LATTICE OPTIONS FOR THE CLIC DAMPING RINGS

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Abstract

Optics design optimisation studies have been undertaken for the CLIC damping ring (DR) lattice. Main parameters such as the ring energy and output longitudinal emittance were reconsidered in order to reduce the detrimental effect of collective instabilities. In this respect, the low emittance arc cell length was rationalized taking into account space and magnet design requirements. The straight section cell filled with super-conducting wigglers was modified to accommodate a robust absorption scheme. Several low emittance rings were considered and compared with respect to their dynamic aperture and the intra beam scattering (IBS) dominated output emittances.

INTRODUCTION

The CLIC DR is designed to “cool” high intensity bunches to extremely low emittances, in all three dimensions, which are critical for the required high luminosity performance of the linear collider. The target emittance is reached by the combined effect of theoretical minimum emittance (TME) arc cells and super-conducting damping wigglers [1] filling the long straight sections. The final emittance is determined by the combined effect of radiation cooling, quantum fluctuations but also intrabeam scattering (IBS) which is a major contributor of emittance growth in high bunch density, low-energy regimes. In this respect, a compact 365m racetrack ring has been proposed [2] and adapted to the latest main linac 12GHz-RF system requirements [4]. This design achieved the target transverse normalized emittances of 500nm horizontal and 5nm in the vertical plane and the longitudinal emittance was kept to less than 5keV.m, as required by the downstream ring to main linac transport (RTML) [3]. The purpose of this paper is to review the main DR parameters and rationalize the lattice design. This includes the refinement of parameters such as RF voltage, ring energy but also the ring lattice drift space constraints for the accommodation of absorption systems and main magnet field requirements. The lattice solutions are compared with respect to their dynamic aperture (DA) and the impact to collective effects, especially IBS.

RF VOLTAGE AND ENERGY

Parameters related with the RF system and the final emittances are shown in Table 1. For the CLIC DR, an RF voltage of 4.1MV [4, 5] was initially assumed. This was setting the final longitudinal normalized emittance, with the effect of IBS included, very close to 5keV.m, the upper limit required in the RTML. With an energy loss per turn

Table 1: CLIC damping rings parameters related to the RF system and impact to final emittances.

Parameter, Symbol [unit]	value
energy loss / turn, U_0 [MeV]	3.9
RF voltage, $V_{\rm RF}$ [MV]	5.0
rms bunch length, σ_z [mm]	1.4
rms momentum spread, σ_δ [%]	0.1
normalized horizontal emittance, $\gamma\epsilon_x$ [nm]	470
normalized vertical emittance, $\gamma\epsilon_y$ [nm]	4.3
normalized longitudinal emittance, $\gamma\epsilon_s$ [keV.m]	3.5

of 3.9MeV, the synchronous phase ϕ_s was equal to 72° and the energy acceptance was 0.8%. In order for the bucket to become more linear and increase the energy acceptance to 2.6%, the voltage had to be raised to around 5MV, setting the synchronous phase to $\phi_s = 51°$ [6]. This increase of the voltage, unavoidably decreased the rms bunch length and energy spread of the beam, and the longitudinal emittance is reduced to 3.5keV.m. The shrinking of the longitudinal phase space volume by around 30%, triggers the growth of the transverse emittances, as shown in Table 1. This is mostly reflected in the horizontal emittance which increases by 20%, to 470nm.

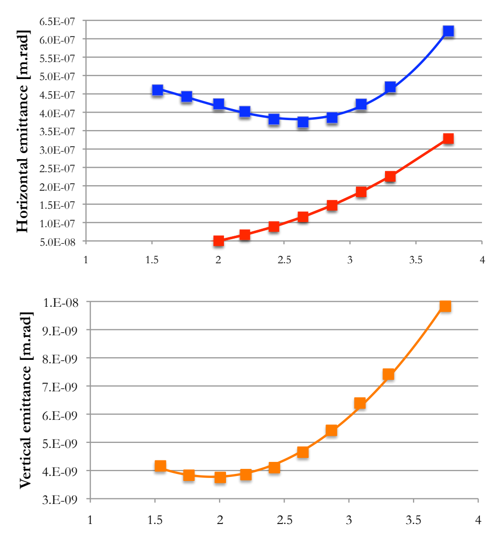

Figure 1: Horizontal normalized emittance (top) versus the energy, with (blue) and without the effect of IBS (red) and vertical normalized emittance (bottom).

The review of the energy was triggered from a study of the transverse emittance scaling with respect to critical DR parameters [4]. In this scaling, it was assumed that the bending angles are constant and the length of the main dipoles are matched to the field variation which follows the energy change. The wiggler characteristics remain unchanged and the longitudinal emittance is kept constant. The horizontal emittance dependence to the energy for constant longitudinal emittance is presented on the top of Fig. 1. For higher energies, where the effect of IBS should become smaller, the emittance increases following a power law, similar to the one of the "zero- current" one (red curve), to which it should finally converge for high energies. For small energies, where the effect of IBS dominates, the horizontal emittance is almost inversely proportional to the energy. The minimum is quite broad and it is located between energies of 2 to 3GeV. The vertical emittance dependence to the energy is shown in the bottom plot of Fig. 1. It scales linearly with the energy for high energies, thus the geometrical emittance is energy independent. This is due to 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. This scaling suggests that a higher energy, e.g. the next half-integer value of the spin resonance at 2.86GeV, would be beneficial for the reduction of the effect of IBS as the ratio between zero current and IBS dominated emittance is reduced. At the same time, several collective effect are relaxed, and especially the vertical space-charge tune-shift of around 0.2 [7] will be radically reduced. The vertical emittance will be slightly increased which translates to tighter alignment and low emittance tuning tolerances. The geometrical aperture should be decreased by 10%, in order to compensate for the increase of magnet strength, or the length of the magnets should be increased by the same amount. Finally, the energy loss per turn (scaled to the third power of the energy) will be increased by almost a factor of 1.7 which will necessitate an increased RF voltage and higher beam loading. In this respect, the absorption system should be also able to sustain the higher radiated power.

NEW LATTICE DESIGNS

The DR has a racetrack shape with two arcs consisting of low-emittance TME cells and two long straight sections with FODO structure to accommodate the damping wigglers (38 wigglers/section), RF cavities, injection and extraction equipment.

Super-conducting damping wigglers installed in the long straight sections of the damping ring reduce the emittance by a factor of almost 6.5 for a 2.5T, 5cm-period, 2m-long wiggler. The radiation power of 8kW for a bunch train current of 170mA is absorbed by a dedicated system [8]. In this respect, the distance between the wiggler and quadrupole had to be increased by 0.8m in order to accommodate vacuum pumps, absorbers, corrector magnets, etc. Further emittance minimization can be made by optimizing the lattice functions in the wiggler [9]. For a

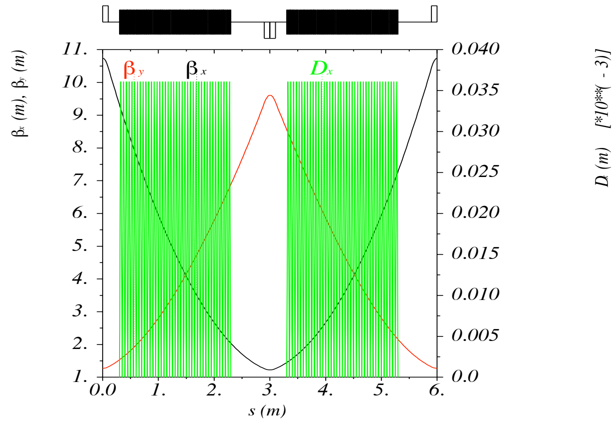

Figure 2: Optical functions (left) and geometry aperture (right) for the optimized FODO cell.

FODO cell, the minimum emittance is reached for horizontal phase advance $\mu_x \approx 0.31$ and for vertical phase tending to zero. The vertical phase advance can then be set as low as possible using other criteria. For example, for $\mu_y \approx 0.12$ the chromaticity is minimized. Another possible choice is $\mu_y \approx 0.25$ corresponding to minimum vertical beta and, thus, to maximum vertical acceptance. The optics for this option is plotted in Fig. 2. The cell modification increases the long straight section length by 25%, and beta functions maxima by approximately the same amount.

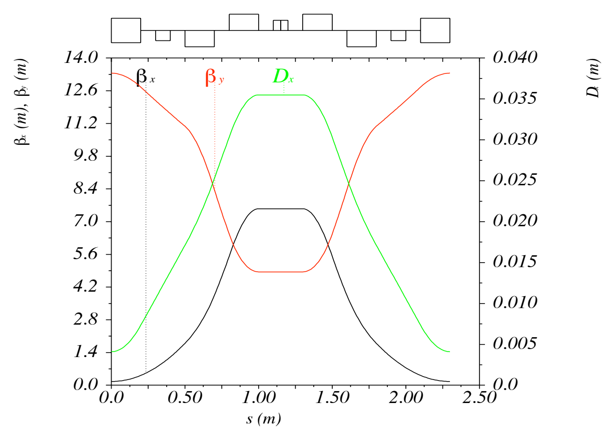

Figure 3: Modified DR arc cell optics.

The original TME cell was designed as compact as possible with a total length of 1.73 m. In order to reach the required transverse emittance and to correct the high natural chromaticity, the magnetic strengths of both quadrupoles and sextupoles are extremely strong, and the associated pole-tip fields, at a radius of 1cm, are out of reach for normal conducting technology magnets. At the same time, the high sextupole strengths degrade the rings' DA, unless a multi-family powering scheme is used for a $-\mathcal{I}$ transformer compensation [2]. Finally, the drift spaces among the elements are quite small to accommodate other equipment or even to avoid fringe-field interference. One more important aspect to be taken into account in the TME cell design is the IBS growth rates. The major contribution is associated to locations where the beam sizes, i.e beta functions, reach their minima. In the TME cell, both horizontal and vertical beam sizes become minimum at the center of the arc cells and it is exactly at these locations where IBS growth rates are maximum. However, the low emittance condition requires only small horizontal betatron function in the bending magnets while the vertical one can be large.

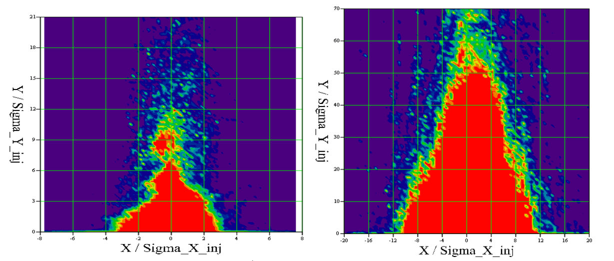

Figure 4: On-momentum DA for the original (left) and the modified DR (right).

As the final emittance is wiggler dominated, the contribution of the arcs to the synchrotron radiation integrals is smaller and the length of the bending magnet can be decreased from 0.545m to to 0.4m saving some drift space. Increasing the magnetic field from 0.93T to 1.27T gives negligible growth of the energy spread. Additional reduction of the emittance in the TME arc cells is achieved by introducing a defocusing gradient in the bending magnet. This is particularly interesting, as the vertical beta is increased at the dipole center, hence reducing the IBS growth rate. The gradient is limited by the iron core saturation and the maximum value of magnetic field in the good field region. If this is fixed to 1.5T for ±3cm in the horizontal plane, the gradient should not exceed 8.6T/m. The optical functions of the modified TME arc cell are shown in Fig. 3. The cell length is increased by 30% as well (2.3m) and thus in total the ring circumference gets 30% longer (around 493m) than in the original design. For this TME cell, the quadrupole gradients do not exceed 60T/m. The chromaticity sextupoles are set to tune the chromaticity to zero and their maximum value is around 700T/m^2. In this respect the on-momentum DA is by far enlarged as compared to the original ring, as plotted in Fig. 4. The same is true for the off-momentum DA as well.

The horizontal emittance obtained without including the effect of IBS is around 139nm for the original lattice and 243nm for the modified one. Using the modified Piwinsky formalism [10], the final emittance is 440nm, which is even 10% smaller than the original design. The effect of IBS in the two TME cells is presented in Fig. 5. They are significantly reduced in the center of the dipole especially for the horizontal and longitudinal plane.

An alternative design based on a scaled version of the arc cell proposed for the SuperB rings [11] is presented in Fig. 6. It differs from the classical TME structure by splitting the central dipole in two pieces and inserting a focusing quadrupole in the center. In this way, the equilibrium emittance can be further reduced and the DA can be increased. This cell has further to be evaluated with respect to the influence of IBS to the final emittance.

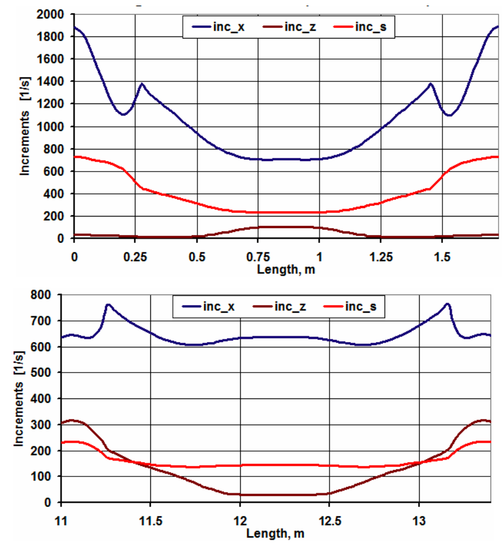

Figure 5: Horizontal (blue), vertical (brown) and longitudinal IBS growth rate increments for the original (top) and the modified TME cell (bottom).

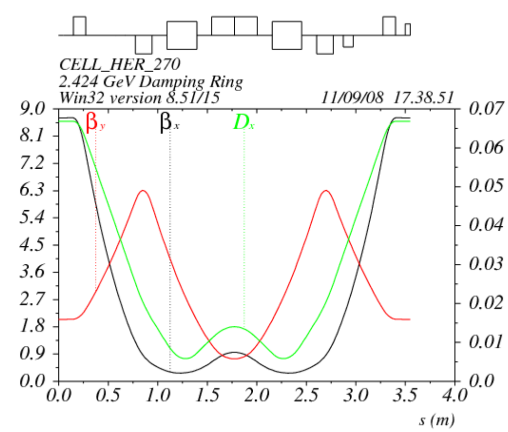

Figure 6: Alternative arc cell optics based on the SuperB ring cell.

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