REAL-TIME FEED-FORWARD/FEEDBACK REQUIRED

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Abstract

In order to counteract disturbances due to decay and snapback of multipole moments, misalignments, ground motion and other dynamic effects, control of the key beam parameters – orbit, tune, chromaticity and energy – will be an integral part of LHC operation. Manual correction of these parameters may soon reach its limit with respect to required precision and expected time-scales. The baseline and requirements of the proposed feed-forward/feedback systems are presented and their possible staging during beam commissioning discussed.

INTRODUCTION

This contribution summarises the tolerance and baseline of automated control of orbit, energy, tune, chromaticity and coupling and highlights the requirements in the light of LHC 'Stage I' operation as described in [1]. Stage I covers commissioning of the LHC with pilot beams till physics test runs with collisions of up to 43 on 43 nominal bunches at an energy of 7 TeV and partially squeezed optics. Details on instrumentation are discussed elsewhere [2, 3].

BEAM PARAMETER REQUIREMENTS

Most requirements on key beam parameters and the time-line of their control strongly depend on the capability to control particle loss inside the accelerator. The constraints are not only mainly driven by machine protection, collimation and quench prevention, but also commissioning and operational efficiency such as the optimisation of (integrated) luminosity and other parameter for physics. Looking at the Stage I requirements discussed here, it is visible that the requirements on orbit, energy, tune and chromaticity scale rather with total beam intensity and beam energy than with stages as shown in the following sections.

Orbit

There are many more or less strict requirements on the orbit, which are summarised in Table 1. The performance of the LHC Cleaning System depends critically on the orbit. The system's cleaning inefficiency η is defined as the ratio between the number of protons impacting the primary collimator and the number of protons escaping the cleaning system and getting lost in the cold aperture that requires protection. As analysed in [4, 5], the maximum allowed cleaning inefficiency is determined by the minimum quench limit R_q of the superconducting magnets, the total number of stored protons N_{max}, the average dilution length L_{dil} and the minimum acceptable lifetime τ_{min}

$$\eta = \frac{\tau_{min} \cdot R_q \cdot L_{dil}}{N_{max}} \qquad (1)$$

Inserting the expected nominal values for $R_q \approx 7.6 \cdot 10^6\,\text{protons/s}$, $N_{max} \approx 3 \cdot 10^{14}$, $L_{dil} = 50\,\text{m}$ and $\tau_{min} := 10\,\text{min.}$ while running at 7 TeV, cleaning inefficiency has to be in the order of $\eta \approx 10^{-3}$ (see [4, 5] for details). To meet nominal requirements, the LHC Cleaning System consists of a two-stage collimation approach. Figure 1 shows its cleaning inefficiency versus the peak-to-peak orbit error at the primary collimator with respect to the secondary collimator, retracted by $1\,\sigma$ (σ being the r.m.s. beam size at the collimator). The total orbit error

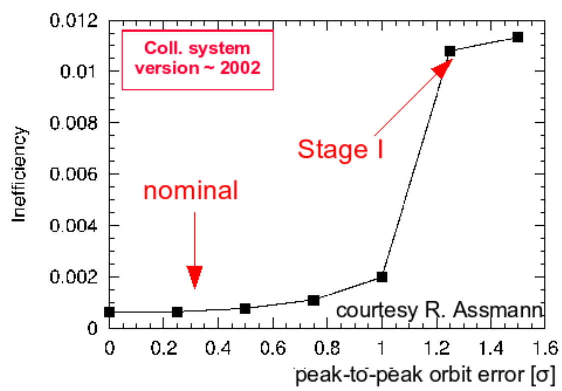

Figure 1: Collimation inefficiency vs. peak-to-peak orbit error [4]. An increase of the cleaning inefficiency is visible as soon as the orbit error approaches $1\,\sigma$.

should be less than $0.6\,\sigma$ to achieve the required cleaning inefficiency. The total budget is shared between different systematics such as jaw positioning precision, jaw surface flatness and orbit at the jaws. The orbit has an assigned budget of about $0.3\,\sigma$.

However, during 'Stage I', it is expected to accelerate only up to 43 nominal bunches with a bunch intensity of $5 \cdot 10^{12}$ protons and total intensity per beam N_{max} of about $5 \cdot 10^{12}$ protons. Comparing the reduced total intensity with equation 1 and assuming operation at 7 TeV, the maximum acceptable cleaning inefficiency is more relaxed:

$$\eta \lesssim 0.05 \qquad (2)$$

Comparing the required inefficiency with Figure 1, a peak-to-peak orbit stability of about $1\,\sigma$ should be sufficient for Stage I.

To ensure proper function of the Cleaning System and protection devices, the orbit in the arc has to be controlled

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System	Tolerance	Region
LHC Cleaning System:	$< 0.3\,\sigma$	IR3, IR6
Machine Protection & Absorber:		
TCDQ (protection against asynchronous beam dumps)	$< 0.5\,\sigma$	IR6
Injection collimator & absorber	$< 0.3\,\sigma$	IR2, IR8
Tertiary collimator for collisions	$< 0.2\,\sigma$	IR1, IR5
Injection arc aperture w.r.t. collimator and protection devices [1]:	$0.3 - 0.5\,\sigma$	global
Active systems:		
Transverse damper, Q-meter, PLL BPM	$\sim 200\,\mu$m	IR4
Beam interlock BPM	$\sim 200\,\mu$m	IR6
Performance:		
Stability of collision points	minimise drifts	IR1,2,5,8
TOTEM/Atlas Roman pots	$\sim 10\,\mu$m	IR1, IR5
Reduce perturbation from higher multipole feed-down	$0.5\,\sigma$	global
Maintain beam on cleaned surface (e-cloud)	$1\,\sigma$	global

Table 1: LHC orbit stabilisation requirements: The magnitude of requirements are similar; a distinction between local and global requirements is less obvious. [1] see text for details.

to a level which guarantees that the protection devices and collimators always define the aperture. For instance, at 450 GeV, the injection protection absorber TDI is positioned at $7\,\sigma$ (see [6]) and the estimated arc aperture is around $7.5\,\sigma$: the distinction between global and local orbit requirements is less evident. As a consequence, the global orbit has to be steered to about the same level as inside the protection and collimation regions, as described in [7].

A control of the global orbit also helps minimise the dynamic feed-down of coupling due to vertical orbits in the lattice sextupoles and other decay and snap-back related effects.

In summary, a global orbit stability better than $< 1\,\sigma$ seems to be sufficient for Stage I operation with less than 43 bunches at 7 TeV.

Energy

To minimise RF capture losses of the injected beam, the energy offset between SPS and LHC due to b_1 decay and tides should be minimised using the horizontal arc correctors in the LHC. A priori, the control of energy is not urgently required for low intensity beams during Stage I. However, it may help to keep capture losses below an acceptable limit and to minimise potential abort gap population. Since it would simplify the setup of nominal beam after commissioning the capture of pilot bunches, control of energy should be performed at an early stage. Once the control loop is implemented, maintenance of nominal stability of $\frac{\Delta p}{p} < 10^{-4}$ is desired [8].

Tune

The maximum tolerance and requirements on tune and chromaticity is determined by the available space in the tune diagram, which is about $\Delta Q|_{av} \approx 1.15 \cdot 10^{-2}$ around the LHC tune working points for injection ($q_x = 0.28$,$q_x = 0.31$) and collision ($q_x = 0.31$,$q_x = 0.32$). Figure 2 shows the corresponding diagram. The nominal tune requires a

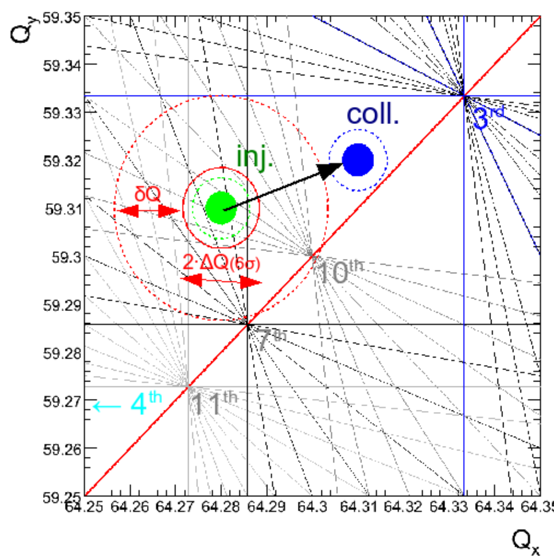

Figure 2: Tune diagram: The LHC injection (inj.) and collision (coll.) tunes are marked. δQ is the maximum allowed tune shift during early commissioning. The solid line envelopes correspond to the expected tune spread ΔQ due to linear chromaticity only ($6\,\sigma$).

stability δQ better than 0.003 and 0.001 during injection and collision, respectively [9, 10]. As a working assumption, ignoring non-linear effects and taking the third and fourth order resonance into account, one may be able to tolerate tune shifts δQ of up to 0.015 at injection during commissioning and accept the temporarily rather poor lifetime. However, for precise beam measurements and storing beam at 450 GeV, tune stability should reach, within commissioning, the nominal injection stability requirement.

Chromaticity

For nominal operation to guarantee long lifetimes, chromaticity has to be stabilised within ± 1 units. Shorter lifetimes may be acceptable at injection during commissioning, since the beam is not expected to be stored for long on the injection plateau. As a working assumption, one can ignore the non-linear contributions to the chromaticity. Accordingly, the maximum allowed linear chromaticity $Q'|_{max}$ is given by SPS momentum spread $\Delta p/p \approx 2.8 \cdot 10^{-4}$ and available space $\Delta Q|_{av} \approx 1.15 \cdot 1.15 \cdot 10^{-2}$ in the tune diagram.

$$Q'|_{max} = \frac{\Delta Q|_{av}}{\Delta p/p} \qquad (3)$$

Requiring that a beam envelope of about $5-6\,\sigma$ fits into the tune diagram around the desired working points, the maximum tolerable chromaticity during Stage I is in the order of about 10 units. The working point for the chromaticity should of course be chosen sufficiently large, in order to guarantee chromaticity always being positive. These numbers are estimates and other more or less strict choices are possible. The actual requirements will be clarified while commissioning the LHC with beam.

Coupling

Linear coupling C_- may eventually define the minimum possible tune split $\Delta_- = |q_x - q_y|$ and push and rotate the planes of the measured tune eigenmodes apart as soon as the unperturbed tune crossing reaches the magnitude of coupling. The LHC tune split will be $\Delta_- = 0.03$ and $\Delta_- = 0.01$ for injection and collision, respectively. Thus the coupling has to be controlled to be at least less than the desired tune split.

A much stronger requirement is driven by the operation of (feedback) control systems that rely on decoupled planes. In order to enable a semi-automated control of orbit, tune, chromaticity and other parameters, the coupling should, for operational efficiency, be less than 10 % of the required tune split. It is worth noting that there is a proposal for an alternate higher tune split of $\Delta_- = 0.1$ ($q_x = 0.285$,$q_y = 0.385$) in case coupling poses a problem during commissioning [11], thus significantly relaxing the requirements.

EXPECTED DYNAMIC PERTURBATIONS

It is assumed that the systematic magnetic field imperfections are sufficiently corrected. Thus, the perturbations relevant for feedbacks are mainly driven by random ground motion (see [12]), squeeze of the final focus, eddy currents and snap-back of the persistent current during the start of the ramp[13, 14]. Table gives subset of snap-back values expected for early commissioning relevant for dynamic perturbation of the discussed beam parameters. The values are based on early measurements of the first-delivered main dipole and quadrupole magnets [13, 14]. The snap-back values take into account the dependence of the expected maximum decay on the duration of the magnets at top energy. This is expected to be less during commissioning than during nominal operation with long stores at 7 TeV [15].

	Main Dipole				**MQ**
	$\mathbf{\Delta b_1}$	$\mathbf{\Delta a_1}$	$\mathbf{\Delta a_2}$	$\mathbf{\Delta b_3}$	$\mathbf{\Delta b_2}$
system.	$+0.78$	-0.75	-0.01	$+1.64$	$+1.68$
random	± 0.72	± 2.61	± 0.22	± 0.42	± 0.56

Table 2: Expected snap-back of main dipole and main quadrupole multipole components during early commissioning[13, 14].

One can derive the following propagation factors for the first order effect of snap-back of the systematic Δb_n and random $\sigma(\Delta b_n)$ error onto the beam parameters.

$$\Delta x \approx 0.28 \cdot \sigma(\Delta b_1) \qquad (4)$$
$$\frac{\Delta p}{p} \approx 10^{-4} \cdot \Delta b_1 + \text{tides} \qquad (5)$$
$$\Delta Q_{x(y)} \approx 8 \cdot 10^{-3} \cdot \Delta b_2 \qquad (6)$$
$$\Delta Q'_{x(y)} \approx 44(-39) \cdot \Delta b_3 \qquad (7)$$
$$\Delta C_- \approx 0.46 \cdot \Delta a_2 \qquad (8)$$
$$\Delta C_- \approx 0.014 \cdot \sigma(\Delta a_2) \qquad (9)$$

The factors have been evaluated using MAD and recent LHC injection optics (v. 6.5) while keeping the other parameters constant. The factors do not include feed-down effects driven by systematic orbit offsets inside the higher multipoles, which are difficult if not impossible to predict. As prior analysis performed for static perturbation shows, these contributions can be large especially for tune shift and coupling perturbation. Analysis described in [10, 11] gives worst-case estimates of tune and coupling, including feed-down effects.

Table 3 summarises the expected dynamic parameter perturbations and parameter requirements for single pilot beam, Stage I and nominal beam operation. Comparing the expected perturbation with Stage I requirements, it is visible that chromaticity is the most critical parameter to control, defining lifetime and dynamic aperture of the beam inside the ring. The tune may be less critical during early commissioning. Further, it may be required to control the coupling especially during the start of ramp in order to enable the control of other beam parameters.

For the orbit, the expected contribution due to random ground motion is in the order of $0.3 - 0.5\,\sigma$ over 10 hours [12] and due to the random b_1 snapback in the order of $0.3\,\sigma$ over about 100 seconds. Both effects can be sufficiently compensated by a slow automated orbit control loop running at a rate of about 1 Hz. Higher correction rates of up to 25 Hz may only be required during squeeze to nominal β^* of 0.5 m which, based on the initial quadrupole misalignment, may create an absolute uncorrected orbit shift of up to 30 mm, corresponding to a maximum orbit drift of about $0.1\,\sigma/\text{s}$.

	Orbit	**Tune**	**Chroma.**	**Energy**	**Coupling**
	[σ]	[Q]	[Q']	$\Delta p/p$	C_-
Exp. Perturbations:	0.5	0.0014 (0.06)	70 (140)	$\pm 1.5 \cdot 10^{-4}$	0.01 (0.1)
Pilot Bunch:	-	± 0.1	+10	-	0.1
Stage I Requirements:	$\pm \sim 1$	$\pm 0.015 \rightarrow 0.003$	> 0 & ± 5	$\pm \cdot 10^{-4}$	$\ll 0.1 \rightarrow 0.03$
Nominal:	$\pm 0.3/0.5$	$\pm 0.003/\pm 0.001$	> 0 & ± 2	$\pm \cdot 10^{-4}$	$\ll 0.01$

Table 3: Summary of pilot, Stage I and nominal requirements in comparison to expected dynamic perturbation. Static worst-case estimates are given in brackets [10, 11].

The simulated expected snapback of chromaticity decay and its rate of change is shown in Figure 3.

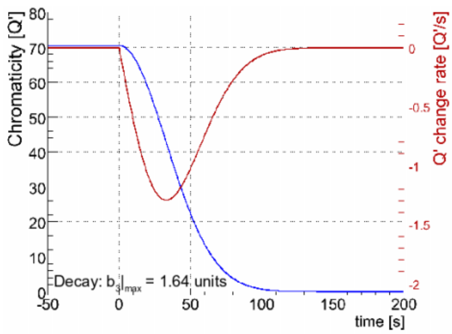

Figure 3: Chromaticity during snap-back.

The maximum rate $\Delta Q'/\Delta t$ at which the chromaticity changes is less than about 1.3 units/s. Assuming this as a constant snap-back rate and that a maximum chromaticity of 10 units can be tolerated, tolerance is reached after about 10 seconds. Hence, an automated control every 10 seconds or less may be sufficient during Stage I operation.

FORESEEN FEEDBACK BASELINE

Two basic parameter control techniques, feed-forward and feedback, are available. In the LHC, the use of a hybrid combining both these techniques is foreseen, as illustrated in Figure 4.

- Feed-Forward control is applied in case expected perturbations and machine responses are well known. The foreseen LHC feed-forward model is based on magnet measurement as described in [16]. However, model uncertainties as well as random and potential model imperfections may limit the achievable parameter stability required. In any case, this will be the first and only control choice for the LHC sector test and the very first beam inside the LHC.

- Feedback control using beam-based measurements, on the other hand, does not require a precise model of machine parameter response or prediction of the expected perturbations and are particularly robust with respect to random and unknown non-included perturbations. However, the Achilles' heel of such systems is often the measurement of the parameter itself. Certain parameters are not directly accessible for measurements, or measurements do not fulfil the required level of "transparency", in the sense that they potentially perturb the beam. Two types of feedbacks relevant for the LHC can be distinguished: feedbacks that act within a cycle and at repetition rates in the order of minutes to fractions of seconds and those that use (commonly averaged) measurements of one cycle but with applications as corrections for the next cycle. Although the latter, occasionally referred to as 'cycle-to-cycle feed-forward', has often relaxed requirements on timing, it is strictly speaking still a feedback and has the same issues with respect to required beam instrumentation, diagnostics and control algorithms.

From the point of view of available correctors circuits, all discussed beam parameters can be controlled [17]. The actual decision between feed-forward or feedback is thus mainly driven by the availability and robustness of the corresponding beam instrumentation and diagnostics.

From the controls point of view, the work of an operator is equivalent to a manual 'smart' feedback system. Semi-automated feedbacks are, if resources permit, the preferred choice, since they free operators, engineers in charge and other people involved in the operation of the machine for more important tasks such as beam measurements proposed in [18]. Also, robust and reliable feedback implementations are helpful for fast commissioning of the ramp, squeeze and other machine phases. Experience with LEP commissioning showed that many beams were lost due to absence of orbit and tune feedbacks [19]. In the LHC, this may become an issue with respect to the turnaround time, which is expected to be in the order of a few hours.

The following sections summarise the foreseen feedbacks as well as their principles and requirements concerning beam instrumentation.

Orbit

The LHC orbit feedback is the most advanced feedback, driven by collimation and machine protection requirements. The (present) design is based on a Singular Value Decomposition (SVD)-based global correction scheme with local constraints in space-domain as well as a Proportional-Integral-Derivative (PID) controller in time-domain, common in all modern light sources. The feedback has been optimised for a robust and failure-tolerant operation. Its prototype has been very successfully tested in the SPS [20, 21].

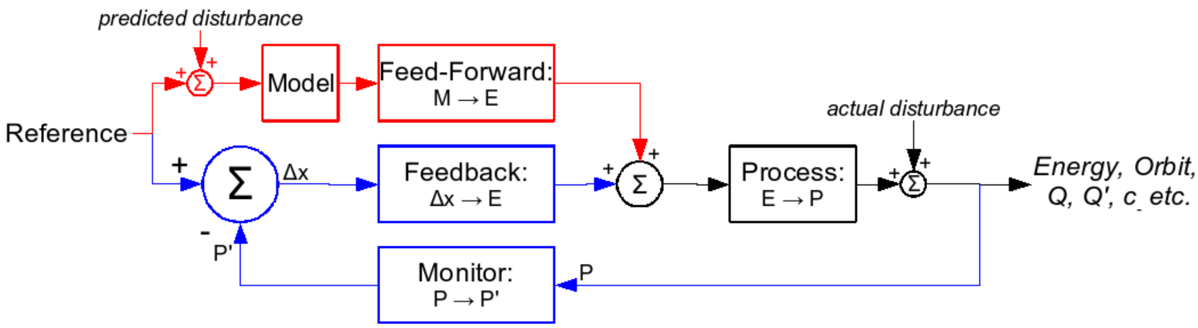

Figure 4: Schematic hybrid FF/FB scheme: For coherent control and avoidance of cross-talk, the feedback (blue) should be aware of the feed-forward correction (red).

In case of problems with the LHC-wide synchronised acquisition trigger, it is possible to run the feedback controller in self-triggered mode at about 1-2 Hz. The early use of an orbit feedback operation would help minimise dynamic feed-downs due to the orbit. The orbit feedback does not, by design, correct the dispersion orbit in order to minimise the cross-talk between energy feedback and measurements such as the chromaticity, that may require a change of momentum $\Delta p/p$.

An early use of the orbit feedback is feasible since threading of the first injected beam requires the availability of beam position monitors (BPMs) as well as the verified polarity of BPMs and orbit dipoles. The proposed baseline can and should be used at an early stage as soon as circulating beam has been established. It is favourable to use this system prior to the first ramp.

Energy

The feedback minimising the SPS to LHC energy offset is based on a robust measurement using the oscillation amplitude Δx of the injected beam with respect to the closed orbit to estimate the injection momentum mismatch $\Delta p/p$ as sketched in Figure 5. The individual measurement is averaged over all $N \approx 300$ arc monitors to minimise effects due to BPM systematics and oscillations due to imperfect injections:

$$\frac{\Delta p}{p} = \frac{\sum_i^N D_i \cdot \Delta x_i}{\sum_i^N D_i^2} \quad (10)$$

The strength of this measurement is that the BPM systematics on the dispersion D_i and oscillation amplitude Δx_i at the BPM intrinsically cancel each other. Hence, a time-consuming high-precision calibration of about 1060 BPMs using beam is not necessarily required. Already, a moderate turn-by-turn acquisition resolution of $\Delta x \approx 200\,\mu\mathrm{m}$ (pilot) and the averaging over about 300 arc monitor yields a $\Delta p/p$ resolution of a few 10^{-6}, sufficient for nominal operation. The horizontal arc corrector dipole magnets will be used to adjust LHC energy. At a later stage, it is possible to extend the feedback and to compensate for solar and lunar tides in order to optimise (preserve) the aperture during collisions.

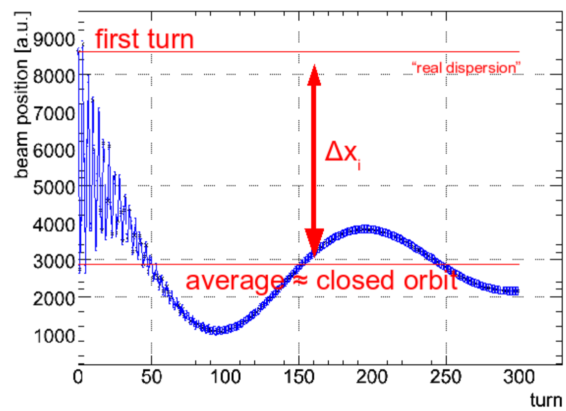

Figure 5: Schematic injection oscillation due to energy mismatch. The momentum mismatch $\Delta p/p$ is proportional to the difference Δx between first turn amplitude and closed orbit after energy oscillation has been attenuated.

In order to be available for Stage I, the beam synchronous timing (BST) should be able to trigger a turn-by-turn acquisition on the injection of an individual batch in the presence of a circulating beam, if applicable. The read-out of the 100k data should not block orbit acquisition.

The energy feedback could be used at an early stage as soon as circulating beam is established. It should be used before RF capture losses become an issue.

Tune

The traditional method of tune measurement requires a kick of the beam and a Fourier analysis of the acquired BPM multi-turn turn data. The kick should be in the order of 1 mm (1 σ beam r.m.s.) for a good signal-to-noise ratio of the turn-by-turn acquisition. This may cause emittance blow-up and is hence not ideal for a continuously running feedback. The kick is also an issue with respect to machine protection and collimation that requires beam oscillation to be less than $0.3\,\sigma$. As a consequence, these types of measurements may only be possible with slightly retracted collimators or with low intensity beam. Since this is a simple method, it will be a backup option in case of problems.

The new BI baseline foresees the Base-Band-Q Meter

(BBQ), which has been successfully tested at RHIC, Tevatron and SPS [23], as the standard tune-meter. The instrument can measure the tune without any excitation and resolution in the 10^{-4} range. An example of the BBQ measured tune traces in the SPS is shown in Figures 6 and 7. The BBQ may require small kicks to enhance the signal-to-noise ratio of the tune signal in the presence of high residual noise on the beam and thus will be used within a phase-locked-loop (PLL) to improve the robustness of the measurement. If required, the excitation level is expected to be in the range of $0.1 - 10\,\mu\mathrm{m}$ level, depending on the residual noise level on the beam. The expected emittance blow-up is negligible. In case the BBQ is used in combination with a kick, the Q-kicker limits the maximum rate of the tune measurement to less than about 2 Hz, which is sufficient for Stage I operation. The BBQ is expected to be available during the first days of LHC operation and will be used in a tune feedback.

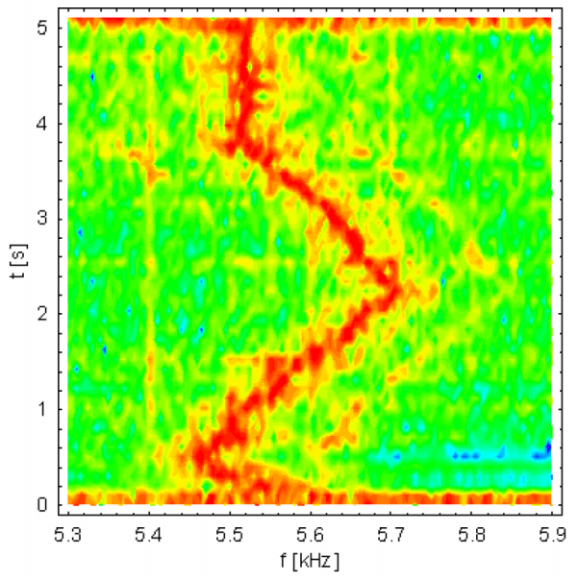

Figure 6: Logarithmic colour-coded tune trace measured with the BBQ in the SPS. The synchrotron side band is visible. No excitation of the beam was required for this measurement [23].

However, there remain some issues such as potential locking of the PLL on other signals than the tune that potentially hamper the use of BBQ within a feedback system:

- Synchrotron side bands located 30-60 Hz on both sides of the main tune peak. The error corresponds to about 0.005 in units of the tune and may be acceptable for commissioning and Phase I operation.
- Multiple of mains (50 Hz) signal: The BBQ sensitivity is high enough to measure the residual mains ripple on the beam, which is in the order of a few 10 nm. In case the tune is close to one of these lines, the mains signal is enhanced and the BBQ PLL may (measure) lock rather on these lines than on the actual tune, as seen in Figure 7. If not compensated through a higher excitation of the tune peak (PLL), this would introduce a quantisation effect in the order of $\delta Q \approx 0.002$, which might be acceptable for commissioning and Phase I operation.

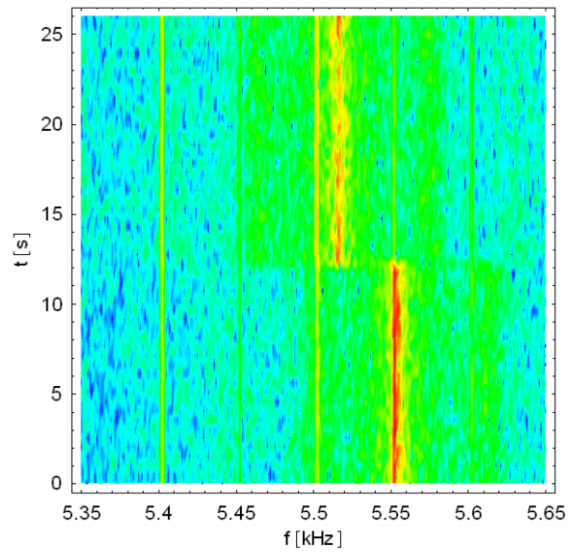

Figure 7: Logarithmic colour-coded tune trace measured with the BBQ in the SPS. It is visible that the mains signal (vertical lines) is enhanced if the tune approaches the multiple mains signal.

- Coupling: Experiences at RHIC with a prototype feedback loop described in [24, 25] show that global coupling may be an issue for tune measurement in the LHC. In the presence of coupling, the BBQ (as any other classic Q-meter) does not measure the unperturbed tunes but instead the rotated eigenmodes that cannot be reliably used to stabilise the tune within a feedback loop.

Since the BBQ system is available with first beam, the tune feedback may be used during commissioning. However, it is of paramount importance that potentially large global coupling contributions are corrected before performing feedback on the BBQ tune measurements. Commissioning will show the relevance of coupling. In order to minimise the transition between 'measurement only' and feedback operation, it would be helpful if the high-level BBQ GUI application is capable to not only display and identify the tunes but has also the possibility to control the tunes in a semi-automated fashion on the time-scale of few seconds. This would help to test and evaluate robustness as well as debug the algorithms involved under operator supervision before being implemented in a faster low-level real-time controller, running at the rate of a few Hz.

Chromaticity

For control of the linear chromaticity during commissioning and Stage I operation, the well-proven momentum modulation and tune tracking method will be used, as was in LEP. The resulting chromaticity can be derived through the following equation:

$$Q' \approx \frac{\Delta Q}{\Delta p/p} \quad (11)$$

A slow trapezoidal excitation of $\Delta p/p \approx 10^{-4}$ seems to be feasible within the RF baseline [8]. This feedback could be implemented and used for early commissioning and may be enough to cope with snap-back and ramp-induced b_3 drifts expected during Stage I operation. Since this measurement relies on the tracking of the tune, it requires a good control of coupling.

At a later stage the head-tail-chromaticity measurement may be used. Presently this method requires large kicks and can, consequently, only be used in dedicated machine runs. However, modification of the measurement to a similar principle as in the BBQ is envisaged. This would reduce the required excitation level and make it potentially compatible with continuous feedback during nominal operation. This system requires time for commissioning and is not likely to be available for commissioning.

Coupling

Prototype studies at RHIC show that a reliable tune feedback operation has been thwarted by transition crossing and coupling [24, 25]. In reply to this experience, a real-time coupling measurement based on a BBQ-PLL principle was developed and tested at RHIC and will be tested in the SPS this year and later used in the LHC. Besides a direct measurement of the coupling C_-, this system can measure the unperturbed tunes and the split Δ_- that would be present in the absence of coupling. These signals are favourable for a robust tune feedback loop. Figure 8 shows an example of this measurement during a copper beam ramp at RHIC.

A common problem of tune, chromaticity and coupling feedback is that the measurement may break in the presence of large coupling and chromaticity. As a result, the control of tune, chromaticity and coupling will evidently fail. The proposed solution to break this ’chicken-egg’ problem is to control the chromaticity and coupling before its measurement becomes an issue. Thus, it would be favourable to commission these feedbacks at an early stage, possibly before starting the first ramp in order to counteract potential problems during the ramp. Some control strategies for global coupling control exist but need more refined analysis. Since a coupling feedback system will be used at RHIC during 2006, valuable experiences may be gained that could be helpful for commissioning the tune and coupling measurement system in the SPS and LHC

CONCLUSIONS

The beam parameter perturbation predicted for Stage I operation indicate that automated control of energy, orbit, tune, chromaticity and coupling is required to a certain level. The control of the parameters has a direct impact on losses in the machine. Their requirements scale rather with the total stored beam intensity and energy than with the actual operational phase.

Feedbacks are most useful and efficient at an early commissioning stage where the machine is in a less precisely known state. They cope well with random effects and machine uncertainties that are minimised intrinsically during continuous operation. The beam instrumentation required for feedbacks could partially be an issue. The orbit and energy feedback pose the least problems since the BPM system is expected to be fully available right from commissioning. However, tune, chromaticity and coupling feedback may not be available on day 0 due to potential PLL issues, which must be clarified with first beam during early commissioning.

There are two reasons to foster and establish feedbacks at an early stage: If working properly, they free the LHC engineers in charge, operators and others for more important tasks during commissioning. Secondly, large uncontrolled coupling and chromaticity makes it difficult to measure and control tune, coupling and chromaticity in the first place.

In order to meet their requirements at an early stage, it would be favourable to commission the tune PLL and coupling measurement to an operational stage as early as possible to counteract potential problems of tune and other measurements due to coupling and chromaticity.

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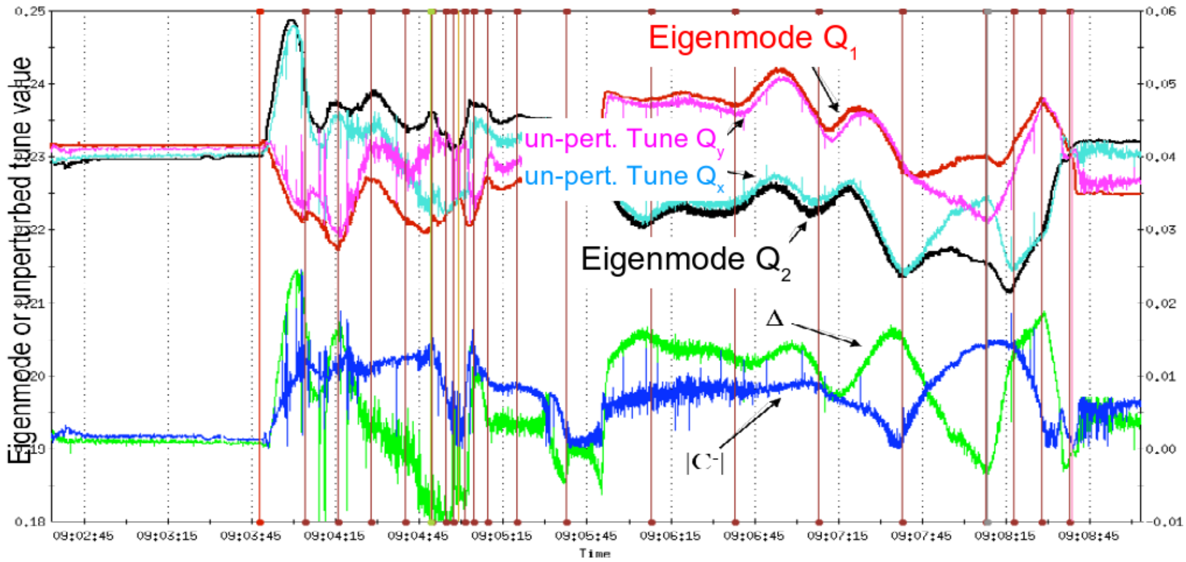

Figure 8: Continuous coupling measurement during RHIC Cu ramp[25]. The unperturbed tunes and measured eigenmodes are shown in the upper half of the plot and the resulting coupling and unperturbed tune split in the lower half. While the unperturbed tunes cross, the separation of the measured eigenmodes is entirely defined by coupling, making measurement and feedback on the real tune and chromaticity impossible. The perturbations at the early part of the ramp are due to transition and will not be an issue for the LHC.

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