A COMBINED $\Delta T + \Delta F$ BEAM LOADING COMPENSATION SCHEME FOR POWER SAVING *

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Abstract

The NLC low frequency (S and L band) 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 generates a large energy spread along the bunch train. For these linacs, the bunch train is much shorter than the filling time of these linac structures, and the energy of the beam drops approximately linearly with time during the pulse as a result of beam loading. For such a case, there are two natural choices for beam loading compensation, ΔT (which achieves compensation by injecting the beam before the accelerator structure is full) and ΔF (which compensates by having some accelerator sections at $f_0 \pm \Delta F$). There are, however, disadvantages with these methods: non-local compensation in the ΔF method (except using many short ΔF sections) and low efficiency in the ΔT method due to short filling time and amplitude modulation required for compensation. In this paper, we will discuss a combined $\Delta T + \Delta F$ method. In this scheme, the filling time of the structure is optimized for ΔT compensation for phase-I operation. In phase-II operation, ΔF sections are used to compensate the extra 50% beam loading due to higher current. Simulations have shown that up to 30% of power can be saved by using this method.

1 INTRODUCTION

The NLC [1] S-band L-band linacs are heavily loaded by a beam of about 130 ns in macropulse length (90 bunches) and a current up to 2.75 Amps. Energy compensation is required in order to obtain a small energy spread along the bunch train. 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 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 produce a slope in the acceleration voltage that cancels the beam loading; 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.

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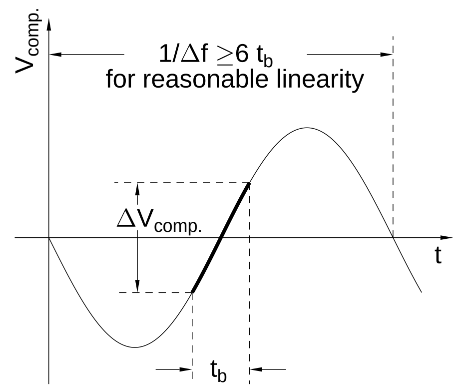

Figure 2.1: Compensation voltage $V_k(t)$ of a ΔF section.

The seven S-band and four L-band low rf frequency linacs in the NLC complex each accelerates a different beam current. For example, in phase-I operation, current in the S-band e^+-drive linac is 1.5-A while in the e^--prelinac is 1.0-A. Further more, the currents will be 50% more in phase-II operation. This requires the compensation schemes to be capable of compensating beam loading of wide range of beam currents. Both ΔF and ΔT schemes have been proven to be effective with NLC operation parameters [2]. However, there are advantages and disadvantages with the ΔF and ΔT methods. While the ΔF scheme has high efficiency (for high currents), it yields a poor energy spectrum along the accelerator. The ΔT scheme, on the other hand, gives a good energy spectrum, but is low in efficiency for high beam currents. To solve the problem, we present, in this paper, a hybrid approach using $\Delta T + \Delta F$. Under high beam loading conditions, compensation is distributed between ΔT and ΔF. Both ΔT and ΔF are operated to compensate a lower beam current, which improves the efficiency (ΔT) and reduces energy spread (ΔF). The machine parameters used in this paper are for the present design. They may evolve in the future.

2 ΔF COMPENSATION

In an compensation 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.2.1. 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.

The frequency offset ΔF of the compensation sections need to be chosen between the requirement of compen-

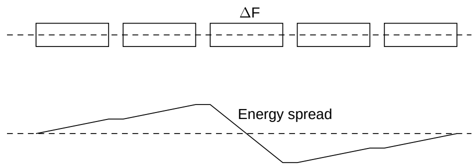

Figure 2.2: Energy spread in an accelerator module with ΔF compensation in the middle.

sation power ($\propto 1/\Delta F^2$) and the residual energy spread ($\propto \Delta F^2$). We have chosen a ΔF (1.4 MHz for S-band) such that the phase spread of the bunch train in the ΔF section is about 60^0. The maximum compensable beam loading voltage in this case is equal to the maximum acceleration of the ΔF section. With 25% maximum beam loading at nominal operation, one ΔF section can compensate beam loading of a module of four regular sections.

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 as shown in Fig. 2.2. The compensation section then over corrects by a factor of two which reverses correlation of energy with time during the pulse. 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. However, the high power microwave distribution system to many short ΔF compensation sections becomes unreasonably complicated and expensive. In addition to non-localness of ΔF compensation, the residual energy spreads (difference between the sine and "linear" beam loading curves) of all modules in an accelerator have the same distribution along the bunch train and they add up.

3 ΔT COMPENSATION

The way ΔT compensation works is shown in Fig. 3.3 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.

For SLED-I driven structures, the input power to the structure decreases exponentially [3]. As a result, the slope of the acceleration voltage decreases with time. To compensate at high beam currents in the NLC, it is preferable to used a reasonably short filling time. In addition, the power profile needs also be modulated to change the slope of the acceleration voltage, which enables to compensate beam loadings of different currents. 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. The residual energy spread ΔE at the end of the accelerator will be $\sqrt{N}\Delta E_{module}$. The relative energy spread is proportional to $1/\sqrt{N}$.

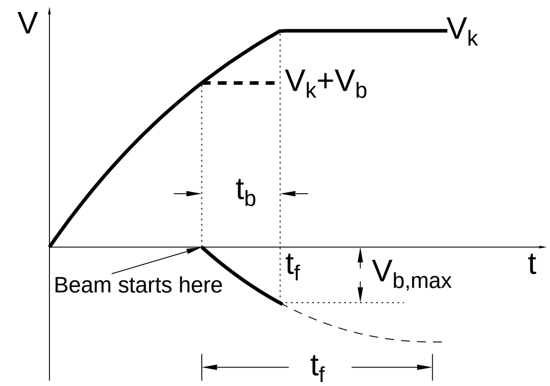

Figure 3.3: ΔT beam loading compensation using early injection.

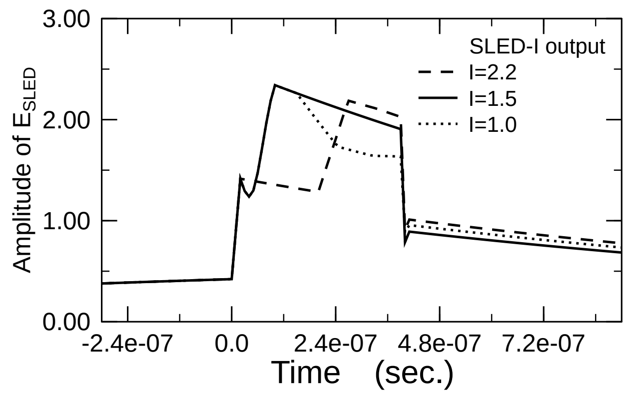

Figure 3.4: SLED-I wave forms for compensating 1, 1.5, and 2.2-A beam currents using ΔT compensation scheme.

For 1.5-A current with optimized filling time, the efficiency of ΔT is comparable to ΔF. For 1- and 2-A currents, the efficiency is about 30% lower due to amplitude modulation, Fig. 3.4.

4 HYBRID $\Delta T + \Delta F$ APPROACH FOR POWER SAVING

Low efficiency with ΔT compensation is mainly due to amplitude modulation of the SLED output. One can improve the efficiency of the ΔT compensation scheme by optimizing the filling time of the structure for each given beam loading current to avoid amplitude modulation. It is effective at relatively low beam currents, fails at high beam currents where the filling time of the structure would become too short. For the later case, a compromise can be found between energy spectrum and efficiency by combining ΔT and ΔF. With the combined scheme, the filling time of the structure is optimized to compensate a lower

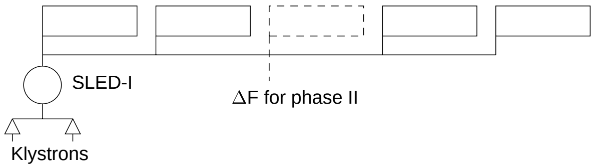

Figure 4.5: A sketch of $\Delta T + \Delta F$ compensation scheme.

Table 4.1: ΔT and $\Delta T + \Delta F$ results for the NLC prelinacs

	Phase-I	Phase-II
Current (A)	1.0	1.5
E_{accel}/module (MeV)	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 (MW)	0.0	5
P saved	38%	30%

beam current using ΔT, and ΔF sections are used to compensate the extra beam loading when operating at high currents. In this case, the ΔF section compensates only a small fraction of total beam loading, non-localness of ΔE is less a problem. A sketch of an accelerator module with $\Delta T + \Delta F$ compensation is shown in Fig. 4.5.

In the NLC, The current in phase-II is 50% more than in phase-I. With the combined $\Delta T + \Delta F$ concept, it is natural to optimize the filling time of the structure for ΔT compensation for phase-I. In phase-II, ΔF sections are used to compensate the extra beam loading, which is only 30% of the total phase-II beam loading.

A comparison between ΔT and hybrid $\Delta T + \Delta F$ in power requirement is shown in table 4.1 for the S-band prelinacs operating in phase-I and phase-II. The numbers in parentheses are for pure ΔT compensation. More than 30% of power can be saved with the hybrid approach in both phase-I and II operations for the prelinacs. Similar results were found for other NLC low rf linacs with the $\Delta T + \Delta F$ approach.

5 SUMMARY

In this paper, we have discussed the advantages and disadvantages of using ΔT and ΔF beam loading compensation schemes in term of efficiency and local energy spectrum for SLED-I driven disk-loaded waveguide structures. Compromise between efficiency and energy spread was found by using a hybrid $\Delta T + \Delta F$ approach. With the NLC S-band prelinac parameters, over 30% of power can be saved by using the hybrid scheme as compared with pure ΔT scheme (filling time optimized for 1.5-A current). Similar power saving can be obtained for other low rf frequency lincas in the NLC complex.

6 REFERENCES

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[3] Z. D. Farkas and *et al*, “SLED: A Method of Doubling SLAC’s Energy,” SLAC-PUB-1453, March 1974.