Nominal LHC parameters

The nominal LHC peak luminosity $L = 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ corresponds to a nominal bunch spacing of 25 ns and to $\beta^* = 0.5$ m, full crossing angle $\theta_\mathrm{c} = 300\,\mu$rad, and bunch population $N_\mathrm{b} = 1.1 \times 10^{11}$.

At Chamonix 2003 I have presented a revision of these parameters to partially recover previous operational margins, compatible with a primary collimator aperture $n_1 > 6\,\sigma$, in connection with a 1 mm reduction of the available mechanical aperture at the triplet magnets (see 21st and 29th LCC meetings).

The LTC should either validate these revised parameters or discuss possible alternatives, including reduced operational margins and/or a reduced nominal machine performance $\Longrightarrow$ we are talking of SMALL changes

Parameter	Units	75 ns spacing	25 ns spacing	nominal
number of bunches	k_b	936	2808	2808
protons per bunch	N_b [10^{11}]	0.9	0.4	1.15
norm. tr. emittance	ε_n [μm]	3.75	3.75	3.75
r.m.s. bunch length	σ_s [cm]	7.55	7.55	7.55
r.m.s. energy spread	σ_E [10^{-4}]	1.13	1.13	1.13
IBS growth time	τ_x^{IBS} [h]	135	304	106
beta at IP	β^* [m]	1.0	0.55	0.55
full crossing angle	θ_c [μrad]	250	285	285
luminosity lifetime	τ_L [h]	22	26	15
peak luminosity	L [10^{34} cm^{-2} s^{-1}]	0.12	0.12	1.0
events/crossing		7.1	2.3	19.2
lumi over 200 fills	L_int [fb^{-1}]	9.3	9.5	66.2

Possible scenarios discussed at Chamonix 2003 with 75 ns and 25 ns bunch spacing for an early luminosity run and revised nominal LHC parameters.

To compensate the aperture reduction at Q2 and recover previous operational margins, we can increase β^* and reduce the crossing angle $\theta_{\rm c}$ at constant relative beam separation:

$$\theta_{\rm c} \simeq 10\,\sigma_\theta = 10\sqrt{\frac{\varepsilon}{\beta^*}} \quad \Longrightarrow \quad \frac{\Delta\theta_{\rm c}}{\theta_{\rm c}} = -\frac{1}{2}\,\frac{\Delta\beta^*}{\beta^*}.$$

$\hat{x} \simeq \ell^*\,\theta_{\rm c}$ transverse beam offset at Q2

$\hat{\sigma} = \sqrt{\epsilon \times \hat{\beta}} \simeq \ell^* \sqrt{\frac{\epsilon}{\beta^*}}$ r.m.s. transverse beam size at Q2

$$\Longrightarrow \quad \frac{\Delta\hat{x}}{\hat{x}} = \frac{\Delta\hat{\sigma}}{\hat{\sigma}} = -\frac{1}{2}\,\frac{\Delta\beta^*}{\beta^*}$$

With nominal LHC parameters, $\hat{x} = 8\,\mathrm{mm}$ and $\hat{\sigma} = 1.6\,\mathrm{mm}$.

The tertiary beam halo extends to a betatron amplitude $n_\mathrm{r} \simeq 1.4\, n_1$, larger than the aperture $n_1 \simeq 6\,\sigma$ of the primary collimators.
To compensate the 1 mm aperture reduction at Q2 we require

$$-\Delta(\hat{x} + 1.4 \times 6\,\hat{\sigma}) = 1\,\mathrm{mm} = \frac{1}{2}\,\frac{\Delta\beta^*}{\beta^*}\,(\hat{x} + 1.4 \times 6\,\hat{\sigma}),$$

and thus

$$\frac{\Delta\beta^*}{\beta^*} = -2\,\frac{\Delta\theta_\mathrm{c}}{\theta_\mathrm{c}} = \frac{2}{8 + 8.4 \times 1.6} \simeq 10\%.$$

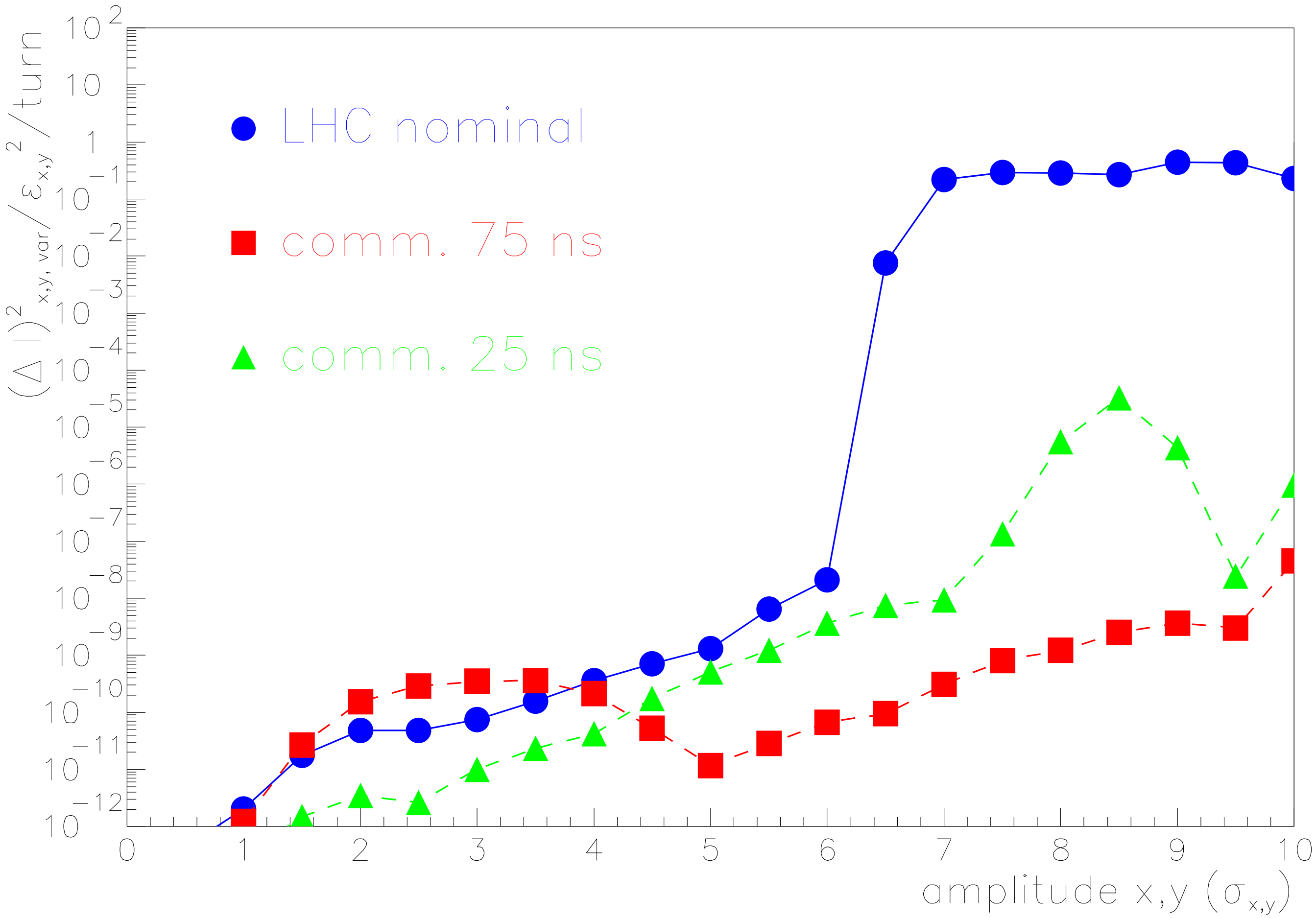
Therefore the revised nominal LHC parameters become

$$\text{old } \beta^* = 0.5\,\mathrm{m} \quad \Longrightarrow \quad \text{new } \beta^* = 0.55\,\mathrm{m},$$

$$\text{old } \theta_\mathrm{c} = 300\,\mu\mathrm{rad} \quad \Longrightarrow \quad \text{new } \theta_\mathrm{c} = 285\,\mu\mathrm{rad},$$

and to recover the nominal LHC luminosity:

$$\text{old } N_\mathrm{b} = 1.1 \times 10^{11} \quad \Longrightarrow \quad \text{new } N_\mathrm{b} = 1.15 \times 10^{11}.$$



LHC diffusive aperture from parasitic beam-beam encounters for 25 ns bunch spacing with new nominal crossing angle and nominal intensity (solid blue), commissioning intensity (dashed green) and 75 ns spacing with reduced crossing angle of 250 μrad (dashed red) (F. Zimmermann).

Operational margins and mechanical aperture at Q2

- $\hat{x} = 8\,\mathrm{mm}$, $\hat{\sigma} = 1.6\,\mathrm{mm}$ $\Longrightarrow$ $2 \times 5\,\hat{\sigma}$ beam separation
- $n_1 \simeq 6\,\hat{\sigma}$ $\Longrightarrow$ $n_\mathrm{r} \simeq 8.4\,\hat{\sigma}$ beam envelope
- 3 mm peak orbit excursion
- up to 4 mm additional orbit due to spurious dispersion
  - spurious dispersion at Q2 ranging from 3.5 m to 4.7 m
  - RF bucket momentum aperture $\Delta p/p = 0.36 \times 10^{-3}$
  - additional momentum sweep for static dispersion measurement by RF frequency change $\Delta p/p = 0.5 \times 10^{-3}$
- 1.6 mm mechanical tolerances
- 20% β-beating

Pessimistic 1D estimate of the required aperture at Q2:

$$A_{\rm Q2} > 1.1 \times (5 + 8.4) \cdot \hat{\sigma} + (3 + 4 + 1.6)\,{\rm mm} \simeq 32\,{\rm mm}.$$

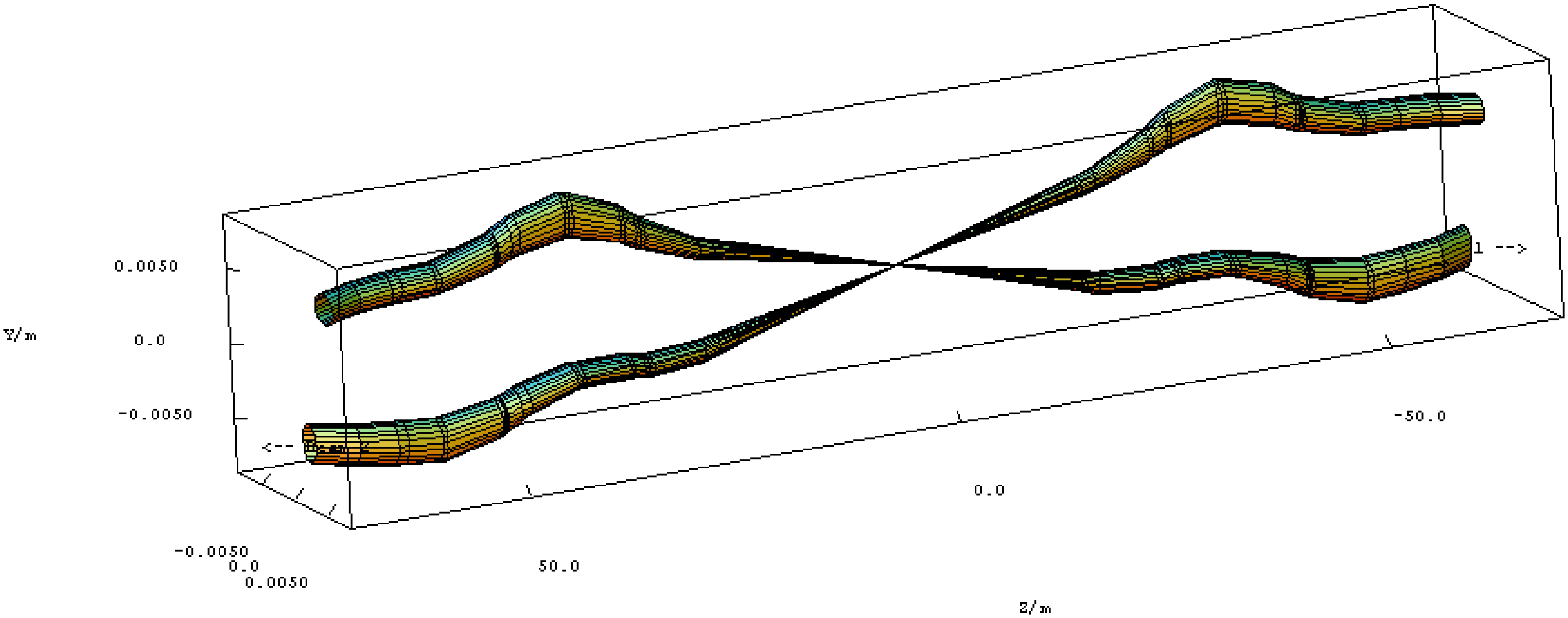
After the introduction of beam screens in the triplets and minor layout changes the available mechanical aperture is $A_{\rm Q2} = 29\,{\rm mm}$.

A more accurate 2D calculation by Stephane Fartoukh for nominal $\beta^* = 0.5\,{\rm m}$ and $\theta_{\rm c} = 300\,\mu{\rm rad}$ yields an equivalent n_1 aperture of $5.8\,\sigma$.

Alternative possibilities

1. adopt revised nominal LHC parameters to recover 1 mm aperture loss at Q2 $\Longrightarrow$ n_1 aperture would be increased by about $0.5\,\sigma$
2. increase β^* but not N_b $\Longrightarrow$ no impact on the LHC injectors
3. leave nominal parameters unchanged and reduce operational margins:
   - give up measuring dispersion with two squeezed beams or use PLL and RF modulation to reduce required $\Delta p/p$ down to 0.1×10^{-3} $\Longrightarrow$ reduced total $\Delta p/p = 0.86 \to 0.46 \times 10^{-3}$ gives almost 2 mm aperture gain from orbit due to spurious dispersion
   - give up 20% tolerance on β-beating (once β^* is properly adjusted)? $\Longrightarrow$ β-beating and c.o. already optimistic for end-of-squeeze
   - accept to live with $n_1 < 6\,\sigma \Longrightarrow$ background/lifetime problems?
4. offset Q2 magnets to optimize available aperture for the TWO beams $\Longrightarrow$ up to 0.25 mm aperture gain? Probably still marginal for n_1.

LHC beam envelopes at IR1



Beam separation and 3D envelopes ($1\,\sigma$) around IP1 for LHC version 6.4 collision optics (courtesy John Jowett).