upgrade scenarios & parameter space

Frank Zimmermann

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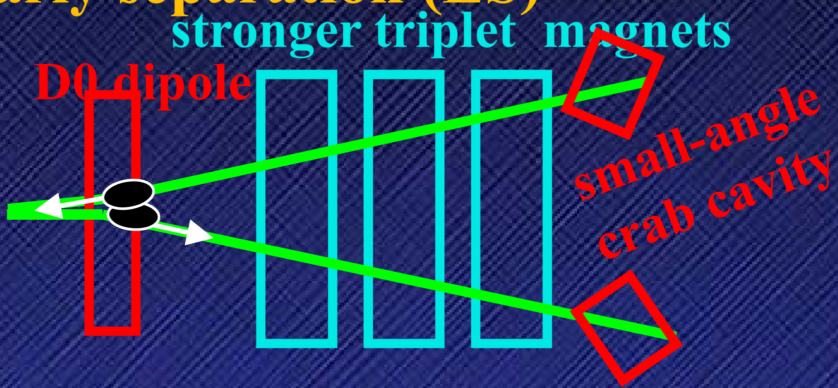
some "phase-2" scenarios

- early separation (ES) [my version]
  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) [my version]
  β^*~0.1 m, 25 ns, $\gamma\varepsilon$~1-2 μm, N_b=1.7x10^{11}

“phase-2” IR layouts

early separation (ES)

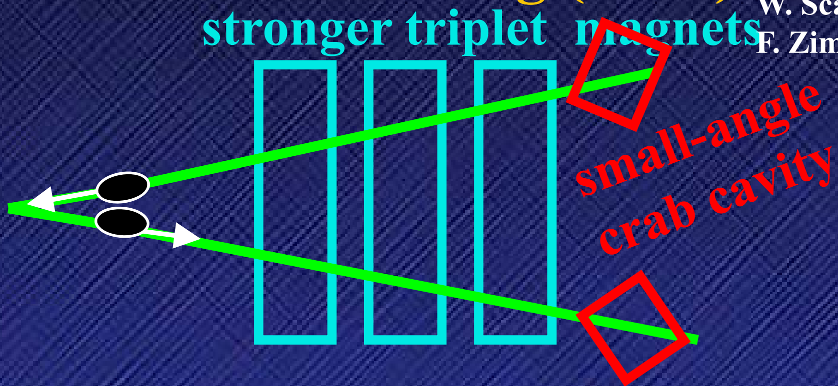
J.-P. Koutchouk



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

full crab crossing (FCC)

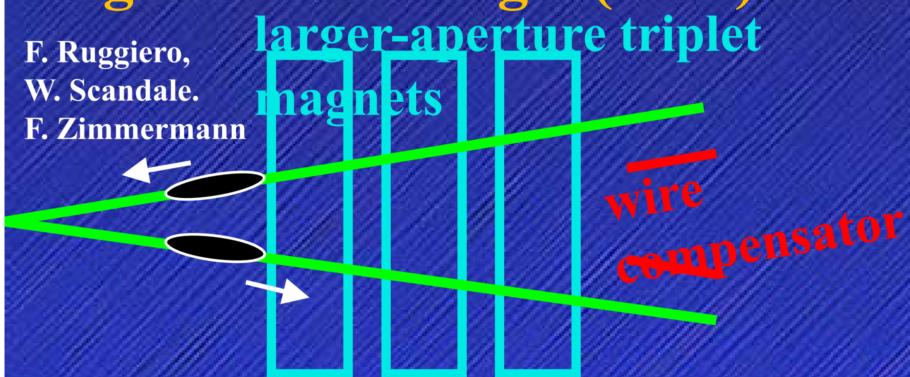
L. Evans,
W. Scandale,
F. Zimmermann



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

large Piwinski angle (LPA)

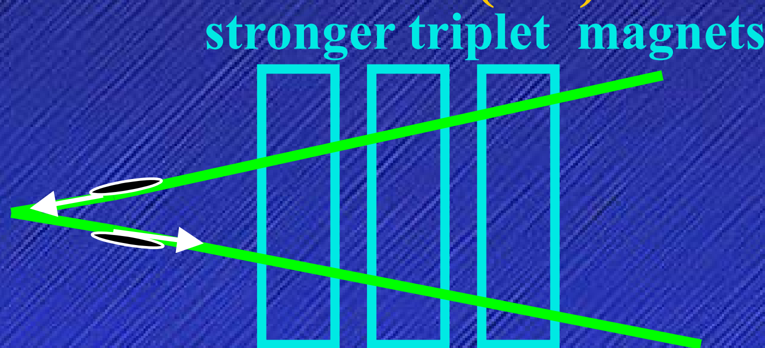
F. Ruggiero,
W. Scandale.
F. Zimmermann



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

low emittance (LE)

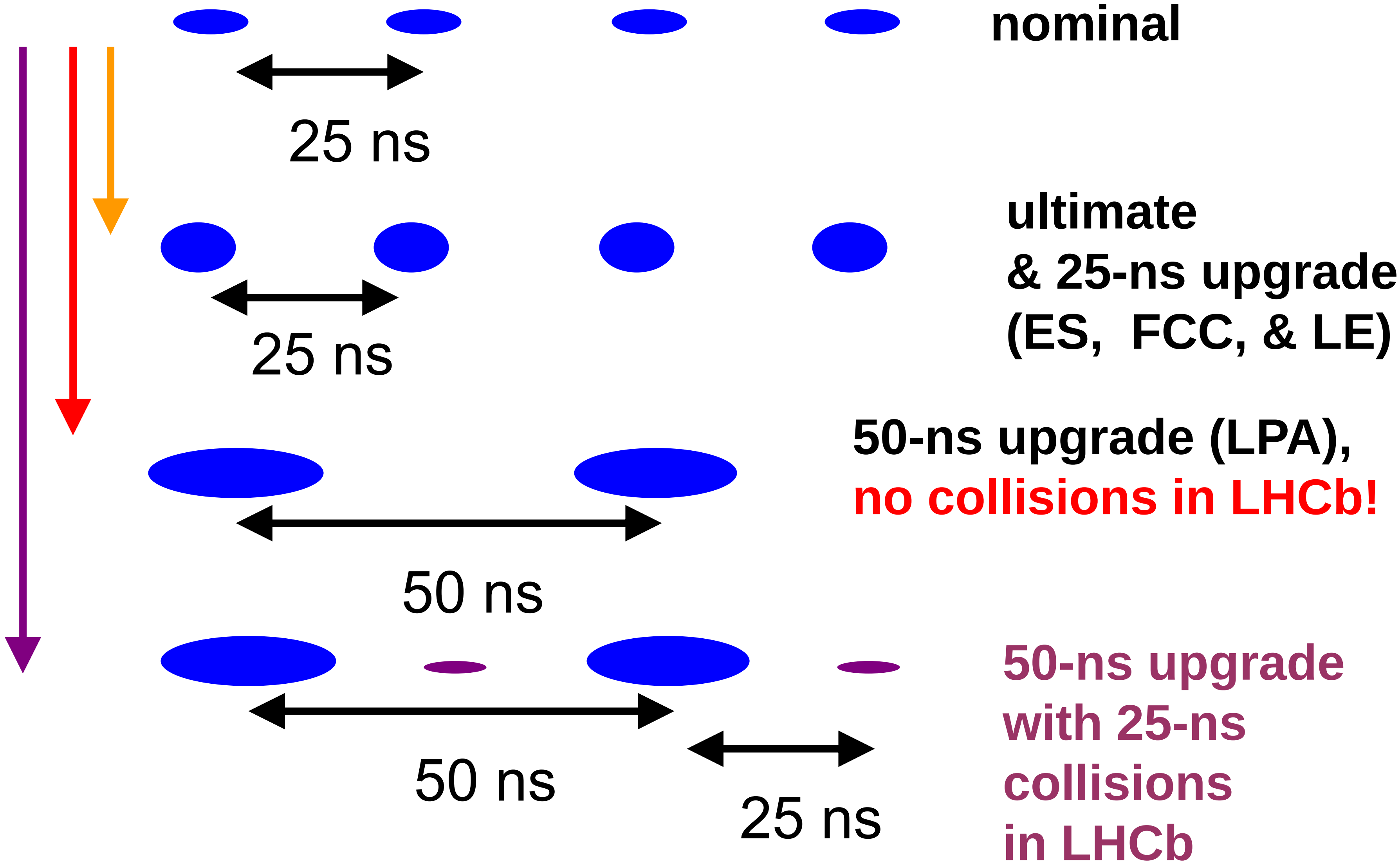
R. Garoby



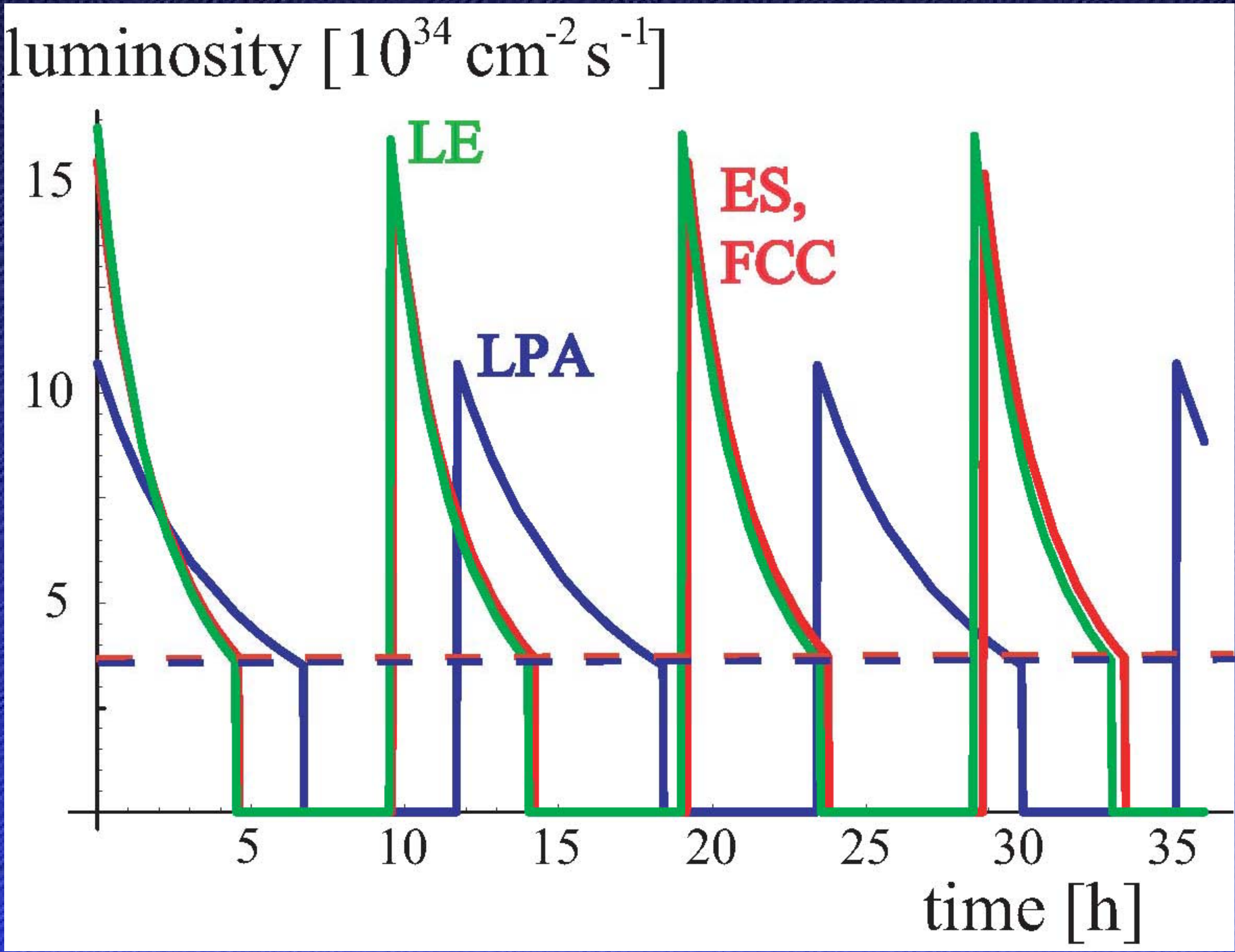
- smaller transverse emittance
  → constraint on new injectors, off-δ β-beat

parameter	symbol	nominal	ultimate	ES	FCC	LE (1)	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**	**1.6**	**5.3**
comment		nominal	ultimate	**D0 + crab**	**crab**		**wire comp.**

upgrade bunch patterns

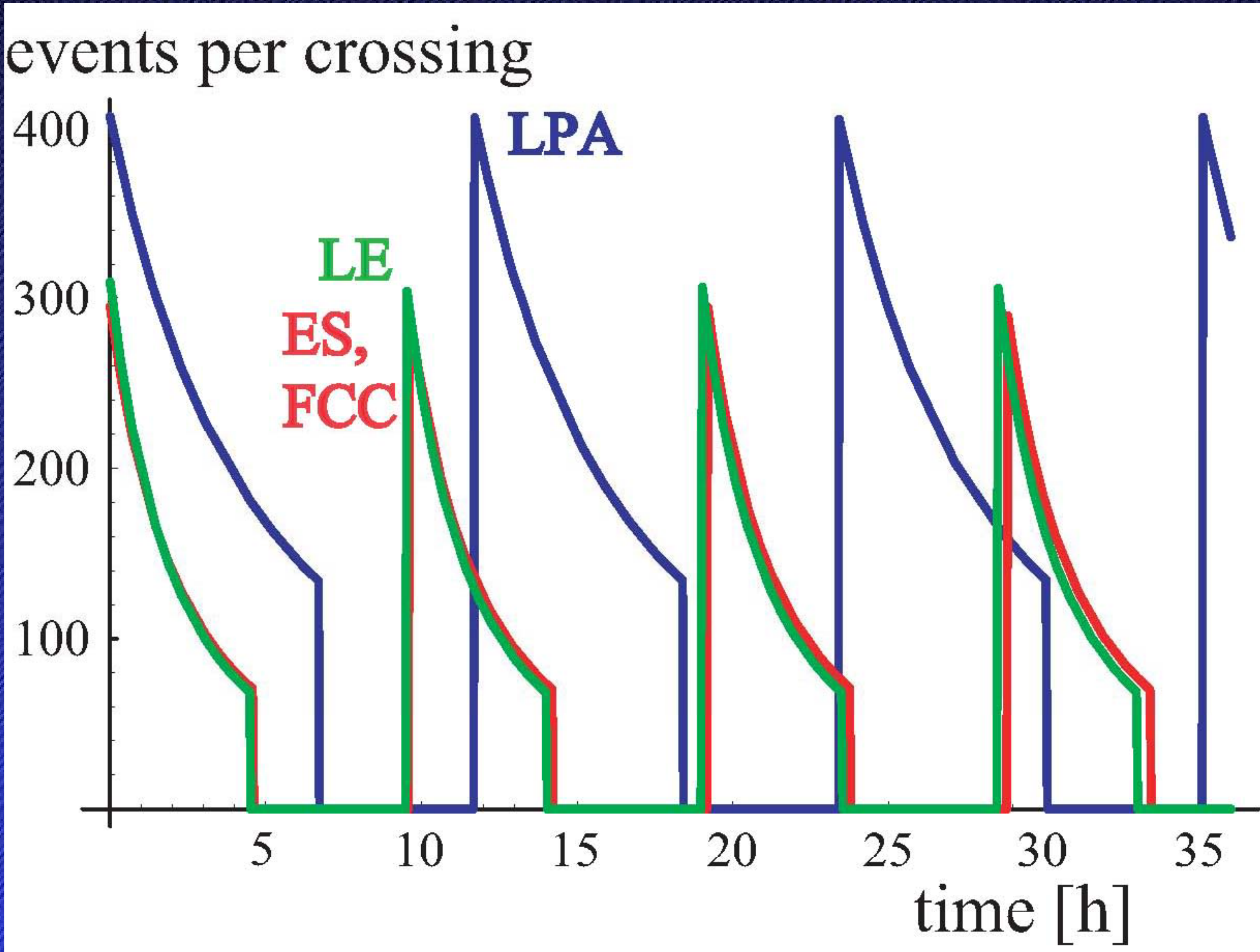


luminosity evolution



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)

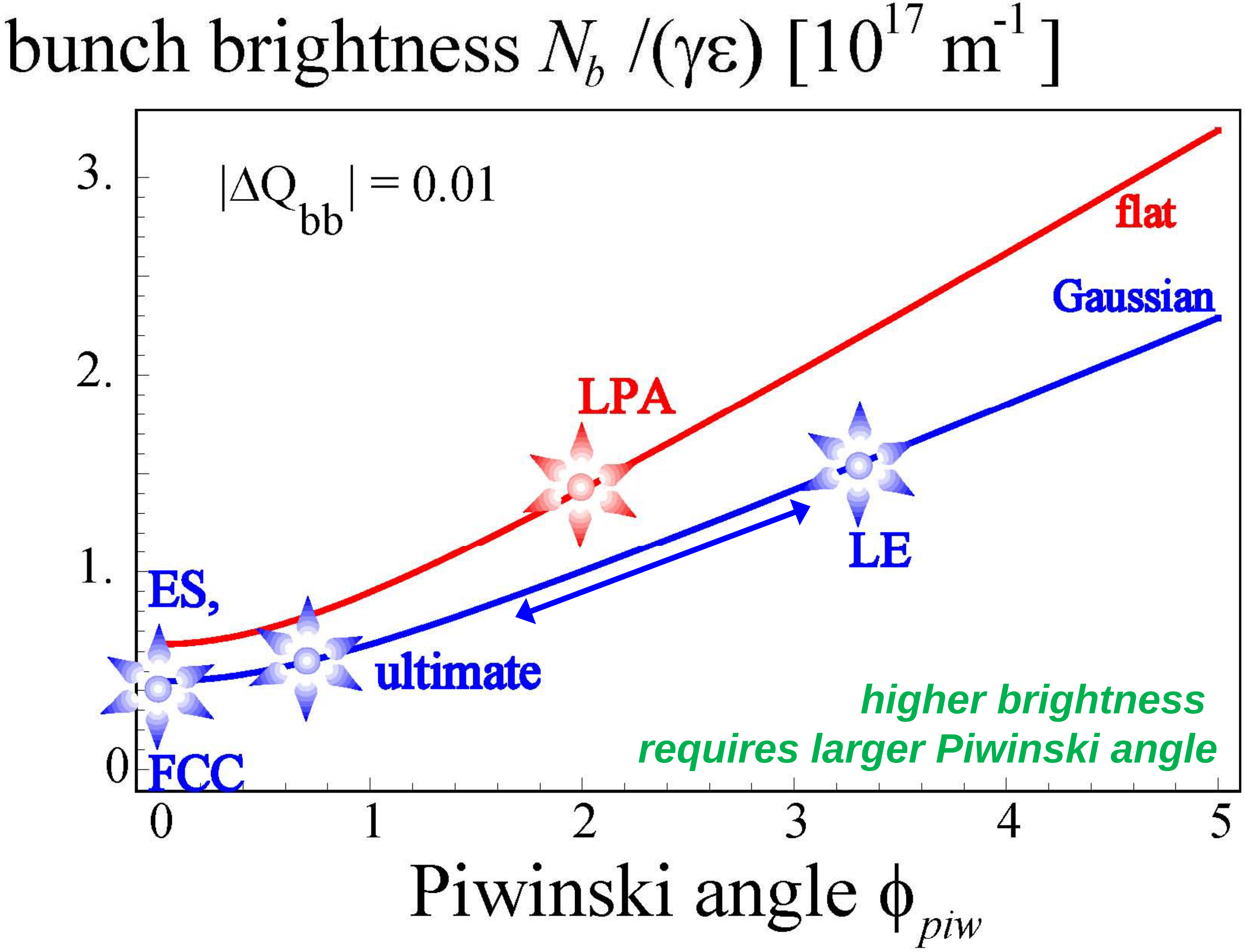
$$L = \frac{1}{4\pi} f_{rev} n_b \gamma \frac{1}{\beta^*(\gamma\varepsilon)} N_b^2 F_{hg} \frac{1}{\sqrt{1+\phi_{piw}^2}}$$

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

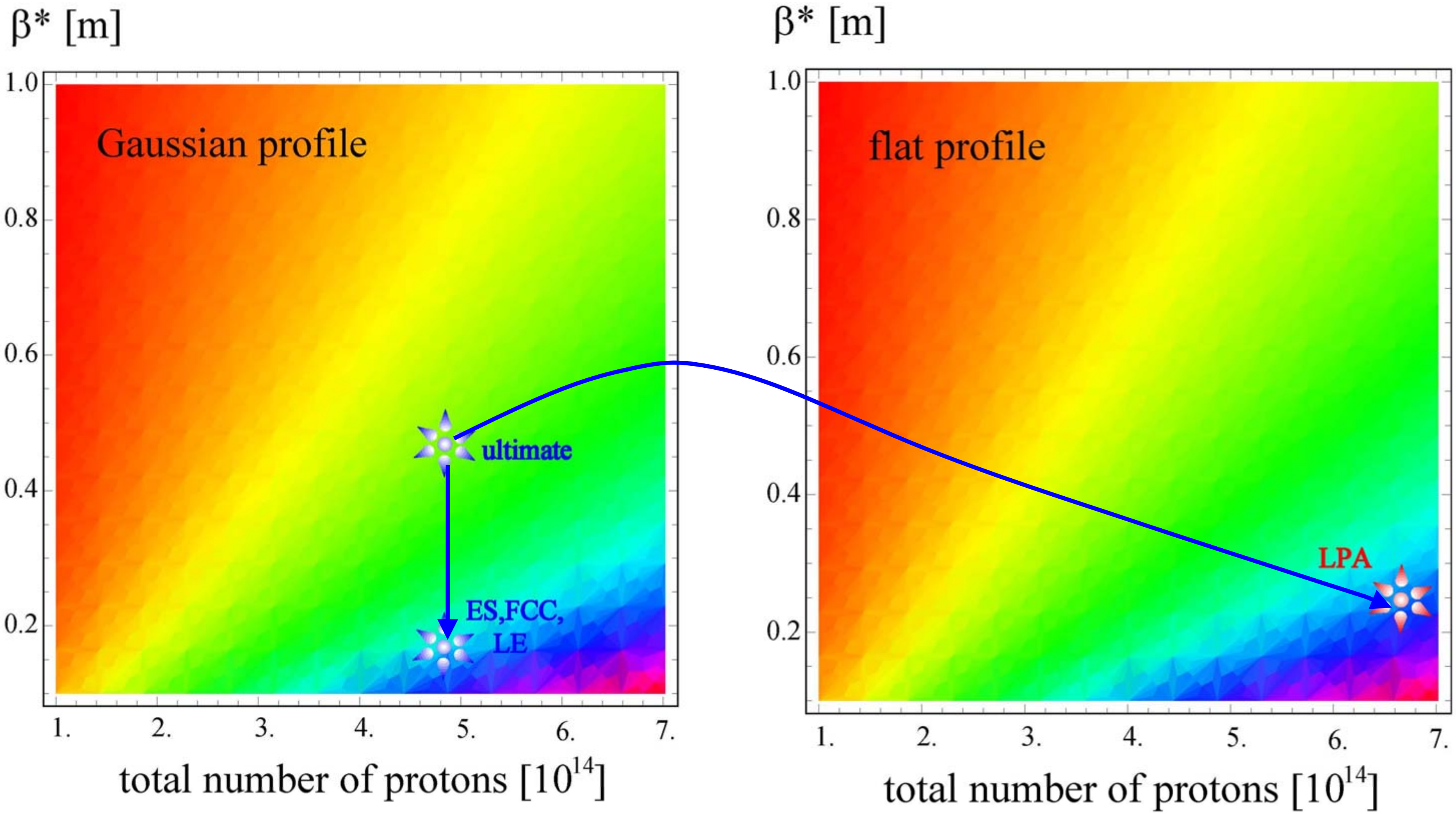
$$= \frac{\pi}{r_p^2} f_{rev} n_b \gamma \frac{(\gamma\varepsilon)}{\beta^*} \Delta Q_{bb}^2 F_{profile}^2 F_{hg} \sqrt{1+\phi_{piw}^2}$$

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

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

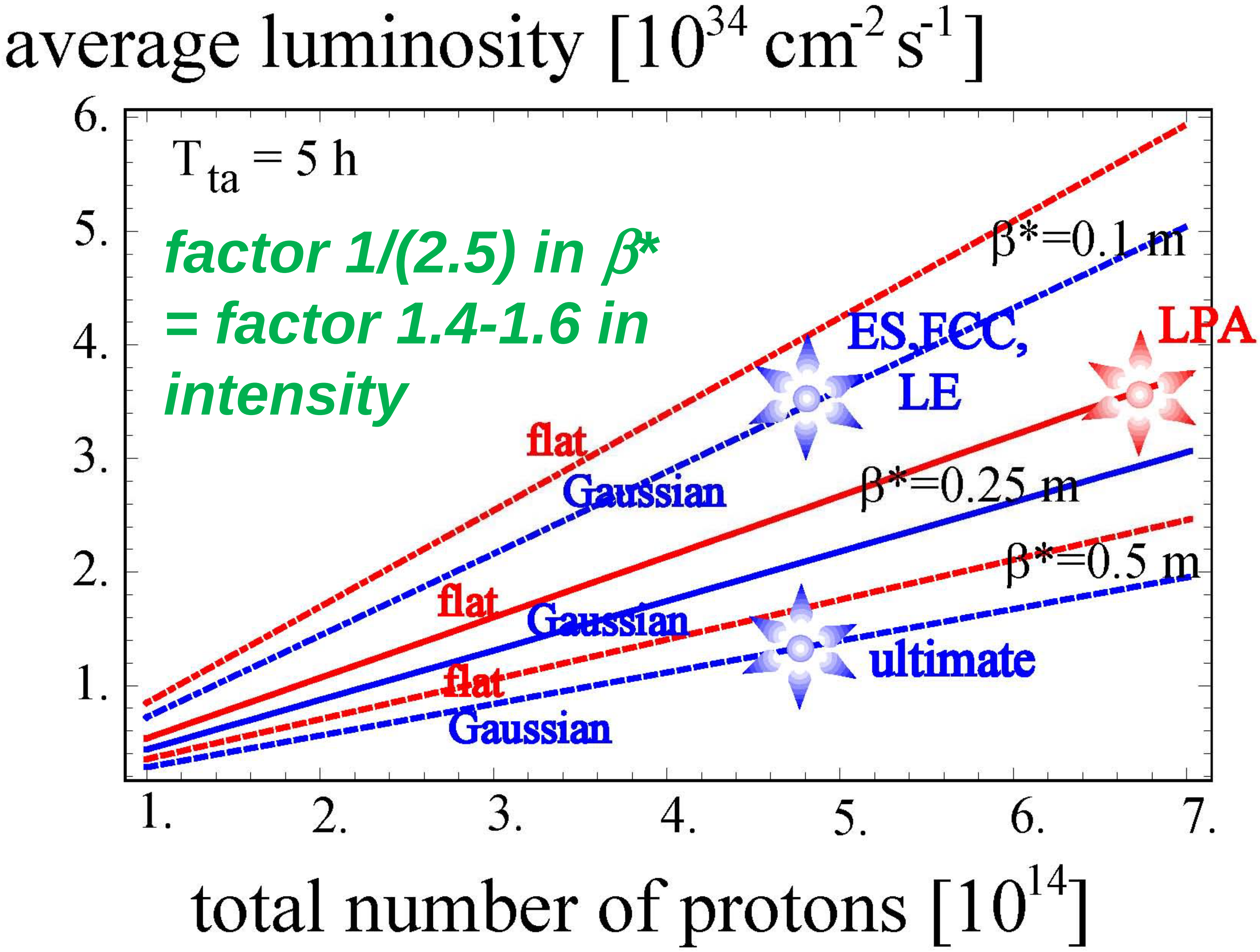


av. luminosity vs #*p*'s & β*



"linear" scale from 10^{33} to $2x10^{35}$ $cm^{-2}s^{-1}$

av. luminosity vs #*p*'s



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?

<u>ES, or FCC:</u> dynamic β squeeze, or dynamic θ change (either IP angle bumps or <u>varying crab voltage</u>); <u>LE:</u> β or θ change;
<u>LPA:</u> 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	$L_{ave} = \hat{L} \frac{\tau_{eff}}{\left(\tau_{eff}^{1/2} + T_{turn-around}^{1/2}\right)^2}$	$L_{ave} = \frac{L_0}{1 + \frac{L_0 \sigma_{tot} n_{IP}}{\Delta N_{\max} n_b} T_{turn-around}}$

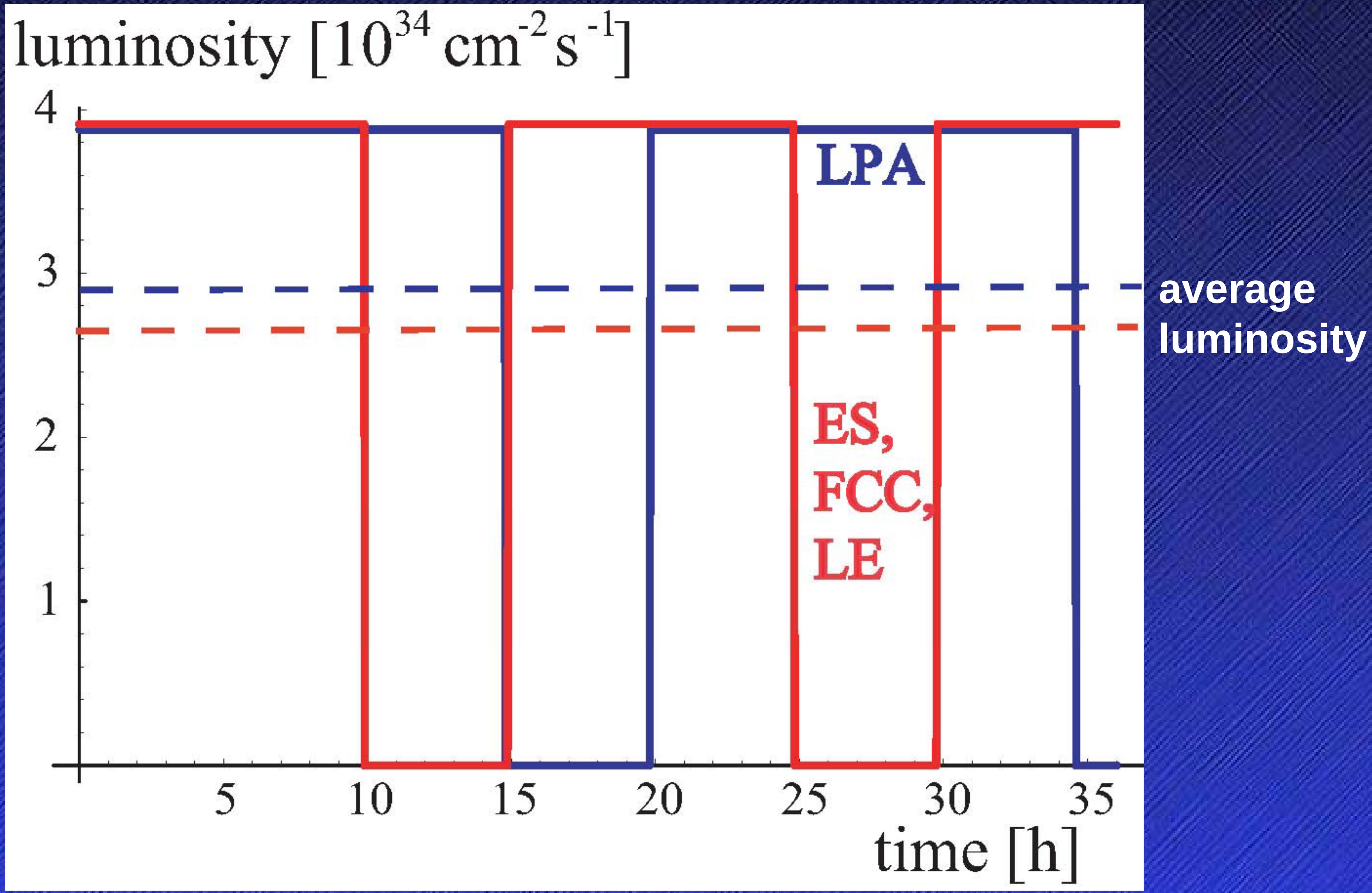
$$\tau_{eff} = \frac{N_0 n_b}{n_{IP} \hat{L} \sigma_{tot}} \qquad \tau_{lev} = \frac{N_0 n_b}{n_{IP} L_0 \sigma_{tot}}$$

luminosity lifetime scales with total # protons!

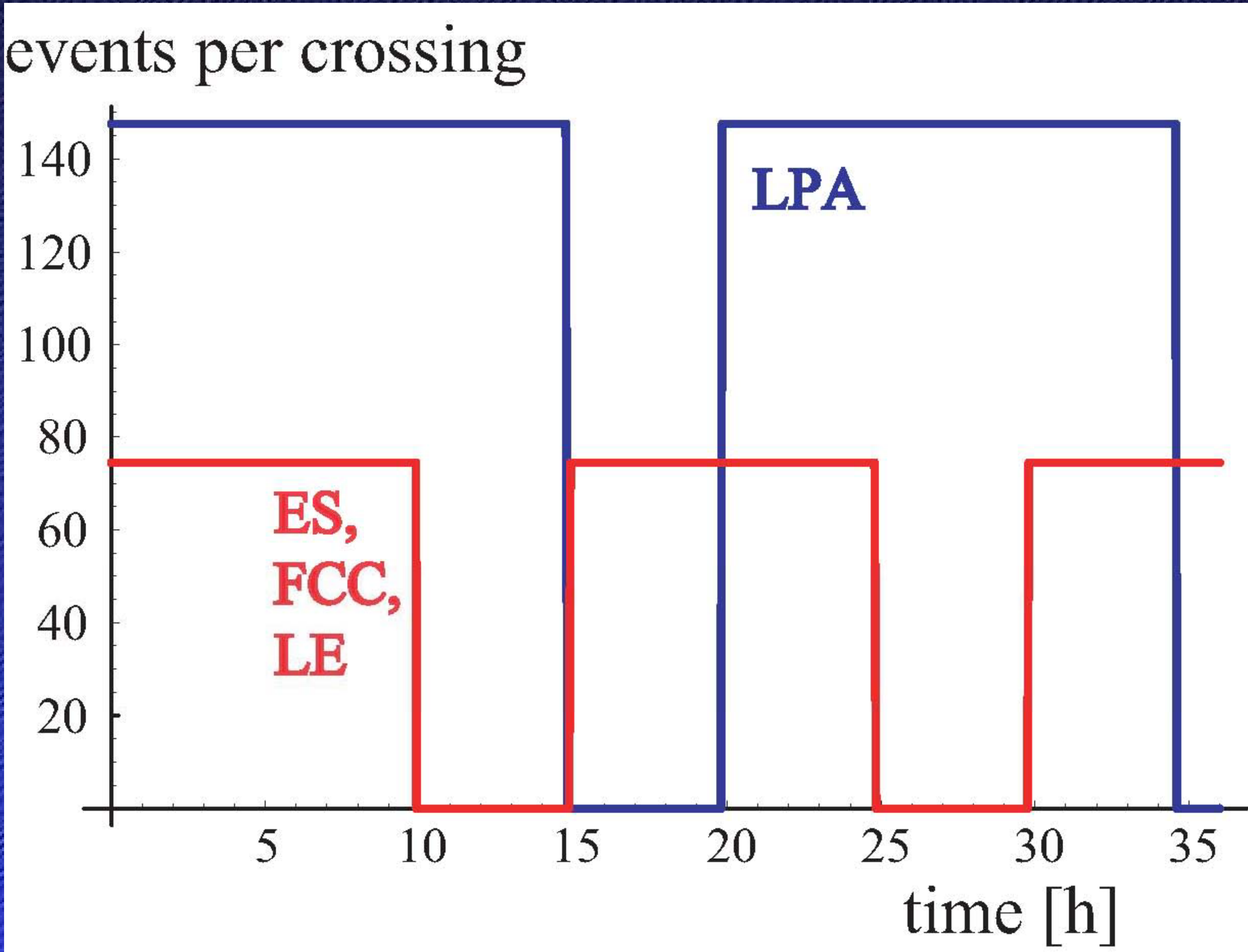
examples	ES, FCC, or LE, with leveling	LPA, with leveling
events/crossing run time av. luminosity	300 N/A N/A	300 2.5 h $2.6x10^{34}s^{-1}cm^{-2}$
events/crossing run time av. luminosity	150 2.5 h $2.6x10^{34}s^{-1}cm^{-2}$	150 14.8 h $2.9x10^{34}s^{-1}cm^{-2}$
events/crossing run time av. luminosity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

assuming 5 h turn-around time

luminosity with leveling



event pile up with leveling



(no) experience with leveling in Tevatron Run-II

- Typical luminosity variation during store is 5-6 times
- Any luminosity leveling would affect the luminosity integral
- CDF and D0 can operate at present maximum luminosity
  - Maximum number of collisions per crossing ~10 (σ=60 mb, $L=2.9\cdot10^{32}$)

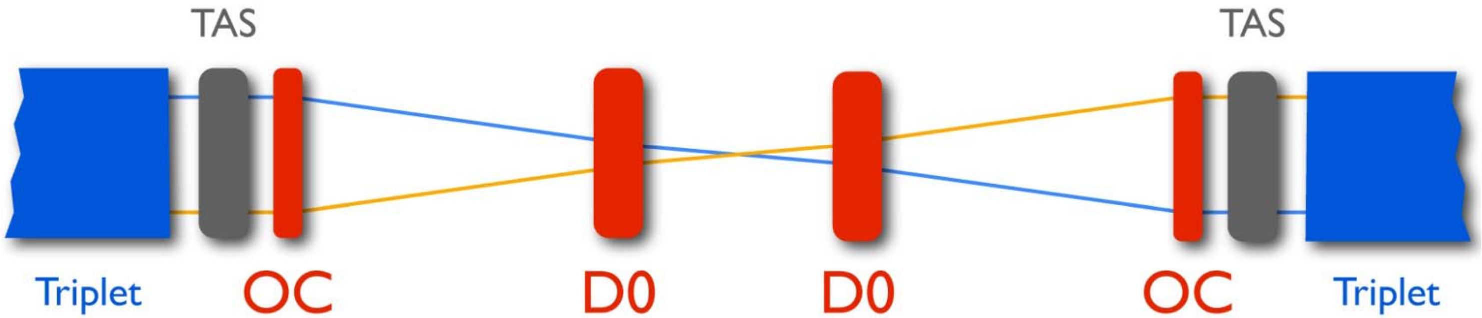
V. Lebedev, CARE-HHH BEAM'07

- Leveling with β^* was never tried at Tevatron
  - Nevertheless the accumulated experience supports one or few steps leveling. Time required for beam manipulations is small relative to the store time and will not affect the average luminosity
- Even the single step β^* leveling allows one to reduce the peak luminosity by ~2 times with only ~15-20% loss in the average luminosity
- Tevatron experience does not support continues (smooth) β^* change
  - The main limitation is the required commissioning time

more comments on the four upgrade schemes

Early Separation

J.-P. Koutchouk,
G. Sterbini et al.



magnets in front of calorimeters ruled out

D0 at ~14 m from IP retained as option (*HHH-2008*)

integrated field of **~13T-m** required for D0 at 14 m

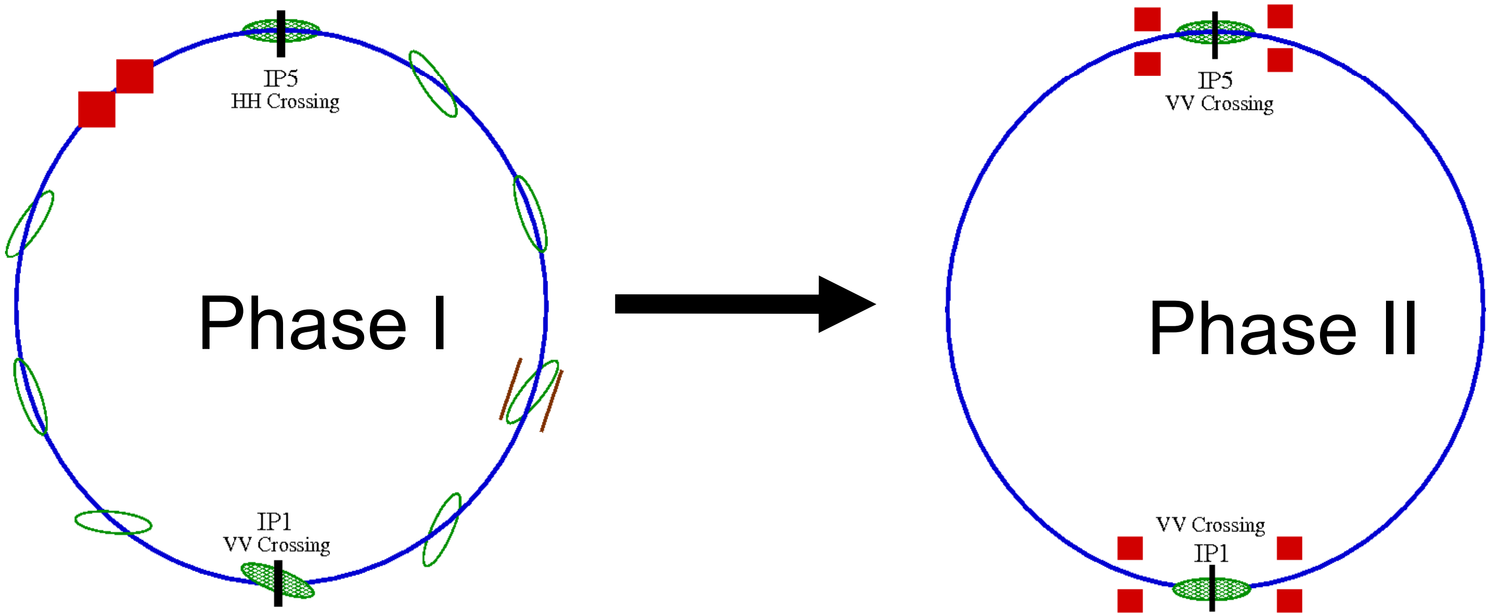
peak luminosity gain ~30-60% for β^*=0.15 m depending on minimum acceptable beam-beam separation between the D0's (7 or 5σ)

heat load can be a problem (also effect of CMS solenoid, impact on background,…)

Crab Cavities – Phases

R. Calaga

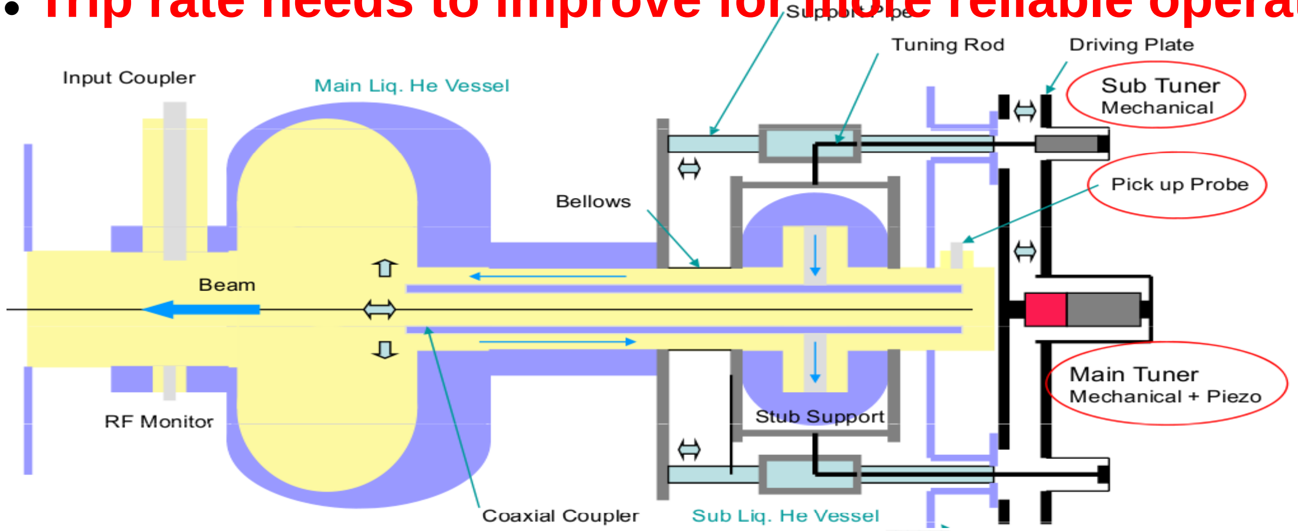
- **Phase I:**
  - **Test prototype – one cavity/beam (@IR4, 2013)**
  - **Feasibility of crab crossing in hadron machine, superconducting RF limits in deflecting mode, collimation, impedance**
  - **Operations - Cryogenics, operation at injection/ramp/top energies, luminosity gain and leveling, emittance growth**
- **Phase II:**
  - **Complete IR redesign (IR1 & 5) with crab crossing optics (2017/18?)**
  - **Perhaps need for special compact cavities due to space constraints**



Crab Cavities: KEK-B Test Bed

R. Calaga

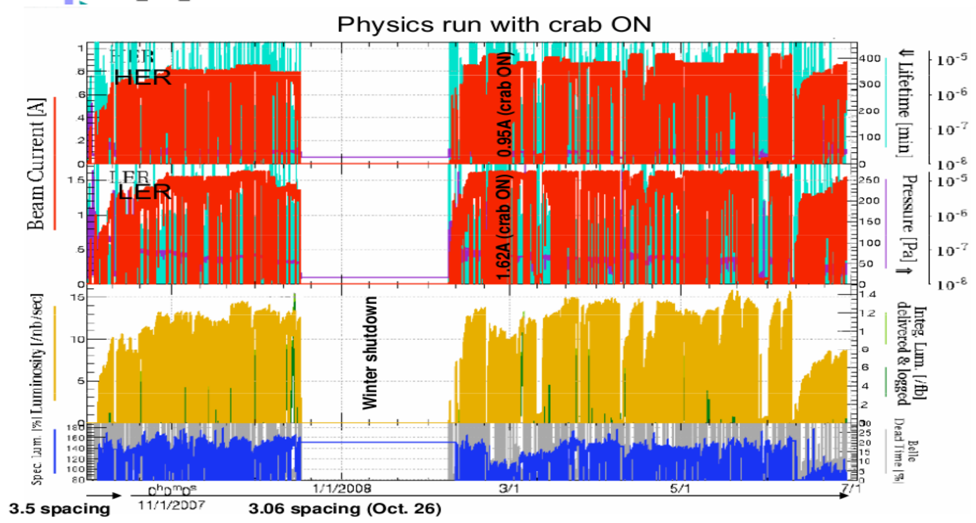
- **No serious instabilities at high currents (1.62/0.9 A) w. crab cavities**
- **Similar luminosity as before at ~30% lower beam current**
- **Trip rate needs to improve for more reliable operation**



Y. Morita et al (KEK-B)

KEK-B experiments will probe many LHC related concerns (Dec 08, Spring 09):

KEK-CERN crab collaboration



Crab Cavities: Motivations

R. Calaga

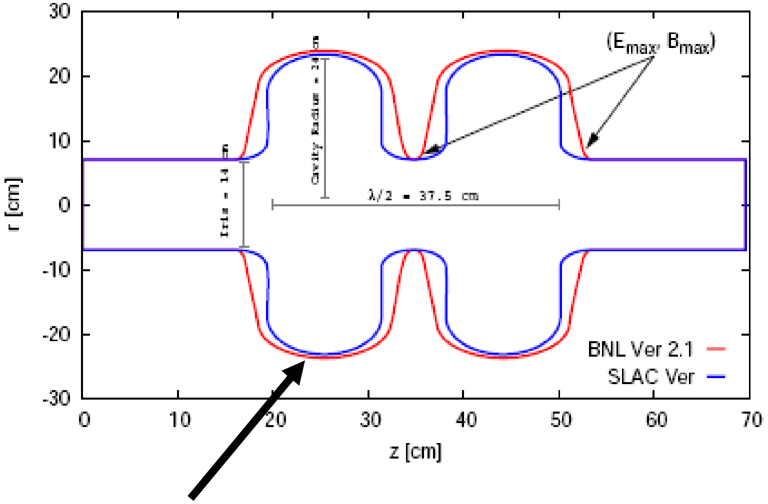
- ~ 50% or more **luminosity gain** for β^*=25 cm or smaller
- natural **luminosity leveling** knob, explore beyond the BB limit
- **global interest** in crab cavity technology, exploit synergies

& Challenges:

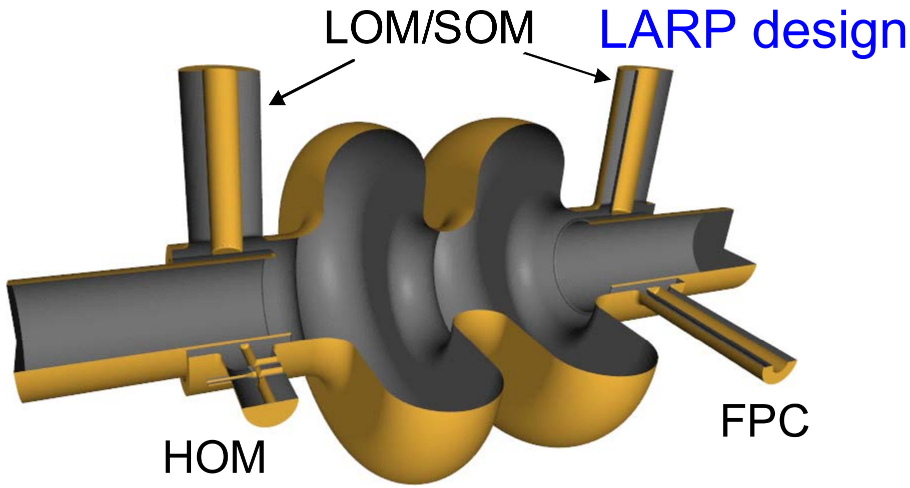
- **separation between two beams** (**190 mm** in most of LHC)
- bunch length, 7.55 cm (800 MHz maximum)
- **constraints** from collimation/machine protection

Prototype: Cavity & Couplers

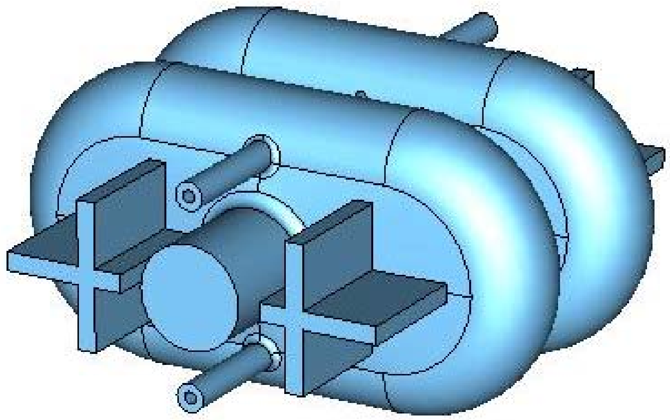
R. Calaga

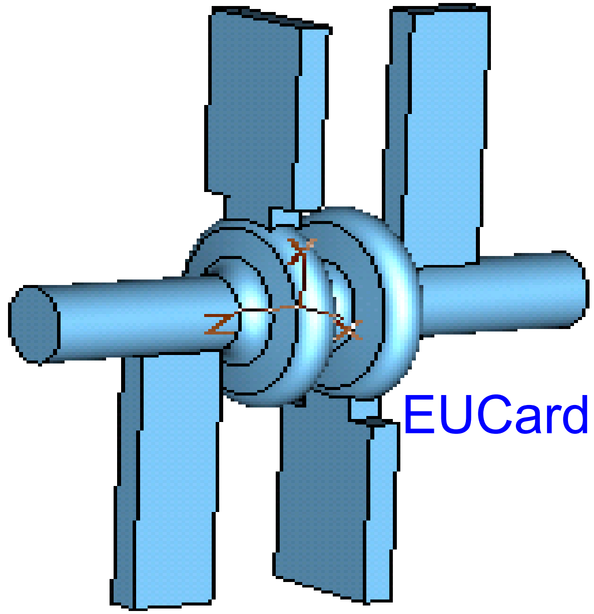


Note the cavity radius ~ 23 cm



Super-KEKB type design



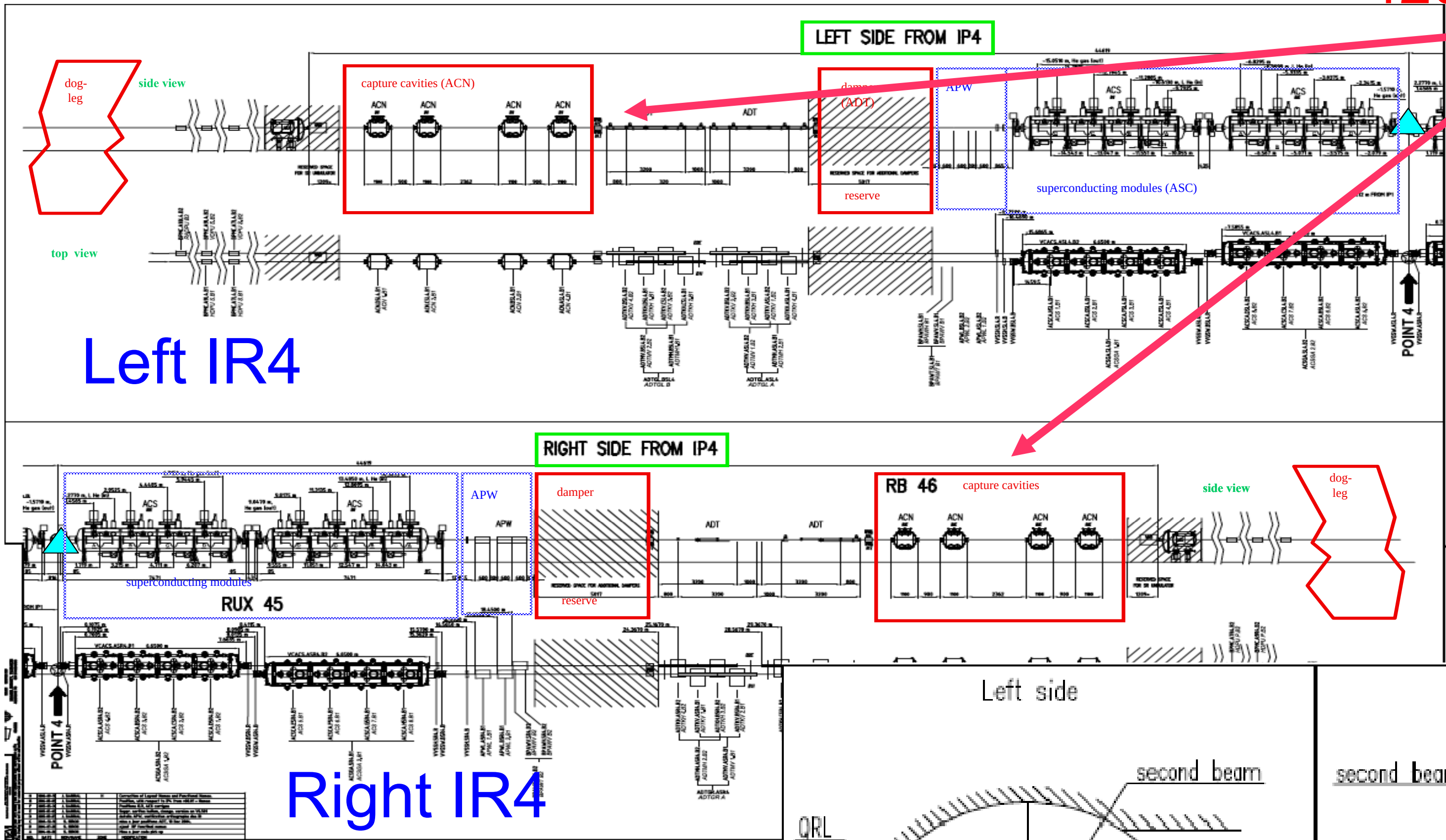


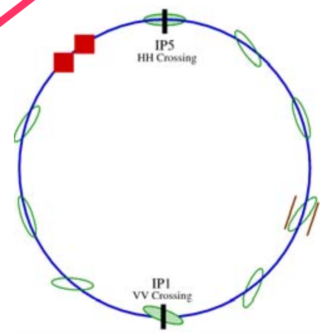
** Down-Selection within 1yr

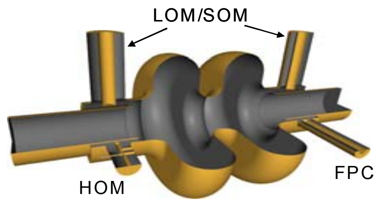
Prototype: IR4 & Cryostat

Potential Locations

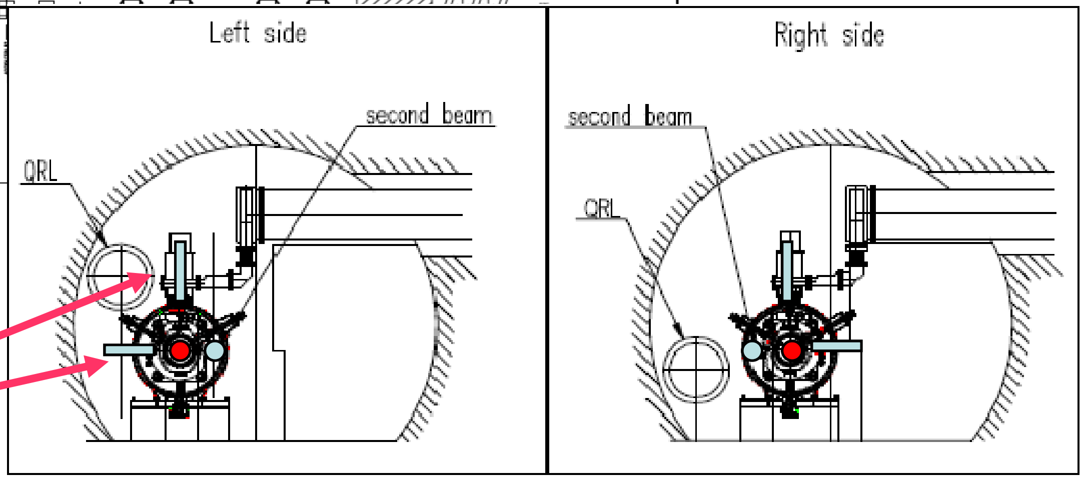
420 mm separation







N. Solyak et al, (FNAL)



FPC & HOM Couplers

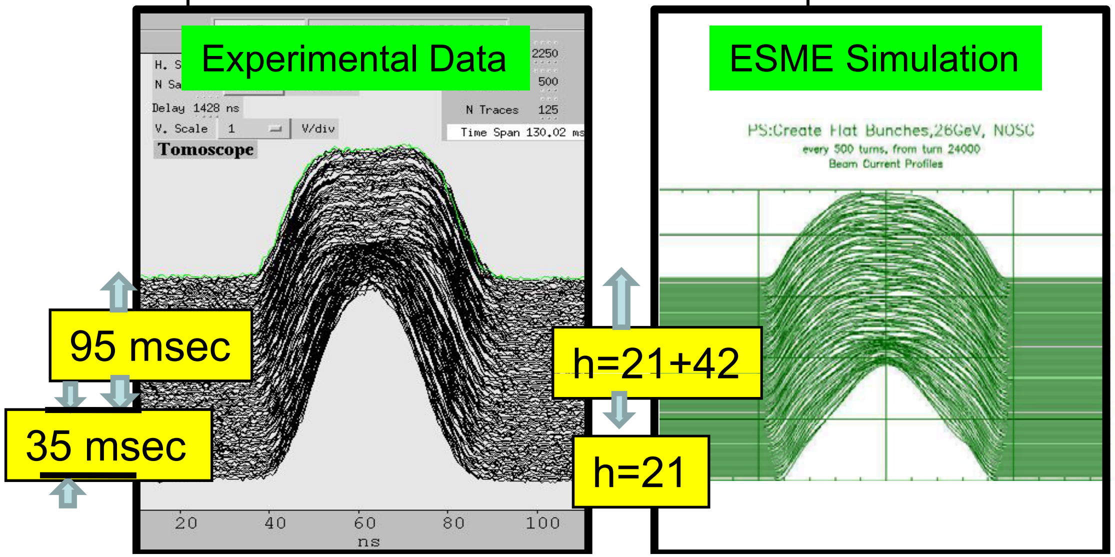
Tunnel cross-section

“large Piwinski angle” (LPA)

generation & stability of 50-ns long flat intense bunches

R. Garoby *CARE-HHH* *BEAM’07*	**If SPS can accelerate 6×10^{11} p/b (ε_L~0.7 eVs)**	**If SPS <u>cannot</u> accelerate 6×10^{11} p/b (ε_L~0.7 eVs)**
“Best” choice	**Generate beam in PS2 at capture [PS2/1]**	Slip stacking at high energy [SPS/4] ?
“Alternative” choice	Generate beam in PS2 by merging [PS2/2]	?
Other (new) ideas	?	?

SPS may be bottleneck!



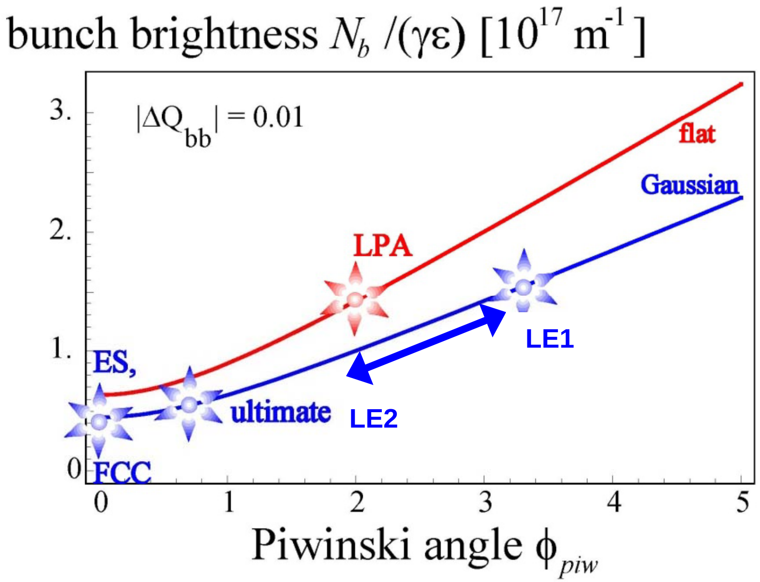
studies of flat-bunch generation in the CERN PS, C. Bhat (FNAL), 2008

HHH-LARP collaboration

low emittance (LE) schemes

parameter	symbol	LE 1	LE 2
transverse emittance	ε [μm]	1.0	2.6
protons per bunch	N_b [10^{11}]	1.7	2.36
beam current	I [A]	0.86	1.19
beta* at IP1&5	β* [m]	0.1	0.15
full crossing angle	θ_c [μrad]	311	322
Piwinski parameter	$\phi=\theta_c\sigma_z/(2^*\sigma_x^*)$	3.2	1.7
geometric reduction		0.30	0.51
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	16.3	13.2
peak events per #ing		309	250
initial lumi lifetime	τ_L [h]	2.0	2.5
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	2.5	2.7
	$T_{run,opt}$ [h]	6.4	8.4
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	3.7	3.9
	$T_{run,opt}$ [h]	4.5	5.9
e-c heat SEY=1.4(1.3)	P [W/m]	1.0 (0.6)	~1.6 (1.1)
SR heat load 4.6-20 K	P_{SR} [W/m]	0.25	0.35
image current heat	P_{IC} [W/m]	0.33	0.64
gas-s. 100 h (10 h) τ_b	P_{gas} [W/m]	0.06 (0.6)	0.08 (0.8)
extent luminous region	σ_l [cm]	1.5	2.8

trade off
intensity vs. emittance



smaller brightness is easier for injectors, but it comes together with higher bunch charge, higher heat load etc.

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

appendix:

more details on collimation constraints

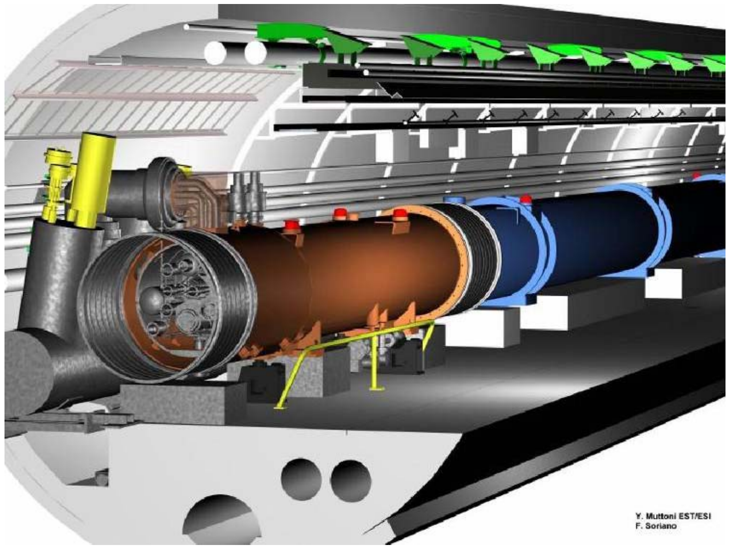
collimation – quench prevention

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

500 kW

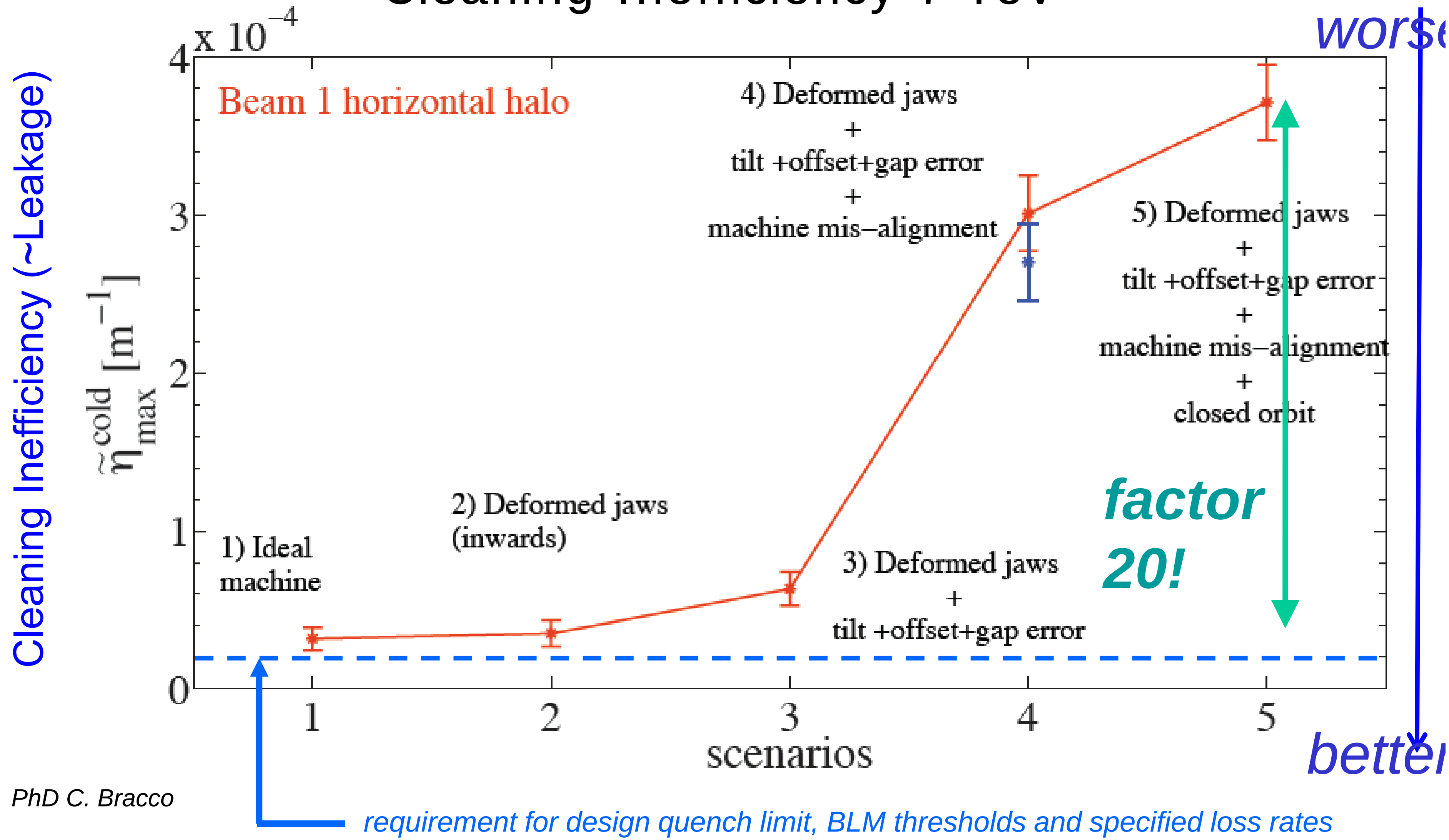
Quench limit of SC LHC magnet:

8.5 W/m



collimation performance

- Cleaning Inefficiency 7 TeV -

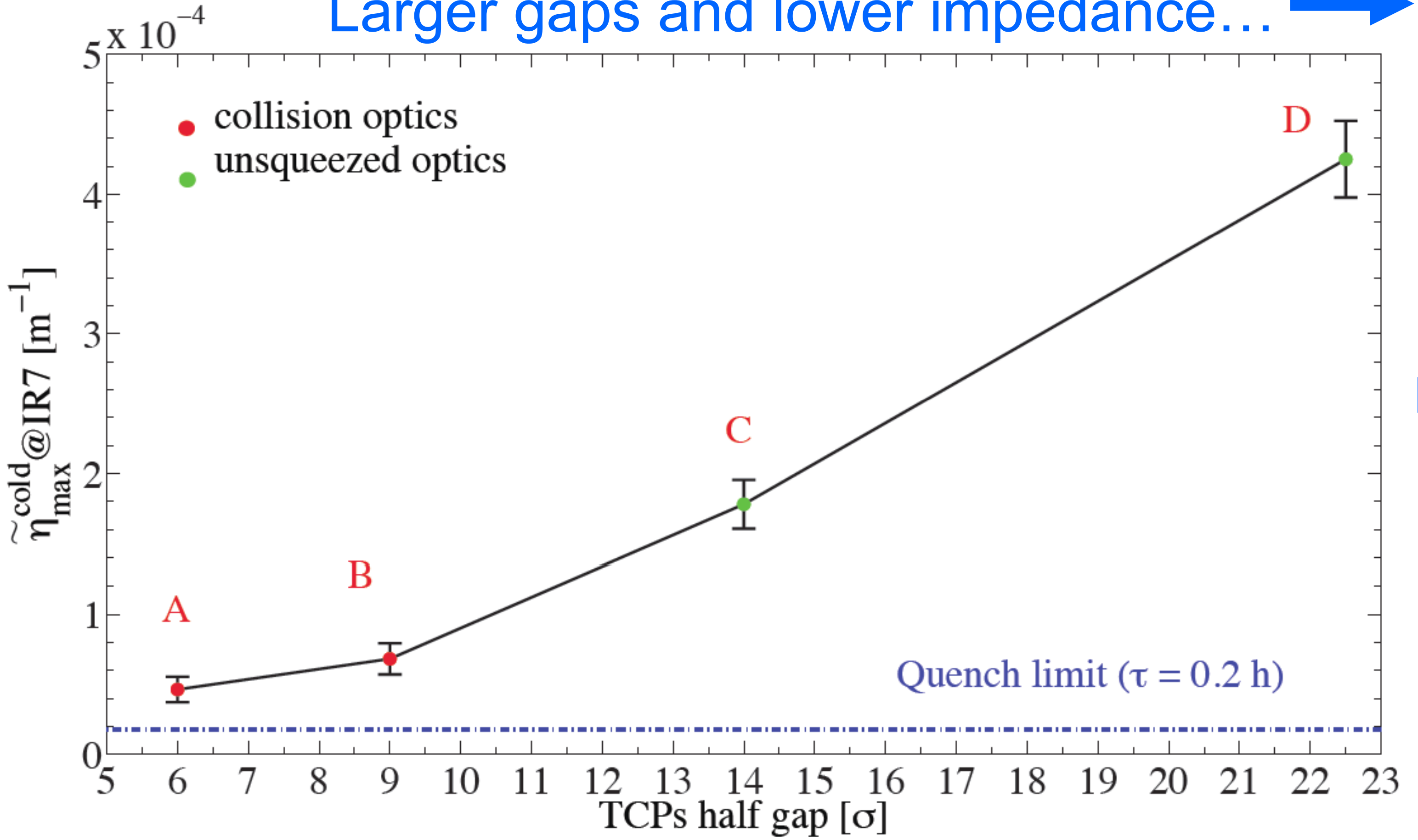


R. Assmann - HHH 2008

limit: about 5% of nominal!

collimation performance II

Larger gaps and lower impedance…



Higher inefficiency, less cleaning performance

PhD C. Bracco

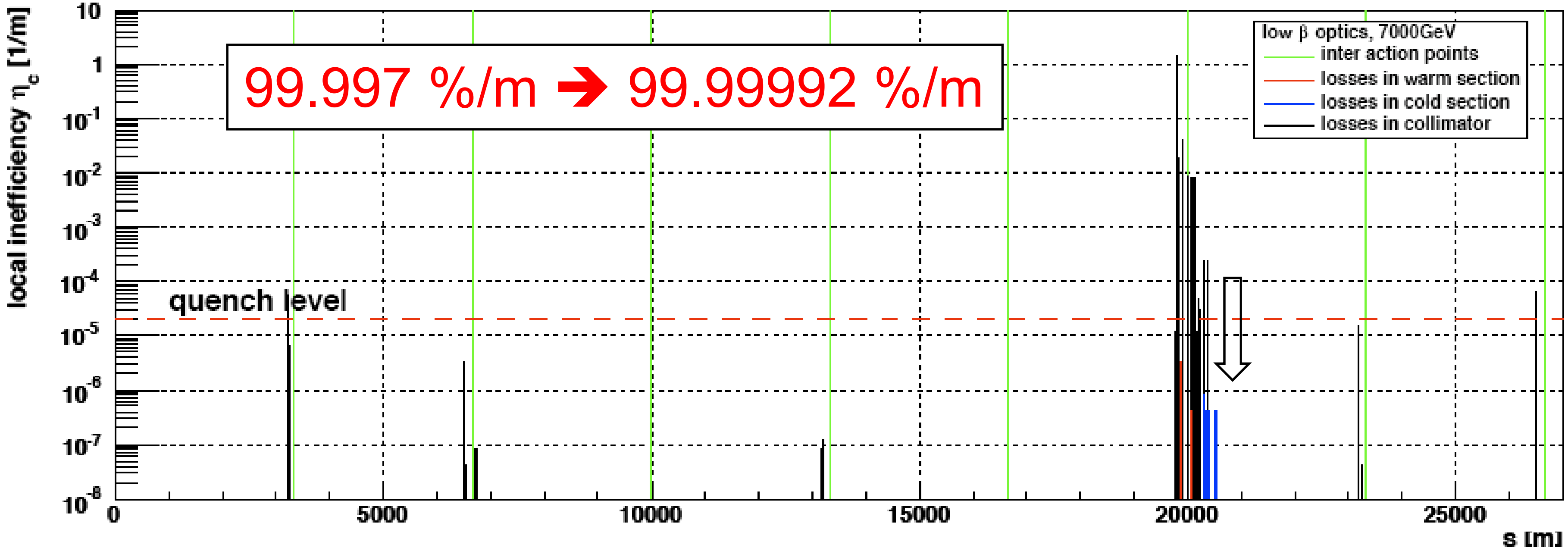
➔ **Phase I IR upgrade will not improve intensity limit from phase I collimation!**

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 (→ ***nominal/ultimate intensity!***)

caution: further studies must show feasibility of this proposal

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