Parameters and tolerances

presented by Massimo Giovannozzi

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G. Arduini, R. Assmann, R. Bailey, S. Fartoukh, W. Herr, S. Redaelli, **J. Uythoven, J. Wenninger, F. Zimmermann**

Parameters and tolerances – Outline

- Present status
- General approach to derive phase-dependent tolerances
- Examples
  - Mechanical aperture
  - Dynamic aperture
  - Luminosity
  - Lifetime
  - Others: tune control, emittance
- Summary and outlook

Parameters and tolerances – Present status - I

- Target parameter tables prepared by Roger.
  - Target parameter tables reviewed.
  - Some parameters added:
    - Transverse IP shift to optimize aperture. It is applied in order to make more symmetric the crossing bump.
      - In IP1/5 it is used in collision for beta*=0.55 m.
      - In IP2/8 it is used at injection.
    - Crossing angle in IP8 for both polarities of the spectrometer.
  - Table for 156 bunches scenario added.
  - Situation concerning the longitudinal emittance at injection:
    - It should be lower than 1 eVs to decrease capture losses
    - The SPS produced beam with longitudinal emittance between 0.7 and 0.8 eVs.

- First presentation of the parameters with proposal of tolerances at the LHCCWG#19 by Frank -> starting point for this iteration.

Parameters and tolerances – Present status - II

proposal/guesses	2007 com.	nominal	effect/reason
peak closed orbit	4 (6?) mm	4 / 3 mm [2]	mechanical aperture
rms closed orbit	0.7 mm	0.40 mm [2]	feed down, dynamic aperture
orbit stability	0.6 σ [5]	0.2 σ [6,13]	arc beam losses, collimation
static off-momentum (1.5×10^{-3}) peak β–beat	< 90% ?	21% [1,2,3]	aperture, collimation
transient peak β–beat	< 4% [1]	< 8% [6,13]	arc beam losses, collimation, aperture
peak dispersion $D/\sqrt{\beta}$	< 40%?	30 / 28% [4]	collimation, aperture
coupling κ	0.01 [7]	0.001 [7,8]	tune control, diag.
tune	0.01 [7]	0.003/0.001 [7]	stable tune region, & tune spread
δ deviation	2×10^{-3}	1.5×10^{-3}[2] 2×10^{-3}[7]	aperture, collimation
δ stability	2×10^{-4}	10^{-4} [8]	rf capture, HERA
dynamic aperture	~4 σ	6 (10-12) σ [2]	lifetime, beam control

From F. Zimmermann, LHCCWG#19

Parameters and tolerances – Present status - III

From F. Zimmermann, LHCCWG#19

proposal/guesses	2007 com.	nominal	effect/reason
chromaticity Q'	5±5 [5,7]	2±1 [7]	instabilities, dynamic aperture
2nd order Q''	few 1000	1000/2000 [2]	head-tail stability for Q' meas., ΔQ
3rd order Q''	$3x10^6$?	>$-5x10^5$ [7,9], <$3x10^6$	head-tail stability, dynamic aperture, ΔQ
detuning/amplitude@6σ	0.005?	0.002 [7]	dynamic aperture, ΔQ
$\partial^2 Q/(\partial\varepsilon)/(\partial\delta)$	?	$7x10^6$ m^{-1} [2]	total tune spread ΔQ
bunch-to-bunch intensity	?	±10% peak [11]	PS booster rings, PS
bunch-to-bunch transv. emittance variation	?	±10% peak [11]	PS booster rings, PS
bunch-to-bunch longit. emittance variation	?	±10% peak [11] +0/-10% [12]	PS booster rings, PS
minimum / maximum transverse emittance	?	3.5 μm<ε <3.75μm	beam-beam, collimator survival, aperture
vacuum beam lifetime	1 (30?) h ?	100 h [10]	nuclear interaction

Such performance was actually achieved! It can be used as input for analysis of other parameters.

Proposed approach to derive phase-dependent tolerances

- The first issue is given by the interdependencies between parameters -> global approach should be devised rather than changing one parameter at a time.
- This implies defining a number of fundamental functions of the target parameters. Some examples:
  - Peak closed-orbit
  - Beta beating
  - Dispersion beating

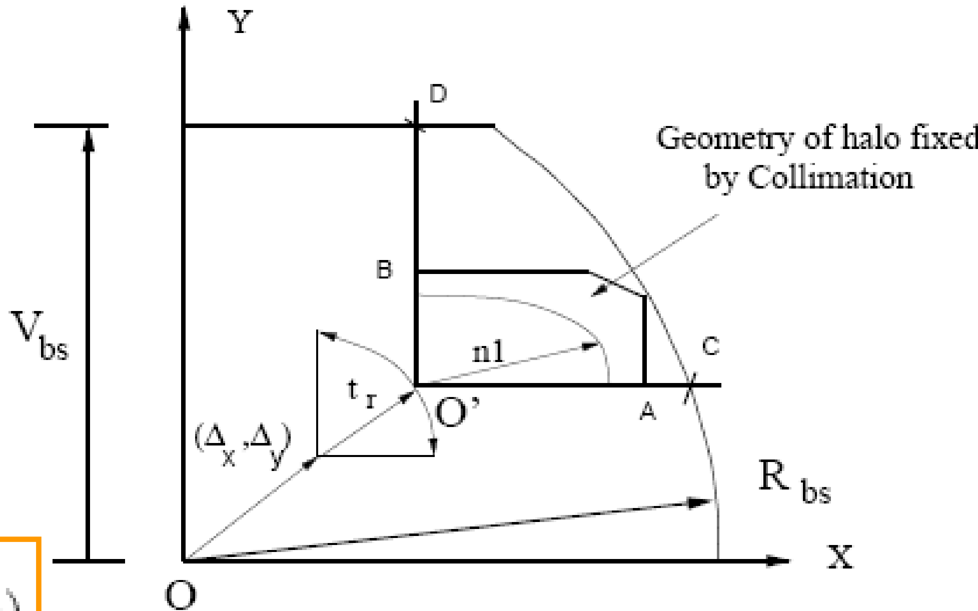
  Linked via mechanical aperture definition

  - Emittance variation bunch-to-bunch
  - Intensity variation bunch-to-bunch

  Linked via luminosity definition
- Then, appropriate criterion should be defined to compute the change in fundamental functions -> relaxed tolerances on parameters.

Mechanical aperture – I

Some definitions (LHC DR and J.-B. Jeanneret and R. Ostojic, LHC PN 111)



NB: $\sqrt{\vec{V}} = \left(\sqrt{V_1}, \sqrt{V_2}\right)$

$$\overrightarrow{OO'}(s) = \vec{\Delta}(s) + \vec{u} + \vec{d}_{\mathrm{disp}}(s)$$

$$\vec{\Delta}(s) = \vec{d}_{\mathrm{sep}}(s) + \vec{d}_{\mathrm{axis}}(s) + \vec{d}_{\mathrm{inj}}(s)$$

$$\vec{u} = (t_r + CO)(\cos\alpha, \sin\alpha) \quad \text{with} \quad \alpha \in [0, \pi/2]$$

$$\vec{d}_{\mathrm{disp}}(s) = (1 + k_\beta)\left[\vec{D} + k_D \frac{D_{\mathrm{x,QF}}}{\sqrt{\beta_{\mathrm{x,QF}}}}\sqrt{\vec{\beta}}\right]\delta_p$$

- **Target value for n1 -> 7 sigma.**
- **Relaxing the specification for n1 would allow reviewing the budget for the closed orbit, beta-beating, and dispersion beating.**

Mechanical aperture – II

No margin available under nominal conditions.

During early stages of commissioning, maximum aperture gain ~ 0.5 σ!

Settings during injection (in σ_β, $\delta=0$)

a_{abs}	=	~ 10.0 σ	Active absorbers in IR3 and IR7
a_{sec3}	=	9.3 σ	Secondary collimators IR3 (H)
a_{prim3}	=	8.0 σ	Primary collimators IR3 (H)
a_{ring}	**=**	**7.5 σ**	**Ring cold aperture**
a_{prot}	≥	**7.0 σ**	TCDQ (H) protection element
a_{prot}	=	**6.8 σ**	TDI, TCLI (V) protection elements
a_{sec}	=	**6.7 σ**	Secondary collimators IR7
a_{prim}	=	**5.7 σ**	Primary collimators IR7
a_{TL}	=	**4.5 σ**	Transfer line collimators (ring protection at **6.9 σ**)

➔ Tight settings below “canonical” 6/7 σ collimation settings!

Tighter for larger beta beat (smaller cold aperture)!

Mechanical aperture – III

- Present situation:
  - Closed orbit -> 4 mm 2/3
  - 20% beta-beating -> 1 mm 1/6
  - 30% dispersion beating -> 1 mm 1/6
- Two possibilities to gain additional margin (basic principle: easier to correct orbit than beating -> increase beating budget):
  - Re-distribute aperture margin (0.6 mm) to beating components only:
    - **Closed orbit -> 4 mm**
    - **(20+6)% beta-beating -> 1.3 mm**
    - **(30+9)% dispersion beating -> 1.3 mm**
  - Re-distribute aperture margin (0.6 mm) and transfer part of CO budget (1 mm) to beating components only.
    - **Closed orbit -> 3 mm**
    - **(20+16)% beta-beating -> 1.8 mm**
    - **(30+24)% dispersion beating -> 1.8 mm**

Dynamic aperture - I

- Target value for DA (without beam-beam) at injection is 12 sigma.
- Analysis of neglected sources of uncertainty made (J.-P. Koutchouk et al. PAC99).
- Break down of contributions to DA uncertainty

– Target DA at 10^5 turns			12.0
– Finite mesh size in tracking	5 %		
– Linear imperfections	5 %		**CPU-time**
– Amplitude ratio	5 %		
– Extrapolation to 4×10^7 turns	7 %		9.6
– Time-dependent effects	10 %		
– Ripple	10 %		7.8
– Safety margin	20 %		6.2

- Finite mesh size and amplitude ratio uncertainties were recently tested and found in good agreement with estimate.
- Hence, a factor of two is to be applied to the DA value from numerical simulations.

Dynamic aperture - II

- A reduced DA will impact on the beam lifetime. How can this be relaxed? This would imply knowing:

$$\boxed{Lifetime = Lifetime(DA)}$$

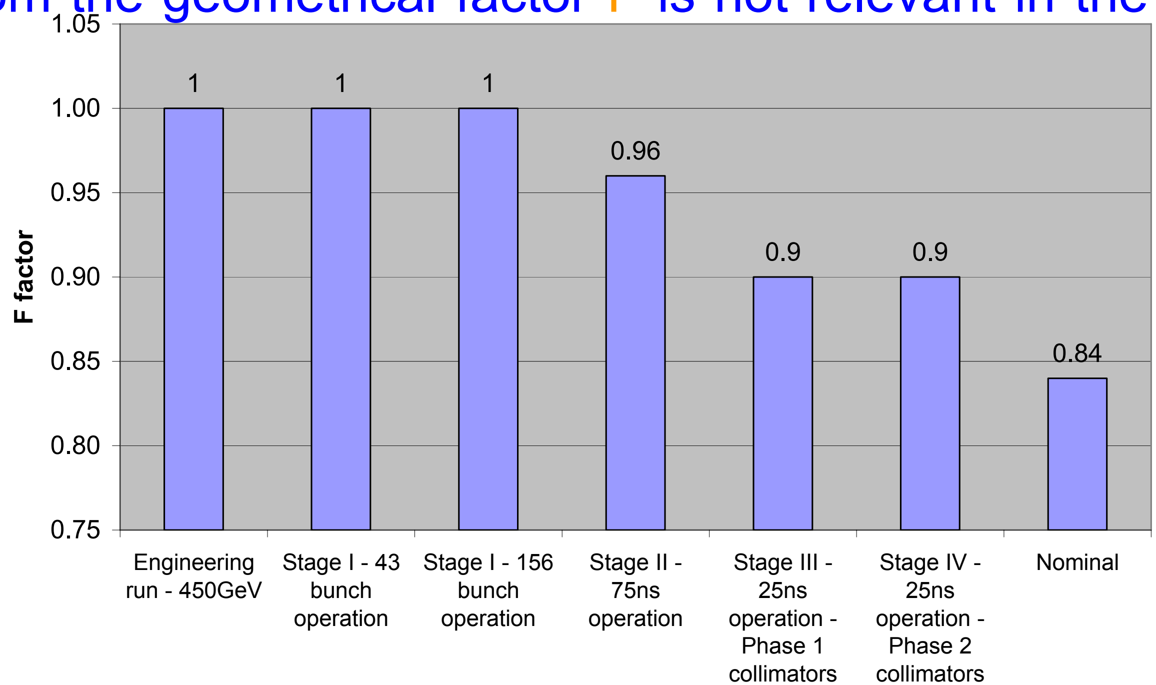
- Studies to tackle this problem (R. Assmann et al. EPAC2002):
  - 7 TeV: In presence of beam-beam and/or scattering phenomena a link between lifetime and DA established.
  - 450 GeV: strong chaos found with long-range beam-beam interactions, yet no quantitative model to derive lifetime.
- Therefore, it does not seem possible to evaluate the impact on the beam lifetime by a reduced DA at injection, unless studies are launched...
- Measurements on existing machines could be organized…
- Proposal: stick to the nominal target.

Luminosity - I

- The interval of variation can be estimated by using the performance of the injectors in terms of bunch-to-bunch variation (intensity and emittance) as well as beta-beating estimate:

$$\frac{\Delta L}{L} = \sqrt{2\left(\frac{\Delta N_b}{N_b}\right)^2 + \left(\frac{\Delta \varepsilon}{\varepsilon}\right)^2 + \frac{1}{2}\left(\frac{\Delta \beta^*}{\beta^*}\right)^2}$$

- This gives about 22% as natural variation for the luminosity.
- Of course, injectors' complex performance should not be relaxed!
- NB: The contribution from the geometrical factor F is not relevant in the first stages.
- NB: the bunch-to-bunch variation of the luminosity is about 17%.



Luminosity - II

- The acceptance of the beam parameters (intensity, emittance, beta*) at the end of the squeeze could be fixed by this criterion.
- Similarly, this can be used also to qualify beam parameters (intensity, emittance) at the end of the ramp.
- Proposal: each additional variation should be in the shadow of the natural one, e.g., a factor 2/3 smaller.
- By using sum in quadrature this gives ~ 30% as total natural variation.

Vacuum lifetime – I

- Various factors contribute to the luminosity lifetime: nuclear interaction, rest-gas, IBS.

$$\boxed{\tau_{\mathrm{nuclear}} = \frac{N_{\mathrm{tot},0}}{L\sigma_{\mathrm{tot}}k}}$$

$$\boxed{t_{1/e} = (\sqrt{e}-1)\tau}$$

- IBS and nuclear interaction can be easily computed for the various commissioning stages.
- IBS is almost negligible in the early stages.
- Assuming the nominal value for the luminosity lifetime, one can infer the lifetime due to rest-gas interaction.

$$\boxed{\frac{1}{\tau_L} = \frac{1}{\tau_{\mathrm{IBS}}} + \frac{2}{\tau_{\mathrm{rest-gas}}} + \frac{1}{\tau_{\mathrm{nuclear},1/e}}}$$

Vacuum lifetime – II

Summary table for beam lifetime (various processes) assuming NOMINAL value for luminosity lifetime. The approximate rule

$$\tau(\text{rest-gas}) \approx 2\,\tau_x\,(\text{luminosity})$$

is reasonably respected.

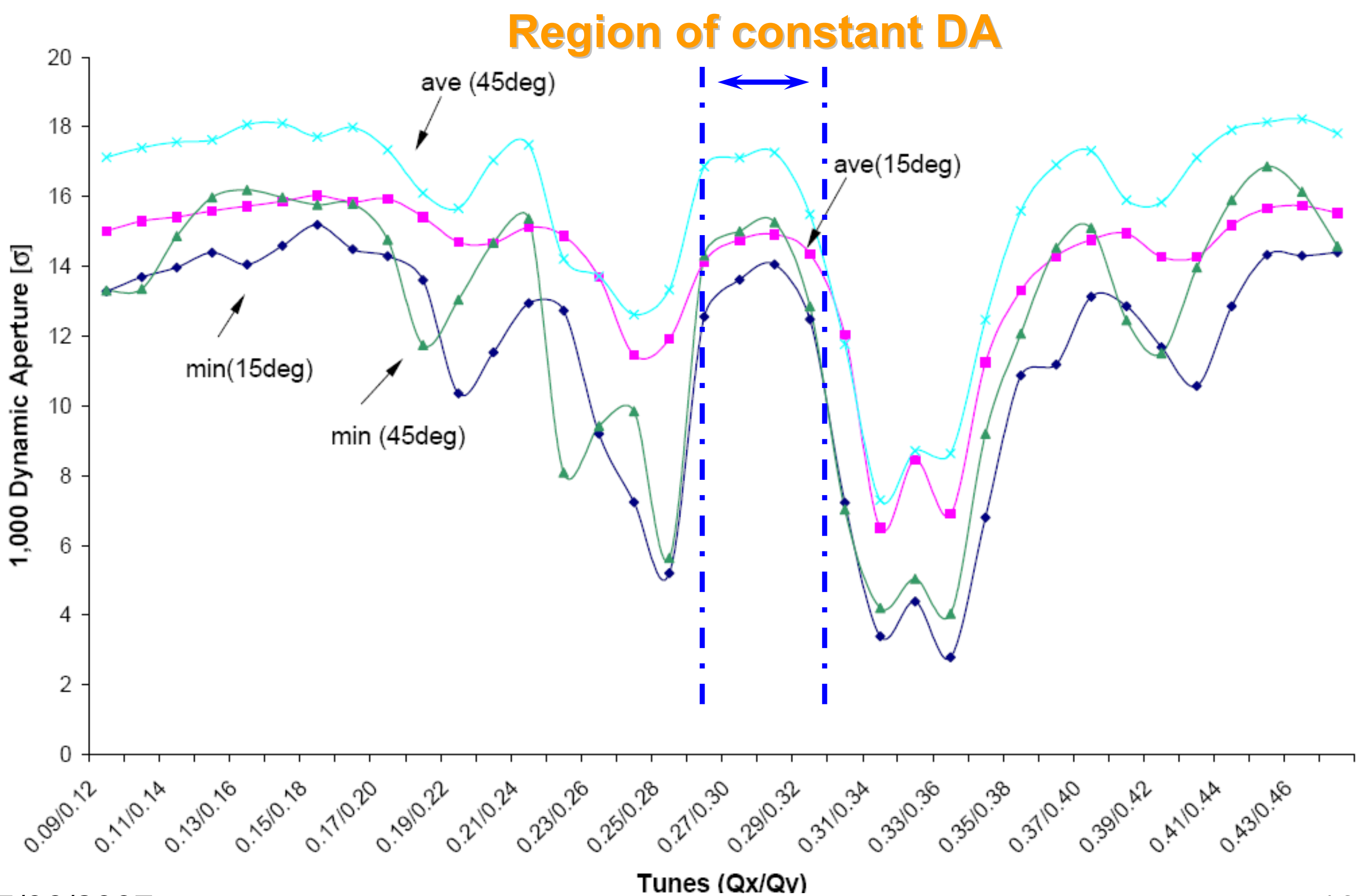
Lifetime (h)	Stage I 43 bunches	Stage I 156 bunches	Stage II 75 ns	Nominal
τ_x (IBS)	305	135	305	106
τ_z (IBS)	178	79	178	62
τ (luminosity)	15	15	15	15
τ (nuclear, 1/e)	254	113	254	29
τ (rest-gas)	34	40	34	87

Assume 30-40 h as acceptable value for rest-gas lifetime.

NB: pressure and rest-gas lifetime are linearly dependent…

Others: Tune control

- The original range of 10^{-2} for the tune control is determined by the sharp decrease of DA around the nominal tunes.
- The detuning with amplitude should not be relaxed to more than 5×10^{-3} at 6 σ (particles at the collimators' amplitude would be in the region close to low order resonances).



Others: Emittance variation

- The lower bound to the acceptable emittance is given by the estimate from beam-beam tune shift.

$$\boxed{\xi = \frac{N_{\text{bunch}} r_p}{4\pi\epsilon_n}}$$

- Limits are set to the values corresponding to the nominal and ultimate beam-beam tune shift.

	ξ	Stage I 43 bunches	Stage I 156 bunches	Stage II 75 ns
ε (μm)	4×10^{-3}	1.3	2.9	1.3
ε (μm)	6×10^{-3}	0.9	2.0	0.9

The upper bound is set by the mechanical aperture.

Summary and outlook

- **New iteration on the tolerance tables presented.**
- **Proposed criteria to evaluate relaxed tolerances**
  - **Not much margin available for relaxing parameters linked with machine aperture.**
  - **Proposal to transfer part of closed orbit budget to beating budget.**
- **Outcome of the analysis presented will be collected in reference tables.**
- **Revised target parameters tables prepared.**

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Some after-meeting developments - I

- Stage-dependent tolerances for closed orbit, beta and dispersion beating can be based on collimation system inefficiency.
- This assumes that the machine protection function of the TDI, TCLIs, and TCDQ can be relaxed/skipped.
- The actual position of the protection devices can be kept fixed to the nominal one (see p. 8), but it is considered acceptable that the cold ring aperture goes below 6.8-7 sigmas.
- The underlying principle is that with reduced intensity an increased inefficiency can be tolerated, which corresponds to reducing the effective cold machine aperture according to:

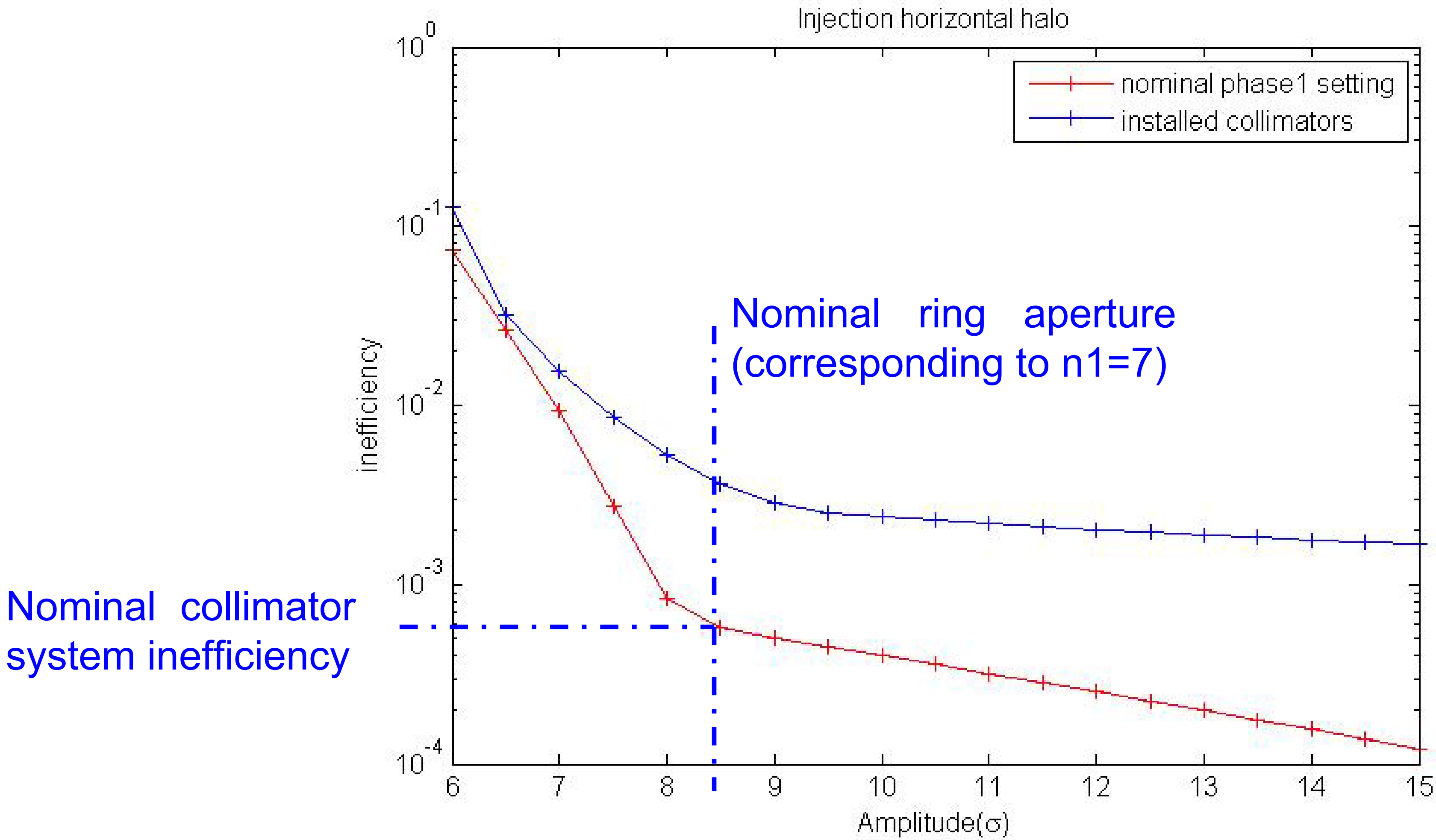
$$\boxed{\frac{N_{tot,nom}}{N_{tot,comm}} = \frac{\tilde{\eta}(A_{comm})}{\tilde{\eta}(A_{nom})}}$$

With:

- N_{tot}: total beam intensity
- η: collimation system inefficiency
- A: cold machine aperture in sigmas

Some after-meeting developments - II

Courtesy of C. Bracco



Some after-meeting developments - III

Injection	Stage I 43 bunches	Stage I 156 bunches	Stage II 75 ns
$N_{tot,nom}$/ $N_{tot,comm}$	82	10	3.75
ΔA (σ)	2	1.3	0.9
Aperture gain (mm)	2.4	1.6	1.1
New CO (mm)	4	4	4
New beta-beating (%)	20+25	20+16	20+11
New disp-beating (%)	30+37	30+24	30+17
New CO (mm)	3	3	3
New beta-beating (%)	20+36	20+27	20+21
New disp-beating (%)	30+52	30+39	30+32

The nominal intensity used is indeed that for the Stage III, i.e. 5×10^{10} p/b and 1.4×10^{14} p/beam.