EVALUATION OF CLOSED ORBIT CORRECTION METHODS FOR THE HELIUM LIGHT ION COMPACT SYNCHROTRON HELICS

H. Huttunen*[1], F. Asvesta, European Organization for Nuclear Research, Geneva, Switzerland
E. Benedetto, Tera-Care, Geneva, Switzerland
[1] also at University of Helsinki, Helsinki, Finland

Abstract

Within the framework of the Next Ion Medical Machine Study (NIMMS) collaboration at CERN, closed orbit correction schemes are developed for the Helium Light Ion Compact Synchrotron (HeLICS) - a novel synchrotron design in development for cancer treatment. Different options for closed orbit correction are presented, including the possibility of applying beam-based quadrupole alignment without dedicated corrector magnets. The limitations and advantages of the different closed orbit correction methods are evaluated against each other in order to determine the best scheme for HeLICS.

INTRODUCTION

HeLICS is a compact synchrotron currently under design within the NIMMS collaboration — an initiative focused on developing next-generation accelerator technologies for ion therapy with reduced size and cost [1–4]. Its compact design imposes tight constraints on the lattice layout and available space for beam instrumentation [5, 6].

Closed-orbit distortions arising from magnet misalignments can significantly increase the transverse excursion of the beam trajectory, particularly at low injection energies where the beam size is inherently larger. To evaluate the operational robustness of HeLICS under realistic conditions, it is essential to evaluate both the impact of such misalignments on the closed orbit and the effectiveness of available correction strategies. Here, corrector-based schemes are investigated, considering various configurations in terms of the number and placement of correctors. Subsequently, orbit correction using beam-based quadrupole alignment is examined as a more space-efficient alternative to conventional corrector magnets.

HELICS SYNCHROTRON

The triangular HeLICS lattice, with a circumference of 35 m, consists of three 120° bending sections with normal-conducting 60° dipole magnets connected by longer dispersion free straight sections accommodating quadrupoles for tune control, injection and extraction septa, an RF cavity and beam instrumentation [5]. Due to space constraints, the plan for HeLICS is to place Beam Position Monitors (BPMs) inside some of the quadrupoles in the lattice, while orbit corrector magnets would be integrated into the sextupoles [6].

HeLICS employs three sextupoles for chromaticity control, each positioned in one of the bending sections. On top of these sextupoles, at least one additional sextupole is required for slow extraction. The potential locations for the additional sextupoles were determined based on the available space in the ring, taking into account which sextupole combinations are capable of producing the desired resonance excitation for slow extraction [7]. Due to space constraints of the lattice and the flexibility required for operation, a single extraction sextupole cannot be positioned at a favorable phase advance relative to the electrostatic septum for the formation of this excitation. Instead, a virtual sextupole with a specific strength and phase advance is required. The functional sextupole combinations are identified based on their relative phase advance. Following this, the sextupole strengths are determined by first generating a transfer matrix with MADX, and then performing a least-squares optimisation in Python to obtain the required strengths, similar to the approach described in [8]. Finally, the results are verified using MADX.

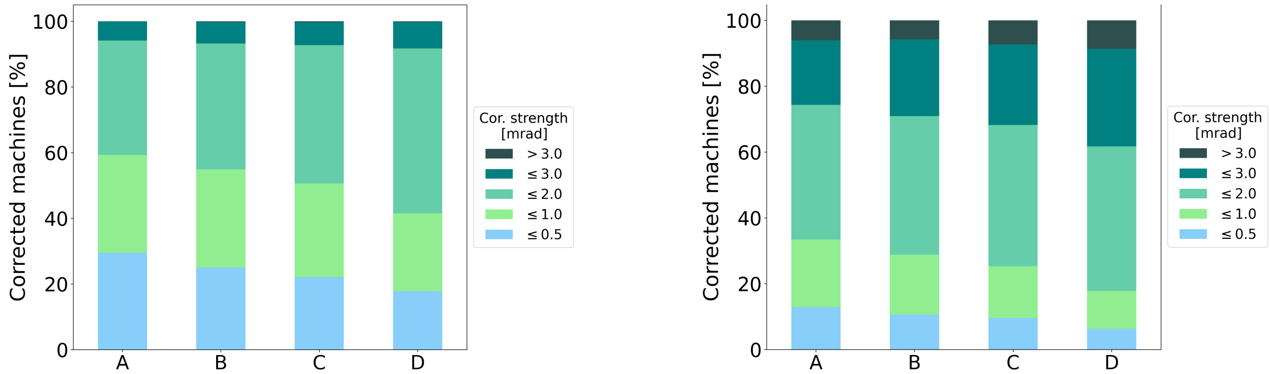
Three sextupole schemes are identified. Scheme A introduces two dedicated extraction sextupoles in the dispersion-free straight sections. Scheme B also employs two dedicated extraction sextupoles, but places one in a dispersive bending section, thereby affecting the chromaticity unfavorably. Scheme C uses one additional sextupole in a dispersion-free straight section in combination with the three chromaticity sextupoles to provide both chromaticity correction and the desired resonance excitation. These preliminary sextupole schemes set the basis for the potential locations of the orbit corrector magnets, but still require final confirmation from slow extraction studies.

CORRECTOR BASED ORBIT CORRECTION SCHEMES

The primary operational limit caused by alignment errors arises from perturbations on the beam dynamics such as closed orbit distortions [9]. In HeLICS, the tolerances for closed orbit distortions have been determined as $\mathrm{CO}_x = \pm 10$ mm in the horizontal plane and $\mathrm{CO}_y = \pm 7.5$ mm in the vertical plane [6]. The misalignments are evaluated at the injection working point $(Q_x, Q_y) = (2.4, 1.15)$, where the aperture is most critical due to the low beam energy.

Previous studies have shown that the vertical plane requires orbit correction, while the horizontal plane remains relatively robust due to the choice of the working point [6]. This is attributed to the choice of the working point: the

* heli.huttunen@cern.ch



(a) 0.5 mm or mrad

(b) 0.8 mm or mrad

Figure 1: Comparison of maximum corrector strengths required for vertical orbit correction using correction schemes A–D, with misalignment / tilt tolerances of 0.5 and 0.8 mm or mrad. Each color represents the fraction of machines requiring corrector strengths within the ranges specified in the legend.

vertical tune lies closer to the integer resonance, enhancing orbit distortions, while the horizontal tune is closer to the half-integer, inherently mitigating them. Building on this, the potential benefits of introducing additional correctors in the vertical plane are investigated to reduce required strengths and improve operational reliability. Mitigating the sensitivity to misalignments by adjusting the vertical tune is nontrivial in HeLICS. Higher fractional tune increases the maximum vertical beta function, resulting in a larger beam size at certain locations that exceeds the aperture requirements [10]. The change in optics also lowers the minimum vertical beta function leading to larger space-charge-induced tune spread, thereby increasing susceptibility to resonance conditions. Therefore, this approach is not considered further here.

Although alignment methods for accelerator components continue to improve, in most hadron accelerators, 0.3–0.5 mm is considered a sufficient standard alignment tolerance for operation [11]. To study the correction schemes, random displacements and tilts are applied to all magnetic elements using a truncated normal distribution, with tolerances of 0.3, 0.5, 0.8, and 1.0 mm or mrad. For each tolerance level, 1000 machine instances are generated. These misalignments are implemented in MAD-X, after which vertical orbit correction is performed using available BPMs and correctors per scheme, employing the MICADO algorithm based on least-squares minimization [12,13]. The correction schemes A–C, based on the sextupole schemes described above, are evaluated against scheme D employing correctors only at the chromaticity sextupoles previously investigated in [6]. In scheme B, the corrector integrated into the extraction sextupole on the dispersive bending section, is not used as this minimizes the strength requirements for the correction. This effect can be explained by the non optimal phase advance between the two adjacent correctors. This leaves scheme A with 5 correctors, B and C with 4 correctors and D with 3 correctors.

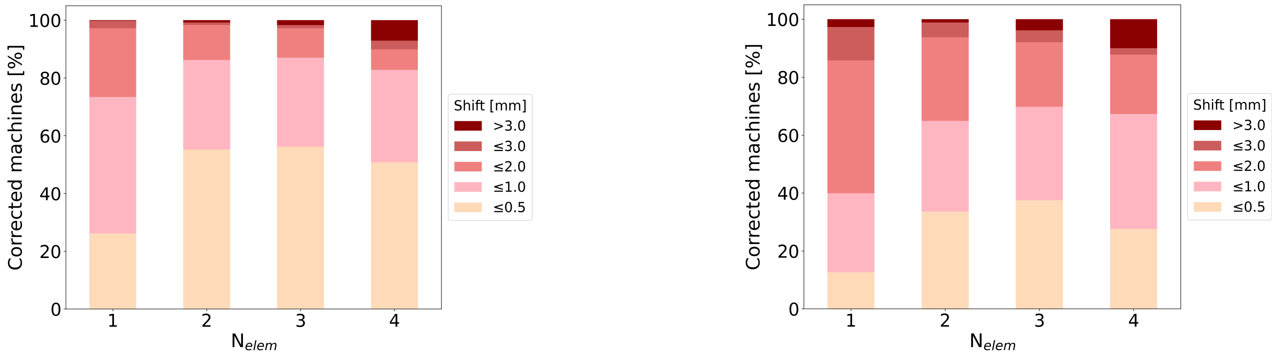
The distribution of correction strengths required for successful correction is shown in Fig. 1 for misalignment / tilt tolerances of 0.5 and 0.8 mm or mrad. From these figures it is evident that configurations with a higher number of correctors are more favorable in terms of maximum kick strength of the correctors. At 0.3 mm or mrad misalignment / tilt tolerance, no correction is required in >40% of machine instances as the induced closed orbit distortion is within the target. For the other cases, integrated corrector strengths fall in the range of 0.3–2.0 mrad, with a maximum of 1.2 mrad sufficient to correct approximately 80% of all cases. At 1.0 mm or mrad misalignment / tilt tolerance, correction is required for nearly all cases, with integrated corrector strengths reaching up to 6 mrad, and a 3 mrad limit is sufficient to correct approximately 80% of cases.

Regardless of the chosen corrector scheme, a realignment threshold of maximum 0.8 mm is recommended, for which vertical integrated corrector strengths of roughly 2.5 mrad are sufficient in approximately 80% of cases. From a design perspective, scheme A provides the most effective correction at the cost of an additional sextupole and space from the straight section, scheme B has slightly lower correction efficiency with similar hardware requirements, and scheme C represents a more space- and cost-efficient solution with further reduced correction performance.

BEAM-BASED ALIGNMENT

Beam-based alignment (BBA) typically uses the beam response to quadrupole strength variations to infer magnet misalignments [14]. Here, this concept is applied in reverse: simulated orbit distortions are used to determine the quadrupole displacements and tilts that optimally restore the desired beam trajectory. This is the first study of the HeLICS lattice fully transferred to Xsuite. The results presented above will be verified within Xsuite [15] at a later stage.

An alignment algorithm for HeLICS was developed as a generalized extension of the PSB alignment method described in [16]. The algorithm determines the quadrupole displacements and tilts required to correct vertical orbit distortions by combining a physics-based response model with



(a) 0.5 mm or mrad

(b) 0.8 mm or mrad

Figure 2: Comparison of maximum realignment shifts required for vertical orbit correction via beam-based quadrupole alignment with 1–4 elements, for misalignment / tilt tolerances of 0.5 and 0.8 mm or mrad. Each color represents the fraction of machines requiring shifts within the ranges specified in the legend.

numerical optimization. A response matrix R, relating orbit deviations at beam position monitors to quadrupole misalignments, is inverted using singular value decomposition (SVD) to obtain the optimal set of horizontal and vertical corrections. In addition, a MICADO-like iterative procedure identifies the most effective subset of quadrupoles by progressively selecting elements that maximize the reduction in RMS orbit distortion. The implementation consists of python scripts interfaced with Xsuite, where misalignments are applied to the lattice, response matrices are computed at the chosen working point, and the optimal realignment strategy is determined. The resulting corrections are then applied and validated through closed-orbit recomputation in Xsuite.

The beam-based quadrupole alignment study follows the same setup as the orbit-correction analysis described above, with 1000 randomly misaligned machines generated for each tolerance. Realignment of up to four elements is then applied to correct the orbit. Across all misalignment tolerances and correction configurations, the method is capable of achieving the required closed-orbit tolerance, provided sufficiently large element shifts are allowed as shown in Fig. 2. Using a single quadrupole for realignment generally requires larger shifts compared to multi-element corrections. The most efficient overall performance—balancing correction quality and required shifts—is achieved with two elements. While introducing a third element provides marginal additional benefit in some cases, extending the realignment to four elements leads to a noticeable increase in instances requiring large shifts (>3 mm), without significant improvement over two- or three-element configurations. The larger shifts in the four-element correction could be explained by a suboptimal phase advance between two adjacent elements, or by the fact that increased number of elements improves the ability to reduce the RMS orbit closer to zero, leading to more excessive orbit correction. Increasing the number of elements beyond two can be beneficial when the RMS closed orbit needs to be significantly reduced; with four-element corrections, an average reduction in the RMS closed orbit of over 80% is achieved compared to single-element alignment.

DISCUSSION

Corrector-based schemes exhibit a stronger dependence on misalignment tolerance, with kick strengths increasing significantly at higher tolerances, whereas beam-based alignment shows weaker scaling, with comparable element shifts sufficient across all cases. This difference likely arises from the greater flexibility of the alignment approach, where quadrupoles distributed around the ring can be used for correction, effectively increasing the number of possible correction locations from 3-5 up to 15. In addition, while corrector-based schemes aim only to reduce the closed orbit within acceptable tolerances, the beam-based alignment algorithm that was used explicitly minimizes it toward zero, leading to generally lower RMS closed orbit values.

Despite these advantages, the practical applicability of beam-based alignment in HeLICS can be limited in a medical context, where robustness and operational simplicity are essential, and physical realignment of accelerator components may be challenging. However, due to the compact size of the machine, it should not evolve much in time concerning misalignments, and beam-based alignment could show potential as a long-term realignment option either by itself or alongside with the closed orbit correctors.

CONCLUSION

Vertical orbit correction in HeLICS can be effectively achieved using both corrector-based schemes and beam-based quadrupole alignment. Among the corrector configurations, scheme A, with 5 correctors, provides the best performance, while scheme C, with only 3 correctors, offers a more compact and cost-efficient alternative with reduced correction capability. Beam-based alignment demonstrates strong correction potential, particularly with two-element realignment, though practical implementation may be constrained by operational considerations in a medical context.

Although the focus of orbit correction is put on the vertical plane, the installation of horizontal dipoles for closed orbit bump generation for multi-turn injection and slow extraction need to be investigated in the future.

REFERENCES

[1] M. Vretenar *et al.*, "The next ion medical machine study at CERN: Towards a next generation cancer research and therapy facility with ion beams", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 1240-1243. doi:10.18429/JACoW-IPAC2021-MOPAB413

[2] E. Benedetto and M. Vretenar, "Innovations in the next generation medical accelerators for therapy with ion beams", in *J. Phys.: Conf. Ser.*, Jan. 2024, pp. 5083-5086. doi:10.1088/1742-6596/2687/9/092003

[3] M. Vretenar *et al.*, "A compact synchrotron for advanced cancer therapy with helium and proton beams", in *J. Phys.: Conf. Ser.* 2420, Jan. 2023, pp. 811-814. doi:10.1088/1742-6596/2420/1/012103

[4] E.Benedetto *et al.*, "A compact synchrotron for cancer therapy with helium ions", in *Proc. IPAC'25*, Taipei, Taiwan, Jun. 2025, pp. 1159-1162. doi:10.18429/JACoW-IPAC2025-TUPB105

[5] H. Huttunen *et al.*, "Optics design of a compact helium synchrotron for advanced cancer therapy", in *Proc. IPAC'24*, Nashville, Tennessee, USA, May 2024, pp. 2991-2994. doi:10.18429/JACoW-IPAC2024-THPC13

[6] H. Huttunen, F. Asvesta, and E. Benedetto, "Orbit error correction schemes for the Helium Light Ion Compact Synchrotron HeLICS", in *J. Phys.: Conf. Ser.* 3094, Sep. 2025, pp. 012036. doi:10.1088/1742-6596/3094/1/012036

[7] R. Taylor, "Slow extraction: Upgrades for next ion medical machines at FLASH timescales", Ph.D. thesis, Phys. Dept., Imperial College London, London, UK, 2024. https://cds.cern.ch/record/2915795

[8] F. Asvesta *et al.*, "Resonance compensation for high intensity and high brightness beams in the CERN PSB", in *Proc. HB'21*, Batavia, IL, USA, Oct. 2021, pp. 40-45. doi:10.18429/JACoW-HB2021-MOP06

[9] S. Y. Lee, "Accelerator physics (fourth edition)", Singapore: World Scientific, 2018. doi:10.1142/11111

[10] H. Huttunen, "Research on helium synchrotron design", in *Joint Symposium of CERN NIMMS & HUS & CERN Baltic Group: "Particle therapy technologies"* Jan. 2024. https://indico.cern.ch/event/1356955/#5-research-on-helium-synchrotr

[11] S. Redaelli, "Dynamic alignment in particle accelerators", CERN, Geneva, Switzerland, Rep. CERN-2009-005.535, 2009. doi:10.5170/CERN-2009-005.535

[12] MAD - Methodical Accelerator Design, https://cern.ch/madx

[13] B. Autin and Y. Marti, "Closed orbit correction of A.G. machines using a limited number of magnets", CERN, Geneva, Switzerland, Rep. CERN-ISR-MA-73-17, Mar. 1973. doi:10.17181/CERN-ISR-MA-73-17

[14] A. Wolski, "Beam dynamics in high energy particle accelerators", Liverpool, UK: World Scientific, 2014. doi:10.1142/p899

[15] G. Iadarola *et al.*, "Xsuite: An integrated beam physics simulation framework", in *Proc. HB'23*, Geneva, Switzerland, Oct. 2023, pp. 73-80 doi:10.18429/JACoW-HB2023-TUA2I1

[16] F. Antoniou *et al.*, "The PS booster alignment campaign and a new tune control implementation after the LHC injectors upgrade at CERN", in *Proc. HB'21*, Batavia, IL, USA, Oct. 2021, pp. 89-94. doi:10.18429/JACoW-HB2021-MOP14