10/6-18-91 JSO

SLAC-PUB--5438

DE91 013605

2505-162

Multibunch Energy and Spectrum Control in the SLC High Energy Linac*

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Introduction

Three intense bunches (two electron and one positron) are accelerated on each RF pulse in the SLC Linac. Careful control of the energy and energy spectrum of each bunch is needed to provide acceptable beams at the collision point and the positron production target. The required RF amplitude, timing, and phase adjustments can be calculated and adjusted in real time to correct for changing conditions. BNS damping and energy feedback systems reduce the available reserve energy, which is limited. Observations and stability of actual beams are reviewed. Implications for a future collider are discussed.

Specifications of Energy

The energy of both positrons and electrons must be carefully set to produce collisions at the Z^0 resonance (91.1 GeV). Since synchrotron radiation in the Arcs removes about 1 GeV from each beam, the required beam energies at the end of the linac are 46.6 GeV [1,2]. (The beam energy defined here is the average energy of all particles in the bunch.) In the Final Focus extraction lines there are spectrometers which define the absolute energy to about +/- 0.05 percent. However, relative energy measurements are made in a dispersive region at the end of the linac which are used in a feedback loop to ensure the energy stability to +/- 0.1 percent. A second energy feedback is located near the scavenger bunch extraction point (30 GeV). An over head of about 0.25 GeV is needed for each feedback system to provide an adequate operating range.

Average Bunch Phase

The energy spectra are adjusted by using the overall linac phases (the phase between the linac RF and the damping ring / bunch length compressor RF) for each of the bunches. These phases are adjusted to minimize the final spectrum widths at low currents and to make the proper 'double horned' spectra at high currents [3,4]. The spectrum measurements of the beams destined for the IP are taken in a dispersive region at the end of the linac where the acceptance is - 0.5 % to +1.5 % (defined by collimators). The measured spectrum and energy as a function of linac phase is shown in Fig. 1. The spectrum of the scavenger bunch is taken in the extraction line at about 30 GeV. The energy window there is +/- 1.5 %. The overall phase must be maintained within 0.4 degrees for energy stability.

The individual klystrons are most accurately phased by measuring the energy gain as a function of its RF phase, similar to Fig. 1. The measurement error is about 3 degrees. The 227 klystrons can be phased with an automated computer program in about 8 hours [5]. The absolute phases are then recorded. All subsequent phase changes (for example BNS changes) are made relative to this absolute value. Measurements over several years have shown that these absolute phases are stable to about 5 degrees over six months. Of course, hardware changes or cable adjustments often cause the loss of knowledge of the absolute phase of an individual klystron. Then, rephasing must be done.

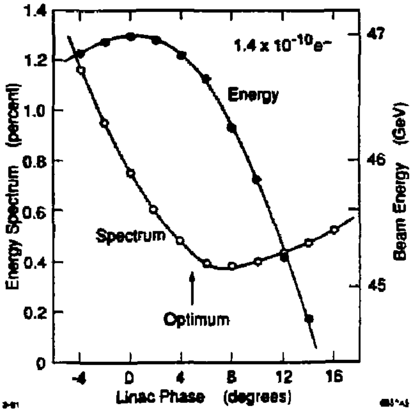

Fig. 1 Measured energy and spectrum versus RF phase

Beam Loading

Longitudinal wakefields produce energy reductions within each bunch and on all trailing bunches. For example, at 5×10^{10} particles per bunch with a gaussian bunch length of 1 mm, the average longitudinal self loading over the two mile linac is 1.3 GeV, the loading for a bunch trailing by 60 nsec is 0.89 GeV, and 0.61 GeV for 120 nsec separation [3,4]. The self beam loading varies (approximately) inversely with the bunch length. The loading on subsequent bunches does not depend on the bunch length of the leading bunch as only the fundamental wakefields remain coherent after about 15 nsec. All loading is linear in the leading beam intensity.

The desired average phases have been calculated using the wake potentials for the SLAC structure under many bunch length and current conditions. The measured variation of the bunch energy spread and energy with linac phase for one beam condition are shown in Fig. 1 and agree with calculations. Values of the best average phases and best bunch lengths for various intensities using BNS damping are shown in Fig. 2. Values within the range are chosen during operations.

BNS Damping

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* Work supported by Department of Energy contract DE-AC03-76SF00515.

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Presented at the IEEE Particle Accelerator Conference, San Francisco, CA, May 6–9, 1991

BNS damping is used to reduce the effects of transverse wakefields [6]. BNS damping is implemented by backward phasing early klystrons to introduce a head to tail energy spread [7]. The energy spread is removed by forward phasing the later klystrons. The present BNS arrangement at 3 X 10^{10} particles per bunch has the first 55 klystrons backward phased at -20 degrees and the remaining klystrons at +15 degrees. The average bunch phase over the linac is independent of the BNS setup as that phase is determined by the longitudinal wakes, the bunch length, and the RF curvature. The penalty for the use of BNS is the loss of overall energy given by the offset phases.

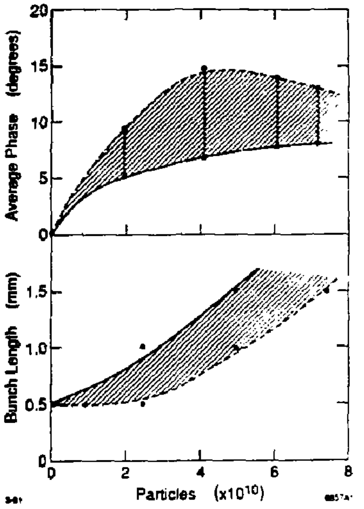

Fig. 2 Desired average phase and bunch length versus current

Effective Klystron Energy Gain

The acceleration provided by each klystron is measured using the spectrometer in the early Arc. The position resolution of the spectrometer is about 15 microns (with some averaging) at a location where the dispersion function is 70 mm. Thus, the energy resolution is about 7.5 MeV or 3 % of the expected klystron gain. Each measurement takes about 5 minutes and disrupts collisions. Alternatively, the energy gain of a klystron can be calculated from RF power measurements and the calibrations of the RF couplers. These RF measurements are not absolutely accurate (10%), but are relatively accurate. They are used for short and long term observations. From many measurements, the 'average' klystron provides 249 +/- 8 MeV.

An additional factor, g, is included in the energy calculation due to inefficiencies. Maintenance crews routinely tune the modulators and klystrons for peak performance but can not keep them all at their maximum simultaneously. Also, the beam phase measurements are not done very often and slow but small phase errors can appear. Therefore, an average inefficiency loss of 2 % (g =0.98) is used.

SLED Timing

The acceleration provided by the 67 MW klystrons is enhanced using SLED RF pulse compression (X 1.77 at 3.5 ms). The SLED pulse [8] produces a time dependent output which is used to adjust the energy difference between bunches spaced about 60 nsec apart. The measured SLED energy gain [9] for a group of eight klystrons is shown in Fig. 3. Even though a parabola nearly fits the curve, a six term polynomial has been used in the calculation to accurately represent the SLED curve which is sharper on the delayed time side. The measured curve for a single klystron is a little sharper than the eight klystron data as small relative timing errors between klystrons smooths the peak.

Klystron Population

There are 232 potential slots for klystrons and accelerators between the damping ring exit (1.15 GeV) and the end of the linac. Not all slots are filled. Several slots are used for injection and extraction transport lines and a spin manipulation solenoid. Many structures have been shortened to accommodate diagnostic equipment. Thus, the useful number of accelerating klystrons is 226. At any given moment several klystrons are out of service for repairs or tuning. Also, several klystrons are operating on standby (not at beam time) to prepare for replacement of future failures. The maximum energy reachable by the SLC for three bunches must include these 'unavailable' klystrons. For this study three out-of-service klystrons and three standby klystrons are assumed for the whole accelerator. Thus, a total of 220 'effective' klystrons is available for a total single particle energy of 55.9 GeV (= 54.75 + 1.15).

The klystron population is designated in three regions for calculations. (1) The early linac region where the RF is back-phased for BNS. (2) The middle linac region with BNS forward-phases but ahead of the scavenger extraction line. Regions (1) and (2) share 139 klystrons (- 2 broken and - 2 standby) for 135 'effective' klystrons. (3) The linac region downstream of the extraction line with BNS forward phases has 87 klystrons for 85 effective.

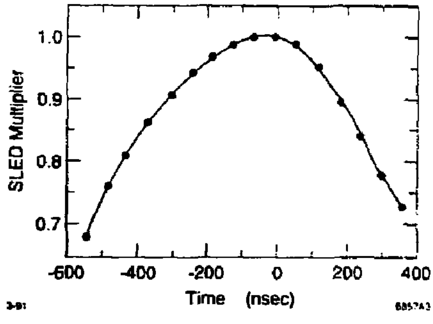

Fig. 3 Measured SLED multiplier versus bunch time for eight klystrons. A value of 1.0 means the gain is 1.77 times the acceleration without SLED.

Energy Gain Equations

The correct energy spectra and energies of the three SLC bunches must be obtained simultaneously through choosing the RF phases, the number of used klystrons, and the SLED timing. Basically, the damping ring phases set the energy spectra, the number of klystrons sets the energy of the first electron bunch at the end of the linac, and the SLED timing adjusts the energy difference between the electron and positron bunches. The energy of the scavenger electron bunch is made as high as is convenient given the number of available klystrons and the above constraints but the spectrum is set correctly using a rapid phase change [10].

The generic energy equation for each bunch is

$$E = E_0 + g \, dE \, \mathrm{SLED}(t) \, (n_1 \cos(\phi_1 + \phi_{DR}) + n_2 \cos(\phi_2 + \phi_{DR})) + b_{load}$$

where $E_0 = 1.15$ GeV, $dE = 249$ MeV, t = bunch time on the SLED curve, b_{load} the beam loading for that bunch, and ϕ_1 (n_1) and ϕ_2 (n_2) are upstream and downstream BNS phases (number of klystrons), respectively. ϕ_1, n_1, and ϕ_2 are usually chosen in advance to provide the proper energy spectrum profile along the early linac. The respective damping ring phases ϕ_{DR} are determined by choosing the proper average phase according to the Fig. 2 given that all bunches must share BNS phases ϕ_1 and ϕ_2. The BNS phases are usually set to make the bunch with the most charge stable with its $\phi_{DR} = 0$.

These equations have been solved for the SLED time t and for n_2 using a minimization algorithm. Many examples of high current SLC running have been explored. Several of the results are shown in Table 1. The number of klystrons needed is a strong function of beam current. Furthermore, a difference between the electron and positron energies (given the sum is constant) is also important since raising the positron energy allows all three bunches to have SLED time values nearer the peak. As the beam intensities increase the bunch lengths are increased to reduce beam loading which keeps the required energy within limits. Consequently, the transverse wakefields become stronger and better launch control at the linac entrance is needed.

Next Linear Collider

In most designs for future linear colliders many bunches per beam (10 to 200) are used. Fortunately, the SLC has successfully controlled the spectra and energies of three bunches, signaling well for the future. The control of these quantities requires independent phase and amplitude control for each bunch. Some control may be relaxed if a spread in final average bunch energies is acceptable. Independent controls for the next linear collider means: (1) rapid RF structure filling times to allow RF power changes from bunch to bunch (a few nsec), (2) careful attention to the RF rise time and phase stability, (3) rapid phase adjustments (a few nsec) to allow bunch to bunch phase changes, (4) careful control of single bunch currents, and (5) a wide energy acceptance in the final focus system. Instrumentation required for independent measurement and feedback of each bunch is very important and needs fresh approaches. Many investigations around the world are concentrating on these problems.

Acknowledgments

Many thanks are extended to SLC Operations, Controls, and Maintenance for their help with measuring, phasing, and monitoring the RF system. Conversations with K. Bane, M. Ross, D. Schultz, H. Schwarz, and J. Sheppard have been very helpful.

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Table 1 Multibunch parameters for various beam currents in the SLC Linac at 46.6 GeV average per beam.

$N^- = N^+$	σ_z	n_1	ϕ_1	n_2	ϕ_2	n_{total}	t_{SLED}	$E^-_{bunch\,2}$	$E^- - E^+$
X 10^{10}	mm	klystrons	degree	klystrons	degree	klystrons	nsec	GeV	MeV
									0
1	0.50	32	-20	160	10	192	- 86	32.6	0
3	0.75	56	-20	152	22	208	- 122	30.5	0
5	1.25	72	-15	136	22	208	- 164	30.6	0
6	1.35	80	-12	127	20	207	- 190	30.7	0
7	1.50	88	-12	124	22	212	- 213	30.3	0
5	1.25	72	-15	132	22	204	- 106	30.5	- 500
5	1.25	72	-15	141	22	213	- 240	30.3	+ 500