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# ALIGNMENT TOLERANCE STUDIES FOR THE cSTART STORAGE RING

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*Abstract*

The KIT cSTART project (compact STorage ring for Accelerator Research and Technology) aims to demonstrate the injection and storage of a high intensity ultra-short electron bunch in a large acceptance storage ring using the FLUTE linac and a laser plasma accelerator (LPA) as injectors. Amongst the unique features of the cSTART project is the wide dynamic range of machine and beam parameters to be employed, i.e. bunch charge, bunch length, beam energy, etc. The comparably low energy beam (40-90 MeV) will be injected on-axis and will be stored for about 100 ms without reaching equilibrium due to the absence of significant radiation damping. In order to ensure stable operation of the storage ring, we need to specify tolerable magnetic lattice misalignments and understand the impact on the beam dynamics to be able to implement adequate correction schemes. In this paper, we report on first studies and simulation results on the effects of magnet misalignment, roll angles, and field errors on the dynamic aperture and momentum acceptance of the cSTART storage ring and propose a suitable correction strategy.

## INTRODUCTION

The cSTART project [1] aims to demonstrate injection of ultra-short bunches and LPA bunches into a storage ring. At the heart of the cSTART project is the cSTART Very Large Acceptance compact electron Storage Ring (VLA-cSR) with an adjustable energy between 50 MeV and 90 MeV. The lattice structure is based on 4 double bend achromat (DBA) cells including sextupoles and octupoles. Figure 1 shows the optics in the DBA mode including the lattice structure. For the two objectives, the VLA-cSR uses different optics. The LPA injection optics is based on a double bend achromat (DBA) optics [2], while the ultra-short bunch optics is based on ultra-low momentum compaction factors (low-alpha) [3, 4].

Therefore, there are two objectives to consider for the evaluation of acceptable misalignments and resulting optics parameters: On the one hand, there is the requirement to keep the large momentum acceptance for the optics for LPA injection, and on the other hand, there is the requirement for precise control over and achievability of low values of the momentum compaction factor [4]. The results presented here focus on the DBA optics.

## EXPECTED MISALIGNMENTS

The expected misalignments are mainly dominated by the accuracy of the laser tracker setup that is used to position the magnets. Due to the distance between the laser tracker and the magnets, the translational measurement error of the laser tracker is estimated between 60-70 µm which results in a misalignment of about 120 µm after considering the specified 50 µm alignment tolerances. The given values in this article are to be understood as plus and minus maximum values.

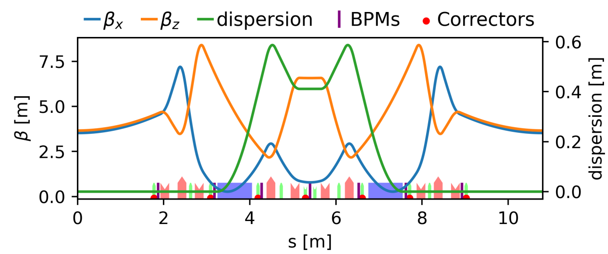


Figure 1: Lattice structure and optics function for the DBA mode of cSTART. Shown is one quarter of the ring.

Due to the comparably small diameter of the magnets (about 25-35 cm for quadrupoles and sextupoles), the angular misalignments are more difficult to determine. For measuring the roll angles (rotation around the beam axis), the accuracy is improved by adding metal rods ("arms") to the magnets, perpendicular to the electron beam direction. For pitch and yaw errors (missalignments caused by rotations around horizontal and vertical axes), no improvement for the laser tracker based alignment is opssible. The alignment is foreseen to be refined with beam based measurements.

The calculated, predicted errors are composed, as translational offsets, of a tolerance of 100 µrad and a contribution by the error of the laser tracker measurement. The alignment procedure and accuracies are still under investigation and misalignment estimates at time of writing are listed in Table 1. These are the values used in the simulations presented here.

## PERFORMANCE BEFORE CORRECTIONS

For the simulations, 250 total seeds of random, normal distributed errors (cut at $1\sigma$) are applied. After misalignment

Table 1: Estimated errors relevant for orbit correction and beam stability. Some errors have multiple origins and are assumed to be pessimistic estimates.

| Source | Unit | Value |
|---|---|---|
| Magnet Offsets | µm | 120 |
| Magnet Roll | µrad | 800 |
| Calibration Error | – | $1 \times 10^{-3}$ |
| BPM Noise | µm | 100 |
| BPM Offset | µm | 500 |

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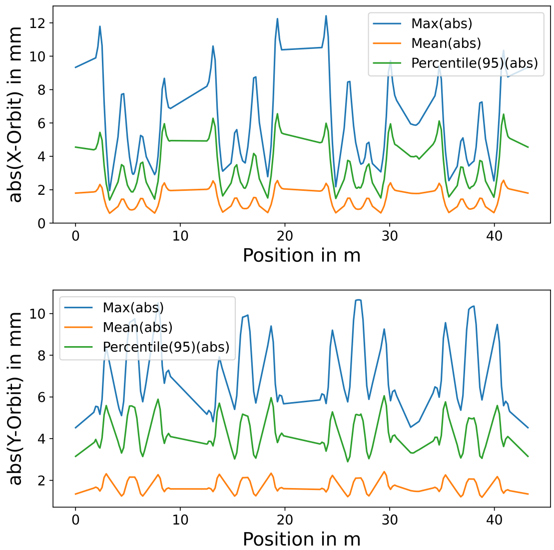


Figure 2: Horizontal (top) and vertical (bottom) statistical orbit deviations for the DBA lattice before any corrections are applied. Data generated from all seeds resulting in sufficient transmission without corrections. Orbit was calculated as average trajectory over 10k turns.

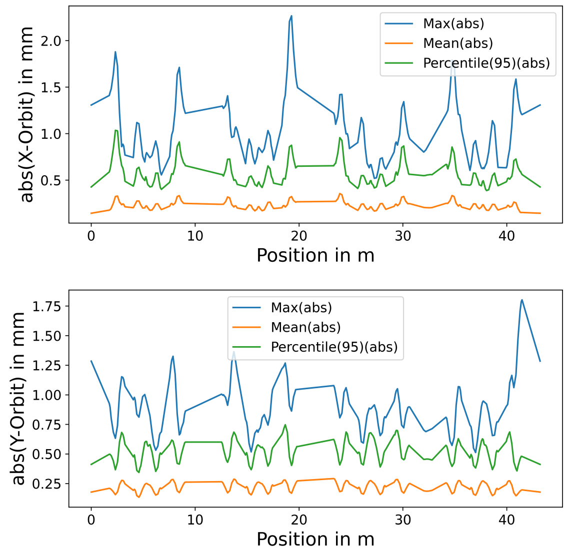


Figure 3: Horizontal (top) and vertical (bottom) statistical orbit deviations for the DBA lattice after corrections are applied. Orbit was calculated as average trajectory over 10k turns.

errors are applied to the DBA lattice, a significant number of seeds result in sufficient transmission to generate data such as orbit deviations. For these seeds, statistics on the orbit are shown in Fig. 2. The maximum orbit deviation reaches horizontally about 12.5 mm and vertically about 10.5 mm. This is too much to reach the design goals of cSTART, and therefore corrections are required. The simulations are performed in Python with Accelerator Toolbox [5, 6] and the proposed corrections are described in the following section together with some results.

## CORRECTIONS

The injection rate into cSTART is expected to be 10 Hz and, therefore, the beam will be dumped after 100 ms. cSTART will thus operate in non-equilibrium. For corrections of parameters resulting from misalignments, this means that the orbit, tune, chromaticity etc. will not be constant over time. In order to be able to correct anyways, all corrections are performed on multi-turn data considering the first 150 turns. This number is chosen as compromise between betatron motion and small enough effects of non-equilibrium behaviour. The beam position monitors (BPM) are deliberately selected for turn-by-turn measurements [7]. The shown orbit data is the result of averaged orbits over the first 150 turns. To get good results for tune measurements, the NAFF [8, 9] algorithm will be used reducing the required number of turns to observe. Incremental corrections are performed on an injection-to-injection basis as the beam storage time is expected to be 100 ms.

To achieve a good performance of the lattice, multiple corrections are employed. First-turn corrections are performed using one- and two-turn data. These corrections are based on the SC/pySC [10] first turn correction algorithm. As a second step, regular orbit corrections are performed using Tikhonov regularization, after which beam-based alignment, to reduce the BPM offsets, follows. After a second round of regular orbit correction, two families of quadrupoles are used for a tune correction followed by a chromaticity correction with two sextupole families. The short storage time of 100 ms prevents a conventional chromaticity measurement in the real machine. A possible way around this could be off-energy injections to achieve the momentum variation required for chromaticity measurements. For this, each momentum/tune pair would be measured at a separate injection and the tune would be determined from a low number of turns.

The mean, maximum and 95 percentile orbit over 250 seeds after applying the currently implemented set of corrections is shown in Fig. 3. The maximum orbit deviation reduces to about 2.2 mm horizontally and 1.8 mm vertically. Excluding the worst 5 % of machines, the horizontal maximum is reduced to below 1 mm and the vertical maximum to about 0.8 mm.

### *Beam-Based Alignments*

To improve the alignment accuracy further, a beam-based (re-)alignment (BBA) is planned. In a first step, a parallel beam-based alignment algorithm is studied. The parallel algorithm is required as the quadrupoles in cSTART are powered in 5 families. The aim of this first step of beam-based alignment is purely the determination of BPM offsets. The procedure is planned to be similar to the one in [11].

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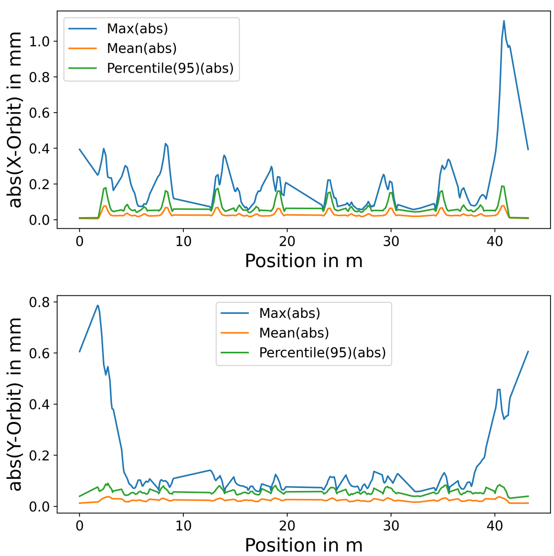


Figure 4: Horizontal (top) and vertical (bottom) statistical orbit deviations for the DBA lattice after corrections are applied. The BPM offsets were reduced to 50 µm to emulate the orbit correction after beam-based alignment. Orbit was calculated as average trajectory over 10k turns.

For the moment, since the BBA routines have not yet been implemented, the offset error on BPMs is reduced to the expected BBA precision of 50 µm. The resulting orbit after corrections is shown in Fig. 4. Now,the worst case horizontally is at 1.1 mm and vertically at about 0.8 mm. However, it is worth to notice that the 95 percentile orbit is now at 0.18 mm horizontally and 0.1 mm vertically.

For these corrections, the momentum acceptance is in the range from ±3.5 % to ±4 % and is on a good track to accept the wide momentum spread beam from the LPA injector [12]. Figure 5 shows the momentum acceptance from simulations with indications of 5th and 95th percentile (blue area) as well as the average acceptance.

## SUMMARY AND OUTLOOK

Effects of misalignments have been presented in terms of orbit and momentum acceptance. Performance after corrections including orbit and tune corrections is acceptable with 2.2 mm orbit horizontally and 1.8 mm vertically without BBA and a 95 percentile orbit of 0.18 mm horizontally and 0.14 mm vertically after a pseudo-BBA assuming a precision of 50 µm.

The results shown are valid for the DBA lattice and next steps are to simulate the low-alpha lattice.

Further steps include parallel BBA to reduce the effective BPM offsets as well as implement additional beam-based measurement to be used in realignment campaigns to reduce the expected measurement uncertainty and reduce misalignments.

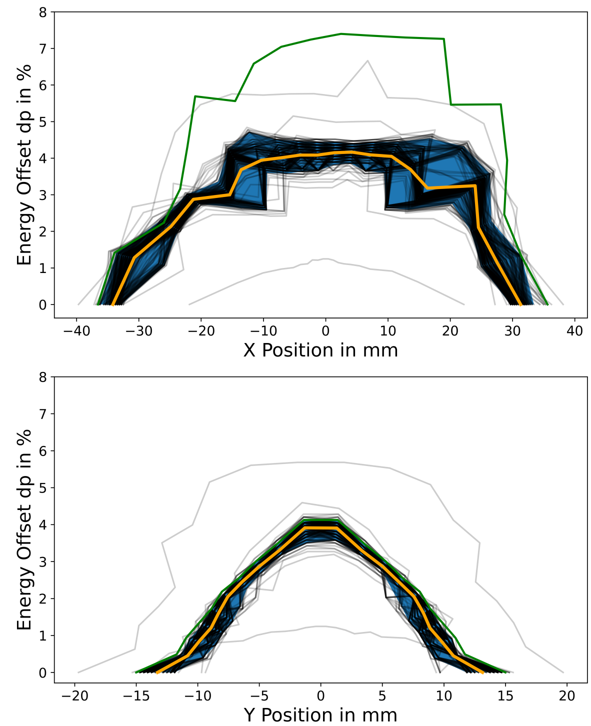


Figure 5: Horizontal (upper panel) and vertical (lower panel) momentum acceptance after corrections. The semi-transparent black lines are the individual simulations with 250 seeds. The orange line is the average acceptance while the blue area indicates the area between the 5th and 95th percentile and the green line represents the case without any errors.

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