PARAMETER SCAN FOR THE CLIC DAMPING RINGS

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Abstract

Triggered by the RF frequency reduction of the CLIC main linac cavities, the damping ring parameters had to be reevaluated and the rings' performance adapted to the new luminosity requirements. In view of a staged approach for reaching the ultimate energy of the collider, the dependence of the rings output emittances under the influence of Intrabeam Scattering is evaluated with respect to different beam characteristics such as bunch population, beam energy, coupling and longitudinal beam characteristics.

CLIC DAMPING RINGS PARAMETERS

Since 2005, the design and layout of the CLIC damping rings (DR) have not substantially changed [1]. Their performance was further optimized to achieve the target normalized emittances at their output. These studies were principally documented in the PhD thesis of M. Korostelev [2] which describes the baseline design. At a later stage, and in view of the change in the main CLIC structures, the impact of the imposed new parameters in the DR output emittances was studied but without a further optimization of their performance. The actual DR parameters are displayed in Table 1.

Table 1: CLIC damping rings parameters as registered in the 2005 note and new parameters after the main RF structure redesign.

Parameter [unit]	symbol	old value (2005)	new value (2007)
beam energy [GeV]	E_b	2.424	2.424
circumference [m]	C	360	365.2
bunch population [10^9]	N	2.56	3.70 ×1.1
bunch spacing [ns]	$T_{\rm sep}$	0.533	0.5
bunches per train	$N_{\rm b}$	110	312
number of trains	$N_{\rm train}$	4	1
store time / train [ms]	$t_{\rm store}$	13.3	20
rms bunch length [mm]	σ_z	1.547	1.53
rms momentum spread [%]	σ_δ	0.126	0.143
final hor. emittance [nm]	$\gamma\epsilon_x$	550	381
hor. emittance w/o IBS [nm]	$\gamma\epsilon_{x0}$	134	84
final vert. emittance [nm]	$\gamma\epsilon_y$	3.3	4.1
coupling [%]	κ	0.6	0.13
vertical dispersion invariant	$\mathcal{H}_y$	0	0.248
no. of arc bends	$n_{\rm bend}$	96	100
arc-dipole field [T]	$B_{\rm bend}$	0.932	0.932
length of arc dipole [m]	$l_{\rm bend}$	0.545	0.545
arc beam pipe radius [cm]	$b_{\rm arc}$	2	2
number of wigglers	$n_{\rm w}$	76	76
wiggler field [T]	$B_{\rm w}$	1.7	2.5
length of wiggler [m]	$l_{\rm w}$	2.0	2.0
wiggler period [cm]	λ_w	10	5
wiggler half gap [cm]	b_w	0.6	0.5
mom. compaction [10^{-4}]	α_c	0.796	0.804
synchrotron tune	Q_s	0.005	0.004
horizontal betatron tune	Q_x	69.82	69.84
vertical betatron tune	Q_y	34.86	33.80
RF frequency [GHz]	$f_{\rm RF}$	1.875	2
energy loss / turn [MeV]	U_0	2.074	3.857
RF voltage [MV]	$V_{\rm RF}$	2.39	4.115
h/v/l damping time [ms]	$\tau_x/\tau_y/\tau_s$	2.8/2.8/1.4	1.5/1.5/0.76
revolution time [μs]	$T_{\rm rev}$	1.2	1.2
repetition rate [Hz]	$f_{\rm rep}$	150	50

The electron and positron bunches with energy of 2.424 GeV are injected into the two rings whose layout is of racetrack shape. The two arcs are filled with 1.8 m long theoretical minimum emittance (TME) cells and the straight sections contain FODO cells with damping wigglers. A zone for injection and extraction is included after the dispersion suppressor of one of the arcs. The total length of the ring was slightly increased to 365.2m by raising the total number of TME cells to 100 and reducing some space in the dispersion suppressors. The phase advance per TME cell was kept to 210° in the horizontal and 90° in the vertical plane, providing a detuning factor of 1.8, defined as the ratio between the achieved emittance with respect to the minimum emittance of the corresponding TME cell. The chromaticity is controlled by two sextupole families.

The previous injection and extraction procedure was based on an interleaved bunch train scheme where two pairs of two bunch trains were injected and extracted simultaneously and than recombined with the help of a delay loop and RF deflectors. This scheme had the interesting feature of doubling the bunch spacing in the DR, thus reducing the effect of electron cloud and fast ion instabilities. This solution was abandoned due to its complexity. At the same time, the reduction of the repetition rate from 150 to 50 Hz leaves enough time (20 ms) for the emittances to reach their equilibrium. The injection and extraction process is quite simple with only one pulse stored in the damping ring per cycle. The change of parameters in the main CLIC cavities increased the bunch spacing to almost the same level as for the interleaved scheme. The number of bunches with the above mentioned bunch spacing fill 13 % of the rings. Note finally the increase of the RF frequency to 2 GHz.

A further reduction of the horizontal emittance is achieved with the inclusion of 76 damping wigglers. With the previous set of parameters, the target transverse emittance was not reached due to the strong effect of IBS which increases the horizontal output emittance by almost a factor of 5 with respect to the equilibrium emittance. It was thus necessary to choose higher wiggler fields, above the saturation level of iron dominated magnets, and shorter wiggler wavelengths. In the present design, the wiggler field is of 2.5 T with a period of 5 cm [3], which necessitates superconducting materials for achieving it. With these wiggler parameters, the achieved normalized horizontal emittance at the damping rings output drops below 400 nm.

The change in the wigglers' parameters triggered the increase of the energy loss per turn and the decrease of the damping times. In this respect, the RF voltage had to increase to 4.1MV in order to provide enough energy recovery while keeping the longitudinal emittance below 5000 eV. m. The vertical tune of the DR had to be reduced by a unit to accommodate the wigglers' field change.

The previous parameter set included the influence of misalignments on the vertical emittance which was considered to be dominated by coupling with a coefficient of 0.6 %. A detailed study of alignment tolerances and their influence to the vertical emittance was undertaken [2] and showed that the vertical emittance growth is dominated by vertical dispersion and less by coupling. The evaluation of vertical emittance value of 4.1 nm quoted in the latest parameter set includes this non-vanishing dispersion invariant for the vertical plane, and uses the complete set of coupled differential equations for evaluating the effect of IBS.

SCALING OF PARAMETERS

Bunch charge

Figure 1 presents the dependence of the transverse emittances with respect to bunch charge. The horizontal emittance scales linearly with the square root of the bunch charge (for high charges) and inversely with the square root of the longitudinal emittance, i.e. $\epsilon_x \propto \sqrt{\frac{N}{\epsilon_s}}$. The vertical and longitudinal emittance have a much weaker dependence to the bunch charge and actually of the same order. As the bunch charge changes, the vertical and longitudinal emittance seem to be linear with each other. This confirms that the vertical emittance is dominated by vertical dispersion and not coupling.

The change of the CLIC RF structure design parameters, had a major impact on the bunch charge which increased by a factor of 1.6, including a 10 % margin for losses in the downstream injector systems. Taking into account the previous scaling, the impact of the increased bunch charge to the horizontal and vertical emittance was small and well within the target values.

Longitudinal emittance

The longitudinal emittance can be controlled by the RF voltage, with a lower limit given by the energy loss per turn. We consider to relax the longitudinal emittance of 5 keV.m required by the downstream linac. The longitudinal emittance can be increased up to 9keV.m, by decreasing the RF voltage, while keeping the same bunch charge (Fig. 2). The horizontal emittance presents the inverse square root dependence shown before and can be reduced by 25 %. The

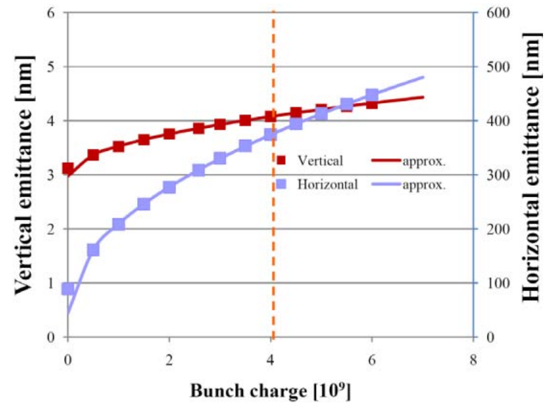

Figure 1: Horizontal and vertical emittance dependence on bunch charge

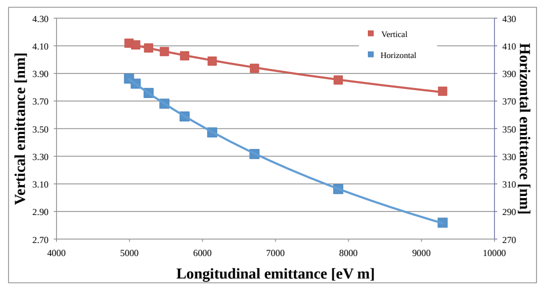

Figure 2: Horizontal (blue) and vertical (red) emittance dependence on longitudinal emittance.

dependence of the vertical emittance is much weaker and scaled as $\epsilon_y \propto \epsilon_s^{-1/7}$.

Energy

The "zero-current" equilibrium emittance is written as

$$\epsilon_{x;0} = \frac{C_q \gamma^2}{12(\mathcal{J}_x + \mathcal{F}_w)} \left(\frac{\theta^3}{\sqrt{15}} \epsilon_r + \frac{\mathcal{F}_w |B_w^3| \lambda_w^3 \langle \beta_x \rangle}{16 (B\rho)^3} \right) \quad (1)$$

with the relative damping factor $\mathcal{F}_w = \frac{L_w B_w^2}{4\pi (B\rho) B}$ and ϵ_r the TME detuning factor. Assume that the damping partition number $\mathcal{J}_x = 1$ (no gradient in dipoles) and that the bending angle $\theta = \frac{L}{\rho}$ and the bending field are constant. As the bending radius is proportional to the energy, the dipole length and the circumference should be scaled in the same way. Scaling the total wiggler length as $L_w \propto \gamma$, makes the relative damping factor energy independent.

The average beta function in a wiggler FODO cell is $\langle \beta_x \rangle = 2 \frac{3f^2 - L_w^2}{3\sqrt{f^2 - L_w^2}}$ and scales as the wiggler length or the energy, considering constant focusing strength. Keeping the wiggler characteristics constant, the second term of the equation (1) is energy independent whereas the first is scaled with the square of the energy. This term will dominate for high-energies, so that the horizontal normalized emittance is $\epsilon_{x;0} \propto \gamma^3$.

The normalized longitudinal emittance is $\epsilon_s = \gamma \sigma_s \sigma_\delta m_0 c^2$. The rms bunch length can be written as

$\sigma_s = \frac{c|\eta|}{\omega_s}\frac{\sigma_\delta}{m_0c^2}$, with the slippage factor approximately equal to the momentum compaction factor for leptons:

$$\eta \approx \alpha_p = \frac{3\pi}{2}\left(\frac{4\sqrt{15}}{9}\right)^{2/3}\frac{(B\rho)(1+\mathcal{F}_w)^{2/3}}{C|B|\gamma^2}\times$$
$$\left(\frac{\gamma\epsilon_{x;0}}{C_q} - \frac{\mathcal{F}_w|B_w^3|\lambda_w^2\langle\beta_x\rangle\gamma^3}{192(B\rho)^3(\mathcal{J}_w+\mathcal{F}_w)}\right)^{2/3}\frac{\sqrt{5}+\sqrt{\epsilon_r^2-1}}{\epsilon_r^{2/3}} \ .$$

Under the assumptions made for the scaling of the "zero-current" equilibrium emittance, the momentum compaction factor is energy independent. The rms momentum spread is proportional to $\frac{\sigma_\delta}{m_0c^2} = \sqrt{\frac{C_q\gamma^2}{\mathcal{J}_s\rho}} \propto \sqrt{\gamma}$. Finally the synchrotron frequency is written as $\omega_s = \frac{c}{C}\sqrt{\frac{2\pi h\alpha_p(e\hat{V}^2-U_0^2)^{1/2}}{m_0c^2}}$. Taking into account that the harmonic number is proportional to the circumference and therefore to the energy, based on our previous consideration, and assuming an increase of the RF voltage with the energy loss per turn, the synchrotron frequency is $\omega_s \propto \frac{1}{\sqrt{\gamma}}$. This makes the rms bunch length linear with the energy and finally the longitudinal normalised emittance is $\epsilon_{s;0} \propto \gamma^{5/2}$. The horizontal damping time is expressed as $\tau_x = \frac{3B\rho C}{2\pi r_e c\gamma^3 B(\mathcal{J}_w+\mathcal{F}_w)}$ and thus it is inversely proportional to the energy.

Under the influence of IBS, it is difficult to find an analytical scaling due to the complexity of the growth rate formulas. Using the previous scaling laws and without redesigning a new lattice, a numerical scaling can be obtained, by integrating the same set of coupled difference equations of the standard IBS theory. In Fig. 3, the dependence of horizontal and longitudinal emittance with respect to the energy is plotted. This gives that the longitudinal and horizontal emittance scale approximately as $\epsilon_s \propto \gamma^4$ and $\epsilon_x \propto \gamma^{-2}$. Note that they still respect the inverse square root scaling with each other.

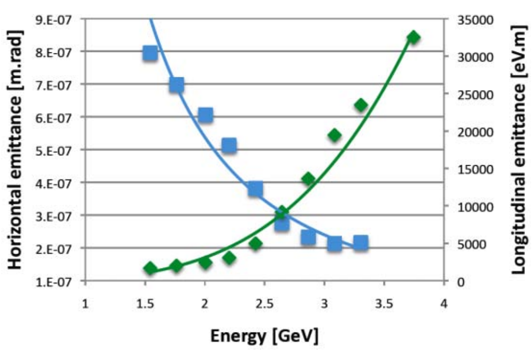

Figure 3: Horizontal (blue) and longitudinal (green) emittance dependence on the energy.

The horizontal emittance dependence with the energy for constant longitudinal emittance is presented in Fig. 4. There seem to be two regimes: for higher energies, where the effect of IBS should become smaller, it increases following a power law, similar to the one of the "zero-current" equilibrium emittance. For small energies where the effect of IBS dominates, the horizontal emittance is almost inversely proportional to the energy. The energy providing the minimum emittance is around the one of the CLIC damping rings.

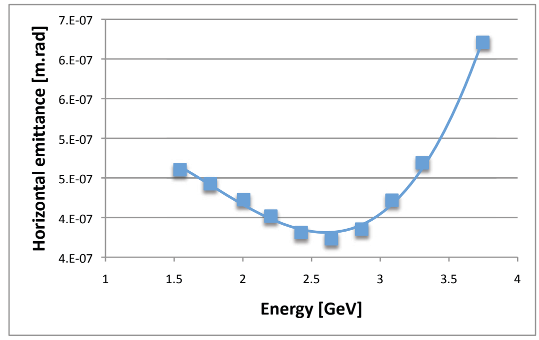

Figure 4: Horizontal emittance dependence on the energy while keeping a constant longitudinal emittance.

The vertical emittance dependence to the energy is shown in Fig. 5. The top curve is for varying longitudinal emittance whereas in the bottom curve the longitudinal emittance is kept constant. In the former case, the vertical emittance follows a quadratic polynomial law with the energy. As before, the minimum vertical emittance is close to the energy of the CLIC damping rings. In the latter case, it scales linearly with the energy for high energies, thus the geometrical emittance is energy independent. This comes from the fact that the vertical emittance depends mostly on the alignement tolerances which are energy independent. For low energies the vertical normalized emittance seems to saturate to a constant value which means that when the IBS becomes strong, the vertical geometrical emittance should be inversely proportional to the energy.

Considering a low energy version of the CLIC project, the scaling laws presented in this paper can be used for providing conservative emittances for the DR, based on existing designs of future light sources [4].

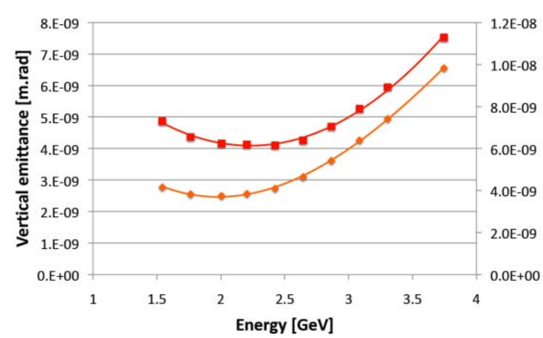

Figure 5: Vertical emittance dependence on the energy. The bottom curve corresponds to constant longitudinal emittance.

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