CERN – EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-AB-2006-072
CLIC Note 673

CORRECTION OF VERTICAL DISPERSION AND BETATRON COUPLING FOR THE CLIC DAMPING RING

M. Korostelev, F. Zimmermann

CERN, Geneva, Switzerland

Abstract

The sensitivity of the CLIC damping ring to various kinds of alignment errors has been studied. Without any correction, fairly small vertical misalignments of the quadrupoles and, in particular, the sextupoles, introduce unacceptable distortions of the closed orbit as well as intolerable spurious vertical dispersion and coupling due to the strong focusing optics of the damping ring. A sophisticated beam-based correction scheme has been developed to bring the design target emittances and the dynamic aperture back to the ideal value. The correction using dipolar correctors and several skew quadrupole correctors allows a minimization of the closed-orbit distortion, the cross-talk between vertical and horizontal closed orbits, the residual vertical dispersion and the betatron coupling.

Presented at
EPAC'06, Edinburgh, UK,
June 26-30, 2006

Geneva, Switzerland
June 2006

CORRECTION OF VERTICAL DISPERSION AND BETATRON COUPLING FOR THE CLIC DAMPING RING

M. Korostelev and F. Zimmermann, CERN, Switzerland

Abstract

The sensitivity of the CLIC damping ring to various kinds of alignment errors has been studied. Without any correction, fairly small vertical misalignments of the quadrupoles and, in particular, the sextupoles, introduce unacceptable distortions of the closed orbit as well as intolerable spurious vertical dispersion and coupling due to the strong focusing optics of the damping ring. A sophisticated beam-based correction scheme has been developed to bring the design target emittances and the dynamic aperture back to the ideal value. The correction using dipolar correctors and several skew quadrupole correctors allows a minimization of the closed-orbit distortion, the cross-talk between vertical and horizontal closed orbits, the residual vertical dispersion and the betatron coupling.

INTRODUCTION

The lattice performance of the CLIC damping ring [1] has to test with regard to various error sources. In the real lattice, transverse kicks $\Delta x'$, $\Delta y'$ caused by transverse alignment errors ΔX, ΔY excite a nonzero closed orbit. It is easy to distinguish three types of sources which increase the vertical emittance via the betatron coupling C_β or the vertical dispersion D_z:

1. Transverse quadrupole misalignments, dipole errors and their effects:

- Dipol tilt errors $\rightarrow\ D_y$
- Dipolar orbit correctors $\rightarrow\ D_y$
- Vertical closed orbit (CO) in quadrupoles $\rightarrow\ D_y$

2. Sextupole misalignments and their effects:

- Vertical sextupole displacements $\rightarrow\ D_y,\ C_\beta$
- Vertical CO in sextupoles $\rightarrow\ D_y,\ C_\beta$

3. Quadrupole tilt errors:

- Skew quadrupoles $\rightarrow\ D_y,\ C_\beta$

A non-zero vertical orbit through the sextupole magnets, vertical sextupole misalignments, or rotational misalignments of the quadrupoles couple the particle motion in the horizontal and vertical planes. A displaced quadrupole does not introduce any betatron coupling.

ALIGNMENT SENSITIVITIES

The tracking code BETA-LNS [2] was used to study the sensitivity of the damping ring lattice to misalignment errors. The misalignment errors were assigned to the elements by a random generator. Many different "seeds" of random numbers have been averaged by the BETA-LNS code in order to obtain a statistically significant result. In the simulations, the random errors were generated with gaussian distributions truncated at $\pm 3\sigma$.

As one can see from Fig. 1, quadrupole vertical misalignments $\langle \Delta Y_{\rm quad} \rangle$ randomly assigned to all quadrupole magnets have a strong impact on the closed orbit in the CLIC damping ring if there is no dipole or dispersion correction. The simulation was done with sextupoles turned on and at $\langle \Delta X_{\rm sext} \rangle = \langle \Delta Y_{\rm sext} \rangle = 0$.

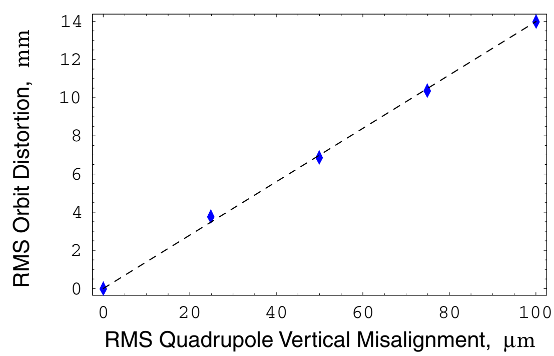
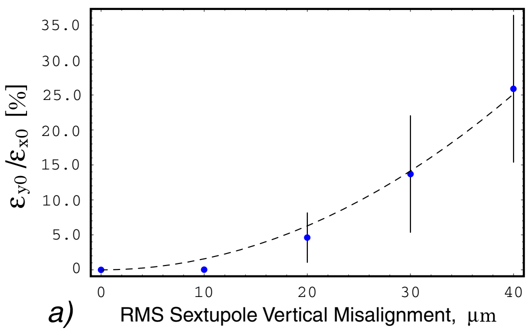


Figure 1: Correlation between rms closed orbit distortion and quadrupole vertical misalignment $\langle \Delta Y_{\rm quad} \rangle$ with sextupoles turned on, $\langle \Delta X_{\rm sext} \rangle = \langle \Delta Y_{\rm sext} \rangle = 0$, $\langle \Delta X_{\rm quad} \rangle = 0$.

The random tilt errors $\langle \Delta\Theta_{\rm arc\ dipole} \rangle$ of the dipole bending magnets induce quite a small closed orbit distortions (compared to the quadrupole misalignment). For $\langle \Delta\Theta_{\rm arc\ dipole} \rangle = 100\ \mu{\rm rad}$, the vertical and horizontal orbit distortions are 38 μm and $< 0.01\ \mu$m, respectively.

Figure. 2 shows the sensitivity of the vertical dispersion and zero-current transverse emittances ratio to the sextupole misalignments. The quadrupole rotations were set to zero when the effects from sextupole misalignments were computed. The dashed line corresponds to the fitted quadratic curve $\epsilon_{y0}/\epsilon_{x0} = 1.57 \times 10^{-4} \langle \Delta Y^2_{\rm sext} \rangle$ The blue rhombic points and the points with error bar correspond to the rms dispersion and emittance ratio $\epsilon_{y0}/\epsilon_{x0}$, respectively, as computed by the BETA-LNS code. The dashed lines represent a fit to the data.

As one can see from these simulations, fairly small magnet errors introduce unacceptable distortions in the closed orbit as well as vertical dispersion and coupling, due to the



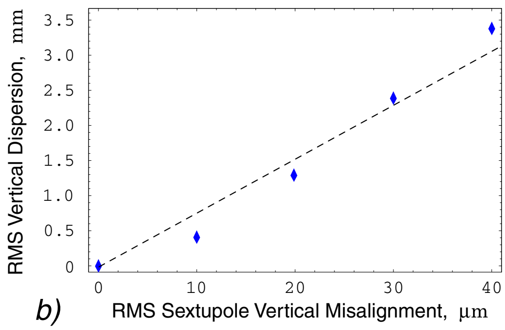


Figure 2: a) The zero-current emittance ratio $\epsilon_{y0}/\epsilon_{x0}$ including contribution from the vertical dispersion and betatron coupling as a function of the rms vertical sextupole misalignment $\langle \Delta Y_{\rm sext} \rangle$; b) RMS vertical dispersion as a function of the rms vertical sextupole misalignment $\langle \Delta Y_{\rm sext} \rangle$.

strong focusing optics of the damping ring.

CORRECTION

To reach a very low vertical emittance, we need to control the betatron coupling and dispersion. It is necessary to develop an effective correction system which will restore the transverse emittances to the values $\gamma\epsilon_y = 3.3\ nm$ and $\gamma\epsilon_x = 550\ nm$ (taking into account IBS) achieved for the ideal machine (without any imperfections).

The CLIC damping ring consists of two 48-cell arcs and two wiggler straight sections. The arc cell comprises one dipole magnet, two identical focusing quadrupoles QF, two identical defocusing quadrupoles QD and three sextupoles SF-SD-SF located between the quadrupoles [1].

We arranged the horizontal correctors HC as additional coils in the focusing arc quadrupoles QF, where β_x is maximum and the vertical correctors VC are set as additional coils in the SD sextupoles of the arcs. In the dispersion-free FODO straight section, horizontal and vertical correctors are located near each focusing and defocusing quadrupole, respectively. Moreover, three horizontal and vertical correctors are inserted in each dispersion suppressor. We installed two BPMs in each arc cell and also near each quadrupole of the FODO straight section. At these BPMs the dispersion can be monitored. As a result of this set up, the total number of BPMs are 292 units. The total number of horizontal and vertical correctors over the ring are 246 and 146 units, respectively.

Using the BETA-LNS code, we have studied dipole correction of the closed orbit and the vertical dispersion which are generated by quadrupole misalignments and rotational errors of the bending magnets. In our simulations the sextupoles are turned on. We assigned tilt errors $\langle \Delta\Theta_{\rm arc\ dipole} \rangle$ of 100 μrad for all bending magnets and quadrupole misalignment $\langle \Delta X_{\rm quad} \rangle = \langle \Delta Y_{\rm quad} \rangle = 90\ \mu$m for all quadrupole magnets. The dedicated dipole correction scheme provides quite an efficient COD correction that can reduce the zero-current vertical emittance $\gamma\epsilon_{y0}$ down to $2.2\ nm$, where $77.5\ \%$ and $22.5\ \%$ of $\gamma\epsilon_{y0}$ arise from spurious vertical dispersion and betatron coupling, respectively.

However, these simulations were done without any misalignments of sextupoles. If we assign small random sextupole misalignments of 20 μm, then after COD and dispersion correction performed only by dipole correctors, a large vertical emittance $\gamma\epsilon_{y0} = 10.8\ nm$ remains where $82.7\ \%$ and $17.3\ \%$ of the $\gamma\epsilon_{y0}$ arise from spurious vertical dispersion and betatron coupling, respectively. The vertical emittance from the rms sextupole misalignments of 20 μm is larger than the ones due to the residual closed orbit by about a factor of 5.

We tested also the tolerance to the rotational error of quadrupoles of 100 μrad for $\Delta X_{sext} = \Delta Y_{sext} = 0$. After the COD correction at presence of the following errors — $\langle \Delta\Theta_{\rm arc\ dipole} \rangle = 100\ \mu$rad, $\langle \Delta Y_{\rm quad} \rangle = \langle \Delta X_{\rm quad} \rangle = 90\ \mu$m and $\langle \Delta\Theta_{\rm quad} \rangle = 100\ \mu$rad —, the resulting vertical emittance is $9\ nm$, where $86.4\ \%$ and $13.6\ \%$ of the $\gamma\epsilon_{y0}$ come from spurious vertical dispersion and betatron coupling respectively.

In the CLIC damping ring, the dominant contribution to the emittance after closed-orbit distortion (COD) correction is the vertical dispersion. During correction of the COD, the kicks from the dipole correctors reveal a so-called cross-talk between vertical and horizontal closed orbits [3] (CTCO). The strength of the CTCO is defined by the difference between the two vertical closed orbits, when an horizontal corrector HC is turned on and when it is turned off. Minimization of the effect of the CTCO is equivalent to the minimization of the coupling. We have searched a set of skew correctors which minimize the CTCOs, and vertical spurious dispersion together.

Skew quadrupole correctors are inserted as additional coils into each second sextupole SD. Thus, 48 units of the skew correctors are included in the damping ring. The standard deviations of random errors assigned for the simulations of the correction are listed in Table 1. Note that in these simulations the random errors are generated with Gaussian distributions truncated at $\pm 2\sigma$.

The distribution of zero-current vertical emittance $\gamma\epsilon_{y0}$ shown in Figs 3 results after the correction of the COD, CTCOs, residual vertical dispersion and betatron coupling carried out by 246 horizontal, 146 vertical dipolar correctors and 48 skew quadrupole correctors. The distribution of $\gamma\epsilon_{y0}$ along a half of the ring structure was simulated

Table 1: Random alignment errors assigned to the CLIC damping ring.

Imperfections	Simbol	1 r.m.s.
Quadrupole misalignment	$\langle \Delta Y_{\rm q} \rangle$, $\langle \Delta X_{\rm q} \rangle$	90 μm.
Sextupole misalignment	$\langle \Delta Y_{\rm s} \rangle$, $\langle \Delta X_{\rm s} \rangle$	40 μm
Quadrupole rotation	$\langle \Delta \Theta_{\rm quad} \rangle$	100 μrad
Dipole rotation	$\langle \Delta \Theta_{\rm dipole\ arc} \rangle$	100 μrad.
BPMs resolution	$\langle R_{\rm BPM} \rangle$	2 μm.

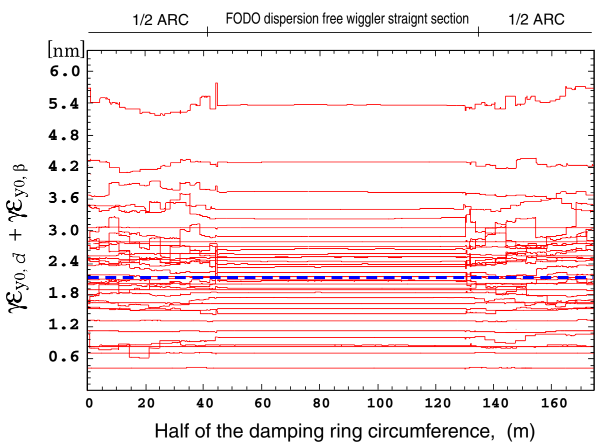


Figure 3: The deviation of the zero-current vertical emittance ϵ_{y0} along half of the ring after the closed orbit and skew quadrupole correction.

for 35 different samples of errors distribution along the ring. The dashed line corresponds to the mean value. The mean value of the vertical emittance $\langle \gamma \epsilon_{y0} \rangle$ is 2.14 nm. The mean value of the vertical dispersion invariant $\langle \mathcal{H}_y \rangle$ is 0.248 μm. It means that the contribution of spurious vertical dispersion to the vertical emittance $\gamma \epsilon_{y0,d}$ is equal to 1.97 nm when the NdFeB hybrid permanent magnet wigglers [4] are used. The mean value of betatron coupling $\langle \epsilon_{y0,\beta} / \epsilon_{x0} \rangle$ is 0.13 %. The contributions from the vertical dispersion are roughly 9 times larger than the contributions due to the betatron coupling.

Taking into account design bunch population N_{bp} of 2.56×10^9, we must include in our simulation the effect of intra-beam scattering (IBS). The vertical beam size is dominated by vertical dispersion. We performed IBS calculations based on modified Piwinski theory [5] where we take the mean values $\langle \mathcal{H}_y \rangle = 0.248\ \mu$m, $\langle C_\beta \rangle = 0.13$ %, $\langle \gamma \epsilon_{y0} \rangle = 2.14\ nm$, $\langle \gamma \epsilon_{x0} \rangle = 131\ nm$, $\sigma_{p0} = 9.15 \times 10^{-4}$ and $\sigma_{s0} = 1.21\ mm$. The average IBS emittance growth rates over the ring obtained by calculations for these parameters are $\langle 1/T_x \rangle = 255$ s^{-1}, $\langle 1/T_y \rangle = 119$ s^{-1} and $\langle 1/T_p \rangle = 175$ s^{-1} at $N_{bp} = 2.56 \times 10^9$ and rf voltage of 2250 kV. Taking into account IBS, the equilibrium emittances, rms bunch length and rms energy spread after dipole and skew quadrupole correction are the following:

- Horizontal emittance $\langle \gamma \epsilon_x \rangle$: 530 nm
- Vertical emittance $\langle \gamma \epsilon_y \rangle$: 3.3 nm
- Emittance ratio $\langle \epsilon_y / \epsilon_x \rangle$: 0.62 %
- RMS bunch length $\langle \sigma_s \rangle$: 1.63 mm
- RMS energy spread $\langle \sigma_p \rangle$: 12.35×10^{-4}
- Longitudinal emittance $\langle \gamma m_e c^2 \sigma_p \sigma_s \rangle$: 4892 eVm

Note that IBS has a strong effect since $\epsilon_x/\epsilon_{x0} = 4.1$, $\epsilon_y/\epsilon_{y0} = 1.54$ and $\sigma_s\sigma_p/\sigma_{s0}\sigma_{p0} = 1.8$, where the subindex "0" characterizes values without IBS.

Distortion of the dynamic aperture after skew quadrupole and dipole correction carried out in the presence of all alignment errors listed in Table 1 is shown in Fig. 4. The dynamic aperture is expressed in terms of sigmas of the injected beam equal to $\sigma_{x\,\rm inj} = 270\ \mu$m, $\sigma_{y\,\rm inj} = 34\ \mu$m. The simulations were done for 8 different samples of error distributions along the ring. The mean value of the dynamic aperture is pointed out by the dashed line while the thick solid line refers to the dynamic aperture for the ideal machine.

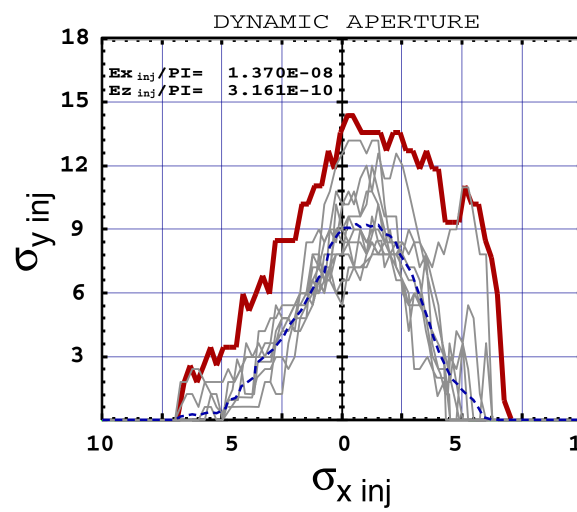


Figure 4: Dynamic aperture of the damping ring after dipole and skew quadrupole correction. The dashed line corresponds to the mean value of the dynamic aperture.

REFERENCES

[1] Updated CLIC parameters 2005, CLIC Note 627, CERN.

[2] J. Payet, BETA-LNS code.

[3] A. Loulergue, J. Payet, Correction of Vertical Dispersion and Betatron Coupling For SOLEIL Storage Ring, Proceedings EPAC98, 22-26 June 1998, Stockholm.

[4] M. Korostelev, F. Zimmermann, CLIC damping ring optics design studies, Proceedings of PAC 2005, Knoxville, Tennessee.

[5] K. Bane, A simplified model of intrabeam scattering, Proceedings of EPAC 2002, Paris, France.