THE SLAC INJECTOR*

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Summary

The injector for the Stanford Two-Mile Linear Accelerator has been designed to achieve optimum bunching, optimum beam optics and flexible operational control of beam parameters. A test injector has achieved 5-degree bunching and 10^{-2}mc-cm area in the x-p_x plane.

Description

The SLAC Injector (Fig. 1) is a single-section linear accelerator consisting of the following components:

1. An electron gun.

2. A prebuncher consisting of a velocity modulation cavity.

3. A bunching section with phase velocity equal to 3/4 the velocity of light, c.

4. A ten-foot long constant gradient accelerator section with velocity equal to the velocity of light.

5. A focusing solenoid (surrounding the buncher and the accelerator) and associated lenses and steering dipoles.

6. A bunch monitor and other beam monitoring equipment.[1]

The beam of 80 keV electrons from the electron gun is initially bunched by the cavity prebuncher, is further bunched and accelerated to 250 keV in a 10-cm—long traveling wave buncher, and then enters the 10-foot-long accelerator section in which it is still further bunched to a 5-degree phase interval and accelerated to 30 MeV.

Design Requirements

The prime objectives of the SLAC Injector design are achievement of optimum bunching and beam optics, and maximum flexibility and reliability of operation. The bunch size is important since it sets the ultimate limit on the narrowness of the energy spectrum which can be achieved with the two-mile accelerator. A broad spectrum both reduces the number of useable electrons for many experiments and increases the radiation background which these experiments must discriminate against. The contribution of the bunch size to the energy spectrum of an otherwise perfect accelerator has been set at 0.1%. For optimum phasing of the injector relative to the rest of the accelerator, the relative energy spectrum is given by

$$\frac{\Delta E}{E} = 1 - \cos\frac{\theta}{2} \approx \frac{\theta^2}{8} \qquad (1)$$

where θ is the bunch length in radians. For a 0.1% spectrum, a 5-degree bunch is required.

The maximum current at which the two-mile accelerator can run routinely may be set by the radiation along the length of the accelerator, and consequently by the beam optics rather than by the maximum current the injector can deliver. The specification for beam loss is that the power radiated due to beam interception in each of the 30 sectors (330-foot-long module of the accelerator) shall not exceed 0.1% of the maximum beam power at the end of the accelerator. From this it follows that 80% of the current from the injector must reach the end of the two-mile accelerator when the accelerator is run at full beam power. Since the energy of the beam increases along the accelerator, the current lost per sector must decrease, half of the intercepted current being intercepted in the first sector. The admittance (defined here as $\pi r \times p_r$ at beam minimum) of the accelerator is determined by the admittance of the first sector and is about 0.1 mc-cm.

Flexible operation of the injector is mandatory for good utilization of the beam from the accelerator. A triode gun permits the beam current and pulse length to be selected on a pulse-to-pulse basis from any of the three preset levels. Each of the three preset pulse lengths can be continuously varied from 0.02 to 2.2 μsec, and, similarly, each current level can be varied from 0.001 to 1.0 amperes. In addition the energy of the accelerator beam can be varied from pulse to pulse by switching klystrons beyond the injector in and out of time with the beam. These features permit carrying on several experiments simultaneously. They also enable the operator to set up a new beam at a low repetition rate while a previous experiment is using most of the pulses.

These requirements are reflected in the specifications presented in Table I. The klystron driving the injector will be conservatively run at 1/2 to 2/3 full power to improve its life and reliability. To further improve reliability, a standby klystron and klystron modulator will be installed. A waveguide "switch," consisting of two 3-db hybrids and a hybrid phase shifter in the configuration commonly used for variable directional couplers, will be installed. When the phase shifter is moved 180 degrees, the power from the standby klystron is delivered to the accelerator and power from the other is dissipated in a dummy load.

Buncher Design

The buncher design concept is one suggested by Lichtenberg[2,3] of matching the longitudinal phase space emittance of a prebuncher to the admittance of the accelerator with a quarter-wave transformer. Consider the following:

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TABLE I

INJECTOR SPECIFICATIONS

1.	Klystron Peak Power	12 MW
	Power to prebuncher	≈ 1 kW
	Power to buncher (v_p = 0.75c)	≈ 0.4 MW
	Power to accelerator	10.5 MW
2.	Beam Radius	0.5 cm
3.	Radial Phase Space ($\pi r \times p_r$)	3×10^{-2} mc-cm
4.	Bunch Length (80% of Accelerator Current)	5 degrees
5.	Phase Coherence of Bunches	± 5 degrees
6.	Resolution of Bunch Monitor	1 degree
7.	Loaded Beam Energy	30.7 MeV (at 0.09 ampere)
8.	Unloaded Beam Energy	34.1 MeV
9.	Energy Spectrum[a)]	± 3%
10.	Peak Beam Current	
	Short pulses	1 ampere
	Long pulses, typical operation[b)]	0.09 ampere
	Long pulses, maximum capability	0.45 ampere
11.	Allowable Current Variation	
	Within pulse	± 0.5%
	Pulse-to-pulse	± 0.75%
12.	Current Pulse Length	Adjustable within a range of 0.02 to 2.1 μsec
13.	Repetition Rates	1, 60, 120, 180, 240, 300, and 360 pps
14.	Multiple Beam Capability	Three interlaced beams with independently adjustable pulse length and current

a) Beam loading partially compensated by early injection.
b) 10% beam loading.

1. A prebuncher whose emittance can be approximated by an erect* ellipse with a momentum extent of p_1 and phase extent φ_1;

2. An accelerator whose admittance for the desired final bunch can be represented by an erect ellipse p_3 by φ_3; and

3. An intermediate traveling wave structure, or buncher, which can be characterized by the fact that a particle performing phase oscillations with a maximum phase excursion of φ_2 will have a maximum momentum excursion p_2.

The problem is to find the essential properties of the buncher so that it will transform the prebuncher emittance ellipse into the accelerator acceptance ellipse.

It has been shown by a number of authors[4,5] than an electron bound to a wave with constant phase velocity less than the velocity of light oscillates in phase and also, of course, in momentum. For reasonably small oscillations and field strengths the equations can be linearized, and the oscillations in phase and in momentum are sinusoidal and in quadrature with each other. Consequently, in a plot of momentum against phase, an electron traces out a closed path which is an erect ellipse. Electrons with differing initial values trace out concentric, linearly-scaled ellipses.

*By "erect" we mean that the principal axes of the ellipse are parallel with the p and φ axes, respectively.

The function of the buncher is presented graphically on the momentum-phase plane in Fig. 2. The coordinate system chosen is one in which the electron in the middle of the bunch is at rest. The ellipse labeled "prebuncher emittance" with principal semi-axes p_1 and φ_1 encloses the initial conditions of all electrons considered to be within the bunch. The ellipse labeled "accelerator admittance" with semi-axes p_3 and φ_3 encloses the desired end points of all electrons in the bunch. The dashed lines represent electron orbits in the buncher which will map initial points a, b, c, d, and e, within the prebuncher emittance into points a', b', c', d', and e' in the accelerator admittance. The orbits are segments of concentric similar ellipses. If p_2/φ_2 is the ratio of the semi-axes of the orbit ellipses within the buncher, then to map points a and c to a' and c', p_2/φ_2 must satisfy the condition

$$p_3 = \frac{p_2}{\varphi_2} \varphi_1 \qquad (2)$$

Since the transformation maps a point on the φ axis onto a point on the p axis, the buncher must be $(2n+1)/4$ phase oscillations long. Similarly, in order to map b and d into b' and d', p_2/φ_2 must satisfy

$$\varphi_3 = \frac{\varphi_2}{p_2} p_1 \qquad (3)$$

From Eqs. (2) and (3) the conditions for the mapping are found to be

$$p_3\varphi_3 = p_1\varphi_1 \qquad (4)$$

and

$$\frac{p_2}{\varphi_2} = \sqrt{\frac{p_1 p_3}{\varphi_1\varphi_3}} \ . \qquad (5)$$

From the linear nature of the mapping it follows that the entire prebuncher emittance is mapped into the accelerator admittance. Equation (4) requires the areas of the two ellipses to be equal. Equation (5) is analogous to the condition on the impedance of a quarter-wave matching transformer in transmission line theory. The buncher orbit ellipticity p_2/φ_2 is the analog of the transformer impedance, while the ellipticity of prebuncher emittance p_1/φ_1 and the ellipticity of accelerator admittance p_3/φ_3 are analogs of the input and output impedances, respectively. The ratio p_2/φ_2 must be the geometric mean of p_1/φ_1 and p_3/φ_3.

In the buncher design for the present injector the buncher approximately doubles the momentum spread while reducing the phase spread by a factor of about 2.

The phase velocity of the wave in the buncher is 0.75 c, the field strength 25 kV/cm and the buncher length (1/4 phase oscillation) $4/3\ \lambda_g$. The mean velocity of the electrons entering the buncher is 0.5 c and is 0.75 c leaving the buncher. Thus the buncher accelerates the electrons as well as transforming the ratio of the momentum extent to the phase extent. The phase velocity in the accelerator is c and the field strength is 120 kV/cm.

Bunch Monitor

Since the bunch size is one of the most important beam parameters, and since the bunch is formed in the injector and remains substantially constant in size throughout the rest of the accelerator, it is desirable to measure the bunch size at the end of the injector. This makes possible an evaluation of bunching independent of the operation of the rest of the accelerator. The function of the bunch monitor is to provide a signal which is simply related to bunch size, enabling an operator to optimize bunching. It is desirable that the bunch monitor should neither intercept nor degrade the bunching or optics of the beam. A bunch monitor has been designed which should fulfill these objectives. It samples the harmonic content of the electron beam at the fundamental frequency, 2856 Mc/sec, and at the fifth harmonic by means of a pair of cavities. The difference between the power from the two cavities is proportional to the square of the bunch length. This can be shown by comparing the derivatives of the envelope of the Fourier current amplitudes with the standard definition of the moment of a distribution. One finds that the n^{th} harmonic current can be expanded in a Taylor series whose coefficients are the moments of the charge distribution

$$I_n = I_o \sum_{m=o}^{\infty} \frac{(i)^m}{m!} \mu_m (n\omega_o)^m \qquad (6)$$

where μ_m is the m^{th} moment of the charge distribution and ω_o is $2\pi \times 2856$.

The full bunch width in radians is most reasonably defined as

$$\theta = 2\sqrt{\mu_2}\,\omega_o \ . \qquad (7)$$

With appropriate choice of coordinates, μ_1 vanishes, so for $n\theta \ll 1$

$$I_n \approx I_o \left(1 - \frac{(n\theta)^2}{8}\right) . \qquad (8)$$

This is easily verified for simple charge distributions, but it is true regardless of bunch shape within the limits of the approximation.

The power from each of the two cavities will be detected, the difference taken and normalized to form the quantity

$$\frac{P_1 - P_n}{P_1} = \frac{\theta^2}{4}(n^2 - 1) \ . \qquad (9)$$

The fifth harmonic has been chosen as the highest harmonic which is cut off in an adequate drift tube (1 cm) for the beam.

Experimental Tests

A test injector has been built embodying all the design concepts of the SLAC injector. The prebuncher and buncher electrical parameters are the same as will be used on the two-mile accelerator, but the mechanical design differs somewhat. The test injector has only the first 50 cm of the accelerator structure which will be used on the final injector. At this point the bunch is essentially formed, but keeping the energy low (6MeV) reduces shielding and radioactivity problems and permits easier measurement of bunching than if the full 10-foot accelerator section been used.

The beam analysis equipment in the test injector includes:

1. Two vertical slits, 2 meters apart, with suitable adjustments for measuring the beam optics in the x, p_x plane;

2. A momentum spectrometer with a 1% resolution;

3. Toroidal transformers for measuring the injector beam current at several points; and

4. A traveling wave rf beam sweeper[6] for measuring bunching.

Power for the rf beam sweeper is coupled from the output of the 24-MW klystron driving the test injector. With 2-MW input to the sweeper, the beam spot gets a maximum deflection of about 30 cm after the 1.5 meter drift. Under these conditions the phase resolution is about 0.5 degrees. Tuning of the test injector for best bunching and semi-quantitative bunch measurements can be done by viewing the swept beam as it strikes a fluorescent screen at the end of the drift space. Precise measurements are made by moving the beam past a slit by driving a calibrated phase shifter in the input waveguide to the rf sweeper. The current reaching a Faraday cup behind the slit is recorded as a function of the phase shifter position. Figure 3 presents charge distributions in the bunch taken in this manner. Curve A of Fig. 3 is a typical case with the injector running at nominal current. Curve B is the tightest bunching observed so far. The gun current in this case was 7 mA peak, the current from the injector, 5 mA. In a different test, a slit which would accept a 5.1-degree phase interval was placed at the end of the drift space. With 117 $\pm$ 5 mA from the injector, the current through the slit was 110 $\pm$ 5 mA.

The optics measurements were made using two slits separated by 2 meters along the beam axis. For each position x_1 on the first slit, the current density at the second slit was measured as a function of their position x_2. Since the transverse momentum is given by

$$p_x = \frac{x_2 - x_1}{L} p ,$$

this experiment measures the current density at the first slit as a function of x_1 and p_x. In the y direction both slits extended farther than the beam. Figure 4 is an example of this data presented as a contour map. The contours are lines of equal current density labeled as percentages of the total current in the beam. The area inside the 90% contour is 9.8×10^{-4} cm-rad. The momentum of the beam was 11.7 mc, so the area is 1.15 mc-cm in the x-p_x plane.

Figure 5 illustrates the momentum spectrum of the test injector beam.

The electronics for the bunch monitor using the 1st and 5th harmonic cavities are not yet completed. However tests using a differential amplifier indicate that the device will be useable for optimizing bunching. Normalization is necessary since the best bunching corresponds to the minimum difference signal, but the signal can also be reduced by mistuning the injector so as to reduce the captured current, thereby reducing the output of both cavities.

List of References

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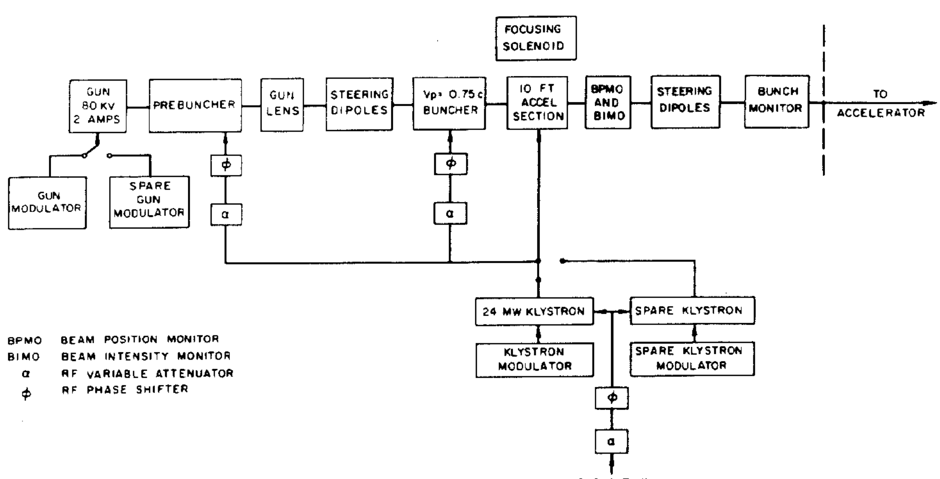

Fig. 1. Main Injector Schematic.

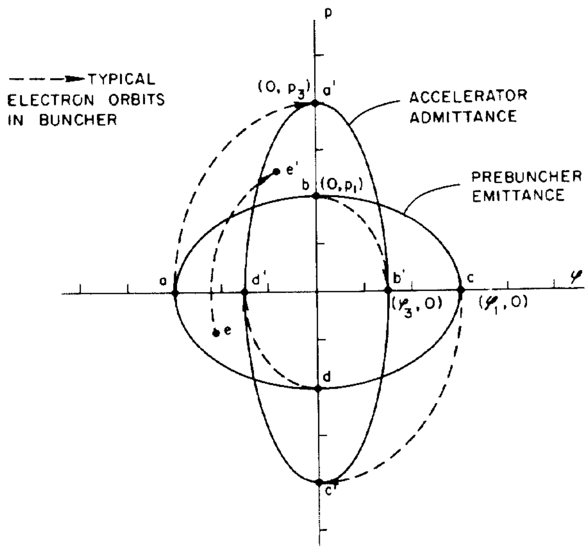

Fig. 2. Buncher Phase Space.

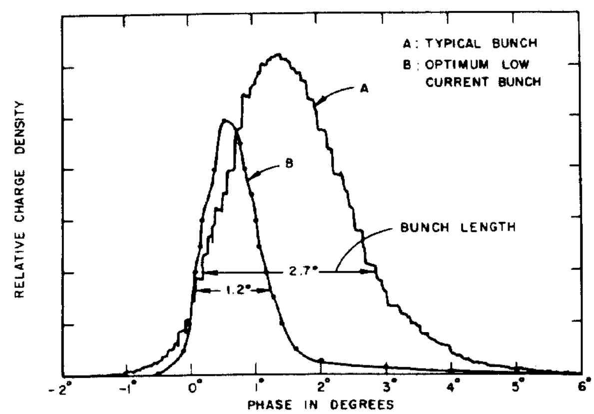

Fig. 3. Charge Distribution in Bunch.

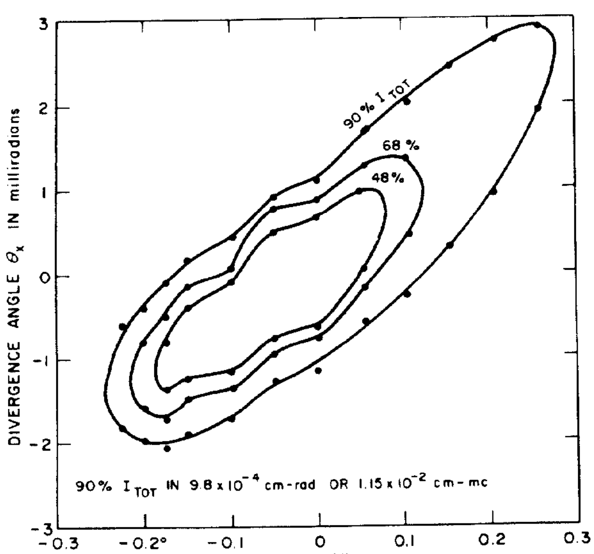

Fig. 4. Test Injector Beam Optics.

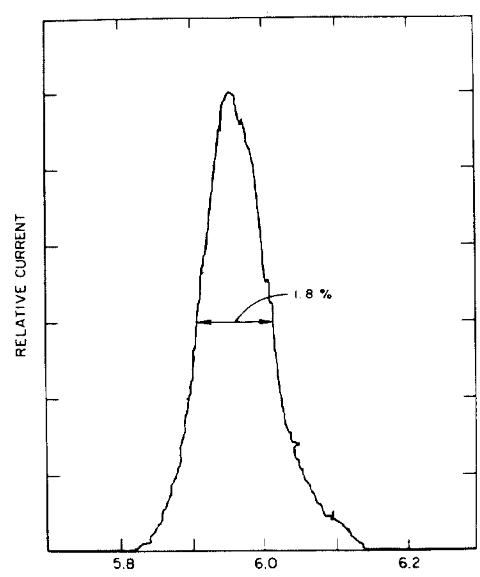

Fig. 5. Test Injector Momemtum Spectrum.