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BUNCH COMPRESSION FOR THE TLC*

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Abstract The length of the bunch for the TeV Linear Collider (TLC) must be decreased, while simultaneously preserving its small transverse emittance. To achieve a short bunch length ($\sim 70\ \mu$m) needed for the TLC, it is necessary to use two-step compression of a 5 mm bunch which is extracted from the damping ring. The corresponding increase of momentum spread requires that chromatic aberrations of the transport line must be corrected at least up to second order. This goal is achieved by building the compressor out of second-order achromats, which also eliminates geometric aberrations. The utilization of flat beams restricts the design to an uncoupled, mid-plane symmetric transport line. The first compression is performed by a conventional compressor. For the second, it is possible to use a 180° bend. The emittance growth due to the synchrotron radiation is kept to several percent.

INTRODUCTION

Research program at SLAC includes developing of a linear collider in the TeV energy range (TLC).[1] Here, we describe the design of a bunch *compressor* for the TLC which will transform a *long* bunch with small momentum spread Ap extracted from a damping ring into a *short* bunch with a larger momentum spread for injection into the main linear accelerator. The compressor is needed for two reasons:

1. Short bunch length is required for controlling the adverse effects caused by the transverse wakefield; and
2. The high luminosity of the linear collider is achieved by decreasing the value of the beta-function at the interaction point. Such a decrease is effective only when the value of the beta-function is greater than the effective bunch length.

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On the other hand, the adverse effects of the longitudinal wakefields, which become more pronounced when the bunch length decreases, limits the shortness of the bunch. As a compromise, a bunch length of the order of 70 μm has been chosen for the present design of the TLC.[2] A bunch of this length is not readily obtainable from a damping ring[1] and, hence, a compressor is needed.

During compression, the magnitude of the momentum spread (the result of the bunch compression) must be limited to avoid increasing the transverse emittance due to chromatic aberrations. The consequence, in our case, is that two stages of compression are needed. For example, the bunch extracted from the TLC damping ring has the momentum spread typically $\Delta p/p \approx 10^{-3}$ with a length of $l \approx 5$ mm. Decreasing this bunch length to 50 μm would then require increasing the momentum spread to 10%; this is clearly unacceptable when chromatic aberrations and practical aperture limitations are considered. Therefore, a two-stage compressor with an intermediate acceleration is assumed in the present design.

TABLE I Compressor input and output parameters.

			2nd Stage			
N	Parameter	1st Stage	Version 1	Version 2	Version 3	Version 4
1	Energy (GeV)	1.8	16.2	16.2	16.2	16.2
2	Δl_{in} (mm)	5.0	0.46	0.46	0.46	0.46
3	$(\Delta p/p)_{in}$ (%)	0.1	0.12	0.12	0.12	0.12
4	Δl_{out} (mm)	0.46	0.037	0.086	0.061	0.044
5	$(\Delta p/p)_{out}$ (%)	1.1	1.6	0.648	0.915	1.254
6	$\gamma\epsilon_x$ (mrad)	2.10^{-6}	2.10^{-6}	2.10^{-6}	2.10^{-6}	2.10^{-6}
7	$\gamma\epsilon_y$ (mrad)	2.10^{-8}	2.10^{-8}	2.10^{-8}	2.10^{-8}	2.10^{-8}

Electrons or positrons are initially accelerated to 1.8 GeV in a linac and then cooled in a damping ring. Bunches extracted from the damping ring first pass through a matching section, where the beta- and eta-functions of the ring are matched to the corresponding periodic functions of the first-stage compressor. The bunch travels through the first 0° phase accelerating section which increases the momentum spread from a small value in the damping ring up to approximately 1%. After compression in the first transport line, the beam is accelerated from 1.8 GeV to 16.2 GeV, which reduces the momentum spread $\Delta p/p$ back to a value $\approx$ 0.1%. A second 0° phase accelerator section, again, introduces the desired correlation with a resulting momentum spread of 1%. The beam now compresses to its final length in the second transport line and enters the main linac.

Important parameters for each of the two compressor stagesare collected in Tables I, II and III. Four versions of the second stage of the compressor are represented here. Version 1 utilizes a small total bend angle of $\approx 11^\circ$. The three remaining are for a total bend of 180°, and differ in their respective minimal obtainable bunch length, which ranges from 44 μm to 86 μm.

TABLE II Focusing and dispersion functions.

			2nd Stage			
N	Parameter	1st Stage	Version 1	Version 2	Version 3	Version 4
1	$\beta_{x,max}$ (m)	5.30	10.50	9.83	7.02	5.15
2	$\beta_{x,min}$ (m)	1.40	2.40	0.50	0.36	0.26
3	$\beta_{y,max}$ (m)	1.70	13.85	9.83	7.02	5.15
4	$\beta_{y,min}$ (m)	8.30	2.52	0.50	0.36	0.26
5	$\eta_{x,max}$ (m)	1.25	0.47	0.032	0.023	0.017

THE OPTICAL PROPERTIES OF THE COMPRESSOR

The design of the first stage of the compressor is conceptually similar to that of the SLC compressor[3] and uses the concept of a second-order achromat[4] to prevent emittance growth due to second-order aberrations and chromatic effects. The transport line consists of four identical cells with 90° betatron phase advance in each plane. Two families of sextupole magnets compensate the natural first-order chromaticities and at the same time eliminate all second-order chromatic aberrations.[4,5] Cells are chosen to be symmetric about their center, making the phase ellipses on the entrance to the achromat upright and facilitating optical matching.

The main characteristics of the *optical junctions* for the achromat of the first stage (and those for different versions of the second stage) can be found in Table II.

The design of the second compressor stage depends substantially on the magnitude of the deflection angle of the reference trajectory. For a small bend of the order of several degrees, a solution similar to the first stage can be found. Optical functions for Version 1 of the second stage can also be found in Table II.

TABLE III Compressor main parameters.

N	Parameter	1st Stage	2nd Stage Version 1	Version 2	Version 3	Version 4
1	Total deflection angle (degrees)	57.64	10.89	180	180	180
2	Radius of curvature (m)	4.771	84.218	213.6	149.5	106.8
3	Total length (m)	18.67	31.04	703.32	501.72	367.32
4	Number of achromats	1	1	21	21	21
5	Number of cells per achromat	4	4	8	8	8
6	Number of half-magnets per cell	4	4	8	8	8
7	Betatron phase advance per cell (degrees)	90	90	135	135	135
8	Bend angle/ magnet (degrees)	7.205	1.361	0.268	0.268	0.268
9	Half-magnet length (m)	0.3	1.0	1.000	0.700	0.500
10	Correlation $(\delta p/p)/\delta l$ (%/mm)	0.21517	3.4012	1.37451	1.95971	2.69622
11	V_o (MV)	61.6	1540.0	640	900	1230
12	Compressor RF (GHz)	3.0	17.0	17.0	17.0	17.0
13	λ (cm)	10.0	1.76	1.76	1.76	1.76
14	$\theta = 2\pi l/\lambda$	0.314	0.164	0.164	0.164	0.164
15	$\Delta\epsilon$ (μm·μrad)	2.03	4.45	12.0	12.6	17.7
16	$\Delta\epsilon/\epsilon$ (%)	0.36	0.78	2.12	2.22	3.12
17	$\Delta(\Delta p/p) = \theta^{2/6}$	0.016	$4.48 \cdot 10^{-3}$	$4.48 \cdot 10^{-3}$	$4.48 \cdot 10^{-3}$	$4.48 \cdot 10^{-3}$

On the other hand, the second compressor stage may also be designed to accommodate a 180° bend. Such a design may have the advantage of allowing a somewhat shorter length of the collider site as well as providing for fast feedback systems. In this case, the second stage transport line consists of many achromats and resembles the SLC arcs.[6] A natural consequence of increasing the total bend is the need to decrease the dispersion function by an order of magnitude; versions 2, 3 and 4 in Table II are of this type. They differ from each other by the magnitude of the dispersion and, consequently, by the bunch compression rate.

EMITTANCE GROWTH DUE TO RADIATION AND NONLINEAR EFFECTS

Of special concern is the emittance increase due to the quantum character of the radiation in a magnetic field. The design should provide that such a growth is small compared to the transverse emittance of the bunch. Sands has evaluated this effect.[7] For a given magnetic field strength, the emittance increase is proportional to the fifth power of the particle energy or for a given radius of curvature to the fifth power of the total bend angle of the reference trajectory. Hence, special precautions must be taken in the design of the second stage with 180° of bend.

For a FODO lattice with a given cell length, the emittance increase as a function of the betatron phase advance per cell decreases as the phase advance increases, until it reaches a minimum near 135°; then rises steeply for greater values.[8] To minimize emittance growth, the second stage lattice for the 180° bend is built out of cells with 135° betatron phase advance in both planes. The absolute and relative values of the emittance increase due to radiation are to be found in Table III.

Another concern is the effect of longitudinal and transverse nonlinearities in the particle motion. Due to the sinusoidal time dependence of the accelerating field, its nonlinear terms produce a nonlinear momentum distribution which, in turn, increases the effective length of the bunch.[9] In the last row of Table III, the effect of the main such terms is evaluated and is seen not to produce any significant changes in the momentum spread for both compressor stages.

The same is true for the nonlinearity due to second-order terms in the transformation matrix (T_{566} terms in TRANSPORT notation). The effect of the transverse wakefields has to be evaluated later, when an accelerating structure is better known.

CHECKING RESULTS WITH SIMULATIONS

The compressor design was checked with the help of the program TURTLE.[10] The bunch compression and the particle distributions in the transverse phase space were calculated. The simulation results show that the ideal system (without imperfections) successfully transmits transverse emittances without distortions (at least up to the second-order terms) and, at the same time, produces the desired bunch length of the order of 70 μm.

Evaluation of tolerable alignment and production errors demands a separate investigation. Preliminary results show that the transverse emittance of the bunch is preserved if random transverse magnet displacements are smaller than several dozens of micrometers.

CONCLUSIONS AND ACKNOWLEDGEMENTS

In this paper, we describe the conceptual design of the TLC bunch compressor. The neccessary short bunch length is achieved by utilizing two-step compression with an intermediate acceleration. It is shown that the compression can be combined with a 180" bend if so desired. The emittance growth due to the synchrotron radiation is kept to several percent by using short strong-focusing magnets.

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