A proposal to use microwave quadrupoles to shorten the beam delivery section of CLIC

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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 cicumvent these problems, we explore the potential of microwave quadrupoles. They could be used for chromatic corrections since, in the presence of a correlation between momentum and position within 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, 3][1], which were formerly envisaged for use in the main linac of CLIC, to perform BNS damping [4, 5, 6]. This proposal was abandoned

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

because the transverse excursion of the beams should have been too tightly controlled to avoid harmful RF kicks [7]. This problem does not really hold in the final focus section. With nanometric beam sizes at the collision point, nanometric transverse alignment of the elements of the final doublet is mandatory anyway to get collisions with good luminosity. If this condition is satisfied for the quadrupoles it can de facto be satisfied for the microwave quadrupole (RFQ). 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 instead of classical DC magnets. It is then quite obvious that this performance would be more easily reached with a short beam delivery section. 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.

2 Basic principle

At the end of the linac, after reduction of the energy correlation needed for BNS damping and of the single bunch energy spread, the particles in the longitudinal plane are concentrated along a curve of small thickness as shown in Figure 1[8]. Moreover around $z = 0$ and $\delta_p = 0$ the curve is linear up to $|\delta_p| \sim 4 - 5 \times 10^{-3}$ (in the case shown in Figure 1) with z the longitudinal coordinate along the bunch and δ_p 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 $\delta_p \sim 7 \times 10^{-5}$ at 1.5 TeV, as deduced from [9]. The RFQ offers a quadrupolar gradient which is proportional to z, for $z \ll \lambda_{\rm RF}$, 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 of a quadrupole is written as

$$L_Q K(\delta_p) = \frac{L_Q K_Q}{1 + \delta_p} \ . \qquad (1)$$

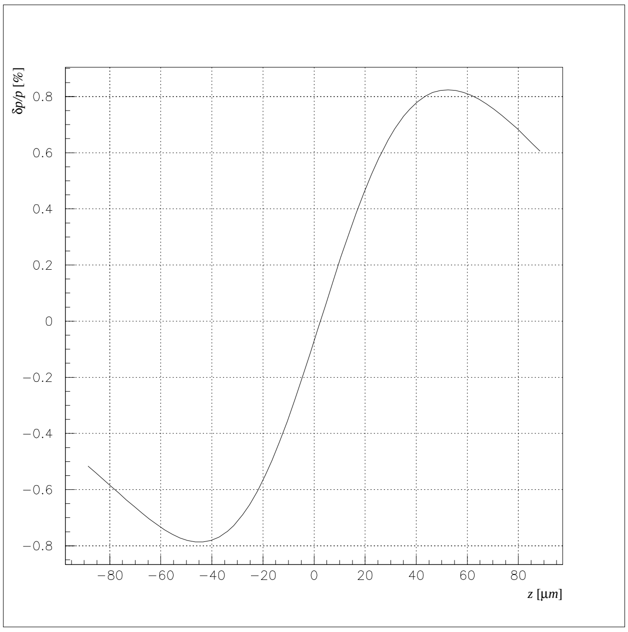

Figure 1: The density of particles in the longitudinal plane at the end of the main linac of CLIC.

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

$$L_{\rm RFQ}\tilde{G}(z,\delta_p) = A\sin\left(\frac{2\pi z}{\lambda}\right)\frac{L_{\rm RFQ}}{1+\delta_p} \quad \text{with} \quad \mathrm{A} = \frac{\eta_{\rm eff}\pi}{\mathrm{c}\lambda}\mathrm{G}_0 \qquad (2)$$

with $\tilde{G}$ expressed in T/m, G_0 in MV/m, $\lambda = c/f_{\rm RF} = 10^{-2}$ m the RF wavelength, $f_{\rm RF} = 30$ GHz, c the speed of light, $L_{\rm RFQ}$ the length of the RFQ, $\eta_{\rm eff}$ an efficiency factor close to unity [2, 3] and G_0 its nominal peak gradient to be determined. 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 element. We modify (2) by writing $\sin(2\pi z/\lambda) \sim 2\pi z/\lambda$ with $z \approx \sigma_z = 30$ μm $\ll \lambda$ and by introducing the correlation $z = \alpha\delta_p$. With now $L_{\rm RFQ} = L_Q$, we get

$$L_{\rm RFQ}\tilde{G}(z,\delta_p) = L_Q G(\delta_p) = \frac{2\pi\alpha A\delta_p}{\lambda}\frac{L_Q}{1+\delta_p} \qquad (3)$$

With our simplified hypothesis of exact overlapping of a quadrupole and an RFQ the combined effect of the two elements is obtained by adding (1) and (3). We get

$$L_Q K(\delta_p) + L_Q G(\delta_p) = L_Q K_Q \frac{1}{1+\delta_p}\left(1 + \frac{2\pi\alpha A}{K_Q \lambda}\delta_p\right) \ . \tag{4}$$

An assembly is achromatic if

$$\frac{2\pi\alpha A}{K_Q\lambda} = 1 \ . \tag{5}$$

Expanding A from (2) and solving for G_0 we get

$$G_0 = \frac{c\lambda^2 K_Q}{2\pi^2 \eta_{\rm eff}\alpha} = \frac{2c^3 K_Q}{\omega_{\rm RF}^2 \eta_{\rm eff}\alpha} \tag{6}$$

with $\omega_{\rm RF} = 2\pi c/\lambda$.

4 Needed RFQ strength

The needed gradient G_0 is evaluated for a gradient of $K_Q = 450$ T/m in the quadrupoles of the final doublet [10]. The slope $\alpha = 3.75 \times 10^{-3}$ m is deduced from Figure 1, $\eta_{\rm eff} = 0.85$ [2, 3], $c = 3 \times 10^8$ m/s, $\omega_{\rm RF} = 2\pi \times 3 \times 10^{10}$ rad/s. We would therefore need

$$G_0 = 210 \text{ MV/m} \ . \tag{7}$$

This value is 40% larger than the present maximum accelerating field of the main linac cavities $E_{\rm RF} = 150$ MV/m from which the RFQ would be derived. But this value is obtained for equal element length or $L_{\rm RFQ} = L_Q$. This condition is not mandatory and the RFQ's can be located at other positions with the right phase, but different length. We might also consider doubling the RF frequency, thus doubling G_0. This is further discussed in Section 6.

5 Merits and drawbacks of the RFQ

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 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 wpuld 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 2×5 mm$\times$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 spead in the main linac.

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 r.m.s. horizontal beam size of $\hat{\sigma} = 120$ μm for $\hat{\beta}_x = 80$ km in the final doublet. With a perfectly centered beam, that is a mandatory condition to collide, the correction would be well made up to 4σ. This is adequate but leaves little margin.
- In RFQ's, long-range wakefields effects will be stronger than in accelerating structures if high order modes cannot be damped. Transverse wakefields affect the quality of the gradient and are approximately proportional to the third power of the radius of the iris. The total length of RFQ's will be very limited, but a quantitative study must to be done.
- 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 nominal RF gradient $\hat{G}_1$ derived from the CLIC accelerating structure corresponds to $G_0 = 150$ MV/m, or to a peak gradient

$$\hat{G}_1 = \frac{\eta_{\mathrm{eff}}\pi}{c\lambda} G_0 = \frac{\eta_{\mathrm{eff}}}{2c^2} G_0 \omega_{\mathrm{RF}} = 134 \text{ T/m} . \tag{8}$$

This value is low compared to the expected performance of a classical quadrupole pushed to the slightly extreme performance $G_{\mathrm{DC}} = 450$ T/m.

With $\hat{G}$ being proportional to ω_{RF} (8), we therefore consider a double frequency and get $\hat{G}_2 = 2 \times \hat{G}_1 = 268$ T/m. According to Ian Wilson, an RFQ might not sustain a peak field of 150 MV/m. With 100 MV/m we get $\hat{G}_2 = 180$ T/m. Inside a range to be further evaluated, a longer quadrupole can compensate a weaker gradient (see [11]). As a working hypothesis, we consider this compensation to be granted in the sequel. With double frequency the wavelength is halved, or $\lambda_{RF} = 5$ mm, but the condition $\sigma_z \ll \lambda_{RF}$ is still fulfilled.

Now, a single RFQ can be made achromatic by choosing adequately the phase of the cavity relative to the passage of the bunches. Writing

$$G_F(\delta_p, \phi) = \hat{G}_2 \sin\left(\frac{2\pi\alpha}{\lambda}\delta_p + \phi\right) \frac{1}{1+\delta_p} \tag{9}$$

with now $\lambda_{60\mathrm{GHz}} = 5 \times 10^{-3}$ m and using the achromaticity condition $\partial G_F / \partial \delta_p = 0$ we get the phase

$$\phi_{\mathrm{achrom}} = \tan^{-1} \frac{2\pi\alpha}{\lambda} = 78^\circ . \tag{10}$$

The focusing gradient is $G_F = \hat{G}_2 \sin(\phi_{\mathrm{achrom}}) = 0.98\hat{G}_2$. The chromatic correction is therefore obtained with a marginal loss of gradient of 2%.

We finally mention that this achromatic use of the RFQ has the unique advantage of not suffering from the change of momentum of the electrons by synchrotron radiation between the chromatic section and the final focus. In our case, the RFQ is achromatic independently of local momentum variations along the device, except for a slight loss of the correlation $z - \delta_p$, to be further evaluated. We can conclude that with an RFQ operated at $f_{\mathrm{RF}} = 60$ GHz, a final doublet might be made more compact than a DC one and in addition it would be inherently achromatic, provided of course that the correlation $z - \delta_p$

of the particle leaving the linac is granted. It remains also to compare the precision needed for ϕ_{achrom} to the precision at which it can be controlled.

7 Summary

We did a preliminary investigation of the use of RFQ's to make the chromatic correction or even the focusing of the final doublet. We found no basic drawbacks to the schemes that we envisaged, but detailed studies remain to be done.

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