MULTI-BUNCH ENERGY COMPENSATION IN THE NLC BUNCH COMPRESSOR*

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Abstract

The task of the NLC bunch compressor is to reduce the length of each bunch in a train of 90 bunches from 4 mm, at extraction from the damping ring, to about 100 μm, suitable for injection into the X-band main linac. This task is complicated by longitudinal long-range wake fields and the multi-bunch beam loading in the various accelerating sections of the compressor. One possible approach to compensate the multi-bunch beam loading is to add two RF systems with slightly different frequencies ('Δf' scheme) to each accelerating section, as first proposed by Kikuchi [1]. This paper summarizes the choice of parameters for three such compensating sections, and presents simulation results of combined single- and multi-bunch dynamics for four different NLC versions. The multi-bunch energy compensation is shown to be straightforward and its performance to be satisfactory.

1 INTRODUCTION

The NLC bunch compressor consists of two stages, at 2 GeV and 10 GeV, which reduce the bunch length by a factor of about 10 and 5, respectively. The first stage follows the damping ring. It comprises an RF section and a wiggler, and performs a 90 degree rotation in longitudinal phase space. The second stage is formed by an arc, an RF section and a chicane. It rotates the bunch by 360 degrees prior to injection into the main X-band linac. The detailed layout is described in Refs. [2, 3, 4].

One goal of the compressor design is to minimize the sensitivity to beam loading in the damping rings and in the intermediate S-band pre-linac, which accelerates the beam from 2 GeV to 10 GeV. The effect of single-bunch beam loading and of the quadratic dependence of path length on energy (T_{566} in TRANSPORT notation) in wiggler and chicane can be corrected by additional decelerating RF sections (or, alternatively, by adjusting the phase of the compressor main RF systems). A detailed discussion of single-bunch longitudinal nonlinearities and their compensation is given in Refs. [3] and [4].

The real purpose of the bunch compressor is not to reduce the length of a single bunch, but the length of each in a train of 90 bunches. This task is complicated by the longitudinal long-range wake fields and the resulting multi-bunch beam loading in the various accelerator sections of the compressor. In this report, we discuss the multi-bunch longitudinal dynamics and a possible scheme for multi-bunch energy compensation.

One approach to compensate multi-bunch beam loading, called the Δf scheme and first proposed by Kikuchi [1], is to add two (or more) RF sections with slightly different frequencies to each acceleration section. The RF phases of these sections are chosen so as to yield an additional voltage which increases linearly along the bunch train and which can be adjusted to cancel the linear part of the multi-bunch beam loading. In the following, we will show that Δf compensation provides a satisfactory final inter-bunch energy variation. Nevertheless, a recent design modification [5] proposes the use of Δt compensation (early injection), instead of Δf, for the first compressor stage and the pre-linac, and a combination of Δf and Δt techniques for the second compressor stage. Power and length requirements for the two techniques are roughly the same. The Δf compensation is thought to be easier to tune, but it is a less local correction, which, for equal magnet alignment, will cause larger chromatic and dispersive transverse emittance growth.

2 SIMULATION STUDY

To test the Δf technique and the interplay of longitudinal single- and multi-bunch dynamics in the NLC bunch compressor a simulation study has been performed. For the purpose of this study, the long-range longitudinal wake fields were limited to the fundamental mode. Thus, the long-range wake field of a structure was characterized by only three numbers: the loss factor k, the mode frequency f and the quality factor Q. In terms of these quantities, the long-range wake field at a distance z is written as

$$W(z) = 2k \cos\left(\frac{2\pi f z}{c}\right) \exp(-\pi f z/Q) \qquad (1)$$

where c denotes the velocity of light. Also taken into account in the simulation is the group velocity of the fundamental mode, which introduces a small nonlinear component to the beam loading and makes perfect beam-loading compensation impossible—at least for the Δf technique. Wake-field parameters for the different structures were provided by Miller [6]. They are compiled in Table 1.

The short-range longitudinal wake fields assumed in the multi-bunch simulations are the same as those which were used in the single-bunch studies [3, 4]: the short-range

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Parameter	L-Band	S-Band	X-Band
frequency f [GHz]	1.428	2.856	11.424
loss factor k [V/C/m]	9×10^{12}	1.85×10^{13}	10^{14}
group velocity v_g/c	0.012	0.012	0.08
quality factor Q	18,000	13,000	7000
struct. length l [m]	6	3	1.8

Table 1: Wake-field and structure parameters for the different accelerating sections in the bunch compressor.

wake field for the X-Band structure was derived by Bane [7]; the wake fields for other frequencies were estimated from an approximative formula in Palmer's report [8].

The effect of the long-range longitudinal wake fields, *i.e.* the multi-bunch beam loading, can be compensated by the Δf technique. This technique is based on the following consideration: if two RF structures are driven at slightly different frequencies $f_0 \pm \Delta f$, and 180° out of phase, the effective total voltage for the nth bunch is

$$\Delta V_n = V_c \cos\left[\left(\frac{2\pi(f_0+\Delta f)z_n}{c} - \frac{\pi}{2}\right) - V_c \cos\left(\frac{2\pi(f_0-\Delta f)z_n}{c} - \frac{\pi}{2}\right)\right] \approx 4\pi V_c \frac{\Delta f}{c} z_n \tag{2}$$

where z_n denotes the longitudinal position of the nth bunch, f_0 is a multiple of the bunch frequency ($= c/b$; b being the bunch spacing) and it was assumed that the first bunch (for which z_1=0) arrives at the zero crossing of the RF and that $2\pi\ \Delta f z_n/c \ll 1$. The effective voltage (2) increases linearly along the bunch train. The multi-bunch beam loading is compensated when the compensating voltage V_c is approximately equal to [1]

$$V_c = qc\frac{k_m L_m + 2k_c L_c}{b\,2\pi\Delta f}, \tag{3}$$

where (q $k_m L_m$) and ($2qk_c L_c$) are the beam-loading voltages in main RF structures and compensating structures, respectively, q denotes the charge per bunch, and b is, again, the bunch spacing. For the subsystems of the NLC bunch compressor, a compensation frequency in the S-Band region was chosen, detuned from the main S-Band frequency (2.856 GHz) by $\Delta f \approx \pm 1$ MHz. Several aspects determine the optimum choice of Δf. In general, a larger Δf reduces the compensation voltage and the additional beam loading. The compensation, however, becomes less linear for larger beat frequency. It seems best to choose the frequency difference so as to partially cancel the nonlinear component of the beam loading. In the simulation this is done empirically by minimizing the rms energy variation (or phase variation) as a function of Δf.

Initial parameters for the compensating RF were found by considering only one macroparticle per bunch in order to increase the computational speed of the simulation. Subsequently, the main RF-voltages and phases were re-optimized for single-bunch dynamics. This is necessary because of the additional short-range wake fields in the compensating RF structures. Finally, a train of 90 bunches, of 50 macroparticles each, was tracked through the entire compressor system, and also through the X-Band main linac. We have assumed that the long-range wake fields in the main linac will be perfectly compensated by RF-pulse shaping; so they are not included in the simulation.

The simulation does include, however, an initial linear phase variation of ±3 mm along the bunch train, as caused by beam loading in the damping ring. This initial phase variation does not need to be compensated by a dedicated multi-bunch RF system, since the compressor was designed to handle single-bunch phase errors up to ±6 mm or larger [3, 4].

Table 2 illustrates four different NLC versions considered in the multi-bunch simulations. Optimized compressor parameters for two of these versions are summarized in Table 3. Assuming about 10% overhead, e.g., for off-line klystrons, the length of the pre-linac corresponds to an average accelerating gradient of 33 MV/m, which may be unrealistically high. Regardless, the compressor performance is not expected to be much different for a greater pre-linac length and an accordingly lower gradient.

Version	NLC-Ia	NLC-Ic	NLC-IIa	NLC-IIc
bunch length	100 μm	150 μm	125 μm	150 μm
N/bunch $[10^{10}]$	0.65	0.85	0.95	1.25
$E_{\max}$ [GeV]	267	233	534	473

Table 2: Four different NLC scenarios considered in the bunch-compressor simulations.

3 RESULTS

A typical simulation result is depicted in Fig. 1, which shows the final energy variation, bunch length and longitudinal positions along the bunch train for collider version NLC-Ia. The bunch-to-bunch fluctuation visible in the figure arises from the finite number of macroparticles per bunch (50), and is an artifact of the simulation. By contrast, the slow change of energy, position or bunch length over many bunches represents the effect of the long-range wake fields that we are interested in.

Table 4 summarizes the results of the simulation study. It lists longitudinal bunch-to-bunch phase variation, bunch-to-bunch energy spread, intra-bunch energy spread, and rms bunch length at the end of the main linac, for the four different NLC versions investigated. The longitudinal bunch position varies by 30–35μm about the average value, while the bunch length fluctuates by ±10μm. The resulting rms bunch-to-bunch energy variation is roughly 0.1–0.2%, corresponding to a peak-to-peak energy variation along the bunch train (not listed) of 0.8% for NLC-I, and 0.6% for NLC-II. In all cases, the average rms intra-bunch energy spread is 0.3–0.4%. We conclude that inter- and intra-bunch energy spreads are sufficiently small to be

Parameter	Collider Version		Comment
	NLC-Ia	NLC-IIa	
V_{LB} [MV]	136.0	136.0	1^{st} Stage
ϕ_{LB} [deg.]	-89.88	-89.92	Main L-Band RF
L [m]	8.5		$f = 1.428$ GHz
V_{SB} [MV]	± 26.7	± 38.4	Multi-Bunch Comp.
Δf [kHz]	$\pm$ 856.8		S-Band RF
ϕ_{SB} [deg.]	$-90.$		$f_0 = 2.856$ GHz
L [m]	2×3.0		$f_c = f_0 \pm \Delta f$
V_{SB} [MV]	8050	8054	Pre-Linac
ϕ_{SB} [deg.]	-4.0	-3.0	S-Band RF
L [m]	270		$f = 2.856$ GHz
V_{SB} [MV]	± 805	± 1159	Multi-Bunch Comp.
Δf [kHz]	$\pm$ 856.8		S-Band RF
ϕ_{SB} [deg.]	$-90.$		$f_0 = 2.856$ GHz
L [m]	2×27 / 2×39		$f_c = f_0 \pm \Delta f$
V_{SB} [MV]	3850	3730	2^{nd} Stage
ϕ_{SB} [deg.]	-89.6	-89.7	Main S-Band RF
L [m]	130		$f = 2.856$ GHz
V_{SB} [MV]	± 338	± 492	Multi-Bunch Comp.
Δf [kHz]	$\pm$ 1142.4		S-Band RF
ϕ_{SB} [deg.]	$-90.$		$f_0 = 2.856$ GHz
L [m]	2×15.0		$f_c = f_0 \pm \Delta f$
V_{XB} [GV]	270.32	535.69	Main Linac
ϕ_{XB} [deg.]	-15.7	-8.3	X-Band RF
L [m]	8130	8900	$f = 11.424$ GHz

Table 3: Some RF parameters of compressor subsystems, as used in the multi-bunch simulation study.

accommodated by the NLC final-focus system, whose energy bandwidth is about 1.2% [9].

Parameter	Collider Version			
	Ia	Ic	IIa	IIc
$\delta_{b,rms}$ [%]	0.18	0.20	0.09	0.14
$\sigma_{\delta,ave}$ [%]	0.31	0.38	0.31	0.36
$\sigma_{z,ave}$ [μm]	100	153	125	156
$\sigma_{z,rms}$ [μm]	9	13	10	15
$z_{b,rms}$ [μm]	28	33	31	36

Table 4: Inter-bunch energy variation $\delta_{b,rms}$, average intra-bunch energy spread $\sigma_{\delta,ave}$, average bunch length $\sigma_{z,ave}$, bunch-length variation $\sigma_{z,rms}$, and rms longitudinal phase variation $z_{b,rms}$ at the end of the X-Band main linac, for a train of 90 bunches in two different versions of NLC-I and NLC-II. Numbers were obtained by a macroparticle simulation, and include the effect of short- and long-range wake fields, multi-bunch energy compensation, and an initial linear phase variation of 6 mm along the train.

4 CONCLUSION AND OUTLOOK

For the NLC bunch compressor, multi-bunch energy compensation based on the Δf technique is straightforward, and in the simulation its performance is satisfactory. The primary disadvantage of the Δf method is that it is a non-local correction, for which dispersive and chromatic emit-

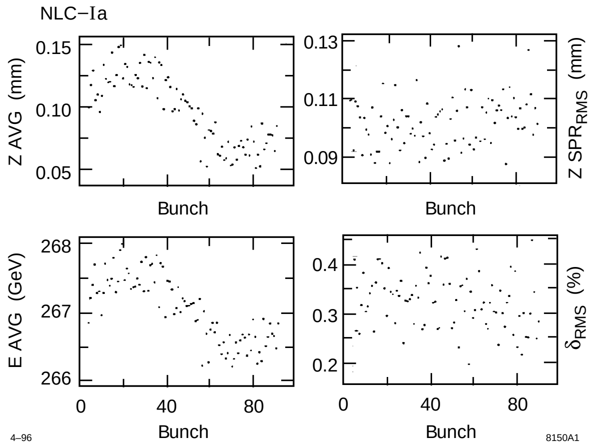

Figure 1: Bunch centroid position, rms bunch length, average bunch energy, and rms energy spread, as a function of bunch number in a train of 90 bunches, for NLC-Ia.

tance dilutions will be larger than for the alternative Δt technique. The Δf technique also requires the fabrication of different types of detuned RF structures, which is a second disadvantage. Thus, to contain the dilutions, to ease alignment tolerances, and to save cost, a recent design modification [5] advocates a combination of Δf and Δt techniques that is expected to outperform the pure Δf scheme reported here.

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