TUNABLE ACHROMATS AND CLIC APPLICATIONS

E. T. d'Amico, G. Guignard, CERN, Geneva, Switzerland

Abstract

It is imperative for linear colliders that the bunch length be adjustable. In most cases bunch compression is required, but recently, in the design of the Compact LInear Collider (CLIC) RF Power Source, it was shown that bunch stretching may also be necessary. In some situations, both modes may be needed, which implies the need for tunable magnetic insertions. This is even more essential in a test facility, to span a wide experimental range. In addition, flexible tuning provides a better control of the stability of an isochronous insertion. To start a numerical search for a tunable insertion from scratch is very uncertain because the related phase space is very uneven. However, a starting point obtained with an analytical approximation is often sufficient to ensure convergence. Another advantage of the analytical treatment described in this paper is that it sheds light on the shape of the entire phase space. To achieve this the isochronous achromat developed previously has been given tuning capabilities by expanding the expressions obtained for its main parameters. An application to the future CLIC Test Facility (CTF3) is shown.

1 INTRODUCTION

Lately the CLIC study [1], [2] made two very important advances. Firstly a consistent set of parameters for the main linac was found, which made the relative tolerances comparable with those of the other proposed electron-positron colliders [3]. Secondly an efficient RF Power Source was designed [4]. Among the many parameters, the length of the bunch is an essential quantity. It should be 30 μm inside the main linac and carefully controlled in the bends of the injector complex. The isochronous rings and transfer lines of the RF power source also require that the bunch length of the drive beam be modified, either by stretching, in order to limit the coherent synchrotron radiation effects, or by compression, in order to optimise the power transfer to the main beam. In the first order approximation the bunch length is proportional to the R_{56} parameter which is defined by the following integral :

$$R_{56} = \int_{s_1}^{s_2} \frac{D_x}{\rho(s)} ds \quad (1)$$

where D_x is the horizontal dispersion, $\rho(s)$ the radius of curvature, and s_1,s_2 are the longitudinal coordinates of the beginning and end of the beamline considered. The R_{56} parameter is positive if high momentum particles of the bunch travel longer paths. Of course the values of the R_{56} parameter of the various insertions can be fixed at the design stage, but the operation of both the accelerator and the decelerator are much easier if some flexibility is given to modify it in a given range. This flexibility becomes a feature in a test facility such as CTF3 [5], whose purpose is to validate most of the RF Power Source design and at the same time to study the behaviour of coherent synchrotron radiation for which the theory and the simulations remain to be confronted with experimental data. Thus a study was started to find an ensemble of several magnetic components (dipoles and quadrupoles) called an "insertion", which would be able to generate both a negative or a positive R_{56} parameter by only modifying the strength of the quadrupoles. Quite naturally the isochronous insertion developed five years ago [6] was chosen as a promising candidate. It turned out that it was possible to obtain the expression for the absolute values of the focal lengths as a function of the R_{56} parameter in the thin lens approximation. This will be shown in the next section. It demanded much more algebra to derive the conditions on the minimum and maximum values of the R_{56} parameter and on the drift lengths, such that the absolute values of the focal lengths were positive. Actually sixteen different sets of conditions exist [7]. It is impossible to decide analytically which one is best. This depends on the geometry and on the constraints imposed on the Twiss parameters at the entrance and exit of the insertion. A simple interactive program guides the user towards the best choice. The last section shows an application to the transfer line between the Delay Loop and the Isochronous Ring of CTF3.

2 THE TUNABLE ACHROMAT

Let us consider a module consisting of three bending magnets, geometrically and magnetically symmetric around the median plane of the second magnet [6]. To simplify the algebra, these magnets are treated as sector magnets of the same length l_m but of different deflection angles ϕ_1 and ϕ_2 for the first and second dipole respectively. The space between the first two magnets is filled by a drift length L_1, by a focusing quadrupole of length l_q and normalised gradient k_1, by a second drift length L_2, by a defocusing quadrupole of length l_q and normalised gradient k_2, and finally by a third drift length L_3 [6]. Assuming that the dispersion and its derivative are zero at the entrance of the first dipole, the contributions of the first dipole and of half the second dipole to the integral (1) are [6] :

$$\begin{gathered} \rho_1 \left(\phi_1 - \sin\phi_1\right) \\ \text{and} \\ D_j \sin\left(\phi_2/2\right) - \rho_2 D_j' \left[\cos\left(\phi_2/2\right) - 1\right] + \\ \rho_2 \left[\phi_2/2 - \sin\left(\phi_2/2\right)\right] \end{gathered} \quad (2)$$

respectively, where ρ_1 and ρ_2 are the curvature radii of the first and of the second dipole respectively and D_j and D'_j are the dispersion and its derivative at the entrance to the second dipole. Adding the two contributions, the R_{56} parameter for half the insertion is given by :

$$\frac{R_{56}}{2} = \rho_1 (\phi_1 - \sin\phi_1) + D_j \sin(\phi_2/2) - \rho_2 D'_j [\cos(\phi_2/2) - 1] + \rho_2 [\phi_2/2 - \sin(\phi_2/2)] \quad (3)$$

In order to obtain a nondispersive module, the derivative of the dispersion at the point of symmetry should be zero, providing a second equation :

$$-\frac{\sin(\phi_2/2)}{\rho_2} D_j + D'_j \cos(\phi_2/2) + \sin(\phi_2/2) = 0 \quad (4)$$

From these two equations it is easy to obtain :

$$\begin{aligned} D'_j &= \frac{x}{\rho_2} \\ D_j &= \rho_2 \left[1 + D'_j \cot(\phi_2/2)\right] \\ x &= \frac{R_{56}}{2} - l_m \left(\frac{3}{2} - \frac{\sin\phi_1}{\phi_1}\right) \end{aligned} \quad (5)$$

It is possible to obtain, in the same way as in reference [6] the following expressions for the first two drift lengths as functions of k_1,k_2 and of the third drift length L_3 :

$$\begin{aligned} L_1 &= a\frac{C_2 q_1}{C_1 q_2}\left(\widetilde{L_3} + q_2\right) - l + q_1 \\ L_2 &= q_1 - q_2 + \frac{b}{\widetilde{L_3} + q_2} \\ \widetilde{L_3} &= L_3 - \frac{D_j}{D'_j} \end{aligned} \quad (6)$$

where

$$l = \rho_1 \tan(\phi_1/2) \qquad a = -\frac{x}{\rho_2 \sin\phi_1} \quad (7)$$

$$b = \frac{q_2}{C_2}\left(\frac{q_2}{C_2} + \frac{q_1}{aC_1}\right) \qquad q_i = \frac{C_i}{S_i\sqrt{k_i}} \quad (8)$$

$$C_1 = \cos\left(l_q\sqrt{k_1}\right) \qquad S_1 = \sin\left(l_q\sqrt{k_1}\right) \quad (9)$$

$$C_2 = \cosh\left(l_q\sqrt{k_2}\right) \qquad S_2 = \sinh\left(l_q\sqrt{k_2}\right) \quad (10)$$

These drift lengths depend on the parameter R_{56} through the quantities D_j and D'_j. The aim of the study is to achieve R_{56} tuning i.e. the ability to vary this parameter between a minimum value (negative) $R_{56,min}$ and a maximum value (positive) $R_{56,max}$ without of course displacing the quadrupoles. Thus L_1, L_2 and L_3 are fixed and the normalized strengths k_1 and k_2 should be expressed as functions of R_{56}, which implies inverting the two equations (6). Unfortunately these are trascendental equations and no closed form may be obtained for k_1 and k_2. However it can be shown that it is possible in the thin lens approximation, that is for such a small l_q that the assumptions $C_1 = C_2 = 1$, $S_1 = l_q\sqrt{k_1}$ and $S_2 = l_q\sqrt{k_2}$ hold to a very good accuracy. Then the absolute values of the focal lengths $f_1 = l_q k_1$ and $f_2 = l_q k_2$ replace q_1 and q_2 respectively and the set of equations (6) becomes :

$$\begin{aligned} L_1 &= a\frac{f_1}{f_2}\left(\widetilde{L_3} + f_2\right) - l + f_1 \\ L_2 &= f_1 - f_2 + \frac{f_2(f_2 + f_1/a)}{\widetilde{L_3} + f_2} \end{aligned} \quad (11)$$

which can also be expanded in the form :

$$\begin{aligned} \frac{a+1}{a} f_1 f_2 + \widetilde{L_3} f_1 - \frac{L_1 + l}{a} f_2 &= 0 \\ \frac{a+1}{a} f_1 f_2 + \widetilde{L_3} f_1 - \left(\widetilde{L_3} + L_2\right) f_2 - L_2 \widetilde{L_3} &= 0 \end{aligned} \quad (12)$$

Subtracting the two equations, f_2 can be obtained :

$$f_2 = \frac{a L_2 \widetilde{L_3}}{L_1 + l - a\left(L_2 + \widetilde{L_3}\right)} \quad (13)$$

and by replacing this value in the first equation, f_1 is also obtained :

$$f_1 = \frac{L_2 (L_1 + l)}{L_2 + L_1 + l - a\widetilde{L_3}} \quad (14)$$

By using the expressions (5) and (7) the quantity $a\dfrac{D_j}{D'_j}$ which enters in $\widetilde{L_3}$, becomes :

$$a\frac{D_j}{D'_j} = -\frac{1}{\sin\phi_1}[x\cot(\phi_2/2) + \rho_2] \quad (15)$$

Using this expression and the definition of a, f_1 and f_2 can be expressed as functions of x, which is linearly related to the R_{56} parameter as shown by equation (5) :

$$\begin{aligned} f_1 &= L_2 \frac{\rho_2(\mathcal{L}_1 + \rho_2)}{x\mathcal{L}_3 + \rho_2(\mathcal{L}_1 + L_2 \sin\phi_1)} \\ f_2 &= L_2 \frac{-x\mathcal{L}_3 + \rho_2^2}{x(L_2 + \mathcal{L}_3) + \rho_2 \mathcal{L}_1} \end{aligned} \quad (16)$$

where :

$$\begin{aligned} \mathcal{L}_1 &= (L_1 + l)\sin\phi_1 - \rho_2 \\ \mathcal{L}_3 &= L_3 - \rho_2 \cot(\phi_2/2) \end{aligned} \quad (17)$$

In order to design a R_{56} tunable module, it is necessary to find the intervals of L_1, L_2, L_3 such that the absolute values of the focal lengths remain positive when R_{56} varies in the interval $R_{56,min} < R_{56} < R_{56,max}$ with $R_{56,min} < 0$ and $R_{56,max} > 0$. The algebra is very tedious and can be found in [7]. Sixteen different sets of conditions satisfy the imposed constraints. A simple interactive program permits to choose the best one according to the geometry and Twiss parameter requirements. A standard program for accelerator design, such as MAD can then be used to derive the thick lens solutions using the thin lens results as a very effective starting point.

3 APPLICATION TO A CTF3 TRANSFER LINE

The CTF3 transfer line between the Delay Loop and the Combiner Ring should be able to increase or decrease the bunch length by 1.6 mm. Given the $\Delta p/p$ of the order of $1\ \%$, the range of R_{56} is between -0.16 m and 0.16 m. To accomodate this transfer line in a 'S' shape inside the available space, it is made of two insertions, one bending the beam by $75°$ and the other bending it back by $-75°$. The analytical approach has permitted an identification of the ranges of possible solutions without using numerical searches which are very unstable in this specific problem. Thus the insertion could be optimised to find a compromise between the overall length imposed by the building dimensions, and the optics (Twiss parameters). The most useful condition in the design of this CTF3 transfer line has been the fifteenth set [6]. The three dipoles of the selected insertion have the same length (0.4 m) and generate the same beam deflection ($25°$). The drift lengths are L_1 = 1.2 m, L_2 = 0.6 m and L_3 = 1.55 m. All the quadrupoles have the same length of 0.2 m. For a beam energy of 400 MeV, the gradients of the first and second quadrupoles vary between 12.04 T/m and 7.81 T/m, and between 12.13 T/m and 1.29 T/m respectively. The Figures 1, 2 and 3 show the optical functions of the full insertion when the R_{56} parameter of half one single insertion is -0.04 m, 0 m, 0.04 m respectively.

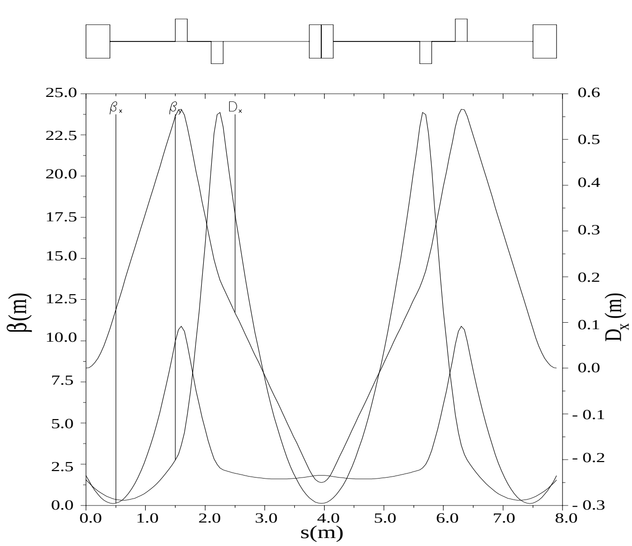

Figure 1: Optical functions for $R_{56} = -0.04$ m.

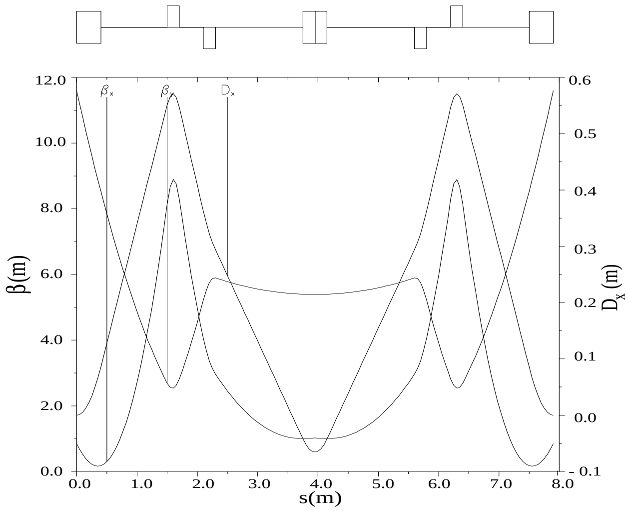

Figure 2: Optical functions for $R_{56} = 0$ m.

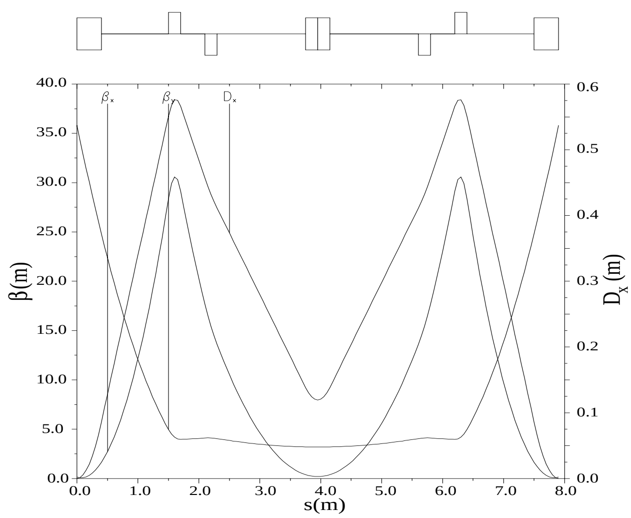

Figure 3: Optical functions for $R_{56} = 0.04$ m.

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