Longitudinal Single-Bunch Dynamics and Synchrotron Radiation Effects in the Bunch Compressor

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1 Introduction

A possible NLC bunch compressor has been outlined in Refs. [1, 2]. The compressor comprises two stages. A first stage, at 2 GeV, consists of an rf and a wiggler section. It rotates the beam by 90 degree in the longitudinal phase space, such as to convert initial phase errors due to beam loading in the damping ring into energy errors, and reduces the bunch length by a factor of 10, from about 5 mm to 500 μm. A 500 m long S-band pre-linac then accelerates the beam to 10 GeV. This is the operating energy of the second compressor which performs a 360 degree rotation in phase space. A 360 (or 180) degree rotation is required, to prevent bunch-to-bunch energy errors, caused by beam loading in the pre-linac, from translating into phase errors. An arc, a second rf section and a chicane are the components of this second stage, which reduces the bunch length to 100 μm, appropriate for injection into the main X-band linac.

2 Longitudinal Dynamics and Choice of Parameters

The parameters of the compressor system have to be chosen such that, firstly, the energy spread (both full-width-half-maximum and rms-value) at the end of the X-band linac is as small as possible (to comply with the bandwidth of the final focus system, and, possibly, also to give freedom for a crossing angle with dispersion [3]), and that, secondly, both the mean energy and the energy spread at the end of the linac are insensitive to the phase and energy errors resulting from beam loading in damping rings and pre-linac, respectively.

It is anticipated that the phase error at extraction from the damping ring is as large as 20 degree S-band (or 6 mm) [4], while at the end of the pre-linac the energy variation over the bunch train is of the order of 0.1% [5]. For the compressor-parameters proposed in this note, an initial phase error of 6 mm gives rise to an energy error of 0.22% at the end of the pre-linac. In that sense, the beam loading in the damping ring appears more important than that in the pre-linac.

The rf phase in the X-band linac is about 70 degree (here 90 degree means on crest), and, consequently, the tolerance for the final phase error at the exit of the second compressor is rather tight, namely

\[ |Δz| < 10 \ μm \] (in the main linac)
if the relative energy change at the end of the main linac is to be smaller than 0.1%.

Simulations of the longitudinal dynamics in the different compressor stages and in the full system have been performed for two different intensities, 0.7 \times 10^{10} and 1.5 \times 10^{10} particles per bunch, using the program LITRACK written by K. Bane. The higher intensity represents an upgrade option for the NLC. All simulations include the nonlinearity of the rf, the longitudinal wakefields in the rf section and the \( T_{566} \) matrix elements (i.e. quadratic dependence of final longitudinal position on energy) of chicane, arc, and wiggler. In these studies an X-band (11.4 GHz) and S-band version (2.8 GHz) of the second compressor have been compared, and an L-band (1.4 GHz) and S-band version of the first.

For both compressor stages only the lower frequency version, i.e. L-band for the first and S-band for the second, is acceptable, thanks to the smaller nonlinearity of the rf in those cases.

Furthermore, it is clearly advantageous to choose small \&s-values for the arc and the chicane, which reduces the negative effects of the \( T_{566} \), discussed later, and, as a result, gives rise to a smaller energy spread in the final focus. It is straightforward to see that for wiggler and chicane we have

\[
T_{566}^{w,c} = -\frac{3}{2} R_{56}^{w,c}
\]

while for the present lattice of the arc we find

\[
T_{566}^{a} \approx 1.9 \cdot R_{56}^{a}.
\]

Let the rf voltage of the second compressor be given by \( V_2 \sin(-k z + \phi_2); \phi_2 \approx 0 \) being the phase of the compressor rf with respect to the bunch. In our convention, the longitudinal coordinate (or phase) \( z \) is positive for electrons arriving before the ideal reference particle (which, in general, is not the center of the bunch, since the latter may be injected with a phase error), and negative for delayed particles. Choosing for the arc the value \( R_{56}^{a} = -0.25 \) m, the voltage and phase of the second compressor-rf and the \( R_{56}^{c} \) of the chicane are adjusted to give the correct bunch length and the right energy, and so that the total \&s-element of the second compressor stage is equal to zero,

\[
R_{56}^{2nd \, comp} = R_{56}^{a} + R_{56}^{c} - f_2 R_{56}^{a} R_{56}^{c} = 0, \quad \text{where} \quad f_2 \equiv \frac{V_2 k_2 \cos \phi_2}{E} = \frac{2\pi V_2}{\lambda_2 E}.
\]

Note that, once the \( R_{56} \) of the arc (or the chicane) is chosen, there is no free parameter left.

In addition to small \( T_{566} \)-effects, small \( R_{56} \)-values have the further advantages of reducing both the peak value of the dispersion in the chicane, thus easing alignment and field tolerances, and the emittance growth due to synchrotron radiation. The latter will be addressed in the following chapter. A possible disadvantage is the rather long rf section which is necessary to achieve the desired demagnification \( l/M \approx \frac{1}{7} - \frac{1}{5} \) of the bunch length. The latter is given by

\[
\frac{1}{M} = 1 - R_{56}^{c} f_2 = \frac{1}{1 - f_2 R_{56}^{c}}
\]

and the \( R_{56}^{c} \approx 0.036 \) m for the case studied necessitates a 200 m long section of S-band rf (the space for quadrupoles not included), assuming an average gradient of 20 MV/m. The value \( R_{56}^{w} \approx 0.5 \) m for the wiggler has been adopted from Ref. [2].

Having chosen all parameters as described, the tracking simulation still shows a fairly large variation of rms-energy-spread, and, in particular, of the mean energy at the end of the main linac as a function
of initial phase error. For instance, a 6 mm initial phase error causes a change of the final beam energy by about 0.2%–0.3%, which seems too large to be tolerable. Furthermore, mean energy and energy spread show a very asymmetric dependence on positive and negative phase errors. The large variation of the final energy as well as the asymmetry is a result of the nonzero $T_{566}^{w,c}$ for wiggler and chicane. (The $T_{566}^{w}$ of the arc is not significant.) There are two effects that are important: Initial phase errors give rise to energy errors $\delta_1$ after the first compressor rf, which in turn, due to the $T_{566}^{w}$ of the wiggler, cause a phase offset in the pre-linac. The result is an additional energy change $\Delta \delta_p$, which may either add to or cancel the energy error $\delta_1$, dependent on the sign of the offset. The second compressor further enhances the energy error and, due to the $T_{566}^{c}$ of the chicane, generates a significant phase error in the main linac. A second negative effect is that, if the bunch is longitudinally off-set, the $T_{566}^{w,c}$ can either increase or counteract the nonlinearity of the rf, giving rise to an asymmetry in bunch length versus phase error, for each compressor separately.

These results strongly suggest to compensate the sensitivity to initial phase errors caused by the $T_{566}^{w,c}$ of wiggler and chicane. A compensation can be performed, for instance, with an additional decelerating rf [6], designed such as to cancel the quadratic component of $z_f(z_{rf})$, where $z_{rf}$ denotes the longitudinal position or phase error at the compressor rf. Consider the main compressor rf

$$V \sin(-kz) \quad (6)$$

and a compensating rf

$$-V_c \cos(-k_c z) \quad (7)$$

with $V_c$ small compared with the beam energy $E$, $V_c \ll E$, followed by a chicane or a wiggler. The phase $z_f$ at the exit of this system depends on the initial phase $z_{rf}$ at the rf as

$$z_f = (1 - R_{566}^{w,c} f) z_{rf} + T_{566}^{w,c} f^2 z_{rf}^2 + \frac{1}{2} R_{566}^{w,c} f_c k_c z_{rf}^2 \quad (8)$$

Here, $f_c$ is the value of $V_c k_c/E$ for the compensating rf, and $f \equiv V k/E$ the corresponding value for the main compressor rf: $k \equiv 2\pi/\lambda$ being the wave number. The quadratic term in Eq. (8) is compensated if we choose

$$V_c = -2 \frac{T_{566}^{w,c}}{R_{566}^{w,c}} \frac{k^2 V^2}{k_c^2 E} = 3 \frac{\lambda^2 V^2}{\lambda^2 E} \quad (9)$$

where we have used Eq. (2). The required voltage $V_c$ is about 7 MV and 300 MV for an S-band and an X-band compensation in the first and second compressor stage, respectively. Table 1 and 2 summarize the parameters of the compressor for the two intensities $N_e = 1.5 \times 10^{10}$ and $N_e = 7 \times 10^8$, assuming initial Gaussian bunches of length $\sigma_z = 5$ mm and energy spread $\sigma_r = 0.1\%$. The total length of the bunch compressor (including the pre-linac and the quadrupoles and drifts of the rf-sections) is about 1900 m.
Table 1: Parameters for bunch compressor and main linac assuming injected Gaussian bunches with \( \sigma_0 = 0.1\% \) and \( \sigma_z = 5 \text{ mm} \), for \( N_e = 1.5 \cdot 10^{10} \) particles per bunch. All values on the right-hand side refer to the beam distribution at the end of an element.

<table>
<thead>
<tr>
<th>Element</th>
<th>( \sigma_0 [%] )</th>
<th>( \Delta \sigma_{FWM} [%] )</th>
<th>( \sigma_z [\text{mm}] )</th>
<th>( E [\text{GeV}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-band rf, ( V = 136 \text{ MV}, \phi = 12^\circ, L_{rf} = 8.5 \text{ m} )</td>
<td>1.01</td>
<td>2.32</td>
<td>5.01</td>
<td>2.00</td>
</tr>
<tr>
<td>S-band rf, ( V = 6.9 \text{ MV}, \phi = -90^\circ, L_{rf} = 0.4 \text{ m} )</td>
<td>1.01</td>
<td>2.39</td>
<td>5.01</td>
<td>1.99</td>
</tr>
<tr>
<td>Wiggler, ( R_{56} = .5 \text{ m}, T_{566} = -.75 \text{ m}, L \approx 60 \text{ m} )</td>
<td>1.01</td>
<td>2.39</td>
<td>0.50</td>
<td>1.99</td>
</tr>
<tr>
<td>S-band rf, ( V = 8.235 \text{ GV}, \phi = 89^\circ, L_{rf} = 492 \text{ m} )</td>
<td>0.24</td>
<td>0.50</td>
<td>0.50</td>
<td>10.0</td>
</tr>
<tr>
<td>Pre-Linac Arc, ( R_{56} = -.25 \text{ m}, T_{566} = -.48 \text{ m}, L \approx 370 \text{ m} )</td>
<td>0.24</td>
<td>0.50</td>
<td>0.88</td>
<td>10.0</td>
</tr>
<tr>
<td>S-band rf, ( V = 4.07 \text{ GV}, \phi = 4^\circ, L_{rf} = 200 \text{ m} )</td>
<td>2.25</td>
<td>3.04</td>
<td>0.88</td>
<td>10.0</td>
</tr>
<tr>
<td>X-band rf, ( V = 305 \text{ MV}, \phi = -93^\circ, L_{rf} = 8 \text{ m} )</td>
<td>2.30</td>
<td>3.02</td>
<td>0.88</td>
<td>9.70</td>
</tr>
<tr>
<td>Chicane, ( R_{56} = .036 \text{ m}, T_{566} = -.054 \text{ m}, L \approx 200 \text{ m} )</td>
<td>2.30</td>
<td>3.02</td>
<td>0.097</td>
<td>9.70</td>
</tr>
<tr>
<td>X-band rf, ( V = 266.3124 \text{ GV}, \phi = 66^\circ, L_{rf} = 3250 \text{ m} )</td>
<td>0.29</td>
<td>0.29</td>
<td>0.097</td>
<td>250.0</td>
</tr>
</tbody>
</table>

Table 2: Parameters for bunch compressor and main linac assuming injected Gaussian bunches with \( \sigma_0 = 0.1\% \) and \( \sigma_z = 5 \text{ mm} \), for \( N_e = 0.7 \cdot 10^{10} \) particles per bunch. All values on the right-hand side refer to the beam distribution at the end of an element.

<table>
<thead>
<tr>
<th>Element</th>
<th>( \sigma_0 [%] )</th>
<th>( \Delta \sigma_{FWM} [%] )</th>
<th>( \sigma_z [\text{mm}] )</th>
<th>( E [\text{GeV}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-band rf, ( V = 136 \text{ MV}, \phi = 12^\circ, L_{rf} = 8.5 \text{ m} )</td>
<td>1.01</td>
<td>2.33</td>
<td>5.01</td>
<td>2.00</td>
</tr>
<tr>
<td>S-band rf, ( V = 6.9 \text{ MV}, \phi = -90^\circ, L_{rf} = 0.4 \text{ m} )</td>
<td>1.01</td>
<td>2.41</td>
<td>5.01</td>
<td>1.99</td>
</tr>
<tr>
<td>Wiggler, ( R_{56} = .5 \text{ m}, T_{566} = -.75 \text{ m}, L \approx 60 \text{ m} )</td>
<td>1.01</td>
<td>2.11</td>
<td>0.50</td>
<td>1.99</td>
</tr>
<tr>
<td>S-band rf, ( V = 8.104 \text{ GV}, \phi = 83^\circ, L_{rf} = 492 \text{ m} )</td>
<td>0.22</td>
<td>0.48</td>
<td>0.50</td>
<td>10.0</td>
</tr>
<tr>
<td>Pre-Linac Arc, ( R_{56} = -.25 \text{ m}, T_{566} = -.48 \text{ m}, L \approx 370 \text{ m} )</td>
<td>0.22</td>
<td>0.48</td>
<td>0.87</td>
<td>10.0</td>
</tr>
<tr>
<td>S-band rf, ( V = 4.07 \text{ GV}, \phi = 4^\circ, L_{rf} = 200 \text{ m} )</td>
<td>2.25</td>
<td>1.11</td>
<td>0.87</td>
<td>10.0</td>
</tr>
<tr>
<td>X-band rf, ( V = 305 \text{ MV}, \phi = -93^\circ, L_{rf} = 8 \text{ m} )</td>
<td>2.25</td>
<td>4.14</td>
<td>0.87</td>
<td>9.74</td>
</tr>
<tr>
<td>Chicane, ( R_{56} = .036 \text{ m}, T_{566} = -.054 \text{ m}, L \approx 200 \text{ m} )</td>
<td>2.29</td>
<td>1.11</td>
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</tr>
<tr>
<td>X-band rf, ( V = 266.3124 \text{ GV}, \phi = 66^\circ, L_{rf} = 3250 \text{ m} )</td>
<td>0.15</td>
<td>0.16</td>
<td>0.069</td>
<td>250.0</td>
</tr>
</tbody>
</table>
Fig. 1 shows the longitudinal distribution at the end of the main linac for $A^*=1.5 \times 10^{10}$ and an initial phase offset equal to 0 and ±6 mm. The dependence of final energy and energy spread on the initial phase error is depicted in Fig. 2 for $N_e=0.7 \times 10^{10}$, and in Fig. 3 for $N_e=1.5 \times 10^{10}$ particles. In both cases, the mean energy is fairly constant for offsets as large as ±9 mm, but the rms spread shows an asymmetric dependence on the initial phase and increases significantly for negative phase errors, while the full-width-half-maximum spread is decreasing. At high intensity, a phase error of -9 mm — which is larger than the expected phase errors of ±6 mm — gives rise to 0.9% rms energy spread and would not be tolerable. The variation of energy spread is due to the generation of a large energy tail in the main linac, which could be avoided or eliminated by collimation.

It may be illustrative to find the source of the asymmetric dependence of final energy spread on initial phase errors. Suppose a bunch is injected with initial offset $z_0$. Due to the compensating rf of the first compressor, it is at the design phase when it enters the pre-linac. $z_{pl} = z_0$. However, its energy deviates from the design by

$$\delta_1 \approx -f_1 z_0$$

where $f_1 = \frac{V_1 k_1}{E}$ (10)

which amounts to about ±24 MeV for a 6 mm offset $z_0$. In the pre-linac the energy of an individual electron is changed due to the nonlinear rf and due to longitudinal wakefields. From the typical rf-parameters of Tables 1 and 2 we have

$$\Delta \delta_{pl}, r_f = -f_{pl} \cos \phi_{pl} \cdot z - \frac{1}{2} f_{pl} \sin \phi_{pl} \cdot z^2 \approx -9 \text{ m}^{-1} \cdot z_0 - 1400 \text{ m}^{-2} \cdot z^2$$

where, in this case, $z$ agrees with the longitudinal position inside the bunch. In addition, the effect of the wakefield can be approximately expressed as a Taylor series,

$$\Delta \delta_{pl}, w_f(z) = -\frac{W N_e e^2 L_{struct}}{E} \left(1 - \frac{z}{2 \sqrt{2 \pi} \sigma_z} \frac{z^2}{4 \sigma_z^2} \cdot \cdot \cdot \right)$$

where $W \approx 2.5 \times 10^{14} \text{ V C}^{-1} \text{ m}^{-1}$ is the wakefield generated by a point charge at distance zero, and $E$ the beam energy at the end of the pre-linac; $L_{struct}$ denotes the length of the rf structure. Inserting values and dropping the constant loss term, for $N_e = 7 \times 10^9$ we find, up to quadratic order,

$$\Delta \delta_{pl}, w_f \approx 11 \text{ m}^{-1} \cdot z + 14000 \text{ m}^{-2} \cdot z^2$$

so that the total energy deviation at the end of the pre-linac becomes

$$\delta_{pl} \approx \Delta \delta_{pl}, w_f + \Delta \delta_{pl}, r_f + \delta \approx a_1 z + a_2 z^2 + \delta \approx a_2 z^2 + \delta$$

(14)

where $a_1 \approx 2 \text{ m}^{-1}$, $a_2 \approx 13 \times 10^3 \text{ m}^{-2}$, and the energy error $\delta_1$ was reduced to $\delta \equiv \delta_1/5$ due to the increase of energy at the end of the pre-linac. Now the particles traverse the arc, and, because of their energy offset $\delta_{pl}$, which was generated in the first compressor and the pre-linac, reach the rf of the second compressor with some phase error $z_2$,

$$z_2 \approx R_{56}^a \delta_{pl}$$

(15)

Even though the compensating rf is adjusted such as to cancel the effect of phase errors up to second order, by interaction with the energy offset $\delta_{pl}$ and due to the $T_{56}$ higher-order terms are generated.
Figure 1: Final longitudinal bunch distribution at the end of the main linac for $N_z = 1.5 \cdot 10^{10}$ and 5 initial phase error equal to a) 0; b) $\delta$ mm; c) -6 mm.
Figure 2: Beam energy at the end of the main linac as a function of initial phase error for $N_z = 7 \cdot 10^6$; a) full-width-half-maximum energy spread; b) rms-energy spread; c) mean energy.
Figure 3: Beam energy at the end of the main linac as a function of initial phase error for $N_e = 1.5 \cdot 10^{10}$; a) full-width-half-maximum energy spread; b) rms-energy spread; c) mean energy.
Even though the compensating rf is adjusted such as to cancel the effect of phase errors up to second order, by interaction with the energy offset $\delta_p$ and due to the $T_{566}^c$ higher-order terms are generated which increase the bunch length. These higher-order terms can be derived as follows. The energy after the second compressor rf reads

$$\delta_2 = -f_2 z_2 + \delta_p + \frac{1}{2} f_2 c k_2 c z_2^2$$

and the final phase $z_f$ is

$$z_f \approx T_{566}^c \delta_2^2 \approx T_{566}^c \left[ -2 f_2 R_{56}^a (a_2 z^2 + \delta)^2 - f_2 f_2 c k_2 c R_{56}^a (a_2 z^2 + \delta)^3 \right]$$

$$\approx -T_{566}^c R_{56}^a f_2 a_2 \left[ 2 a_2 z^4 + 4 z^2 \delta + f_2 c R_{56}^a k_2 c 3 a_2 z^4 \delta + f_2 c R_{56}^a k_2 c 3 z^2 \delta + \ldots \right]$$

It is of the general form

$$z_f \approx a z - b z^4 - c \delta^2 z^2 - d \delta z^2 - e \delta z^4 + \ldots$$

where

$$a = 1 - f_2 R_{56}^a \approx 0.14$$

$$b = 2 a_2 f_2 R_{56}^a T_{566}^c \approx 1.6 \cdot 10^8 \text{ m}^{-3}$$

$$c = 3 a_2 f_2 f_2 c k_2 c R_{56}^a T_{566}^c \approx 1.7 \cdot 10^6 \text{ m}^{-1}$$

$$d = 4 a_2 f_2 R_{56}^a T_{566}^c \approx 2 \cdot 10^4 \text{ m}^{-1}$$

$$e = 3 a_2^2 f_2 f_2 c k_2 c R_{56}^a T_{566}^c \approx 3 \cdot 10^{10} \text{ m}^{-3}$$

While the coordinate $z$ denotes, as before, the longitudinal position of a single particle in the pre-linac, $\delta$ is understood as the energy offset of the bunch as a whole, which may be due to an initial phase offset in the first compressor or due to multi-bunch beam loading in the pre-linac. For an energy offset $\delta = \pm 0.004$ (i.e. $z_0 \approx \mp 9 \text{ mm}$) and $z = \sigma_z \approx 5 \cdot 10^{-4}$ the four nonlinear terms b-e are about the same size $\approx 1 - 2 \cdot 10^{-5} \text{ m}$. If the energy offset $\delta$ is positive, the terms $c \delta^2 z^2$ and $d \delta z^2$ as well as $b z^4$ and $e \delta z^4$ have the same sign, while for negative energy offset they cancel each other. This is the source of the asymmetry in Fig. 2 and 3. Note that all terms involve the $T_{566}^c$ of the chicane and the quadratic component $a_2$ of the wakefield in the pre-linac, and that, furthermore: without the compensating rf, i.e. for $f_2 c = 0$, the coefficients $c$ and $e$ are zero and $z_f(\delta)$ shows no asymmetry (albeit the resulting bunch length for zero phase error is larger).

The rms-energy-spread at the end of the linac depends rather critically on the bunch length, which is responsible for the increased energy spread at negative initial phase errors. Fig. 4 shows an analytical curve of the final bunch length as a function of the mean relative energy offset $\delta$ at the exit of the pre-linac, obtained by a simple integration over a Gaussian distribution

$$\sigma_{z_f}^2 \approx \frac{1}{2 \pi \sigma_z^2} \left[ \int_{-2 \sigma_z}^{+2 \sigma_z} z_f^2(z, \delta) \exp(-z^2/(2 \sigma_z^2)) \right. - \left( \int_{-2 \sigma_z}^{+2 \sigma_z} z_f(z, \delta) \exp(-z^2/(2 \sigma_z^2)) \right)^2]$$

where $z_f(z, \delta)$ is given by Eq. (18). The agreement with the tracking is good. For instance, in the tracking, initial phase errors of 19 mm, which cause a relative energy error of $\mp 0.36\%$ at the end of the pre-linac, yield a bunch length of 64 $\mu$rn and 120 $\mu$rn, respectively, consistent with Fig. 4.
3 Synchrotron Radiation

Table 3 shows the effects of synchrotron radiation in the longitudinal and the horizontal phase space for wiggler, arc and chicane. The mean number of radiated quanta \( N_\gamma \) is given by

\[
N_\gamma = \frac{5}{2\sqrt{3}} \frac{\gamma \theta}{131},
\]

\( \theta \) being the total absolute bending angle of the section. In all cases the number of photons is large compared with one so that the resulting net effect can be described by a Gaussian distribution. The critical energy \( E_c \) is

\[
E_c = \frac{3}{2} \frac{\hbar c \gamma^3}{\rho},
\]

and its typical values are much smaller than the momentum spread of the bunch. In particular, therefore, the radiating particles stay inside the energy acceptance of the system. The average energy loss reads

\[
\Delta E_{\text{rad}} = \frac{8}{15\sqrt{3}} E_c N_\gamma
\]

and is also smaller than the momentum spread. The additional momentum spread due to synchrotron radiation is about

\[
\Delta \delta_{\text{rms}} \approx \sqrt{\frac{11}{27} \frac{E_c}{E} \sqrt{N_\gamma}}
\]

and negligibly small. The effect on the transverse emittance can be estimated from [1]

\[
\Delta (\gamma \epsilon_x) = 4 \cdot 10^{-8} \left( \frac{E}{\text{GeV}} \right)^6 I_5
\]

where \( I_5 \) denotes the fifth synchrotron radiation integral [7]. The total increase of the horizontal normalized emittance is about 2.6%. A ‘mismatch’ between the synchrotron radiation effects and
the original beam distribution can lead to an emittance growth which is larger than predicted by Eq. (30) [8]. This difference could be especially important for the chicane, since the phase advance over the four bending magnets is only about 90 degree. To estimate the actual emittance growth, a simulation study has been performed using the computer code MAD [9]. In the simulation 10 000 particles are tracked through the chicane. To represent the effect of synchrotron radiation in the bending magnets their energy is randomly changed according to

\[
\Delta \epsilon_{\text{rms, } B}^2 = \frac{55}{\epsilon_{\gamma}} r_e \lambda_e \theta_B \approx 1.4 \times 10^{-2} \gamma \theta_B^2 \text{ m}^2, \tag{31}
\]

where \( r_e \) is the classical electron radius, \( \lambda_e \) the Compton wavelength of the electron, \( \theta_B \) the bending angle and \( I_B \) the length of the magnet. If the initial emittance is equal to the design, no statistically significant change of emittance is found. For a 10 times smaller emittance, the resulting emittance growth is approximately \( \Delta(\gamma \epsilon_x) \approx 2 \times 10^{-3} \text{ mm mrad} \), which is consistent with the simple estimate of Eq. (30). In other words the effect of the radiation-lattice mismatch is small.

We may conclude that, for the proposed compressor, the effects of synchrotron radiation are not important.

<table>
<thead>
<tr>
<th>Wiggler</th>
<th>Arc</th>
<th>Chicane</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{\gamma} )</td>
<td>99</td>
<td>662</td>
</tr>
<tr>
<td>( E_x [\text{keV}] )</td>
<td>3.5/4.6</td>
<td>25</td>
</tr>
<tr>
<td>( 4 E_{\text{rad}} [\text{keV}] )</td>
<td>134</td>
<td>5300</td>
</tr>
<tr>
<td>( \Delta \epsilon_{\text{rms}} [%] )</td>
<td>1.3 \times 10^{-3}</td>
<td>4 \times 10^{-3}</td>
</tr>
<tr>
<td>( \Delta(\gamma \epsilon_x) \text{ [mm mrad]} )</td>
<td>0.039</td>
<td>0.038</td>
</tr>
<tr>
<td>( \Delta(\epsilon_x)/(\epsilon_x [%]) )</td>
<td>1.3</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 3: Effects of synchrotron radiation in wiggler, arc, and chicane.

## 4 Conclusions

A set of parameters for the NLC bunch compressor has been proposed, for which the compressor is sufficiently insensitive to beam-loading effects in damping rings and pre-linac. and seems to work well, as far as the longitudinal single-bunch dynamics is concerned. The increase of the horizontal emittance due to synchrotron radiation is almost negligible.

A possible disadvantage of the proposed system are the rather long rf sections in the two compressor stages. There is also a residual dependence of final energy and final energy spread on the initial phase, which becomes significant if the initial phase error of the injected beam is larger than 20 degree S-band.

Multi-bunch effects in the compressor have not yet been studied. Furthermore, the transverse dynamics including field and alignment tolerances, possible tuning procedures and diagnostic requirements still need to be addressed.
References


