OPTIMIZATION OF CLIC DAMPING RING DESIGN PARAMETERS

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Abstract

Damping-ring design parameters for CLIC are optimized by taking into account the combined action of radiation damping, quantum excitation and intrabeam scattering. We present a ring optics which corresponds to the optimum parameters and discuss its performance.

1 INTRODUCTION

The electron-positron Compact Linear Collider CLIC [1] is designed for operation at 3 TeV. Intense bunches injected into the main linac must have unprecedentedly small emittances to achieve the design luminosity $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The positron and electron bunch trains will be provided by the CLIC damping ring complex. This paper describes a damping ring optics producing such low-emittance beam.

The evolution of electron (positron) beam emittances in the damping ring is defined by the interplay of radiation damping, quantum excitation, and intra-beam scattering (IBS). A change in the momentum deviation of a particle in a dispersive region of the ring results in a change of its betatron oscillation amplitude. The growth rate of the emittance due to either IBS and quantum excitation then follows from a consideration of the statistics of the transverse excitation. An increase of the transverse beam emittance through quantum excitation occurs only when synchrotron radiation is emitted at a place with nonzero dispersion. The emittance growth due to IBS is similar, but in contrast to synchrotron radiation it also arises outside of the bending magnets.

The horizontal ε_x, vertical ε_y and longitudinal ε_t emittances evolve with time according to a set of three coupled differential equations [2]:

$$\dot{\varepsilon}_\mu = -\frac{2}{\tau_\mu}(\varepsilon_\mu - \varepsilon_{\mu 0}) + \frac{2\varepsilon_\mu}{T_\mu(\varepsilon_x, \varepsilon_y, \varepsilon_t)},\ \mu \in \{x, y, t\} \quad (1)$$

where τ_x, τ_y, τ_t are the radiation damping times of the betatron (xy) and synchrotron (t) oscillations, respectively, ε_{x0}, ε_{y0}, ε_{t0} the equilibrium emittances in the absence of IBS as determined by the balance of radiation damping and quantum excitation, and T_μ is the IBS growth time. The longitudinal emittance is expressed by

$$\varepsilon_t \approx \sigma_\delta \sigma_\tau c = C\sigma_\delta^2 \sqrt{\frac{\alpha E_0}{2\pi h \sqrt{e^2 V_m^2 - U_0^2}}} \quad (2)$$

where V_m is the RF peak voltage (in case of the sinusoidal variation of RF voltage), c the speed of light, U_0 the energy loss per turn, α the momentum compaction, h the RF harmonic number, and C the ring circumference. The three differential equations (1) are coupled through the IBS growth times $T_\mu(\varepsilon_x, \varepsilon_y, \varepsilon_t),\ \mu \in \{x, y, t\}$, which are nonlinear functions of emittances. The equilibrium emittances follow from the equation $\dot{\varepsilon}_x = \dot{\varepsilon}_y = \dot{\varepsilon}_t = 0$. There are two well known formalisms for computing the IBS growth times $T_\mu(\varepsilon_x, \varepsilon_y, \varepsilon_t)$, namely the Bjorken-Mtingwa theory [3] and Piwinski's theory [4, 5]. Both approaches determine the local, two-particle Coulomb scattering. Nevertheless, they give different growth times at very low emittance. These differences were investigated in the report [6]. In practice the vertical emittance is limited by nonzero betatron coupling, by residual vertical dispersion, and by IBS. A more fundamental limit of about $C_q\langle\beta_y\rangle/\rho$, where $C_q \approx 3.84 \cdot 10^{-13}$ m and ρ the bending radius, is set by the opening angle of the synchrotron radiation. For beta functions below 5 m and a 2-T field, this value is smaller than but close to our emittance goal.

2 RING PARAMETERS

To attain the very low emittances needed for the CLIC main linac, the lattice should have a small I_5 synchrotron integral. A small I_5 is obtained by using a TME (Theoretical Minimum Emittance) lattice [7, 9], with compact arcs. Without IBS, the horizontal equilibrium emittance of a TME-cell damping ring including wigglers is [8]

$$\gamma\varepsilon_{x0} \approx \frac{C_q\gamma^3}{12(J_{x0}+F_w)}\left[\frac{\varepsilon_r\theta^3}{\sqrt{15}} + \frac{F_w|B^3{}_w|\lambda_w^2\langle\beta_x\rangle}{16(B\rho)^3}\right] . \quad (3)$$

Here, the factor $F_w = I_{2w}/I_{2a} = L_w B_w^2/4\pi(B\rho)|B_a|$ represents the relative damping in the wiggler compared to the arcs, I_{2w} and I_{2a} are the synchrotron radiation integrals over the wigglers and arcs, respectively, $(B\rho)$ is the standard energy dependent magnetic rigidity, θ bending angle of dipole magnet, B_a and B_w are strength of magnetic field for bending magnet and wiggler, J_{x0} is the horizontal damping partition (without wiggler), λ_w the wiggler period, L_w the total length of wiggler section, and ε_r a detuning factor [7]. In this case the damping partition numbers are: $J_x = (J_{x0}+F_w)/(1+F_w)$, $J_z = 1$, $J_e = 3 - J_x$.

Dispersion-free regions are needed for injection, extraction and the damping wigglers. Using a FODO-cell lattice with zero dispersion function, the average beta function $\langle\beta_x\rangle$ through the wiggler can be kept reasonably small by placing wigglers between quadrupole magnets. The horizontal beta function in a wiggler must not exceed the value

$$\beta_x \leq \frac{384}{275}\sqrt{3}\ \frac{(mc^2)^3}{\hbar c e^3}\ \frac{16\varepsilon_{x0}E}{\lambda_w^2 B_w^3}\ , \quad (4)$$

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if the wiggler shall not increase the equilibrium beam emittance. In the limit of many wiggler poles and a short wiggler period λ, without IBS the final emittance approaches

$$\varepsilon_{xw0} \to \frac{5}{12} \cdot \frac{55\hbar c}{32\sqrt{3}(mc^2)^3} \cdot \frac{\beta_x}{\rho_w} E^2 \theta_w^2 \,. \qquad (5)$$

In this limit the damping and quantum excitation occur only in the wiggler magnets, and, thus, (5) does not depend on the unperturbed beam emittance in the arcs.

The ring circumference C is related to the harmonic number h and the frequency $f_{\rm rf}$ and must be large enough to accommodate the $N_{\rm train}$ bunch trains $C = hc/f_{\rm rf} \geq cN_{\rm train}T_{\rm train}$. Here $T_{\rm train}$ is the length of a bunch train plus the gap between trains, $T_{\rm train} = (k_{bt} - 1)\tau_b + \tau_k$ where the bunch train has k_{bt} bunches with a bunch spacing of τ_b and τ_k is a gap between the bunch trains to allow a kicker to rise or fall for injection and extraction.

As CLIC will operate with polarized beams [10], the damping ring must maintain a high spin polarization. Therefore, the ring energy should be chosen so that the spin tune is a half integer to stay away from the strong integer spin resonance. This constrains the ring energy to $a\gamma = n + 1/2$. Here, $a = 1.16 \times 10^{-3}$ is the anomalous magnetic moment of the electron. Another goal of the design is to keep the momentum compaction α_p relatively large to avoid instability. Table 1 summarizes the main parameters required for the CLIC damping ring. The length of the CLIC bunch train is $cT_{\rm train} = 38.4$ m.

Table 1: Beam parameters required for CLIC.

Parameter	Symbol	Value
Bunch population	N_b	4.2×10^9
No. of bunches per train	k_{bt}	154
Repetition frequency	f_r	100 Hz
Bunch spacing	τ_b	0.2 m
Min. kicker rise time	τ_k	25 ns
Final transv. emittances	$\gamma\epsilon_{x,y}$	450, 3 nm
Longitudinal emittance	$\gamma mc^2\epsilon_t$	$\leq$ 5000 eVm

To minimize the effect of intrabeam scattering, the equations (1) were solved numerically on a two-dimensional grid, as a function of both the equilibrium emittance without IBS, ε_{x0}, and the radiation damping time, τ_d, assuming a constant emittance ratio ϵ_y/ϵ_x. The optimum strengths of the arc dipoles and the wigglers were then inferred from the minimum transverse emittance computed at extraction for which the magnet fields were still considered reasonable.

3 OPTICS

The optics design followed the approach described in [8], but using the optimum values of dipole and wiggler strengths which were determined by solving (1) in a smooth approximation based on the Piwinski IBS formalism. The energy for the damping ring was chosen as 2.424 GeV which corresponds to $n = 5$. The emittance is minimum if the horizontal phase advance μ_x per TME arc cell is $284°$. This phase advance is not ideal with regard to chromatic correction, and the horizontal and vertical phase advances per TME arc cell were adjusted to $270°/60°$, since this allows the placement of identical sextupoles separated by an odd integer multiple of $180°$, which minimizes both non-linear chromaticity and resonance driving terms. The damping ring accommodates two long straight wiggler sections, in which the dispersion is almost negligible and whose chromaticity is compensated by the arc sextupoles.

A TME arc cell in the CLIC damping ring comprises three quadrupole magnets and a combined function bending magnet. The optics of an arc cell is shown in Fig. 1. The emittance detuning factor for this cell is $\varepsilon_r = 1.1$. The defocusing gradient in the bending magnet decreases the emittance by about 10-15% via the associated change of J_x [8], which is $J_{x0} \approx 1 - (1 + \varepsilon_r)(1 + K\rho^2)\theta^2/12$, where K denotes the normalized gradient. The combined function magnet also facilitates the matching. The defocusing gradient of the bending magnet is 173 kG/m.

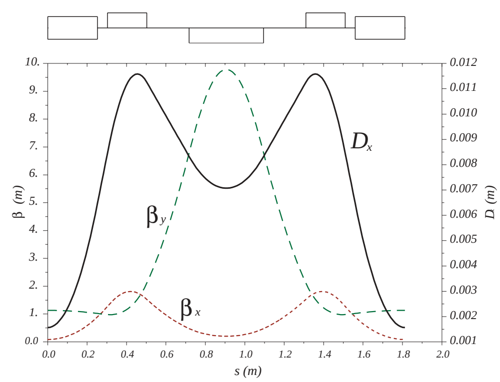

Figure 1: Optical functions over the arc cell.

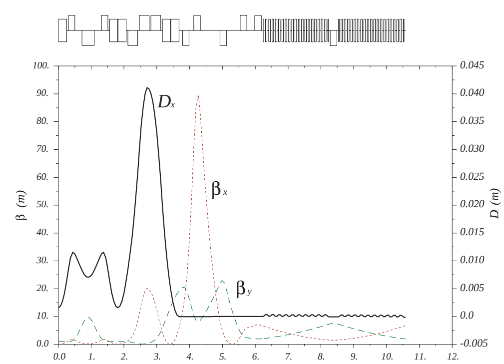

Figure 2: Optical functions from the end of the arc to the first wiggler FODO cell.

At the beginning and at the end of each of the two arcs a dispersion suppressor is located, which connects the arcs to the dispersion-free straight sections that include RF cavities, FODO cells with wigglers, and injection/extraction sections, as is illustrated in Fig. 2. In the straight sections,

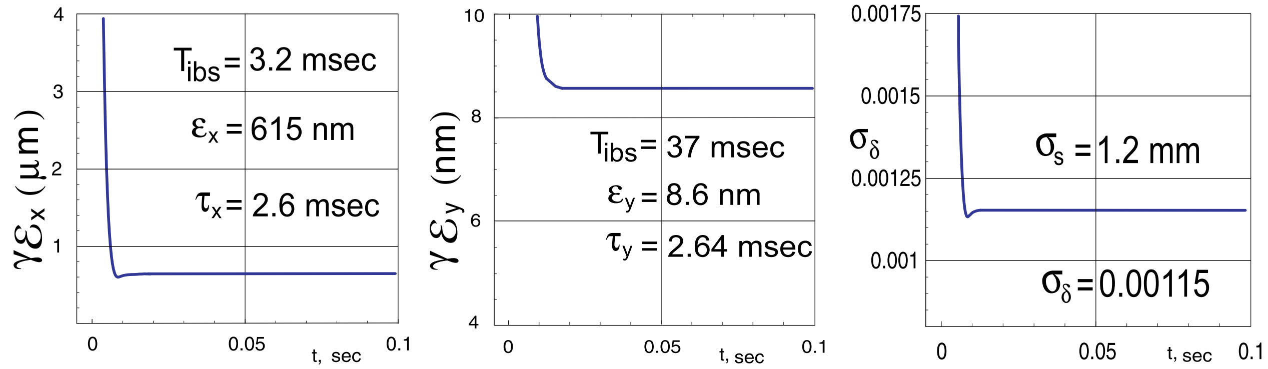

Figure 3: The evolution of $\varepsilon_x, \varepsilon_y$ and σ_δ if IBS is calculated by Bjorken-Mtingwa formalism.

the phase advance of a FODO cell is $90°/70°$ for the horizontal and vertical motion, respectively. The damping ring parameters for the design lattice are listed in Table 2.

Table 2: CLIC damping ring parameters.

Parameter	**Symbol**	**Value**
Nominal e^+ ring energy	γmc^2	2.424 [GeV]
No. of bunche trains stored	N_{train}	9
Ring circumference	C	345.6 [m]
Number of cells	N_{cell}	84
Betatron coupling	$\varepsilon_{y0}/\varepsilon_{x0}$	2.1%
Extracted hor. emittance	$\gamma\varepsilon_x$	615 [nm]
Extracted vert. emittance	$\gamma\varepsilon_y$	8.6 [nm]
Extracted long. emittance	$\gamma mc^2\varepsilon_t$	3425 [eV·m]
Extracted energy spread	σ_δ	1.15×10^{-3}
Damping time	τ_x	2.60 [msec]
Damping time	τ_y	2.64 [msec]
Damping time	τ_t	1.33 [msec]
Horiz. emittance w/o IBS	$\gamma\varepsilon_{x0}$	405 [nm]
Field of bending magnet	B_a	11.76 [kG]
Field of wiggler	B_w	17.64 [kG]
Wiggler period	λ_w	20 [cm]
Length of bending magnet	L	0.506 [m]
Total length of wigglers	L_w	144 [m]
Energy loss per turn	U_0	2.126 [MeV]
RF voltage	V_m	3.0 [MV]
RF frequency	f_{rf}	1521 [MHz]
Harmonic number	h	1728
Momentum compaction	α_p	0.76×10^{-4}

The strength of IBS increases with decreasing bunch dimensions. To achieve the low equilibrium emittances required, the damping times have to be considerably decreased using wigglers. The wiggler sections include a total of 72 units, each 2.1 m long and consisting of 21 pairs of magnetic poles. The wiggler parameters fulfill (4).

At injection into the positron ring, the beam parameters are $\gamma\varepsilon_{x,\text{inj}} = 63\ \mu$m, $\gamma\varepsilon_{y,\text{inj}} = 1.5\ \mu$m, $\sigma_{\delta,\text{inj}} = 5 \times 10^{-3}$, and $\sigma_{z,\text{inj}} = 10$ mm. Using (1) the time evolution of $\varepsilon_x, \varepsilon_y, \sigma_\delta$ was calculated for the proposed lattice. Computing the IBS growth times by the Bjorken-Mtingwa formalism, we obtain the results summarized in Fig. 3. If the Piwinski formalism is applied instead, the resulting equilibrium emittances are smaller by factors of 1.38, 1.2 and 1.17 for ε_x, ε_y, σ_δ, respectively.

4 OUTLOOK

The CLIC damping-ring lattice described here is based on a semi-analytical optimization of the ring parameters for minimum emittance including IBS. It produces a beam which almost meets the requirements for the longitudinal and horizontal emittances, but it falls short of the design goal in the vertical plane. In the future, we will study the dynamic aperture, optimize the higher-order chromatic correction, and explore electron-cloud effects [2].

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