A POSITRON LINEAR ACCELERATOR DESIGN

Craig S. Nunan

Varian Associates
Palo Alto, California

Abstract

A 450 Mev electron 350 Mev positron linear accelerator system is described which has been designed as an injector for a storage ring. Several positron containment systems are considered and a stepped solenoidal magnetic field is chosen as optimum with the converter immersed in the high magnetic field. The parameters of this system are derived for maximum positron beam within specified energy spread and emittance. Performance is reported for initial operation at 40 Mev positron energy.

Introduction

Experiments with high energy colliding beams of electrons and positrons offer a possible field of spectacular developments for high energy physics. Such experiments provide a unique opportunity for a consistent and direct exploration of the electromagnetic properties of elementary particles.[1] Most of the annihilation processes take place through the conversion of the e^+ - e^- pair into a virtual photon of mass equal to the total center-of-mass energy. The photon then converts into the final products. Because all of the energy of collision is in the laboratory frame, 1.5 Gev energy per beam is sufficient to produce elementary particle-antiparticle pairs of highest known rest mass.

A major application of this accelerator will be for injection of e^- and e^+ beams into a 30 meter orbit diameter storage ring for further acceleration at 9.5 megacycles to 1.5 Gev. Because of the nature of the storage ring injection conditions, the accelerator is designed to optimize the product of energy and 1/3 power of current of the e^- and e^+ beams within the limits of $\pm 1/2\%$ energy spread and 10^{-3} radian centimeter emittance.

The linear accelerator beams at the end of the high current section and at the end of the high energy section will also be used directly for experiments, many of which will require narrow energy spread and maximum average current. For example, the e^+ beam can be used for production of a nearly monoenergetic photon beam of smoothly controllable energy for photonuclear research.

The accelerator consists of 12 guides, each pulsed with 10 megawatts peak, 12 kilowatts average r-f power at 2856 mc from six klystrons. The first four guides produce 27 megawatts electron beam power at 65 Mev and 0.42 ampere peak at the positron converter. The next eight accelerator guides increase the total output electron energy to 450 Mev at zero current and accelerate positrons to 350 Mev. Calculated total e^+ current is 1600 microamperes peak and 1.28 microampere average, with 32% within $\pm 1/2\%$ energy spread and 10^{-3} radian centimeter emittance.

Positron Generation

Bremsstrahlung x-rays generated by the deceleration of electrons in a high z converter cause pair production and some of the positrons escape from the converter. The e^+ intensity is relatively uniform over a large solid angle because of elastic scattering of the pairs prior to escape. For example, the r.m.s. scatter angle for an 8 Mev positron originating 0.1 radiation length from output face of converter is about 0.8 radian and the energy loss by ionization in this distance is about 1 Mev.

Measurements[2] of e^+ yield on axis as functions of incident e^- energy from 55 Mev to 220 Mev, target thickness from 1/2 to 3 radiation lengths and e^+ emission energy from 6 Mev to 100 Mev show that the yield is essentially flat and optimum for target thickness from one to two radiation lengths with a broad optimum for positron emission energy at about one tenth the incident electron energy.

The e^+ yield in the above measurements[2] can be approximated by:

$$i_+ = 240\left(1 - \frac{25}{V_-}\right)(\Delta V_+)(\Omega)(P), \qquad (1)$$

where

i_+ = μamps peak positron current,
ΔV_+ = Mev positron energy spread,
Ω = Steradians,
P = Megawatts peak electron power at converter,
V_- = Electron energy at converter.

The first four sections of the accelerator produce a total energy of 105 Mev at zero current with load line to half this energy at 0.55 ampere. For this load line, the above equation gives maximum positron current of $i_+ = 4(\Delta V_+)(\Omega)$ millampere peak per Mev steradian at 65 Mev electron energy and more than 90% of this current from 53 Mev to 77 Mev.

Positron Transmission

Several positron containment systems are discussed below and summarized in Table I. Eight Mev emission kinetic energy and 2 cm diameter useful aperture are assumed. The waveguide irises vary from 2.96 cm to 2.09 cm diameter over each of the eight 5.04 meter long guides. The distance is 5.2 meters from converter to output of the first guide and 43 meters to output of the eighth guide.

No Focusing

With acceleration, the relativistic length is foreshortened according to the relation:

$$L_e = L \frac{\gamma_1}{\gamma_2 - \gamma_1} \ln \frac{\gamma_2}{\gamma_1} \quad (2)$$

where γ_1 and γ_2 are total energy in rest mass units at beginning and end of acceleration. For 348 Mev energy gain over the eight sections, the above lengths foreshorten to two meters to end of first section and 3.8 meters to end of eighth section. Without focusing, e^+ transmission is low and is a fast function of total acceleration.

Full Length Uniform Solenoid

Positrons emitted on accelerator axis in a uniform axial magnetic field follow helices tangent to the accelerator axis. The helix radius, ρ is defined by:

$$H\rho = \frac{m_o c}{e} p_t^* = 1706 p_t^* \text{ gauss centimeter,} \quad (3)$$

where p_t^* is transverse momentum in units of $m_o c$. For 10^{-3} rad cm emittance at 350 Mev, $p_t^* = 0.7$ maximum, for which $H_2 = 2400$ gauss. At the converter, $p_z^* = 16.6$ and the solid angle is

$$\pi\left(p_t^*/p_z^*\right)^2 = 5.6 \times 10^{-3} \text{ steradian.}$$

Positron current at spectrum peak through first and eighth guides is 22 μamps/Mev, with or without acceleration.

Short Solenoid Only

With the converter immersed in a short high intensity magnetic field, positrons complete one half cycle of helix in a "focal length",

$$f = 1.05 \times 10^4 \, V_T/H_1 \text{ cm} \quad (4)$$

For $\Omega_o = 0.2$ steradian solid angle acceptance at converter (emission angle $\theta_o = 0.25$ radian) the length of solenoidal field for helix half cycle is 6.2 cm. At $H_1 = 14{,}300$, $V_T = 8.51$ Mev and positrons of 8 Mev kinetic energy will emerge from H_1 parallel to the axis and offset from it by the helix diameter. Positrons of energy different by ΔV leave H_1 with corresponding radial momentum, p_t, and radial angle,

$$\theta_r = \frac{p_t}{p_z} = \theta_o \cos\left(\frac{\pi}{2} \frac{V_T}{V_T + \Delta V}\right) \quad (5)$$

$$\frac{\Delta V}{V_T} \sim \frac{2}{\pi} \frac{\theta_r}{\theta_o} \qquad \text{for} \quad \frac{\theta_r}{\theta_o} \ll 1 \quad (6)$$

At 8 Mev injection and full acceleration, positrons beyond $\theta_r = +0, -0.0053$ radian are lost on the guide irises. This limits transmitted ΔV to 0.11 Mev at $\theta_o = 0.25$ radian, giving 90 μamps total positron current.

Stepped Solenoid

By combining the short high field solenoid before acceleration with the lower field full length solenoid over all eight guides, the positron transmission is made independent of final acceleration energy and the total transmission is maximized. Positrons emitted from axis with energy different from V_T by ΔV describe helices of smaller radius in the high intensity field H_1 than in the low intensity field H_2 because they keep their radial momentum in the transition from high to low magnetic field. Thus, the acceptance solid angle decreases for off-energy positrons according to:

$$\frac{\Omega}{\Omega_o} = \left(\frac{V_T}{V_T + \Delta V}\right)^2 \left(\frac{\rho_1}{\rho_2}\right)^2 \quad (7)$$

where:

$$\left(\frac{\rho_2}{\rho_1}\right)^2 = \left(\frac{H_1}{H_2}\right)^2 \cos^2\left(\frac{\pi}{2} \frac{V_T}{V_T + \Delta V}\right) + \sin^2\left(\frac{\pi}{2} \frac{V_T}{V + \Delta V}\right) \quad (8)$$

Figure 1 shows curves of solid angle for off-energy positrons. Curves A, B and D show that for chosen value of H_1, the emission energy spread to half intensity accepted by H_2 varies linearly with H_2. Since Ω_o is independent of H_2, the total positron current varies linearly with H_2. However, if the beam transport system beyond the accelerator accepts a limited emittance beam, then this puts an upper limit on the useful product of H_2 and aperture area. With limitation on useful output emittance, the larger aperture of L-band (1300 mc/s) guide would permit use of lower H_2 but would not provide higher transmission than S-band (2856 mc/s) guide.

In Figure 1, curves C, D, and E show that for fixed H_2 the emission energy width is relatively independent of H_1, which may therefore be tuned for optimum positron emission energy. Curve B represents conditions for this accelerator of $H_2 = 2400$ gauss for 10^{-3} radian cm emittance at 350 Mev. Integration under curve B for 3.5 Mev useful energy width and $\Omega_o = 0.2$ steradian gives 0.4 Mev steradian and total positron transmission of 1.6 milliamperes peak.

Quadrupole Lenses

In a very long accelerator, economics require that solenoid focusing be used only for a limited distance after the converter, beyond which quadrupole focusing can be used. A logical point for transition from long solenoid is where the beam emittance permits placement of the quadrupole sets between accelerator sections. Quadrupole sets could be used between sections for the last four guides for positron energies above 175 Mev. However, for maximum positron current over the full range of output energy from a few Mev, solenoids are preferred over the full length of accelerator, provided the corresponding emittance is usable.

Thin Lens

Positron yield has been measured[3] in an accelerator with 17 Mev electrons incident on a positron converter using a thin lens with 0.03 steradian maximum acceptance solid angle and long solenoids over two 1.5 meter L-band accelerator sections producing 600 to 800 gauss. The optimum emission energy for the converter was found to be about one-tenth the incident electron energy.

The focal length of a thin lens is proportional to $V(1 + V)$ where V is the positron energy in Mev. Positrons emitted at angle θ_o with off-energy V will leave the thin lens with radial angle

$$\theta_r = \frac{p_t^*}{p_z^*} = \theta_o \left[\frac{V_o\left(1 + V_o\right)}{(1 + V)} - 1 \right] \tag{9}$$

$$\frac{\Delta V}{V_o} \sim \frac{1}{2} \frac{\theta_r}{\theta_o} \quad \text{for} \quad V_o \gg m_o c^2 \quad \text{and} \quad \frac{\Delta V}{V_o} \ll 1 \tag{10}$$

Comparison with eq. (6) shows that the thin lens transmits $\pi/4$ of the energy spread and total positron current transmitted by the short solenoid. There are also difficulties at 8 Mev in achieving the required magnetic field in a thin lens to collect 0.2 steradian solid angle.

Positron Source Size

Multiple scattering of the incident electrons causes a spreading of the brehmsstrahlung lobe to about ± 6° at 15 per cent intensity, which, in turn, causes a spread in positron source diameter of about one mm. With 0.42 ampere incident electron beam, the pulse heating of the converter is about 170°C per microsecond for two mm diameter focus of uniform current density. For one mm focal spot the normal 3.2 μsec pulse length would have to be shortened to about one μsec to limit pulse heating. Thus, the effective positron source size can be about two mm diameter at short pulse length and three mm diameter at full pulse length.

The effect of positron source size has been calculated[4] for this accelerator with stepped solenoid. The total current transmission is reduced to 96% for two mm diameter positron source of uniform emission density and to 76% for three mm diameter.

The specified output emittance limits useful source emittance at 8 Mev to 0.04 radian cm corresponding to about 3 mm diameter at 0.25 radian. Hence, $\Omega_o = 0.2$ is a suitable design choice.

Output Positron Energy Spread

In a high energy machine of the type described here, phase spread of the impinging electron bunch (less than 8°) and phase spread introduced by the range of flight paths over the acceptance solid angle after the converter contribute to energy spread. Summing these and all other contributions to phase error such as klystron and injection phase errors with ± 1/4% pulse voltage accuracy and waveguide phase errors with ± 0.1°C temperature control, for the worst condition the 17° positron bunch drifts from 1.6° to 3.7° in each of the guides after the converter.[5] Other contributions are due to positron energy spread from the converter, klystron power variations and an assumed 1% due to variation of accelerating energy gradient over the two cm aperture. The r.m.s. sum of all contributing factors is 2.4% energy spread, containing 68% of the total positron current. The calculated portion of total current within 1% energy spread is 32%.

Measurements at 40 Mev

Figure 2 shows a cross section of the converter region and Figures 3 and 4 show the accelerator arrangement used for these tests with four guide sections before the positron converter and one section after the converter.

During the first few hours of operation of this system, the following results were obtained:

(1) 1400 microamperes total peak positron current.
(2) 600 microamperes peak positron current within 3 Mev energy spread. (Pulse amplitude of r-f power to the first section after the converter was low and had not been tuned flat. It was a major source of energy spread.)
(3) Optimum positron current at 9 Mev kinetic energy of emission from converter at 16,000 gauss, dropping to 85% at 6 Mev, 50% at 3 Mev energy of emission.
(4) Maximum positron current at 300 milliamperes electron current on the converter at 76 Mev, dropping to 2/3 this current at 170 milliamperes electron current at 89 Mev. The accelerator has produced 550 milliamperes at the converter but positron yield has not yet been measured at electron

current above 300 milliamperes.

(5) The electron current was comparable to the positron current but at lower energy.

(6) Positron current was approximately proportional to magnetic field of the long solenoid.

(7) Positron current with long solenoid turned on but with short solenoid turned off was about 50% more than the calculated value listed on line 3 of Table I. This suggests that the yield for small solid angle on axis may be higher than indicated by the Orsay data[2] used for this calculation.

(8) With short solenoid turned on but long solenoid turned off, positron current was about 1/5 the calculated value listed on line 5 of Table I. A point source was assumed for the calculation. The acceptance of the section without long solenoid is only 6 milliradian centimeters, whereas the source emittance for 2 mm diameter and 0.2 steradian is 30 milliradian cm.

The total positron yield reported here corresponds to transmission of 4.7×10^{-3} positrons per incident electron.

References

(1) Cabibbo, N. and Gatto, R., "Electron-Positron Colliding Beam Experiments," Phys. Rev., Vol. 124, 1961, p. 1577.

(2) Aggson, T. L. and Burnod, L., "Production de Positrons a L'Accelerateur D'Orsay, Determination de la Section Efficace A 0° Sur Cibles Epaisses," Laboratoire de L'Accelerateur Lineaire, Rapport LAL.27, Octobre, 1962.

(3) Sund, R. E., Walton, R. B., Norris, N. J. and MacGregor, M. H., "Positron Yields From a 45 Mev L-Band Electron Linear Accelerator," Nucl. Instr. and Meth., Vol. 27, 1964., p. 109.

(4) Ferlenghi, E. and Mango, L., "Calcoli per L'Ottica di Trasporto dei Positroni nell 'Acceleratore Lineare di Frascati," Laboratori Nazionali di Frascati Nota interna: n 218, LNF - 63/70, 12. 11. 1963.

(5) "Laboratori Nazionali di Frascati Electron Positron Linear Accelerator," Varian Associates Technical Proposal VATP-R63, April 24, 1963.

Table I

	Arrangement			Positron Pulse Current (Calculated)	
	Short Solenoid	Long Solenoid	Acceleration	One Guide	Eight Guides
1.	No	No	No	0.046 μA/Mev	0.0007 μA/Mev
2.	No	No	Yes	0.33 μA/Mev	0.09 μA/Mev
3.	No	Yes	Yes or No	22 μA/Mev	22 μA/Mev
4.	Yes	No	No	70 μA	8 μA
5.	Yes	No	First guide only	180 μA	40 μA
6.	Yes	No	Yes	180 μA	90 μA
7.	Yes	Yes	Yes or No	1600 μA	1600 μA

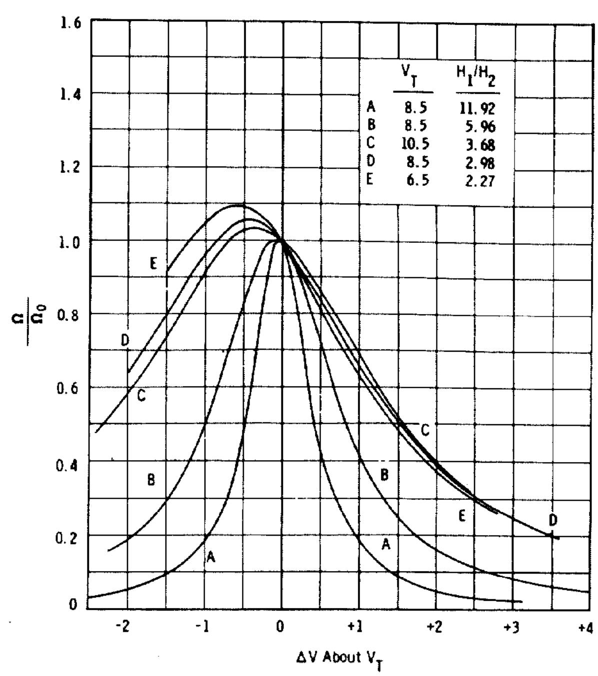

Fig. 1. Normalized acceptance solid angle versus emission energy in MeV for selected ratios of short to long solenoid magnetic field.

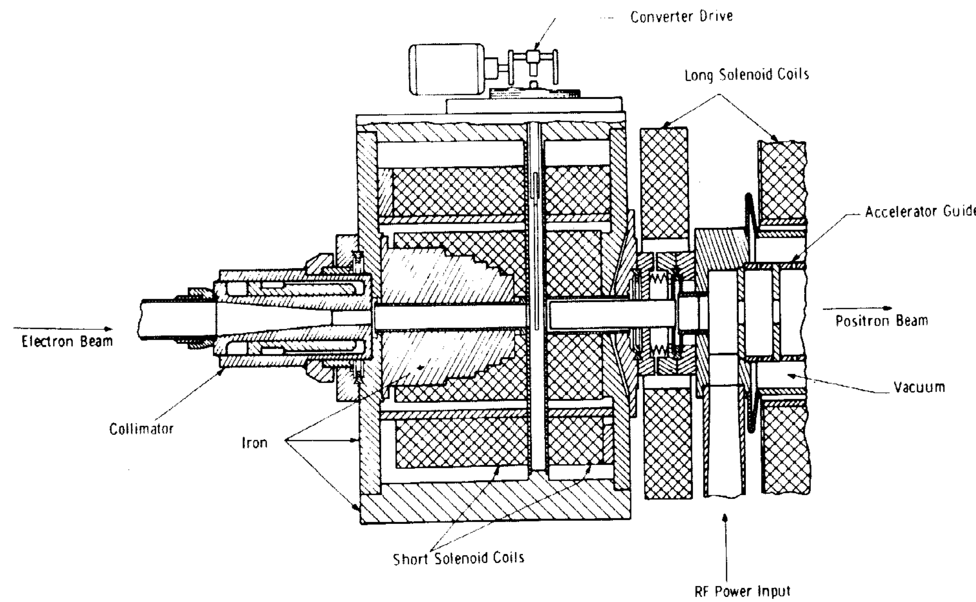

Fig. 2. Cross section of positron converter region.

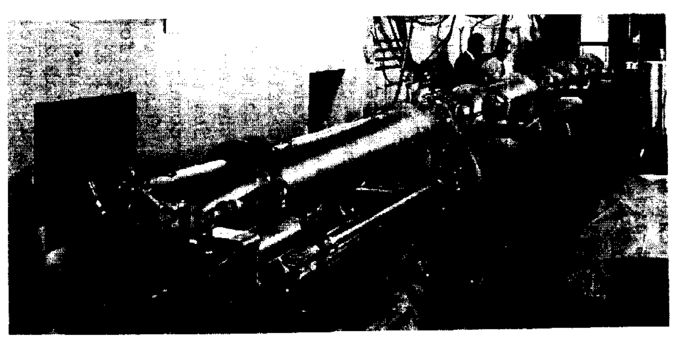

Fig. 3. Four electron accelerator sections before converter.

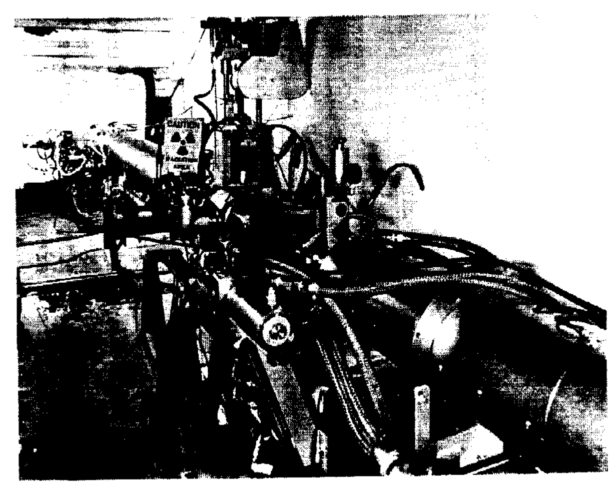

Fig. 4. Converter region and first positron accelerator section, with spectrum analyzer.