SLAC-PUB-7429
March 1997

BEAM LOADING COMPENSATION FOR THE NLC LOW FREQUENCY LINACS

Zenghai Li, Roger Miller, David Farkas, Tor Raubenheimer, Huan Tang and Dian Yeremian
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Abstract

The NLC low rf linacs are heavily loaded by a beam of about 130 ns in macropulse length (90 bunches) and a current up to 2.75 Amps. Beam loading voltage generates a large energy spread along the bunch train. This energy spread is critical for lattice design and, if not properly compensated, induces emittance growth and in turn lowers the luminosity of the machine. In this paper, we study the ΔF and ΔT beam loading compensation techniques for the NLC low rf linacs. We will apply these methods to the NLC low rf linacs to demonstrate the efficacy of these methods. Finally, we discuss a hybrid $\Delta T + \Delta F$ method to improve the efficiency of beam loading compensation.

I. Introduction

The NLC complex has 7 S-band linacs and 4 L-band linacs [1]. The main L-band linac accelerates the positron beam from the positron target to 2 GeV where it enters the damping ring. In addition there are one 80 MeV L-band linac associated with the positron energy compressor at the output of the positron booster linac and two 134 MeV L-band linacs associated with the electron and positron first stage compressors at the output of the two damping rings. The seven S-band linacs are: the Positron Drive Linac which accelerates the electrons which strike the positron target; the Electron Booster Linac which accelerates the electron beam to 2 GeV where it enters the Electron Damping Ring; 42 MeV electron energy compressor at the output of the electron booster linac; the Electron and Positron Preaccelerators which accelerate the beams from the damping rings to 10 GeV where the second bunch compression occurs; 3.85 GeV S-band linacs to produce the linear energy correlation required for each of the second stage compressors.

All of these linacs are heavily loaded by a beam of about 130 ns in macropulse length (90 bunches) and a current up to 2.75 Amps, except for the first 250 MeV portion of the Positron L-band linac which is inside a 0.5 T solenoid and needs to accelerate a total effective current of about 14 amperes since both electrons and positrons get captured onto their respective accelerating crests, $\lambda/2$ apart. Under nominal operating conditions, the currents in these linacs are different, which produces different beam loading for each linac. In addition, the beam loading is different in the acceleration and compressor linacs in terms of its phase relation relative to the rf voltage. In the acceleration linacs, the beam loading voltage is 180^0 off while in the compressor linacs the beam loading voltage is 90^0 off since in such linacs the rf runs in phase quadrature with the beam to introduce a linear correlation between time and energy within each bunch. Beam loading voltage in all these linacs generates a large energy spread along the bunch train. A rough estimation of the beam loading for a 2-A current in a typical S-band structure is about 25% of the acceleration. This energy spread is critical for lattice design and, if not properly compensated, induces emittance growth and in turn lowers the luminosity of the machine. The NLC design can tolerate a energy spread of less than 0.2% before the beams enter the damping rings. It is necessary to compensate the beam loading effect in order to operate the machine in a multi-bunch mode.

The pulse length of the bunch train in these accelerators is much shorter than the reasonable filling times of the structures which are in turn shorter than the ringing time, $2Q/\omega$, for

*This work was supported by the U.S. Department of Energy, under contract No. DE-AC03-76SF00515.

(Submitted for Publication)

the structure. In this situation, the energy of the beam will drop approximately linearly with time during the pulse as a result of beam loading. For this case there are two natural choices for beam loading compensation: 1) ΔT (early injection and amplitude modulation), i.e., inject the beam before the structure is full and modulate the amplitude of the input power to change the slope of the acceleration; 2) ΔF, i.e., having one or more accelerator structures running at a frequency 1 to 2 MHz above or below the nominal frequency and roughly in phase quadrature from the accelerating phase. Thus the beginning of the pulse can be decelerated by the off frequency section(s), while the end of the pulse is accelerated.

In this paper, we will study the ΔF and ΔT compensation techniques for SLED-I driven accelerator structures. We will discuss the advantages and disadvantages of these methods, and apply them to the NLC low rf linacs. To reduce the length of this paper, we will not cover the details of beam loading compensations for each of the low rf linacs. Instead, we will present some typical examples to demonstrate the efficacy of these methods. Finally, we present a hybrid approach using $\Delta T + \Delta F$ for power saving.

II. SLED-I pulse compression and beam loading

The low frequency linacs of the NLC will be powered with SLED-I pulse compression [2] systems, Fig. 2.1. The SLED-I contains a low power supply, a modulator, a klystron, and two resonant cavities. A part of the klystron power is used to build up rf fields inside the cavities. The rest of the klystron power is reflected from the waveguide/cavity interface. As a consequence of the $\pi/2$ phase-shift imparted to waves crossing the coupler slot, all of this power is transmitted to the accelerator. Energy stored in the cavities re-radiates an rf wave which travels to the accelerator exactly out of phase with the transmitted klystron wave. At time t when the phase of the klystron is reversed, the emitted and transmitted waves add, producing a surge of high power into the accelerator. These process can be described by the following equations

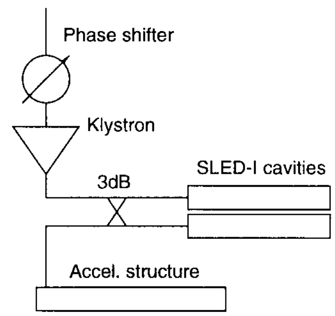

Figure. 2.1. SLED-I pulse compression.

$$\frac{d\vec{E}_e}{dt} + q\vec{E}_e = \frac{\alpha \vec{E}_i}{T_L} \quad (2.1)$$

$$\vec{E}_r = \vec{E}_e + \vec{E}_i \quad (2.2)$$

$$q = \frac{1 - j\tan\psi}{T_L} \quad (2.3)$$

$$\tan\psi = 2Q_L\frac{\Delta f}{f} \quad (2.4)$$

$$\alpha = \frac{2\beta}{1+\beta} \quad (2.5)$$

where β is the cavity coupling coefficient, T_L is the loaded time constant of the SLED cavities and Δf is the frequency offset. In Fig. 2.2 is shown a result of SLED-I pulse compression for a S-band structure. The acceleration voltage (Fig.2.2(c)) is dominantly contributed by the compressed pulse within 0-840 ns.

Charged bunches, when passing through the structure, generate wakefields that decelerates the subsequent bunches. For a constant gradient structure, the beam loading voltage can be obtained analytically [3]

$$V(t) = \frac{ri_0}{2}\left(\frac{\omega l e^{-2\tau}}{Q(1-e^{-2\tau})}t - \frac{l}{1-e^{-2\tau}}(1-e^{-\frac{\omega}{Q}t})\right) \quad 0 \le t \le t_f \quad (2.6)$$

$$V(t) = -\frac{ri_0 l}{2}\left(1 - \frac{2\tau e^{-2\tau}}{1-e^{-2\tau}}\right) \quad t \ge t_f \quad (2.7)$$

Fig.2.2(d) shows the time dependence of the loading voltage. For a bunch train much shorter than the filling time of the structure, the beam

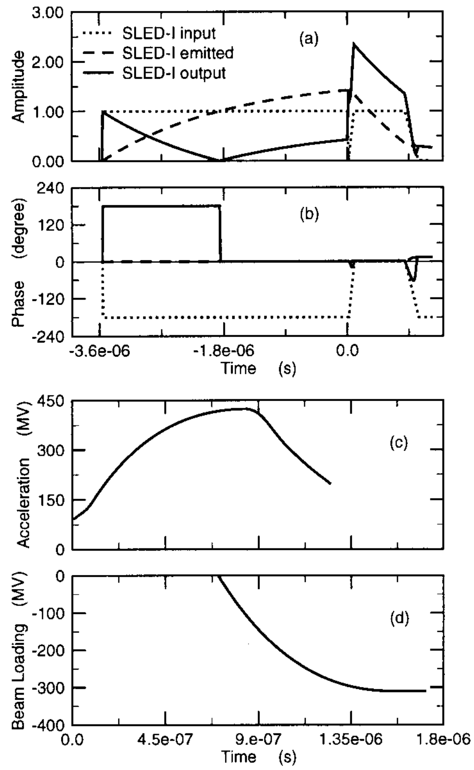

Figure. 2.2. SLED-I wave form and beam loading voltage

loading is quite linear with time. The proposed Gaussian detuned accelerating structure for the NLC is very close to a constant gradient structure. In this paper, we use Eqs. 2.6 and 2.7 to estimate the beam loading of the NLC structures.

III. ΔF compensation

To illustrate the principle of ΔF compensation, the voltage gain $V_{comp}(t)$ of a beam with an F_0 bunch structure in a ΔF compensation section operating at a frequency $F_0 \pm \Delta$F is plotted in Fig. 3.3. The beam is bunched with a bunch repetition frequency of 714 MHz, a subharmonic of the accelerator frequency F_0. In an accelerator section powered by rf at a frequency $F_0 \pm \Delta F$, the bunches see a field which appears to vary with the difference frequency ΔF as shown in Fig.3.3. If the beam pulse length satisfies the relation $t_b \leq \frac{1}{6\Delta F}$ and is phased as shown, the energy gain will vary quite linearly with time.

To the first order, the amplitude of the compensation voltage needed to compensate a

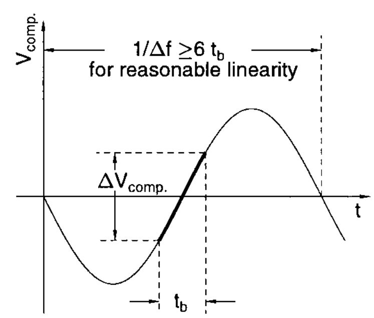

Figure. 3.3. Compensation voltage $V_k(t)$ of a ΔF section.

given beam loading voltage is proportional to $1/\Delta F$, and the power for the compensation section is proportional to $1/\Delta F^2$. In order to save power, it is preferable to use a large ΔF. However, the residual energy spread after ΔF compensation is proportional to ΔF^2, assuming linear beam loading voltage within the beam time, which prefers a small ΔF. The ΔF should also be a subharmonic of the nominal operating frequency (11.424 GHz) as this simplifies the trigger system. For the S-band linacs, we have chosen a ΔF to be around 1.4 MHz. With this ΔF, the phase spread of the bunch train in the ΔF section is about 60^o. The maximum compensable beam loading voltage in this case is equal to the maximum acceleration of the ΔF section.

The elastance of the structure, defined as

$$s = \frac{E_a^2}{W} = \frac{r\omega}{Q} \tag{3.8}$$

with E_a the maximum energy gain, W the stored energy in the structure, r the shunt impedance, also plays an important role in the power requirement for the compensation sections. The acceleration voltage is proportional to the square root of the elastance ($V_k \propto \sqrt{sPL}$) while the loading voltage is proportional to the elastance ($V_b \propto IsL$). The ratio V_b/V_k is proportional to the square root of elastance. With large s, one gets a large V_b/V_k, which means more power for the compensation sections in order to obtain the same loaded energy gain.

With ΔF compensation, one is free to chose the filling time of the structure. For the NLC design, the S-band linac structure is chosen to be like the SLC 3-m structure with a filling time

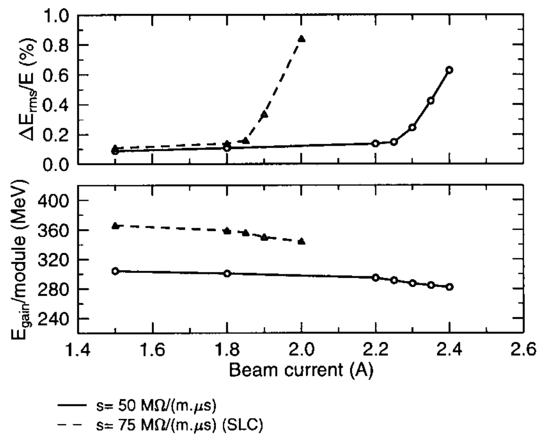

Figure. 3.4. ΔF compensation results for S-band modules with average elastances of 50 and 75 $MOmega/m \cdot \mu s$.

of about 840 ns. With such a filling time, typical elastance is in the range of 50 $\mathrm{M}\Omega/m \cdot \mu s$ to 75 $\mathrm{M}\Omega/m \cdot \mu s$. The beam loading voltage for a 2-A current in such a structure is about 25% of acceleration. One ΔF section running at 1.4 MHz off frequency can compensate for four regular sections - which we call a module. An accelerator contains many modules to make up the total energy gain. The four regular sections in a module will be powered by one SLED-I station. The compensation section will share a power system with other three sections in different modules.

Fig. 3.4 shows the simulation result of residual energy spread $\Delta E/E$ and energy gain E_{gain} for one accelerator module with $s = 75$ and 50 $\Omega/m \cdot \mu s$ respectively. For an accelerator composed of many modules, the residual energy spreads of these modules are correlated. The relative energy spread at the end of the linac will just be the same as obtained for a single module except when the initial energy E_0 of the beam is non-zero. In which case, the relative energy spread becomes $\Delta E/(E_{gain}+E_0/N)$, with N the number of modules in a linac. Taking 0.2% as the upper limit for the energy spread, the maximum compensable beam current for $s = 75$ $\mathrm{M}\Omega/m \cdot \mu s$ is 1.9-A, below the required maximum current of 2.2-A. By lowering the elastance to 50 $\mathrm{M}\Omega/m \cdot \mu s$ and keeping the filling time the same (by changing the disk thickness), the beam loading ratio is reduced and the maximum compensable beam current is up to 2.3-A, shown in solid line in Fig 3.4. The loaded energy gain for the latter case is also lower as expected.

It is worthwhile to mention that in the ΔF sections, the bunches are on the slope of the acceleration voltage, which generates a single bunch energy spread. To compensate this effect, we arrange the ΔF sections to run at $\pm\Delta F$ frequencies alternatively along the accelerator. The single bunch effects of the $\pm\Delta F$ sections cancel.

The results shown in Fig. 3.4 is the energy spread at the end of the module. Within each module, with the ΔF section in the middle, the beam energy spread reaches half of the compensation voltage of a single off-frequency section. The compensation section then over corrects by a factor of two which reverses correlation of energy with time during the pulse. The energy spread at some locations along the linac can be very large, and are important at the low energy end of the linac. In order to maintain a small enough energy spread to achieve an acceptable emittance growth it appears necessary to distribute the power from one klystron running off frequency to a number of short accelerator sections, so that each correction is acceptably small. It appears to us that the high power microwave distribution system to many short ΔF compensation sections becomes unreasonably complicated and expensive. The non-localness of the compensation is a principal disadvantage of the ΔF scheme.

IV. ΔT compensation

The way ΔT compensation works is shown in Fig. 4.5 in which the voltage $V_k(t)$ produced by a step function rf pulse is plotted as a function of time for a traveling wave linac section. Also plotted is the beam induced voltage $V_b(t)$. The resultant sum of $V_k(t)$ and $V_b(t)$ is plotted for the case where the beam is turned on before the linac structure is full.

With ΔT compensation, the acceleration voltage must satisfy

$$\frac{dV_k}{dt} = -\frac{dV_b}{dt} \tag{4.9}$$

during the beam time. For a SLED-I driven structure, the slope of the acceleration voltage decreases with time as shown in Fig. 2.2. For

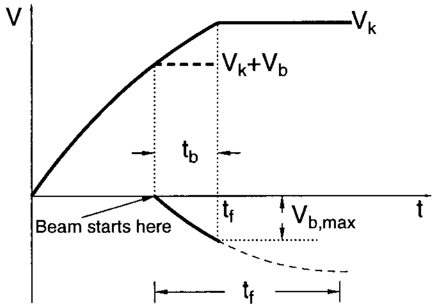

Figure. 4.5. ΔT beam loading compensation using early injection.

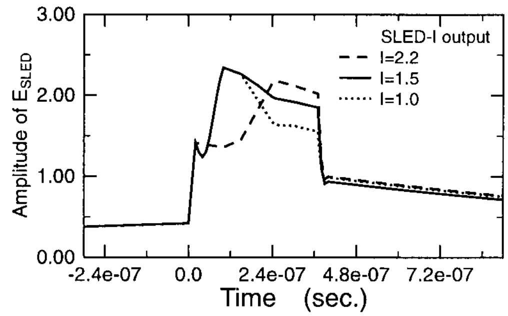

Figure. 4.6. SLED-I wave forms for compensating 1, 1.5, and 2.2-A beam currents using ΔT compensation scheme.

compensating beam loading of high beam currents in the NLC, it is preferable to used a reasonably short filling time. In addition to the filling time, one can also modulate the power profile to change the slope of the acceleration voltage. This enables to compensate beam loadings of different currents, which is advantageous for the NLC low rf linacs where the beam currents can very from 1-A to 2.2-A depends on the individual linac and operating mode of the machine. The modulation of the SLED amplitude can be realized by modulating the amplitude of its input. Since phase modulation of the klystron is easier and faster than amplitude modulation, two klystrons phase-modulating at opposite directions will be used to obtain a amplitude modulated input for the SLED. The klystrons will run at saturation all the time which is more stable than operating at low power. The advantage of ΔT compensation is that the compensation occurs in every accelerator section, so that the energy spectrum can be good through out the linac, thus minimizing emittance growth from dispersion and chromatic effects. In addition, the amplitude modulations in different modules of an accelerator is independent and the residual energy spread can be made random among these modules. At the end of the accelerator, the relative energy spread will be $1/\sqrt{N}$ times of the single module energy spread.

Among the S-band linacs for the NLC, the prelinacs account for more than 50% of the total length. In order to save power, we have chosen a filling time of 371 ns for the S-band structure, which is close to a optimal for the prelinacs operating in phase-II (I=1.5-A). To compensate beam currents at 1.0 and 2.2-A, the amplitude of the SLED-I output need to be modulated to obtain the desired acceleration slopes.

Table 4.1
Power Comparison Between ΔT and ΔF

Current (A)	1.0	1.5	2.2
$P_{\Delta F}/P_{\Delta T}$	0.73	0.93	0.71
Power saved in ΔF	0.27	0.07	0.29

Fig.4.6 shows the SLED-I wave forms for compensating beam currents of 1.0, 1.5, and 2.2-A. Except for the 1.5-A beam current, strong amplitude modulations are needed for compensating 1- and 2.2-A beam currents because they generate different beam loadings.

Amplitude modulations for 1- and 2-A currents reduce the total energy of the SLED pulse, which in turn results in lower efficiency for these currents. It is instructive to compare the efficiency of ΔT and ΔF compensation schemes. Table 4.1 shows the ratio of the power needed in ΔT and ΔF sections for the same energy gain. For 1 and 2.2-A beam currents, using ΔF scheme can save up to 30% of power. For 1.5-A beam current, ΔT and ΔF compensation requires almost the same amount of power.

V. ΔT compensation for compressors

In the compressors (bunch length and energy), the bunches are 90^o off the acceleration crest. The slope of the acceleration voltage generates a linear energy correlation along the bunch needed for bunch length or energy compression.

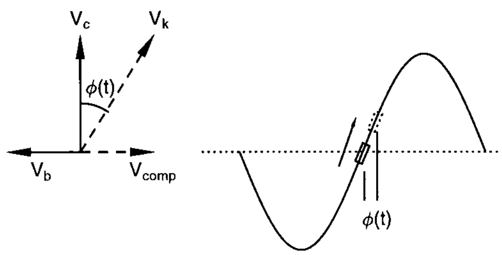

Figure. 5.7. Beam loading compensation for the compressors using ΔT and phase modulation.

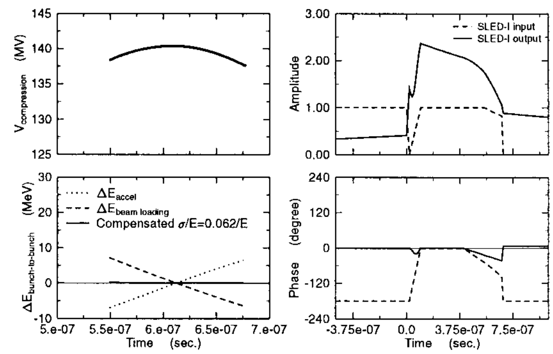

Figure. 5.8. Beam loading compensation for the L-band compressor linacs.

The compression voltage, defined as the amplitude of the acceleration voltage, is unloaded by the beam and is in general non-uniform along the bunch train for SLED-I driven structures. In addition to the beam loading compensation, one also need to produce a uniform compression voltage (V_c) along the bunch. A $\Delta V_c < 5\%$ is considered acceptable. The uniform compression will be obtained by ΔT amplitude modulation.

The beam loading in the compressors is 90^0 off the rf voltage. Simple ΔT compensation method does not provide any beam loading compensation. To obtain an in-phase component voltage to the beam loading voltage, a phase offset $\Delta\phi(t)$ is introduced during the beam time. This phase offset projects a portion of the acceleration voltage onto the axis of the beam loading voltage as shown in Fig. 5.7. The effect of this phase offset is to shift the rf phase of the bunches toward the acceleration crest so that the later bunches will be accelerated by the klystron power. Phase offset $\Delta\phi(t)$ can be obtained by phase modulating the two klystrons in the same direction.

Fig.5.8 shows the energy spectrum of the compressor linac and the SLED-I input and output wave forms. A residule energy spread of $6\times10^{-2}/E_0$ and a 3% variation in compression voltage can be obtained for the L-band compressor linac by using this method.

The phase modulation of the SLED output in the compressors introduces a frequency offset $\Delta F = d\phi(t)/dt$. The actual compensation process is a combination of ΔT (amplitude) and ΔF (phase). The ΔF due to phase modulation shown in Fig. 5.8 is about 3 MHz. Since the structure is designed to operate at the nominal frequency, the frequency offset causes a phase slippage between the particle and the fields. Consider that the phase modulation is turned on only during the last one third of the filling time and the power is in the high group velocity end of the structure, the effect of phase slippage due to ΔF is small. Our numerical simulation assumes no slippage in the structure, which we believe is a reasonable approximation.

VI. Power saving by using a $\Delta T + \Delta F$ approach

As discussed in the previous sections, the ΔT compensation is less efficient as compared with the ΔF compensation. The reason here is mainly due to the amplitude modulation of the SLED-I output. For the 1-A current case, for example, one has to reduce the power at the end of the SLED-I pulse in order to reduce the slope of the acceleration voltage. One can gain some efficiency by increasing the filling time of the structure for the low current case. At higher current, e.g. the 2.2-A current case, the natural slope of the acceleration voltage is not enough to compensate the beam loading even with very short filling time. Further more, shortening the filling time would also reduce the loaded energy gain thus reduces the efficiency. For such cases, we can optimize the structure to compensate beam loading at a lower current, and use a ΔF section to compensate the extra beam loading for high currents. With this in mind, we want to optimize the beam loading compensation using a combined $\Delta T + \Delta F$ method.

The main S-band linacs for the NLC can be grouped into two groups based on the beam

Table 6.2
Comparison Between ΔT and hybrid $\Delta T + \Delta F$ compensation schemes

	Phase-I	Phase-II
Current (A)	1.0	1.5
E_{accel}/module	310 (244)	305 (254)
$\Delta E/E_{accel}$	1.1×10^{-3} (3.2×10^{-4})	9×10^{-4} (1.1×10^{-5})
$P_{\Delta F}$/module	0.0	5
P saved	38%	30%

current in the linacs. The current distribution in the major S-band linacs is the following: the e^- booster linac operates at 1.5 and 2.2-A in phase-I and phase-II respectively; the prelinacs operate at 1.0 and 1.5-A in phase-I and II respectively, the e^+ drive linac operate at 1.5-A for both phase-I and II. To optimize the power requirement, we will use two different S-band structures with filling time optimized for phase-I operation for the booster linac and the prelinacs respectively. In phase-II operation, the extra beam loading due to the increment of beam current will be compensated by using ΔF sections. The e^+ drive linac will have the same design as the prelinacs and will operate with phase-II mode. With the hybrid beam loading compensation scheme for phase-II operation, the ΔF sections only need to compensate one third of the total beam loading. Non-localness due to the ΔF method will be less a problem. To avoid extra beam loading, the space for the ΔF sections will be left as drift spaces in phase-I.

Table 6.2 shows a comparison between ΔT and hybrid $\Delta T + \Delta F$ compensation schemes for the prelinacs operating in phase-I and phase-II. The numbers in parentheses are for pure ΔT compensation. By using the hybrid approach, more than 30% of power can be saved in both phase-I and phase-II operations for the prelinacs.

VII. Summary

In this paper, we have studied both ΔT and ΔF beam loading compensations for SLED-I driven disk-loaded waveguide structures. A detailed beam loading study has be done for each low frequency linacs of the NLC. It has been shown that with ΔT compensation method can provide very good energy spectrum through out the whole accelerator linacs. A hybrid approach using $\Delta T + \Delta F$ method has been demonstrated effective for saving klystron power.

References

[1] Zeroth-order design report for the Next Linear Collider, LBNL-PUB-5424, SLAC Report 474, UCRL-ID-124161, 1996.

[2] Z. D. Farkas and *et al*, "SLED: A Method of Doubling SLAC's Energy," SLAC-PUB-1453, March 1974.

[3] J. Wang, RF Properties of Periodic Accelerating Structures for Linear Colliders, SLAC-Report-339, July 1989.