BEAM-BASED MISALIGNMENT STUDIES FOR PHYSICAL REALIGNMENT OPTIONS AT cSTART

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Abstract

One of the objectives of the cSTART project (compact STorage ring for Accelerator Research and Technology) is the injection and storage of ultra-short electron bunches into a storage ring. With a planned storage time of 100 ms and a beam energy between 41 and 90 MeV, the beam will not reach equilibrium conditions. KIT plans injection from two sources, a laser-plasma accelerator and the linac-based FLUTE accelerator. Precise magnet positioning will be important for keeping the intended ultra-short bunch lengths. The initial laser-tracker-based alignments may not be sufficient to meet the requirements for such bunch lengths, resulting in the need for additional realignment options. This contribution presents the first studies of methods for beam-based misalignment measurements at cSTART targeted at the possibility to physically realign the magnets for improved alignment accuracy.

INTRODUCTION

The cSTART project [1] contains the VLA-cSR, the Very Large Acceptance compact Storage Ring for electrons. It is a storage ring with a circumference of 43.2m and a fourfold double bend achromat lattice. The standard optics [2] that will be used for commissioning is shown in Fig. 1. It will operate at an injection rate of 10 Hz resulting in a storage time of less than 100 ms. Due to the long damping time, the beam will therefore never reach equilibrium. The storage ring will be built in about 3.3m height above one of its injectors, FLUTE (Ferninfrarot Linac und Test Experiment). To achieve this, a steel construction will be built inside the FLUTE experimental hall. Due to these circumstances the alignment procedure of magnets is expected to be challenging. The planned alignment procedure consists of a rough element alignment on each girder followed by finer magnet alignments using laser trackers after girder installation. The alignment accuracy of the laser tracker depends on the distance to the components and will be limited to approximately 120 µm peak-to-peak. Following that, a beam-based determination of magnet offsets is foreseen. This determination requires methods and algorithms that need to be developed. Depending on the outcome of these determined offsets, a physical realignment of the main magnets is planned. For this, magnet positioning units (MPU) will be installed for each magnet enabling fine adjustments of the alignment of each magnet with 6 degrees of freedom (3 translations and 3 rotations). To simulate the beam dynamics for the VLA-cSR the accelerator toolbox (AT) [3] is used. Random errors are applied by simulated commissioning (SC) [4]. Since the distribution of errors is created as random distributions, the algorithms for correction, beam-based alignment (BBA) etc. require statistics. As compromise between good statistics and practical computation times, a number of 250 random error configurations have been generated and simulated.

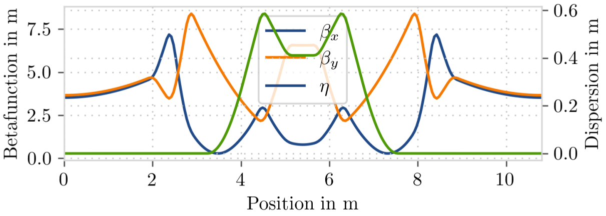

Figure 1: Optics functions for the initial optics used for commissioning of cSTART.

BEAM-BASED ALIGNMENT

A beam-based alignment will be performed to compensate the rough alignment of beam position monitors (BPMs). Being a non-equilibrium machine, the VLA-cSR will never reach closed orbit and thus, methods based on variations of the closed orbit cannot be used. A strategy based on single turn measurements should be employed and such a beam-based alignment procedure has been implemented in simulations. The strategy tries to minimize the effect of a change of quadrupole strength on the beam positions of downstream BPMs closely following the idea behind classical BBA algorithms. Due to the lower number of correctors in relation to the number of quadrupole magnets, it is not possible to build clean orbit bumps. Therefore, the first corrector upstream of the quadrupole magnet is used to distort the orbit and a single turn measurement is done. This also corresponds to the requirement of single or low number of orbits for the measurements due to the non-equilibrium nature of the VLA-cSR. A single turn is tracked using AT, starting at a random injection position. After recording the readings of the first downstream BPM ($\mathrm{BPM_D}$) along with the overall closest BPM ($\mathrm{BPM_C}$) to the quadrupole, the quadrupole magnet strength is changed and the change in position seen by the downstream BPM is taken. Then, the strength of corrector magnet in front of the quadrupole is changed and the procedure repeats. This is done for multiple corrector magnet strengths allowing to fit the reading of $\mathrm{BPM_C}$ and extract the reading for minimal disturbance caused by the change to the quadrupole strength. These readings then form the new beam-based alignment orbit that is used for subsequent orbit corrections.Due to the distance between BPMs and quadrupoles, their distribution and the level or misalign-

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ments, this procedure is not perfect, and the resulting orbit is closer to the quadrupole centers but still shows some offsets. This is emphasized by the fact that the injection position and angles will jitter along with the BPM readings due to noise. These facts require averaging over multiple injection shots.

QUADRUPOLE TO BEAM OFFSET MEASUREMENT

A beam moving acentric through a quadrupole will experience a kick. This kick is similar to a kick by a corrector magnet with the important distinction that the strength of the kick is depending on the offset of the beam relative to the center of the quadrupole. This fact can be used to estimate the offset between beam and quadrupole center. To exploit this we developed two methods shown below exemplary for the horizontal plane. Both methods rely on single pass measurements.

Response-Based Method

The effect of a kick by a magnet, e.g. quadrupole, at position s_1 on the orbit position seen by a BPM at position s_2 depends on the kick strength and the resulting kicks of elements between s_1 and s_2. By changing the strength of the quadrupole an additional kick is produced that is relative to the offset of the beam to the magnet center. This kick induces an orbit shift in the BPM which can be used to estimate the offset between beam and magnet center can be estimated. To do this and to take into account the effects of elements between s_1 and s_2, the response of a known offset in simulations with an ideal lattice is generated, similar to the orbit response matrix used for orbit correction

$$\Delta K_q \times O_\mathrm{s} = \Delta x_\mathrm{s}, \tag{1}$$

where ΔK_q is the change to the gradient of the quadrupole, O_s is the offset of the quadrupole used on the ideal lattice to generate the response and Δx_s is the recorded movement of the beam. By repeating this procedure either on the real accelerator or, as it is not yet built, in simulations on a lattices with errors, the offset between beam and quadrupole can be determined from the relation between the two results which gives

$$O = \frac{\Delta x_\mathrm{s}}{\Delta x} O_\mathrm{s}, \tag{2}$$

where O is the offset between magnet and beam for the lattice with errors and Δx is the recorded change of the bpm reading.

Results For the simulations, one set of random misalignment errors were applied to the lattice. Then, a set of orbit corrections following first turn corrections were performed. The resulting machine is stable with residual orbit offsets. Determining the offsets between quadrupoles and beam with the response-based method gives the results shown in Fig. 2.

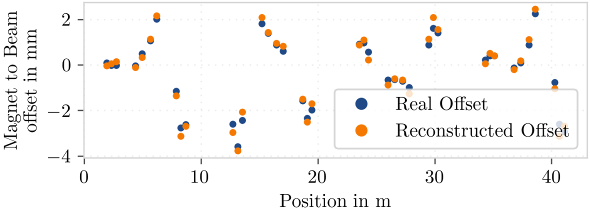

Figure 2: Offset between beam and quadrupole for a random lattice of the VLA-cSR. Blue indicates the real offset and orange indicates the reconstructed offset by using the response-based method.

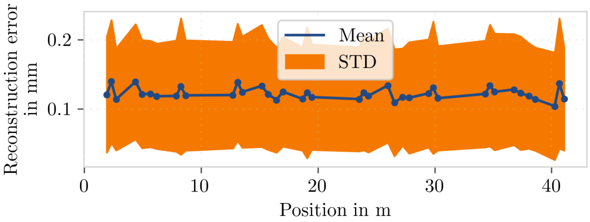

Figure 3: Average and standard deviation of the reconstruction errors for each bpm. The data is generated on 250 sets of random misalignment errors for the VLA-cSR lattice. It uses the response-based method and shows in blue the mean error and in orange the spread via standard deviation.

The results show quite good agreement between real and reconstructed offsets. However, this is only one set of random errors and to evaluate the effectiveness over a statistically significant number of random errors, the same mechanism was run on 250 different sets of random misalignment errors. The results in terms of average error between real offset and reconstructed offset as well as the standard deviation thereof, are shown in Fig. 3.

Kick-Based Method

The kick angle of a quadrupole due to an off-center beam can also be evaluated by using a downstream corrector magnet when turning off all quadrupole, sextupole and octupole magnets between the quadrupole and the corrector. This is achieved by setting the corrector strength such that the kick, caused by the change to the quadrupole gradient, is compensated for. This allows to reconstruct the change to the kick angle of the quadrupole and therefore the offset between beam and quadrupole center. The following procedure is used: First, the applicable corrector and BPM are identified. For the corrector, this is the first downstream corrector of the quadrupole and for the BPM this is the first BPM downstream of this corrector. Then, all magnets between quadrupole and this BPM are turned off. A baseline reading for this BPM is taken and the strength of the quadrupole is changed. Afterwards, the beam position at the BPM is recorded again and the corrector strength modified until the orbit position at the BPM is the same as in the baseline reading taken before. The strength of the corrector is now

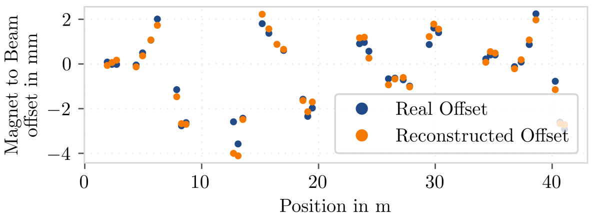

Figure 4: Offset between beam and quadrupole for a random lattice of the VLA-cSR. Blue indicates the real offset and orange indicates the reconstructed offset by using the kick-based method.

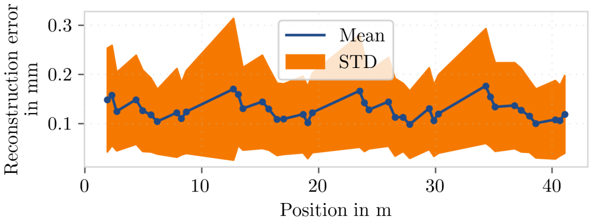

Figure 5: Average and standard deviation of the reconstruction errors for each bpm. The data is generated on 250 sets of random misalignment errors for the VLA-cSR lattice. It uses the kick-based method and shows in blue the mean error and in orange the spread via standard deviation.

$$O = \frac{k}{\Delta K_q} \frac{d_2}{d_1 + d_2}, \tag{3}$$

where k is the kick angle of the corrector magnet, ΔK_q is the change to the integrated quadrupole gradient, d_1 is the distance between quadrupole and corrector, d_2 is the distance between corrector and BPM.

Results The simulations use the same general procedure as for the response-based method, with the exception that the quadrupole to beam offset was determined with the kick-based method. The results with this method for one random error configuration are shown in Fig. 4. This is the same error configuration as used for Fig. 2.

The results show again a relatively good agreement between real and reconstructed offsets. However, this is only one set of random errors and to evaluate the effectiveness over a statistically significant number of random errors, the same mechanism was run on 250 different sets of random misalignment errors. The results in terms of average error between real offset and reconstructed offset as well as the standard deviation thereof, are shown in Fig. 5.

REALIGNMENT

To improve the alignment of magnets in the storage ring, physical movement of the magnets would be ideal. All magnets will be equipped with a magnet position unit (MPU) that allows fine adjustments of magnet alignment in 6 dimensions. As the accuracy of laser-tracker-based measurements is already exhausted with the planned alignment, a beam-based method would be required. The measurement presented in the previous section is a step in this direction, however it can only determine the offset between beam and magnets in contrast to the required offset between magnet and ideal orbit. o this end, the ideal orbit must first be defined. We define this as the orbit the beam takes with perfect alignment of all elements and all corrector magnets turned off. This orbit however is only theoretical and cannot be directly observed. Among the reasons are the inevitable misalignment of elements, particularly the BPMs. Therefore, a direct measurement between the magnets and this ideal orbit is not possible. While the planned measurements presented here already give insight into the magnet positions, they are not sufficient to reach the goal of minimum offsets to the ideal orbit. Some options to come closer to the goal are in preparation and are planned to be explored in simulations in the future, including iterative corrections, minimizing both the individual and the overall corrector strength.

SUMMARY

Two methods to determine the distance between quadrupole centers and beam were shown. Both methods work with an average residual error between about 0.1-0.2 mm depending on the applied random errors. The implementation of both methods shown will have to consider the effects of BPM noise in the range of up to 100 µm and the fact that each required sub-measurement will have to be done on individual injections since the storage time of the electron bunch will be shorter than 100 ms, leaving not enough time for multiple consecutive measurements. These individual injections are then also accompanied by injection jitter. Both these effects can be mitigated by averaging over several injection shots which will increase the required time. The determination of quadrupole to beam offsets is a first step in the direction of physical realignment of quadrupoles using beam-based measurements. Further steps will include finding algorithms to leverage beam-based measurements to determine the distance of elements to the ideal orbit.

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