Requirements on beam observables for the LHC

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Tolerance of the LHC to tune-shift at 450 GeV and in collision (1/2)

- Tolerance at 450 GeV given by the distance of the working point to dangerous non-linear resonances (typically third order): $\Delta Q \sim \pm 10^{-2} \longrightarrow$ Target: $\Delta Q_{x,y} \sim 3 \times 10^{-3} = (Q_x^{(0)} - Q_y^{(0)})/10.$

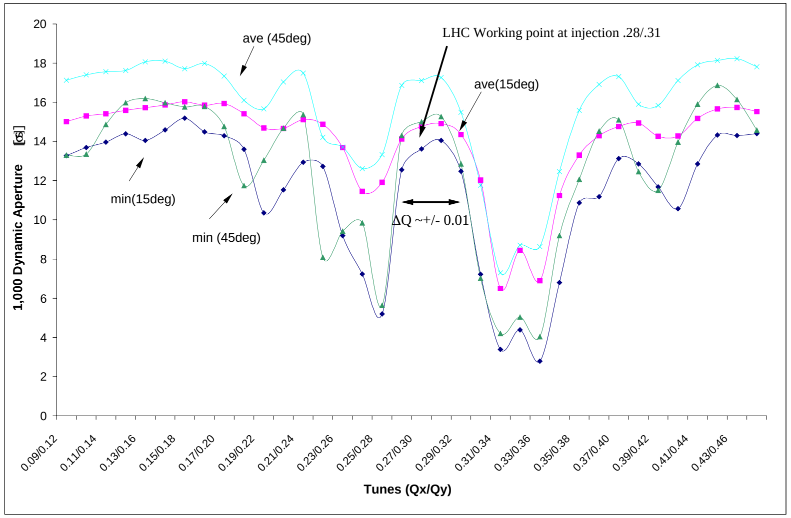

Figure 1: *Short-term dynamic aperture (1,000 turns) v.s. tune for the LHC optics Version 6.0. Each pair of tunes are separated by 0.03 (F. Schmidt et al.)*

Tolerance of the LHC to tune-shift at 450 GeV and in collision (2/2)

- Tolerance in collision : from the experience in the $S\bar{P}PS$ and Tevatron, the tune footprint must be lodged in between resonances of order ≤ 12, which, in case of the LHC, corresponds to $-0.01 \leq \Delta Q_{x,y}^{(\text{spread})} \leq 0 \longrightarrow$ Target: $\Delta Q_{x,y} \sim 10^{-3} = \Delta Q^{(\text{spread})}/10.$

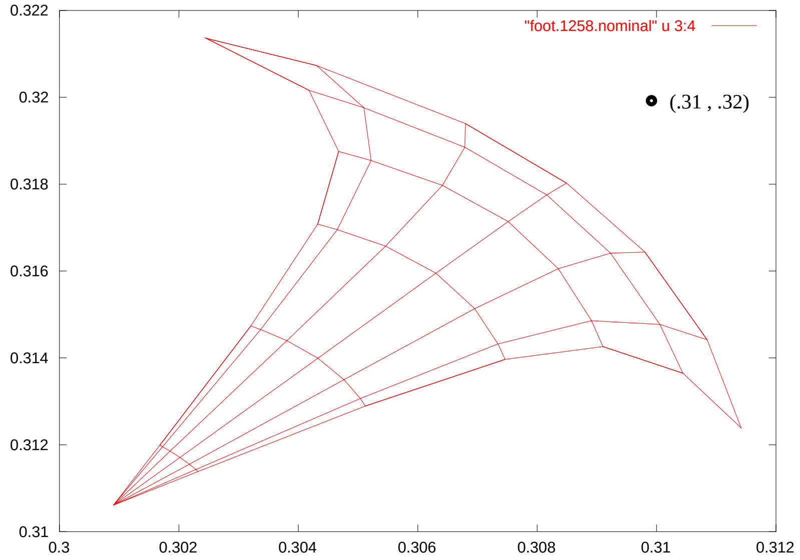

Figure 2: *Typical tune footprint for the LHC in collision (H. Grote).*

Tolerance of the LHC to chromaticity expressed in terms of tune-shift for online off-momentum measurement (1/3)

- Constraints coming from *single particle dynamics* considerations
  1. about 1σ reduction of the DA at injection for a uncorrected Q' of $\Delta Q' = \pm 5$ units.
  2. minimisation of the additional tune spread due to Q' in collision:
     $$Q' \times \left(\frac{\Delta E}{E}\right)_{\mathrm{bucket}} \lesssim 10\% \times \Delta Q^{(\mathrm{spread})}_{\mathrm{beam-beam}} \longrightarrow |Q'| < 3 \text{ units}.$$
- Constraints coming from *transverse instability thresholds*:
  1. $0 \le Q' \lesssim 2$ units to prevent from fast head-tail instability at injection (with nominal current).
  2. Less critical at top energy.

$\longrightarrow$ Target: Q' must be controlled within

$$\begin{cases} \pm 1 \text{ units} & \text{at 450 GeV} \\ \pm 3 \text{ units} & \text{at 7 TeV.} \end{cases}$$

Tolerance of the LHC to chromaticity expressed in terms of tune-shift for online off-momentum measurement (2/3)

- Different type of procedures for on-line chromaticity measurements.

1. Head-tail monitor (H. Schmickler et al.) which satisfies requirements on speed and accuracy but blows up the beam emittance.
$\longrightarrow$ Proof of feasibility demonstrated on the SPS.

2. *Fast* ($>$ 100 Hz) modulation of the RF phase (O. Brüning, T. Linnecar et al.).
$\longrightarrow$ results obtained in 2001 on the SPS are promising (no particle loss during RF modulation, transverse tune modulation $\propto Q'$ clearly detectable ...).
$\longrightarrow$ possible limitations for the LHC: the available RF power at top energy will limit the modulation amplitude in δ_p to a small fraction of 10^{-4}.
$\longrightarrow$ looks perfectly adequate for snap-back effects.

3. Standard method based on a *slow* ($<$ 10 Hz) frequency modulation of $f_{\rm RF}$.
$\longrightarrow$ Perfectly adequate to control Q' for the end of ramp up to 7 TeV.

Tolerance of the LHC to chromaticity expressed in terms of tune-shift for online off-momentum measurement (3/3)

- Maximum tolerable momentum deviation/modulation (Method 2 & 3)

  Injection energy:

  For slow RF modulations (< 1 Hz): $|\delta_p| < 5 \times 10^{-4}$ (constraint from the mechanical aperture).

  For fast RF modulation (method 3): $|\delta_p| < 0.5 - 1 \times 10^{-4}$ to minimise particle losses (the 400 MHz RF bucket is almost full at 450 GeV).

  Collision energy:

  $\delta_p \lesssim 10^{-4}$ requesting that the C.O. modulation due to the δ-modulation does not exceed $\sigma/5$ in the machine (from collimation and beam-beam related considerations).

- $\longrightarrow$ In view on the specs on Q', the required accuracy of the tune meter drops below 10^{-4}.

Typical time scale for tune and chromaticity variations in the LHC (1/2)

- Typical time constants for *injection and smooth ramping*:
  20 min.'s $\longrightarrow$ not critical from the dynamic effects point of view.

- Time scale for *snap-back* at the beginning of ramp:

$$60 \text{ sec.'s} \longrightarrow \begin{cases} \Delta Q \approx \pm 0.8 - 1.6 \times 10^{-3}/s & (b_2 \text{ feed-down from } b_3 \text{ and } b_1 \text{ decay}) \\ \Delta Q' \approx \pm 2.5 - 5 \text{ units } /s & (b_3 \text{ decay of 3 units over 30–60 s.}) \end{cases}$$

- Time scale for the (parabolic) *slow down of the ramp* at 7 TeV from 10 A/s to 0:
  60 sec.'s $\longrightarrow \Delta Q \approx 2.5 \times 10^{-3}$/s (due to a b_2 ramp induced errors of 17 units in MQ's).
  $\longrightarrow$ can be partly anticipated by adjusting the ramp of the MQ power supplies.

- *Squeeze* duration:
  not yet specified, probably a few minutes, but certainly less critical for dynamic effects in tune and chromaticity.

- $\Rightarrow$ Requirement on the bandwidth of a tune and chromaticity feed-back:
  $\longrightarrow$ $0.2 - 1$ Hz for the tune with an accuracy of the order of 10^{-3}.
  $\longrightarrow$ from a few Hz to 5 Hz for Q' (depending on the reliability of the 8 reference dipoles) with an accuracy better than 10^{-4} (expressed in terms of tune shift).

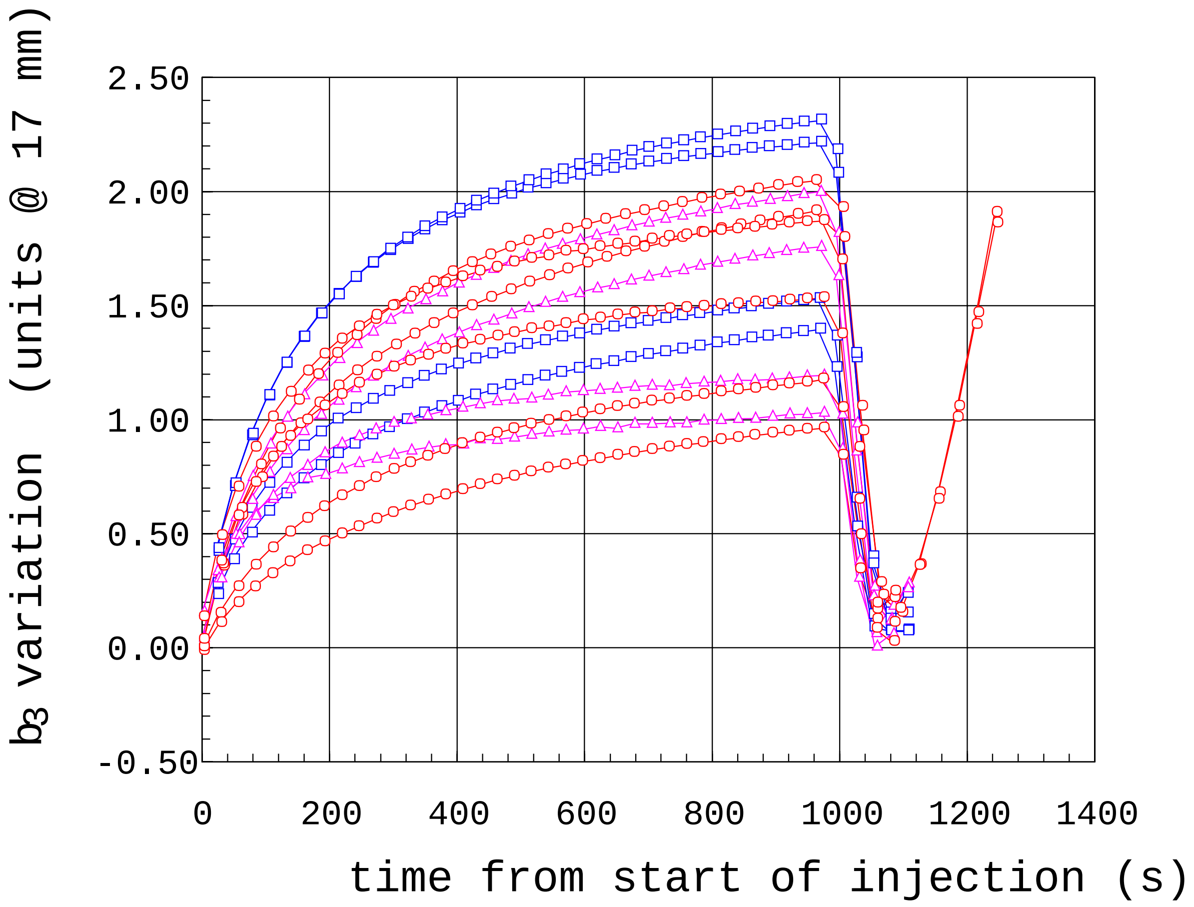

Figure 3: *Decay and snap-back of b_3 measured in seven 2-in-1 LHC dipoles (L. Bottura et al.).*

Correction of non-linear field errors via tune measurement (1/2)

- **1.** b_5 compensation at injection (decapole harmonics of the main field).
  $\longrightarrow$ the DA can drop by more than 1σ at injection for 0.2 units of uncorrected b_5.
  $\longrightarrow$ the good observable for b_5 is the induced Q''' :

$$Q''' \sim 5 \times 10^6 \langle b_5 \rangle \rightarrow \Delta Q = \frac{1}{6} Q''' \delta_p^3 \sim 2 \times 10^{-5}!$$

for $b_5 = 0.2$ units and $\delta_p = 5 \times 10^{-4}$ (i.e equal to the momentum acceptance of the ring at injection with the collimators in).
$\longrightarrow$ Online measurement of b_5 looks challenging and precise b_5 compensation will probably require dedicated machine settings with an enlarged momentum window (e.g. $\delta_p = \pm 2 \times 10^{-3}$, LHC Note 113 J.P. Koutchouk)

Correction of non-linear field errors via tune measurement (2/2)

- **2.** Correction of b_6 in the triplet at collision.

  $\longrightarrow$ Significant improvement of the DA in collision with triplet correction (LHC Project Report 502, F. Schmidt et al.), mainly driven by b_6.

  $\longrightarrow$ Measurement of b_6 via orbit bump in the triplets (J. P. Koutchouk):

$$\Delta Q = \pm \frac{1}{4\pi} \times \int_{\mathrm{Triplet}} ds K(s)\beta(s)x_0^4(s) \ \times \frac{5\, b_6}{R_{ref}^4} \approx \frac{5\left\langle x_0^4\right\rangle}{R_{ref}^4} \times Q'_{\mathrm{Triplet}} \times b_6$$

$\longrightarrow$ For π-bumps of average amplitude of 8mm (limited by the Mechanical Aperture of the triplet) and $\beta^* = 0.5$ m ($Q'_{\mathrm{Triplet}} \approx 30$), the induced tune-shift scales as

$$\Delta Q \sim 7 \times 10^{-4} \times b_6 \,.$$

$\longrightarrow$ Required accuracy for the tune metre: $\Delta Q \lesssim 10^{-5}$ (for $b_6 = 0.2 - 0.4$ units as expected in the FNAL and KEK triplet quadrupoles).

Concluding remarks

Machine parameter	Most Critical demand on the sampling rate during LHC cycle	Required accuracy (expressed in tune shift)
Tune	$0.2 - 1$ Hz	$\sim 10^{-3}$
Chromaticity	few Hz $\longrightarrow$ 5 Hz	$\lesssim 10^{-4}$
Field Non-linearity via tune measurement	No real constraint ($< 0.01 Hz$)	$\lesssim 10^{-5}$

The red colour means that the naive "uncertainty principle"

$$\Delta Q_{\rm min.} \times \frac{f_{\rm rev.}}{f_{\rm sampling}} \geq 1$$

is not (or just) fulfilled.

$\longrightarrow$ Q' correction during snap-back will require

1. challenging on-line measurements ($f_{\rm sampling} \sim 1$ Hz, $\Delta Q_{\rm min.} = 10^{-4}$).

2. precise magnetic model for the b_3 snap-back in the LHC main dipoles and pre-adjustment of the b_3-spool settings.