Using microwave quadrupoles to shorten the CLIC beam delivery section

S. Fartoukh and J.B. Jeanneret, CERN, Geneva, Switzerland

Abstract

The chromatic correction of the final focus, based on sextupoles and dipoles, requires for CLIC at 3 TeV a section which is long with respect to the main linac and the bare de-magnification telescope. The length needed is in conflict with the tight alignment of the beam delivery elements, necessary for the control of the collisions. This scheme also implies large peaks of betatron amplitudes which generate aberrations. To circumvent these problems, we explore the potential of microwave quadrupoles. They could be used for chromatic corrections since, in the presence of a correlation $z - \delta$ between momentum and position along the bunch, they play a role similar to that of sextupoles in the presence of dispersion. The correlation is done in the linac and no special optics is required, thus strongly reducing the space needed for the correction. Furthermore, the final doublet of the telescope could be only made of microwave quadrupoles, provided sufficiently high gradients be achievable, since a judicious choice of the RF phase render them achromatic. This would make the beam delivery at high energies even more compact and simple. We underline advantages and drawbacks of this proposal and list some items which need further study.

1 INTRODUCTION

We quickly explore the possibility to make the chromatic correction of the final doublet of CLIC with microwave quadrupoles [1, 2][1]. Micro wave quadrupoles (RFQ) were formerly envisaged in the past to perform BNS damping of the CLIC main beam [3, 4]. This proposal was abandoned because of the extremely tight alignment tolerances required for these structures to avoid harmful RF kicks [5]. This problem does not really hold in the final focus section. With nanometric beam sizes at the collision point, nanometric transverse alignment of the final doublet is mandatory anyway to get collisions with a good luminosity. If this condition is satisfied for the quadrupoles it can de facto be satisfied for the microwave quadrupole. In that respect, the real issue in the beam delivery section is therefore the static and dynamic control of the alignment at the nanometric scale which is independent of the use of RFQ's instead of classical DC magnets. It is then quite obvious that this performance would be more easily reached with a short beam delivery section (BDS). The aim of our proposal is to provide a way to do a chromatic correction within a marginal longitudinal length compared to the kilometric scale needed with a classical correction based on the use of sextupoles. We also show that the final doublet might be made entirely with RFQ's used in a achromatic mode, therefore offering a great simplicity.

[1]During the course of this study, we discovered that W. Schnell already mentioned this possibility in [1].

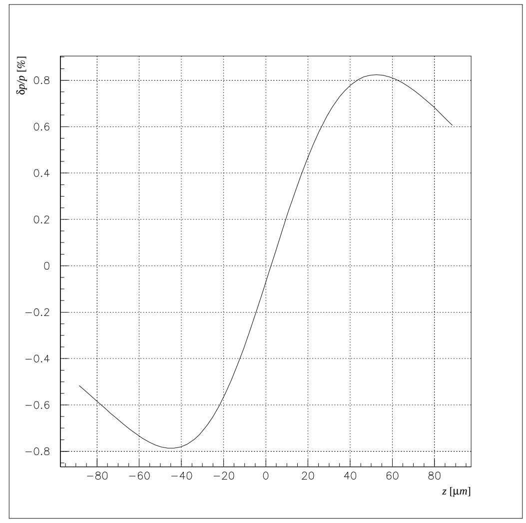

Figure 1: Correlation $z - \delta_p$ at the end of the main linac of CLIC.

2 BASIC PRINCIPLE

At the end of the linac, after reduction of the energy correlation needed for BNS damping and of the uncorrelated single bunch energy spread, the particles are concentrated in the longitudinal plane along a curve of small thickness as shown in Figure 1 [6]. Moreover around $z = 0$, the curve $\delta_p(z)$ is linear up to $|\delta_p| \sim 4-5\times 10^{-3}$ (in the case shown in Figure 1) where z and δ_p denote the longitudinal coordinate along the bunch ($z < 0$ at the bunch tail) and the relative momentum offset. The thickness of the line is the uncorrelated energy spread coming from the damping ring multiplied by the ratio of the top energy over the damping ring energy and amounts to $\delta_p \sim 5 \times 10^{-5}$ at 1.5 TeV, as deduced from [7]. The RFQ offers a quadrupolar gradient which is proportional to z for $z \ll \lambda_{\mathrm{rf}}$, with $z = 0$ corresponding to a longitudinal RF phase $\phi = \pm\pi/2$ relative to the peak of the accelerating field. Therefore with a linear correlation $z = \alpha\,\delta_p$, a chromatic correction can be made with the RFQ provided that adequate gradients can be obtained.

3 CHROMATIC CORRECTION

The integrated strength [m^{-1}] of a quadrupole seen by an off-momentum particle is written as

$$g_{\mathrm{q}}(\delta_p) = \frac{L_{\mathrm{q}}\,K_{\mathrm{q}}}{1+\delta_p}\ . \qquad (1)$$

The aim of the chromatic correction is to cancel the dependence on δ_p. The integrated quadrupole strength of an RFQ is given by

$$\left\{\begin{array}{l} g_{\rm rfq}(z,\delta_p) = A\,\sin\!\left(\dfrac{2\pi z}{\lambda_{\rm rf}}\right)\,\dfrac{L_{\rm rfq}}{1+\delta_p} \\[2ex] \text{with } A \stackrel{\rm def}{=} \dfrac{\pi}{c\lambda_{\rm rf}}\,\dfrac{\eta_{\rm eff}\hat{E}}{(p_0/q)} \end{array}\right. \tag{2}$$

where p_0/q is the nominal beam rigidity of the BDS, $\hat{E}$ [V/m] and $\lambda_{\rm rf} \stackrel{\rm def}{=} 2\pi c/\omega_{\rm rf}$ denote the peak accelerating field and the wavelength of the RFQ of length $L_{\rm rfq}$ ($\lambda_{\rm rf} =$ 1 cm for CLIC) and $\eta_{\rm eff}$ is an efficiency factor close to unity [2]. To simplify a bit, we presently assume that an RFQ will be associated to each quadrupole of the final doublet. We assume that the quadrupole and the RFQ overlap exactly longitudinally so as to have the same betatron functions in both elements. We modify (2) by writing $\sin(2\pi z/\lambda_{\rm rf}) \sim 2\pi z/\lambda_{\rm rf}$ (which is quite valid for CLIC since $\sigma_z/\lambda_{\rm rf} = 3 \times 10^{-3}$) and by introducing the correlation $z = \alpha\,\delta_p$. For $L_{\rm rfq} = L_{\rm q}$, the integrated quadrupole strength of the combined element is then given by

$$g_{\rm q}(\delta_p) + g_{\rm rfq}(z,\delta_p) = \frac{L_{\rm q}K_{\rm q}}{1+\delta_p}\left(1 + \frac{2\pi\alpha A}{K_{\rm q}\lambda_{\rm rf}}\,\delta_p\right). \tag{3}$$

An assembly is achromatic if $2\pi\alpha A/(K_{\rm q}\lambda_{\rm rf}) = 1$. Expanding A from (2) and solving for $\hat{E}$, we get

$$\hat{E} \stackrel{\rm def}{=} \frac{2\,c^3\,G_{\rm q}}{\omega_{\rm rf}^2\,\eta_{\rm eff}\,\alpha} \tag{4}$$

with $G_{\rm q} \stackrel{\rm def}{=} K_{\rm q}\,(p_0/q)$ [T/m] the nominal gradient of the DC quadrupole.

4 NEEDED RFQ VOLTAGE

The needed accelerating voltage $\hat{E}$ is evaluated for a gradient of $G_{\rm q} = 450$ T/m in the quadrupoles of the final doublet [8]. The slope $\alpha = 3.75 \times 10^{-3}$ m is deduced from Figure 1. For $\eta_{\rm eff} \sim 0.85$ [2], $c = 3 \times 10^8$ m/s, $\omega_{\rm rf} = 2\pi \times 3 \times 10^{10}$ rad/s, we would therefore need

$$\hat{E} = 210\,\mathrm{MV/m}\,. \tag{5}$$

This value is 40% larger than the present nominal gradient of 150 MV/m of the CLIC accelerating structures from which the RFQ would be derived. Nevertheless, note that this value is obtained for equal element lengths, i.e. $L_{\rm rfq} = L_{\rm q}$. This condition is not mandatory and the RFQ's can be located at other positions with the right phase, but different length (see also Section 6).

5 MERITS AND DRAWBACKS

1. Merits

- The length of the classical chromatic correction section is presently $L_{\rm ccs} \sim 3000$ m. With RFQ's there would be no CCS proper. The RFQ's would be integrated in the final doublet, for a total length amounting to $L \sim 20$ m. A matching doublet would be located at the end of the main linac. The drift distance between the two doublets would be $L \sim 150$ m. The entire beam delivery would thus be shorter than 200 meters. Apart from an economy in terms of tunnel cost, the crucial point of nanometric alignment would be substantially simplified with an overall length which is ten times shorter.

- There would be no need of bending magnets in the beam delivery section, almost suppressing the problem of the synchrotron radiation in that area.

- The half inner dimensions of the cavity are approximately $2\,\mathrm{mm} \times 5\,\mathrm{mm}$. The spent beam will pass at > 20 mm of the axis of the cavity (10 mrad $\times$ several meters). By orienting the cavity with the small dimension of the hole being in the horizontal plane, the distance from its edge to the axis of the spent beam would be larger than 15 mm. The body of the cavity could therefore house a hole to leave space for the spent beam and most of the beamstrahlung halo surrounding it to go through the cavity.

- The need of a linear correlation between z and δ_p allows for a larger BNS energy spread in the main linac.

2. Drawbacks

- With a correlation $z - \delta_p$ similar to the one displayed in Figure 1, the range of good chromatic correction is limited to the linear part of the correlation, or $|\delta_p| \leq 5 \times 10^{-3}$ compared to a momentum width of $|\delta_p| \leq 8 \times 10^{-3}$. In that respect, it would be interesting to know how the $z - \delta_p$ correlation can be optimised in the main linac with the chromatic correction made by RFQ in view.

- Our proposal relies entirely on the stability and linearity of the correlation $z - \delta_p$. A study of this point is therefore mandatory.

- A potential limitation might be the area of good gradient in the RFQ. From [2] we guess an area of radius $r \leq 0.5$ mm. For a maximum r.m.s. horizontal beam size in the final doublet $\hat{\sigma}_x = 135$ μm (corresponding to $\hat{\beta}_x = 80$ km) and for a perfectly centred beam (which is a mandatory condition to collide), the correction would be well made up to $4\,\sigma_x$ (much more vertically). This is adequate but leaves little margin.

- In RFQ's, long-range transverse wakefields will be stronger than in standard accelerating structures if high order modes cannot be damped. Nevertheless, the total electrical length of RFQ's remains very limited (compared to the linac), the beam is at top energy and that, as an element of the BDS, the RFQ alignment tolerances will be imposed by the control of the IP offset and IP spot size, that is less than 100 nm [8] to be compared with the 10 μm tolerances [9] announced for the accelerating structures of the linac.

- A drive beam is needed to power the RFQ's.

6 A FURTHER STEP: FOCUSING MADE WITH RFQ'S

We might consider the radical option of a final focus made only of RFQ's. At 30 GHz, the peak RF quadrupole gradient $\hat{G}_{\rm rfq}$ [T/m] derived from the CLIC accelerating structures can be obtained from (2)

$$\hat{G}_{\rm rfq} = \frac{\eta_{\rm eff}\pi}{c\lambda_{\rm rf}}\,\hat{E} = \frac{\eta_{\rm eff}\,\omega_{\rm rf}}{2\,c^2}\hat{E} = 134\ {\rm T/m} \tag{6}$$

for $\hat{E} = 150$ MV/m. This value is low compared to the expected performance of a classical quadrupole pushed to the slightly extreme performance $G_{\rm DC} = 450$ T/m. Using the results obtained in [10] for $l^* = 2$ m, the total length of the RFQ's would be $l_{QF} = 4$ m and $l_{QD} = 9$ m. These dimensions are not prohibitive. We might also consider to double the frequency $f_{\rm rf} = 60$ GHz, which potentially offers to double the RF quadrupole gradient for the same accelerating field. This option requires a specific study and is not further discussed here.
A single RFQ can be made achromatic by choosing adequately the phase of the cavity relative to the passage of the bunches. By writing

$$g_{\rm rfq}(\delta_p,\phi) \stackrel{\rm def}{=} \frac{G_{\rm rfq}}{p/q} = \frac{\hat{G}_{\rm rfq}}{p_0/q(1+\delta_p)}\,\sin\left(\frac{2\pi\alpha}{\lambda_{\rm rf}}\delta_p+\phi\right), \tag{7}$$

the achromaticity condition $\partial g_{\rm rfq}/\partial\delta_p \equiv 0$ yields

$$\phi_{\rm a} = \tan^{-1}\frac{2\pi\alpha}{\lambda_{\rm rf}} = 67^\circ \tag{8}$$

for $\lambda_{\rm rf} = 1$ cm and $\alpha = 3.75\times10^{-3}$ m. The loss of effective focusing gradient is marginal, equal to $1-\sin(\phi_{\rm a})$=8 %.
We can conclude that a RFQ final doublet operated at the achromatic phase would be much more compact than a DC one, provided of course that the correlation $z-\delta_p$ of the particle leaving the linac is granted. But we show in the next section that the required RF stability is much beyond the precision at which it can be controlled.

7 PHASE STABILITY REQUIREMENT

We discuss the stability of phase for the case of the achromatic final doublet. The effect of a small phase error $\Delta\phi$ is obtained by expanding (7) around the achromatic phase $\phi_{\rm a}$:

$$\frac{\Delta G_{\rm rfq}}{G_{\rm rfq}} = \left(\frac{\Delta\sin(\phi)}{\sin(\phi)}\right)_{(\phi=\phi_{\rm a})} \approx \frac{\cos(\phi_{\rm a})}{\sin(\phi_{\rm a})}\,\Delta\phi = 0.42\,\Delta\phi$$

for $\phi_{\rm a} = 67^\circ$. According to [8], the tightest tolerance to field errors is obtained in the last quadrupole; it is approximatively equal to 10^{-5} for 2 % luminosity loss. Allowing a luminosity loss of 10%, this tolerance can be relaxed to approximatively 2.2×10^{-5}. The tolerance on the RFQ phase is then easily deduced from Eq. (7):

$$\Delta\phi \lesssim 0.003^\circ\,. \tag{9}$$

This result would be similar if the chromatic correction was separated from the focusing. Presently, the required RF phase stability in the main linac is estimated to be $\Delta\phi \sim 0.2^\circ$ [11] and it is still not known if the latter can be easily met. The tolerance for the chromatic correction with RFQ is therefore 65 times harder.
Similar conclusion can be obtained concerning the tolerance on the RFQ accelerating voltage.

8 SUMMARY AND FUTURE WORKS

We did a preliminary investigation of the use of RFQ's to make the chromatic correction or even the focusing of the final doublet. This approach would strongly reduce the length of the beam delivery section, but we find that the tolerance on the RF stability (phase and gradient) is too tight and most likely rules out the present proposal.
An hybrid scheme made on DC sextupoles, RF dipoles and RF quadrupoles is presently under investigation to circumvent this major problem.

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