# REVERSE BENDING MAGNETS IN A COMBINED-FUNCTION LATTICE FOR THE CLIC DAMPING RING

J.P. Delahaye, J.P. Potier,
CERN, 1211 Geneva 23, Switzerland

## Abstract

Damping rings with very short damping times and small normalized emittances at equilibrium are required to deliver bunches at a high rate (kHz) to high-luminosity linear colliders. In conventional rings, strong damping can only be provided by raising the energy at the expense of an increase of the equilibrium emittances or by a large number of wigglers at the expense of the dynamic acceptance. After derivation of a cell optimized for small equilibrium emittance, a compact lattice based on combined function magnets and reverse bends providing additional damping has been developed. Parameters of a small circumference ring working at a reasonable energy and fulfilling the CLIC requirements are presented with particular emphasis on dynamic acceptance.

## Introduction

The CERN Linear Collider (CLIC)[1] is based on collision at the energy of 1 TeV/c of electron and positron beams composed by a train of 1 to 10 bunches with $5.10^9$ part./bunch and very small normalized emittances ($\varepsilon_x^* = 3.10^{-6}$ radm and $\varepsilon_y^* = 1.10^{-6}$ radm) at a repetition rate of $f_r$ = 1.69 kHz.

Such small emittances will possibly be reached for electron beams generated with high brightness guns presently in development but impossible to get with positron sources usually yielding emittances three orders of magnitude larger. Therefore a Damping Ring Facility will be necessary at least for the positron beam.

Two proposals have recently been made which demonstrate that a single ring at a reasonable energy (E = 2 to 4 GeV) could provide the main beam parameters: a 6 km circumference ring built with FODO cells [2] or a more compact ring derived from an optimised Chasman Green lattice [3]. They are both based on the extensive use of wigglers (∼ 200 m) with possible adverse effects still to be studied.

After a review of the basic requirements of the Damping Ring, a compact cell optimised for small emittances is developed. Then alternating bending magnets are introduced in the basic lattice to improve the damping. The main parameters of a ring based on each cell are then derived, providing beam characteristics at low intensity which fulfill the requirements without any wiggler. They are summarised in Table 1.

## Basic Requirements

One train of 1 to 10 bunches is successively injected and extracted at the linac repetition frequency, $f_r$, but a number, k, of trains is simultaneously circulating and damped in the Damping Ring in order to leave a larger time for damping $T = k/f_r$.

The ring circumference, C, is chosen to house the k trains leaving a time separation between trains just enough for the injection and extraction kickers rise and fall times ($\tau_k$=25 nsec). The transverse damping times ($\tau_{x,y} \leqslant T/5$) have to be short enough that the beam emittance at extraction is not larger than the equilibrium beam emittance by more than 10%. In these conditions:

$$\tau_{x,y}/C \leqslant 16\ \mu\text{sec/m}$$

The CLIC beam dimensions at the interaction point are based on:

- an uncoupled normalized equilibrium [1]

$$\varepsilon_0^* = \varepsilon_{x\ c}^* + (J_y/J_x)\varepsilon_{y\ c}^* = 4.10^{-6}\ \text{radm}$$

where $J_x$ and $J_y$ are the transverse damping partition numbers.

- a bunch length of $\sigma_L$=200μm which implies a longitudinal emittance [2] of

$$\varepsilon_L = \sigma_L\ \sigma_{p/p} \leqslant \pm\ 4.10^{-6}\text{m}$$

Finally, the frequency of the Damping Ring R.F. cavity imposed by the bunch distance in the train, is unusually high (F = 3 GHz). The design of such a ring is specially tricky for mainly two reasons: i) the contradictory requirement of small emittances, and short damping times, ii) the high density in both transverse and longitudinal planes of the equilibrium beam leading to significant collective effects.

## Optimum lattice for small equilibrium transverse emittance

The transverse beam emittance at equilibrium of a ring working at an energy E and composed of bending magnets of length, l, and bending angle, Θ, can be expressed as a function of the optics parameters in the middle of the bending magnets, α, β, γ, D, D', after integration of the synchrotron integral in the approximation of small bending angle [4]:

$$\varepsilon_0^* = 2.88\ 10^{-30}\ \frac{\Theta\ E^3}{J_x}\left[\frac{\gamma D^2 + 2\ \alpha\ DD' + \beta D'^2}{l} - \left(\frac{\alpha D' + \gamma D}{12}\right)\Theta + \left(\frac{\beta}{12\ l} + \frac{\gamma\ l}{320}\right)\Theta^2\right]$$

This expression is minimum for :

$$\alpha_m = 0 \qquad D'_m = 0$$

$$\frac{\beta_m}{l} = \frac{1}{\gamma_m} = \frac{1}{\sqrt{60}} = 0.129 \qquad \frac{D_m}{l} = \frac{\Theta}{24}$$

and becomes: $\varepsilon^*_{min} = 6.198\ 10^{-32}\ \dfrac{\Theta^3\ \ E^3}{J_x}$ .

As a consequence, the equilibrium emittance is minimum if the optics and dispersion functions go both through a minimum in the middle of the bending magnets whith optimum values $\beta_m$ and $D_m$ (Fig. 1).

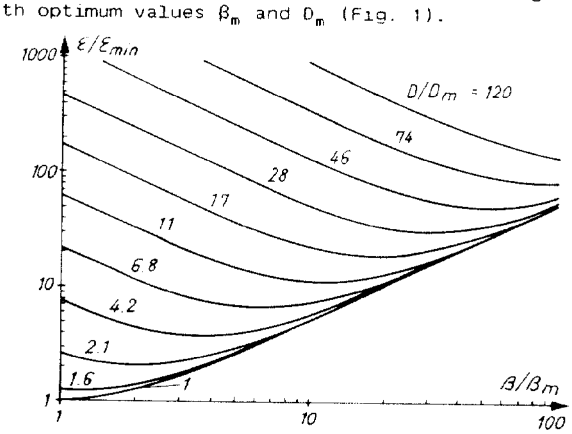


Fig. 1: Emittance blow-up versus ratio of optics functions to their optimum values in the middle of the bending magnet ($\alpha_m$=0, $D'_m$=0)

The simplest compact lattice which fulfills these conditions is composed of a combined function bending magnet horizontally defocusing, surrounded by two half F quadrupoles. (Fig. 2). Moreover, the defocusing quadrupole included in the bending magnet contributes to increase the damping partition number $J_x$ through the synchrotron integral $I_4$. As a consequence the equilibrium emittance and horizontal damping time are further reduced. For the sake of flexibility, two small correcting D quadrupoles are added at each side of the bending magnet in order to adjust independently transverse tunes and damping partition numbers by sharing with the bending magnet the defocusing gradient strength.

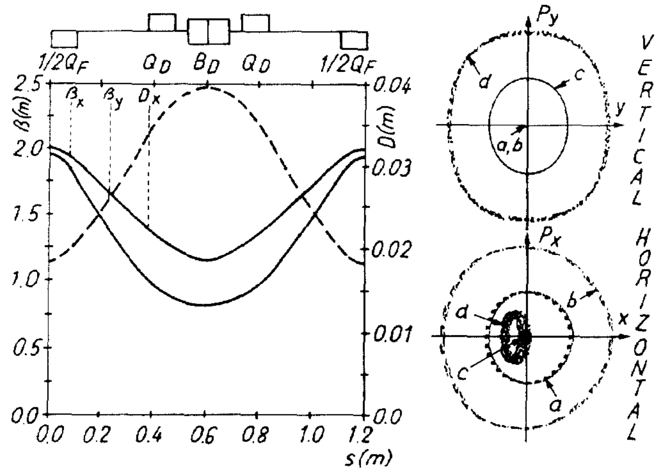


Fig. 2: Optics functions and particle tracking for a ring of 250 cells based on the optimum emittance lattice:
(a) $\varepsilon_x$ = 10 µradm (b) $\varepsilon_x$ = 40 µradm
(c) $\varepsilon_y$ = 10 µradm (d) $\varepsilon_y$ = 40 µradm

The energy of the ring (E = 3 GeV) is chosen in order to fulfill the damping time requirements

$$\text{for } i = x,y \quad \frac{\tau_i}{C} = \frac{4.74\ 10^{23}}{J_i\ I_2\ E^3} = \frac{2.52\ 10^{14}}{J_i\ B\ E^2} \leqslant 16\ \mu\text{sec/m}$$

with the magnetic field in the combined functions bending magnets B = 1.6T at the limit of saturation.

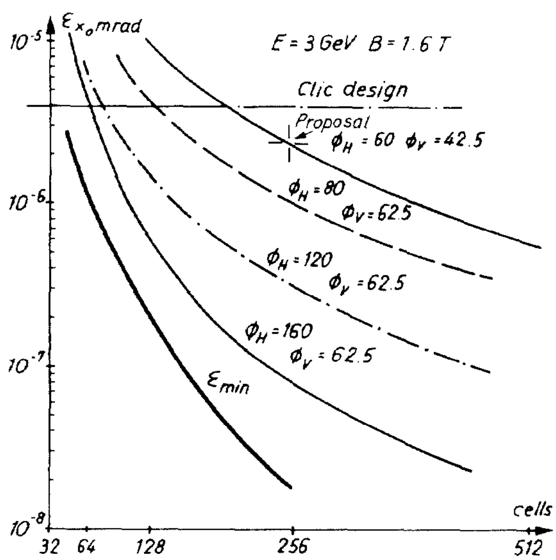


Fig. 3: Normalized equilibrium emittance versus number of cells for different cell phase advances as compared to the minimum equilibrium emittance

The Table 1 gives a consistent set of parameters for a 300 m circumference ring based on 250 optimised cells with a low 60° horizontal phase advance per cell. (Fig. 3). All the required beam characteristics are fulfilled.

The exchange of damping partition number between horizontal and longitudinal planes $J_x = 2$, $J_\varepsilon = 1$ has a double benefit: it strengthens the horizontal damping leading to smaller equilibrium beam emittance and horizontal damping time constant, and it reduces the longitudinal damping making the equilibrium bunch length longer and therefore the beam more stable.

At this relatively high energy, the intrabeam scattering constants are much higher than the damping time constants making negligeable the corresponding emittance blow-up at the nominal charge per bunch.

The low phase advance per cell induces small chromaticities which can easily be compensated by reasonable sextupole strengths. As a consequence, the dynamic acceptance estimated by tracking particles with the program MAD reaches values A > 40 µradm (fig. 2) much larger than the necessary physical acceptance for positron injection ($\varepsilon_I$ = 1.5 µradm).

## Reverse Bending Magnet Lattice

The introduction of a reverse bending magnet at the place of the F quadrupole in the above lattice (Fig. 4) improves the small emittance performance and increases the damping.

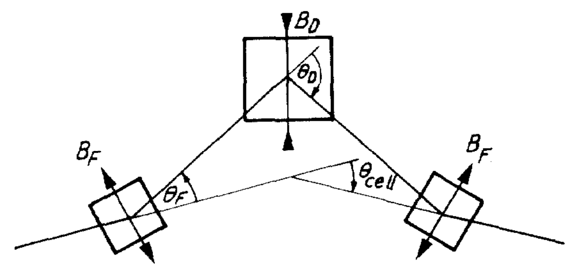


Fig. 4: Schematic layout of the reverse bending magnet lattice

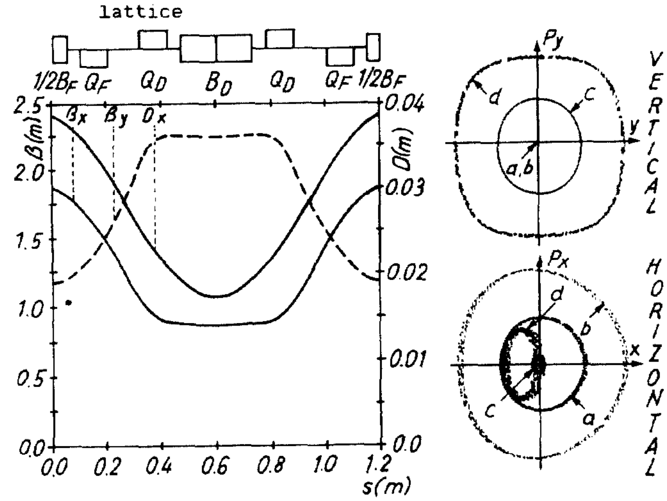


Fig. 5: Optics functions and particle tracking for a ring of 170 cells based on reverse bending magnet lattice
(a) $\varepsilon_x$ = 10 µradm (b) $\varepsilon_x$ = 40 µmradm
(c) $\varepsilon_y$ = 10 µradm (d) $\varepsilon_y$ = 40 µradm

The absolute value of the dispersion function, $D_x$, is reduced all along the cell (Fig. 5) without affecting the $\beta_x$ function and therefore the transverse tunes and chromaticities. As a consequence, the dispersion function in the bending magnet is closer to the optimum (Fig. 1) and the emittance can be reduced by up to one order of magnitude (Fig. 6a). Moreover, the emittance blow-up by intra-beam scattering is minimized as inferred from the approximation [5] of its heating time constant:

$$\frac{1}{\tau_{IBS}} \sim \frac{1.9\ 10^{-21}\ N_b}{\kappa\ \varepsilon_x^{*2}\ \varepsilon_L} < \frac{D_x}{\beta_x^{1/2}\ \beta_y^{1/2}} >$$

where $\kappa$ is the tranverse coupling and < > is the mean value all along the cell.

The integrated magnetic field per cell and therefore the second synchrotron integral $I_2$ are increased thus reducing by the same amount both the equilibrium emittance and the ratio of the damping time constant, $\tau$, to the circumference, C (Fig. 6).

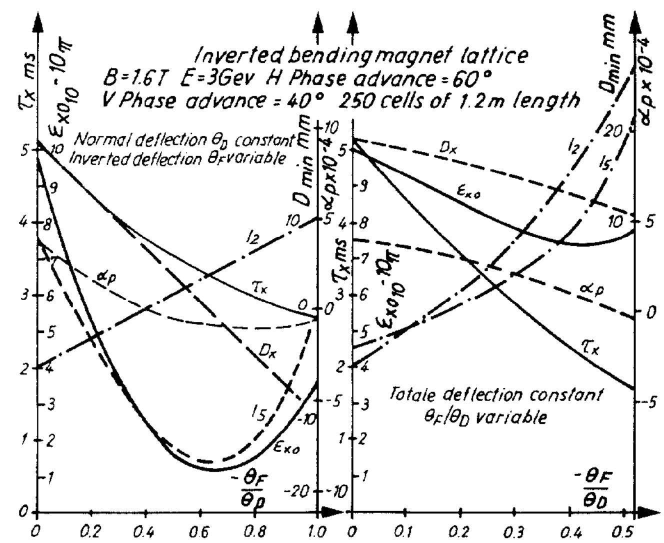


Fig. 6: Variation of the main optics parameters with the deflection ratio of reverse $\theta_F$ to normal $\theta_D$ bending magnet: (a) $\theta_D$ = cste (b) $\theta_{cell} = \theta_F + \theta_D$ = cste

As an alternative, keeping the damping constants unchanged, the working energy can be reduced to E =2 GeV leading to a further reduction of the equilibrium emittance. For the same emittance, the number of cells and the ring circumference can be substantially reduced.

A consistent set of parameters for a ring based on the alternated bending magnet lattice and fulfilling all design characteristics is presented on Table 1.

The relatively low horizontal phase advance, $\mu_x$ = 60°, is identical to the previous lattice leading to small chromaticities. But because of the reduced dispersion function, the sextupole strengths necessary for chromaticity compensation are sensibly larger. In spite of a large coupling between transverse planes, the dynamic acceptance (Fig. 5) is still comfortable.

In fact the only adverse effect of the alternated bending magnet is a reduction of the momentum compaction factor and therefore of the instability threshold.

## Conclusion

Two consistent sets of parameters for damping rings which comply with the requested performance for CLIC without any wigglers have been worked out. They both have small circumferences (200 to 300 m) and are working at low energy (E = 2 to 3 GeV). They are based on two new cells specially developed: namely a compact lattice optimized for small equilibrium emittance and a cell equipped with reverse bending magnets to improve damping. It is a combination of a wiggler lattice [6] developed earlier for the same purpose and a compact cell recently proposed [7] for small emittance and large dynamic acceptance. The very small dispersion function all along the cell makes negligible the blow-up induced by intrabeam scattering. The performance of these cells could possibly be pushed up by stronger phase advances or larger deflections of alternating bending magnets but needs to be carefully investigated.

This study is far from a final proposal as dispersion-free straight sections have still to be inserted for injection and extraction devices, possibly wigglers, RF cavities and instrumentation. Moreover, collective effects have still to be studied with possible beam intensity limitations and performance deterioriation.

## References


[1] W. Schnell: Proc. 1988 Linear Acc. Conf. Williamsburg. Virginia
[2] L. Evans, R. Schmidt, CLIC Note 58
[3] P. Krejcik: Proc. 1st Eur. Part. Acc. Conf., Rome 7 - 11 June 1988
[4] L.C. Teng: (ANL - FNAL), LS-17, 1985
[5] J.J. Bisognano: LBL 19771
[6] K. Steffen: DESY PET-79/05
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Table 1 : Tentative sets of parameters for the CLIC Damping Ring Design

| Parameters | Symbol | Units | Optimised cell for low $\varepsilon_0$ | Cell with altern. bending magnets |
|---|---|---|---|---|
| Ring | | | | |
| Energy | E | GeV/c | 3.0 | 2.0 |
| Circumference | C | m | 300 | 204 |
| No of bunches | | k | 40 | 27 |
| Charge per bunch | $N_b$ | $10^9 e\pm$ | 5 | 5 |
| Number of cells | - | - | 250 | 170 |
| Transverse tunes | $\nu_x, \nu_y$ | - | 41.2;27.9 | 28.2; 18.9 |
| Chromaticities | $\xi_x, \xi_y$ | - | -1.0;-1.25 | -1.0;-1.29 |
| Momentum compaction factor | $\alpha_p$ | $10^{-4}$ | 3.89 | 1.28 |
| Damping partition number | $J_x, J_\varepsilon$ | - | 1.93,1.07 | 1.91, 1.09 |
| Damping time constant | $\tau_x, \tau_y$ | msec | 2.7, 5.2 | 1.8, 3.4 |
| Circul.time per bunch | $T_x, T_y$ | msec | 23.7 | 16.0 |
| Energy loss/turn | $U_0$ | MV | 1.14 | 0.79 |
| RF voltage | $V_{RF}$ | MV | 10 | 2 |
| RF frequency | $F_{RF}$ | $MH_z$ | 3000 | 3000 |
| Dynamic accept. | A | $10^{-6}$radm | > 40 | > 40 |
| Equilibrium Beam Parameters | | | | |
| Normalised trans. emitt. | $\varepsilon_0^*$ | $10^{-6}$radm | 2.90 | 1.95 |
| Longit. emitt. | $\varepsilon_L$ | µm | 1.47 | 0.87 |
| Bunch length | $\sigma_L$ | mm | 1.05 | 0.76 |
| Momentum spread | $\sigma_\varepsilon/E$ | $10^{-3}$ | 1.40 | 1.14 |
| Intrabeam Scattering Growing Time Constants | | | | |
| Horizontal | $\tau_{xIBS}$ | msec | 134.9 | 177 |
| Vertical | $\tau_{yIBS}$ | sec | -1419 | - 43.7 |
| Longitudinal | $\tau_{\varepsilon IBS}$ | msec | 212 | 9.2 |