Bunch Compressor Options for the New TESLA Parameters

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ABSTRACT

A more aggressive set of parameters for the TESLA linear collider has been proposed to achieve a very high luminosity [1]. In order control the disruption parameter, the rms bunch length at the interaction point (IP) has been reduced from 600 μm to 400 μm at the center of mass energy (CM) of 500 GeV. At 800 GeV CM the required bunch length reduces to 300 μm. The reference design of the collider [2] presently includes a wiggler-based single-stage compressor at 3.2 GeV which is limited to a minimum rms bunch length of 600 μm due to the inherent non-linearity of the system in conjunction with the relatively large longitudinal emittance of the damping ring. In this note we explore options for new and modified bunch compressor designs to achieve the shorter bunch.

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1 Introduction

The reference design of the collider includes a wiggler-based single-stage compressor. An important characteristic of magnetic bunch compressors is the ratio of their non-linear momentum compaction, T_{566}, to their linear compaction, R_{56}. For simple bend systems such as wigglers and chicanes, which include no focussing elements at dispersion points, the particle's path length, s, is proportional to the square of the dipole's bend angle, θ (<<1), which is inversely proportional to the particle's relative energy deviation ($\delta \equiv \Delta E/E_0$).

$$s \propto \frac{\theta_0^2}{(1+\delta)^2} = \theta_0^2\left(1 - 2\delta + 3\delta^2 - 4\delta^3 + \cdots\right) \tag{1}$$

Using a standard notation for the longitudinal coordinate within the bunch, z ($\equiv s_0 - s$), as a function of the relative energy deviation,

$$z(\delta) = R_{56}\delta + T_{566}\delta^2 + \cdots \ , \tag{2}$$

explicitly shows the momentum compaction ratio

$$T_{566}/R_{56} = -3/2 \ . \tag{3}$$

For longitudinal coordinates with bunch head at $z < 0$, the R_{56} coefficient for a wiggler (or a chicane) is always negative and the T_{566} coefficient is then always positive. The sign of R_{56} determines the sign of the RF phase (with respect to accelerating crest) necessary for bunch compression. It will be seen that for a wiggler (or chicane) the 2nd order compression terms associated with the sinusoidal shape of an RF *accelerating* field and the T_{566} always add (see below). For an RF phase at zero-crossing (*i.e.* no quadratic RF term) and a gaussian initial bunch distribution, the minimum compressed bunch length is still limited (by the ratio $T_{566}/R_{56} = -3/2$) to [2]

$$\sigma_{z_f} > \sqrt{3\sqrt{2}\sigma_{\delta_i}\sigma_{z_i}} \ . \tag{4}$$

Here the rms bunch length before (after) compression is given by σ_{z_i} (σ_{z_f}) and the initial rms energy spread is given by σ_{δ_i}. For the reference design of the TESLA damping ring ($\sigma_{z_i} \approx 9$ mm, $\sigma_{\delta_i} \approx 0.1\%$) the minimum rms bunch length after the wiggler compressor is 590 μm. Without a major reduction of the damping ring bunch length the present single-stage wiggler-based compressor cannot be used to achieve the required bunch length of 300-400 μm.

Figure 1 shows an example of this second order compression limitation where the bunch length has been pushed to the minimum in a system very similar to the reference design. The fold-over effect from the T_{566} element is clearly seen in the longitudinal phase space plot at lower right.

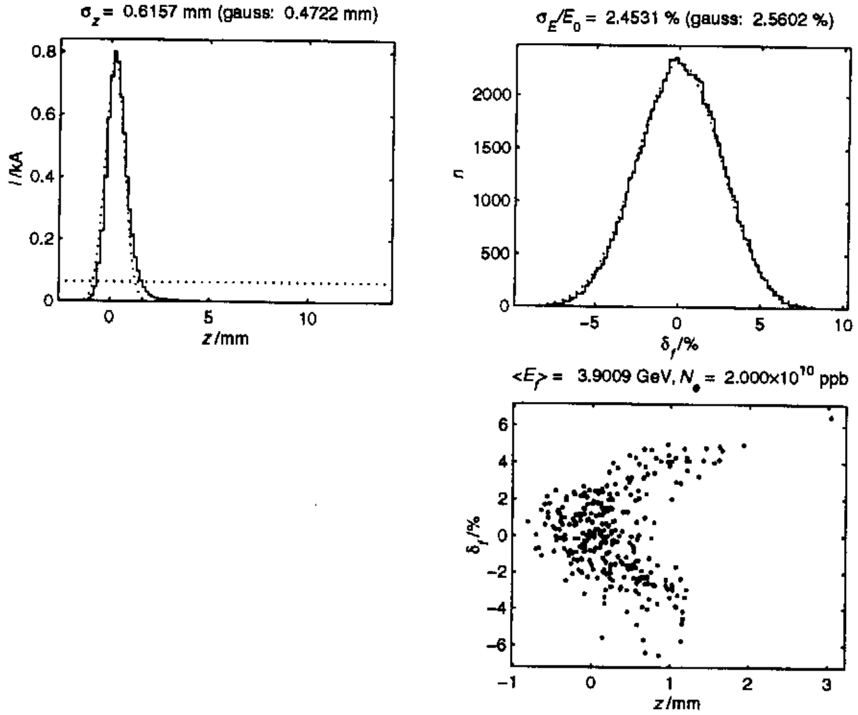

Figure 1. Tracking of reference design compressor pushed to its minimum bunch length (600 μm). The quadratic fold-over of the T_{566} effect is evident. Dotted lines in upper plots are gaussian fits.

A new single-stage compressor, a 2nd compressor stage, or a sharp reduction in the damping ring bunch length needs to be implemented. The options associated with each are discussed here.

2 An Arc-Based Single Stage Compressor

The limitation given by the wiggler-based compressor is completely defined by the sign of the ratio $r \equiv T_{566}/R_{56}$ ($= -3/2$). In fact, a simple arc composed of FODO-cells generates a positive R_{56} and, more importantly, a reversed sign ratio T_{566}/R_{56}. It can be shown that, for a FODO-cell arc, the ratio is $T_{566}/R_{56} \approx +1.9$ [3]. This reversal can be used to setup a cancellation where the quadratic component of the RF shape is exactly cancelled against the T_{566} effect allowing compression to a shorter bunch.

2.1 Quadratic Compensation

The final energy, E_f, of a particle after a linac of length, L, with RF gradient, G, wavelength, λ, and phase, φ_0, and temporarily ignoring wakefields, is

$$E_f = E_{i0} + \Delta E_i + GL\cos(\varphi_0 + 2\pi z_i/\lambda)\,. \tag{5}$$

Here E_{i0} is the nominal initial particle energy, ΔE_i represents a possible small initial energy deviation, and z_i is the initial longitudinal coordinate of the particle with respect to the bunch center ($\langle z_i \rangle = 0$). The RF phase is defined with respect to the crest where maximum acceleration occurs ($\varphi_0 = 0$) and the bunch head ($z_i < 0$)

receives more acceleration than the tail for $\varphi_0 > 0$. Eq. (5) is now expanded to second order in z_i ($<< \lambda/2\pi$).

$$E_f = E_{i0} + \Delta E_i + GL\left[\cos\varphi_0 - \frac{2\pi\sin\varphi_0}{\lambda} z_i - \frac{2\pi^2\cos\varphi_0}{\lambda^2} z_i^2\right] \qquad (6)$$

With the final energy of the reference particle ($\Delta E_i = 0$, $z_i = 0$) defined as $E_{f0} \equiv E_{i0} + GL\cos\varphi_0$, the final relative energy deviation, δ_f, is introduced as

$$\delta_f \equiv \frac{E_f}{E_{f0}} - 1 = \frac{E_{i0}}{E_{f0}}\delta_i - \frac{2\pi GL\sin\varphi_0}{\lambda E_{f0}} z_i - \frac{2\pi^2 GL\cos\varphi_0}{\lambda^2 E_{f0}} z_i^2 \ . \qquad (7)$$

Here the initial energy deviation, ΔE_i, has been replaced by the *relative* initial energy deviation, $\delta_i \equiv \Delta E_i/E_{i0}$. Eq. (7) includes linear and quadratic terms in z_i and for brevity is rewritten as $\delta_f \equiv A\delta_i + Bz_i + Cz_i^2$.

Eq. (2) is now used for the final longitudinal coordinate, z_f, after the bunch compressor, with $r \equiv T_{566}/R_{56}$.

$$z_f = z_i + R_{56}\left(\delta_f + r\delta_f^2\right) \qquad (8)$$

Eq. (7), in brief, is now substituted into (8) and only 2nd order terms in z_i are retained.

$$z_f \approx AR_{56}\delta_i(1 + rA\delta_i) + (1 + BR_{56} + 2BR_{56}rA\delta_i)z_i + R_{56}\left(C + rB^2 + 2CrA\delta_i\right)z_i^2 \quad (9)$$

This is further simplified by recalling order of magnitude values of $|\delta_i| << 1$, $A \sim 1$, and $|r| \sim 1$.

$$z_f \approx AR_{56}\delta_i + (1 + BR_{56})z_i + R_{56}\left(C + rB^2\right)z_i^2 \qquad (10)$$

Eq. (10) shows the linear and quadratic dependence of the final bunch coordinate on the initial coordinate. At this point, the limitation of the reference design is more obvious. Since, for acceleration, C is always negative [see Eq. (7)] and B^2 is positive, then for $r < 0$ (as in the case of the wiggler), the quadratic term at right of Eq. (10) cannot be manipulated to zero. Applying a decelerating phase ($|\varphi_0| > \pi/2$) makes C positive and may salvage the wiggler as a compressor. This is described in section 3.

For an arc, however, where $r > 0$, a cancellation can be arranged using an accelerating phase ($|\varphi_0| < \pi/2$). Solving for $C + rB^2 = 0$ sets the condition for the unique RF phase, φ_0', such that the quadratic term of (10) vanishes.

$$\varphi_0' = \cos^{-1}\left\{\frac{\sqrt{E_{i0}^2 + 8rG^2L^2(1 + 2r)} - E_{i0}}{2GL(1 + 2r)}\right\} \qquad (11)$$

In this case, Eq. (10) reduces to

$$z_f \approx AR_{56}\delta_i + (1 + BR_{56})z_i \ , \qquad (12)$$

and the final rms bunch length, σ_{z_f}, assuming the typically uncorrelated initial longitudinal coordinates (*i.e.* $\langle \delta_i z_i \rangle = 0$), is then given by

$$\sigma_{z_f} \approx \sqrt{A^2 R_{56}^2 \sigma_{\delta_i}^2 + (1 + BR_{56})^2 \sigma_{z_i}^2}\ , \tag{13}$$

where σ_{z_i} is the initial rms bunch length before the compressor, and σ_{δ_i} is the initial rms relative energy spread before the linac section. The minimum possible bunch length then reduces to the standard linear limit when $(1+BR_{56}) = 0$.

$$\breve{\sigma}_{z_f} = \left|\breve{R}_{56}\right| \frac{E_{i0}}{GL\cos\varphi_0' + E_{i0}} \sigma_{\delta_i} \tag{14}$$

$$\breve{R}_{56} \equiv \frac{\lambda\left(GL\cos\varphi_0' + E_{i0}\right)}{2\pi GL\sin\varphi_0'} \tag{15}$$

Note (14) indicates the bunch length can be compressed without limit (for this 2nd order calculation). The final rms relative energy spread is taken from (7) where the small effect of the quadratic term in z_i is now ignored.

$$\sigma_{\delta_f} \approx \frac{1}{GL\cos\varphi_0' + E_{i0}} \sqrt{{E_{i0}}^2 \sigma_{\delta_i}^2 + \left(\frac{2\pi GL\sin\varphi_0'}{\lambda}\right)^2 \sigma_{z_i}^2} \approx \frac{\sigma_{z_i}}{\left|\breve{R}_{56}\right|} \tag{16}$$

As the minimum bunch length is reduced using a small value of R_{56}, the final energy spread is increased.

For the TESLA damping ring (DR) and linac-section parameters we take [1] those listed in Table 1. Note the DR beam energy is taken from reference [1] although the bunch length is from reference [2]. This is necessary since a specific damping ring design does not yet exist for the new parameter set.

Table 1. TESLA damping ring and linac-section parameters assumed in the figures to follow. The figures are plotted for two RF gradients to show the impacts of a future gradient upgrade.

parameter	symbol	unit	value
DR beam energy	E_{i0}	GeV	3.9
relative rms energy spread at DR extraction	σ_{δ_i}	%	0.1
rms bunch length at DR extraction	σ_{z_i}	mm	9
linac RF wavelength	λ	mm	230
linac RF gradient	G	MeV/m	25 & 40

The value r ($\equiv T_{566}/R_{56}$) in the following figures is that of an arc (*i.e.* $r = +1.9$). Figure 2 shows the RF phase required for quadratic compression compensation [see Eq. (11)] as a function of the length of linac used, L, prior to the compressor arc. The gradient used for the solid curves in all plots is 25 MeV/m. The dashed curves are for a gradient of 40 MeV/m. The required phase moves towards the crest for a longer linac.

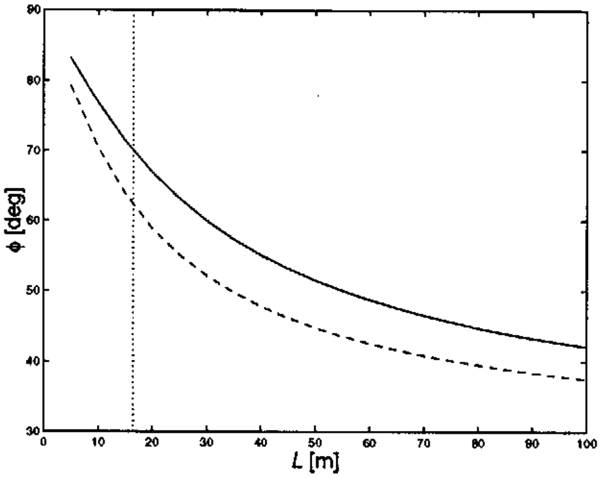

Figure 2. RF phase, with respect to crest, for G = 25 MeV/m (solid) and G = 40 MeV/m (dash), and parameters of Table 1 for the arc compressor with r = +1.9.

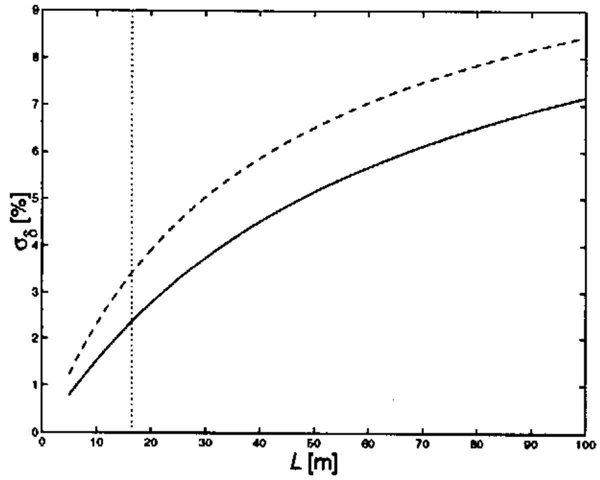

Figure 3. RMS relative energy spread in the arc, for G = 25 MeV/m (solid) and G = 40 MeV/m (dash), and parameters of Table 1.

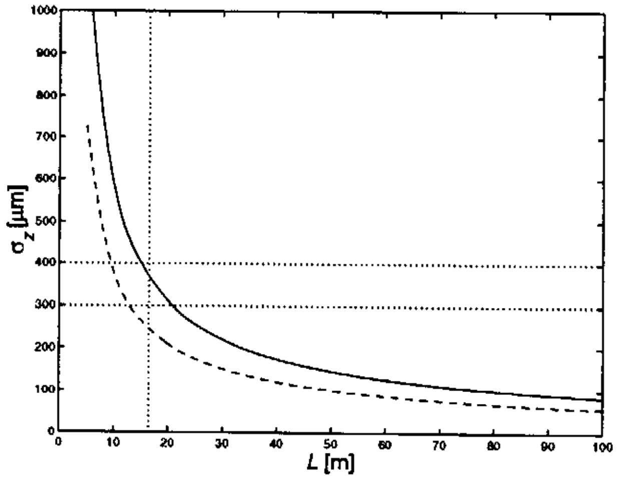

Figure 4. RMS minimum bunch length after the arc, for G = 25 MeV/m (solid) and G = 40 MeV/m (dash), and parameters of Table 1.

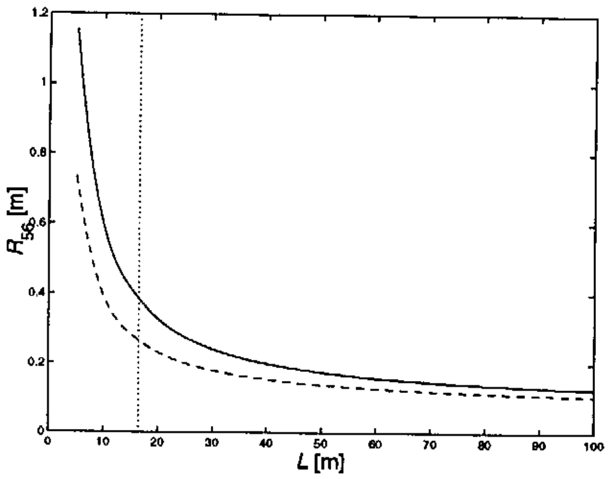

Figure 5. Required momentum compaction of the arc for minimum bunch length, for $G = 25$ MeV/m (solid) and $G = 40$ MeV/m (dash), and parameters of Table 1.

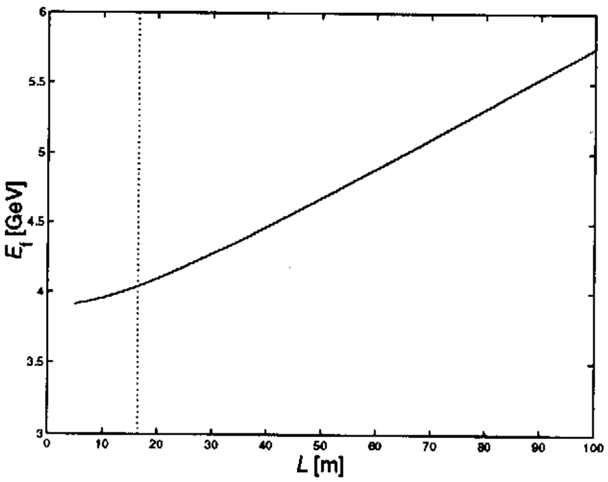

Figure 6. Final beam energy in the arc, for $G = 25$ MeV/m (solid) and parameters of Table 1.

The induced energy spread is shown in Figure 3 [see Eq. (16)] and increases to unreasonable levels (>3%) for a longer linac. The minimum achievable bunch length is shown in Figure 4 [see Eq. (14)]. At $G = 25$ MeV/m a linac length of $L \geq 15$ m is required in order to produce a bunch length of $\sigma_{z_f} \leq 400\,\mu$m. This sets a lower limit on the linac length used and forces the energy spread toward relatively high levels (> 2%). An rms bunch length of 300 μm can also be achieved with the same compressor system by upgrading the RF gradient towards 40 MeV/m. The energy spread in this case becomes > 3%. Figure 5 shows the necessary value of R_{56} of the arc for minimum compression, while Figure 6 shows the final nominal energy of the arc, both versus L.

For the TESLA parameters of Table 1, these plots suggest a single-stage arc-based bunch compressor with parameters given in Table 2. The parameters are chosen to produce a minimum bunch length just under the required value of 400 μm at 500 GeV

CM. This is to allow some room for 3rd order aberrations and to keep the energy spread as low as possible. The smaller 300 μm bunch length is obtainable by increasing the RF gradient to 40 MeV/m and changing the phase advance per cell of the arc in order to achieve the smaller value of R_{56} (see Figure 5 at 40 MeV/m).

Table 2. Possible parameters of a single-stage arc-based bunch compressor to achieve a 400 μm rms bunch length using DR and linac parameters of Table 1 and an RF gradient of 25 MeV/m.

parameter	symbol	unit	value
linac length prior to arc compressor	L	m	16.5
RF phase with respect to crest	φ_0	deg	70.0
minimum achievable rms bunch length	σ_{z_f}	μm	370
rms relative energy spread in arc	σ_{δ_f}	%	2.36
momentum compaction of arc	R_{56}	mm	382
beam energy in arc	E_{f0}	GeV	4.04

So far these calculations have ignored wakefields and 3rd order aberrations, such as arise with the RF phase near zero crossing. In the next section we present a full multi-particle tracking simulation which includes wakefields and the full sinusoidal character of the RF accelerating fields and does not make simplifying approximations such as used in Eqs. (9) through (16).

2.2 Tracking of the Arc Compressor

Figure 7 shows the longitudinal phase space and distributions after a 16.5-m linac and the compressor arc, where $R_{56} = 389$ mm, $r = +1.9$. The longitudinal geometric wakefields are represented by the point wake function [4]

$$w(s) \approx A\frac{Z_0 c}{\pi a^2}\left[(1+\beta)e^{-\alpha\sqrt{s/s_0}} - \beta\right], \tag{17}$$

with $Z_0 \approx 377\ \Omega$, c the speed of light and a (≈ 35 mm) as the iris radius. Here we take $A \approx 1.31$, $s_0 \approx 6.8$ mm, $\alpha \approx 1.33$ and $\beta \approx 0.18$ as in reference [4]. For the 16.5-m linac, the wakefields are quite insignificant.

Figure 7 also clearly shows the small 3rd order contribution to the bunch length. By cutting out <1% of the particles in the bunch tails (extending out to ~$6\sigma_z$) the rms is 420 μm. A gaussian fit (dots) to this distribution gives 399 μm. The rms relative energy spread is 2.27%. Figure 8 shows this same beam now taken to 250 GeV through 10 km of L-band linac with the wakefield of (17) convoluted over the bunch. The final rms relative energy spread, including the coherent and incoherent components, is 4.6×10^{-4} (before synchrotron radiation of the beam delivery system).

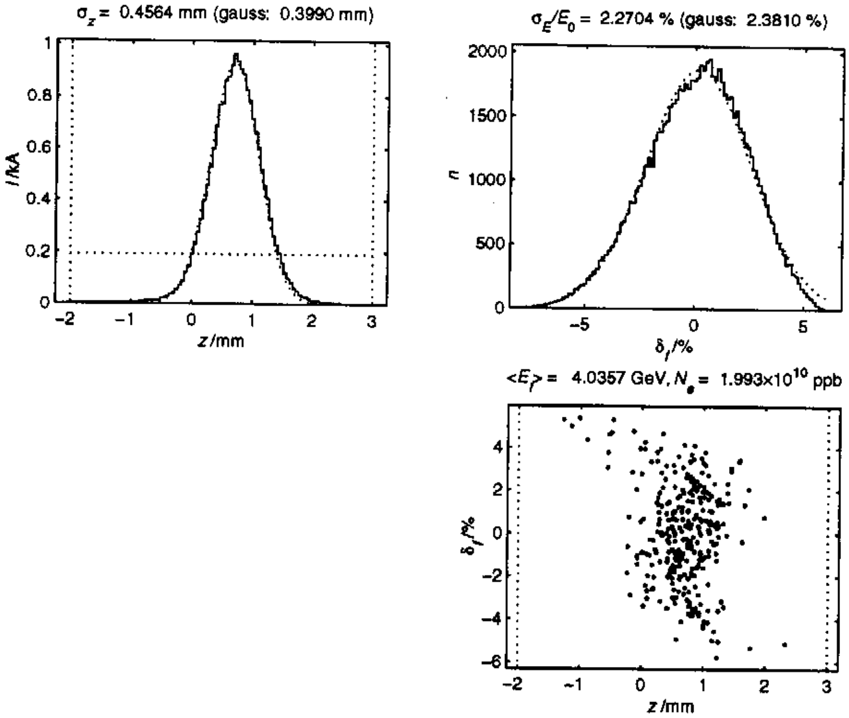

Figure 7. Tracking calculation of 16.5-m linac and arc compressor including wakefields and full sinusoidal character of the RF. Parameters are those of Table 2 with 2×10¹⁰ particles per bunch. Dotted lines in both upper plots are gaussian fits.

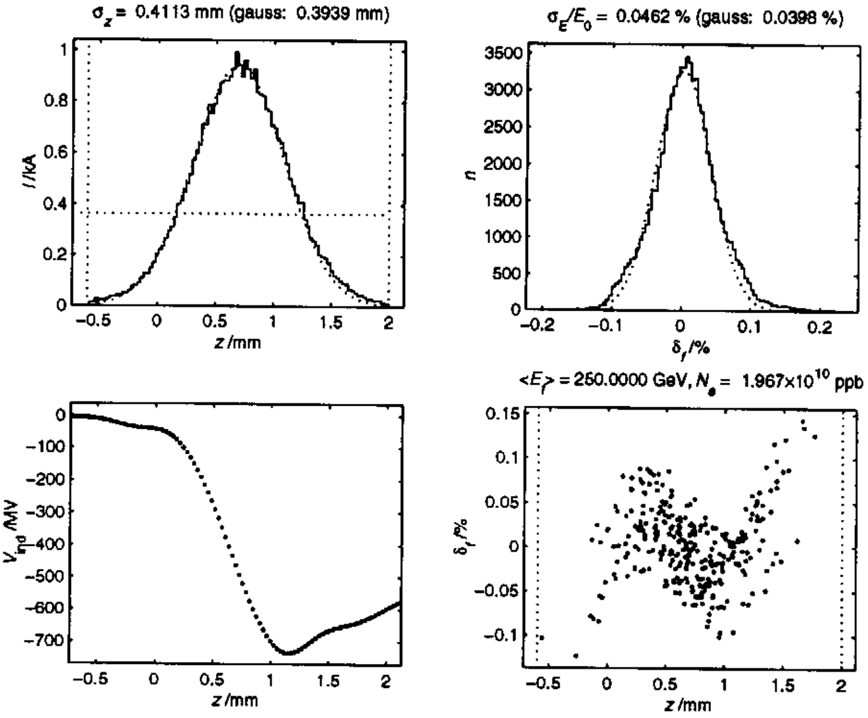

Figure 8. Tracking of arc compressor taken through 10 km linac including wakefields with 2×10¹⁰ particles per bunch and an RF phase of –6°. Dotted lines in both upper plots are gaussian fits.

2.3 Basic Parameters of the Arc

The parameters of the FODO-cell arc with $R_{56} \approx 390$ mm are listed in Table 3 where we use a full turn-around arc with net bend, $\theta_T = \pi$. The arc described in Table 3 requires 25 cells and therefore 50 quadrupole magnets. The chromaticity of the system will need sextupole compensation, especially with a 2.3% energy spread. The R_{56} value required for a 300 μm minimum bunch length is 270 mm and can be obtained using the same arc with the horizontal phase advance per cell set to ~120°.

The main problem with a large energy spread in the turn-around arc is that a polarized electron beam will be significantly depolarized as the spin precession through the arc varies for different energies. The mean polarization of an electron beam, with its spin oriented in the horizontal plane, and gaussian rms energy spread, σ_δ, bent through a net angle π with beam energy $\gamma = E_{f0}/mc^2$ is

$$\langle P \rangle = \frac{1}{\sqrt{2\pi}\sigma_\delta} \int_{-\infty}^{+\infty} P_0 e^{-\delta^2/2\sigma_\delta^2} \cos(a\gamma\delta\pi) d\delta = P_0 e^{-(a\gamma\pi\sigma_\delta)^2/2}, \qquad (18)$$

where $a \equiv (g-2)/2 \approx 1.16 \times 10^{-3}$ is the anomalous magnetic moment of the electron. For a 2.3% energy spread at 4.04 GeV the beam is depolarized by 20%. This is intolerable so the arc must be formed by two $\pi/2$ half-arcs of opposite bends so that no net bend angle is formed. The spin will then precess forward then backward such that no depolarization takes place. For unpolarized positrons, however, the full turn-around arc may be used as long as the chromaticity is properly compensated.

Table 3. Basic parameters of FODO-cell arc ($r = +1.9$) used to compress to a 400 μm bunch length. The emittance growth due to incoherent synchrotron radiation is designed to be negligible.

parameter	symbol	unit	value
beam energy in arc	E_{f0}	4.04	GeV
momentum compaction	R_{56}	mm	390
net bend angle of arc	θ_T	—	π
number of FODO cells (2 bends/cell)	N_c	—	25
net length of arc	L_T	m	50
length of FODO cell	L_c	m	2.0
horizontal phase advance per cell	$\Delta\psi_x$	deg	90
Bend magnet length	L_B	m	0.6
Bend magnet field	B_0	kG	14
Quadrupole magnet length	L_Q	m	0.3
Quadrupole magnet pole-tip field	B_Q	kG	7.1
Quadrupole magnet pole-tip radius	r_Q	mm	10

3 Salvaging the Single Stage Wiggler Compressor

3.1 Wiggler Compressor with Quadratic Compensation

As Eq. (10) shows, the quadratic cancellation can also be used for the wiggler compressor ($r = -1.5$) if the RF phase is chosen to make $C > 0$ (*i.e.* $|\varphi_0| > \pi/2$), which implies deceleration. In this case, Eq. (11) becomes

$$\varphi_0' = -\cos^{-1}\left\{\frac{\sqrt{E_{i0}^2 + 8rG^2L^2(1+2r)} + E_{i0}}{2GL(1+2r)}\right\}, \qquad (19)$$

and Eqs. (12) through (16) remain unchanged. The wiggler-based compressor parameters can then be chosen as listed in Table 4. The deceleration is just 0.12 GeV, but the relative energy spread is larger at >2.5%. The simple optical system of the wiggler, as compared to the 50-quadrupole arc, is however, more tolerant of high energy spread. There is also no net bend angle with the wiggler and therefore no net depolarization. The energy spread at the beginning of the main linac, as in the case of the arc-based compressor, is quite possibly too large for adequate transverse emittance preservation. This is an inevitable result of using a single-stage compressor.

Table 4. Possible parameters of single-stage wiggler-based bunch compressor using DR and linac parameters of Table 1, where the RF phase is chosen to decelerate and compensate the T_{566}.

parameter	symbol	value	unit
linac length prior to wiggler compressor	L	16.5	m
RF phase with respect to crest	φ_0	–107.3	deg
minimum achievable rms bunch length	σ_{z_f}	363	μm
rms relative energy spread in wiggler	σ_{δ_f}	2.56	%
momentum compaction of wiggler	R_{56}	–352	mm
beam energy in wiggler	E_{f0}	3.78	GeV

3.2 Tracking of the Compensated Wiggler Compressor

Figure 9 shows the longitudinal phase space and distributions after the 16.5-m decelerating linac and the wiggler, where $R_{56} = -362$ mm, $r = -1.5$. The bunch length from the gaussian fit is 398 μm while the rms is 442 μm due to long, sparsely populated tails. If just 1% of the tail particles are cut at $|z| < 1.4$ mm, the rms is then 410 μm. The energy spread is 2.5% and the wiggler beam energy is 3.78 GeV. Finally, a nearly identical set of plots and numbers as those of Figure 8 can be generated (not shown) for the compensated wiggler adding the 250-GeV linac with RF phase at –5°.

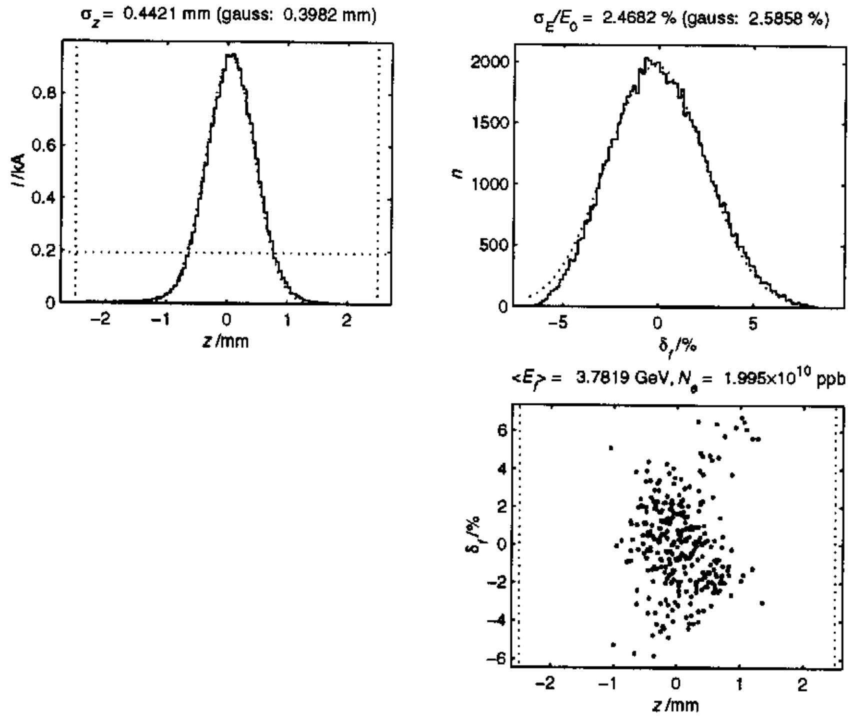

Figure 9. Tracking for the compensated wiggler compressor including wakefields and the full sinusoidal character of the RF. Parameters are those of Table 4 with 2×10^{10} particles per bunch. Dotted lines in both upper plots are gaussian fits.

4 A Two-Stage Compressor System

Another option is a second stage compressor added at a higher energy downstream of the present wiggler design. We start by allowing the first stage to essentially remain as described in reference [2], but increase the damping ring energy to 3.9 GeV as described in reference [1]. We also add the quadratic compensation as described here in section 3.1, but accept the 750 μm rms minimum bunch length allowed by an 8.2-m linac section in this first stage. The next section then only needs to compress by a factor of ~2. With these conditions, and $G = 25$ MeV/m in both stages, the first stage wiggler compressor takes on the parameters of Table 5.

Table 5. Parameters of 1st (wiggler compressor) of a two-stage compressor system using DR and linac parameters of Table 1, where the RF phase of this first stage is chosen compensate the T_{566}.

parameter	symbol	value	unit
linac length prior to wiggler	L	8.2	m
RF phase with respect to crest (compensation)	φ_0	−99.0	deg
rms bunch length after wiggler	σ_{zf}	750	μm
rms relative energy spread in arc	$\sigma_{\delta f}$	1.26	%
momentum compaction of wiggler	R_{56}	−720	mm
beam energy in wiggler	E_{f0}	3.87	GeV

The wiggler is not dramatically different from that of reference [2]. The value of $|R_{56}|$ has increased from 600 to 720 mm and the energy is higher requiring some minor modifications such as longer bend magnets.

The second stage is based on a chicane since the emittance growth due to synchrotron radiation is less for a chicane than a wiggler at high energy [5]. The choice of the RF phase and R_{56} for this second stage is more arbitrary than the first stage since there is no T_{566} compensation constraint for this mild factor of ~2 compression. The RF phase was chosen so as to keep the energy spread reasonable (<1%) while not requiring a large value of $|R_{56}|$ for the chicane, which can drive synchrotron radiation effects up. A potential set of parameters is given in Table 6. These are not a unique solution and might be further optimized.

The total chicane length is quite long at 34.3 meters so as to keep the horizontal emittance growth small with respect to the 8-μm nominal emittance at 800 GeV CM. Lowering the energy can shorten the length, but the RF phase must then mover farther off crest, which increases the relative energy spread.

Finally, the two-stage compressor system is tracked including wakefield effects (Figure 10). The two-stage compressor has the advantage of shaping the bunch distribution by pulling the gaussian tails in toward the core. This makes the wakefield along the bunch more linear and therefore decreases the coherent component of the final energy spread (see lower right plot). With an RF phase of –5.5° in the main linac, the net energy spread at 250 GeV is ~3.5×10^{-4} rms (compare to Figure 8).

Table 6. Parameters of second stage of a two-stage compressor system using DR and linac parameters of Table 1, where the parameters have been roughly optimized.

parameter	symbol	value	unit
linac length prior to chicane	L	360	m
RF phase with respect to crest	φ_0	–32.0	deg
minimum achievable rms bunch length	σ_{z_f}	400	μm
rms relative energy spread in chicane	σ_{δ_f}	0.86	%
momentum compaction of chicane	R_{56}	–80	mm
beam energy in chicane	E_{f0}	11.0	GeV
Total length of chicane	L_T	34.3	m
Length of each bend magnet (4 total)	L_B	6	m
Peak dispersion in chicane	η_x	0.733	m
Additive emittance growth due to synch. rad.	$\Delta\gamma\varepsilon_x$	0.13	μm
Incoherent energy spread due to synch. rad.	$\Delta\sigma_{\delta_{SR}}$	1.5	10^{-5}
Field of bend magnets	B_0	4.1	kG

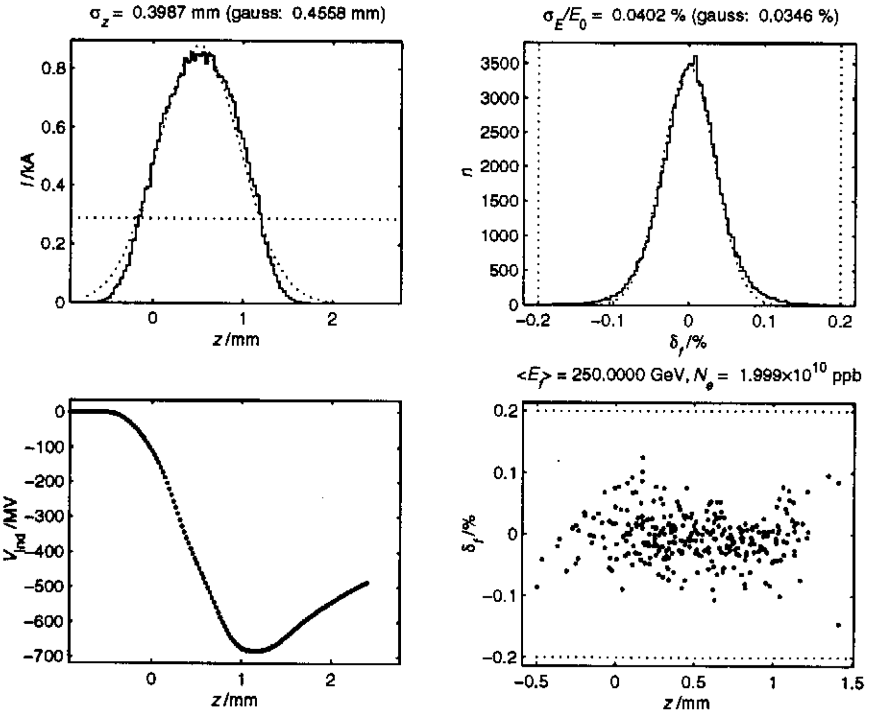

Figure 10. Tracking to 250 GeV for the two-stage compressor system including wakefields and the full sinusoidal character of the RF. Parameters are those of Table 5 and Table 6 with 2x10^{10} particles per bunch. Dotted lines in both upper plots are gaussian fits.

5 Reducing the Damping Ring Bunch Length

Many of the problems associated with the compressor systems (*i.e.* the large energy spread after compression and the non-linear limitations) stem from the relatively long bunch extracted from the damping ring. If the DR bunch length can be shortened significantly (*e.g.* by raising the DR RF voltage and/or reducing the DR momentum compaction), the limitations implied by Eq. (4) may be alleviated. In order to compress to a 300-μm bunch, however, the DR bunch length will have to be reduced by a factor of 2 (assuming the DR energy spread remains unchanged). If it is possible to produce a 4.5-mm rms bunch length at DR extraction, the single-stage wiggler system can probably be retained without adding the quadratic compensation. The R_{56} value will, however, need to be decreased in order to reduce the linear limit given by Eq. (14). Decreasing the R_{56} value also requires an increase in the linac-section length. The single-stage wiggler and linac-section parameters then need to be modified from those of reference [2] by decreasing the R_{56} value by a factor of ~2 and increasing the linac-section length by a factor of ~2. This is at the limit set by the T_{566} effect and the bunch distribution begins to show some of this non-gaussian character (see Figure 11). The energy spread at 3.9 GeV, however, is held to a more reasonable 1.8%.

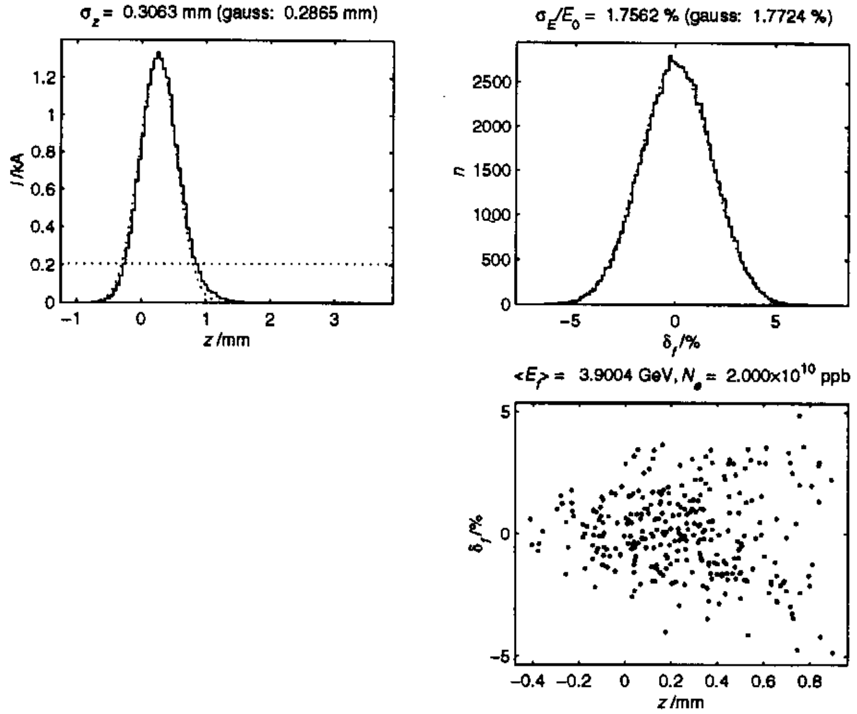

Figure 11. Tracking of non-T_{566}-compensated wiggler with DR bunch length reduced to 4.5 mm. Parameters are $L = 14$ m, $G = 40$ MeV/m, $\varphi_0 = -90°$, $E = 3.9$ GeV, $R_{56} = -258$ mm.

Another solution, which does not require a large reduction of the DR bunch length, is to use the quadratic compensated single-stage wiggler compressor of Table 4 and also reduce the DR bunch length as much as reasonably possible. For example, a DR bunch length of 7 mm, for 400-μm compression, will hold the post-compression energy spread to less than 2% rms.

6 Conclusions

Several bunch compressor options have been described which keep open the possibility of generating an rms bunch length as short as 300 μm. For the long DR bunch length (9 mm), an RF phasing compensation of the T_{566} non-linearity is required in order for a single stage compressor (arc or wiggler based) to achieve the 300 μm requirement. The single-stage arc-based compressor is probably too problematic due to the large energy spread over the long arc. Chromaticity and alignment tolerances will be tight and good spin transport adds geometry constraints. The modified wiggler-based single-stage compressor, including quadratic compensation, is probably the most robust (see Table 4), especially if accompanied by a reduction of the DR bunch length. The large energy spread at the beginning of the main linac generated by a single-stage compressor may, however, be a significant problem. A large reduction of the DR bunch length is another possibility, but it may not be a realistic one. The two-stage compressor is a reasonable option which reduces the linac energy spread, but requires a fairly long chicane and an extended length of linac (360 m) with still a fairly large (~1%) energy spread. These trade-offs will eventually need to be weighed against the evolving design and future requirements of the collider.

7 References

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