DESIGN OPTIMISATION OF THE CLIC DAMPING RINGS

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Abstract

The CLIC damping rings should produce the ultra-low emittance with high bunch charge necessary for the luminosity performance of the collider. This large bunch density triggers a number of beam dynamics and technical challenges. Lattice studies have been focused on low emittance cells with optics that reduce Intra-beam scattering. Collective effects such as electron cloud and fast ion instability can severely limit the performance and mitigation techniques have been identified and tested. The final beam emittance is reached with the help of superconducting damping wigglers. Results from recent simulations and prototype measurements are presented, including an absorption scheme design. Tolerances for alignment and technical system design such as kickers, RF cavities, magnets and vacuum have been finally established.

DESIGN GOALS AND CHALLENGES

The high luminosity of a linear collider at the lowest power depends strongly on the generation of ultra-low emittance high-intensity bunches, with remarkable stability. The required cooling mechanism is provided by the natural synchrotron radiation damping of the beam when circulating in rings. The performance challenges of these damping rings (DRs) are driven by the main parameters of the collider and the requirements of the upstream and downstream systems.

The parameters guiding the design of the CLIC DRs are presented in Table 1, as compared to the ones of NLC [1]. The two lists resemble but the CLIC DRs have almost one order of magnitude smaller emittance requirements in all three dimensions (500nm horizontal, 5nm vertical and 6keV longitudinal). Although these emittances are unprecedented, modern light sources in operation or in the construction phase, are rapidly approaching these regimes [2]. Figure 1 presents the horizontal and vertical normalized emittance in a number of low emittance rings, including test facilities, DRs, B-factories and synchrotron light sources, under operation (red) or design (blue).

The large input emittance especially coming from the positron source and the high repetition rate of 50Hz, requires that the beam damping is done in two stages, with a pre-damping ring (PDR) for each particle species. A careful lattice design and non-linear dynamics optimisation is necessary for providing a solid PDR design, with large dynamic and momentum aperture, enabling the efficient digestion of the incoming beam [3]. Most of the design challenges of the CLIC main DRs are driven from the extremely high bunch density and the collective effects associated with it. In this respect, the DR parameters shown in Table 2 are carefully chosen and optimised in order to reduce these effects. In addition, these parameters drive the technology of a number of components such as wigglers, RF system, kickers and vacuum.

Table 1: CLIC Versus NLC Parameters Driving the DRs Design

Parameters [unit]	NLC	CLIC
Bunch population [10^9]	7.5	4.1
Bunch spacing [ns]	1.4	0.5
Number of bunches/train	192	312
Number of trains	3	1
Repetition rate [Hz]	120	50
Horizontal norm. emittance [nm]	2400	500
Vertical norm. emittance [nm]	30	5
Longitudinal norm. emittances [keV.m]	11	6

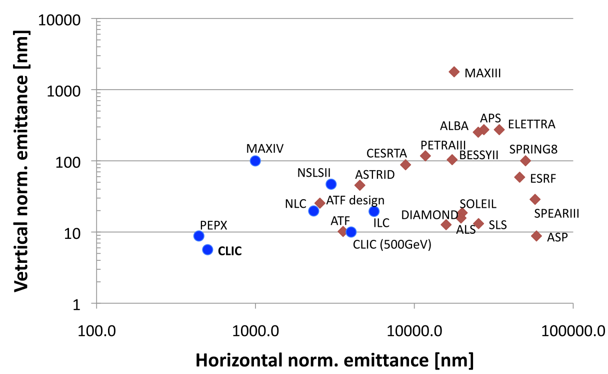

Figure 1: Horizontal versus vertical normalized emittance for low emittance rings in operation (red) and under design (blue)

Table 2: CLIC DRs Design Parameters

DR parameters [unit]	Value
Energy [GeV]	2.86
Circumference [m]	420.6
Energy loss/turn [MeV]	4.2
RF voltage [MV]	4.9
Compaction factor	8×10^{-5}
Damping time x / s [ms]	1.9 / 0.96
Number of arc cells/wigglers	100/52
Dipole/wiggler field [T]	1.4/2.5

LATTICE DESIGN AND COLLECTIVE EFFECTS

The steady state emittance is dominated by Intra-beam scattering (IBS) and the ring energy has to be chosen in a regime where the ratio between the IBS-dominated emittance and the "zero-current" one is the lowest possible and within the required tolerance. In this respect, the energy of 2.86 GeV was chosen for the CLIC DR, which is close to a steady state emittance minimum but also reduces the IBS impact [4]. Although higher energies may be also interesting for reducing further collective effects, the output emittance is strongly increased due to the domination of quantum excitation.

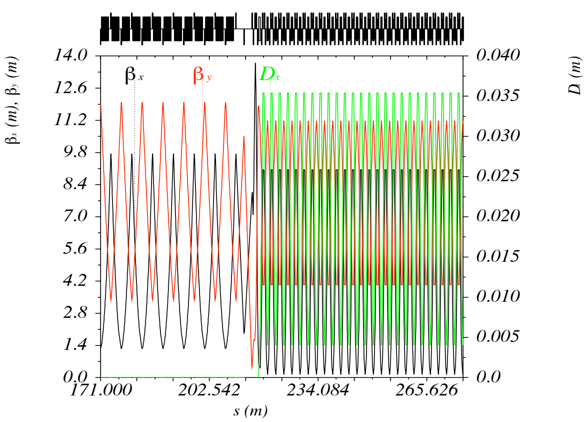

Figure 2: Optical functions for a quarter of the CLIC DR.

The lattice, based on a racetrack shape with TME arc cells and long straight sections (LSSs) filled with wiggler FODO cells, has been optimized, in order to reduce the IBS growth rates [5]. The optics of one quarter of the ring including one half LSS and arc, matched by a dispersion suppressor, is shown in Fig. 2. The dynamic aperture of the ring is quite large, although some further studies are needed, including the effect of magnet imperfections and wigglers. The final emittances are within the required tolerances as further proved by the dedicated simulation code SIRE [6], which was benchmarked successfully [7] with the classical IBS theories [8].

The ultra-low vertical emittance requirement of 5 nm, corresponds to a geometrical emittance of less than 1 pm. Although this value has never been reached, electron storage rings such as SLS, DIAMOND and the Australian synchrotron and test facilities such as ATF have recently reported measurements of vertical emittance of 1-3 pm [2]. In order to reach this emittance, not only low magnetic error tolerances and extremely good control of the geometric alignment of the magnets are required, but also a combination of diagnostics for precise beam size, position and emittance measurement as well as on-line correction techniques. All these issues will be addressed in a dedicated R&D program at SLS.

Due to the very small beam size especially in the vertical plane, the space charge tune-shift

$$\delta\nu_{x,y} = -\frac{N_b r_e}{(2\pi)^{3/2}\gamma^3\sigma_z}\oint\frac{\beta_{x,y}}{\sigma_{x,y}(\sigma_x+\sigma_y)}ds \qquad (1)$$

is large (≈ 0.2). Although simulations have shown that the emittance growth is small [10], an effort was undertaken in order to reduce the vertical tune-shift to around 0.1. In order for the space charge to be reduced, the ring has to become as compact as possible, as the optics integral in the right hand side of (1) is getting smaller. At the same time, the bunch length σ_z has to be increased without affecting the performance of the downstream bunch compressors [9]. This was achieved by increasing the equilibrium bunch length $\sigma_{z0} = \sigma_{\delta 0} C \sqrt{\frac{\alpha_p E}{2\pi h \sqrt{V_0^2 - U_0^2}}}$ through combined reduction of the circumference C (removing wiggler cells), lowering the harmonic number h by reducing the RF frequency and increasing the momentum compaction a_p.

High bunch density in combination with the short bunch spacing triggers two stream instabilities. In the electron ring, the fast ion instability can be avoided with ultra-low vacuum pressure of 0.1nT [10]. This necessitates coating of vacuum chambers with getters like NEG for increasing pumping. In order for the electron cloud build up to be reduced and the instability not to occur in the positron ring, it is necessary that the vacuum chambers present a secondary emission yield (SEY) below 1.3 and the photoemission yield should not exceed 0.1% [11]. The low SEY can be achieved with special chamber coatings. In particular, a novel amorphous carbon coating pioneered at CERN SPS [12], has shown a great reduction of the electron cloud activity in coated chambers at CESR-TA [13]. This experimental program will continue, as part of the CLIC/ILC collaboration and will be complemented with studies of photon simulated desorption of coated surfaces in electron storage ring.

The requirements in terms of longitudinal and transverse broad band impedance (low frequency part of the total impedance) are not too stringent because a few Ω in longitudinal and a few MΩ/m in the transverse plane would still be acceptable to guarantee the beam stability against single bunch effects [10]. Resistive wall multi-bunch effects do not seem to be critical because of the large rise time of the associated instabilities (a few hundreds of turns) [10]. In order to study further resistive wall phenomena in much higher frequency regimes, where coating become important, a new analytical method was used [14] for computing the impedance and wake functions of axisymmetric structures with multiple layers and applied to the DR parameters [2]. These computations provide the necessary input for studying in more detail instabilities using multi-particle codes like HEADTAIL [15].

DAMPING RING TECHNOLOGY

Producing the ultra-low horizontal emittance in a compact ring within the machine pulse of 20 ms necessitates the use of damping wigglers. The highest field and relatively short period is needed in order to reach the target emittances [7]. Pure permanent magnets are not able to reach high field (around 1.2 T for Sm_2Co_{17}), so pole concentrators are used (e.g. vanadium permendur) to enhance the field to a maximum value of 2.3 T. Figure 3 shows the simulated peak field reached in a hybrid permanent magnet wiggler as a function of the period length, for a fixed 14 mm magnetic gap. The behavior is almost linear and shows that only 1.1 T are reached for 40 mm period and up to 1.8 T for 100 mm period. The maximum field of 2.3 T is reached for 140 mm period. In that case, the output horizontal emittance gets more than doubled and far above the required 500 nm. In order to remain in the target DR performance, the number of wigglers has to be more than doubled, which results to a 40% increase of ring circumference. In this respect, the only way to achieve high field for high gap/period ratio is by using 52 superconducting damping wigglers with 2.5 T peak field and 50 mm period, based on NbTi technology. A prototype is presently under measurements at Budker Institute with very encouraging results. Another more challenging design (2.8 T field, with 40 mm period) wound with Nb_3Sn wire is also under construction at CERN. This short mock-up was first wound with NbTi wire and peak field of 2.5 T was achieved, either at 1.9K or at 4.2K as extrapolated to a 50 mm design [16]. It is expected that in the near future, full prototypes will be ready for testing under beam conditions in an electron storage ring.

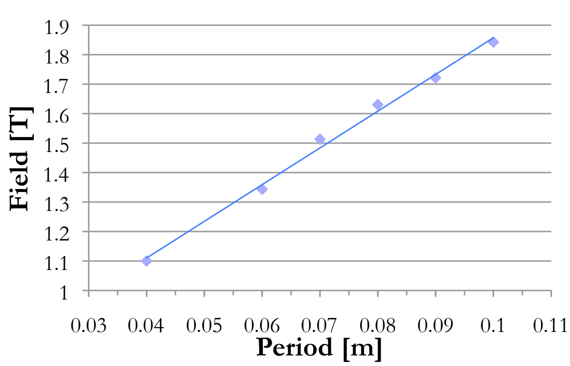

Figure 3: Simulated dependence of a hybrid permanent magnet wiggler peak field with the period length.

Radiation power of around 19kW is produced by each wiggler and an absorption system is necessary and critical to protect machine components and wigglers against quench, but also lower the photo emission yield for reducing the e-cloud effect. The power limit is set between 1 and 10 W/m, depending the wire technology and the vacuum chamber cooling. A series of horizontal and vertical absorbers are placed downstream of the wigglers and a terminal absorber at the end of the long straight section is absorbing the remaining around 100kW of photon power [17].

The very high peak and average current corresponding to the full train of 312 bunches spaced by 0.5ns presents a big challenge due to the transient beam loading, especially for a 2GHz RF system. In this respect, it was decided to consider two bunch trains with 1ns bunch spacing. This reduces significantly the beam loading, the RF system with frequency of 1GHz is more conventional and an extrapolation from existing designs is possible. Nevertheless, the trains have to be recombined in a delay loop downstream the DRs with an RF deflector. As the beam stability requirement is quite low (typically 10% of the beam size), this imposes tight jitter tolerances not only for the DR extraction kicker [18] (a few 10^{-4}) but also for the RF deflector (around 10^{-3}). The first tolerance has been already demonstrated in ATF using a double kicker system, but for much shorter flat tops [19]. The second tolerance will necessitate measurements in CTF3 which are equipped with similar RF deflectors for the drive beam recombination and frequency multiplication [20].

In conclusion, a robust and realistic conceptual design of the CLIC DRs was undertaken in recent years achieving the collider target requirements. All critical beam dynamics issues associated with the high-bunch density are addressed and an experimental program is already underway for demonstrating the technological challenges, including wiggler, RF, vacuum and kicker technology.

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