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IMPEDANCE EFFECTS IN THE CLIC DAMPING RINGS

E. Koukovini-Platia, K. Li, N. Mounet, G. Rumolo, B. Salvant
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Due to the unprecedented brilliance of the beams, the performance of the Compact Linear Collider (CLIC) damping rings (DR) is affected by collective effects. Single bunch instability thresholds based on a broad-band resonator model and the associated coherent tune shifts have been evaluated with the HEADTAIL code. Simulations performed for positive and negative values of chromaticity showed that higher order bunch modes can be potentially dangerous for the beam stability. This study also includes the effects of high frequency resistive wall impedance due to different coatings applied on the chambers of the wigglers for e-cloud mitigation and/or ultra-low vacuum pressure. The impact of the resistive wall wake fields on the transverse impedance budget is finally discussed.

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Due to the unprecedented brilliance of the beams, the performance of the Compact Linear Collider (CLIC) damping rings (DR) is affected by collective effects. Single bunch instability thresholds based on a broad-band resonator model and the associated coherent tune shifts have been evaluated with the HEADTAIL code. Simulations performed for positive and negative values of chromaticity showed that higher order bunch modes can be potentially dangerous for the beam stability. This study also includes the effects of high frequency resistive wall impedance due to different coatings applied on the chambers of the wigglers for e-cloud mitigation and/or ultra-low vacuum pressure. The impact of the resistive wall wake fields on the transverse impedance budget is finally discussed.

INTRODUCTION

The interaction of charged particle beams with the surroundings, and therefore energy loss and transverse kick due to a particular machine element or the vacuum chamber, is expressed in terms of impedance in the frequency domain. These interactions need to be known in order to estimate the thresholds of coherent instabilities which may limit the achievable beam current. They have to be taken into account early in the design stage of an accelerator, as they define a total impedance budget for the various elements that will be installed and limit the choice of materials and shapes of the components required for its operation. Since collective effects may limit the achievable beam current, it is necessary the total impedance budget to be consistent with the intensity requirements.

The full ring is usually modeled with a total impedance made of three main components: resistive wall, several narrow-band resonators and one broad-band resonator. A narrow-band resonator models cavity-like objects. Its wake field is long range and mainly affects many bunches, therefore, it is responsible for multibunch instabilities. A broad-band resonator models the global effect of all discontinuities of the beam pipe and replaces the effect of the actual impedance consisting of many small short range contributions. It is responsible for single bunch instabilities.

The aim of this paper is to review the impact of impedance for the CLIC DR for single bunch instabilities taking into consideration two contributions: a broad-band resonator modeling all the ring and a resistive wall modeling the contribution from the wigglers with their tiny apertures. For the macroparticle simulation, the HEADTAIL code [1] is used. The parameters of the DR, at the current stage of design, are summarized in Table 1 [2].

Table 1: DR parameters used in the simulation

Energy	E (GeV)	2.86
Norm. transv. emitt.	$\epsilon_{x,y}$ (nm)	456, 4.8
Bunch length	σ_z (mm)	1.8
Momentum spread	σ_δ	1.07×10^{-3}
Bunch spacing	ΔT_b (ns)	1
Bunch population	N	4.1×10^9
Circumference	C (m)	427.5
Mom. compact. factor	α	1.3×10^{-4}
Tunes	$Q_{x,y,s}$	48.35, 10.4, 0.0057
Energy loss	ΔE (MeV/turn)	3.98
Damping times	$\tau_{x,y,z}$ (ms)	2, 2, 1
RF frequency	f_{rf} (GHz)	1
RF voltage	V_{rf} (MV)	5.1
Wiggler length	L_w (m)	2
Wiggler field	B_w (T)	2.5
Number of wigglers	N_w	52
Wiggler half gap	r_w (mm)	6

SINGLE BUNCH EFFECTS

Broadband resonator

The broad-band model is used as a first approximation to model the whole ring. The goal is to scan over different impedance values, in order to define the instability threshold. The impedance budget is then estimated. The impedance source is assumed to be identical in the horizontal and vertical planes.

In the transverse plane, a strong head-tail instability or Transverse Mode Coupling Instability (TMCI) can occur and cause rapid beam loss. In the case of a round beam and axisymmetric geometry for a short bunch there is a criterion to find the threshold of TMCI [3]:

$$\frac{R_T[k\Omega/m]{f_r}^2[GHz]}{Q} \leq 0.6\frac{E[GeV]Q_s}{\langle\beta_y\rangle[m]Q_b[C]\sigma_t[ps]} \qquad (1)$$

In this formula, R_T is the transverse impedance in kΩ/m, f_r=ω_r/2π represents the resonant frequency in GHz where ω_r is the resonant angular frequency of the resonator and is assumed to be the cut off frequency of the beam pipe, Q the quality factor, $\langle\beta_y\rangle$ the average beta value in the y plane in m, Q_b=Ne the bunch charge in Coulomb and σ_t = σ_z/βc represents the rms bunch length in ps. Since the CLIC DR bunch is short, compared to the wavelength of electromagnetic waves propagating in the beam pipe, Eq.

* also affiliated at EPFL

1 can be used to predict the TMCI threshold. By using the DR parameters from Table 1, Eq. 1 translates into a threshold of 10.7 MΩ/m for the transverse broad-band resonator in the vertical plane for Q=1 and f_r=5 GHz.

The HEADTAIL code gives the evolution of the bunch centroid over several turns for different impedance values. By applying the Sussix algorithm [4] on the coherent bunch motion, the spectrum of the bunch modes can be obtained. The relative tune shift (Q-Q_x)/Q_s with respect to the zero-current tune Q_x is normalized to the synchrotron tune Q_s to identify each of the azimuthal modes. The mode spectrum represents the natural coherent oscillation frequencies of the bunch. The tune shift is plotted, for the case of zero chromaticity, as a function of impedance in Figure 1.

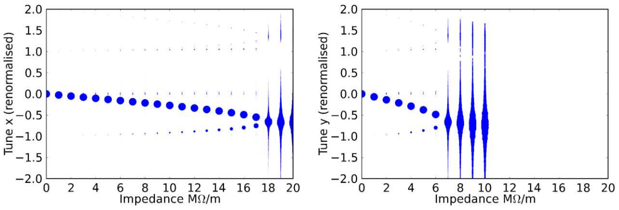

Figure 1: Mode spectrum of the horizontal (left) and vertical (right) coherent motion for zero chromaticity, as a function of impedance. A TMCI is observed at 18 MΩ/m and 7 MΩ/m in x and y plane respectively.

Modes 0 and -1 are observed to move and couple for impedance values of 18 MΩ/m and 7 MΩ/m in the horizontal and vertical plane respectively, causing a TMCI. The value, in the y plane, is about 34% lower than that naively calculated with the analytical formula 1. The difference in the impedance thresholds in the two planes is explained by the difference in the average beta values over the DR used in this simulation for the broad-band resonator, where $\langle\beta_x\rangle$ = 3.475 m and $\langle\beta_y\rangle$= 9.233 m. In HEADTAIL the effect of the impedance is simulated by kicks given each turn at a certain point of the ring, proportional to the macroparticles offset and therefore to the $\sqrt{\langle\beta_{x,y}\rangle}$. The effect of such kicks is also expected to be proportional to the $\sqrt{\langle\beta_{x,y}\rangle}$. Therefore in the vertical plane, the impedance has an effect higher by a factor of 2.7 compared to the horizontal plane and the TMCI threshold is smaller by almost the same fraction, 2.6.

Positive and negative chromaticity

Chromaticity is believed to raise the TMCI threshold thanks to the tune spread that it causes and because it locks the coherent modes to their low intensity values, making mode merging weaker. For this reason, a simulation was done for different positive and negative values of chromaticity. For positive chromaticity, the dipole mode m=0 is damped whereas for negative chromaticity it becomes unstable.

As expected, the presence of chromaticity causes the modes to move less and not to merge and by consequence to avoid a TMCI, but another type of instability, the head-tail instability, is occurring. In Figure 2, it is observed that in the case of positive chromaticity, higher order modes get excited whereas m=0 is damped, showing that while a TMCI can be avoided, a head-tail instability develops on a single mode. The TMCI quickly becomes very fast above the threshold for the onset, but for the case of head-tail instability the calculation of its rise time is needed and the comparison with the damping time given by the parameters in Table 1. If the rise time is lower than the damping time, the instability is faster than the damping mechanism. In Figure 3, the damping time of 2 ms given by the DR parameters in Table 1, defines an instability threshold at 6.5 MΩ/m and 6 MΩ/m in the horizontal and vertical plane respectively. For the future, it is planned to implement the damping mechanism into the HEADTAIL code.

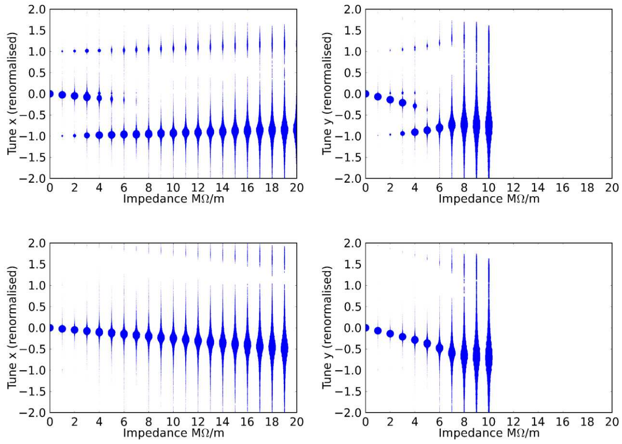

Figure 2: Mode spectrum of the horizontal (left) and vertical (right) coherent motion as a function of impedance, for positive 0.018 and 0.019 (top pictures) and negative chromaticity -0.018 and -0.019 (bottom pictures) in x and y plane respectively.

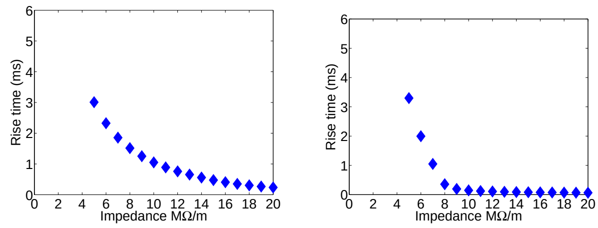

Figure 3: Rise time in the horizontal (left) and vertical (right) plane for positive 0.018 and 0.019 chromaticity in x and y plane respectively. Damping time is 2 ms in the two planes, therefore the instability threshold is at 6.5 MΩ/m and 6 MΩ/m in the horizontal and vertical plane respectively.

The results from Table 2 show that the instability thresholds are even lower for the case of positive or negative chro-

Table 2: Impedance thresholds in MΩ/m for slightly positive and negative chromaticity.

Chromaticity ξ_x/ξ_y	Threshold in x (MΩ/m)	Threshold in y (MΩ/m)
0.018/ 0.019	6.5	6
0.055/ 0.057	4	4
0.093/ 0.096	5	3
-0.018/ -0.019	4	5
-0.055/ -0.057	2	2
-0.093/ -0.096	2	2

maticity compared to 18 MΩ/m and 7 MΩ/m in the horizontal and vertical plane respectively for the case of zero chromaticity. Lower instability thresholds translate into a lower impedance budget for the DR. The goal is to operate at zero chromaticity which has also the advantage to allow for a larger impedance budget, however, since chromaticity will be certainly slightly positive, a lower impedance budget than that given by the TMCI for zero chromaticity has to be considered. Therefore, the impedance budget is estimated to be 4 MΩ/m.

Resistive wall in the wigglers

The resistive wall in the wiggler sections with 6 mm vertical half aperture is expected to be a strong source of impedance. Because of the small aperture, compared to 9mm for other parts of the ring, the contribution of the wigglers is expected to take a significant fraction of the available impedance budget. Moreover, layers of coating materials, which are necessary for e-cloud mitigation or good vacuum, can significantly increase the resistive wall impedance especially in the high frequency regime. The materials used in these simulations are stainless steel (ss) and copper for the pipe of the wigglers, which is assumed to be flat, and the goal is to check whether it is possible to perform at the nominal intensity. Copper has a conductivity of $5.9 \times 10^7\,\Omega^{-1}m^{-1}$ and stainless steel of $1.3 \times 10^6\,\Omega^{-1}m^{-1}$. Amorphous carbon (aC), used for e-cloud mitigation, and non-evaporated getter (NEG), used for good vacuum, were chosen as coating materials. Different material and coating combinations were tried, in order to study the effect of coating on the threshold over the intensity range from 1×10^9 to 29×10^9. The average beta values for the wigglers, $\langle\beta_x\rangle$ = 4.200 m and $\langle\beta_y\rangle$= 9.839 m, were used for this simulation.

Table 3 shows that for the case of copper, the thresholds are higher compared to those of stainless steel and above the intensity range simulated for most cases. This makes copper a better choice in terms of instabilities but it is also a more expensive material. In addition, it is observed that adding a layer of coating material on the beam pipe reduces the intensity thresholds and in fact the thicker the coating is, the more the threshold is reduced. However, in the case of coating, the instability thresholds are still in the range of tolerance and much higher than the nominal intensity. However, if the worst case in terms of instability threshold is considered, 17×10^9, this would correspond with a simple scaling law to an impedance of ∼1 MΩ/m since the nominal intensity 4.1×10^9 corresponds to 4 MΩ/m for the broad-band model. This already reduces by 25% the total impedance budget.

Table 3: Intensity threshold in the y plane for non-coated and coated wigglers. The thickness of the coating layers is given in mm.

Stainless steel (ss)	21×10^9
aC on ss (0.0005 mm)	19×10^9
aC on ss (0.001 mm)	17×10^9
NEG on ss (0.001 mm)	20×10^9
NEG on ss (0.002 mm)	19×10^9
Copper	$> 29 \times 10^9$
aC on copper (0.0005 mm)	$> 29 \times 10^9$
aC on copper (0.001 mm)	$> 29 \times 10^9$
NEG on copper (0.001 mm)	$> 29 \times 10^9$
NEG on copper (0.002 mm)	26×10^9

CONCLUSIONS

In conclusion, in the case of the broad-band resonator model for the DR the requirements in terms of impedance are 18 MΩ/m and 7 MΩ/m in the horizontal and vertical plane respectively. Positive or negative chromaticity prevents a TMCI but higher order modes get excited and can be potentially dangerous for this case. The instability thresholds are lower than the ones for zero chromaticity translating into a lower impedance budget, which is however the more realistic case since a slightly positive chromaticity is expected. The impedance budget is therefore estimated at 4 MΩ/m in the two planes. Wigglers made from copper show higher instability thresholds than for stainless steel, but the material choice will also depend on the final cost. The use of aC or NEG does not seem to be critical in terms of instabilities. The contribution from the wigglers already takes an important fraction of ∼1 MΩ/m from the total impedance budget. This budget is expected to be further reduced if all the different contributions from the DR are taken into account. In the future, it is planned to create an impedance database with the contribution of all the components of the ring and further simulations will be done to study in more detail the effect of different coatings and different layers in the wigglers and the rest of the machine.

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