DESIGN FOR A PRACTICAL, LOW-EMITTANCE DAMPING RING

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Introduction

The luminosity requirements for future high-energy linear colliders calls for very low emittances in the two beams. These low emittances can be achieved with damping rings, but, in order to reach the design goal of a factor 10 improvement over present day machines, great care must be taken in their design. Hence the use of the term "practical" in the title of this paper, to emphasize the need to address simultaneously all of the factors which limit the operational emittance in the ring. Particularly since in standard designs there is a conflict between different design parameters which makes it difficult to extrapolate such designs to very low emittances. The approach chosen here is to resolve such conflicts by separating their design solutions. Wigglers are used predominantly in zero-dispersion regions to achieve the desired damping rate, whereas in the arcs "high dispersion insertions" are made in regions of zero curvature to allow for easier chromaticity control.

The design presented here tries to fulfill the requirements of the CLIC (CERN LInear Collider) study [1]. The main parameters for the damping ring are:

normalized horizontal emittance = 3×10^{-6} m rad
normalized vertical emittance = 1×10^{-6} m rad
i.e. modest coupling
bunch repetition frequency = 1.69 kHz.

The bunch repetition frequency can be translated into a damping time requirement by considering the number of bunches in the ring. The minimum bunch separation is given by the attainable rise-times of the kickers, and the quoted figure for this is about 25 ns at present. Assuming that each bunch is to stay in the ring for 3 damping time constants this gives a required ratio of damping time / circumference ≤ 0.026 ms m^{-1}.

Damping ring design requirements

A fundamental treatment of the synchrotron radiation process can be found, for example in [2] and [3]. Some general statements can be made about the damping ring requirements to meet the above parameters. To obtain a fast damping time,

$$\tau_i = \frac{4\pi R\rho}{C_\gamma E_o^3 J_i}$$

asks for a high beam energy, E_o, and small bending radius, ρ. A low final emittance asks that the amplitude,

$$\delta a \propto \frac{E_o^2}{\rho}\mathscr{H}(s)$$

induced in the betatron oscillation by a quantum emission be small. In contrast to the damping time, a low energy and large radius is favored. Very large rings, such as those suggested to occupy the CERN tunnels [4,5], can thus reach low emittances. In compact rings care must be taken in minimizing the function

$$\mathscr{H}(s) = \frac{1}{\beta}\{D^2 + (\beta D' - \frac{1}{2}\beta' D)^2\}$$

Which means that in the dipoles, where the photons are emitted, the dispersion, D, must be low and the β function optimized.

The damping ring must also have sufficient dynamic aperture for the injected beam. This can be achieved if the sextupole strengths are low, so the chromaticity correction can only be realized under these circumstances if the dispersion is large and the natural chromaticity of the ring low. This is at odds with the previous requirement for a minimum $\mathscr{H}$

To avoid problems of low instability thresholds it is also advantageous to have a momentum compaction that does not approach zero. This requirement also asks for a larger dispersion.

On top of all this the final design should not exhibit an undue sensitivity to errors so that the machine can be built and operated within reasonable tolerances.

The classical design approach

A proven design chosen in many existing damping rings and light source facilities is a lattice divided up into individual achromatic cells, such as the Double Bend Achromat and the Triple Bend Achromat. The focusing in each cell is configured firstly to satisfy the achromatic requirement and secondly to optimize the value of $\mathscr{H}$ in the dipoles [6]. Since the value of the maximum dispersion in each dipole is then a function of bending radius, ρ, and bending angle, ϕ, it is not difficult to deduce that the final emittance of such rings is proportional to ϕ^3.

To achieve a very low emittance it is therefore necessary to make the lattice with very small ϕ per achromat, or in other words, many lattice cells. Since the phase advance across each achromat remains constant during such scaling the result is inevitably a high final tune. This now leads to problems with tolerances in the ring [7].

The strong focusing in such a design also gives rise to a large natural chromaticity term. Unfortunately, since the dispersion was purposefully made small everywhere, very strong sextupoles are thus necessary for chromaticity control. The main disadvantage then of such designs is the severe reduction in dynamic aperture.

One cannot also neglect the further disadvantage of very small momentum compaction factor resulting from the strong focusing and low dispersion, which, as already mentioned gives a very low threshold for beam instabilities.

This design approach is faced with many problems, but it may still turn out that, given enough care in the design, adequate parameters can still be reached for demanding applications [8].

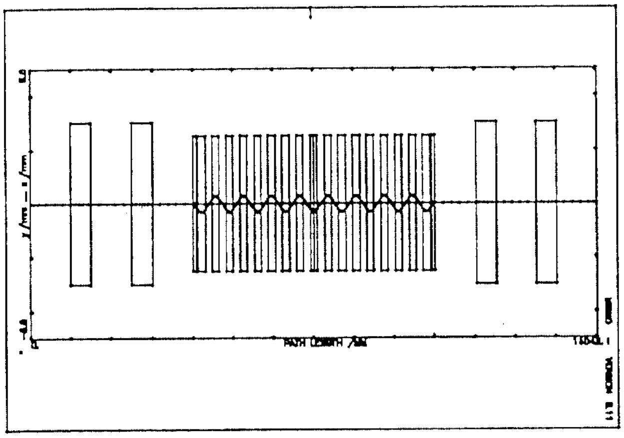

Figure 1. Example of a wiggler cell made up of reverse bends with 1/2 bends placed at each end to match the dispersion to zero. Quadrupole doublets interspersed in the wiggler maintain the required phase advance.

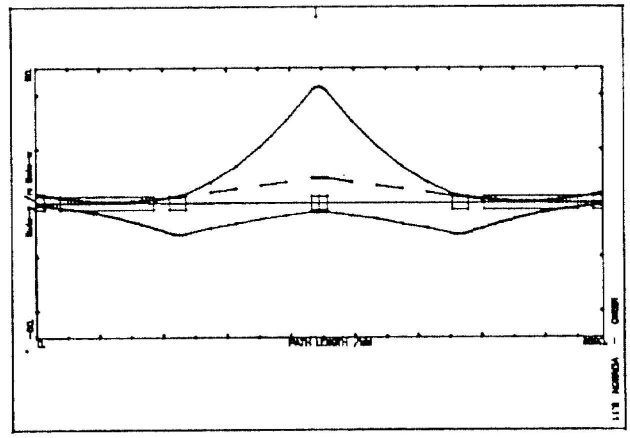

Figure 2. Unit cell for the arcs consists of: QF/2 – Dip. – QD – QF – QD – Dip. – QF/2.

The advantages of wigglers

An alternative approach studied here and elsewhere [9] is to exploit the advantages of wiggler insertions in the ring. Wigglers are made up of reverse bends so they can fulfill the achromatic condition without the use of strong focusing. The dispersion and hence $\mathcal{H}$ can be made very small with little difficulty. Fast damping still results from the small bending ρ and large number of bends. It has been found with simulation programs [10] that adding wigglers in zero dispersion regions in a lattice can reduce the emittance and the damping time by a factor of 10. This was also predicted in studies for the PEP ring [9].

The emittance reduction is limited ultimately by the self generated dispersion of the wiggler. An example is shown in fig. 1 where the peak value of the wiggler dispersion is reduced by a factor two by making it alternate in sign as a result of matching the dispersion to zero using two half dipoles at the ends.

Separated design solution

With the advantages offered by wigglers it is possible to separate the design solution into two groups which are loosely called arc requirements and wiggler requirements. The fast damping is done primarily in the wiggler. As a consequence the damping contribution of the arcs can be made smaller by choosing ρ_{arc} large. Although the dispersion becomes bigger as a result, the rate of quantum emissions is less than in the wigglers, so the equilibrium emittance including the wigglers is still low enough.

The arc requirements are now easier to meet as a result of the larger dispersion. Sextupole correction is easier and the momentum compaction factor contribution from the arcs is also larger. Less damping from the arcs means that fewer arc cells are needed so their tune contribution in the ring is less. Thus the other restraint on sensitivity to errors is also relaxed.

Unit cell for the arcs

The design for the unit cell presupposes that the wiggler insertions will further reduce both the damping time and the emittance by a factor 10, so that more emphasis can be placed on meeting the "arc requirements". An achromatic configuration is used, fig. 2, with large radius dipoles. A novel feature is the use of large dispersion straight sections between the dipoles. As a result the dispersion function peaks at about 1 m in the central F quadrupole. The high dispersion drift lengths do not contribute to beam heating by quantum excitation, but do allow the convenient placement of chromaticity correction sextupoles near the F and D quadrupoles respectively. The quadrupoles are grouped into families of three so that the achromatic condition can be satisfied over a wide range of tunes. The tunes are then optimized (using the program MIRKO [11]) to optimize the horizontal beta function in the dipoles to minimize the value of $\mathcal{H}$ in the dipoles. The theoretical minimum [6] in $\mathcal{H}$ is not reached here if one demands also that the natural chromaticity does not exceed some limit. Staying below this limit has meant that with the chromaticity correction described above a more than adequate dynamic aperture has been attained.

The emittance and damping times were calculated with PETROC [10] and a design iteration was made choosing a superperiodicity for the cell (and hence fixing ϕ_{bend}) which would give the required final emittance.

Racetrack configuration

In an ideal machine it makes no difference if the wiggler is inserted in each of the zero dispersion regions between the cells or if they are grouped together in two long straight sections. However, in practice it is important that the dispersion in the insertions occupied by wigglers be accurately trimmed to zero to within the limits of observation. Residual dispersion in the wigglers will add to the beam heating effects.

Experience with operating machines shows that this is not a trivial exercise and is influenced by orbit errors and so on. The ring will have improved chances of meeting its design parameters if this trimming need be done in only 2 straight sections and not 16. Studies at ESRF have shown that in low emittance rings there is a spurious dispersion in the zero dispersion insertions which can be as high as the dispersion in the arc itself, even after orbit corrections have been applied. This was attributed to changes in the phase advance along the arc resulting from orbit errors coinciding with the locations of strong sextupoles.

The disadvantage of grouping the wigglers into long straight sections is that the chromaticity contribution from the wigglers must be compensated by a lumped correction in the arcs. Tracking studies show this not to be serious.

Design parameters

Beam Energy	2.0 GeV
No. arc cells	16
Length of arc cell	8.89 m
Tunes (arcs only):	
Horizontal	12.82
Vertical	5.62
Chromaticity before correction (arcs only):	
Horizontal	−3.2
Vertical	−2.4
bending ρ in arcs	7.5 m
β_{min}(horiz.) in dipole	0.5 m
Max. dispersion in st. section	1.0 m
Normalized Emittance (arcs only):	
Horizontal (for zero coupling)	3×10^{-5}
Damping time (arcs only), τ_d	10 ms
÷ circumference, τ_d/C	0.07 ms m^{-1}
Length of wigglers	≈ 150 m
bending ρ in wiggler	3 m
Including wigglers:	
Horizontal emittance	3×10^{-6}
Damping time / circumference	0.003 ms m^{-1}

Conclusion

The emphasis in this paper has been on presenting a design method. The performance quoted demonstrates the validity of the solution, though the work is by no means complete as many more design iterations have to be done to reach the optimum for all parameters. Improvements are still needed, for example, in the matching of the wiggler cells to the beta functions of the arcs. Although the design aims intentionally for a low sensitivity to errors this is still to be quantified. Finally, improved methods of modelling the nonlinear contributions from the wigglers are being pursued to fully test their contribution to the dynamic aperture.

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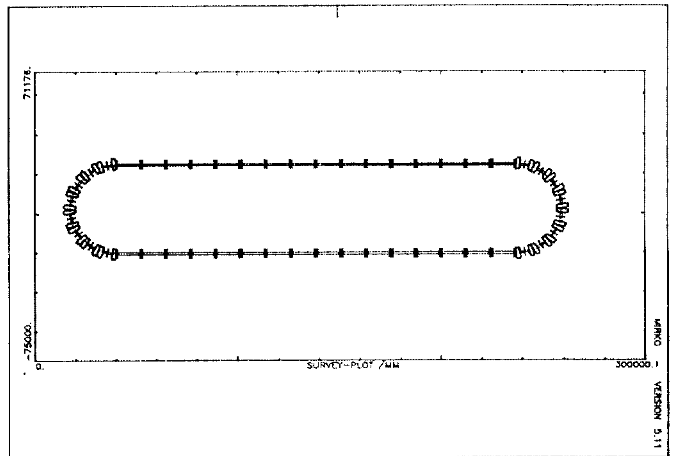

Figure 3. Racetrack layout of the damping ring, chosen for operational simplicity.

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