SLAC-PUB-3285
January 1984
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MAKING ELECTRON BEAMS FOR THE SLC LINAC*

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Summary

A source of high-intensity, single-bunch electron beams has been developed at SLAC for the SLC. The properities of these beams have been studied extensively utilizing the first 100-m of the SLAC linac and the computer-based control system being developed for the SLC. The source is described and the properties of the beams are summarized.

Introduction

In contrast to storage rings, the duty factor for colliders is relatively low. The interaction rate for the SLC will be limited to 180 PPS. Under these conditions a high luminosity can be achieved only by increasing the charge density of the beam. The SLC proposal[1] indicated this would be accomplished by increasing the intensity of the beam while simultaneously decreasing the beam emittance. These requirements necessitated the design and construction of an entirely new electron source. The source, which is shown in Fig. 1, is now operational and will be described below.

SLC Requirements

The luminosity of the SLC can be expressed as

$$L \propto N^2/(\epsilon_x \epsilon_y)^{1/2}$$

where N is the number of particles in the beam and ϵ_x (ϵ_y) is the transverse emittance of the beam in the horizontal (vertical) plane. The desired luminosity is 10^{30} cm^{-2}s^{-1}, while the expected emittance is about $\gamma\epsilon = 3 \times 10^{-5}$ rad-m. This results in a requirement of $N = 5 \times 10^{10}$ e^- at the interaction region.

In an RF traveling wave accelerator, the charged particles are accelerated in a bunch on the crest of the RF wave. If the duration of the gun pulse is greater than one RF cycle, multiple bunches are created. For the SLC electron beam it is desirable to have only one bunch per RF pulse while a second bunch separated from the first by about 59 ns will be used eventually to generate the positron beam.

The bunching process which will insure that all the source particles are captured within a single RF cycle restricts the minimum transverse emittance of the beam injected into the linac to $\gamma\epsilon \simeq 10^{-4}$ rad-m for 5×10^{10} e^- in a single bunch. Using an electron damping ring which has been constructed near the 1 GeV point of the linac, it is possible to reduce the emittance by an order of magnitude within one interpulse period.

Wakefields are produced by charged particles passing through accelerating structures.[2] For a high-intensity bunch, the wakefields left behind by the head of the bunch perturb the tail. For distances on the order of a few mm, the longitudinal wakefields, which degrade the spectrum, decrease with distance, while the dipole wakefields, which increase the transverse emittance, grow. The dipole wakefields depend both on the intensity and the displacement of the charge from the center of the accelerating structure. Regardless of how well the beam position can be monitored and displacements corrected, the pulse-to-pulse jitter in the beam position will set a lower limit on the emittance which can be achieved in practice. For a given focusing system, the beam size varies as the square root of the emittance. If the beam size exceeds the extent of the limiting aperture, the transmission of the beam will be reduced. Thus to transport the SLC beam from the injector to the damping ring it is necessary to keep the emittance low, meaning that the bunch length must be short and the jitter low.

The energy acceptance of the damping ring is limited. Since longitudinal wakefields decrease the energy of a particle, the energy spread within a bunch can be minimized by accelerating to high energy with the bunch ahead of the crest of the accelerating RF.

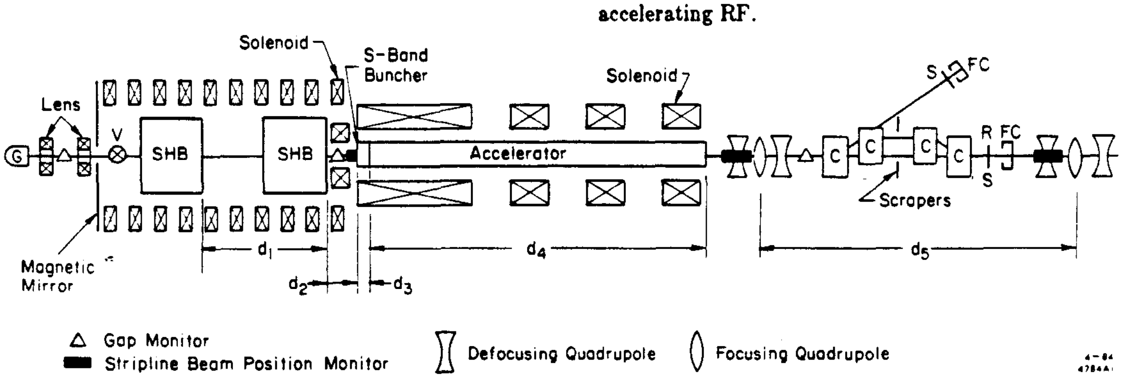

Fig. 1. Schematic drawing of the SLC electron source. Abbreviations which have been used are as follows: C, compressor magnet; FC, Faraday cup; G, gun; L, lens; R, Čerenkov radiator; S, screen for profile monitor; V, valve. The distances d_1 through d_5 are 108, 30, 10.3, 300 and 400 cm respectively. The quadrupole focusing refers to the horizontal plane.

* Work supported by the Department of Energy, contract DE-AC03-76SF00515
Contributed to the 1984 Linear Accelerator Conference, Seeheim/Darmstadt, West Germany, May 7-11, 1984.

High-Intensity Gun and Pulser

Prior to the SLC, the PEP gun was the most advanced short-pulse gun at SLAC. It is a thermionic-cathode gun that will emit up to 1 A in a pulse 1 ns wide. Two separate development routes were chosen for the SLC source. A photoemitting GaAs cathode 1.5 cm in diameter in which valence band electrons are pumped into the conduction band (surface treated to have negative electron affinity) by a pulsed laser has been successfully operated in the laboratory.[3] This gun is designed to be space charge limited to 15 A peak current. If the laser is tuned to the correct frequency, the electron beam is polarized, a useful property for some high-energy physics studies.

A new thermionic gun having a cathode area four times as large as that of the PEP-gun became operational in the spring of 1981.[4] The thermionic gun, although it will not generate polarized beams, has in other respects proven adequate for the SLC. While the gun emission can be as high as 10 A with a 4 ns pulse, the gun is more often operated with an emission of 7 to 8 A for which the pulse width is typically 2-3 ns FWHM. The present avalanche-transistor pulser is capable of driving the gun to produce 1 ns pulses but with the sacrifice of some intensity. At present this gun can be pulsed only once within the time frame of one accelerating RF pulse, but a new pulser utilizing a planar triode tube is being built which will allow two gun pulses to be generated.

Buncher

Since the gun pulse is wider than a single S-band cycle, the particles must be partially bunched prior to injection into the S-band RF. Bunching at the 16th subharmonic of the accelerating frequency was chosen since a proof-in-principle single-bunch L-band accelerator utilizing subharmonic bunching already existed at ANL. A quarter-wave reentrant standing-wave cavity was chosen because of its small radial dimension.

The gun pulse fits within one half-cycle of the subharmonic buncher (SHB) RF. There is adequate bunching with one SHB cavity, but to correct the relativistic asymmetry between the bunching at the front and back of the pulse, a second cavity is needed.

The final bunching before injection into the accelerator section is accomplished with a traveling wave S-band buncher located in front of a 3-m accelerator section. The buncher consists of four cells tuned for a phase velocity of $v_p = 0.75$ c and provided with separate RF phase and amplitude control. This buncher acts as a phase space transformer: the incoming beam has a large phase spread which must be matched to the acceptance of the accelerator which has a small phase spread but which will tolerate a larger energy spectrum. Computer simulations show that for a 15 A peak Gaussian-shaped gun pulse with a σ of 0.5 ns, about 8×10^{10} particles will enter the buncher within 200° of S-band phase and should be compressed within $\pm\sigma_z$ in a final asymtotic bunch with a σ_z of 7 ps.[5] Bunch lengths of $\sigma_z \simeq 9$ ps containing a total charge of about 6×10^{10} e^- have been measured for the beam exiting the accelerator section.

Beam Transport

A symmetrical focusing system is utilized to transport the electron beam to the linac. Although the gun electrode system is designed to produce a slightly converging beam, magnetic focusing is required to prevent the beam from growing radially due to space charge forces. Two magnetic thin lenses are used to match the beam from the gun into a solenoid surrounding the SHB region. The solenoidal field around the SHB and accelerator section is adjusted to counter the space charge forces that increase rapidly as the bunching progresses. Once the beam is completely relativistic, the strength of the focusing field is relaxed and the beam is then transported by a series of quadrupole triplets with a period of about 3-m and adjusted to give a betatron phase shift of 90° per period.

Beam Parameters

The intensity of the bunched beam is measured with a Faraday cup located about 3.5 m beyond the accelerator section shown in Fig. 1. The number of bunches in the beam can be monitored by a gap monitor[6] and a sampling scope. In addition, the normalization data associated with the stripline beam position monitors[7] shown in Fig. 1 are proportional to the beam intensity. The maximum intensity of the bunched beam which has been measured is 1.5×10^{11} e^- corresponding to a capture efficiency of about 60%. The gun emission is usually lowered to give a bunched intensity of 5-10 $\times 10^{10}$ e^-.

The transverse emittance of the beam, assuming no x-y coupling, is simply the square root of the determinent of the sigma matrix for the plane of interest. The sigma matrix at a quadrupole can be deduced from a set of measurements of the beam size at a downstream profile monitor as the strength of the quadrupole is changed.[8] Using this technique, the emittance has been found to vary as the square root of the beam current and to have a value of $\gamma\epsilon \simeq 1.5 \times 10^{-4}$ rad-m for an intensity of 5×10^{10} e^-.[9]

The beam energy and spectrum are measured with the energy analyzer shown in Fig. 1. It consists of a net bend of 28°, a ZnS screen, in air, viewed by a linear photodiode array. An online microcomputer is used to calculate $\delta E/E$ from the digitized photodiode signals as well as to generate a real-time scope display.

Bunch Shaping

Since the effect of wakefields in the linac is so closely related to the longitudinal charge distribution, it is important to be able to control the bunch shape. For this purpose a bunch compressor consisting of four dipole magnets designed to produce an achromatic bump in the beam has been place downstream of the accelerator section. To use the compressor, a correlation between the energy and the phase of the particles within the bunch must be introduced. By placing the bunch forward of the RF crest in the 3-m accelerating section, the head of the bunch will be lower in energy than the tail. The low energy particles take a longer route through the compressor than the high energy particles so that on leaving the compressor the bunch length is shortened.

The present technique used to shift the phase of the bunch with respect to the accelerating RF is to alter within the accelerator section both the accelerating gradient and the phase velocity. Increasing the RF power by about 15 MW will advance the asymtotic phase of the bunch by about 15 degree. The phase velocity can be decreased by raising the metal temperature. For the SLAC accelerating structure, the phase advance of the bunch is about 2° per °C temperature rise. A more convenient technique for advancing the phase of the bunch would be to shift the RF phase of the accelerator klystron in a time significantly less than the filling period of the accelerator section.

The bunch length is monitored with a streak camera which has a nominal resolution of 2 ps. (A slit in front of the camera, as typically adjusted, limits the resolution to about 3.5 ps.) The camera sees the Čerenkov light from a 1 mm quartz, retractable radiatior placed at 45° to the beam just downstream of the compressor. The resolution of the light collecting system is limited by the thickness of the radiator to about 2.3 ps.

With 25 MW of RF peak power and a temperature increase of about 2°C, the bunch length can be reduced to about 13 ps FWHM using the compressor. An example of compression is shown in Fig. 2.

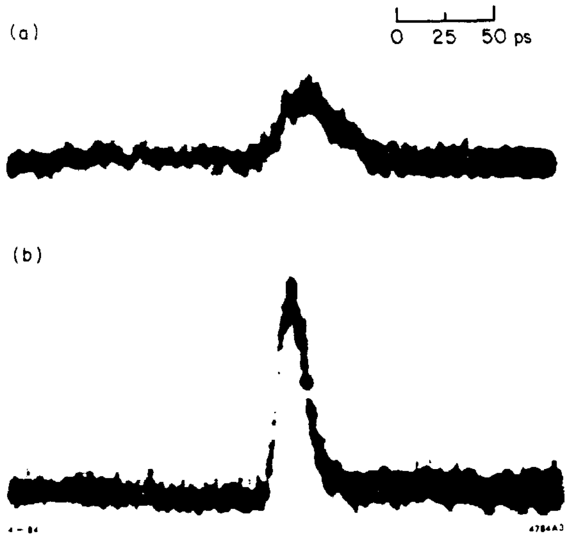

Fig. 2. Longitudinal charge distribution measured by a streak camera for a total charge of $5 \times 10^{10}\ e^-$: (a) no compression, 32 ps FWHM; and (b) same beam with compression (but without scraping), 15 ps FWHM (risetime = 5.3 ps).

Additional bunch shaping is possible using two scrapers that are located in the high dispersion region of the compressor. Either (or both) the high energy or the low energy tail can be removed to better sharpen the front or rear edge of the compressed bunch. Scraping the already sharp front edge doesn't visibly affect the bunch length but presumably would reduce the effect of dipole wakefields. Scraping the rear edge does reduce the the bunch length (to as low a value as 11 ps FWHM when the remaining charge is $3.5 \times 10^{10}\ e^-$).

The source parameters are summarized in Table I.

References

1. SLAC-Report-229 (June 1980).
2. A. W. Chao, AIP Conf. Proc. no. 105, Physics of High Energy Particle Accelerators, SLAC (1982), p. 353.
3. C. K. Sinclair and R. H. Miller, IEEE Trans. Nucl. Sci. NS – 28, 2649 (1981); C. K. Sinclair, private communication.
4. R. F. Koontz, Proc. of the 1981 Linear Accelerator Conference, LA-9234-C (1981), p. 62.
5. M. B. James and R. H. Miller, IEEE Trans. Nucl. Sci. NS – 28, 3461 (1981).
6. R. F. Koontz and R. H. Miller, IEEE Trans. Nucl. Sci. NS – 22, 1350 (1975).
7. J.-C. Denard, G. Oxoby, J.-L. Pellegrin *et al.*, IEEE Trans. Nucl. Sci. NS – 30, 2364 (1983).
8. J. C. Sheppard, J. E. Clendenin, R. H. Helm *et al.*, IEEE Trans. Nucl. Sci. NS – 30, 2161 (1983).
9. M. B. James, J. E. Clendenin, S. D. Ecklund *et al.*, IEEE Trans. Nucl. Sci. NS – 30, 2992 (1983).

Table I. SLC Electron Source Parameters

Thermonic gun		
cathode area	$2.0\ cm^2$	
grid-cathode separation	$150\ \mu$	
anode voltage	150 kV	
net drive (typical)	100 V	
peak current (maximum)	10 A and 4 ns pulse width	
peak current (typical)	7.5 A and 3 ns pulse width	
Subharmonic buncher (178.5 MHz)		
peak power per cavity	1.8 kW	
inner conductor diameter	3.5 cm	
gap width	3.8 cm	
shunt impedance	2.2 MΩ	
S-band buncher (2856 MHz)		
peak power (typical)	450 kW	
phase velocity	0.75 c	
Accelerator (2856 MHz)	Tuned for peak energy, sharp spectrum	Tuned for energy-phase correlation
peak power	12 MW	25 MW
accelerating gradient	13.3 MeV/	16.7 MeV/m
RF phase jitter (typical), σ	0.1°	
RF amplitude jitter (typical), σ	0.02%	
Bunched beam		
charge (maximum)	$1.5 \times 10^{11}\ e^-$	
charge (typical)	$5 \times 10^{10}\ e^-$	
emittance (at $5 \times 10^{10}\ e^-$), $\gamma\epsilon$	1.5×10^{-4} rad-m	
energy, E	40 MeV	50 MeV
energy spread, $\delta E/E$	$\simeq$ 1% FWHM	$\geq$ 10% FWHM
minimum bunch length (at $5 \times 10^{10}\ e^-$)	20 ps FWHM	13 ps FWHM (with no scraping)
position jitter, σ	$\leq 50\ \mu$	
intensity jitter, σ	$\simeq$ 1%	