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COMMISSIONING OF THE SLC INJECTOR*

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ABSTRACT

For every cycle of the SLC, the injector is required to launch two electron bunches and a single positron bunch into their respective emittance damping rings. Each bunch is to have a population of 7.5×10^{10} particles/bunch, an energy of 1.21 GeV, and a full width energy spread of less than 2%. The electron beams are produced from a thermionic cathode, bunched, and accelerated to about 200 MeV. Positrons are injected after electrons at the 200 MeV point. The three bunches, spaced by approximately 60 ns, are subsequently accelerated to the damping ring energy within a single RF pulse. As of September 1986, all of the injector hardware had been installed and tested. Single electron bunches were being produced, stabilized with respect to energy characteristics, and injected into the damping rings. Commissioning of two electron bunch operation is currently in progress. Three bunch running should be commissioned by early 1987 and the SLC injector is expected to be operational by April 1987. This paper will report on the hardware and software developments necessary for the injector. The operational status of the entire system will be discussed.

Introduction

Figure 1 illustrates the layout of the injector. The SLC injector consists of the electron source (CID), electron booster linac (S0), and sector one (S1) of the SLC linac. The purpose of the injector is to produce a pair of electron bunches, spaced by 61.6 ns, and boost these bunches to an energy of approximately 200 MeV at the beginning of sector one. At this point, a single bunch of positrons is injected into S1, 55.9 ns after the trailing electron bunch; positrons enter S1 with an energy of about 200 MeV. The three bunches are subsequently accelerated through S1 to an energy of 1.21 GeV and deflected into the north and south transport lines (LTRs) which lead to the damping rings.

SLC specifications require that each electron and positron bunch have 7.5×10^{10} particles per bunch. At the end of the injector the bunches are to have an energy of 1.21 GeV and a composite energy deviation and spread of less than 2% full width. For colliding beam operation at 120 Hz, it is required that the transverse emittance ($\gamma\epsilon$) of electron bunches injected into the damping ring be less than 180×10^{-5} m-rad. Because of the longer time over which positrons are damped, specification of positron emittance is not relevant.

Electron Source

The electron source[1] consists of a dispenser type cathode thermionic gun, a pair of 16^{th} subharmonic bunchers, an S-band buncher and a 3 meter SLAC accelerator section. The gun is currently operated at a DC voltage of 175 kV and generates 2-3 ns FWHM electron pulses. The charge in each pulse is variable up to a maximum of about 30 nC (for a 3 ns FWHM gun pulse). Typically 60% of the pulsed gun charge is captured and bunched. At the exit of the source accelerating section, the electron bunches have an energy of about 40 MeV, energy spread of 1% FWHM, and bunch length of $\sigma_z = 2.5$ mm. The bunch length is compromised to reduce the deleterious effects of longitudinal and transverse wakefields which accompany the beam during acceleration.

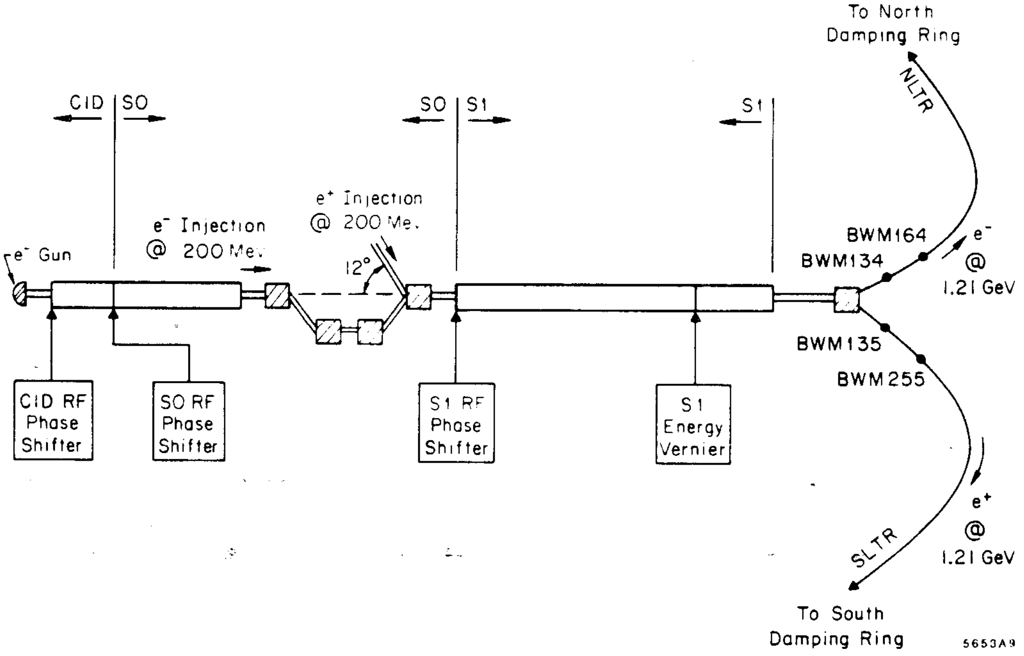

Fig. 1. Overview of the SLC injector showing the electron source region (CID), the electron booster linac (S0), and sector one (S1) of the linac. BAS 1 is a pulsed spectrometer; beam position monitors (BPMs) located in the transport lines leading to the damping rings (NLTR and SLTR) are used to monitor the energies of injected bunches.

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A double gun pulser system[2] is used to produce the required pair of bunches. The spacing of the electron bunches is 61.6 ns, which is set by the pathlength of the positron production system and the requirement to fill specific damping ring buckets on each cycle of the machine. Bunching of the double pulses is accomplished by first adjusting the source RF to optimize the first bunch and subsequently adjusting the timing of the second pulse so that its energy spread is minimized. Until recently, final timing adjustments to the second bunch were made on the picosecond scale using a trombone. A new gun trigger module[3] has been recently installed to permit remote continuous timing variations via the SLC control system. Tests are currently underway to bring this system online.

The basic source system of the thermionic gun, two subharmonic bunchers, S-band buncher and accelerating section, was installed by May 1981. Improvements to the system electronics and beam diagnostics, as well as a gradual build up to the full system, have been made continuously since that time. Of principal concern has been the reduction of gun timing jitter and improvement to the stability of the source RF systems. In April 1986, the thermionic emitter was displaced $+38^0$ off the linac axis to permit installation of a polarized, Ga-As photoemissive cathode, displaced -38^0 off the linac axis. Performance of the off-axis thermionic gun proved to be the same as before the move. Installation and testing of the full polarized source system is pending approval. After nearly a year of continuous operation of CID as the primary electron source for the linac, the old injector guns were removed in September 1986 so as to open up the limiting aperture of the injector.

Electron Booster Linac

The electron booster consists of four SLAC accelerator sections, each powered by a nonSLEDded klystron with a power output level of about 30 MW. Electron energy at the output of the booster section is controlled by a feedback loop which varies the power delivered by the last of the booster klystrons. Positrons are injected into the system at an angle of 12^0 down from the vertical; it was decided to use a DC magnet chicane to deflect the electrons up at the same 12^0 angle so that combination of the two beams occurs in a common magnet. The optics of the booster have been designed to provide strong focusing through the low energy region ($\sim$ 1.5 m spaced FODO array, operated at 76^0 phase shift per cell) and to match into the positron optics of S1. A pulsed, 15^0 vertical bend is located downstream of the positron injection to permit energy and energy spread measurements of electrons and positrons. During this past year of SLC commissioning, the pulsed spectrometer has been operated at several hertz to provide a continuous monitor of the source and S0 performance.

Sector One

Acceleration through sector one is achieved using six SLEDded[4] klystrons, each of which powers four standard SLAC sections. The upstream tube is a SLC type 50-45 klystron[5] which is operated at about 55 MW to provide a large accelerating gradient for the 200 MeV injected beams. The remaining five tubes are the old XK5 type klystrons which are operated at a power output of about 32 MW. As in the electron booster, the energy contribution of the last station in S1 is controlled by a feedback loop to stabilize the energies of the beams delivered to the damping rings.

Strong external focusing has been installed in sector one for the transport of the large positron emittance ($\gamma\epsilon = 1000 \times 10^{-5}$ m-rad). The focusing lattice consists of approximately 75 quadrupoles, installed over a length of 75 m, all operated at nearly the same strength. The spacing of the magnets is increased with beam energy so that the beam size is roughly constant throughout the sector. The strength was chosen so that full emittance positron bunches would have a maximum beam size of 7.00 mm. Beam position monitors (BPMs) and dipole correctors are used to control the transverse beam position through the sector. Because of the lack of space for installation of more BPMs and correctors, considerable attention has been paid to the alignment of the quadrupoles. Unlike the rest of the linac wherein the principal concern about beam position is to reduce emittance growth due to wakefields, the primary interest in beam position through sector one is to maximize the available aperture for the positrons. Induced emittance growth is not expected to be a problem for the large emittance positrons and has not been a problem for the electron beams under present operating conditions. As previously reported[6], the transverse electron emittance has been measured at the exit of the injector (1.21 GeV) to be commensurate with SLC operation at 120 Hz. Emittance measurements made in the last year are consistent with the earlier data. Reduction of the electron emittance at currents greater than 4×10^{10} particles per bunch is expected through tightening of the tolerances on transverse beam position along the injector, particularly in the low energy end of the machine. Measurements at 40 MeV and 90 MeV show that the emittances in the beginning of the machine for 6.5×10^{10} electrons per bunch are less than the $\gamma\epsilon \leq 30 \times 10-5$ m-rad which is required for 180 Hz operation of the SLC.

Automated beam steering, in its final form, was made operational during the spring of 1986. The present form of the steering allows one to steer any of the three bunches. The orbits of the other bunches are subsequently controlled through variation of launch conditions. Initial experiences with double pulse electron beams and with positrons indicate that this scenario is sufficient; more operating experience will point toward possible improvements. Additional dipoles and quadrupoles have been installed at the end of the sector to permit independent targeting of electron and positron beams into their respective LTRs. Software has been written to deduce from BPM readings the launch errors into the LTRs and to compensate for such errors by adjusting the S1 corrector dipole settings. At this time, the software has not been fully tested.

Energy Feedback

Installation of the strong focusing required for positron transport allowed operation of electron currents at the desired intensity. At that time, September 1984, it became evident that energy drift and jitter in the beams at the end of S1 were both serious problems. It was decided to attack these problems in two ways: to locate and eliminate as many sources of energy error as possible, and to develop slow, computer controlled energy feedback processes. Reduction of gun timing jitter and stabilization of the source and overall injector RF systems have greatly reduced the observed energy drift and jitter. A significant improvement has been made through stabilization of RF waveguide temperatures. Microprocessor based controllers[7] have been installed to improve temperature regulation of the water used to cool injector accelerator sections and RF feed waveguides. Variation in waveguide temperature changes the average phase of the accelerating RF as well as the magnitude of the RF power delivered from the SLED cavities which become detuned. The thermal stability of the aforementioned systems is presently about 0.2^0F.

Even with the improved water temperature systems, feedback is still required for compensation of long term drift of both the temperatures and of the power output of subboosters and klystrons. Feedback[8,9] has been implemented to separately control the energies of the three bunches at the exit of the injector, to control the composite energy spread of pairs of electron bunches, and to control the energy spread of the positron bunch[10].

Energy deviations from a reference orbit along the LTRs is deduced from the LTR BPM readings[11]. Differences between the centroid energies of the two electron bunches are nulled by changing the timing of the S1 modulator-klystron triggers so that the beam rides farther up or down the envelope of the

SLEDed S1 RF. Energy deviations of the first electron bunch or positron bunch are corrected by changing the power output of the last klystrons[12] in both S0 (for electron only compensation) and S1 (for positron and electron compensation).

Energy spread compensation is accomplished by adjustments to the phase at which bunches are accelerated through the machine. Several beam position monitors, located at points of large dispersion in the LTRs, have been configured to monitor the beam energy spread on a pulse to pulse, nonintercepting basis[13]. These signals are minimized by a feedback loop which adjusts the RF phase.

Recent Operating Experience

The most recent phase of injector commissioning began in January 1986 with the expressed purpose of bringing the injector up to SLC specifications albeit with a current goal of 5×10^{10} electrons per bunch. In addition to meeting the required specifications it has been necessary to turn an operable system over to the Accelerator Operations Group for continuous delivery of beam to the downstream users, which have consisted primarily of the various SLC subsystems.

During the months of May and June 1986, much of the injector work centered around commissioning automated beam steering from the gun to each damping ring and on bringing up energy feedback for single bunch electron beams. By the end of June 1986, autosteered single electron bunches of intensities greater than about 3×10^{10} particles per bunch were routinely delivered to the damping ring complexes and straight ahead to the linac. At that time, the centroid energies of bunches delivered to the damping ring were successfully being stabilized.

By September 1986, it was possible to control the energy spread of bunches injected into the LTRs using the beam width monitor hardware and computer controlled phase adjustments. Continuous operation of this particular loop has not occurred for two reasons: the work on water temperature stabilization essentially obviated the need for this feedback, and the phase search required to minimize the energy spread is potentially disruptive to the injection of beam into the damping rings. Presently, the principal causes of energy spread variations are step changes associated with the source RF systems. These changes can occur several times a day and are not fully compensated by adjustments to the downstream RF phase settings. Work is continuing on the diagnosis and subsequent fix to this problem.

During October 1986, delivery of energy stabilized two bunch electron injection into the LTRs was established. Over 3×10^{10} electrons in each of two electron bunches have been observed at the end of both the south and north LTRs. Pairs of electron bunches were stored in the north damping ring at this time with the aid of the fast injection kicker. Two bunch extraction from the north ring presently awaits the installation of a fast two bunch extraction kicker. Even though work on two bunch operation is pending, a new gun trigger module has been installed which permits remote, continuous trigger timing adjustments to facilitate double pulse bunching.

In November 1986, positrons were first injected into S1 with an energy of about 170 MeV. At that time, positrons were accelerated on their own RF pulse to the full damping ring energy. A pulsed phase shifter was temporarily installed to allow phasing of the S1 RF for optimal positron acceleration without disturbing the phase setting required for electron beams on subsequent pulses. The pulsed phase shifter was used extensively to measure the energy spread of the accelerated e^+ bunches from which the injected e^+ bunch length could be estimated. During November and December, difficulties in transporting positrons through S1 were attributed to a larger than expected positron bunch length. The e^+ spectrum at the end of S1 was observed to be $\geq 10\%$ FWHM corresponding to a bunch length of $\sigma_z \geq 6.5$ mm. Work during January 1987 reduced the e^+ bunch length to $\sigma_z \approx 4.5$ mm. At the beginning of February 1987, more than 1.75×10^{10} positrons in a single bunch were transported through the ±1.6% energy defining slit of the south LTR. At that time, approximately 80% of the injected positrons were transmitted to the end of S1. Of this number, 83% were transmitted through the energy defining aperture. Since the damping ring energy acceptance has been measured to be ±1%, at least 67% of the positrons transported through the LTR aperture could be expected to be captured in the ring.

In February 1987, the decision was made to reverse the polarity of the south damping ring so as to accept positrons. When the ring came up again, the Operations Group were charged with producing and transporting positrons on a continuous basis without the direction of the injector commissioning group. To date this effort has resulted in a typical delivered positron flux in excess of 1.4×10^{10} e^+ per bunch through the LTR aperture. As many as 2×10^{10} e^+ per bunch have been observed. Work is continuing to increase the number of positrons stored in the ring.

Status and Future Plans

As of March 1987, single electron bunches and single positron bunches are continuously delivered into the SLC damping ring complexes through the SLC injector. All of the hardware necessary for SLC operation of the injector has been installed and checked out. All of the software necessary for operation and control of the injector has been written. Those routines which only require single bunch operation have been commissioned. Some of the multibunch programs have been tested. The electron beams are presently injected within the damping ring energy acceptance and transverse emittance that is commensurate with 120 Hz operation of the SLC. The typical electron current is in excess of 5×10^{10} electrons per bunch delivered to the north damping ring.

Positrons are now injected into S1 with an energy of about 190 MeV. More than 1.4×10^{10} positrons are routinely transported through the LTR aperture. Typical e^+ transmission from injection into S1 through the LTR hole is 65% while the transmission from the end of S1 through the hole is now usually between 85% and 100%. The Operations group is responsible for the maintenance of the beams.

Plans for future work include studies to increase the positron transmission through S1. At present, S1 is steered to flatten the electron orbit while positron transmission is maximized through launch variation. Experiments will be conducted to see if S1 orbit and focusing corrections can increase the fractional e^+ transmission. During the initial period of damping ring and linac checkout with positrons, e^+ bunches are being accelerated in S1 on separate (from e^- beams) RF pulses. Co-acceleration of single bunches of e^- and e^+ through S1 is necessary for colliding beam operation of the SLC at 60 Hz. Co-acceleration of two e^- bunches with the single e^+ bunch through S1 is required for 120 Hz SLC operation. This latter mode of operation requires the installation of a fast two bunch extraction kicker in the north damping ring. With the advent of e^- and e^+ co-acceleration, commissioning of the multibunch energy stabilization will be possible.

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