VERTICAL DEFORMATION OF THE 10 TeV MUON COLLIDER RING FOR NEUTRINO FLUX MITIGATION[*]

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Abstract

Muons offer several advantages for circular colliders: as leptons, they allow for high-precision and similar physics reach as larger hadron colliders, while their higher mass suppresses the synchrotron radiation that limits circular electron colliders. The main challenge of muon colliders is the short lifetime of muons. Muon decay generates an intense neutrino flux emitted in a narrow cone tangential to the beam trajectory. To keep the resulting radiation at the Earth's surface negligible, dedicated mitigation strategies are required. Besides minimizing straight sections, the main mitigation measure under consideration is to periodically deform the beam trajectory and collider ring vertically to spread the neutrino flux over a larger area. This can be achieved by installing all ring magnets on a mechanical system allowing to move them regularly and adding horizontal magnetic field components. However, this affects the collider optics, especially since it introduces vertical dispersion that must be properly matched across the lattice. The present work presents the first studies on the impact of such vertical periodic deformation on beam dynamics and collider performance.

INTRODUCTION

A 10 TeV center-of-mass muon collider complex could serve as a high-energy lepton collider, allowing for high-precision and, at the same time, similar physics reach as larger hadron colliders [1–4]. One of the main challenges of a muon collider complex is the very short lifetime of muons (~ 2.2 μs at rest), which imposes unique challenges at every stage of the complex, from muon beam cooling, which requires the implementation of novel techniques, to the rapid cycling synchrotron chain, which must accelerate the beams within a few tens of turns. In the collider ring, this short lifetime leads to the inevitable decay of muons, significantly impacting the collider design.

First, muon decays lead to muon losses during operation, reducing the beam intensity and consequently the luminosity. The collider ring must therefore be as compact as possible to maximize the number of collisions at the two interaction points. Second, muon decays produce secondary particles that can reach the detectors or be lost in the collider structure. To mitigate these effects, careful design of the Interaction Regions (IR) is required to reduce the beam-induced background [5, 6], and radial tungsten shielding must be added inside the magnet aperture to mitigate the radiation damage and heat load [7]. Among the particles produced by muon decays are high-energy neutrinos emitted in a narrow cone tangential to the muon trajectory. The resulting intense neutrino flux can interact near the Earth's surface, generating hadronic showers and measurable radiation doses. The neutrino radiation dose strongly increases with the collider energy, since the angular distribution becomes narrower and the neutrino interaction cross section larger [8–11]. Radiation dose levels are particularly significant in the direction of straight sections, where neutrinos from successive muon decays accumulate. To keep the radiation at the Earth's surface negligible, dedicated mitigation strategies are required. In the collider IRs, long straight sections housing experiments are unavoidable. To manage the resulting intense neutrino flux, the collider placement is optimized by identifying where neutrinos from these long straight sections reach the surface and ensuring these locations lie in low-occupancy areas or in regions that could be purchased and fenced by the organization [12–14]. In the collider arcs, straight sections can be minimized by using only dipoles and combined-function magnets, with the remaining short straight sections limited to 30 cm-length interconnects between magnets [15].

Beyond minimizing straight sections, implementing additional mitigation strategies is required, as the radiation levels from the arcs straight sections and combined-function magnets are still too high [9, 10, 16]. The main mitigation measure under consideration is to periodically deform the beam trajectory and the collider ring vertically to spread the neutrino flux over a larger area [9, 11]. The so-called Vertical Incremental Periodic Excursion of the Ring (VIPER) scheme requires the addition of horizontal magnetic field components to all ring magnets and installing them on a mechanical system in order to move them regularly [17, 18]. While initial estimates indicate that peak radiation doses can be reduced by approximately two orders of magnitude using the VIPER scheme [9, 16], it also affects the collider optics by introducing vertical dispersion that must be properly matched throughout the ring, and may induce momentum-dependent coupling in strong sextupoles. In this context, it is essential to evaluate the impact of this mitigation scheme on beam dynamics and overall collider performance to assess its feasibility.

This work presents the first studies of the implementation of such vertical periodic deformations in the regular arc cells of the muon collider ring and their impact on the collider optics and performance. The basic VIPER scheme and its implementation in the Flexible Momentum Compaction (FMC) arc cells are described, and a specific VIPER configuration is proposed to address vertical dispersion matching across the FMC arcs. The collider performance is then evaluated

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and compared with the current baseline, demonstrating that neutrino radiation mitigation via the VIPER scheme limited in regular arc cells can be achieved without significant degradation of collider performance.

BASIC VIPER SCHEME

To produce the vertical deflection required to generate the VIPER pattern shown in Fig. 1, small vertical bends are added at the beginning and end of the VIPER section, while an additional horizontal field component, following a step function, is applied to all ring magnets. The horizontal dipolar field component B_x and the maximum vertical beam excursion $\hat{y}$ depend on the vertical deformation period L_p and on the maximum vertical deflection angle $\hat{y'}$ [19]:

$$\hat{y} = \frac{L_p \hat{y'}}{4}, B_x = \frac{4\hat{y'}p/q}{L_p}.$$

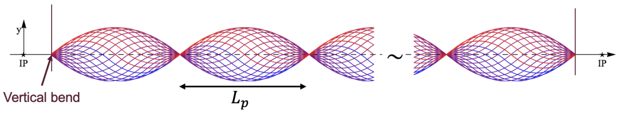
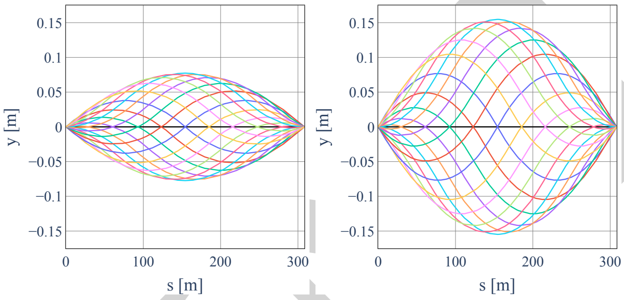


Figure 1: Vertical particle trajectory for several deformation steps of the VIPER scheme [19].

With the currently envisaged VIPER period of a few hundred meters and the maximum slope of 1 mrad [17], the beam trajectory excursion is too significant to remain within the magnet aperture, as was initially proposed in [11]. Consequently, the current proposal is to mount all collider magnets on a mechanical system, moving them to follow the VIPER pattern. The full deformation cycle is divided into several discrete steps, the number of which depends on the range of vertical deflection angles and the distance at which the neutrinos exit the collider. Specifically, it has been shown that 160 deformation steps would be required to reduce the neutrino-induced dose at 60 km from the collider arcs by a factor of approximately 80, assuming a vertical beam deflection of $\hat{y'} = \pm 1$ mrad [16].

To investigate the impact of the VIPER scheme on collider beam optics, a single VIPER period was first implemented on two FMC arc cells. The horizontal field values were adjusted to account for the actual magnetic configuration, including magnets of varying lengths and straight sections in between magnets. As the lattice is made of magnets with finite lengths, a horizontal magnetic field described by a step function is not feasible. Thus, the horizontal field of magnets at the transitions is set to a weighted average of the positive and negative field values. In addition, to simulate the effect of the mover system, all magnets in the VIPER period are displaced using vertical offsets and rotations around the horizontal axis computed at the magnet centers. Since these offsets and rotations are strictly valid only at the element centers, the finite length of the elements introduces dipolar feeddown, leading to small errors in the vertical trajectory. These are corrected by slightly adjusting the horizontal magnetic field values to recover zero vertical displacement and angle at the end of the period. Element rotations were implemented in the beamline using the small-angle approximation, and validated against the recently implemented XSUITE misalignment feature [20], showing no significant additional errors.

The current implementation allows some flexibility in setting key VIPER parameters, such as the number of deformation steps and the amplitude of the vertical deflection angle, which affects the required horizontal magnetic field and the orbit excursion amplitude. This is illustrated in Fig. 2, which shows the vertical orbit deformations over a VIPER period of 308 m (corresponding to two FMC arc cells), for several discrete deformation steps and for deflection angles in the ranges of ±1 mrad and ±2 mrad.



(a) (b)

Figure 2: Vertical orbit deformations over a VIPER period of L_p = 308 m (two FMC arc cells) for several deformation steps and deflection angles in (a) ±1 mrad and (b) ±2 mrad.

VIPER SCHEME IN THE FMC ARCS

The muon collider ring arcs, in which the VIPER scheme must be implemented, are composed of several sections, exhibiting different optics and magnet strengths: the local chromatic correction (CC) sections mitigate the strong chromatic effects introduced by the final focusing triplets using pairs of strong sextupoles placed at dispersive locations with large β-functions; the FMC arc cells, which constitute most of the collider and feature moderate β-functions and sextupole strengths, allow for maintaining short muon bunch lengths by controlling the linear momentum compaction factor across the entire ring; the matching (MA) sections ensure proper optics matching between the CC sections and the FMC arcs [15, 21]. In this work, the VIPER scheme is implemented only in regular FMC arc cells, but not yet considering the more challenging CC and MA sections.

The additional horizontal magnetic field components introduced by the VIPER scheme generate significant vertical dispersion that must be matched across the ring, as shown in Fig. 3. In the current collider lattice, the phase advance per FMC arc cell is 0.75 × 2π in both transverse planes, which makes it possible to devise simple schemes to match the vertical dispersion. Specifically, the vertical dispersion created by a VIPER period consisting of two FMC arc cells ($\mu_x, \mu_y = 1.5 \times 2\pi$) can be canceled by adding a second VIPER cell immediately afterward, as the dispersion kicks compensate each other. The vertical dispersion across the arcs is thus matched by adjusting the number of FMC arc cells in the collider ring. This configuration requires the vertical deformation period L_p to be a multiple of the arc cell length. Depending on the chosen VIPER period, slight modifications to the initial scheme may be required to account for the specific phase advance over one VIPER period. For example, a period of 616 m corresponds to four FMC arc cells with a total phase advance of $3 \times 2\pi$. Under these conditions, vertical dispersion kicks do not cancel but instead accumulate when a similar subsequent VIPER cell is added. A modified scheme with larger vertical bending strengths can be implemented to ensure vertical dispersion cancellation in this case, but such configurations are less favorable and are best avoided [22]. The choice of the VIPER period will ultimately be determined by both the magnet constraints associated with the additional horizontal magnetic field and the mover system.

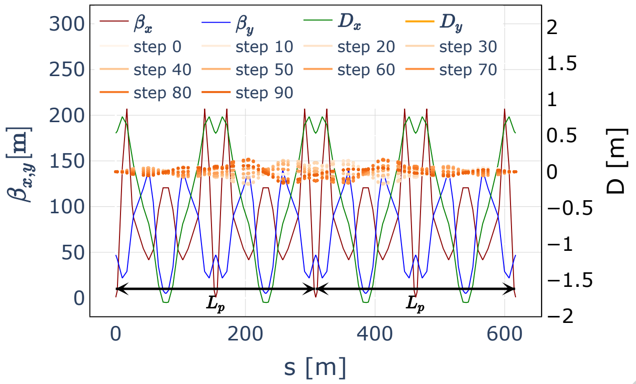


Figure 3: Lattice functions computed over four FMC arc cells, corresponding to two VIPER periods of L_p = 308 m. The vertical dispersion is shown in orange color scales for several discrete steps of the VIPER scheme.

The collider baseline lattice has been adjusted to include 20 FMC arc cells per collider arc, while maintaining a working point and performance similar to the original design [15]. The VIPER parameters (horizontal magnetic fields, vertical offsets, and rotation angles) were then computed for a VIPER period of 308 m (corresponding to two FMC cells) before implementing the full scheme (ten VIPER periods per arc) in both regular collider arcs. The momentum acceptance was then computed for several VIPER deformation steps and for different dynamic aperture (DA) criteria, corresponding to the maximum initial transverse amplitude for which particles survive 1000 turns, with results showing comparable performance across all VIPER steps and relative to the baseline, as indicated in Fig. 4. The tune shift with momentum offset also exhibits similar behaviour for all deformation steps. These results show that the VIPER mitigation scheme, when implemented in regular FMC arc cells, does not significantly affect the muon collider beam dynamics and performance for a machine without imperfections. Acceptable tolerances, particularly for magnet positioning precision, remain to be defined in future work.

While a specific phase-advance configuration may ensure the cancellation of vertical dispersion at both ends of the FMC arcs, this is not expected to be achievable in the collider sections between the regular FMC arcs and the IR long straight sections. In these challenging CC and MA sections, the large β-functions and strong sextupole strengths introduce further complexity in addition to vertical dispersion matching, such as energy-dependent transverse coupling. These effects will be investigated in more detail in future work to demonstrate the feasibility of implementing the VIPER scheme across the entire ring.

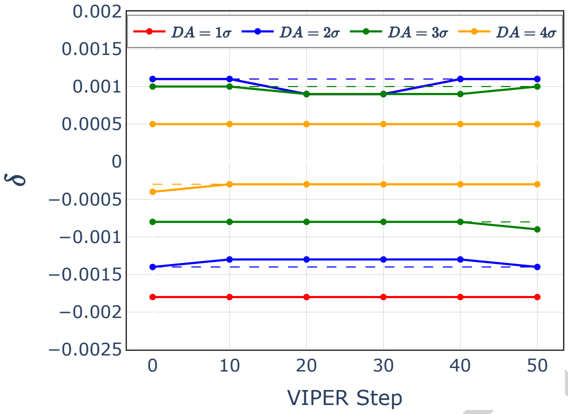


Figure 4: Momentum acceptance for given transverse DAs as a function of the VIPER deformation step. The dashed lines indicate the performance computed for the baseline with 20 FMC arc cells per collider arc.

CONCLUSION

The short lifetime of muons imposes major challenges on the muon collider complex. Among these, the collider neutrino-induced dose at the Earth's surface requires dedicated mitigation strategies to ensure it remains within acceptable limits. The main mitigation measure is to periodically deform the beam trajectory and the collider ring magnet arrangement vertically to spread the neutrino flux over a larger area. In this work, a modular code has been developed to implement the first vertical deformations in the FMC arc cells of the collider, allowing the selection of VIPER parameters such as the number of deformation steps and the vertical deflection angle. To properly match the induced vertical dispersion across the arcs, a dedicated scheme based on the phase advance in the FMC arc cells has been proposed. First results indicate that the collider performance is not significantly impacted by implementing the VIPER scheme in the regular arcs, although the lattice must be adapted to a specific number of FMC arc cells. Further implementation of the VIPER scheme in the more challenging parts of the collider will be performed in future work to demonstrate its feasibility across the entire ring, and in-depth studies are required to evaluate the tolerances of this scheme. Additional mitigation strategies, such as deforming the closed orbit in the horizontal plane and optimizing optics in short arc straight sections, may still be needed to reduce the higher doses expected from more realistic longer interconnects.

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