Tracking Error Measurement and Correction

Measurements:

- Tracking errors of the MB and MQ converters are determined from the orbit (or trajectory) and tune of the machine. Note that such PC errors mix with transfer function errors, and it is only possible to determine the combined error.

Corrections:

- The LSA controls suite has no problem to correct such effects. The measurement results may be used to define individual transfer functions (I-B) for each sector. The settings generation/trim system will then automatically adjust the currents in the individual circuits to obtain the same fields. Works for the entire machine cycle. Note that the corrections will be limited by any difference in field (errors) between the 2 apertures!

- Alternatively PO may 'recalibrate' their DCCTs, but correction over LSA is probably easier and more flexible.

Energy error estimate

- The relative momentum offset δ of the beam with respect to nominal value may be estimated from the beam position by:

$$\delta = \frac{\sum D_{x,i} x_i}{\sum D_{x,i}^2}$$

where i label the BPMs, D_x is the hor. dispersion, x the hor. beam position. In the LHC arc, the BPMs come in 2 'families' with D_x = 2m and D_x = 1m, N_f=25 for each family.
For the simple case where D_x is identical at all BPMs, δ is just proportional to the average radial (hor.) beam position:

$$\delta = \frac{\frac{1}{N}\sum_{1}^{N} x_i}{D_x}$$

- The uncertainty on δ for one sector due to a measured orbit/trajectory r.m.s. σ_x :

$$\sigma_\delta \cong \frac{\sigma_x}{\widehat{D}_x}\sqrt{\frac{4}{5N_f}} \cong \sigma_x 0.1[m^{-1}] \qquad \widehat{D}_x = 2\ (m)$$

For σ_x = 1 mm : $\sigma_\delta \approx 10^{-4}$ → $\Delta I/I_{nom} \approx$ 6 ppm

Orbit correctors

- Before one can dream of PC tracking checks, the trajectory must be corrected to a reasonable level, respectively one must have established a closed orbit.
- A potential problem arises from the orbit correctors that are used to correct the trajectory / orbit, since they can potentially bias the momentum offset determination. ‘Cures’:
  - Avoid massive corrections with (too) many correctors (MICADO) or eigenvalues (SVD).
  - Compare results for different corrector seeds (bare corrections).
  - Check integrated corrector fields.
- At LEP the effect of correctors was an issue for energy calibration. In general it turned out not to be a too serious issue, and the bias from the correctors could be kept at the level of (1-2) $\times 10^{-4}$ for the whole ring and ~ few$\times 10^{-5}$ for a sector.

MB tracking @ 450 GeV – when

First turn:

- Assuming that the trajectory r.m.s. can be brought down to at least 2-3 mm, it is a priori possible to get a good estimate (~ 20 ppm-ish) of the MB tracking from the first turn.
- At such a level of r.m.s., the noise contribution from a pilot (~ 1 mm) is not (yet) an issue. If necessary one can always average multiple measurements.
- Whether it is worth to already correct 10^{-4} effects at that stage is open to debate – I would say no.

First closed orbit:

- Assuming that the trajectory r.m.s. can be reduced to the 1 mm level, the MB tracking errors can be determined to the level of ~ 10 ppm.
- Whether it is done with pilot or nominal bunch does not make a big difference. Noise contributions can be eliminated by averaging over a sufficiently long time interval.
- Systematic effects from the correctors are easier to evaluate than for the first turn…

MB tracking - ramp

- The real-time orbit acquisition allows us to check the relative tracking during the ramp with similar or better accuracy in δ (use the difference with respect to injection) as compared to injection.
- Note that at 7 TeV, $\sigma_\delta \approx \Delta I/I_{nom} \sim 10^{-4}$ ~ 100 ppm-ish because PO define their performance in terms of I_{nom}.

MB absolute calibration – 450 GeV

- The absolute momentum of the LHC at injection can be obtained by transporting the SPS calibration to the LHC. The present SPS extraction energy of ‘450 GeV’ has been measured to be:

  P_{450} = 449.18 ± 0.14 GeV   i.e. $\sigma_P/P = 3\times10^{-4}$

- When the LHC first turn is correctly centered (i.e. $\delta = 0$) then $P_{LHC} = P_{SPS}$.

- The previously quoted errors on δ are small compared to the accuracy of the SPS calibration and are not a limiting factor. A more accurate determination may be obtained with lead ions in the LHC.

MQ-MB tracking

- The tracking between MB and MQ is best measured with the tune once the closed orbit is established. With reasonable conditions it should be no problem to achieve a tune error δQ of 0.001 and less (PLL). Assuming Q'_{nat} ~ 100, this correspond to a relative error of

$$\delta = \quad \delta Q / Q'_{nat} = 10^{-5} \qquad \rightarrow \mathbf{\Delta I/I_{nom} < 1\ ppm}$$

- This value above is probably a bit optimistic because at such a level of accuracy the measurement is dominated by the systematic tune errors due to quadrupole strength errors all around the machine. Clearly a good measurement of the MB-MQ tracking also requires a reasonable β-beat.

MQ tracking

- Small tracking errors between sectors are not critical – lead to negligible β-beat. The phase advance between IPs can however be important for beam-beam…

- Tracking errors between the different MQ converters require a measurement of the phase advance over each sector:
  - Response matrix : 10^{-3} relative errors achievable with first turn (see also presentation on LOCO – this WG), possibly better with closed orbit (depends also on the other optics errors).
  - Phase advance : 10^{-4} level achievable. Reasonable β-beat is an asset…

Summary

- The relative energy errors between sectors can be determined to the level of 10^{-4} provided the closed orbit is reasonable (~ 1 mm r.m.s.). This corresponds to a converter tracking error at injection of ~10 ppm.
- The relative error between MB and MQ can a priori be measured with extreme accuracy, but is probably limited anyhow by the calibration errors on the quads.
- Correction of the effects by LSA – no problems expected.