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The SLAC Linac as Used in the SLC Collider*

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Abstract

The linac of the SLAC Linear Collider (SLC) must accelerate three high intensity bunches on each linac pulse from 1.2 GeV to 50 GeV with minimal increase of the small transverse emittance [1]. The procedures and adjustments used to obtain this goal are outlined. Some of the accelerator parameters and components which interact are the beam energy, transverse position , component alignment, RF manipulation, feedback systems, quadrupole lattice, BNS damping, energy spectra, phase space matching, collimation, instrumentation, and modelling. The method to bring these interdependent parameters collectively into specification has evolved over several years. This review is ordered in the sequence which is used to turn on the linac from a cold start and produce acceptable beams for the final focus and collisions. Approximate time estimates for the various activities are given.

Initial Checks and Tune-up

Before any of the beams can be accelerated, there are a host of mechanical, electrical, and control conditions which must be satisfied. They are listed here for completeness but without much detail. The personnel protection system (PPS) circuits must be tested, people cleared from the tunnel, and the tunnel locked. The machine protection system (MPS) which protects accelerator components from high power beams must be checked and activated. The vacuum pumps must be on and the gate valves open.

The water cooling systems for the magnets, klystrons, accelerator structures, and RF waveguides must be operating at the proper temperatures and the flow indicators checked. The RF high voltage, modulators, klystrons and subboosters are turned on and adjusted to bring them within tolerances. The modulator DQing circuits and the SLED cavities must be tuned.

The computer system [2] must be functional including the micro computers (about 35) and associated CAMAC crates, the communication links, and the VAX mainframe. The magnet, timing, and klystron controls are exercised. The dipole and quadrupole magnets are calibrated, magnetically standardized, set to the proper values, and trimmed to within their respective tolerances.

The profile monitors (about 20) are checked including target in/out, illumination, and iris control. The electronic modules for the beam position monitors (about 290) are calibrated. Finally, the toroids for monitoring beam intensity are checked.

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Establish RF Conditions

The goal for setting the RF parameters is to specify the energy and energy spectrum for both the electron and positron beams at the end of the linac. The bunch length compressors [3] in the ring-to-linac transport lines are checked to have a setting of about 33 MeV where maximum compression occurs. Modest beams of electrons and positrons (< 1 X 10**10 per pulse) are established to the energy measurement region at the end of the linac where the beams are separated horizontally to enter their respective Arcs. A momentum dispersion of about 70 mm is produced in that region.

First, the feedback loop on the overall phase of the two mile long main drive line is turned on [4]. Next, the phase of each subbooster (which drives eight klystrons) is adjusted to maximize the energy given to the electron beam. The phase measurements involve changing the phase over about 90 degrees and fitting the energy change with a sine wave. The best phase settings are recorded. Next, the optimum phases of the individual klystrons are determined in the same way using 180 degree shifts and recorded [5]. Phasing the entire linac requires about 32 hours.

The energy spectrum of the electron beam is measured on a synchrotron radiation Xray monitor [6] or on a profile monitor in the dispersive region at the end of the linac. The spectrum is set to below 0.3 % using the RF phase of the electron damping ring coupled with the RF phase of the electron bunch length compressor in the ring-to-linac transport line. This variable adjusts the time of arrival of the electron bunch in the linac. At low beam intensities the phase of maximum energy and the phase of minimum energy spectrum are almost the same but at high currents the phases can be up to ten degrees different [7]. The energy spectrum of the electrons which are extracted at Sector 19 to go to the positron production target is checked to be small. This spectrum can be set without affecting the spectrum at the end of the linac by separating the subbooster phases upstream and downstream of the extraction line. The electron overall phase can be set in twenty minutes.

The number of klystrons accelerating electrons is adjusted to get the energy close to the desired value of 47.0 GeV. The remaining klystrons are maintained hot in stand-by mode. The slow energy feedback is turned on which fixes the energy to about 50 MeV once per minute. Several extra klystrons are added to the beam to produce an overhead of about 1 GeV for the feedback loop. The slow feedback adjusts the phase of two subboosters in opposite directions to change the overall RF amplitude and not phase. The feedback is established in a few minutes.

The spectrum of the positron beam is set to below 0.3 % at 47 GeV using the positron damping ring (south) phase ramp which adjusts the ring RF phase and the positron bunch length compressor phase.

The positron energy is adjusted by moving the RF timing of all the klystrons (about 500 timing numbers) so that the electron and positron bunches move along the SLED energy gain curve. The electron energy changes with this procedure as well as that of the positrons but the energy

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feedback keeps the electron energy constant. Once the positron energy is within 50 MeV the 'energy difference' feedback is turned on if desired.

At this time the fast energy feedback is turned on which keeps the energy of the electron beam (and most often the positron energy as well) stable to about 20 MeV. The fast energy feedback operates on every beam pulse. The energies are measured by launching both beams into their respective Arcs where position offsets are measured. After the energy scales are determined by looking at the beam energy in the Arcs, the 'set points' of the feedback loops are adjusted to get the Arcs measurements within tolerances. Changes are typically below 100 MeV.

If BNS damping [8] is to be used, phases of the affected subboosters are changed at this time and the energy spectra and energies of the two beams are reestablished. The feedback systems must also know about the 'BNS' phases. BNS damping is now used for all high intensity beams.

Establish The Quadrupole Lattice

The linac quadrupole lattice is loaded into the control system by calculation from a design TRANSPORT computer deck. The energy profile along the linac is determined by the computer program LEM (Linac Energy Management) [9]. The phases of the klystrons and subboosters, beam loading, BNS damping, number of klystrons, and the feedback parameters are taken into account in the calculation. The model energy-independent quadrupole values (KMOD) are loaded into the on-line database. The energy calculation of LEM is used to convert the KMODs into actual desired quadrupole strengths (BDES in Kg). The magnets are then trimmed and the energy profile is stored in the database. The process requires about 20 minutes.

The linac energy profile can change over time when phases drift and klystrons fail. After these events occur the linac can be scaled rapidly using LEM to reestablish the proper quadrupole lattice. The quadrupoles and the steering dipoles are scaled with the difference in energy (5 minutes).

With the proper lattice in place, the on-line model is calculated providing the TWISS parameters at every device along the linac. These parameters are used for autosteering the trajectory, oscillation prediction, feedback systems, and emittance measurements [10]. The model is checked against the actual hardware using a real beam by starting an oscillation early in the linac and comparing the measured and predicted oscillations (15 minutes) [11]. Agreements of the predicted and measured phase advances of about 3 % over 30 wavelengths are common. The overall difference can be reduced by adjusting an energy scale factor in the LEM program.

Trajectory Correction

The trajectories of the positron and electron beams must be corrected to near the axis of the accelerator to avoid emittance enlargement from transverse wakefields and chromatic beam heating. There are 274 quadrupoles in the linac and each one has a stripline beam position monitor (BPM) [12] mounted inside. There is an X-Y pair of dipoles associated with each quadrupole. Since there are not enough controls to steer both beams to every BPM, a decision was made to steer each beam only to the BPMs where there is a focusing quadrupole for that beam. The dipole associated with each BPM is the one at the nearest upstream focusing quadrupole. In this way the positron and electron beams share the dipoles and BPMs in a complementary fashion.

The correction procedure [13] first measures both trajectories, calculates the positron dipole changes, predicts the effects on the electron trajectory, and finally calculates the dipole changes for the electrons. The calculated effects of the electron changes on the positrons are not taken into account with the present code as the electron trajectory changes are usually small. A complete calculation could be done but is not expected to improve the convergence rate very much. With this method the two trajectories converge to the axis with two or three iterations. The entire linac can steered in 10 to 30 minutes depending on the initial state. A typical rms trajectory error is about 200 microns for both electron and positrons when all BPMs are included. The rms is about 50 microns using only the BPMs to which the beams are steered. The eventual goal is for the rms displacement to be 100 microns or less for all the BPMs but this requires improvement in the present quadrupole offsets (about 250 microns) and BPM errors (about 150 microns).

As with most linear correction schemes the exiting beam angle at the end of the correction region is not determined. As a result trajectory correction most often must be applied from front to end in sequence. One consequence of this is that a carefully planned steering section at the end of the linac must be made so that the launch feedback can start easily from the resulting positions produced by the standard correction package.

1.2 GeV Beam Conditions

The beams entering the linac must be properly conditioned so that the linac will not enlarge the emittance. The bunch length, the betatron functions, and the dispersion must be properly matched.

The bunch length is determined by the beam conditions in the damping rings and the effects of the length compressor. The bunch length is most accurately measured using the spectrometer at the one third point in the 3 km linac. The beam is expanded in energy in proportion to its bunch length using eight klystrons phased at 90 degrees. The energy spectrum is subsequently measured which results in a length measurement with a resolution of about 0.05 mm. The compressor RF amplitude is set to about 1 MeV out of 33 MeV to provide the correct length [14]. Bunch length measurements require about four hours.

The dispersion in each beam is minimized at the beginning of the linac by adjusting specially constructed quadrupole combination variables in the ring-to-linac transport line to tune eta and etaprime without changing the betatron functions. The dispersion should be zero in the linac but about one percent of the 1.5 m dispersion in the ring-to-linac tranport line usually emerges on turn-on and must be removed. A few centimeters of dispersion (sometimes less) will double the beam emittance [15,16]. The dispersion is minimized by measuring the emittance and adjusting the dispersion knobs (two hours). The quadrupole strengths are changed only a few percent.

The resulting emittance is compared to the design value. If the horizontal emittance is much larger than the vertical then the damping ring is uncoupled and must be recoupled (one hour). Measurements of the betatron functions also come from emittance measurements and they are compared to the design. The four matching quadrupoles at the beginning of the ring-to-linac transport line are used to match the beam to the proper values (one shift). Beta matching remains a difficult procedure and methods to improve it are under study.

The bunch spacing between the positrons and the electrons must be set to the correct value so that the bunches collide at the proper longitudinal position in the final focus. The measurement is done using a delay line, a BPM stripline and an oscilloscope. The positron damping ring phase ramp is used to adjust the spacing. The correct RF bucket must be chosen. The fine tuning is done by making the energy spectra small.

The timing of the bunches on the damping ring kicker pulse must be checked to verify that the beam centroid will not fluctuate transversely due to kicker timing jitter.

47 GeV Beam Conditions

The condition of the beams at 47 GeV is checked so that they can be launched properly into the Arcs. The bunch intensities are checked using toroids. The transverse beam shapes are measured at four different betatron phases near the end of the linac to measure the emittance and betatron functions. The betatron mismatches are checked by varying the quadrupole strengths over most of the linac to watch for shape oscillations on a downstream profile monitor. If need be the betatron functions can be adjusted in the last 100 m of the linac to match the beam. However, this is rarely done. The stability of the klystrons is checked to verify that the energy is stable (five minutes).

If the transverse beam shape is not stable, then the stability of the damping ring kicker must be checked, the ring-to-linac trajectory corrected, and the trajectory along the linac adjusted to minimize the sensitivity to launch jitter.

The absolute position of the beams in the region at the end of the linac where the beams are split must be checked very carefully so that new dispersive effects [17] are not introduced into the beams and contaminate the beam emittance or make the final focus adjustments difficult.

High Beam Intensity

The beam intensity is now increased to the value used during collisions. Presently, the intensity is about 1.4 X 10**10. Eventually it will be near 6 X 10**10. Care must be taken so that the bunch length is proper, that the beam trajectories do not change, that the beam emittance and shapes do not change, that the tails on the beams do not strike sensitive portions of the machine and cause damage, and that the feedback systems are stable. Detector background must be maintained at acceptable levels.

Feedback Systems

There are two feedback systems in the linac: one at the entrance and one at the exit.

The feedback, at the entrance stabilizes the launch parameters (x,x',y,y' for both beams) [18]. Deviations of the beam from the reference trajectory are measured using BPMs in the early part of the linac and used to control dipole magnets in the ring-to-linac transport lines. The positions are kept stable to about 50 microns. This feedback works once per minute. The feedback process is established including reference trajectories in about thirty minutes.

The feedback at the exit of the linac stabilizes the launch into the Arcs (x,x',y,y',E, sigma E/E for both beams) [19]. The position and angle feedbacks use BPM data in the last 100 m of the linac and uses eight double strength dipoles to correct both beams simultaneously. There is no evidence for x-y coupling in the linac so the calculations are simplified. There are both slow and fast position and angle feedbacks; only one at a time is used. The fast feedback (every pulse) has about twice the resolution of the slow feedback (once per minute) but is not as robust. The fast feedback has progressed slowly but has now become essential for operation. The positions are kept stable to about 40 microns.

The energy feedback looks at the BPMs downstream of the beam splitter magnet to determine the bend angle. The energy adjustment is made by adjusting the phases of two subboosters (oppositely) to change the total acceleration without affecting the energy spectra of the beams. There are both slow and fast energy feedbacks for electrons. The slow feedback keeps the energy stable to about 50 MeV and the fast 20-30 MeV. As used now, the fast feedback controls the beam and the slow feedback is used as a monitor. The feedback of the energy difference between electrons and positrons is a slow feedback which adjusts the RF timing of all the klystrons to keep both beams within 50 MeV of each other. This feedback, often done manually, nr . to be used only once or twice each day.

The energy spectrum feedback digitizes the width of the beam signal on the Xray profile monitor and adjusts the respective damping ring phases [20]. This is a non-linear feedback system and requires robust data for operation. Fortunately, the spectra change slowly and are corrected only a few times each day. The system could correct the spectrum every few seconds if needed.

Reduce Detector Backgrounds

During collisions the backgrounds in the physics detector at the interaction point must be kept low. The sources of backgrounds come from particles far off axis, from particles far off energy, and from synchrotron radiation in the final focus quadrupoles [21]. There are sets of collimators at the end of the linac, in the Arcs, and in the final focus which provide primary and secondary protection. Backgrounds are difficult to control because there are few signals but many possible causes. Adjustments of the collimating system are time consuming and are done only when needed. Thus, the beams in the linac must be monitored for changes in energy, energy spectra, transverse tails, transverse core with betatron mismatch changes, trajectory, and intensity changes. Corrections are made when appropriate. Care must be take to control the number of particles in the three to four sigma region where it is difficult for the collimators to control them. Methods of correlating beam changes with background changes are being studied.

On-line Monitoring

After the beams have been delivered to the final focus for collisions and the accelerator conditions are stable, a collection of on-line monitors are used to verify that the accelerator has not changed.

The present settings of many machine parameters are recorded every five minutes and stored in what are called 'history buffers'. Plots of these variables for the last 24 hours are available. Some of the recorded devices are magnets settings, RF phase and amplitude of the klystrons, feedback commands and readings, parameter adjustments of the operators, and temperatures. The plots are reviewed whenever there is a beam fault or routinely every morning.

The trajectories of the beams in various parts of the SLC are recorded every five to ten minutes and analyzed off-line. Studies of energy, dispersion, BPM errors, focusing changes, feedback drifts, and current dependent effects can be made from these data.

The electron and positron beams are kicked transversely onto off-axis profile monitors located near the end of the accelerator every two seconds. There are four monitors per beam at different phase advances. The betatron phase advances between monitors are such that real time emittance measurements can be made [14]. The TWISS parameters of both beams are also calculated and recorded along with the emittances every few minutes and stored in history buffers for analysis of the last 24 hours. These displays have become essential for accelerator drift studies.

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