LHC Orbit Feedback Tests at the SPS

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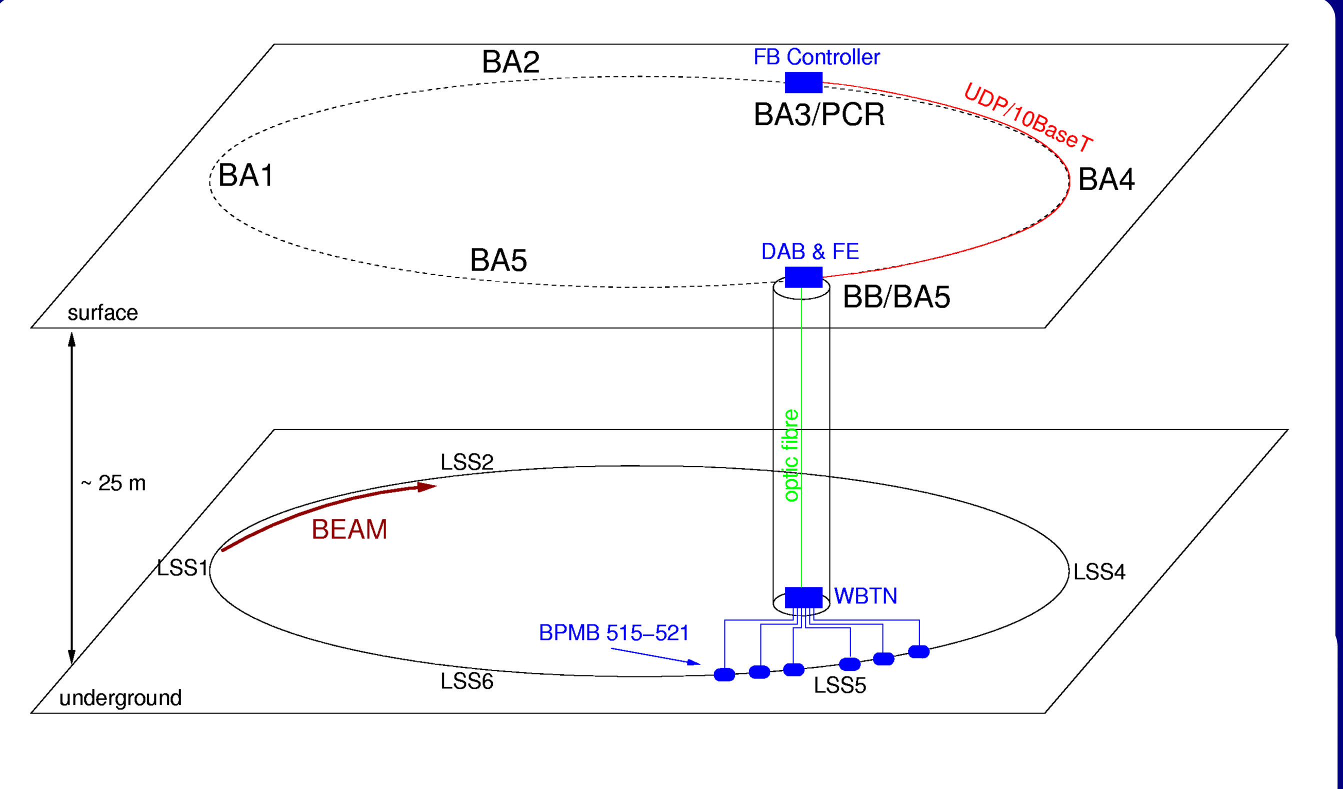
Experimental Results



Site map of the orbit feedback components that were used for the prototype studies in the SPS.
The BPMBs are situated in LSS5, their pre-processing electronic is installed in the underground cavern BB5 and their acquisition cards and front-end in the surface building BA5. The BPM data are send over a low-bandwidth Ethernet connection, to which all SPS front-end computer are installed, to the Prevessin Control Room (PCR next to BA3) where they are processed by a general purpose PC. The corrections are send back via the same Ethernet backbone to the ROCS crate in BA5 that sets the current of the COD power converters. The correction magnets are interleaved with the BPMBs in LSS5.

The Large Hadron Collider (LHC) is the next generation proton collider that is presently built at CERN. The LHC will be installed in the former LEP (Large Electron Positron Collider) tunnel. The presence of a high intensity beam in an environment of cryogenic magnets requires an excellent control of particle losses from the beam. Eventually the performance of the LHC may be limited by the ability to control the beam losses. The performance of the LHC cleaning system depends critically on the beam position stability. Ground motion, field and alignment imperfections and beam manipulations may cause orbit movements. The role of the future LHC Orbit Feedback System is the minimisation of closed orbit perturbations by periodically measuring and steering the transverse beam position back to its reference position.

The LHC is the first proton collider where a continuous control of the beam position is required during all operational phases, with maybe the exception of very low intensity beams. 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 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.

Envisaged Control Solution:

The control of the orbit $\Delta x_i(t)$ with CODs is described by the beam response to dipole kicks δ_j and by the dynamics of the electrical circuit and power converter of the CODs $\delta_j = \delta_j(t)$. To simplify the problem the coupled differential equation system are separated into space and time domain and solved independently using techniques from control theory and linear algebra:

beam response equation due to dipole kicks:

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

COD response due to external excitation $E_j(t)$:

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

Space Domain:

We use a SVD based inversion algorithm for the prototype in order to find a (pseudo-) inverse solution to the beam response equation that will move the spacial orbit distribution to its reference.

Advantages:
- Easy elemination of (near-) singular solutions (e.g. too high required deflections)
- Easy recalculation of the inverse beam response matrix in case of device configuration changes
- Correction through cast of simple matrix multiplication
- Fixed numerical complexity → fixed computational delays (pre-requirement for real-time control)

Solution are of steady state deflections: $\delta = (\delta_0, \delta_1, .., \delta_m)$

Time Domain:

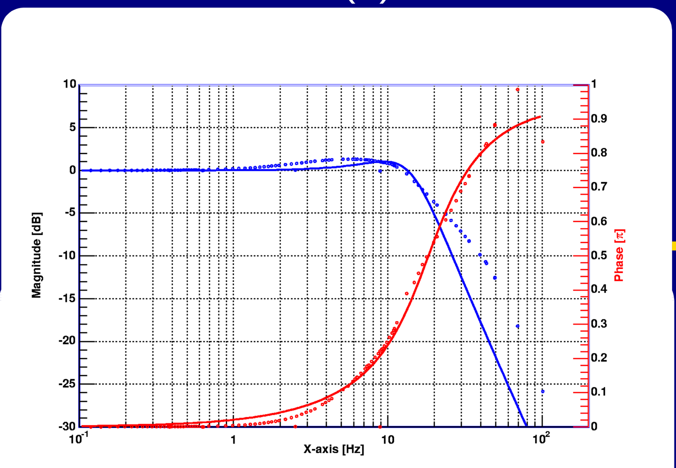
Design of a controller D(s) that sends excitation signals E to the plant (COD power converter) in order to minimise the rise time till $\delta(t)$ reached the steady state δ.
Zero-Pole matching: PID controller (gains K_p, K_i and K_d) compensates the dominant poles of the second order plant:

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

foreseen: Smith-Predictor extension of the PID in order to compensate the pole due to delay (sampling and transport lag due to network and front-end OS)

Theory

The COD Plant D(s):

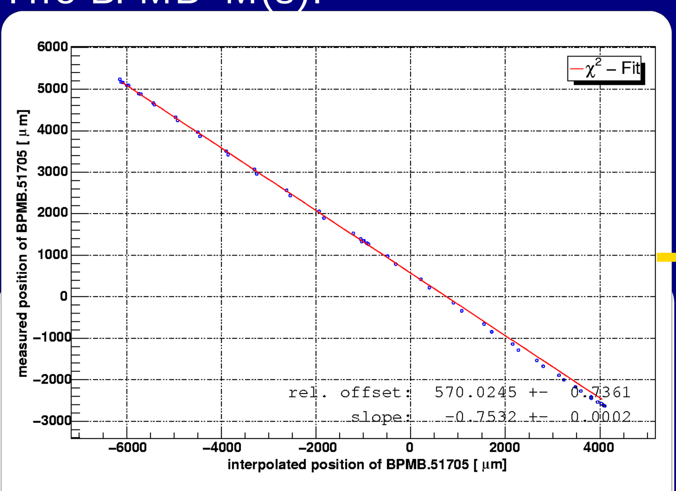


System response function.

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

The magnitude and phase relation are fitted for a second order response with ω_0= 14 Hz and ζ=0.52 (solid lines).

The BPMB M(s):



BPMB calibration using the neighbouring SPS monitors in order to match

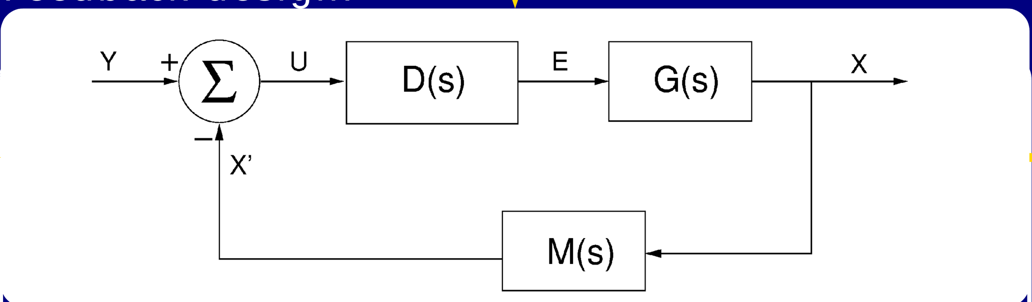
$$X'(s) = X(s) \Leftrightarrow M(s) := 1$$

The magnitude of the slope and its sign shows that this specific BPMB has a sign error that has to be taken into account.
The BPM further introduces a sampling delay (see delays)

Successful tested for sampling rates up to 100 Hz.

Hardware parameter pre-measurements and estimations

Feedback design:



First order feedback loop scheme. G(s) denote the steered plant's (COD & power converter), 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.
optimal control (zero-pole matching of plant) yields:

$$K_p = \frac{2\zeta}{\omega_0 T_s} K_i \;\wedge\; K_d = \frac{1}{\omega_0^2 T_s^2} K_i$$

Controller is digitally implemented and housed on a standard PC. Since all data exchange are unidirectional and retransmitted packets are as bad as lost packets, the exchange of data is done through UDP/IP that can be routed (switched) through the technical network. The correctness of the controller computation, apart from the correct excitation value of PID controller, depends on the time within the result is delivered to the COD system.
The correction in space has a very high numerical complexity (long calculation time). Hence the controller contributes with a delay to the total loop.

Delays:

additional dominant pole due to:

$$G_{delay}(s) = \frac{1}{T \cdot S + 1}$$

$$T = T_s/2 + T_c + T_{net} + T_{misc}$$

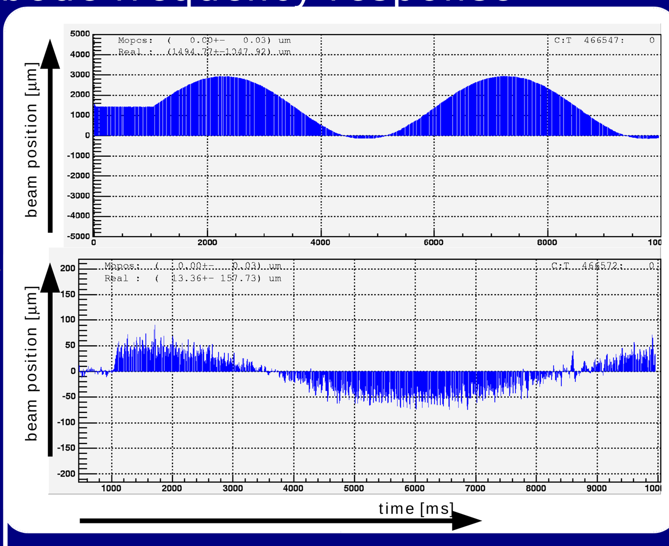
- Sampling of the BPMs
half a sampling period (T_s/2)

$O(n^2)$ of Controller:
SPS: negligible (just 6 Monitors/plane)
LHC: huge (~7.6GFLOP/sample) T_c~14ms

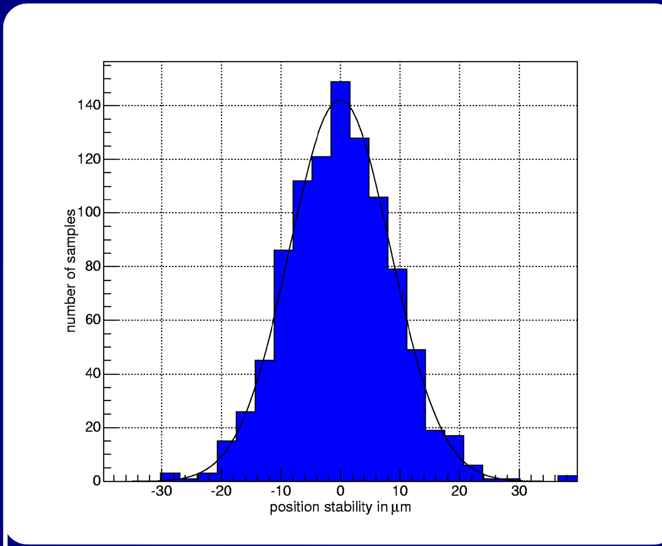
- Ethernet:
SPS (old): routed 10BaseT, large non-deterministic delays (T_{net}=1ms .. 2s!)
SPS (new): switched 100BaseT, worst case delay less than a few µs (to be verified).
LHC (predicted): switched Gigabit Ethernet, ~27 km optical fibre, numerous switches, expected worst case delay below 1ms

- Non-deterministic delays (T_{misc} due to the Operating System and network/controller implementation in the front-end computers in the range of one to tens of ms

performance verification using bode frequency response



Top: external artificial orbit excitation
Bottom: feedback loop on



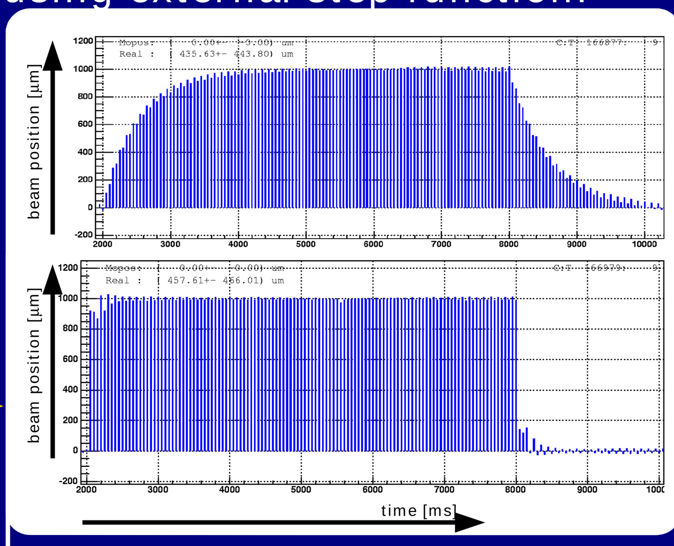
Distribution of the residual orbit derivations (feedback on) around the reference for a sampling frequency of 100 Hz. The fit corresponds to a Gaussian distribution with σ = 8.51µm

The delay pole increases the total response time respectively reduces the performance

$$T_{response} = T + T'$$

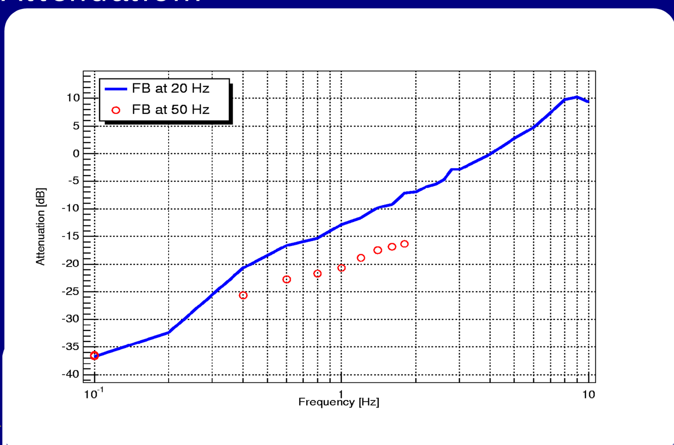
The controller can compensate for the overshoot and T' but not for $T_{response}$ (preservation of causality)

closed-loop response verification using external step function:



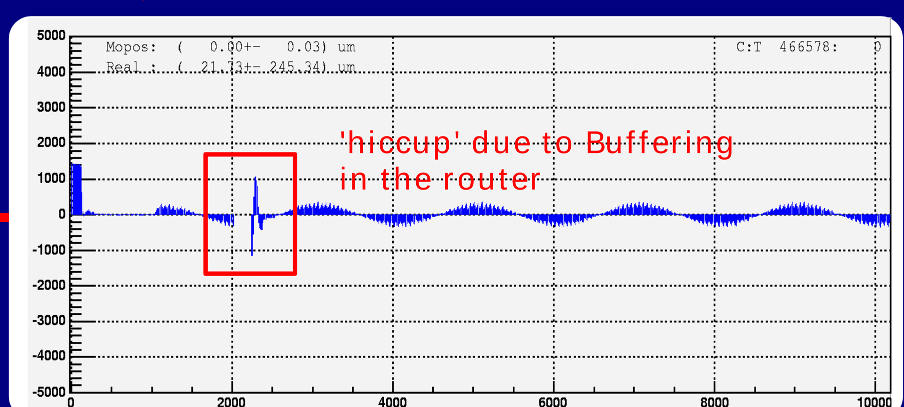
Measured feedback response of different PID gain settings to a step in the reference position (at 2000 ms and 8000 ms).
Top: pure integral controller (K_i= 1)
Bottom: Zero-Pole matching
(the residual difference to the step reference is a result of the uncompensated delay pole)

Total Feedback performance Attenuation:



Measured performance of the feedback loop running at 20 Hz and 50 Hz. The attenuation is given by $-20\log(A_c/A_r)$, 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.

Packet loss & long non-deterministic delays



Conclusion

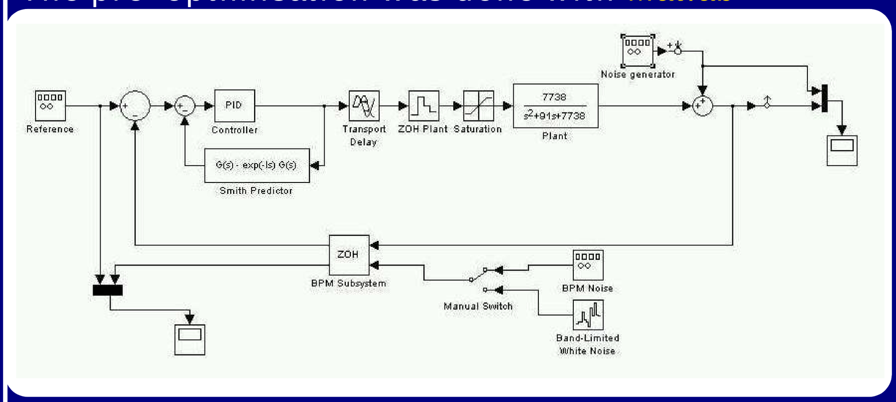
The LHC BPM acquisition system and a prototype feedback loop for orbit control have been successfully tested at the SPS. The local loop was operated up to 100 Hz which gives the possibility to increase the LHC design frequency if it is required.

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 responses.

Simulation and modeling:

MAD-X tool was used to solve the problem in space domain and to simulate the effect of dipole kicks and other machine imperfection on the orbit orbit. A linear model of the machine derived from the MAD-X twiss information simplified and speed up the (SVD) orbit steering algorithm.

The pre-optimisation was done with Matlab

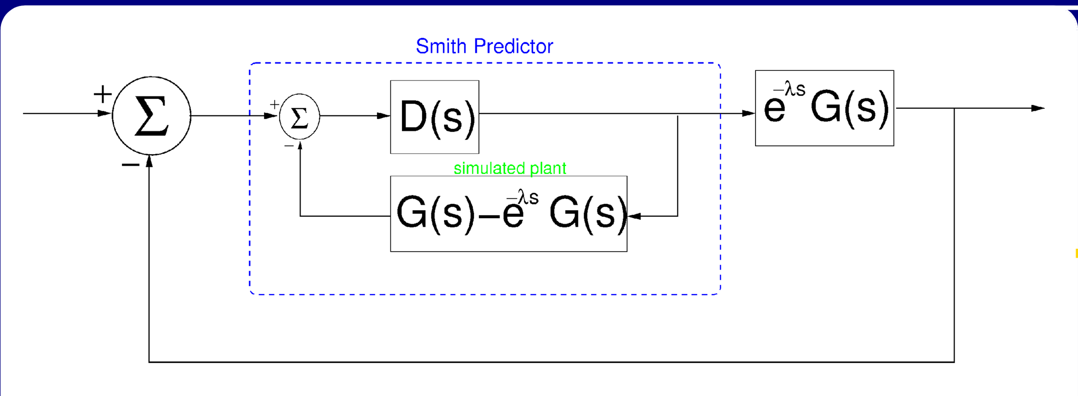


A testbed that simulates the open loop and orbit response consisting of COD->BEAM->BPM was developed. It implements the same data delivery mechanism/infrastructure as the BPM and COD front-ends.

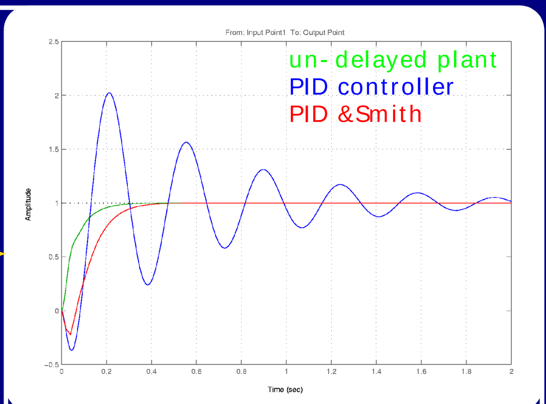
•present and future feedback controller can be tested without beam and running machine
•controller be tested under LHC similar conditions.

The testbed runs up to 1 kHz for a full SPS resp. 50 Hz for a full LHC orbit simulation which is sufficient for a precise simulation of the plants that have bandwidths of ~14Hz (SPS) and ~1 Hz (LHC) and closed orbit movements in the machines.

Smith-Predictor extension of the PID controller:



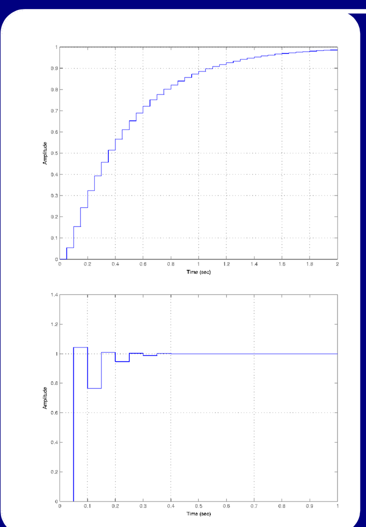
Smith-Predictor scheme. The internal feedback path includes a simulation of the plant



Simulated effect of the FB-loop including Smith-Predictor

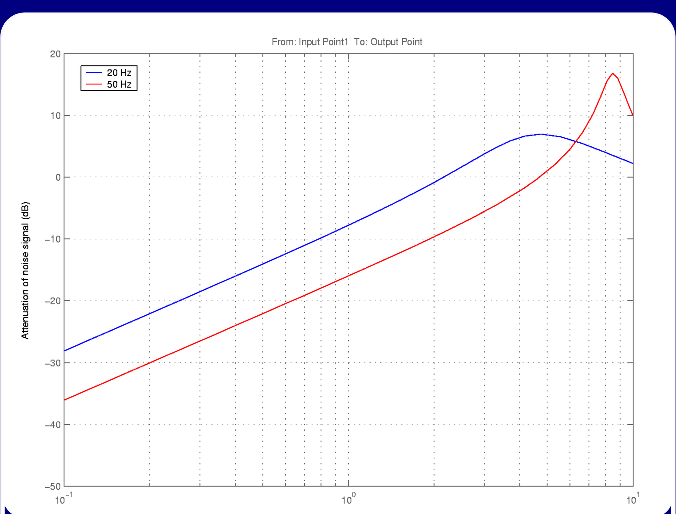
A Smith-Predictor extension is foreseen to be added to the PID controller in order to compensate for the worsening effect of the transport lag T (compensates T'). The Smith-Predictor preserves the design characteristics of the un-delayed plant as shown in the figure. It includes and is sensitive to the plant simulation and delay estimation. A good plant model and deterministic delays (constant) are required.
Wrong delay estimation may drive instabilities in the feedback loop.

Simulated closed-loop response:



Simulated feedback response of the used PID gain settings to a step in the reference position. The normalised position is plotted as a function n of time in s. The reference position changes from 0 to 1 at 0s. The plots correspond within the sampling precision to the experimentally measured responses. Deviations are likely due to unknown and uncompensated delays.

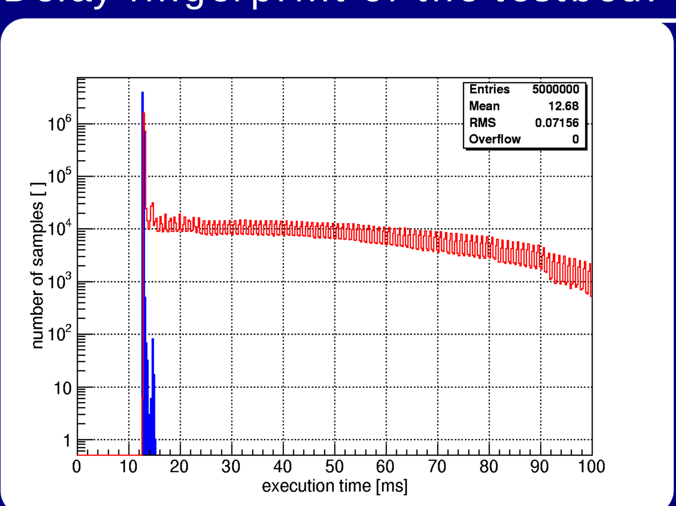
Simulated total feedback performance:



Simulated attenuation of the feedback loop running at 20 Hz and 50 Hz.
The measured attenuation is shown to be lower than the predicted one.
Be believe that the decreasing contribution is due to delay.

->Better knowledge about and control of actual delays in the loop is needed.

Delay fingerprint of the testbed:



In order to work in real-time it is important to measure the worst case delays of the involved subsystems.

The execution time is the time between the external HW timing start trigger till the finished simulation step (includes latencies)
(blue) with real-time control
(red) without real-time control

The worst case jitter (RT case) of 2ms is acceptable for the foreseen slow LHC orbit feedback

J.R. Steinhagen, 2004