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BEAM LOADING COMPENSATION IN THE NLCTA[*]

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Abstract

In the design of the Next Linear Collider (NLC), multi-bunch operation is employed to improve efficiency at the cost of substantial beam loading. The RF pulse that powers the accelerator structures will be shaped to compensate for the effect of the transient loading along the bunch train. This scheme has been implemented in the Next Linear Collider Test Accelerator (NLCTA), a facility built to test the key accelerator technology of the NLC. In this paper we describe the compensation method, the techniques used to measure the energy variation along the bunch train, and results from tests with NLC-like beam currents.

1 INTRODUCTION

In contrast to the single bunch operation of the SLAC Linear Collider, the Next Linear Collider (NLC) design has multiple bunches (90) being accelerated on each RF pulse. This improves the energy transfer efficiency to the beam but results in significant beam loading. In the zero'th order NLC design [1], the loading is about 25% of the unloaded gradient. That is, if the 126 ns long bunch train would pass through an accelerator structure filled with a constant amplitude RF pulse, the energy gain of the bunches would decrease along the train, reaching a steady-state value after one fill time (100 ns) that is about 25% smaller than the initial gain. A more energy efficient parameter set is currently being considered where the beam current, and thus loading, is halved while the bunch train length is doubled. In either case, one faces the challenge of compensating this loading to a level where the bunch energies are equal to a few tenths of a percent as required to preserve the small bunch emittances in the NLC linacs.

2 NLCTA ACCELERATION SYSTEM

The Next Linear Collider Test Accelerator was built at SLAC to test X-band (11.4 GHz) RF system and accelerator concepts for the NLC, in particular the ability to compensate beam loading [2]. Although the NLC design has a 1.4 ns spacing between bunches (2.8 ns in the latest version), the beam loading effects are essentially the same if the bunch spacing equals the X-band period (88 ps) and the bunch charge is reduced to yield the same average beam current. The NLCTA adopted this approach in its design which reduced costs and made the machine much simpler, in part, because only X-band RF components were used.

In the injector of the NLCTA, an electron beam from a thermionic gun is bunched at X-band using two prebunchers followed by a capture section in the upstream end of the first accelerator structure [3]. This structure is a half-length version of the 1.8 m long detuned structure that was developed for the NLC. It is followed by a second half-length structure and then by a chicane-like layout of magnets and collimators which trim off the low energy tails of the beam that result from the bunching process. The beam then enters the linac which can accommodate up to six 1.8 m long structures. Currently it contains a detuned structure and the first prototype damped and detuned structure.

Two RF stations are currently in operation, one which powers the two injector structures and one which powers the two linac structures [4]. The key components of an RF station are shown in Fig. 1. The RF drive to the klystron is phase modulated as described below. The klystron is SLAC's model XL4 which nominally produces 50 MW of power. This power is roughly quadrupled in SLED II, a delay line version of the Stanford Linear Energy Doubler (SLED) [5]. The output SLED power is then split and feed to two accelerator structures (in the injector, part of the power also goes to

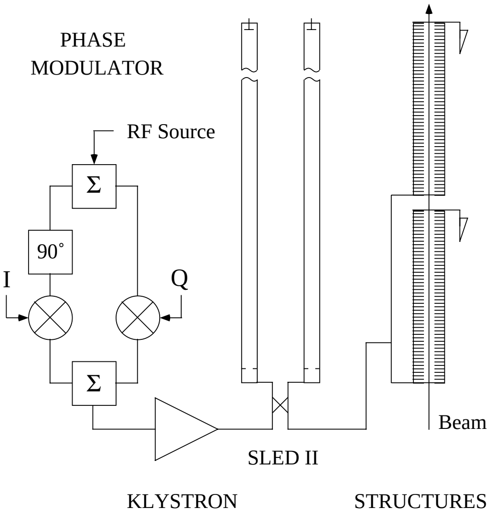

Fig. 1 Layout of an RF station.

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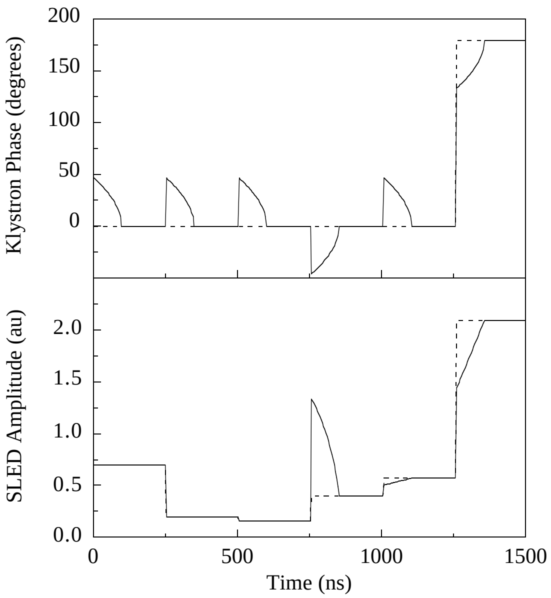

Fig. 2 Phase profile (upper plot) of the klystron drive RF and the predicted SLED output amplitude (lower plot) for 13% loading (solid line) and no loading (dashed line) in the linac.

the prebunchers). An unloaded gradient of 50 MeV/m, the initial NLC goal, is obtained with an input power of 70 (90) MW to the injector (linac) structures. Our high power RF components are not yet fully processed which limits the power at which we can operate. We typically run with an unloaded gradient of 44 MeV/m in the linac and 47 MeV/m in the injector, although the unloaded beam energy gain in the injector is lower (36 MeV/m) due to the phase offset (40°) that results from the capture process.

3 LOADING COMPENSATION

To operate with NLC-like beam currents, we use a loading compensation scheme in which the RF waveform during the 50 (100) ns filling time of the injector (linac) structures is ramped. The ramp is shaped to produce a field profile in each structure equal to the steady-state profile for the operating current. The first bunch enters each structure just after the ramp, and thus witnesses the same fields that would be present if it were part of a long bunch train. The RF waveform remains constant after the ramp so subsequent bunches witness the same steady-state field profile.

Since it is preferable to run with the klystrons saturated, we do not vary the klystron drive amplitude to produce the waveform ramp but instead modulate the drive phase and use the ×6 folding of the RF in the SLED compression process to shape the final waveform while keeping the phase constant. The required drive phase profile and the resulting SLED waveform are shown in Fig. 2 for no loading and for 13% loading. For the loaded case, a 50° phase 'bump' is added to the no-load phase profile at the beginning of each folding, including the final 180° flip that produces the waveform used for acceleration. The shape of this bump was chosen to produce a linear ramp, which is very close to the optimal shape for compensation.

To vary the drive phase, an I/Q phase modulator is used as shown in Fig. 1 [6]. The I and Q signals, which amplitude modulate two out-of-phase components of the RF, are produced by two pulse generators that can be programmed to output any desired waveform. The signals are 'clocked-out' at 238 MHz, in synch with the beam timing system. Ideally, I and Q are proportional to the sine and cosine of the desired phase profile, such as those shown in Fig. 2. In practice, the modulator is first calibrated against a phase demodulator, which does the inverse operation, producing I and Q signals whose arctangent and sum-in-quadrature are the phase and amplitude of the sampled RF. The demodulator itself is calibrated using an RF source with a frequency 10 MHz below the nominal X-band value. For both systems, six parameters (two amplitudes, two phases and two offsets) are derived and used to correct the I and Q values.

Figure 3 shows the results of using the phase profile in Fig. 2. in the linac RF station to produce a ramped waveform with a peak power of 150 MW. The amplitude and phase of the ramped portion of the RF pulse are plotted. One sees some smoothing of the waveform as expected from the finite bandwidth of the system, as well as a few degree variation of the phase, which may be a related effect.

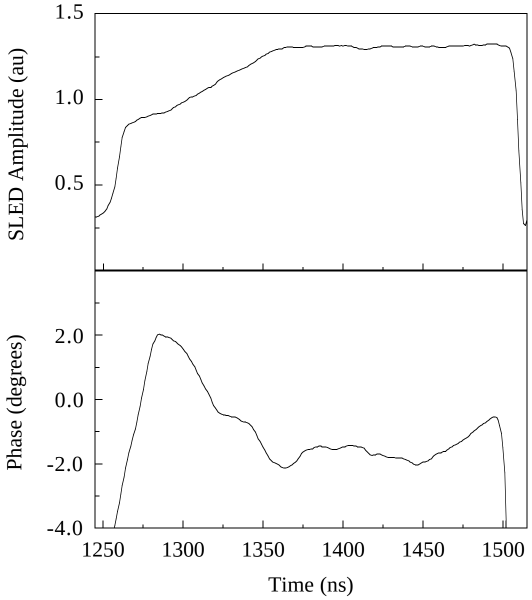

Fig. 3 Measured amplitude (top plot) and phase (bottom plot) of the SLED RF output in the linac for 13% beam loading compensation.

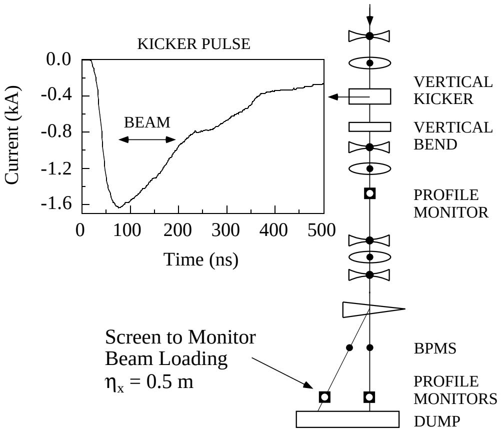

Fig. 4 Spectrometer layout and the kicker pulse shape.

4 LOADING MEASUREMENTS

To verify that the loading compensation scheme works as predicted, the energy variation along the bunch train is measured in the spectrometer section of the NLCTA that follows the linac (see Fig. 4). It contains a SLC solid-epoxy-style kicker magnet [7] for this purpose. It is powered by a thyratron-switched capacitor bank which produces the current pulse shown in Fig. 4. The pulse is timed so the peak field occurs just before the beam arrives. This results in a nearly linear variation of the kicker magnetic field during the pulse, which spreads the bunch train vertically by about 3 cm at the end of the spectrometer (a DC bend magnet just after the kicker is used to offset the average kick to the beam).

For the energy measurement, a horizontal bend magnet steers the bunches into the off-axis beam line, which spreads the electrons horizontally in proportion to their energy. Thus, when viewing the beam on the off-axis profile monitor [8] with the kicker magnet on, one sees the variation of the bunch energy along the train. Figure 5 shows such images for a 120 ns long bunch train with an average current of 0.50 A in the injector (12% loading) and 0.33 A in the linac (13% loading). The current profile along the train was fairly uniform as measured with our toroids [9]. To achieve the loading compensation, the phase profile for each RF station was configured based on the measured beam current and accelerator gradient at that station. The timing of the RF pulse relative to the beam in each station was then adjusted to minimize the energy variation along the train. This yielded the image on the left: running with no RF waveform ramp in the linac yielded the image on the right.

Another measure of loading compensation comes from the RF that is monitored at the output couplers on the structures. An example is shown in Fig. 6. One sees that the RF output amplitude is constant during the passage of the beam, which is expected if the loading is properly compensated. At maximum, the loading reduces the output amplitude by 38%, making the phase shift between the beam-on and beam-off state a good measure of the bunch timing relative to the RF. Figure 6 shows the phase shifts from the two linac structures after the overall klystron drive phase was adjusted to minimize the bunch energy spread. The shifts are only a few degrees, indicting that the relative phasing of the structures is good and that the bunches were near the crest of the net field from the two structures, as expected for minimum energy spread. For the NLC, this beam phasing technique should prove to be very useful.

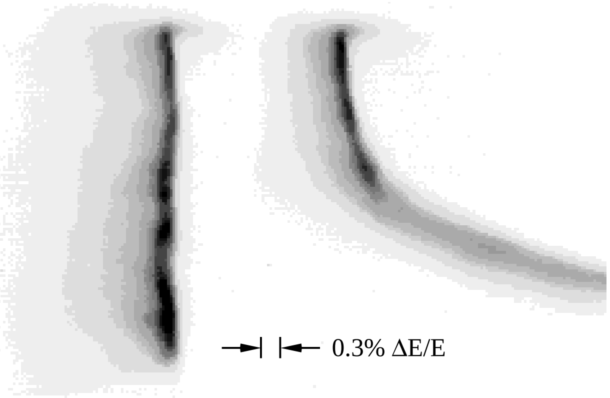

Fig. 5 Profile monitor images of the beam at the end of the spectrometer. The head of the bunch train is at the bottom and higher energy is toward the right (see text).

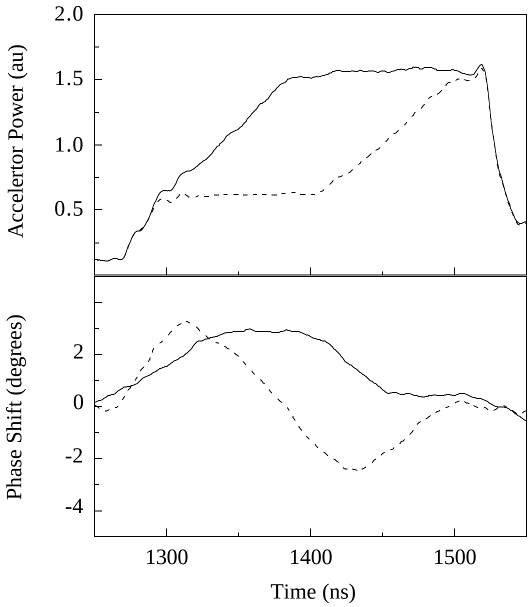

Fig. 6 Power output from a linac accelerator structure (top plot) with the beam off (solid line) and on (dashed line), and the beam on/off phase shift (bottom plot) for the two structures.

In summary, the beam loading compensation scheme purposed for the NLC has been demonstrated to work well in the NLCTA. We will add another RF station shortly and do further tests of loading compensation at higher currents.

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