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Beam orbit correction in future linear colliders, such as the Compact Linear Collider (CLIC), is essential to mitigate the effect of accelerator element misalignment due to ground motion. The correction is performed using correctors distributed along the accelerator, based on the beam position monitor (BPM) readout from the preceding bunch train, with a train repetition frequency of 50 Hz. This paper presents the use of the MICADO algorithm [1] to select a subset of N ≈ 10 correctors (from a total of 576) to be used for orbit correction in the designed 380 GeV centre-of-mass energy first-stage of CLIC. The optimisation of the number N of correctors, the algorithm's gain and the corrector step size is described, and the impact of a number of BPMs and correctors becoming unavailable is addressed. The application of a MICADO algorithm to perform dispersion free steering, by reducing the beam orbit difference between two beams with different energies, is discussed.

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Beam orbit correction in future linear colliders, such as the Compact Linear Collider (CLIC), is essential to mitigate the effect of accelerator element misalignment due to ground motion. The correction is performed using correctors distributed along the accelerator, based on the beam position monitor (BPM) readout from the preceding bunch train, with a train repetition frequency of 50 Hz. This paper presents the use of the MICADO algorithm [1] to select a subset of $N \approx 10$ correctors (from a total of 576) to be used for orbit correction in the designed 380 GeV centre-of-mass energy first-stage of CLIC. The optimisation of the number N of correctors, the algorithm's gain and the corrector step size is described, and the impact of a number of BPMs and correctors becoming unavailable is addressed. The application of a MICADO algorithm to perform dispersion free steering, by reducing the beam orbit difference between two beams with different energies, is discussed.

INTRODUCTION

The Compact Linear Collider (CLIC) is a proposed electron-positron collider, with an ultimate centre-of-mass collision energy of 3 TeV [2]. A first-stage design at a lower energy of 380 GeV, aimed at top quark and Higgs particle production, is currently being proposed [3]. In order to achieve the required collider luminosity, CLIC requires a tightly controlled orbit and emittance growth. An orbit correction technique is essential to achieve and maintain the required small emittance growth in the CLIC main linac (Fig. 1), mitigating the effect of accelerator element misalignment due to ground motion.

The use of one-to-one (1-2-1) steering for the CLIC 380 GeV machine is discussed in [4]. In 1-2-1 steering, the transverse displacement of each quadrupole is used to steer the beam into the centre of the next beam position monitor (BPM) downstream [5]. In this paper, we consider the use of the MICADO[1] algorithm [1] to select a subset of $N \approx 10$ correctors to be used for orbit correction.

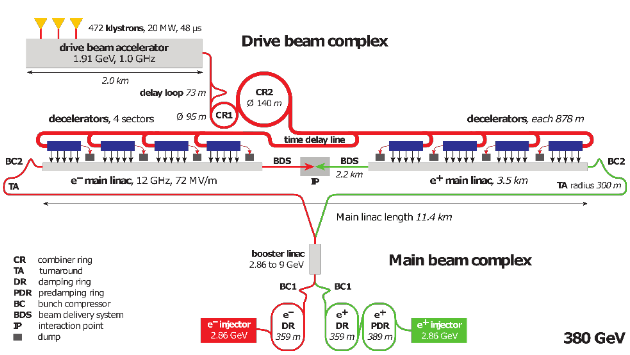

Figure 1: Overview of the CLIC layout at a centre-of-mass collision energy of 380 GeV [3].

MICADO FORMALISM

The MICADO formalism described in [1] is summarised here. The position of the beam is measured at m BPMs to construct a vector $\mathbf{b}$:

$$\mathbf{b} = \begin{pmatrix} b_1 \\ \vdots \\ b_m \end{pmatrix}. \tag{1}$$

These beam position offsets can be corrected by displacing l quadrupole magnets chosen from a total of n. The quadrupole changes in position are described by a vector $\mathbf{x}$:

$$\mathbf{x} = \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix}, \tag{2}$$

where $(n - l)$ elements will be zero. The effect of $\mathbf{x}$ on the orbit, as measured at the BPMs, is $A\mathbf{x}$, where A is a $m \times n$ response matrix. The response matrix is assembled, in advance, by calculating the beam offset at each BPM due to a 1 μm offset of each quadrupole.

The vector $\mathbf{x}$ can be scaled by a gain g. The residual orbit $\mathbf{r}$ on applying the quadrupole offsets $g\mathbf{x}$ is defined as:

$$\mathbf{r} = \begin{pmatrix} r_1 \\ \vdots \\ r_m \end{pmatrix} = \mathbf{b} + Ag\mathbf{x}. \tag{3}$$

The aim is to find the $\mathbf{x}$ which minimises $||\mathbf{r}||^2 = \sum_{i=1}^{m} r_i^2$. The MICADO routine first identifies the single corrector which best minimises $||\mathbf{r}||^2$ and then proceeds to identify the next best corrector until the specified number of correctors has been identified.

MICADO FOR THE CLIC MAIN LINAC

The main linac for the 380 GeV centre-of-mass energy first-stage of CLIC was simulated in PLACET [6]. This linac consists of 576 quadrupoles (i.e. correctors) and 576 BPMs. Starting from a perfectly-aligned machine, 10 hours of ATL ground motion are simulated; for ATL ground motion [7], the relative displacement ΔX after a time T of two points separated by a distance L is:

$$\langle \Delta X^2 \rangle = ATL, \tag{4}$$

[1] In French, *Minimisation des Carrés des Distortions d'Orbite* (Least-Squares Minimisation of Orbit Distorsions).

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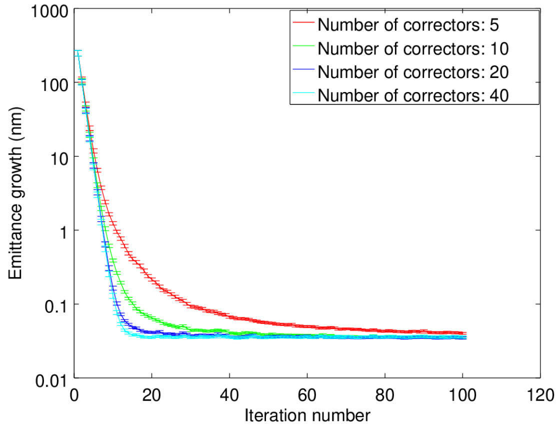

Figure 2: Emittance growth in the main linac vs. MICADO iteration number, for a range of the number of correctors used in each MICADO iteration. The mean, and error, over 100 simulated machines is shown. A gain g of 0.4 and a quadrupole step size of 1 nm were assumed. All correctors were available to be selected by the MICADO correction routine.

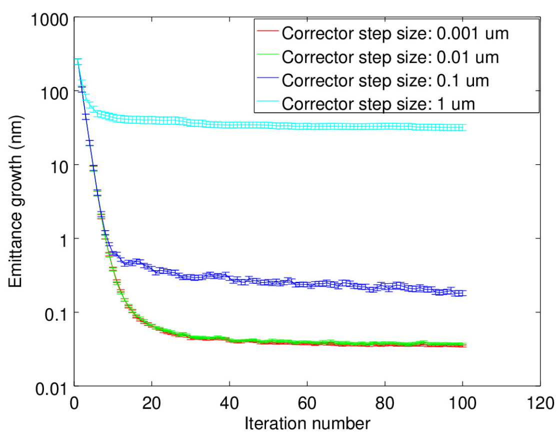

Figure 3: Emittance growth in the main linac vs. MICADO iteration number, for a range of quadrupole step sizes. The mean, and error, over 100 simulated machines is shown. A gain g of 0.4 was assumed and a subset of 10 correctors were selected in each iteration, with all correctors being available.

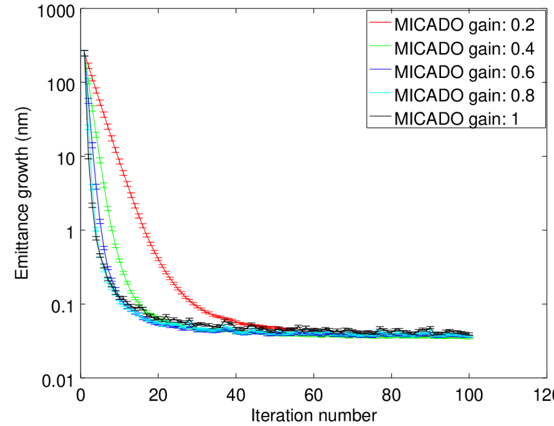

Figure 4: Emittance growth in the main linac vs. MICADO iteration number, for a range of gains g. The mean, and error, over 100 simulated machines is shown. A quadrupole step size of 1 nm was assumed and a subset of 10 correctors were selected in each iteration, with all correctors being available.

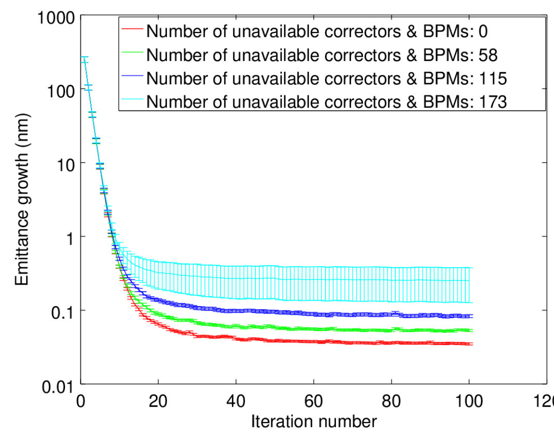

Figure 5: Emittance growth in the main linac vs. MICADO iteration number, where 0%, 10%, 20% and 30% of all quadrupoles and BPMs in the main linac are unavailable. The mean, and error, over 100 simulated machines is shown. A gain g of 0.4 and a quadrupole step size of 1 nm were assumed. A subset of 10 correctors were selected in each iteration.

where $A = 0.5 \times 10^{-6}\ \mu\mathrm{m}^2\,\mathrm{s}^{-1}\,\mathrm{m}^{-1}$.

An incoming beam with a vertical emittance of 10 nm is used. All BPMs are assumed to have a resolution of 0.1 μm. The MICADO routine is iterated 100 times for 100 consecutive trains. At CLIC, the train frequency is 50 Hz. A fresh subset of $N \approx 10$ correctors is selected each iteration.

The performance of the MICADO routine, by successfully reducing the emittance growth in the main linac from >100 nm to around 0.04 nm, is shown in Fig. 2. This performance is better than the 0.061 nm emittance growth that would be achieved after 1-2-1 steering, for the same initially misaligned lattice. A choice of $N \geq 10$ correctors is seen to give a fast convergence within 30 iterations. As a smaller number of correctors reduces the effect of corrector setting errors, $N = 10$ is chosen for the subsequent studies.

The granularity and/or error in the setting of the quadrupole offsets has been simulated by rounding the corrector settings to the nearest 1 nm, 10 nm, 100 nm or 1000 nm. Figure 3 show that either 1 nm or 10 nm step sizes do not degrade the MICADO performance. Given the CLIC specification [3], a 1 nm step size has been assumed for the studies presented here.

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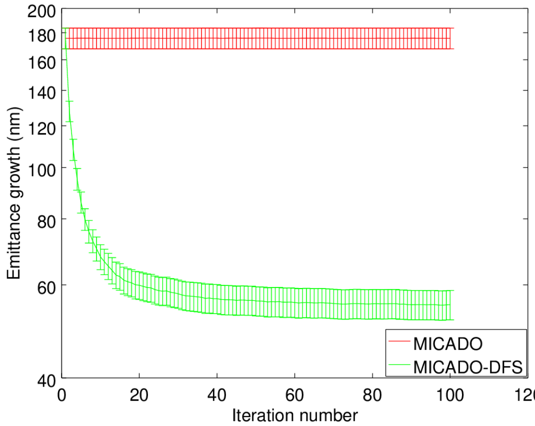

Figure 6: Emittance growth in the main linac vs. iteration number, using MICADO or MICADO-DFS, after 1-2-1 correction. The mean, and error, over 100 simulated machines is shown. BPMs have been vertically offset by a distance drawn from a Gaussian distribution with a standard deviation of 14 μm. A gain g of 0.4 and a quadrupole step size of 1 nm were assumed. A subset of 10 correctors were selected in each iteration.

The effect of reducing the gain g from a full value of 1 is shown in Fig. 4. Gains of 0.4 or more ensure a fast convergence within 30 iterations. A gain of 0.4 also shows a marginally better reduction in the emittance growth, resulting from a reduced amplification of BPM and corrector offset errors, and so is found to be optimum. For the optimised settings of $N = 10$ correctors, a gain $g = 0.4$ and a corrector step size of 1 nm, the emittance growth in the main linac is reduced to 0.044 ± 0.001 nm after 30 MICADO iterations.

The unavailability of a fraction of correctors and BPMs has been simulated by randomly removing, for example, 10% of the correctors and BPMs from the MICADO algorithm. This has been performed by removing the unavailable BPMs to produce a shorter orbit position vector $\mathbf{x}$ and removing the relevant rows and columns from the response matrix A provided to the MICADO procedure. Figure 5 show that removing even 20% of the correctors and BPMs only degrades the linac emittance growth from around 0.04 nm to around 0.1 nm.

MICADO-STYLE DISPERSION FREE STEERING

Dispersion Free Steering (DFS) consists in correcting both orbit and dispersion simultaneously, effectively overcoming systematic errors due to BPM offsets [8]. The beam is not only steered into the centres of the BPMs but also the differences of the trajectories of beams at different energies are minimised [9].

A MICADO-style DFS (MICADO-DFS) procedure was simulated by tracking two beams with energies E_0 and $E_1 = 0.95E_0$. The position vector $\mathbf{b}$ was augmented to double the number of elements,

$$\mathbf{b} = \begin{pmatrix} b_1^{E_0} \\ \vdots \\ b_m^{E_0} \\ b_1^{E_0} - b_1^{E_1} \\ \vdots \\ b_m^{E_0} - b_m^{E_1} \end{pmatrix}, \quad (5)$$

and the response matrix A was correspondingly increased to a $2m \times n$ matrix.

Instead of applying the ATL motion, the BPMs have been vertically offset by a distance drawn from a Gaussian distribution with a standard deviation of 14 μm (corresponding to the CLIC tolerance [3]) to demonstrate the DFS performance. 1-2-1 steering is performed first before doing either MICADO or MICADO-DFS. Figure 6 show a comparison of the performance of MICADO and MICADO-DFS procedures under these conditions. Whilst the MICADO routine is, as expected, limited to the performance of the preceding 1-2-1 steering, the MICADO-DFS procedure reduces the emittance growth from around 180 nm to less than 60 nm. It is worth noting that a traditional DFS procedure would yield an emittance growth to 16 nm, so further work will aim at optimising the MICADO-DFS performance.

CONCLUSIONS

The use of the MICADO algorithm to select a subset of N correctors to perform orbit correction has been demonstrated for the the designed 380 GeV centre-of-mass energy first-stage of CLIC. The use of $N = 10$ correctors in each iteration has been identified as being optimal, together with an algorithm gain of 0.4 and a corrector step size of < 10 nm. The emittance growth in the main linac can be reduced to around 0.04 nm within 30 iterations, starting from a perfectly-aligned machine followed by 10 hours of ATL ground motion, which is better than the 0.061 nm which would be obtained using regular 1-2-1 steering under the same conditions.

A first attempt at applying a MICADO-style algorithm to perform DFS, by reducing the beam orbit difference between two beams with different energies, has been implemented. Unlike the standard MICADO routine, MICADO-style DFS reduces the emittance growth in the presence of BPM vertical offset errors, and further optimisation will be performed to try to match the performance of traditional DFS.

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