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Options for the second bunch compressor chicane of the CLIC main beam line

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Abstract

For the second bunch compressor chicane at CLIC a maximum emittance growth of only 5% in the horizontal plane is allowed. The emittance growth is the consequence of incoherent and coherent synchrotron radiation emitted by the electrons along the chicane. Both effects are reviewed and various chicanes are compared in computer simulations. A chicane layout is found which preserves the emittance well within the specifications.

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1 Introduction

In the main beam line of the multi TeV linear collider CLIC two bunch compressors are required to compress the electron bunches to an RMS length of 30 μm. This is the length the bunches need to have at the interaction point to reach the proposed luminosity [1]. In this paper a recommendation is given for the second bunch compressor chicane (BC2), which is foreseen to reduce the bunch length from 250 μm to 30 μm. To find a suitable layout, the influence of incoherent synchrotron radiation (ISR) and coherent synchrotron radiation (CSR) is studied.
The design work for BC2 started from a proposal given in [2]. The chicane proposed there has a total length of 30 m and is built of four equal dipoles of 7 m length. While the ISR emittance growth in this chicane is only 2.4 nm rad, computer simulations show that the projected emittance grows by about 360 nm rad due to CSR when neglecting the shielding effects due to the vacuum chamber. The very high CSR emittance growth is the reason, why the geometry of the chicane is changed and several different layouts are compared in the following.
Since some early CSR simulations, whose results are not presented here, showed that one can benefit significantly from slightly elongating BC2, the chicanes compared in this paper are 40 m long and use 2 m long dipoles. Regarding the choice of the dipole length refer to sections 2 and 3.
The chicanes which are studied split up in two groups: C-chicanes (fig. 1a) with four dipoles and S-chicanes (fig. 1b) with six dipoles. In case the dipoles are of equal strength the chicanes are called symmetric, otherwise they are called asymmetric.
Parameters common to all chicanes can be found in table 1. The corresponding initial electron beam parameters are given in table 2. A linear correlation between longitudinal position and energy is assumed, i.e. a curvature which might be induced by the preceeding RF is neglected. It is specified that after compression the horizontal emittance should not exceed $\varepsilon_{\mathrm{x}} = 600$ nm rad. Since both the incoherent and the coherent synchrotron radiation affect almost only the electron coordinates in the horizontal phase space, i.e. in the bending plane of the dipoles, vertical effects are not discussed for the moment.
The beam energy of $E_0 = 9$ GeV is a trade-off between ISR and CSR emittance growth. ISR would favor lower beam energy and CSR higher. The combination of momentum compaction factor $R_{56} = -14$ mm and linear position-energy correlation $u = \frac{1}{E_0}\frac{dE}{ds} = -70.5\ \mathrm{m}^{-1}$ is needed to reach a final bunch length of $\sigma_{\mathrm{s,f}} = 30$ μm while keeping the

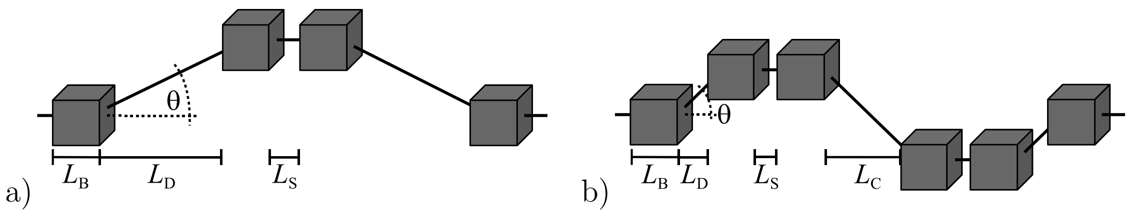

Figure 1: C-chicane (a) and S-chicane (b).

total length	L_{tot}	40.0	m
dipole length	L_{B}	2.0	m
dipole pair separation	L_{S}	1.0	m
momentum compaction factor	R_{56}	−0.014	m

Table 1: Parameters common to all bunch compressor chicanes.

beam energy	E_0	9	GeV
bunch charge	Q_0	0.41	nC
bunch length	$\sigma_{\mathrm{s,i}}$	250	μm
unc. energy spread	$\frac{\sigma_{\mathrm{E,unc}}}{E_0}$	$2 \cdot 10^{-3}$	
linear s-E correlation	$u = \frac{1}{E_0}\frac{dE}{ds}$	−70.5	m^{-1}
normalized emittance	ε_{x}	570	nm rad
beta function	β_{x}	45.0	m
alpha	α_{x}	1.45	

Table 2: Parameters of the electron bunch 1 m in front of the chicane.

total energy spread below 2%. Due to the expected high uncorrelated energy spread $\frac{\sigma_{\mathrm{E,unc}}}{E_0}$, the short bunch length cannot be reached with a higher R_{56}:

$$\sigma_{\mathrm{s,f}} = \sqrt{(1 - R_{56}u)^2\sigma_{\mathrm{s,i}}^2 + R_{56}^2\left(\frac{\sigma_{\mathrm{E,unc}}}{E_0}\right)^2} \qquad (1)$$

The initial values of the optics functions β_{x} and α_{x} were chosen to get a symmetric beta function along the chicane and a small average value of β_{x}. This results in a low ISR and CSR emittance growth, which nevertheless could slightly be improved by shifting the waist of the beta function closer to the end of the chicane [3]. On the other hand, this would increase the initial beta function and chromatic effects might be higher.
Sections 2 and 3 review the impact of incoherent and coherent synchrotron radiation on the emittance. Section 4 compares simulation results obtained with the code CSR-Track [4] for various chicane layouts.

2 Incoherent Synchrotron Radiation

The emittance growth induced by ISR can be estimated by using the equation

$$\gamma\Delta\varepsilon \approx 8 \cdot 10^{-8} E_0^5 \frac{\theta^5}{L_{\mathrm{B}}^2}\left(L_{\mathrm{D}} + L_{\mathrm{B}} + \frac{\beta_{\mathrm{min}} + \beta_{\mathrm{max}}}{3}\right) \qquad (2)$$

which was derived in [5]. The energy E_0 has to be given in GeV. The dipoles are of the length L_{B} and deflect the electrons by the angle θ. L_{D} is the length of the drift between

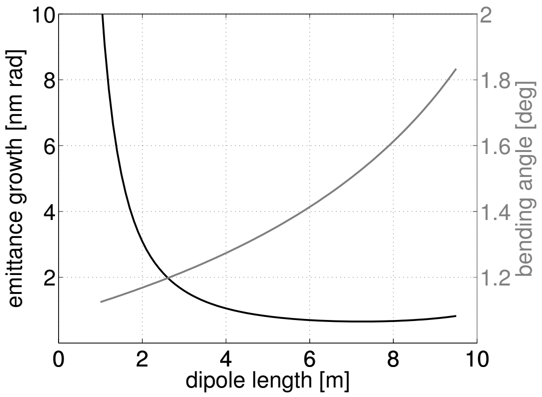

Figure 2: Variation of ISR emittance growth (black, left axis) and bending angle (gray, right axis) with dipole length.

first and second dipole. β_{min} and β_{max} are minimum and maximum beta functions along the chicane. Equation (2) is an approximation of

$$\gamma\Delta\varepsilon = 8 \cdot 10^{-8} E_0^6 I_5 \tag{3}$$

for the case of a symmetric C-chicane with small bending angles and symmetric beta functions. Using these assumptions the fifth synchrotron radiation integral I_5 can be simplified [6].

To study the effect of ISR in BC2 the length of the dipole magnets L_{B} has been varied while the total chicane length L_{tot}, the separation of the central dipoles L_{S} and the R_{56} are kept constant. It is important to note that the bending angle θ is not constant, since to first order it is given by these four parameters:

$$\theta \approx \sqrt{\frac{-R_{56}}{L_{\text{tot}} - \frac{8}{3}L_{\text{B}} - L_{\text{S}}}}$$

That means, the bending angle slowly drops for decreasing magnet length. For each dipole length the ISR emittance growth is calculated by numerically integrating eqn. (3). It is found that for dipole lengths down to about $L_{\text{B}} = 4$ m the emittance growth is almost constant. For dipoles shorter than 4 m it gets stronger, but even for $L_{\text{B}} = 1.5$ m it is still below 1% (figure 2).

This behavior of the emittance growth can be explained because $\gamma\Delta\varepsilon \propto \theta^5/L_{\text{B}}^2$. That means, the variation of the bending angle counteracts the influence of the dipole length. Consequently, within certain boundaries it does not matter for the ISR emittance growth if longer or shorter dipoles are used. The boundaries are of course not universal but depend on chicane parameters. For the parameters given above it is feasible to reduce the dipole length to about $L_{\text{B}} = 2$ m without spoiling the emittance too much.

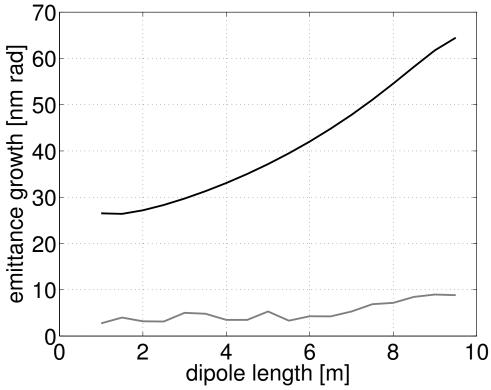

Figure 3: Variation of projected (black) and slice (gray) CSR emittance growth with magnet length.

3 Coherent Synchrotron Radiation

From synchrotron radiation theory it is known that $P_{\mathrm{CSR}} \propto R^{-2/3}$ [7]. Therefore one could expect that for the CSR emittance growth it would be of advantage to choose long dipoles, i.e. large bending radii R. In contrast to this the analysis performed in [8] shows that the total energy loss due to CSR of a bunch of N_{e} electrons passing a single dipole is

$$\Delta E_{\mathrm{tot}} = -\left(\frac{3^{2/3} N_{\mathrm{e}}^2 e_0^2}{4\pi\varepsilon_0 R^{2/3} \sigma_{\mathrm{s}}^{4/3}}\right) R\theta \left(1 + \frac{3^{1/3} 4}{9} \frac{\sigma_{\mathrm{s}}^{1/3}}{R^{1/3}\theta} \left(\ln\left(\frac{\sigma_{\mathrm{s}}\gamma^3}{R}\right) - 4\right)\right) \tag{4}$$

That means, the total energy loss can be lower for shorter dipoles, i.e. smaller bending radii R, depending on the values of bunch length σ_{s}, relativistic factor γ and bending angle θ. Indeed, this is the case for the BC2 parameters. Correspondingly, it can be argued that also the emittance growth which is induced by CSR should drop for chicanes built of shorter dipoles.

This behavior can be seen in figure 3 which shows results of computer simulations for the case of the symmetric C-chicane. The projected emittance has a strong dependence on the dipole length, whereas the slice emittance is almost constant. That means, electrons at the same longitudinal position are transversely shifted by the same amount due to the energy drift induced by CSR. This effect is usually called correlated emittance growth and is the main effect of CSR. Indeed, also the small impact on the slice emittance can be addressed to the correlated emittance growth, since for the calculation slices of finite length have been used.

4 Computer Simulations

The consequence from the above review of synchrotron radiation effects is, that the original layout with its very long dipoles is not optimal. A chicane with the same R_{56}

but shorter dipoles should be the better choice for BC2. The computer simulations desribed below confirm this.
All simulations were performed with the code CSRTrack [4] which makes use of the one-dimensional CSR model based on the analytical formulas derived in [8]. The initial bunch shape was assumed to be Gaussian (fig. 4a1) and the initial energy chirp, which is needed to compress the bunch, is assumed to be linear. That means, the phase space curvature induced in the preceeding accelerator is neglected. Nevertheless, the impact of the very high uncorrelated energy spread dominates over any small non-linearity, e.g. from RF or from non-linear motion, in the final longitudinal phase space (fig. 4b1).
The left side of figure 4 shows as an example the longitudinal phase space distribution in front of and behind the symmetric C-chicane. The length of the bunch is mainly given by the uncorrelated energy spread and the small curvature is induced by the second order term T_{566}. There is no influence of CSR visible. For all chicanes which are compared here the final phase space distributions are almost the same.
Also the final horizontal phase space distributions look very similar to each other, even though the emittances differ slightly. The initial horizontal phase space distribution and as an example the horizontal phase space distribution behind the symmetric C-chicane are shown on the right side of figure 4.
In the simulations, shielding effects due to the vacuum chamber are not taken into account. They are expected to reduce the radiation power of CSR [7] and, due to this, might also have an impact on the optimum chicane layout. A huge disadvantage of using shielding to reduce the CSR power is that resistive wall wake fields can become important. Therefore, it is in any case preferrable to find a chicane which only slightly dilutes emittance due to CSR and thus does not depend on shielding.
The first parameter scan was done to find the optimal position of the two central dipoles of the C-chicane (fig. 5). The minimum of the ISR emittance growth is at $dl = 0.0$ m, i.e. when the chicane is symmetric. For the CSR emittance growth the optimum is found to be around $dl = -4.5$ m, i.e. when the two central dipoles are shifted closer to the front. This behavior is expected, since the dipoles are stronger, i.e. the synchrotron radiation power is increased, when the bunch is still long and weaker, i.e. the synchrotron radiation power is decreased, when the bunch is already compressed. The minimum value for the CSR emittance growth is 27 nm rad, ISR adds another $3 - 6$ nm rad. Therefore, the asymmetric C-chicane is already close to the allowed growth of 30 nm rad.
S-shaped chicanes might be even better since they introduce a partial geometric compensation of the impact of CSR on the horizontal phase space distribution, similar to the case of double C-chicanes devided by a $-I$-transformation of the transverse phase space coordinates [9]. This compensation can be optimized by shifting the central four dipoles closer to the end of the chicane without changing there bending angles [10]. Additionally, like in the C-chicane the CSR emittance growth can be reduced by increasing the bending angles at the front of the chicane and reducing the bending angles at the end.
For the parameter scans the central four dipoles are moved longitudinally and horizontally by the same distances dl and dh, i.e. the central drift lenght L_c was constant. Since the scans were done for several different values of L_c several two-dimensional plots of the

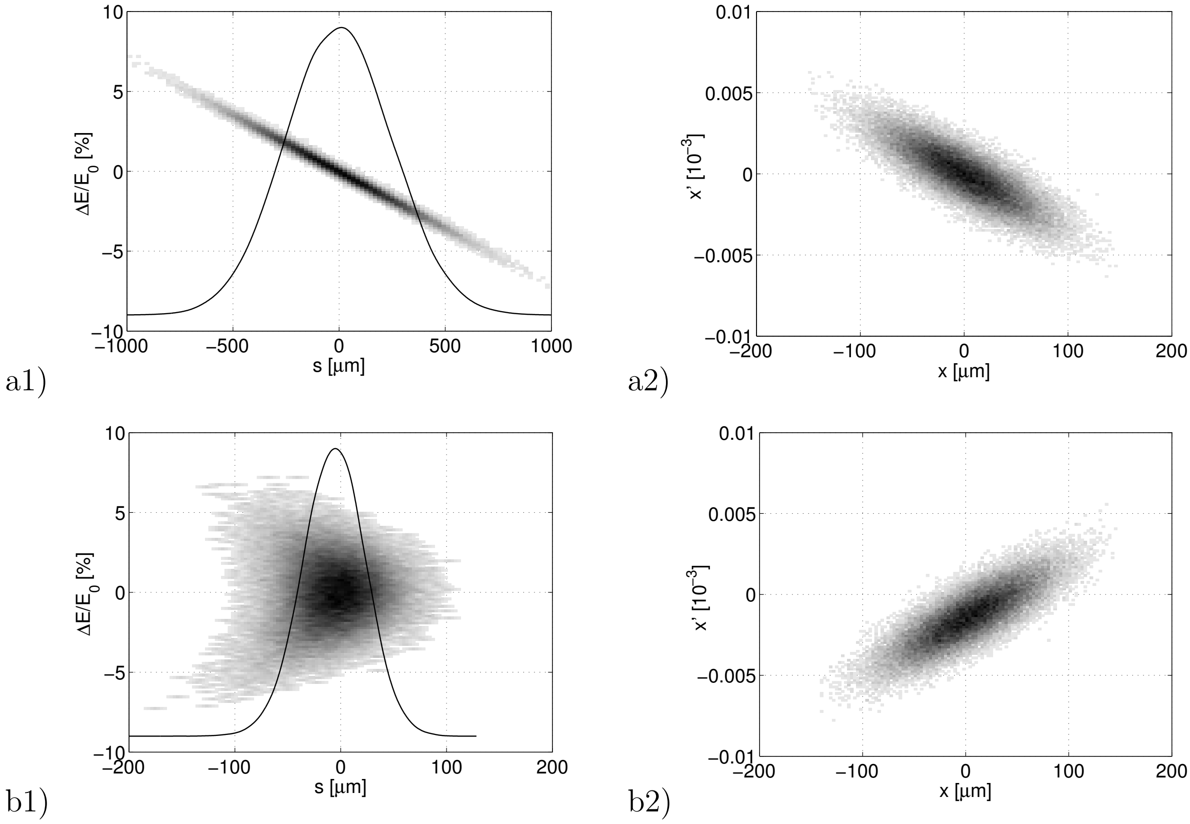

Figure 4: On the left side density plots of inital (a1) and final (b1) longitudinal phase space distribution and charge profiles (a.u) are shown. On the right side density plots of inital (a2) and final (b2) horizontal phase space distribution are shown.

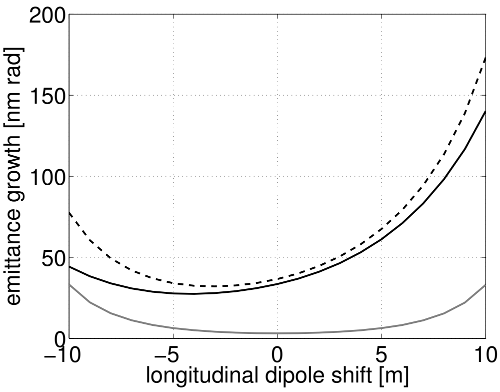

Figure 5: Variation of ISR (gray), CSR (black) and ISR+CSR (dashed) emittance growth with the position of the central dipoles.

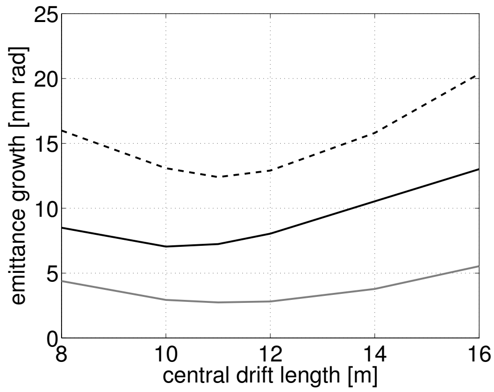

Figure 6: Variation of minimum ISR (gray), CSR (black) and ISR+CSR (dashed) emittance growth with the length of the central drift.

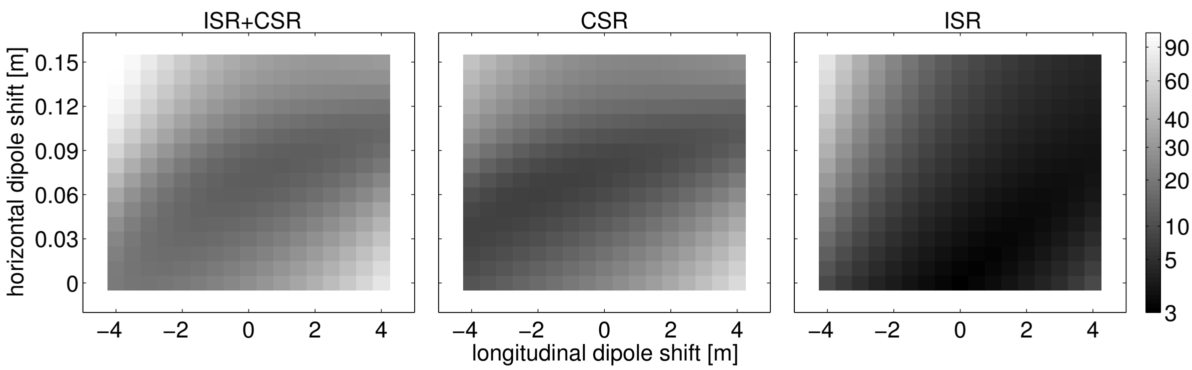

Figure 7: 2D plots of the ISR+CSR (left), CSR (middle) and ISR (right) emittance growth in an S-chicane with $L_c = 11$ m.

emittance growth were acquired. As an example, the ISR and CSR emittance growth for $L_c = 11$ m is shown in figure 7. The minimum values of the CSR emittance growth for several different L_c are plotted in figure 6. The optimum value which is achieved is 12.5 nm rad of total (ISR+CSR) emittance growth. The corresponding chicane has a central drift length of $L_c = 11$ m and the dipoles are only horizontally shifted by $dh = 7.5$ cm.

5 Conclusion

The impact of incoherent and coherent synchrotron radiation in a bunch compressor chicane designed for a multi TeV linear collider has been reviewed. It is shown that one can reduce ISR and CSR emittance growth by optimizing the dipole length, i.e. for the case of BC2 by choosing 2 m long dipoles.

Computer simulations of the impact of CSR on the beam emittance confirm these findings and show the importance of the geometric layout of the bunch compressor chicane. Several different layouts were compared and an asymmetric S-chicane was found to be the best solution in terms of ISR and CSR emittance growth. Nevertheless, also the C-chicanes, including the symmetric case, give good results and, since shielding effects due to the vacuum chamber can reduce the emittance growth, this type of chicanes might be sufficient for BC2. Also optimizations of the optics functions might lead to a further reduction of the emittance growth. That means, the goal of an emittance growth smaller than 30 nm rad can be reached with either C-chicanes or S-chicanes, the latter giving the better results.
The influence of shielding and optimized optics functions will be studied in the near future. Than also RF jitter, misalignments and the CSR microbunch instability will be investigated to find the final layout for BC2.

6 Acknowledgement

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