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ORBIT FEEDBACK SYSTEM FOR THE MAX IV 3 GeV STORAGE RING

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Abstract

The paper gives an overview of the planned orbit correction system for the 3 GeV storage ring at the MAX IV laboratory, a light source facility currently under construction in Lund, Sweden[1, 2]. The ring will have a vertical beam size in the 1-4μm range in the insertion device (ID) straight sections depending on coupling[3], which places high requirements on the orbit stability. To meet this the ring will be equipped with 200 beam position monitors (BPMs) and two different sets of corrector magnets, which will be used by two separate orbit feedback loops; a slow orbit feedback (SOFB) loop to handle misalignments and drifts and a fast orbit feedback (FOFB) loop to reduce beam jitter. The paper also includes a brief description of the various engineering boundary conditions on the orbit feedback design for the MAX IV 3 GeV storage ring.

INTRODUCTION

For the MAX IV 3 GeV storage ring, the vertical beam size on the long straight sections at the 1Å diffraction limit will be $\sigma_y = 4\mu$m, with the possibility of further decreasing σ_y down to 1μm through a reduction in coupling. This small vertical beam size places very high demands on the position stability in the insertion device (ID) straights.

Furthermore, the storage ring lattice includes a significant number of strong sextupoles in the achromats. Orbit excursions in the sextupoles will affect the achievable coupling and introduce vertical dispersion and the orbit feedback system must therefore be able to minimize such orbit errors.

To stabilize the orbit relative to the BPMs a combined SOFB+FOFB system was decided upon, where the former deals with misalignments and long-term drifts while the latter deals with orbit noise.

Starting with reviewing the theory, the beam dynamics of the MAX IV 3 GeV storage ring are highly linear in the vicinity of the design orbit and the plant is thus well described by

$$y_k = R(z)(\mathbf{U}\Sigma\mathbf{V}^T)P(z)u_k + d_k \qquad (1)$$

where

y_k represent the BPM outputs.

$P(z)$ is a diagonal matrix with elements $p_j(z)$ containing the actuator dynamics for corrector j.

$R(z)$ is a diagonal matrix with elements $r_i(z)$ containing the sensor dynamics, including latency, for BPM i.

$\mathbf{U}\Sigma\mathbf{V}^T$ is the Singular Value Decomposition (SVD) of the linear response matrix $\mathbf{M}$. This matrix is constant in the z domain.

u_k represent the corrector magnet set values.

d_k represent orbit disturbances, i.e. BPM noise, beam vibrations, et.c.

k is the iteration number.

SENSORS

The storage ring will be equipped with 200 BPMs, ten for each achromat. The high number is not only motivated by the requirement of adequately sampling the betatron tunes of $\nu_x = 42.2$ and $\nu_y = 16.28$, there is also the previously mentioned requirement to minimize coupling due to orbit errors in the strong sextupoles present in the ring. The BPMs will therefore be calibrated against the sextupole centres using secondary windings powered in quadrupole mode[1], using the standard beam-based calibration method[4].

All BPMs will have a fast acquisition mode to collect data at 10,000 samples/s for both feedback loops, although the SOFB controller will apply a time average on each channel, i.e. position reading. Having fast acquisition capability on all BPMs adds redundancy and preserves modularity, compared with using two different types of electronics.

The sensor dynamics is a pure delay due to signal processing time. The orbit feedback algorithm calls for a sensor latency of below 200 μs, which in the worst-case corresponds to $r_i(z) = z^{-2}$.

ACTUATORS

The individual actuator dynamics $p_j(z)$ depend on the vacuum chamber, the magnet itself and the power supply. Detailed design work is still ongoing for all these systems, apart from the standard slow corrector magnet.

The vacuum chamber in particular has had implications for the orbit feedback system, as the 3 GeV storage ring is equipped with a NEG-coated Cu vacuum system for most of the circumference[1, 5]. The high electric conductivity of Cu severely constrains the achievable actuator bandwidth, as the eddy currents induced by and counteracting any change in the corrector magnet field will persist for a considerable time. However, due to the high thermal conductivity Cu is also suitable from a cooling perspective.

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Power supplies have not yet been ordered, although preliminary specifications have been determined on the basis of the orbit feedback simulations.

The bandwidth of the standard actuators, excluding the power supplies, have been simulated using 2D Finite Element Method (FEM) software and the results can be seen in Fig. 1. For the fast actuators the vacuum chamber eddy currents will be the limiting factor for the bandwidth, while the slow actuators will primarily be limited by the iron core.

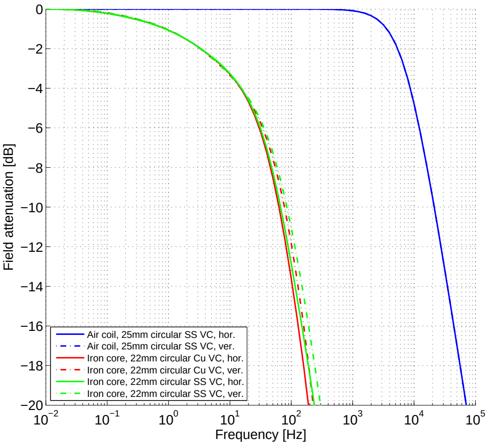

Figure 1: Simulated actuator bandwidth for different actuators, excluding power supplies. Note that the bandwidth of the final fast actuator may end up being constrained by the power supply. The iron core corrector with a stainless steel (SS) chamber is included for comparison only.

Slow Set

As the slow actuators will be used to correct the static and slowly drifting orbit errors the primary consideration is field strength rather than bandwidth. They can thus be placed over a Cu chamber and have a solid iron core, which as a side effect reduces the requirement on power supply jitter as both chamber and yoke will act as a frequency filter. Maximum kick amplitudes for slow actuators are 0.38 mrad in both planes.

In the horizontal plane there will be ten such correction magnets per achromat. In the vertical plane there are unfortunately engineering constraints. Most importantly the SR extraction at each long straight section resulted in the removal of the second vertical corrector in the matching cell following the straight. In total, the slow set will thus include 200 horizontal and 180 vertical corrector magnets.

The bandwidth plot of the slow actuators is visible in Fig. 1 where it can be seen that the iron core is the primary bandwidth limitation; the Cu chamber cut-off frequency (-6 dB) is above 200 Hz.

Fast Set

The fast actuators will be used to attenuate coloured orbit noise with frequencies up into the 100 Hz range and thus require high bandwidth. The magnets will thus be either air coil magnets or have ferrite cores; the detailed design is not yet finalized. Maximum kick strengths will be 10 μrad for both planes.

In order to avoid the shielding effect of the Cu vacuum chamber the magnets will be placed at some of the few locations where the vacuum system design mandates stainless steel regardless. Two such locations are on ion pump locations in the short straight sections, with the remaining two located next to the BPM heads flanking the long straight, which will be made out of steel. The vacuum chamber geometry will be circular, 25 mm inner diameter and with a 1 mm wall thickness, which yields a 11.75 kHz bandwidth (-6 dB, or about 50% amplitude) in FEM simulations. However, this is excluding the power supplies. As power supply specifications have not yet been determined it is not yet certain whether the fast actuator bandwidth will be limited by the vacuum chamber or the power supply.

Each achromat will contain four fast magnets in order to be able to create a closed orbit bump around each long straight and provide redundancy. The exception will be the achromat following the injection straight where the need for an injection channel in both matching cells means these locations are unsuitable due to a different shape of the vacuum chamber. Thus, there will be a total of 78 fast correctors in each plane.

ORBIT FEEDBACK ALGORITHM

The controllers used so far in design simulations for both the SOFB and FOFB loop are standard PI controllers, which perform well. For regular operation, anti-windup will be added to the SOFB controller to deal with possible saturation of the actuators.

Both controllers will be global in the sense that they collect data from all BPMs. Thus the response matrices will describe overdetermined systems when solving for the actuator settings, u_k. This necessitates sensor weighting, as the position stability on the ID straights has priority.

The response matrices will also undergo Tikhonov regularization [7] during their inversion for the feedback controllers, in order to avoid numerical instability. Thus the inverted matrix to $\mathbf{M} = \mathbf{U\Sigma V}^T$ with singular values σ_i is constructed according to

$$\mathbf{M^{-1}} = \mathbf{VDU}^T \tag{2}$$

$$D_i = \frac{\sigma_i}{\sigma_i^2 + \lambda^2} \tag{3}$$

where λ is the regularization parameter.

Slow Orbit Feedback

In the SOFB loop there is some variation between actuators, both in vacuum chamber geometry but especially magnet design. The dynamics $p_j(z)$ of eq. 1 will therefore vary between the different actuators in the SOFB loop.

However, this is not considered a large issue as their cutoff frequency (-6 dB) will be 30-34 Hz and thus in the range where the FOFB loop greatly attenuates orbit disturbances. There is also the possibility of attaching digital filters to each actuator output in the SOFB controller in order to equalize the actuator response. As the SOFB actuator bandwidth is not an important consideration all actuators can be matched to the "slowest", thereby avoiding placing a greater burden on the actuator power supplies.

While the SOFB loop will not be able to correct the vertical orbit error in all 200 BPMs due to having only 180 vertical actuators, simulations in MATLAB Accelerator Toolbox (AT) [8] showed that the static orbit deviation inside the achromats due to field errors and misalignments are manageable in terms of their impact on coupling[6].

Fast Orbit Feedback

Unlike for the SOFB loop, any difference in actuator dynamics for the FOFB loop risks introducing high frequency noise in the kHz region. Therefore, care is taken to keep the actuator response as identical as possible during the design work, so $p_j(z)$ should be equal for all j (see eq. 1). The entire $P(z)$ matrix may then be substited against the scalar function $p(z)$.

The FOFB controller itself will only activate once the orbit error cannot be reduced further by the SOFB controller. If large orbit changes are detected, it will deactivate until the SOFB loop has returned the orbit to the correct references.

Controller Cross-talk

In order to avoid the two orbit feedback controllers fighting eachother without a frequency gap, a similar scheme to that employed at SOLEIL[9] has been implemented and tested in a MATLAB/SimuLink environment (see below). The SOFB controller calculates the orbit it is aiming to reach and feeds this to the FOFB controller, which adds this to its internal reference orbit. The FOFB controller outputs are averaged over time for part of the SOFB sampling period, and the estimated orbit effect of this is then added to the orbit error the SOFB controller is attempting to correct.

ORBIT FEEDBACK SIMULATION

In order to test the orbit feedback algorithm and perform parameter studies, a simulation was set up in SimuLink and MATLAB. An AT model of the MAX IV 3.0 GeV storage ring, including misalignments and field errors, was used as the basis of the plant in order to include nonlinear beam dynamics. Approximate actuator dynamics were included in SimuLink as discrete transfer functions, based on data from COMSOL FEM simulations. The SimuLink model also allowed easy inclusion of saturation effects, BPM signal processing delays and DAC/ADC quantization. As noise input, coloured noise was generated using the measured PSD from the girder test stand, amplified by the calculated "worst-case" lattice amplification factors[1], and added to the 400 sensor channels.

The main limiting parameter for the beam stability is not unexpectedly the resolution of the BPMs, where state-of-the-art resolutions of 200 nm is already a sizeable portion of the expected RMS beam size on the ID straights.

CONCLUSION

The MAX IV 3.0 GeV storage ring will use a combined SOFB+FOFB system for orbit correction, with controller communication scheme similar to that at SOLEIL to avoid a frequency gap. There will be two sets of corrector magnets, a fast set of weak corrector magnets installed over stainless steel chamber sections, and a slow set of iron core magnets installed over the standard Cu chamber.

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