THE SLAC LOW EMITTANCE ACCELERATOR TEST FACILITY*

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Summary

SLAC is proposing to build a new Accelerator Test Facility (ATF) capable of producing a 50 MeV electron beam with an extremely low geometric transverse emittance (1.5×10^{-10} rad·m) for the purpose of testing new methods of acceleration. The low emittance will be achieved by assembling a linear accelerator using one standard SLAC three-meter section and a 400 kV electron gun with a very small photocathode (40 microns in diameter). The photocathode will be illuminated from the back by short bursts (on the order of 6 ps) of visible laser light which will produce bunches of about 10^5 electrons. Higher currents could be obtained by illuminating the cathode from the front. The gun will be mounted directly against the accelerator section. Calculations show that in the absence of an RF buncher, injection of these 400 keV small radius electron bunches roughly 30° ahead of crest produces negligible transverse emittance growth due to radial RF forces. Acceleration of the electrons up to 50 MeV followed by collimation, energy slits and focusing will provide a 3.2 mm long waist of under 1.5 μm in diameter where laser acceleration and other techniques can be tested.

Introduction

SLAC proposes to build an Accelerator Test Facility (ATF) to provide the high energy accelerator community with a beam of unique quality that can be used to test promising new techniques for future accelerators. The ATF will consist of a 50 MeV linear electron accelerator and a transport system to guide the beam to the location of the experiments. One of the main characteristics of the accelerator will be its very low transverse geometric emittance beam. This low emittance (1.5×10^{-10} rad·m) is required for the first major experiment planned for the ATF: acceleration and possibly focusing by laser techniques. This experiment has been proposed by a group headed by Dr. Robert Palmer from Brookhaven National Laboratory, which will be responsible for building and testing the experimental equipment. It will use a grating illuminated by a high-power CO_2 laser built at the Los Alamos National Laboratory. The interaction space of the low emittance beam with the laser field along the grating will be approximately 3 mm long and 1.5 μm in diameter. The effects of this method of acceleration will be measured in a special spectrometer located downstream of the interaction space. The light pulses of the photocathode laser and the CO_2 laser will be synchronized with the RF for the 50 MeV linear accelerator.

Other potential experiments that might be done in the future were discussed at a workshop held at SLAC on December 10 and 11, 1985. The workshop was attended by about forty scientists from many different laboratories and universities. The techniques that were considered included acceleration schemes using plasma or conventional wakefields, two-beams, and switched power radial transmission lines.

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The plan is to design, build and install the ATF in about two years. The location of the facility will be inside End Station B at SLAC. The layout will be flexible so that future experiments other than the laser tests can be incorporated at a later date.

Design Requirements and Technical Description

The initial design of the ATF is driven by the needs of the CO_2 ($\lambda = 10\mu$m) laser acceleration experiment. For proper interaction with the laser, this experiment requires that in the region where the acceleration is to take place, the beam must be contained within a 3.2 mm long cylinder of diameter no greater than 1.5 μm. These dimensions define the geometrical emittance ϵ that is required in combination with the focusing strength β^* at the interaction point. The three relevant equations for a cylindrically symmetric beam of radius σ_r and angular divergence θ around a symmetrical waist are:

$$\begin{aligned} \sigma_r^2 &= \sigma_{r_0}^2 + (\theta_0 z)^2 \\ \sigma_{r_0} &= (\epsilon\beta^*)^{1/2} \\ \theta_0 &= (\epsilon/\beta^*)^{1/2} \end{aligned} \qquad (1)$$

where the subscript 0 designates the coordinate at the waist. For minimum effort (i.e., maximum compatible ϵ and β^*), one makes $\beta^* = z = 1.6 \times 10^{-3}$ m and the required transverse geometric emittance is then $\epsilon = \sigma_{r_0}\theta_0 = 1.76 \times 10^{-10}$ rad-m. A design geometric emittance of 1.5×10^{-10} rad-m has been chosen. Working backwards from here, the invariant transverse emittance, $\epsilon_n = \gamma\epsilon$ (i.e., $p_r\sigma_r$ in units m_0c-m) that is needed is determined by what a practical accelerator can produce. The solution we have chosen is that of a 50 MeV ($\gamma \sim 100$) beam which can readily be obtained with a single 3 m long SLAC section and an XK-5 klystron (36 MW peak power). The required ϵ_n is then 1.5×10^{-8} m_0c-m. Assuming negligible emittance growth between the cathode and the end of the accelerator (see discussion below), the value of ϵ_n then defines the allowable radius of the cathode if one knows the transverse momentum imparted to electrons at the edge of the cathode. Assuming a number on the order of 0.1 eV (6.26×10^{-4} m_0c), one obtains a cathode radius of 2×10^{-5} m (20μm).

The principal characteristics of the ATF are summarized in Table 1 and a schematic diagram is shown in Fig. 1. The boxes which are cross-hatched designate those systems for which the first experimenters (the group headed by R. Palmer from BNL) are responsible. All other systems are the responsibility of SLAC except for the beam transport system for which the responsibility is joint.

The main sub-systems consist of the 400 kV low-emittance gun, the 50 MeV linac with its associated microwave system, the beam transport system with emittance and momentum selection, and an overall instrumentation and control system. The additional sub-systems not shown in Fig. 1 are support and alignment, water cooling, vacuum, power and shielding. A description of the main sub-systems and a discussion of factors affecting emittance growth are presented below.

Table 1. ATF Accelerator Specifications

Photocathode gun voltage	400 kV
Photocathode gun pulse length	6 psec
Photocathode laser wavelength	$\sim 0.5\,\mu$m
Cathode radius	2×10^{-5} m
Transverse momentum at cathode	$6.26 \times 10^{-4}\, m_0c$ (~ 0.1 eV)
Invariant emittance out of gun ϵ_n	$1.25 \times 10^{-8}\, m_0c$-m
Cathode current density	200 A/cm^2
Charge per 6 psec bunch	$\sim 10^5\, e^-$
Traveling-wave accelerator energy (SLAC 3 m section)	50 MeV
XK-5 klystron peak power (2.5 μsec)	36 MW
Klystron pulse repetition rate	≤ 180 pps
Relative electron energy spread $\Delta E/E$	≤ 1 %
Geometric transverse emittance at experiment	1.5×10^{-10} rad-m

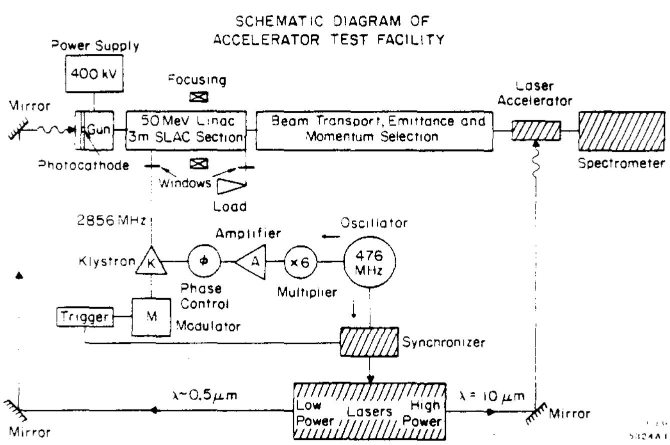

Fig. 1. Schematic diagram of Accelerator Test Facility.

A. 400 kV Photoemission Low-emittance Electron Gun

The gun is designed to deliver a very high-current density (200 A/cm^2) from a very small cathode area (40 μm diameter) for a very short time (6 ps) at a voltage of 400 kV. The photocathode will probably use cesium antimonide (Cs_3Sb) as a photoemitter. This material has been demonstrated to deliver the required current density[1] and it can be deposited on a nichrome substrate with the required area.[2] The field strength at the photoemitter is 10 MV/m, the same as chosen for the lasertron gun[3] and very comparable to the cathode field in the 200 kV SLC polarized gun[4] which has reliably operated at full voltage.

Even though cesium antimonide is more tolerant to imperfect vacuum conditions than other photoemitters used at SLAC, a very good vacuum will be needed in the gun area. The gun will be mounted directly at the entrance of the accelerating structure but will be separated from it by a very small hole ($\sim$ 2 mm in diameter and 1 cm long) with a low conductance ($\sim 0.1\,\ell$/s), one order of magnitude lower than the conductance of the accelerator section. The accelerator section itself will be baked very carefully before use. A residual gas analyzer (RGA) with two heads will be included for monitoring and diagnostics. The gun will use a commercially available 400 kV power supply of the air-insulated type. A ceramic insulator, either single-piece or graded, will be procured for the gun envelope. The laser pulse ($\sim$ 6 ps) will be made available by the experimenters. Its frequency will be close to photoemission threshold ($\lambda \sim 0.5\mu$m) to minimize the amount of energy available for transverse emittance. The pulse, together with the high power CO_2 laser pulse, will be synchronized with the 476 MHz RF source. This will make it possible to control the injection angle of the 6 ps bunch with respect to the 2856 MHz wave in the accelerator section.

For applications other than laser acceleration, bunches of more than 10^5 electrons will probably be desirable. In these cases, it will be possible to use a photocathode with a larger diameter hole for greater illumination from the back, or to illuminate it from the front. Arrangements will be made in the original gun design to allow for these alternatives.

B. 50 MeV Linac

The 50 MeV linac will consist of a single SLAC three-meter accelerator section. A spare section of this type will be selected, inspected, cleaned and baked for this application. In order to avoid the possibility of contamination from the rectangular waveguide and load attached to it, windows will be installed as shown in Fig. 1. The klystron (a SLAC XK-5 36 MW tube), the modulator and most of the microwave equipment are already in existence in End Station B as part of an RF separator system, and only small modifications and additions will be needed to refurbish the equipment and extend the rectangular waveguide to the location of the ATF. The system will be capable of running at a repetition rate of up to 180 pps but the laser repetition rate will at first be only a few pps.

The gun together with the linac and the beamline equipment following it will have to be supported carefully to minimize the effect of vibrations. The vacuum system will include enough pumps to ensure reliable operation of the gun and the system as a whole. A special water-cooling system will be installed to keep the mechanical system from undergoing short-term expansions and contractions. Note that in order to obtain time stability on the order of 1 psec, one needs mechanical stability on the order of 0.3 mm.

C. Transverse Emittance Growth and Energy Spectrum

The ATF differs from other practical linacs in that most of the bunching is done directly at the photocathode by the short laser pulse (6 psec). By using a relatively small number of electrons, the effect of space charge forces can be neglected. Then, by eliminating the usual RF bunching elements (prebuncher and $v_p < c$ buncher) and most importantly, by using a small cathode, the effect of the transverse RF forces is minimized. The bunching and capture process in the traveling-wave ($v_p = c$) three-meter accelerator section is illustrated in Fig. 2(a) in the presence of the E_r and B_ϕ fields. These fields produce time-dependent radial focusing of the beam which can cause emittance growth. Since the radial forces increase linearly with beam radius r, the emittance growth is proportional to r^2. The magnitude of the effect is roughly the same for traveling-wave structures and standing-wave structures illustrated simply in Fig. 2(b). The effect of these radial fields is shown in Fig. 3 where the distribution in transverse phase space of a beam is shown after 10.5 cm of acceleration. For this figure, a zero emittance beam (rays parallel to the axis) was injected with particles at 5 radii from $R_0 = 0$ to $R_0 = 20\,\mu$m and six different initial phases from 50° to 65°. A 16 psec

(~ 15°) bunch length was used to represent a 6 psec pulse which may jitter by ±5 psec relative to the RF fields. Particles entering at a particular phase remain on a straight line (i.e., zero emittance) but the particles entering at a different phase lie along a different line. Thus the projection into the transverse phase plane in Fig. 3 has a finite area. This area is essentially constant from this point to the end of the three-meter accelerator. For this small (20 μm radius) cathode, short pulse (16 psec) and high gun voltage (400 kV), the emittance due to the RF fields is an order of magnitude smaller than the emittance of the beam leaving the cathode.

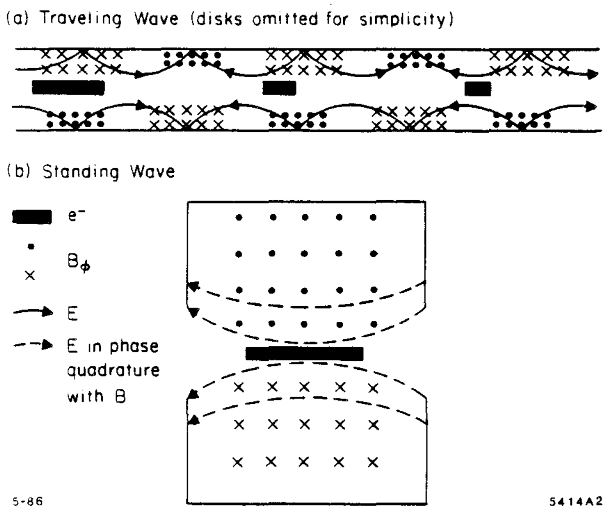

Fig. 2. Simplified field plots a) in traveling-wave accelerator showing radial RF force as electrons are being bunched and fall back on the wave; b) in standing-wave accelerator.

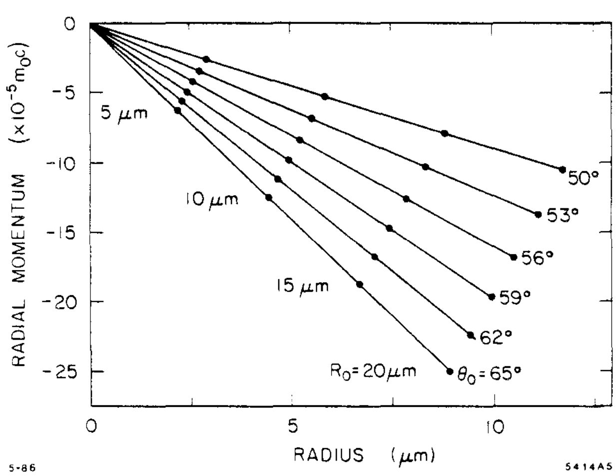

Fig. 3. Transverse phase space after 10.5 cm of acceleration for electrons with initial zero transverse momentum at initial radii R_0 and initial phases θ_0.

Since we assume that the cathode is emission limited at 200 A/cm^2,* if we wanted more current we would have to illuminate a larger area of the cathode. Since the emittance of the beam leaving the cathode is proportional to the cathode radius, but the emittance due to the RF lens effect is proportional to r^2, the RF effect will dominate above some current. This is demonstrated in Fig. 4 which gives the calculated brightness of the ATF beam as a function of charge per bunch. The injected electrons were randomly distributed in time, radius, and transverse momentum. The distributions in time and transverse momentum were Gaussian, while the distribution in radius was uniform out to the radius required for the designated charge per bunch, assuming 200 A/cm^2 emission. The RF effects dominate above several times 10^{-11} Coulomb/bunch. The measured brightness of the SLC injector is plotted in Fig. 4 as a reference point. It is disappointing to find that the laser driven accelerator would be no brighter at high currents than the SLC injector. It is important to point out that these calculations do not include space charge forces, since they are negligible in the region of primary interest for the ATF. The calculations were run into the region above 10^{-10} Coulomb/bunch where neglecting space forces is not valid, in order to display the effect of the time varying radial forces on brightness.

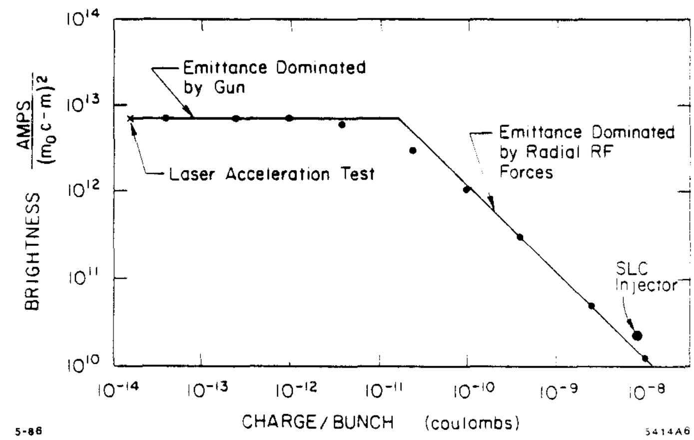

Fig. 4. Calculated brightness versus charge per bunch for ATF-type laser-driven gun as cathode radius is increased to yield greater charge per bunch.

The longitudinal orbits of various electron slices within a 16 psec Gaussian bunch are shown in Fig. 5. Figures 6(a) and (b) respectively show the radial motion of the same slices in the absence and presence of the space harmonics. Note that the space harmonics have a net focusing effect as they should. The difference in the emittance between the two calculations is negligible. In both Fig. 6(a) and (b) the input fringing of the RF field has been suppressed in order to illustrate the space harmonic field effects more clearly.

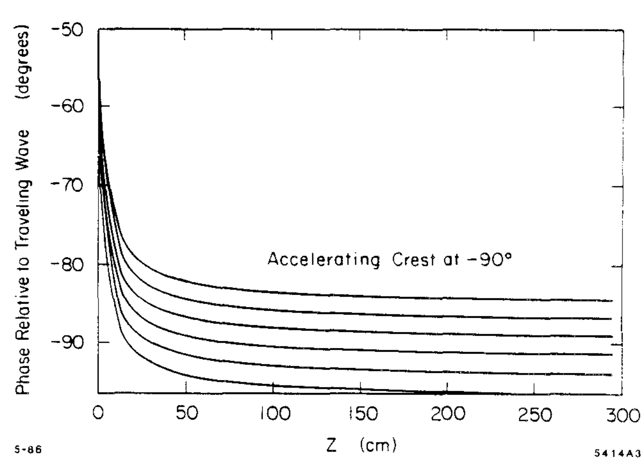

Fig. 5. Longitudinal orbits: phase versus z position.

* Actual current density limit may be much higher.

In the longitudinal direction, it is calculated that the energy spectrum will be well within 1% if one includes the effects of bunch length and time jitter. This corresponds to a ΔE of less than 0.5 MeV at 50 MeV. Even if one did not perform an energy selection at the output of the accelerator, this value of ΔE would be acceptable as compared to the effects of laser acceleration of a few MeV over 3.2 mm which one wants to measure downstream.

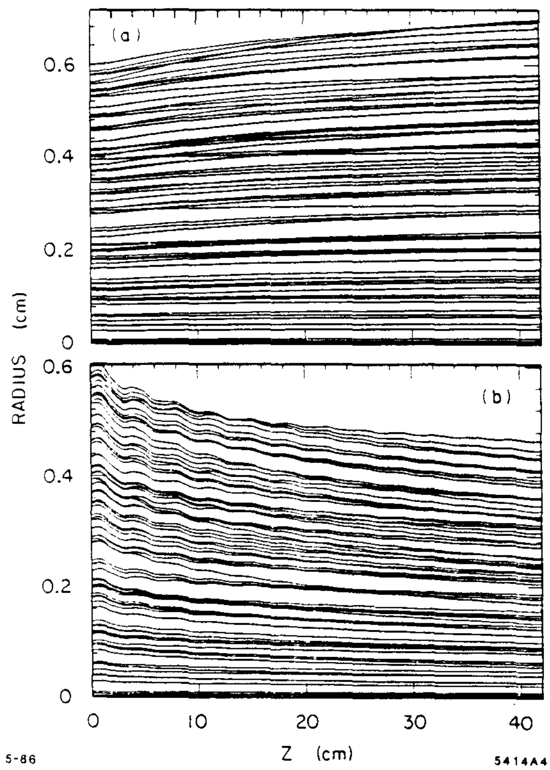

Fig. 6. a) Radial motion with space harmonics suppressed. b) Radial motion with space harmonics included.

D. Beam Line for Emittance and Momentum Selection, and Final Focusing

The 50 MeV beam emerging from the linac will be transported to the experimental area by means of a 25 m long transport system which will permit selection of emittance and energy spread before the beam is focused down to the final micron diameter cross-section.[5] The current attenuation in each stage will be easily adjustable. The emittance and energy spread at the experiment will increase with the number of electrons delivered.

The beamline includes available quadrupoles, new dipoles, steering correctors, slits, collimators, a stopper and a few standard diagnostic instruments. These standard instruments could be used in preliminary tune-up with a higher intensity gun. It is assumed that the ultimate instruments to measure the properties of the beam at the experiment will be furnished by the experimenters. All support and alignment tolerances, vibrational stability and power supply regulation of the equipment in the line that have been estimated are assumed to be of standards comparable to those practiced on the SLC at SLAC.

E. Location and Shielding

After a careful search, it was determined that End Station B at SLAC would be a good location for the ATF. End Station B is a well-shielded 150 ft long by 80 ft wide building. Of the 80 ft width, a strip at least 25 ft wide and 150 ft long can be made available for the ATF, the beamline, the lasers and the experimental area. There is enough room for future expansion when new experiments for other methods of acceleration are added. For the first experiment, it is assumed that a special area will be built for the lasers inside the end station to shield them from the radiation area and make them accessible from the outside while the equipment is operating inside. Shielding will be added to separate the ATF from the other beamlines operating inside End Station B.

F. Instrumentation and Control

The instrumentation and control system that has been planned for this facility will use a microvax computer with interface, CAMAC modules and standard SLAC instrumentation of design taken directly from the SLC systems. The system will be independent of the central SLAC control system but will be connectable to it for transfer and use of existing programs. The microvax will have enough capacity to accept the required signals from the experiments and the lasers. An existing trailer outside of End Station B is available as a control room for the facility.

References

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