THE SPS AS AN ULTRA-LOW EMITTANCE DAMPING RING TEST FACILITY FOR CLIC

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Abstract

In view of the plans for a future electron/positron linear collider based on the CLIC technology, an ultra-low emittance damping ring test facility is proposed, using the CERN SPS. Optics modification, required wiggler length and characteristics, energy and RF parameters are presented in order to reach CLIC performance targets. Considerations about the necessary injected beam characteristics, its production and transfer through the existing CERN accelerator complex are also discussed.

INTRODUCTION

The CLIC damping rings (DRs) target ultra-low emittances in all 3 dimensions for relatively high bunch charge [1]. They are thus located in a regime where their performance is dominated by collective effects including single and multi-bunch instabilities [2, 3], Intra-beam Scattering, (IBS) [4], space-charge [5], e-cloud [6], or ion effects [2]. Their design is thereby focused on the reduction of these effects, either by a parameter optimisation or with mitigation techniques and dedicated feedbacks. These design choices drive the technology of a number of components, such as wigglers [7], RF systems [8], kickers [9], vacuum [10], instrumentation and feed-back systems. In this respect, a vigorous experimental program is put together, in low emittance rings, including X-ray storage rings and test facilities, not only for conducting beam dynamics measurements [11], but also testing the most challenging technology components [7, 9]. With a look to the future, the ideal scenario would be the use of an existing ring as a test facility for DR R&D. This will enable to test all the components and their interdependencies in similar beam conditions, making an essential step towards the construction of a future linear collider.

The requirements for such a ring are driven by the CLIC DR design parameters, summarised in Table 1. The chosen ring should be able to reach the lowest possible emittances in all three dimensions, in energies of a few GeV. It would be essential to have a short bunch train structure similar to CLIC with bunch spacings of 1 ns or even below, which would enable tests of RF cavities between 1 and 2 GHz including low level RF systems and the associate beam dynamics. This ring should have enough space for installing the components to be tested and beam conditions for studying all the collective effects mentioned above. A number of existing or future light source storage rings would be ideal for these tests. The obvious drawback is the beam time availability for experiments, due to their heavily booked user schedule, in a continuous operation mode.

In this paper, an unconventional option is considered, the use of a CERN proton injectors, namely the SPS, as DR test facility. The idea originates back to the early days of CLIC [12], when the SPS was ready to accelerate electrons and positrons and transfer them to LEP [13]. It was then revived, as a possibility for damping the positron beam for the LHeC stydy [14]. Based on the classical formalism for beams dominated by radiation damping, the parameter space is explored, including optics, energy and wiggler characteristics in order to reach some of the targets of the CLIC DR design in the SPS.

Table 1: CLIC DRs Design Parameters for the 1 and 2 GHz RF Frequency Options [1]

Parameters, Symbol [Unit]	2 GHz	1 GHz
Energy, E [GeV]	2.86	
Circumference, C [m]	427.5	
Bunch population, N [10^9]	4.1	
Wiggler peak field, B_w [T]	2.5	
Wiggler length, L_w [m]	2	
Wiggler period, λ_w [cm]	5	
Damping times, (τ_x, τ_y, τ_l) [ms]	(2.0, 2.0, 1.0)	
Momentum compaction, α_c [10^{-4}]	1.3	
Energy loss/turn, U [MeV]	4.0	
Norm. hor. emittance, $\gamma\epsilon_x$ [nm·rad]	472	456
Norm. ver. emittance, $\gamma\epsilon_y$ [nm·rad]	4.8	4.8
Energy spread (rms), σ_δ [%]	0.1	0.1
Bunch length (rms), σ_s [mm]	1.6	1.8
Long. emittance, ϵ_l [keVm]	5.3	6.0
RF Voltage, V_{RF} [MV]	4.5	5.1
Bunches per train, n_b	312	156
Bunch spacing, τ_b [ns]	0.5	1
RF acceptance, ϵ_{RF} [%]	1.0	2.4

SPS LOW EMITTANCE OPTICS

The SPS is a 6-fold symmetric, 6.9 km-long ring, based on a FODO lattice, with missing dipole for dispersion suppression. It was originally tuned to phase advances of $\pi/2$, which provide an integer tune of 26 (Q26-optics). This still remains the working point for fixed target beams. Since last year [15], SPS delivers the LHC-type beams for protons and ions with a new working point at an integer tune of 20 (Q20-optics). Although the FODO cell is not the best optics choice for getting low emittance, an improvement can be achieved by moving the cell horizontal phase advance to around 135° (i.e. $3\pi/4$), which approaches the optimal phase advance for emittance minimisation in FODO cells [16]. In addition, it assures the dispersion suppression, as the total arc phase advance is a multiple of 2π. The evolution of the optics functions in one ring sextant are shown in Fig. 1. In this example, only the horizontal

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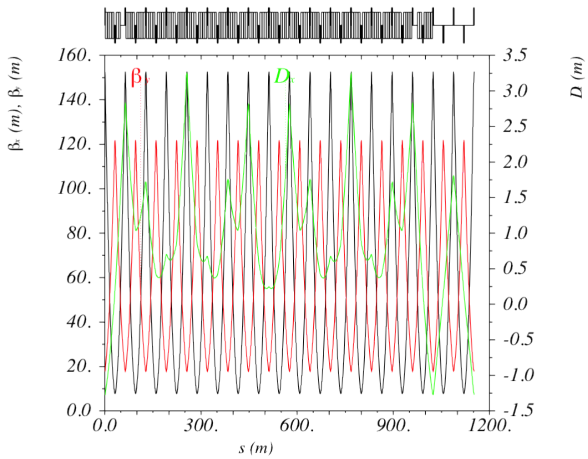

Figure 1: Horizontal (black), vertical beta (red) and horizontal dispersion (green) for one arc of the SPS with low emittance optics.

phase advance is increased to the high value, while the vertical one is kept at $\pi/2$. Both horizontal and vertical beta functions are increased, whereas the horizontal dispersion is diminished. This optics permits the reduction of the horizontal equilibrium emittance with respect to the Q26 optics by a factor of three, e.g., at 4 GeV, the normalised emittance drops from 35 μm to 13 μm. Without any other modification, the corresponding transverse damping time is 6 s.

EMITTANCE, DAMPING TIMES AND WIGGLERS

In the presence of damping wigglers, the horizontal normalised equilibrium emittance ϵ_x and damping time τ_x is given by

$$\epsilon_x = \frac{C_q\gamma^3}{12(1+Fw)J_x}\left(\frac{e_r\theta^3}{\sqrt{15}} + \frac{\langle\beta_{xw}\rangle F_w B_w^3\lambda_w^3}{16(B\rho)^3}\right)$$

$$\tau_x = \frac{3E_0}{2\pi r_0 c}\frac{C}{B\gamma^2(J_x+F_w)} ,$$

where the parameter $F_w = \frac{L_w B_w^2}{4\pi B^2\rho}$ depends on the wiggler characteristics. Based on these formulas and considering the wiggler parameters of the CLIC DR prototype under development, with peak field of $B_w = 3$ T and wavelength $\lambda_w = 5$ cm [7], the dependence of the equilibrium emittance as a function of the energy and the damping time can be established. It is assumed that the bending field B is scaled with the ring energy, while the bending radius ρ and angle θ are given by the actual 744, 6.26 m-long SPS dipole magnets. The detuning factor from the absolute minimum emittance is $e_r = 120$ for the considered lattice, while the average wiggler beta function is set to $\langle\beta_{xw}\rangle = 10$ m, corresponding to the minima of this optics.

The dependence of the horizontal emittance to the ring energy is presented in Fig. 2, for different damping times ranging from 2 ms to 100 ms. The normalised equilibrium emittance can drop to values even below the target 500 nm of the CLIC DR. The dependence of the emittance to the

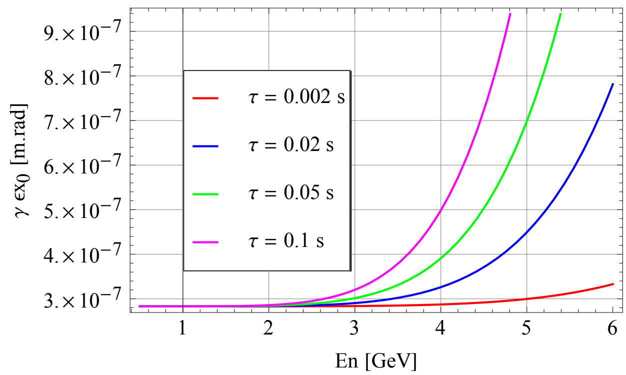

Figure 2: Normalized equilibrium emittance as a function of the ring energy, for different horizontal damping times of 2 (red), 20 (blue), 50 (green) and 100 ms (purple).

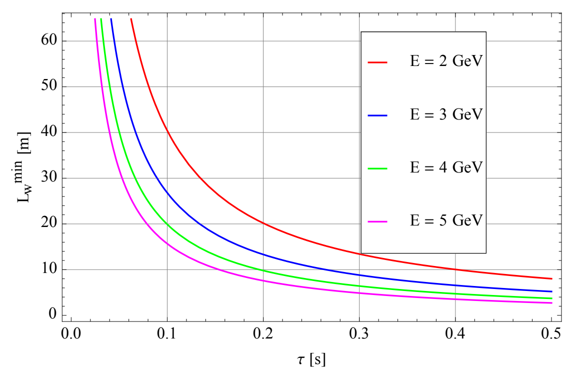

Figure 3: Total wiggler length versus damping time, for different energies of 2 (red), 3 (blue), 4 (green) and 5 GeV (purple).

energy is quite small for very fast damping times, while it becomes stronger for longer damping times. Note also that for a fixed energy, the emittance and the damping time depend linearly on each other.

At the same time, in order to get a very short damping time of a few ms, the corresponding wiggler length is very large, as shown in Fig. 3. It becomes increasingly difficult at lower energies, penalising further the ultra-low emittance reach. This was also faced during the CLIC DR design, where it was necessary to have both TME arc cells, targeting a very small emittance, but also 25% of the ring filled with super-conducting damping wigglers, for the very fast damping times. Hence, in the case of the SPS, a compromise should be made. The natural choice is to target a small emittance, because, apart from the fact that there is no way to fill the ring with tens of meters of damping wigglers, the energy loss/turn becomes unreasonably high. This is shown in Fig. 4, where the energy loss is plotted as a function of the damping time. For damping times of a few ms, the energy loss/turn exceeds 10 MeV, which is beyond the total RF voltage capabilities of the SPS.

In this respect, the optimisation should be reversed by first picking a reasonable total wiggler length, e.g. $L_w = 10$ m, which fits between two quadrupoles in the SPS

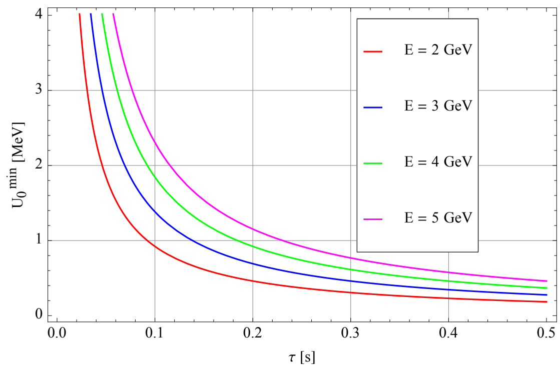

Figure 4: Energy loss per turn versus damping time, for different ring energies of 2 (red), 3 (blue), 4 (green) and 5 GeV (purple).

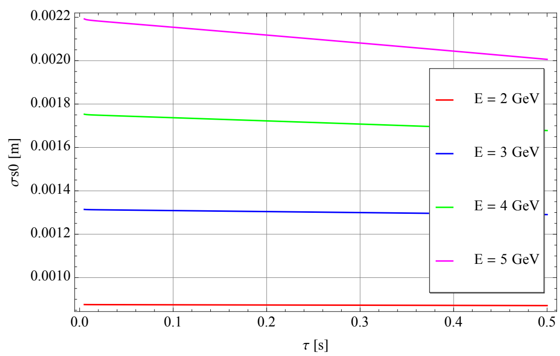

Figure 5: Bunch length as a function of the damping time, for different ring energies of 2 (red), 3 (blue), 4 (green) and 5 GeV (purple).

straight sections. This provides damping times of around 200 ms at 4 GeV (green curve of Figs. 2, 3 and 4) and achieves 400 nm normalised emittance, i.e. 20% below the CLIC DR target. For these parameters, the energy loss/turn is just 1 MeV.

For completeness, the equilibrium bunch length versus the damping time for different energies, and for a fixed RF voltage of 5 MV, is displayed in Fig. 5. This plot shows that the dependence of the bunch length on the damping time is quite weak, especially for lower energies. For 4 GeV, it is equal to 1.7 mm, very close to the CLIC DRs output values. Note that the energy spread has a similar behaviour and for the considered parameters is equal to 0.16%, providing a normalised longitudinal emittance of 11 keV.m.

SUMMARY AND PERSPECTIVES

The projected parameters, as described above, for using the SPS as a DR test facility are presented in Table 2. These are indeed quite close the CLIC DR design, with the exception of the damping times and bunch spacing. These long damping times do not fit with the repetition rate of CLIC at 50 Hz, but this is not a showstopper: for testing equipment associated with this fast repetition rate, a staggered train approach could be used, as the SPS circumference is large. The bunch spacing could be eventually reduced, if

Table 2: Design Parameters for the SPS as DR Test Facility

Parameter [Unit]	Value
Beam energy [GeV]	4
Bunches/pulse	$\leq$ 9221
Bunch spacing [ns]	5
Hor. norm. emittance [nm]	400
Damping time (x,y) [ms]	0.2
RF voltage [MV]	5
Momentum compaction [10^{-4}]	8.8
Bunch length [mm]	1.7
Energy spread [%]	0.16

the SPS fourth harmonic 800 MHz cavity is transformed as the main RF system. It is also important to note that all beam dimensions are computed at their equilibrium and it is necessary to estimate the effect of IBS in order to provide the final steady state emittances. A further step towards the understanding of these conditions would be to test the low emittance optics in machine developments even with protons, in order to explore issues with power supply ripple and magnet errors, at this low energy. Finally, apart from finding space in an already full tunnel for installing wigglers and radiation absorbers, the obvious drawback is the absence of the e^+/e^- pre-injectors and transfer, which were completely dismantled or partially transformed to CTF3, after the stop of LEP. Considerations for the generated lepton beam characteristic, its transport through the existing CERN injector chain and its compatibility with the present hadron program is the subject of on-going work.

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