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Chicane and Wiggler Based Bunch Compressors for Future Linear Colliders*

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Abstract

In this paper, we discuss bunch compressors for future linear colliders. In the past, the bunch compression optics has been based upon achromatic cells using strong sextupoles to correct the dispersive and betatron chromaticity. To preserve the very small emittances required in most future collider designs, these schemes tend to have very tight alignment tolerances. Here, we describe bunch compressors based upon magnetic chicanes or wigglers which do not need sextupoles to correct the chromatic emittance dilution. The dispersive chromaticity cancels naturally and the betatron chromaticity is not a significant source of emittance dilution. Thus, these schemes allow for substantially reduced alignment tolerances. Finally, we present a detailed design for the NLC linear collider.

Introduction

Bunch compressors are needed in the NLC [1], a future linear collider design, to compress the bunch length from roughly 5 mm at the exit of the damping rings to 100 μm. The principal problem that arises is the preservation of the transverse emittances. This becomes difficult because the beam energy spread is increased as the bunch length is decreased (the longitudinal emittance is conserved). Thus, it is extremely important to design a compressor that is insensitive to the inevitable errors and that is tunable so that the emittance dilutions can be corrected easily.

In the past, many bunch compressor designs relied on achromatic arcs to generate the necessary correlation between energy and path length; this correlation is referred to as the R_{56} matrix element or the I_1 synchrotron integral. The dispersive and betatron chromaticities were corrected with sextupoles distributed through the arc. An example of such a system is the Ring-to-Linac (RTL) transport line [2] at the Stanford Linear Collider (SLC). The RTL is designed to compress the bunch by a factor of 10. Unfortunately, the system has proven difficult to operate, partially due to a larger than expected bunch length from the damping rings. Many additional tuning elements, quadrupoles, sextupoles, and even octupoles have been added to the line and yet the emittance is still increased by roughly 25% [3]. The primary source of dilution is thought to be higher order dispersion that is not fully cancelled.

In the NLC, the situation would probably be even worse because the design emittances are much smaller and because the collider is designed to operate with flat beams: $\epsilon_x = 100\epsilon_y$. To preserve the vertical emittance with flat beams, the vertical alignment tolerances on the sextupoles must be very tight; vertical misalignments of sextupoles cause skew fields that will couple the beam and increase the vertical emittance. An initial design of the NLC bunch compressor [4,5] required a 2 μm vertical alignment of the sextupoles [6].

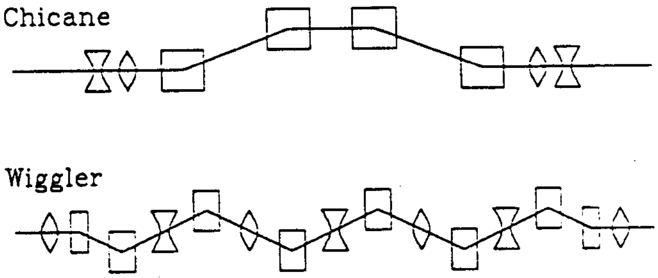

Fig. 1 Schematic of wiggler and chicane to be used for bunch compressors.

For these reasons, we are considering using wigglers or magnetic chicanes to generate the necessary R_{56} for the compressor. It is straightforward to show that in a system consisting only of rectangular bending magnets, all nonlinear contributions to the dispersive chromaticity are cancelled when the first order dispersion is cancelled [7]; the betatron chromaticity is not a significant source of emittance dilution.

Finally, in the NLC, we are considering performing two bunch compressions, one immediately after the damping ring at 1.8 Gev and one at 10 to 20 GeV so that the relative energy spread never exceed 1%; this reduces the tolerances on the compressors and the linacs downstream of the compressors. To perform the first compression, we want to rotate the longitudinal phase space by 90° so that the beam energy spread is translated into the bunch length and the bunch length is translated into energy spread. This will prevent phase deviations in the damping rings from becoming phase deviations in the linac. But, in the next compressor, we want to prevent energy deviations that arise in the linac from becoming phase deviations in the next linac. Thus, we want to perform a "180°" compression in the second compressor where the bunch is rotated by $n\pi$ in longitudinal phase space. This requires at least two R_{56} elements with RF between them.

Wigglers and Chicanes

Figure 1 schematically illustrates a wiggler and a chicane bunch compressor. Both systems have an energy dependant path length and thus can be used for a bunch compressor. In the wiggler system, quadrupoles can be placed at locations where the dispersion goes through zero; this does not generate non-linear dispersion and allows control

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of the beta functions. We only would need to introduce a few weak correction elements for tuning in the dispersive regions that would have nominal strengths of zero. Finally, one can choose the phase advance across the wiggler to be equal to 2π so that systematic errors in the bends cancel.

The R_{56} and Synchrotron Radiation

We can use very simple formula to calculate the R_{56} matrix element for a chicane of wiggler system. The R_{56} is equal to the I_1 synchrotron integral:

$$R_{56} = \int ds \frac{\eta}{\rho} \quad , \tag{1}$$

where η is the dispersion and ρ is the instantaneous bending radius.

In the case of a chicane, constructed from four equal bending magnets of length L_B, bending angle Θ_B, and separated by a distance ΔL, the R_{56} is:

$$R_{56} = 2\Theta_B^2 \left(\Delta L + \frac{2}{3} L_B \right) \quad . \tag{2}$$

Similarly, in a wiggler with N_p periods, each period constructed from two bending magnets with length $2L_B$ and angle $2\Theta_B$, and separated by a distance $2\Delta L$, the R_{56} is:

$$R_{56} = 4N_p\Theta_B^2 \left(\Delta L + \frac{L_B}{2} \right) - (2N_p + 1)\Theta_B^2 \frac{L_B}{3} \quad . \tag{3}$$

Next, we can estimate the emittance dilution due to the synchrotron radiation. As mentioned, in the NLC, we are considering performing two bunch compressions, one immediately after the damping ring at 1.8 Gev and one at 10 to 20 GeV. In the high energy compressor, synchrotron radiation becomes a significant source of emittance dilution. In a transport line, the emittance growth can be estimated using the formalism of Refs. 8 or 9:

$$\Delta\gamma\epsilon_x \,[\text{m-rad}] \approx 4 \times 10^{-8} E^6 \,[\text{GeV}]\, I_5 \,[\text{m}] \quad , \tag{4}$$

where E is the beam energy in GeV and I_5 is the fifth synchrotron integral.

In a chicane, the emittance growth is approximately

$$\Delta\gamma\epsilon_x \approx 8 \times 10^{-8} E^6 \frac{\Theta_B^5}{L_B^2} \left[(\Delta L + L_B) + \frac{\check{\beta} + \hat{\beta}}{3} \right] \quad , \tag{5}$$

while in a wiggler the emittance growth is:

$$\Delta\gamma\epsilon_x \approx 2 \times 10^{-7} E^6 N_p \frac{\Theta_B^5}{L_B^2} \frac{(\Delta L + L_B)}{\sin\psi_c} \quad , \tag{6}$$

where $\check{\beta}$ and $\hat{\beta}$ are in minimum and maximum beta values across the chicane and ψ_c is the phase advance per cell in the wiggler. Notice that for the same length and the same R_{56}, the synchrotron radiation contribution to the emittance is much larger in a wiggler than in a chicane. Finally, more exact calculations of the emittance growth need to consider the match of the synchrotron radiation contribution to the beam [10], but this is unnecessary for our purposes; Eqs. (5) and (6) will tend to over-estimate the growth.

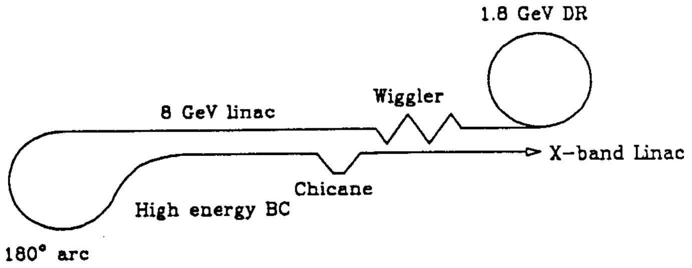

Fig. 2 Schematic of the NLC bunch compression.

Low Energy Compressor

The NLC low energy bunch compressor is located immediately after the damping ring as illustrated in Fig. 2. It must provide a 10:1 bunch length reduction while preserving the small transverse emittances from the damping rings. The compressor consists of a 2.5 meter S-band structure with a voltage of 67 MV followed by a four period wiggler. This rotates the longitudinal phase space by roughly 90°, compressing the bunch length from 5 mm to 500 μm while increasing the energy spread from 0.1% to 1%. The optics are shown in Fig. 3.

The main wiggler section is made up of four 90 degree cells such that each bend magnet (with the exception of the first and last) has an opposing pair at a $-I$ transform separation. This symmetry provides cancellation of systematic dipole magnet errors (e.g. sextupole component). Each main quadrupole is placed where the horizontal dispersion crosses through zero. This placement eliminates the generation of dispersive chromaticity and also locates the quadrupoles where the beam size is small which eases quadrupole field quality tolerances.

Operational experience in the SLC bunch compressors has made clear the need for tuning elements which are designed into the beamline. In addition to a high degree of symmetry and the absence of strong focusing elements at dispersive locations, the low energy bunch compressor incorporates eight small dispersion tuning quadrupoles — four skew and four normal — for orthogonal control of residual angular and spatial dispersion in both planes. Each tuning quad has a $-I$ opposing pair so that dispersion can be controlled independent of beta functions and betatron coupling by varying the quad pair's difference setting and holding the sum setting to zero. There are two skew pairs separated by 90° and two normal pairs separated by 90°.

A set of ≥ 4 wire scanners (not addressed here) must be well placed immediately following the wiggler section in order to measure horizontal and vertical emittance and beta functions. This section will require magnified beta functions (especially vertically) in order to measure beam sizes of 5 to 100 μm rms. Linear combinations of the tuning quads can then be formed to orthogonally correct all dispersion by simply minimizing the emittance with each of the four linear combinations.

In order to test the tuning capability of the wiggler

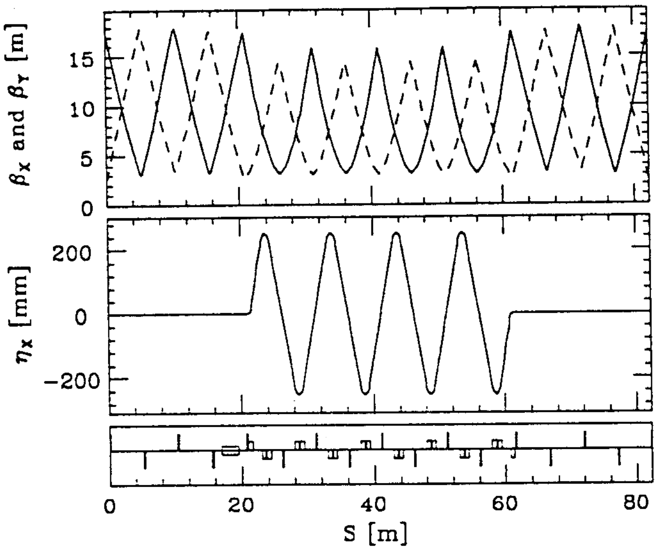

Fig. 3 Optical functions β_x (solid), β_y (dashes), and η_x in the low energy compressor. The RF cavity is a 2.5 meter S-band structure with a voltage of 67 MV. The tuning quadrupoles are located at the bending magnets.

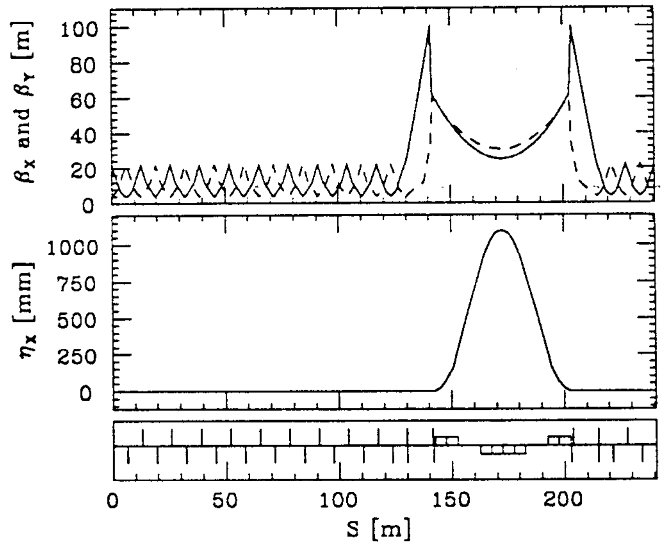

Fig. 4 Optical functions β_x (solid), β_y (dashes), and η_x for the 1.3 GeV S-band correlation linac and chicane of the high energy compressor.

section, several simulations were run using TRANSPORT and TURTLE tracking. Bend magnet rolls of 1°, bend magnet field errors of 1%, and large orbit distortions of 1 mm were each introduced independently and, *in all cases*, the huge emittance dilution, sometimes 50 times the initial emittance, was fully recovered by correcting dispersion with the tuning quads.

High Energy Compressor

A schematic layout of the high energy compressor is illustrated in Fig. 2. The rms bunch length exiting the low energy compressor is ≈ 0.5 mm. After acceleration from 1.8 GeV to 10.1 Gev, the uncorrelated energy spread is 0.2%. At this point, the bunch passes through an arc which reverses its direction of motion and acts as the first stage of the "180°" compressor. The arc is composed of 156 FODO bending cells; sextupoles are not necessary since the beam energy spread is small. Next, a 1.3 GeV S-band linac creates an energy-position correlation which is used in the subsequent chicane to decrease the rms length of the bunch to 0.1 mm; the rms energy spread is increased to 1.0%, correspondingly. The R_{56} of the reversing arc is 0.5 m while that of the chicane is 0.1 m; the optics of the 1.3 GeV linac and the chicane are illustrated in Fig. 4. The synchrotron radiation contribution to the emittance is less that 0.2% at 10 GeV. We are currently studying the effects the effects of errors and the tunability of the system.

Discussion

We have described a bunch compression system that is based upon a wiggler and a chicane. In such devices, the higher-order dispersion cancels naturally without the sextupole magnets that can lead to severe alignment tolerances. Furthermore, in future linear colliders, it is essential that emittance correction elements and procedures be integrated into the design. This appears straightforward in the chicane and wiggler designs. Although we have not completed study of the high energy compressor, the tunability of the low energy compressor is extremely promising.

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