LHC ORBIT FEEDBACK TESTS AT THE SPS

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Abstract

The real-time orbit feedback system foreseen for the LHC will be an essential component for reliable and safe machine operation. A test setup including a number of beam position monitors equipped with the LHC acquisition and readout system have been installed in the SPS ring to perform prototyping work on such an orbit feedback. A closed loop digital feedback was implemented and tested with LHC beams on the SPS during the 2003 machine run. The feedback loop was tested successfully at up to 100 Hz. The performance of the feedback loop and of its constituents will be described.

INTRODUCTION

At the Large Hadron Collider (LHC) that is presently built at CERN, the presence of a high intensity beam in an environment of cryogenic magnets requires an excellent control of particle losses from the beam. For example the performance of the LHC beam cleaning system depends critically on the beam position stability that is affected by ground motion, field and alignment imperfections and beam manipulations ([1] and [2]). The role of the real-time LHC Orbit Feedback System is the minimisation of closed orbit perturbations around its reference position.

In each plane, the beam position of the two LHC rings is sampled by ≈ 1000 beam position monitors (BPMs) and is controlled by ≈ 500 individually powered correction dipole magnets (CODs). Since all equipment is distributed over the $26.7\,\mathrm{km}$ circumference, data exchange between a central feedback controller and the BPMs and CODs is an important issue. It is presently foreseen to use the LHC technical network for data communication. The large geographical distribution makes the LHC orbit control unique.

The aim of prototyping the orbit feedback in the SPS was to test the LHC BPM acquisition system under reasonably realistic conditions, even though the total number of BPMs is smaller, to evaluate the network communications between components and to gain experience with such a feedback architecture. In particular the limitation due to the network was investigated. Valuable experience was gained for the final design of the feedback system for the LHC.

TEST SETUP

For the prototype studies, 6 dedicated position monitors (*BPMBs*) equipped with LHC acquisition systems were installed in the long straight section 5 of the SPS machine (*LSS5*) and the power converters of the local CODs enabled to receive real-time reference current changes. The pre-processed BPMB data is send from the surface building BA5 over Ethernet[1] connection to the Prevessin Control Room (PCR) to a standard PC that houses the controller performing the correction and sends the steering data back to the COD power converter controller. A sketch is shown in figure 1.

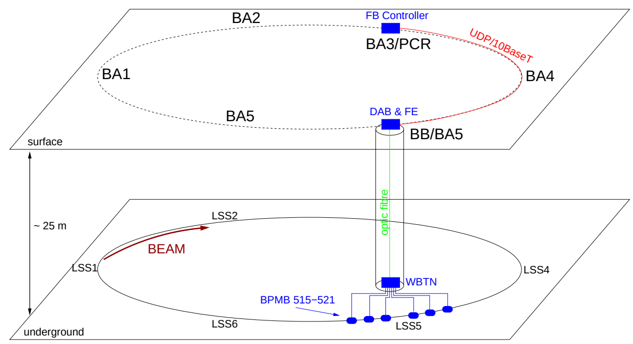

Figure 1: Site map of the orbit feedback components that are used for the SPS studies. The BPMBs and CODs are installed in LSS5, while the feedback control is performed in PCR.

FEEDBACK DESIGN

The control of the orbit with CODs is described by the beam response to dipole kicks and by the dynamics of the electrical circuit and power converter of the CODs.

The beam position change $\Delta X(t)$ at the i^{th} BPM measured at time t is given by

$$\Delta x_i(t) = \sum^{n} R_{ij} \cdot \delta_j(t) \qquad (1)$$

where $\delta_j(t)$ is the deflection due to the j^{th} COD. n is the total number of CODs. R_{ij} is the orbit response matrix. For the SPS CODs, the deflection $\delta_j(t)$ is approximately related to external excitation signal $E_j(t)$ through the second order equation

$$\ddot{\delta_j}(t) + \zeta_j \omega_{0j} \dot{\delta_j}(t) + \omega_{0j}^2 \delta_j(t) = E_j(t) \qquad (2)$$

In first order $E_j(t)$ is proportional to the reference current in the COD. The damping ζ_j and the eigenfrequency ω_{0j} are physical properties of the SPS CODs (magnet, electrical circuit and power converter).

Proper excitation signals $\delta_j(t)$ have to be derived from equations 1 and 2 in order to control the beam position and

[1] The choice for Ethernet is due to the number of clients connected to the network and the huge physical size of the machine.

to fulfil the desired beam reference condition:

$$x_i(t) = x_{reference_i} = const \tag{3}$$

Since the solution of equation 1 is independent from the time evolution of $\delta_j(t)$ and the relation between the reference current in and the deflection of a COD is obviously independent from its physical location in the ring, it is possible to decouple and split the differential equation system and solve the parts independently in *space* and *time domain.*

SPACE DOMAIN

We use a SVD based inversion algorithm for the prototype in order to solve equation 1 studies as described in [3, 4] and limit the steering to the region covered by the BPMBs. The solution is closed using two CODs at each side of the region. The other parts of the SPS are therfore unaffected by the feedback studies.

The possibility to perform the correction by a simple matrix multiplication with a constant numerical complexity $O(m \times n)$ is favourable for the use in a real-time control environment that strongly depends on a deterministic execution in time of the control algorithm.

TIME DOMAIN

The solution in the space domain yields a set of steady state deflections for the CODs that will move the beam to its reference position. Due to the circuit response, the COD does not reach its reference deflection instantaneously. In time domain the task is to design a controller that sends excitation signals (reference currents) $E_j(t)$ to the power converter to optimise the rise time. A simple feedback loop with three subsystems (a controller, the accelerator plant and monitor system) is shown in figure 2.

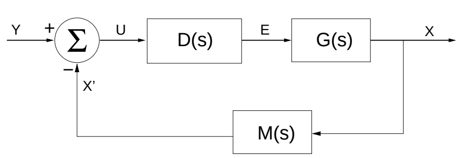

Figure 2: Basic Feedback Loop. G(s) denote the plant's, M(s) the monitor's and D(s) the controller's transfer function. X is the actual, X' the measured and Y the reference state of the plant that is driven by the excitation signal E.

Applying a Laplace transformation to equation 2 yields the following COD response function:

$$G(s) = \frac{\omega_0^2}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \tag{4}$$

In first order the BPMs do not contribute to the feedback response function ($M(s) = 1$). In the absence of other systems that contribute to the total transfer function, a possible control design is to match the controller zeros with the poles of the plant called *zero-pole* matching [5]. We choose a PID controller in order to cancel out the two poles of the COD transfer function:

$$D(s) = K\left(K_p \cdot 1 + K_i \cdot \frac{1}{T_i s} + K_d \cdot T_d s\right) \tag{5}$$

K_p, K_i and K_d are the gains of the proportional, integral and derivative part of the controller. The integration and derivation times are denoted by T_i and T_d. The factor K equals one if the poles are matched. We choose K_i as variable, because of its ability to minimise the steady state error. For a zero-pole matching the following conditions have to be met:

$$K_p = \frac{2\zeta}{\omega_0 T} K_i \qquad \text{and} \qquad K_d = \frac{1}{\omega_0^2 T^2} K_i \tag{6}$$

The second order plant poles are the most dominant ones. In practice the controlled plant has frequently more than one system that contributes with its response function, introducing additional poles. In our case the most important additional pole is due to the delays due to to the sampling (BPMs), the network delays and the digital implementation of the controller. The sampling delay ($T_s/2$, T_s sampling period) as well as the e.g. transport lag is well described by the Padé approximation:

$$G_{sampling}(s) = \frac{2/T_s}{s + 2/T_s} \tag{7}$$

To compensate these poles one could extend the controller by adding a zero and match it to the delay pole. However, using this type of pole matching the PID controller would loose its clear structure and modification would become less transparent. A more elegant solution is to compensate the poles of the plant (without delays) using the PID controller and to compensate the deteriorating effect on the feedback response due to delays using a Smith-Predictor[6]. Independent the choice, both methods are sensitive to the location of the poles and require a precise knowledge of the delays.

RESULTS

In order to confirm the designed PID parameter and feedback performance, the response function of each subsystem was experimentally verified. The measured SPS COD transfer function is shown in figure 3.

The LHC BPM acquisition and feedback system was successfully tested up to a sampling frequency of $100\,\mathrm{Hz}$ for the limited number of BPMBs.

The predicted gain factors have, within sampling errors, been verified by varying the gains and comparing the resulting response functions with the simulation.

The feedback system showed an overall good performance. At a $100\,\mathrm{Hz}$ feedback sampling rate it was possible to stabilise the beam within $8.5\,\mu\mathrm{m}$ as shown in figure 4. The attenuation was $\approx -12\,\mathrm{dB}$ at $1\,\mathrm{Hz}$ and $\approx -37\,\mathrm{dB}$ at

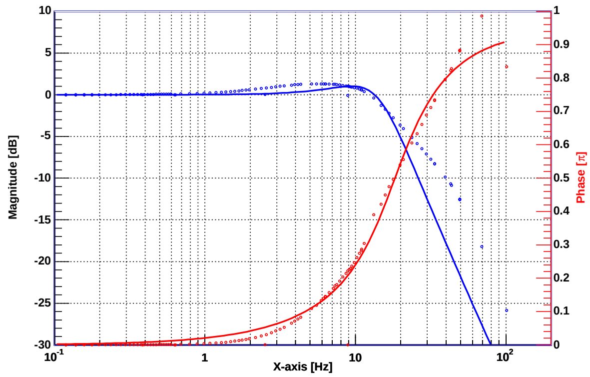

Figure 3: Frequency response function of the system composed of power converter and correction magnet. Measurements are represented by dots. The magnitude and phase relation are fitted for a second order response with $\omega_0 = 14\,\mathrm{Hz}$ and $\zeta = 0.52$ (solid lines).

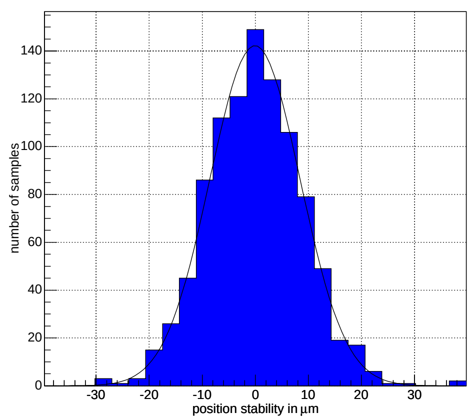

Figure 4: Distribution of the residual orbit derivations around the reference for a sampling frequency of $100\,\mathrm{Hz}$. The fit corresponds to a Gaussian distribution with $\sigma = 8.51\,\mu\mathrm{m}$.

$0.1\,\mathrm{Hz}$. The attenuation is proportion to f^2. The feedback gain is shown as a function of frequency is shown in figure 5. It is visible, that a higher feedback sampling rate results in a significant better attenuation since the bandwidth of the SPS CODs is around $15\,\mathrm{Hz}$. The stability is essentially determined by the noise of the beam position measurement and the sampling frequency f_s of the feedback system. The achievable sampling frequencies are sufficient for the future use to steer the slow cryogenic CODs that have only a bandwidth of about $1\,\mathrm{Hz}$.

The tests have shown that the SPS 10BaseT network backbone and the operating system of the front-end computers were the major sources for data loss and performance decrease due to non-deterministic delays. These additional delays were usually in the range of a few milliseconds but exceeded in worst cases several hundred milliseconds. Lowering the sampling frequencies reduced the risk of data loss due to filling network buffers. In 2004 the

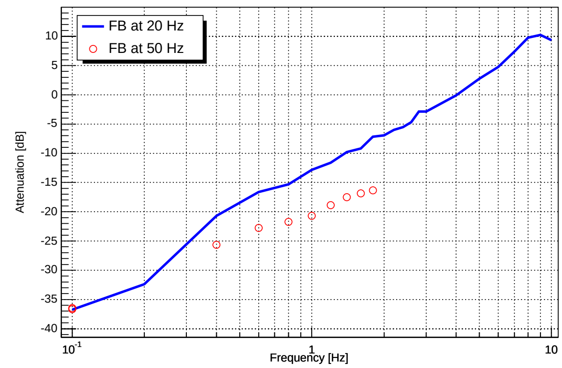

Figure 5: Measured performance of the feedback loop running at $20\,\mathrm{Hz}$ and $50\,\mathrm{Hz}$. The attenuation is given by $-20\log(\frac{A_c}{A_r})$, where A_c is the external excitation signal and A_r the residual maximum oscillation amplitude. The curve corresponds to PID gains of $K_p = 0.2$, $K_i = 0.8$ and $K_d = 0$. The cutoff at low frequencies of the attenuation is due to the residual BPM measurement noise and to the limited sampling duration.

SPS network was renovated, and the new switched technical network (gigabit backbone) reduces the worst case transmission delay to less than $1\,\mathrm{ms}$ which is adequate for the future LHC orbit feedback.

CONCLUSION

The LHC BPM acquisition system and a prototype feedback loop for orbit control have been successfully tested at the SPS. The local loop was operated up to $100\,\mathrm{Hz}$ which gives the possibility to increase the LHC design frequency of $10\,\mathrm{Hz}$ if it is required. The test have highlighted the criticality of the network and of the operating system for the implementation of a digital control loop. Future development will focus on network performance, minimisation of delays and deterministic response.

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