TURN AROUND LOOP AND CHICANE FOR BUNCH COMPRESSION AND PATH LENGTH TUNING IN THE CLIC DRIVE BEAM*

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Abstract

To achieve the proposed luminosity, phase and energy of the CLIC drive beam must meet tight specifications. The phase stability is achieved by a feedforward system consisting of two phase measurement stations intersected by a bunch compressor chicane in front of a turn around loop and a final chicane for bunch compression and path length correction behind the loop. This chicane is foreseen to compress the bunches to a final length of 0.4 mm and should allow a path length tuning of 0.1 mm. Suitable layouts for the turn around loop and the chicanes and results of beam dynamics simulations including incoherent and coherent synchrotron radiation are presented.

INTRODUCTION

Since in CLIC a drive beam is used to power the accelerating cavities of the main linac, there is a potentially detrimental coupling between drive beam energy and phase and the main beam parameters [1]. Therefore, the drive beam energy jitter has to be smaller than $\delta E/E = 1.6 \cdot 10^{-5}$ and the phase jitter has to be smaller than 0.013 deg [2]. To achieve the tight phase tolerance a phase feedforward is foreseen to compensate the jitter generated by the injector facility.

The system proposed below measures drive beam phase and energy in front of the turn around loop and corrects the phase behind it. Additionally, for an efficient energy extraction in the decelerator a bunch length of $\sigma_{\mathrm{s}} = 0.4$mm is needed and the initially $\sigma_{\mathrm{s}} = 4\,\mathrm{mm}$ long bunches have to be compressed by a factor of 10. Consequently, the beam line has to contain the following sections:

1) first phase measurement
2) non-isochronous beam line to get a phase error proportional to the energy error
3) second phase measurement to estimate the energy error
4) turn around loop
5) bunch compressor chicane
6) phase correction

The parameters of the incoming electron bunches are given in Table 1.

A schematic of how the full beam line could look like is shown in Figure 1. The individual components are described in the following sections.

	Symbol	Value	Unit
Beam energy	E_0	2	GeV
Bunch charge	Q_0	10	nC
Bunch length	$\sigma_{\mathrm{s,i}}$	4	mm
Unc. energy spread	$\frac{\sigma_{\mathrm{E,unc}}}{E_0}$	2.5	10^{-4}
Linear s-E correlation	$\frac{1}{E_0}\frac{dE}{ds}$	-2.5	m^{-1}
Total energy spread	$\frac{\sigma_{\mathrm{E,tot}}}{E_0}$	1	%
Normalized emittance	$\varepsilon_{\mathrm{n,x}}$	100	μm rad
	$\varepsilon_{\mathrm{n,y}}$	100	μm rad

Table 1: Parameters of the electron bunch in front of the first phase measurement.

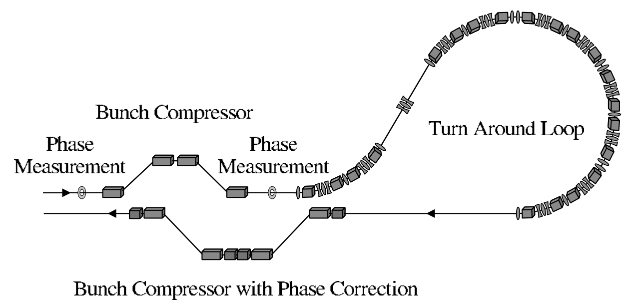

Figure 1: Sketch of the beam line.

PHASE AND ENERGY MEASUREMENT SECTION

Phase and energy of the electron bunches are obtained by two phase measurements ϕ_1 and ϕ_2 intersected by a non-isochronous beam line with a momentum-compaction factor R_{56}, e.g. a simple chicane built of four dipoles. The chicane will shift the bunch phase by a nominal value ϕ_{c}, which is given by the path length of electrons with nominal energy, and an energy dependent value $\Delta\phi \approx \frac{2\pi}{\lambda_{\mathrm{RF}}} R_{56} \frac{\Delta E}{E_0}$. Consequently, we get $\phi_2 - \phi_1 = \phi_{\mathrm{c}} + \Delta\phi$ and finally

$$\frac{\Delta E}{E_0} \approx \frac{\lambda_{\mathrm{RF}}}{2\pi} \frac{\phi_2 - \phi_1 - \phi_{\mathrm{c}}}{R_{56}} .$$

Additionally, the chicane will compress the bunches due to the position-energy correlation $\frac{1}{E_0}\frac{dE}{ds}$ previously imposed on the electrons in the RF cavities:

$$\sigma_{\mathrm{s,f}} \approx \sigma_{\mathrm{s,i}} \left(1 - R_{56} \frac{1}{E_0} \frac{dE}{ds}\right) .$$

Both effects, i.e. phase shift and bunch compression, depend on the momentum compaction factor R_{56} of the chicane. The minimum possible R_{56} is defined by the needs of the phase measurement. Assuming an energy jitter of

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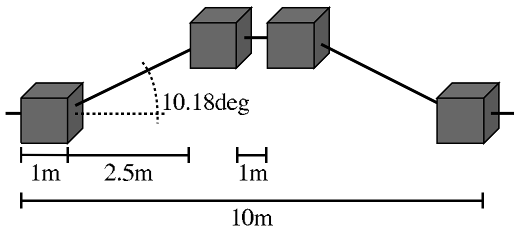

Figure 2: Possible layout of the first bunch compressor chicane.

$\delta E/E = 10^{-5}$ and a momentum compaction factor of $R_{56} = 0.2\,\mathrm{m}$, the phase measurement would need a resolution better than $0.072\,\mathrm{deg}$ (30 GHz). The maximum R_{56} is defined by the minimum allowed bunch length in the chicane and the turn around loop due to the CSR emittance growth which will take place.

Computer simulations using a one-dimensional model of coherent synchrotron radiation (CSR) were performed with the code CSRTrack [3]. They show that in a $10\ \mathrm{m}$ long chicane with $R_{56} = 0.2\ \mathrm{m}$ (Figure 2) the bunches can be compressed from $4\ \mathrm{mm}$ to $2\ \mathrm{mm}$ and the emittance grows by less than 1%. Since the maximum emittance growth, which is allowed along the full beam line including both bunch compressors and the turn around loop, is $\Delta\varepsilon_{\mathrm{n,max}} = 10\ \mu\mathrm{m\ rad}$, this value can be easily tolerated.

TURN AROUND LOOP

The turn around loop is needed to direct the electron beam into the decelerator where the energy is extracted from the drive beam and fed into the accelerating cavities of the main linac. This loop has to be achromatic, but not necessarily isochronous. Either a slight compression of the electron bunches or a slight decompression are possible. A compression in the loop would ease the design of the final bunch compressor but would also lead to stronger CSR in the loop. A decompression in the loop would ease the design of the loop, since naturally the R_{56} of loops has the opposite sign of the R_{56} of chicanes. But then the bunch compression in the second bunch compressor would need to be stronger and the CSR emittance growth would be higher.

The minimum length of the turn around loop is given by CSR effects and the needs of the phase feedforward, since some time is needed to measure the phase, calculate the correction and apply the correction in the correctors. It was estimated that about $200\ \mathrm{ns}$ time are needed for this purpose [4]. That means, the turn around loop must be longer than $60\ \mathrm{m}$. An upper boundary is given by the cost of the system, i.e. the loop should be as short as possible.

Some aspects have to be carefully considered in the loop lattice design. First, along the loop the R_{56} should develop in a way that the electron bunches never become so short that CSR dilutes the emittance. Second, the peak R_{16} should be small, so that the peak beam size stays within practical limits, i.e. the beam pipe should not become too wide. Of course, also the chromatic effects must be small.

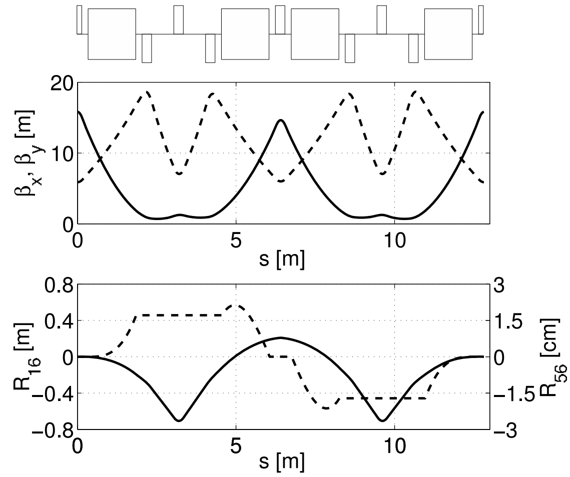

Figure 3: Optics functions in one arc of the turn around loop. The upper plot shows horizontal (solid) and vertical (dashed) beta function. The lower plot shows dispersion R_{16} (solid, left axis) and momentum compaction factor R_{56} (dashed, right axis).

A loop lattice that might be suitable is the lattice of the first drive beam combiner ring [5]. It is based on achromatic and isochronous cells built of four dipoles [6]. For the turn around loop these cells have been adopted (Figure 3). Each dipole deflects the $255\ \mathrm{MeV}$ beam by $15\ \mathrm{deg}$, i.e. each cell deflects the beam by $60\ \mathrm{deg}$. The cell length is $12.8\,\mathrm{m}$. In total five cells are used, one bending to the left and four bending to the right. A sixth cell is substituted by a drift and a quadrupole triplet (Figure 1). The total length of the loop is about $76\ \mathrm{m}$.

First computer simulations performed with the code Elegant [7] show a CSR emittance growth per cell of $1 - 2\ \mu\mathrm{m\ rad}$ when using an electron beam of $2\ \mathrm{mm}$ initial length. This would make a total CSR emittance growth in the loop of $5 - 10\ \mu\mathrm{m\ rad}$. This value is high but still acceptable. Elongating the loop and thus decreasing the strength of the dipoles could be of advantage.

BUNCH COMPRESSOR CHICANE

The second chicane is needed to compress the electron bunches to their final length of $\sigma_{\mathrm{s}} = 0.4\ \mathrm{mm}$. A compression starting from the initial bunch length of $\sigma_{\mathrm{s}} = 4\,\mathrm{mm}$, as was proposed before in Ref. [2], does not seem to be possible in a chicane of reasonable length, i.e. $20\ \mathrm{m}$, due to too strong CSR emittance dilution of about $\Delta\varepsilon_{\mathrm{n,x}} = 9\ \mu\mathrm{m\ rad}$ (Figure 4a). Therefore, it is preferrable that the bunch is compressed before to a length of about $2\ \mathrm{mm}$. Then in the second bunch compressor a momentum compaction factor of $R_{56} = 0.16\ \mathrm{m}$ is needed and the emittance dilution is only about $\Delta\varepsilon_{\mathrm{n,x}} = 3\ \mu\mathrm{m\ rad}$, as computer simulations with the code CSRTRack [3] show (Figure 4b). Comparing the two plots in Figure 4 reveals that the difference in emittance is mainly due to a stronger mismatch of the slices for higher R_{56}. A sketch of the chicane is shown in Figure 5.

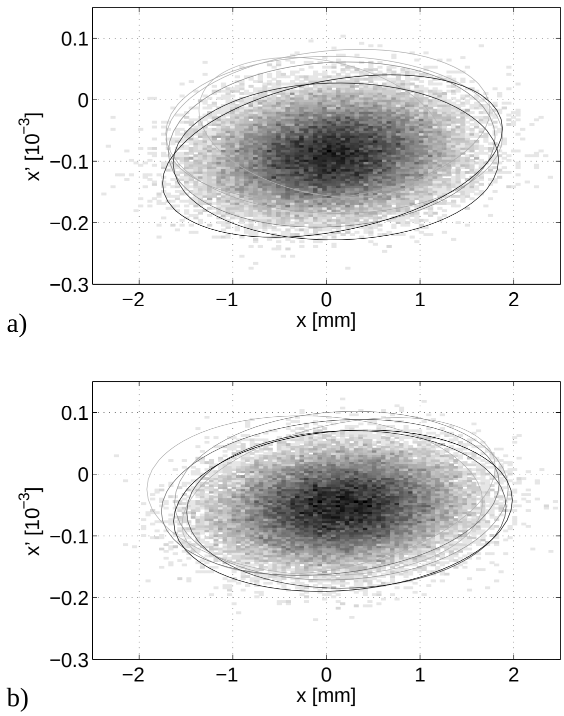

Figure 4: Horizontal phase space distributions behind a chicane with $R_{56} = 0.36$ m (a) and $R_{56} = 0.16$ m (b). The projected emittances are $\Delta\varepsilon_{\rm n,x} = 109\ \mu{\rm m\,rad}$ (a) and $\Delta\varepsilon_{\rm n,x} = 103\ \mu{\rm m\,rad}$ (b). The ellipses show orientation and size of slices of electrons along the bunch.

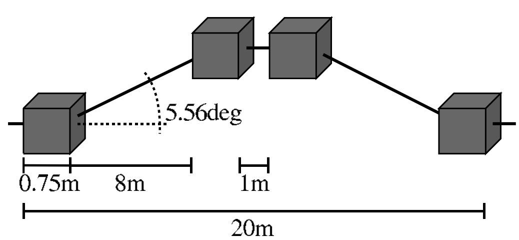

Figure 5: Possible layout of the final bunch compressor chicane.

PHASE CORRECTION

The phase correction must supply a path length tunability of at least $\pm 100\ \mu{\rm m}$. This corresponds to a phase tunability of ± 3.6 deg (30 GHz).

Two different layouts are possible. First, one could use two kickers separated exactly by a phase advance of π. For an efficient relation of the transverse kick to path length tuning a high R_{52} is needed [2]. For example, in the last section of the loop one can find such places. Second, one could use three or four kickers to not rely on the phase advance between them. For example, one could place four kickers near the dipoles of the second bunch compressor chicane. That means, the kickers adjust the R_{56} of the chicane to get the phase correction. For the full tunablity the kickers need to deflect the beam by $\pm 60\ \mu{\rm rad}$ assuming a bunch compressor with $R_{56} = 0.16$ m. The only side effect is a bunch length jitter of $\Delta\sigma_{\rm s} = 2\ \mu{\rm m}$. Graphs of how the bunch length jitter, the path length tuning and the phase correction depend on the kicker strength are plotted in Figure 6.

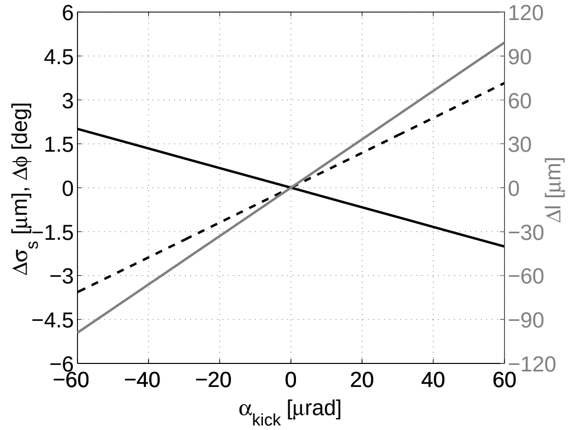

Figure 6: Bunch length jitter $\Delta\sigma_{\rm s}$ (black, solid, left axis), phase correction $\Delta\phi$ (black, dashed, left axis) and path length tuning Δl (gray, right axis) versus kicker strength $\alpha_{\rm kick}$.

CONCLUSION

The beam line for phase correction, turn around and bunch compression has been studied. Possible layouts for the two chicanes, the phase correction and the turn around loop are found. First computer simulations of the CSR emittance growth show that it is possible to stay within the specification of $\Delta\varepsilon_{\rm n,max} = 10\ \mu{\rm m\,rad}$ maximum emittance growth. Refined simulations remain to be performed to check these results. In any case, a few lattice optimizations still need to be done.

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