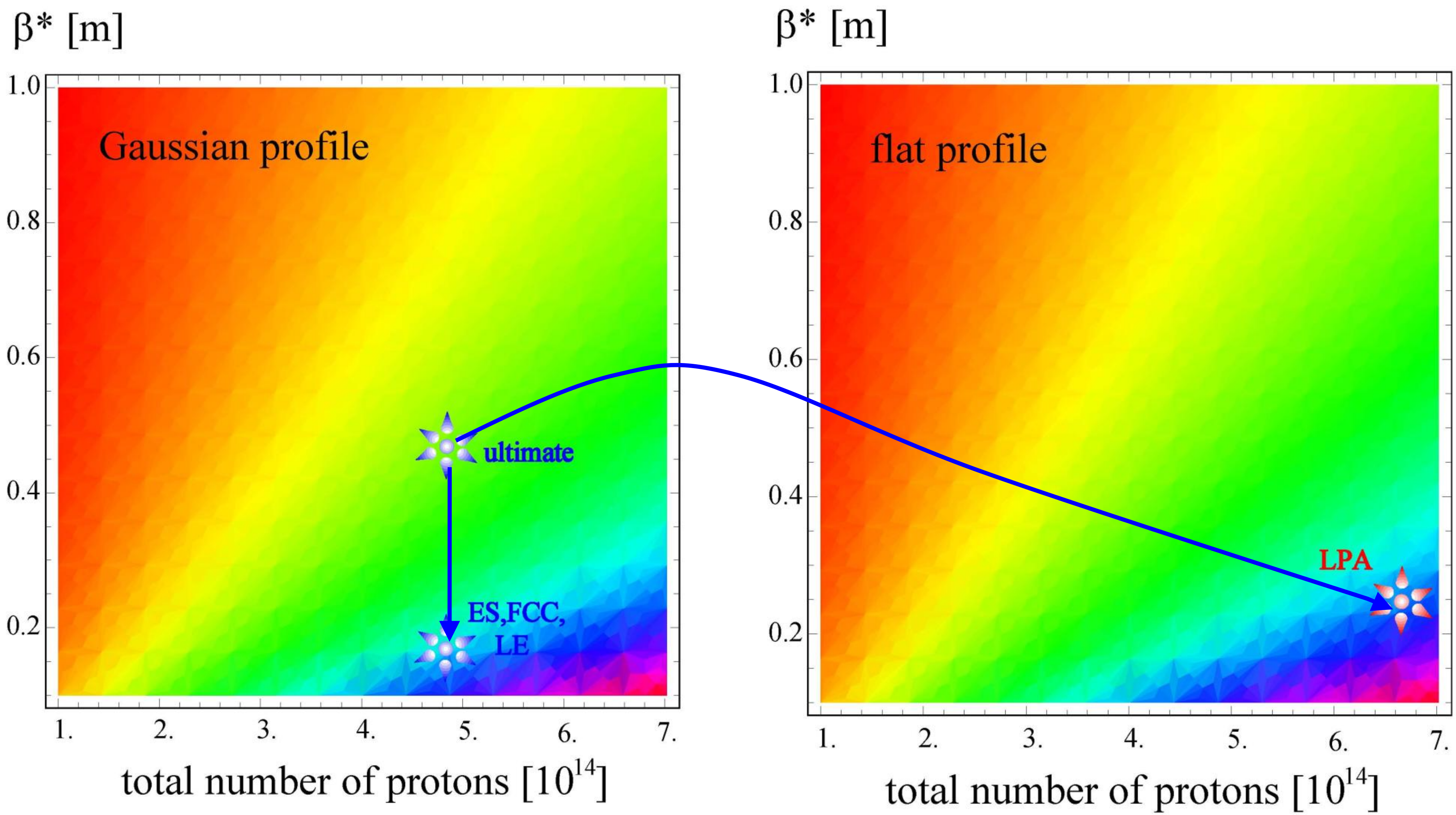
at the b-b limit, larger Piwinski angle &/or larger emittance increase luminosity

$N_b/(\gamma\varepsilon)$ vs ϕ_{piw} plane



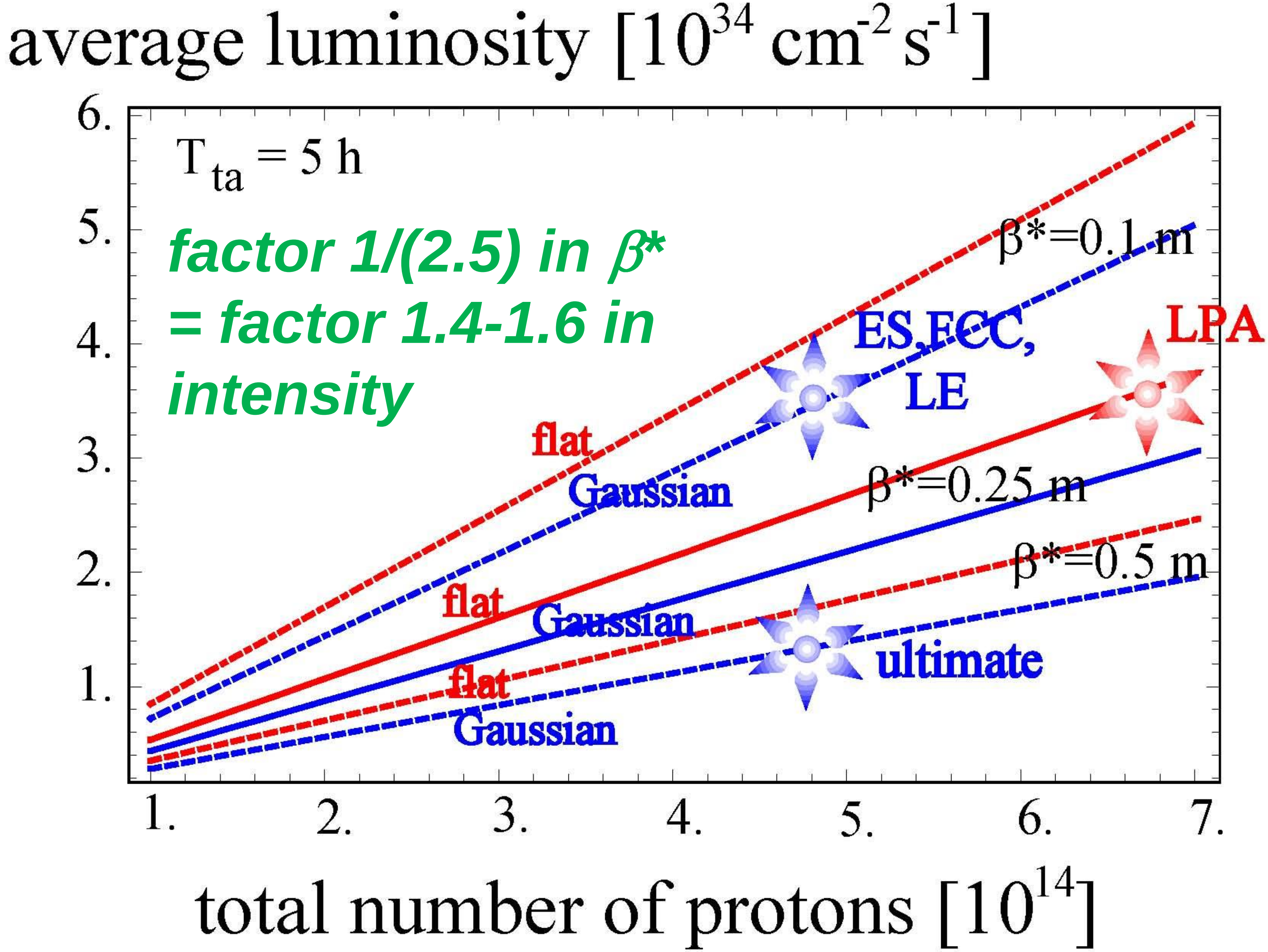
higher brightness requires larger Piwinski angle

av. luminosity vs #*p*'s & β*



"linear" scale from 10^{33} to $2\text{x}10^{35}$ $cm^{-2}s^{-1}$

av. luminosity vs #*p*'s



factor 1/(2.5) in β*
= factor 1.4-1.6 in intensity

luminosity leveling

experiments prefer constant luminosity: less pile up at start of run, and higher luminosity at the end of a physics store

how can we achieve this?

ES, or FCC: dynamic β squeeze, or dynamic θ change (either IP angle bumps or varying crab voltage); LE: β or θ change; LPA: dynamic β squeeze, or dynamic change of bunch length

run time & av. luminosity

	w/o leveling	with leveling
luminosity evolution	$L(t)=\frac{\hat{L}}{(1+t/\tau_{eff})^2}$	$L=L_0\approx const$
beam current evolution	$N(t)=\frac{N_0}{(1+t/\tau_{eff})}$	$N=N_0-\frac{N_0}{\tau_{lev}}t$
optimum run time	$T_{run}=\sqrt{\tau_{eff}T_{turn-around}}$	$T_{run}=\frac{\Delta N_{\max}\tau_{lev}}{N_0}$
average luminosity	$L_{ave}=\hat{L}\frac{\tau_{eff}}{(\tau_{eff}^{1/2}+T_{turn-around}^{1/2})^2}$	$L_{ave}=\frac{L_0}{1+\frac{L_0\sigma_{tot}n_{IP}}{\Delta N_{\max}n_b}T_{turn-around}}$

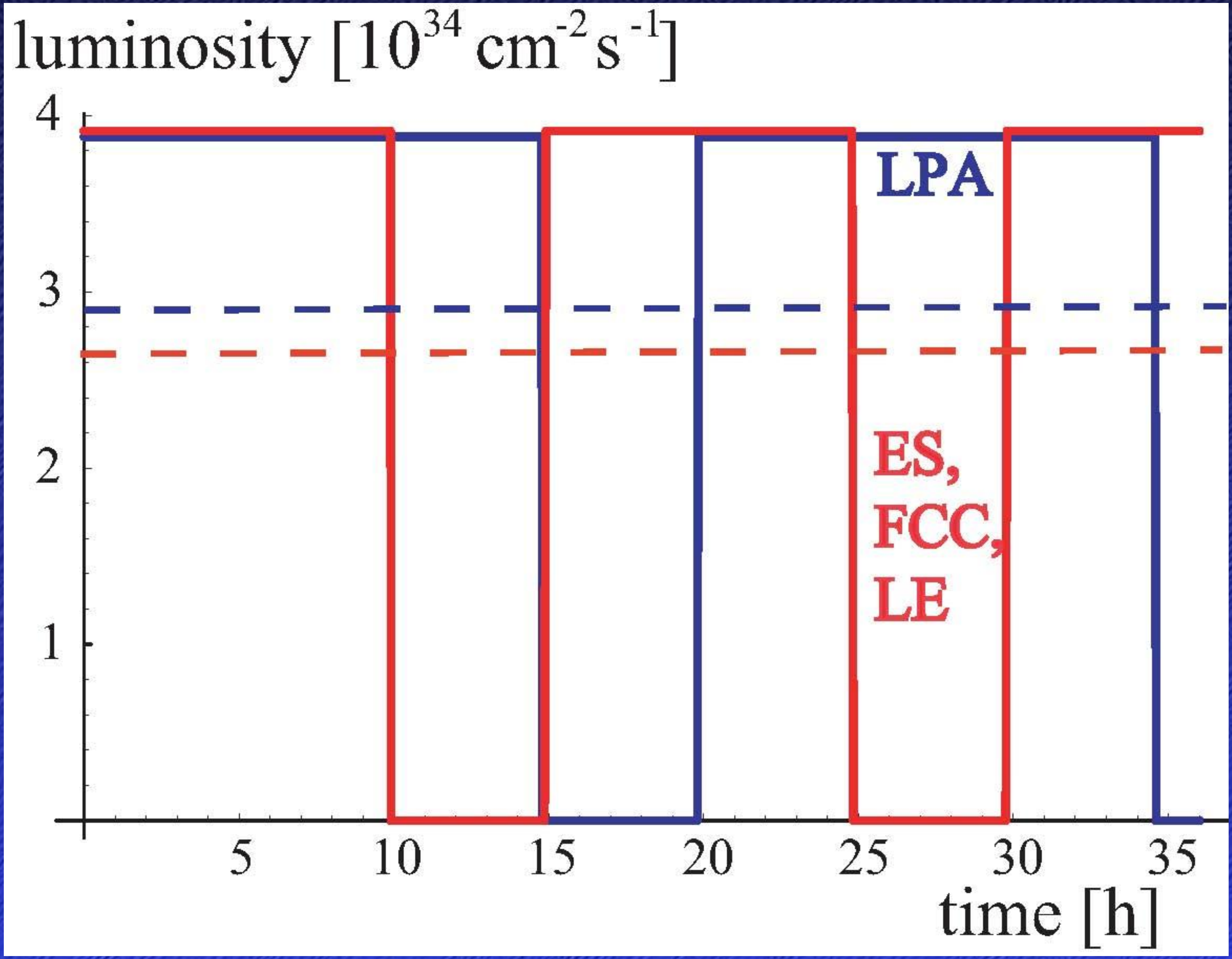
$$\tau_{eff}=\frac{N_0 n_b}{n_{IP}\hat{L}\sigma_{tot}} \qquad \tau_{lev}=\frac{N_0 n_b}{n_{IP}L_0\sigma_{tot}}$$

luminosity liftetime scales with total # protons!

examples	ES, FCC, or LE, with leveling	LPA, with leveling
events/crossing	300	300
run time	N/A	2.5 h
av. luminosity	N/A	$2.6x10^{34}s^{-1}cm^{-2}$
events/crossing	150	150
run time	2.5 h	14.8 h
av. luminosity	$2.6x10^{34}s^{-1}cm^{-2}$	$2.9x10^{34}s^{-1}cm^{-2}$
events/crossing	75	75
run time	9.9 h	26.4 h
av. luminosity	$2.6x10^{34}s^{-1}cm^{-2}$	$1.7x10^{34}s^{-1}cm^{-2}$

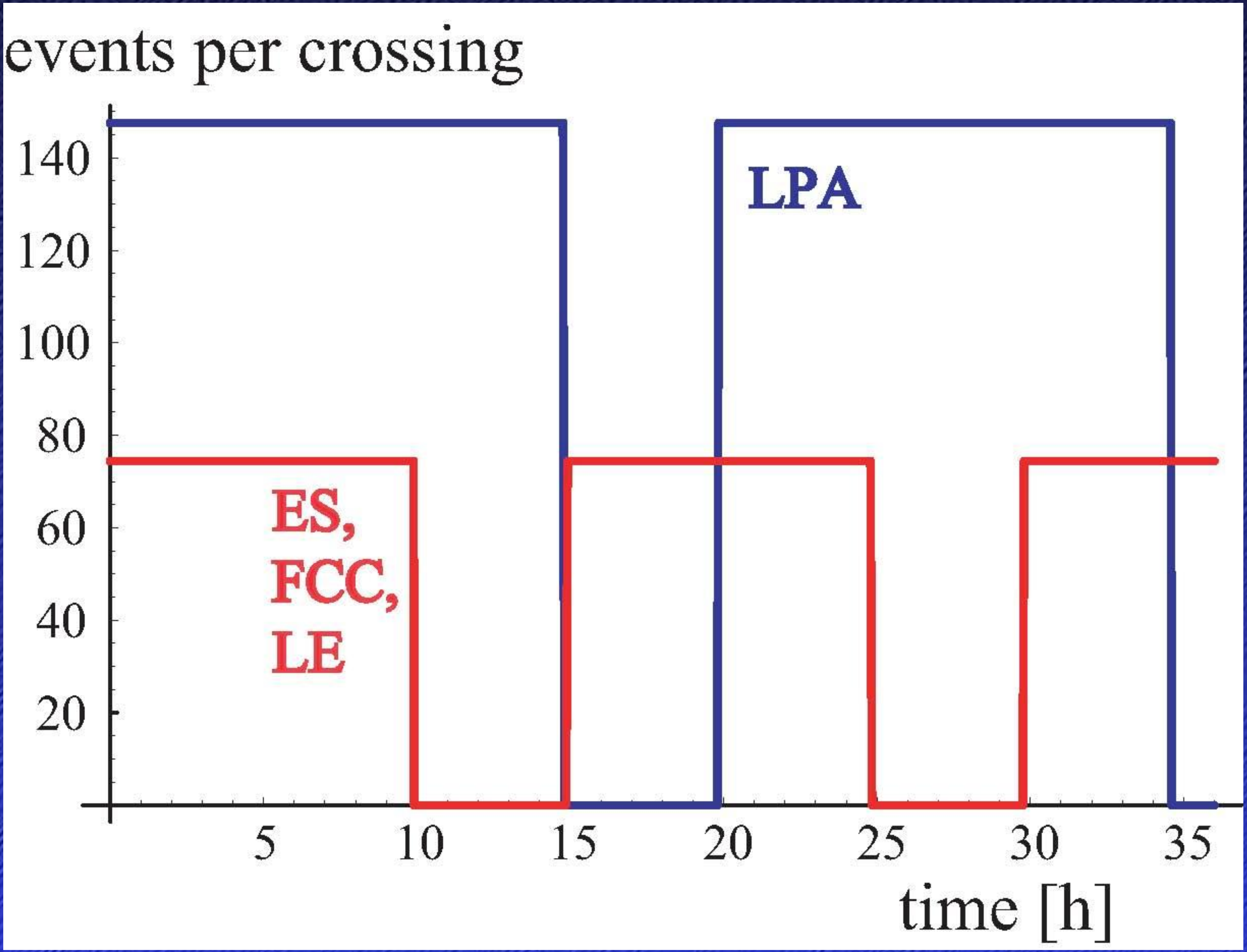
assuming 5 h turn-around time

luminosity with leveling



average luminosity

event pile up with leveling



some conclusions

- ✓ nominal LHC is challenging
- ✓ upgrade of collimation system mandatory
- ✓ beam parameter sets evolved over past 8 years
- ✓ several scenarios exist on paper which can reach 10x nominal luminosity with acceptable heat load & pile up; different merits and drawbacks (*not in a corner*)
- ✓ if possible, raising beam intensity is preferred over reducing β* (better beam lifetime) ; but intensity might be limited by collimation!
- ✓ needed: work on s.c. IR magnets for phase-2 and on complementary measures (LR beam-beam compensation, crab cavities, etc.)
- ✓ close coordination with detector upgrades

thank you!

appendix:

more details on collimation constraints

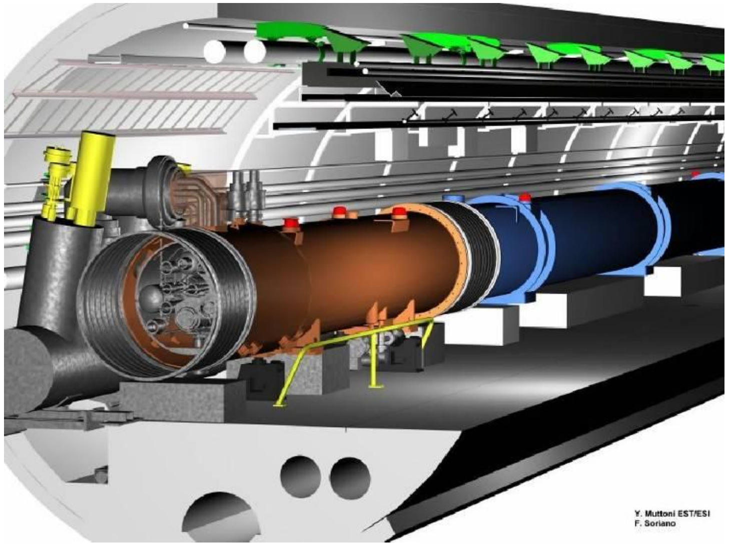
collimation – quench prevention

Maximum **beam loss at 7 TeV**: 1% of beam over 10 s

500 kW

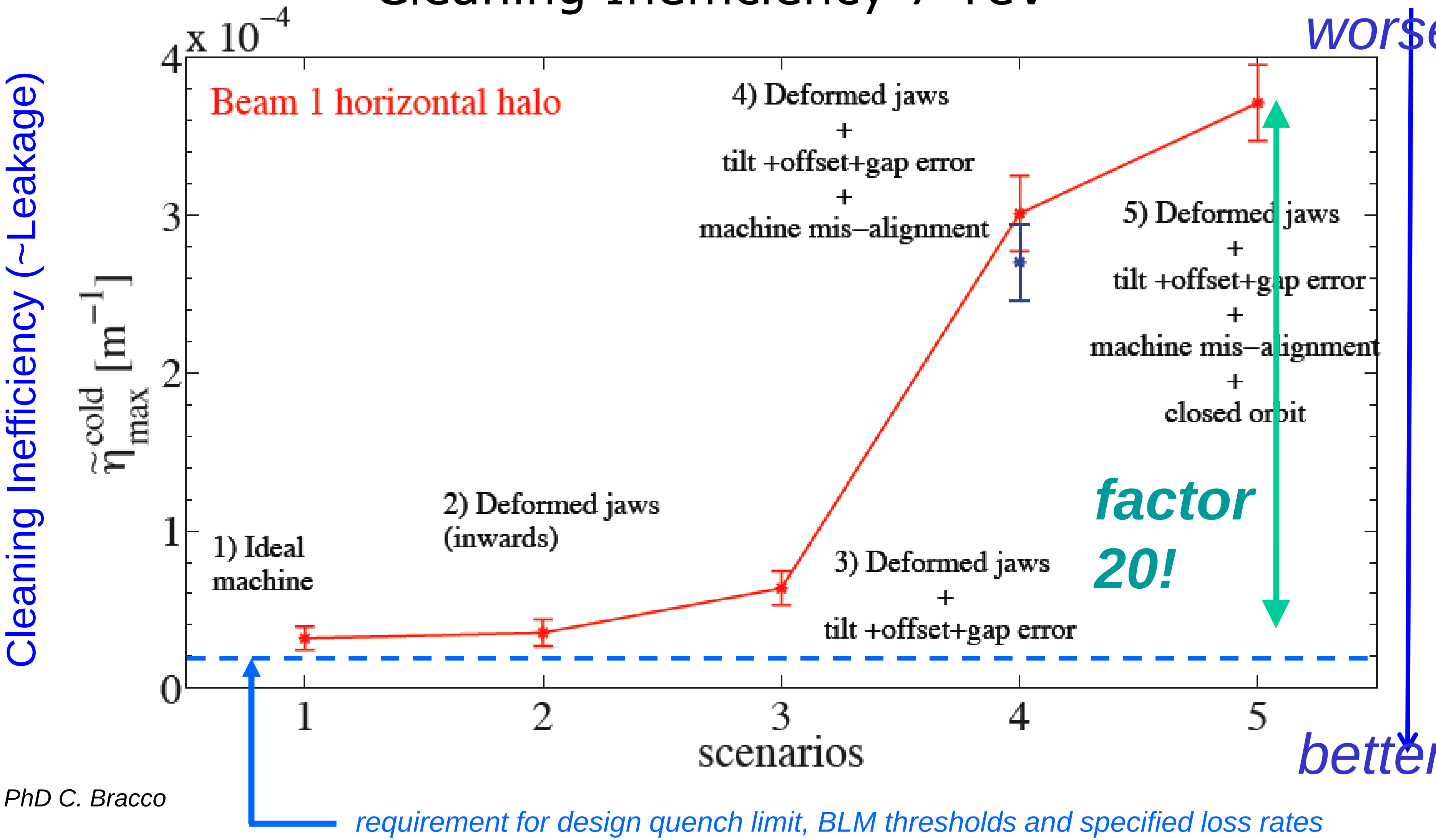
Quench limit of SC LHC magnet:

8.5 W/m



collimation performance

- Cleaning Inefficiency 7 TeV -



PhD C. Bracco

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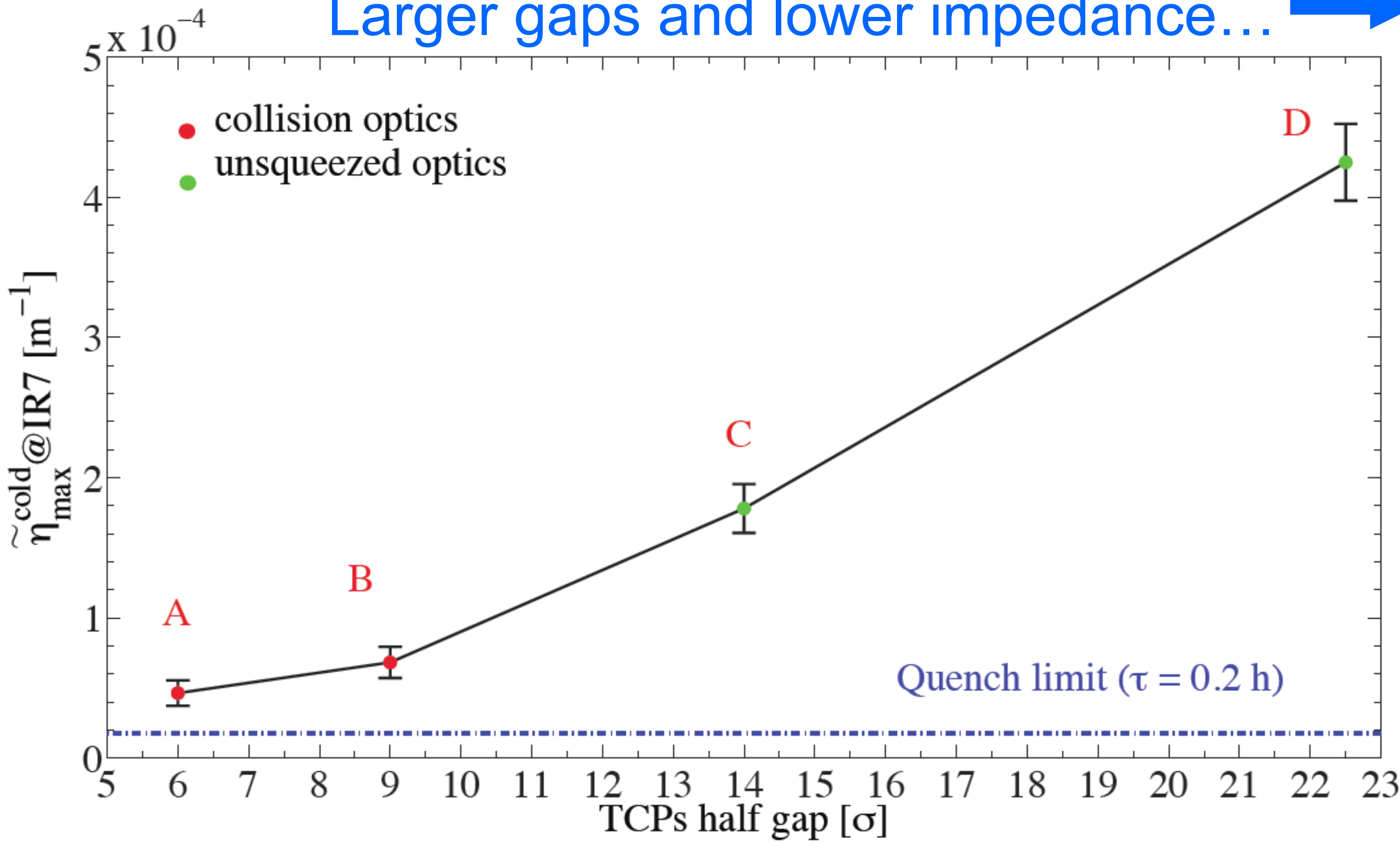
collimation performance II

Larger gaps and lower impedance…



Higher inefficiency, less cleaning performance

PhD C. Bracco

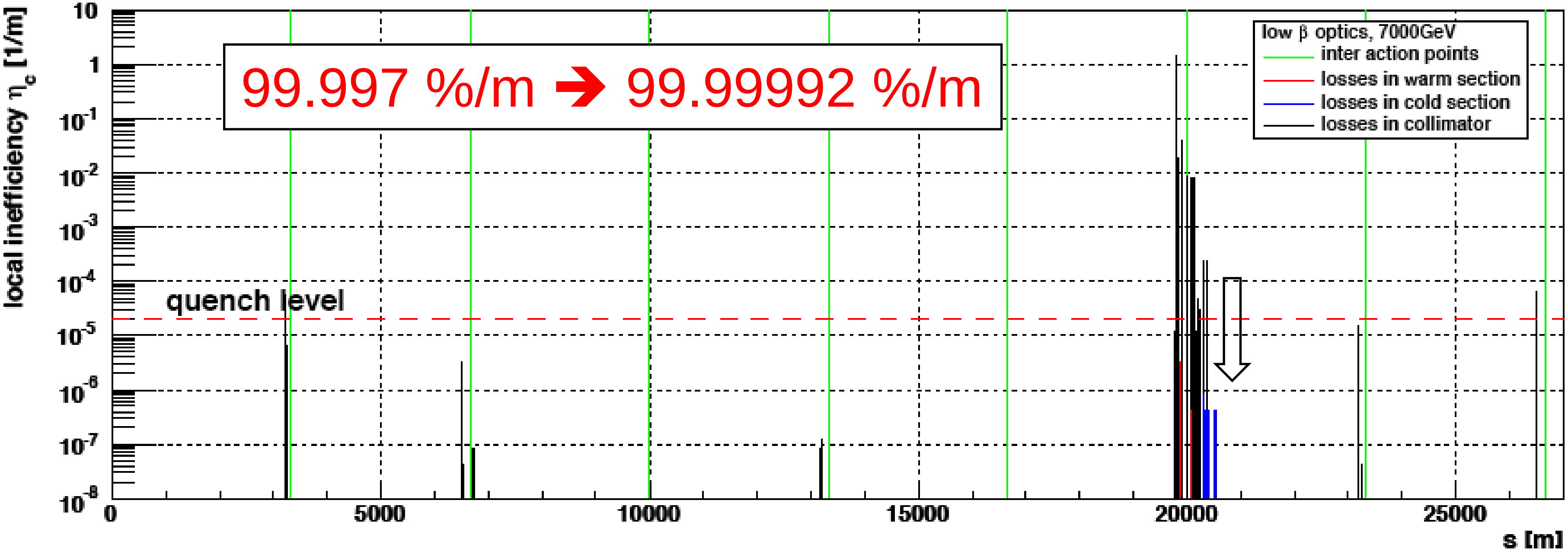
➔ **Phase I IR upgrade will not improve intensity limit from phase I collimation!**

Additional room from triplet aperture can only be used after collimation upgrade

R. Assmann - HHH 2008

p collimation efficiency w. "phase II" Cu & Cryogenic Collimators

T. Weiler & R. Assmann



inefficiency reduces by factor 30 (good for nominal intensity)

caution: further studies must show feasibility of this proposal

cryogenic collimators will be studied as part of FP7 with GSI in Germany

collimation time line

Present view, to be refined in 2009 review:

- **February 2009**: First phase II project decisions. Design work on phase II TCSM ongoing at LARP and CERN. Work on beam test stand at CERN
- **April 2009**: Start of FP7 project on collimation ➔ Start of development for cryogenic collimator and (lower priority) LHC crystal collimator
- **2009-2010**: Laboratory tests on TCSM and cryo collimator prototypes
- **Mid 2010:** Beam test stand available for robustness tests. Safe beam tests with TCSM and cryogenic collimators (catastrophic failure possible)
- **2011**: LHC beam tests of TCSM and cryogenic collimators
- **2011-2012**: Production and installation of phase II collimation upgrade.
- **Mid 2012**: Readiness for nominal and higher intensities from collimation side