SLAC-PUB-2698
February 1981
(A)
CONF 810314--148

SINGLE BUNCH-BEAM MEASUREMENTS FOR THE PROPOSED SLAC LINEAR COLLIDER*

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Abstract

Single S-band bunches of $\sim 10^9$ electrons have been used to study the characteristics of the SLAC linac in anticipation of its operation as a linear collider. Emittance measurements have been made, the longitudinal charge distribution within single bunches has been determined and transverse emittance growth has been produced by deliberately missteering the beam. New equipment is being installed and checked out, and the sensitivity of new traveling-wave beam position monitors has been measured.

Introduction

The proposed SLAC linear collider (SLC) will require a beam consisting of single S-band bunches, each bunch containing about 5×10^{10} particles.[1] A new solid-state, photoemission source[2] is presently being installed which, combined with a new subharmonic buncher[3] (SHB), is expected to produce a single-bunch beam of the desired intensity. The location of the SLC source upstream of the regular gun is shown in Fig. 1.

Single-bunch beams can also be produced with the regular thermionic SLAC gun. Although these beams are about two orders of magnitude lower in intensity than the beam expected from the SLC source, they have proven useful for developing measuring techniques. To produce the single-bunch beams, a 10 ns pulse from the regular gun was passed first through the injector accelerator section to produce a 10 ns train of S-band bunches, each about 5 ps long. A resonant chopper operating at the 72nd subharmonic (39.667 MHz) of the linac accelerating frequency (2856 MHz) then would sweep the beam in the vertical plane. The chopper power was sufficient to eliminate all the bunches except the one timed to coincide with a zero-crossing of the chopper rf. Beams with intensities up to $\sim 10^9$ electrons per bunch were produced. Some vertical jitter was evident in the beam due to phase jitter in the chopper rf.

Transverse Emittance

The SLC will require precise, computer-controlled measurements of the beam emittance. As a model for these measurements, the transverse emittance, ϵ, of the single-bunch beam from the regular gun was measured at the end of the first 100-m sector of the linac.

If the phase space distribution is assumed to be elliptical, the radius of the beam at a given z-location will vary hyperbolically with the strength of an upstream lens. In each plane the beam emittance can then be determined from the minimum of the hyperbola, which is proportional to the divergence of the beam at the lens, and from the asymptote of the hyperbola, the slope of which is proportional to the radius of the beam at the lens.[4]

The profile monitor located at z = 100 m was used to estimate the beam radius, -. The quadrupole located 12-m upstream of the monitor was chosen as the lens to be varied. By changing the focal length, f, of the quadrupole, the phase space ellipse could be rotated at the profile monitor. The results are shown in Fig. 2 where the data for both the horizontal and vertical planes are plotted.

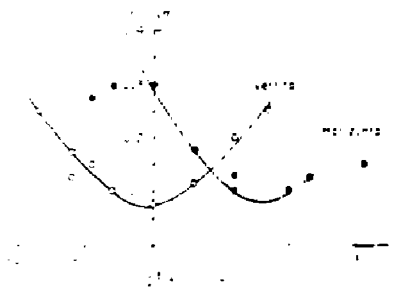

Fig. 2. Beam radius as a function of lens strength. The horizontal (vertical) data are plotted with closed (open) circles. The solid curves are to guide the eye.

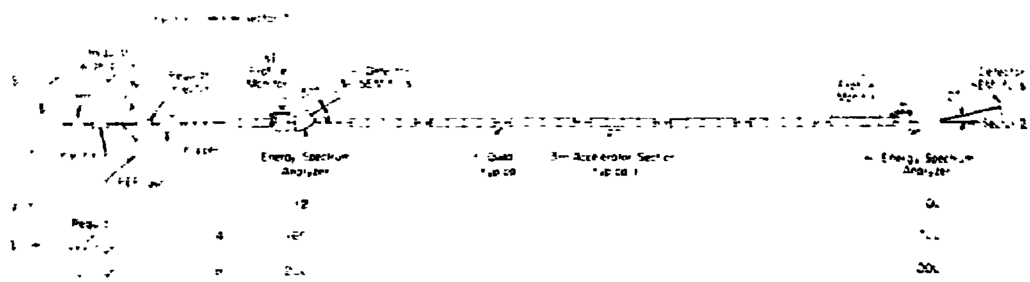

Fig. 1. Schematic diagram of the injector and the first 100-m sector.

*Work supported by the Department of Energy under Contract DE-AC03-76SF00515.

(Contributed to the 1981 Particle Accelerator Conference, Washington, D.C., March 11-13, 1981.)

The dependence of ϵ on r and f is particularly simple if the acceleration between the lens and the monitor is ignored. Transforming the beam radius at the lens, r_o, by the action of the lens and of the drift length ℓ gives:

$$r^2 - r_{min}^2 = \ell^2 r_o^2 (f^{-1} - f_{min}^{-1})^2 .$$

where (r_{min}, f_{min}^{-1}) is the vertex of the hyperbola which fits the data. Since the angular divergence of the beam at the lens, θ_o, is given by $\theta_o = r_{min}/\ell$, the emittance is

$$\epsilon = r_o\theta_o = \frac{r_{min}(r^2 - r_{min}^2)^{1/2}}{\ell^2(f^{-1} - f_{min}^{-1})} .$$

Using this relationship, the emittance areas, $A = \pi\epsilon$, determined from the data of Fig 2 were $A_x = 0.009\ \pi\, m_oc - cm$ and $A_y = 0.012\ \pi\, m_oc - cm$. An earlier measurement by a different method gave $A_x = A_y = 0.008\ \pi\, m_oc - cm$.[5] For comparison, the SLC electron beam, at this same location, is expected to have $A \sim 0.03\ \pi\, m_oc - cm$.

The method described here was chosen because of the ease by which the profile monitors can be interfaced to the same on-line computer that will control the quadrupoles. This interfacing has been accomplished by replacing the regular cameras viewing the CsI screens of the profile monitors with photodiode arrays having digital outputs. The on-line computer will also be able to transform the beam radius, taking into account acceleration, regardless of which upstream quadrupole is used to rotate the phase space ellipses.

Bunch Charge Distribution and Wake Fields

As heavily charged bunches of electrons or positrons pass through linac structures, wake fields within a broad frequency spectrum which depend on the structure are produced by early particles in each bunch, which affect later particles coming behind them within the same bunch. These wake field are of two types: longitudinal and transverse. The longitudinal fields have the effect of broadening the energy spectrum within the bunch[6] while the transverse fields cause transverse deflection and emittance growth.[7] Both effects are proportional to the charge density in the bunch and depend on the charge distribution within it. For times on the order of a few picoseconds (a few degrees at 2856 MHz), the longitudinal fields decay exponentially with time after the passage of the "slice" of particles which excited them, whereas the transverse fields rise linearly within the same time and are proportional to the radial displacement of the bunch centroid with respect to the linac centerline. To verify the theory of longitudinal and transverse wake field effects, it is thus important to measure the charge distribution of the SLC beam at the beginning of the linac.

The length of picosecond bunches can be deduced from measurements of the energy distribution.[4] For the measurement with the single-bunch beam from the regular SLAC gun, the 30° energy analyzer at $z = 12$ m was chosen and klystron K1C, which is located immediately upstream of the analyzer, was used to vary the energy, γ, of the beam. This klystron contributes a peak energy of γ_1.

The measurement was made by first adjusting the magnet current of the analyzer to center the beam on one of the SEM foils with K1C off. Then, with K1C on, the phase, ϕ, of K1C was rotated through 360°. A plot with an x-y recorder of the analyzed current, $dq/d\gamma$, from the single foil as a function of ϕ is shown in Fig. 3. The two spectra shown in the figure, the peaks of which are 180° apart, correspond to the two zero-crossings of the energy contribution of K1C.

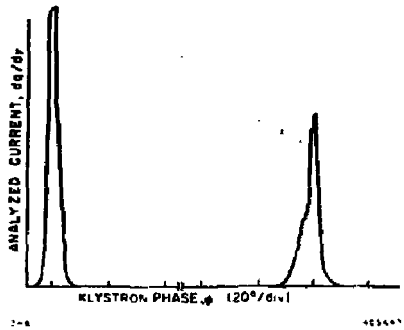

Fig. 3. Spectrometer current measured as a function of the phase of klystron K1C. The beam intensity was $\sim 3 \times 10^8$ electrons/bunch.

For a monochromatic beam, the charge distribution, $dq/d\theta$, is proportional to $dq/d\gamma$, where θ is the relative phase of the beam. However, the dependence of the initial beam energy on θ will broaden one of the two recorded spectra and narrow the other. The effect of the linear term in the distribution of initial energy with phase can be eliminated by combining $dq/d\gamma$ for the same value of θ from each of the two spectra according to the following expression:

$$\frac{dq}{d\theta} = \frac{(dq_a/d\gamma)(dq_b/d\gamma)\ \gamma_1\ 2\sin\frac{1}{2}(\phi_b - \phi_a)}{|dq_a/d\gamma| + |dq_b/d\gamma|} .$$

By assuming that the peaks in the spectra of Fig. 3 correspond to the same θ, and that points at the same percentage of the peak value represent nearly the same θ, it was possible to use this expression to plot the corrected spectrum shown in Fig. 4.

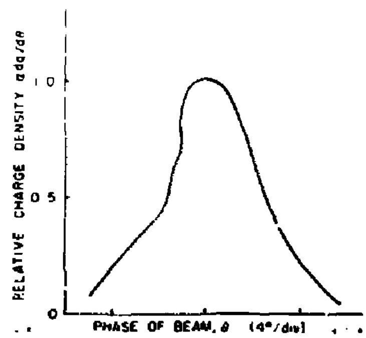

Fig. 4. Longitudinal distribution of charge density derived from the data of Fig. 3.

The charge distribution shown in Fig. 4 has $\sigma_z \sim 0.6$ mm. The SLC beam is expected to have $\sigma_z \sim 1$ mm.

Wake Field Measurements

For SLC operation, an extensive test program is underway to measure the effects of both longitudinal and transverse wake fields at the end of the first 100 m of the linac. The longitudinal measurements which were originally made for the entire 3-km length[6] will be repeated as soon as 5×10^{10} e^- bunches from the new gun become available. For the transverse measurement, a preliminary test of the theory has already been made with the regular gun by deliberately inducing large wake fields by missteering the beam. The first 100-m linac sector is the ideal place to observe these effects since the quadrupole lattice can be adjusted to make the sector equivalent to exactly a half betatron wavelength. This condition is readily checked by steering the beam at $z = 0$ and noting that a very low intensity beam does not move on the profile monitor at $z = 100$ m. After adjusting the betatron wavelength, the test was made by observing the motion of the tail of a bunch of $\sim 9 \times 10^8$ electrons at the $z = 100$ m profile monitor as the horizontal injection angle at $z = 0$ was varied. The horizontal motion of the tail was made easier to observe by first producing a tail in the vertical plane as shown in Fig. 5. The tail was estimated to contain 10 – 40% of the total charge in the bunch.

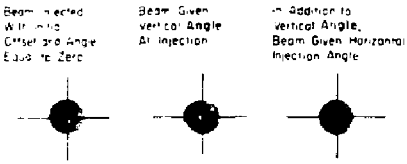

Fig. 5. Beam profile at the end of Sector 1. Cross marks indicate the center of the accelerator tube. The tail is the lighter region.

With the tail visible in the vertical plane, the bunch was given a horizontal injection angle of 0.7 mrad. The centroid of the tail was observed to move in the horizontal plane by 1 ± 0.3 mm relative to the head. For a low-intensity beam, a first-order calculation is sufficient to determine the expected deflection of the tail. Assuming a rectangular charge distribution, uniform betatron focusing, and a linear wake function of $W_0 = 4.9 \times 10^5\ m^{-3}$, the calculated deflection of the center of the bunch is ~ 1 mm. Thus the observed and predicted deflections are in reasonable agreement. More precise measurements will be possible using the previously described computer-interfaced profile monitors.

Beam Position Monitoring

To control transverse emittance growth in the SLC beam, the actual trajectory of the beam must be measured with a precision of $\pm$ 0.1 mm or better. Since within a single accelerator pulse the SLC beam will contain three single bunches separated by as little as 60 ns, the position of the individual bunches can be distinguished only if the monitor has a wide-band structure. To meet these criteria, the nonintercepting, traveling-wave stripline monitors[8] shown in Fig. 6 were installed inside each of the quadrupoles located between 12-m linac girders. Each monitor consists of four 12-cm strips shorted at the downstream end. Upon passage of a beam bunch, a "doublet" pulse is produced at each strip, the time separation of the two impulses being equal to twice the electrical length of the strip. The peak current of each impulse is proportional to the peak beam current and varies inversely with the transverse distance of the beam from the strip. A typical doublet seen by an oscilloscope with a 400 MHz bandwidth at the end of 30 m of ordinary coax cable (RG 223) is shown in Fig. 7. The relative variation of the peak current of an impulse was found to be $\sim 15\%$ per mm of beam motion. Thus the electronics by which the signal pulses are shaped and digitized must have an absolute precision of $\pm$ 1% or better. Such a system has been constructed and is now being tested.

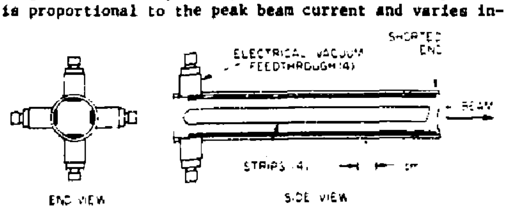

Fig. 6. Cross section of stripline position monitor.

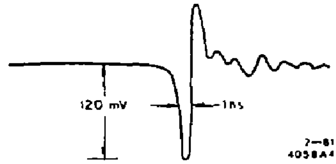

Fig. 7. Typical doublet from single feedthrough of position monitor as seen at end of 30 m of coax. Beam intensity was $\sim 3 \times 10^8$ electrons/bunch.

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