

PRODUCTION OF POSITRONS WITH THE STANFORD MARK III ACCELERATOR†

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A positron beam of intensity 7×10^8 positrons per pulse* (60 pulses per second) has been obtained with the Stanford electron linac. The energy is 300 MeV and the energy spread is 2%. The

method of production of the beam and the factors involved in maximizing the intensity are discussed.

1. Introduction

There has recently been considerable interest in the production of positron beams for experiments utilizing either positrons^{1,2)} or their annihilation gamma rays³⁻⁷⁾. Production and use of positrons from the Mark III accelerator⁸⁾ date from 1958

accepted by the machine. The beam is momentum-analyzed by the double-deflection magnet system, just as is the usual electron beam. Positrons may also be produced in a radiator at the end of the accelerator, in front of the analyzing magnets. However, with these magnets the yield of positrons

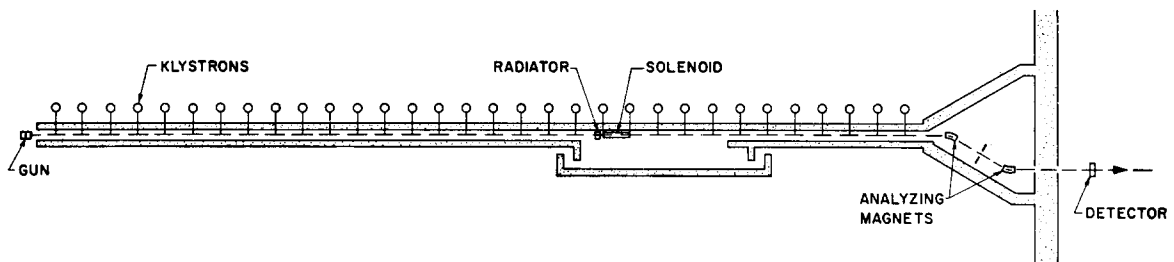


Fig. 1. Schematic drawing of the Mark III accelerator.

(refs.^{9,10)}). A technique has been evolved which yields high-energy beams of useful intensity, high purity, good optical properties, and reasonable energy spread.

Figure 1 shows a schematic drawing of the accelerator. Electrons are accelerated from the gun to the radiator, where they produce positrons by pair production from bremsstrahlung gamma rays. The accelerator following the radiator is used to accelerate positrons. This is easily done by introducing a 180° phase shift in the rf power fed to this part of the accelerator. The solenoid provides focusing which increases the number of positrons

¹⁾ B. Touschek, The Frascati Storage Rings, in: International Conference on Theoretical Aspects of Very High Energy Phenomena at CERN, Geneva, Switzerland, 5-9 June, 1961 (Service d'Information Scientifique, Geneva, 1961), p. 67; and B. Richter, Colliding Beams Experiment, in *ibid* p. 57.

²⁾ D. Yount and J. Pine, Scattering of High-Energy Positrons from Hydrogen, Cobalt, and Bismuth, (to be published).

³⁾ D. M. Binnie, Nucl. Instr. and Meth. **10** (1961) 212.

⁴⁾ J. Miller, C. Schuhl, G. Tamas and C. Tzara, A Photon Monochromator By Annihilation in Flight of Positrons, in: Contributions to the Karlsruhe Photonuclear Conference at Karlsruhe, Germany, August 18 through August 22, 1960, paper G-1.

⁵⁾ F. D. Seward, S. C. Fultz, C. P. Jupiter and R. E. Shafer, University of California Lawrence Radiation Laboratory Report No. 6177 (1960).

⁶⁾ J. Cassels, Stanford Project M. Report M-200-4 (1960).

⁷⁾ L. Katz and L. H. Lokan, Nucl. Instr. and Meth. **11** (1961) 7; and L. Katz, Nucl. Instr. and Meth. **11** (1961) 14.

⁸⁾ M. Chodorow *et al.*, Rev. Sci. Instr. **26** (1955) 134.

⁹⁾ J. A. Poirier, Positron-Electron Scattering at 200 MeV, Doctoral Dissertation, Stanford University, Stanford (1959).

¹⁰⁾ J. A. Poirier, D. M. Bernstein and J. Pine, Phys. Rev. **117** (1960) 557.

* See: note added in proof, p. 50.

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and the purity and optical properties of the beam, are inferior.

In the positron-acceleration technique, the maximum beam intensity is obtained by accelerating the relatively large number of low-energy positrons produced at shower maximum in a thick radiator. These positrons emerge from the radiator with energy $\sim E_c$, the critical energy for the radiator material. We assume throughout that the incident electron energy E^- and the final positron energy (after acceleration) E^+ are much greater than E_c . We will also assume that E^+ corresponds to full use of the accelerator downstream of the radiator. (Lower positron energy may be obtained by turning off klystrons, or phasing them so as to decelerate. A moderate reduction in beam intensity results from this procedure.)

2. Radiator Material

Using very crude approximations to the results of shower theory, it can be shown that the atomic number (Z) of the radiator material should be as high as is convenient. We consider, for a given incident electron energy, a radiator of thickness such that the shower reaches its maximum multiplicity of positrons and electrons. Three factors must be considered: the total number of positrons emerging from the radiator, their energy distribution, and their angular distribution.

The differential energy spectrum of the emerging positrons is roughly proportional to $(E + E_c)^{-2}$ for $E_c \lesssim E \ll E^-$, where E is the positron energy¹¹). Below E_c ionization loss and, to some extent, multiple scattering limit further rise of the differential intensity. The total number of positrons is thus approximately proportional to $1/E_c$, and the majority of the positrons have energy $\sim E_c$. The radiator material is important, since E_c is closely proportional to $1/Z$.

The angular distribution of the positrons must also be considered. Except for a logarithmic dependence on E , the accelerator accepts all positrons with transverse momentum $E\theta_i$ less than some limiting value. This result is implicit in eq. (2), section 5. On the other hand, the angular distribution of emerging positrons is characteristic of multiple scattering in a thickness ~ 1 radiation

length for $E \gtrsim E_c$. The multiple scattering will thus introduce a root mean square transverse momentum ~ 20 MeV/ c independent of E , so long as the mean scattering angle is $\lesssim 1$ radian ($E \gtrsim 20$ MeV). This transverse momentum is much greater than that which can be accepted by the accelerator. Thus, the probability of acceleration is

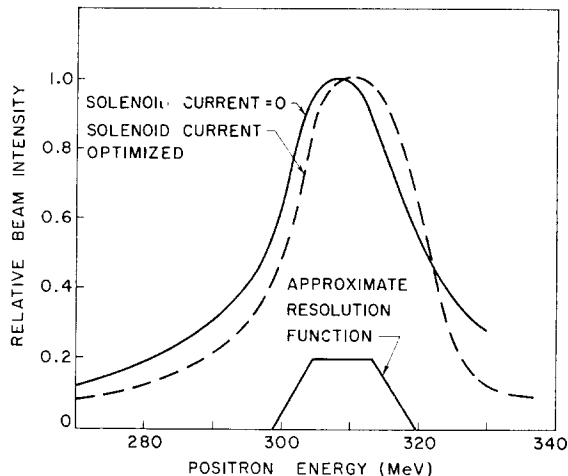


Fig. 2. Positron beam energy spectra. The solid line is for zero solenoid current; the dashed line is with solenoid current adjusted for maximum intensity. The spectra are normalized to equal height. The difference in shape may not be significant, owing to the difficulty in maintaining various accelerator parameters constant. An approximate resolution function, determined by the analyzing magnets, is shown by the trapezoid. The radiator was 2.5 radiation lengths of copper, critical energy 22 MeV; the electron energy $E^- \approx 350$ MeV; the positron-accelerating part of the linac was set for an energy gain of 300 ± 10 MeV. The low energy tail is normal for either electrons or positrons and results from imperfect acceleration of some of the beam.

approximately independent of E for $E \gtrsim 20$ MeV, owing to the properties of the accelerator and the multiple scattering. The differential energy spectrum then is the dominant factor, and the low energy positrons are the most important. Figure 2 shows results which confirm this conclusion. A copper radiator 2.5 radiation lengths thick was located as shown in fig. 1. The low value of E^- is due to the fact that the recent 100 foot addition to the front end of the accelerator had not yet been completed.

¹¹) B. Rossi, High Energy Particles (Prentice-Hall, New York, 1952) Ch. 5; and H. J. Bhaba and S. K. Chakrabarty, Phys. Rev. **74** (1948) 1352.

The preceding discussion indicates that the maximum positron beam intensity should be proportional to Z . However, for $Z \gtrsim 30$, E_c is $\lesssim 20$ MeV, and severe multiple scattering should result in weakening the increase with Z . The logarithmic term in the transverse momentum acceptance of the accelerator also acts to weaken the Z -dependence. However, there remain two factors which favor high Z . The first is that the energy spectrum of the accelerated positrons should be sharper ($\Delta p \sim E_c$ in the crudest approximation), and the second is that the lateral spread of the shower positrons will be less (since the number of centimeters per radiation length is smaller). The latter factor is moderately important for the Mark III accelerator, which has an internal radius of 0.411 inches.

We have experimentally compared copper and tantalum radiators of thickness 2.5 radiation lengths with $E^- \approx 350$ MeV and $E^+ \approx 300$ MeV. The beam analyzing magnets were set to accept a 4% momentum spread. The ratio of the intensity from tantalum to that from copper was 1.75 ± 0.25 . (The relatively large experimental uncertainty arises from the difficulty of maintaining various accelerator parameters fixed during the comparison.) The critical energies of copper and tantalum are in the ratio 2.6:1, so that the crudest calculations¹²⁾. At present, with $E^- \approx 650$ MeV, a tantalum radiator 3.2 radiation lengths thick is used.

3. Radiator Thickness

For $E^- \approx 350$ MeV the yield from tantalum was measured as a function of radiator thickness. The maximum occurred at 2.5 radiation lengths and there was little change from 2 to 3 radiation lengths. This is consistent with Wilson's Monte Carlo calculations¹²⁾. At present, with $E^- \approx 650$ MeV, a tantalum radiator 3.2 radiation lengths thick is used.

4. Radiator Location

The positron intensity (assuming optimum radiator thickness) increases linearly with E^- . The intensity is also roughly proportional to $[\log(E^+/E_c)]^{-2}$, since the angular acceptance of the accelerator is approximately proportional to $[\log$

$(E^+/E_c)]^{-1}$. The critical energy appears here as the injection energy; and magnetic focusing has not been considered. (For the solenoidal focusing discussed below, the conclusion remains valid.) Thus, for maximum current two factors favor placing the radiator near the end of the accelerator. However, other considerations oppose this conclusion. The experimental requirements establish a minimum useful E^+ , the available electron beam intensity decreases somewhat with increasing E^- , and the relative momentum spread at the end of the accelerator which results from the initial energy spread of the positrons is smaller for higher E^+ .

From considerations of convenience and of the requirements of the planned experiments the radiator location shown in fig. 1 has been developed initially. At present, apparatus is being constructed for positron production nearer the gun. The lower electron energy will seriously reduce the intensity, but the desire for $E^+ \sim 1$ GeV makes the choice necessary.

The radiator should be as close as possible to the succeeding accelerator section. This is important because the transverse velocity of the particles is rapidly reduced as they are accelerated. We have found an increase in beam current of approximately a factor of 4 in moving the radiator from a point $3\frac{1}{2}$ in. from the accelerating field to a point 2 in. closer. The procedure which has been adopted is to place the radiator as close as is permitted by rf considerations. For the Mark III accelerator $\frac{1}{2}$ in. is currently the minimum distance. Magnetic lenses could be used to image the radiator inside the accelerator, but in order to be effective the system would have to be approximately achromatic for $\Delta E/E \sim 1$.

5. Magnetic Focusing

The simple theory outlined below was used to evaluate the performance of solenoidal focusing immediately following the radiator. A solenoid eight feet long has been installed, and the beam intensity was increased by a factor of 5. The following assumptions are made in the calculations:

1. The positrons are extremely relativistic, so that $v = c$, and $pc = E$.

¹²⁾ R. R. Wilson, Phys. Rev. **86** (1952) 263.

2. The positrons are emitted from a point source on the accelerator axis.

3. The positrons are accelerated by a uniform electric field, parallel to the accelerator axis[†].

4. The magnetic field is uniform over the length of the solenoid, and parallel to the accelerator axis, and drops abruptly to zero at each end of the solenoid.

Although assumption 1 is the only completely justifiable one, the others result in great simplicity and little loss of usefulness.

In cylindrical coordinates, let z be the distance along the axis of the accelerator, measured from the positron radiator, while r and Φ are the radial and azimuthal coordinates. Let e be the positron charge, ea the positron energy-gain per unit length along the accelerator, and H the solenoid field. Gaussian units will be used. Consider a positron produced at ($z = 0$, $r = 0$, $\Phi = 0$) with energy E_i , which immediately enters the region of uniform magnetic and electric fields. The motion is given by the following equations:

$$\Phi = (H/2a) \ln [(aez + E_i)/E_i], \quad (1a)$$

$$r = (2E_i\theta_i/He) |\sin \Phi|, \quad (1b)$$

where θ_i is the angle at injection between the positron velocity and the z axis. The path is a helix of constant radius $E_i\theta_i/He$, with its axis parallel to the z axis and displaced a distance $E_i\theta_i/He$ from it. The pitch of the helix increases as the positron is accelerated, since $d\Phi/dz$ is proportional to $(z + E_i/ea)^{-1}$.

In the limit $H \rightarrow 0$, $\sin \Phi \rightarrow \Phi$, and eqs. (1a) and (1b) yield the result:

$$r = \frac{E_i\theta_i}{ae} \ln \left[\frac{aez + E_i}{E_i} \right] \quad (2)$$

which applies to a constant gradient accelerator with no solenoidal focusing.

In assessing the effectiveness of a solenoid, the orbit inside it is found from (1a) and (1b) while the

[†] The Mark III is not a constant gradient (i.e., uniform field) accelerator. However, an approximate solution taking account of the non-uniform gradient differs by only a few per cent from the constant gradient case with the gradient set equal to its average value.

orbit downstream of it is found from (2). We assumed that H changes abruptly from a constant value within the solenoid to zero outside it. The positron orbit has continuous values of r , \dot{r} , and $\dot{\Phi}$ across this boundary, while $\dot{\Phi}$ goes to zero as the particle leaves the magnetic field¹³. (Qualitatively, the radial component of H straightens out the orbit.) The complete orbit from radiator to the end of the accelerator consists of properly matched solutions of (1a), (1b), and (2). The displacement from the accelerator axis at the end of the machine is given by:

$$r_3 = \frac{E_i\theta_i}{ea} \left| \frac{\sin \Phi_2}{\Phi_2} \ln \left(\frac{E_2}{E_i} \right) + \cos \Phi_2 \ln \left(\frac{E_3}{E_2} \right) \right|, \quad (3)$$

where subscripts 2 and 3 refer to quantities evaluated at the end of the solenoid and at the end of the accelerator, respectively.

The beam intensity is proportional to $[(\theta_i)_{\max}]^2$, where $(\theta_i)_{\max}$ is the maximum injection angle for which the orbit remains inside the accelerator aperture. For an accelerator of constant inner radius r_a , $(\theta_i)_{\max}$ is given by the smaller of the two values:

$$(\theta_i)_{\max} = \frac{ear_a}{E_i} \left[\frac{\Phi_2}{\ln \left(\frac{E_2}{E_i} \right)} \right] \quad (4)$$

$$(\theta_i)_{\max} = \frac{ear_a}{E_i} \left| \left[\frac{\sin \Phi_2}{\Phi_2} \ln \left(\frac{E_2}{E_i} \right) + \cos \Phi_2 \ln \left(\frac{E_3}{E_i} \right) \right]^{-1} \right|. \quad (5)$$

Eq. (4) comes from eliminating H from (1b) by means of (1a). This equation holds if the orbit first reaches the accelerator aperture inside the solenoid. Eq. (5) holds if the limiting aperture is at the end of the accelerator. For $\Phi_2 = \pi/2, 3\pi/2, 5\pi/2, \dots$ the orbit downstream of the solenoid is parallel to the accelerator axis (the solenoid focuses at infinity) and both equations yield the same result. For a limited range of Φ above these values the solenoid

¹³ W. K. H. Panofsky and M. Phillips, *Classical Electricity and Magnetism* (Addison-Wesley, Reading, Massachusetts, 1955) Ch. 23.

focus is sufficiently optimal that eq. (4) holds; otherwise, eq. (5) is correct. Figure 3 shows the expected relative variation of $(\theta_i)_{\max}$ with Φ_2 for the eight foot solenoid, assuming energy values $E_1 = 8.5$ MeV, $E_2 = 32.5$ MeV, and $E_3 = 300$ MeV.

The simple theory is expected to be optimistic for two reasons. First, in practice the positrons emerge

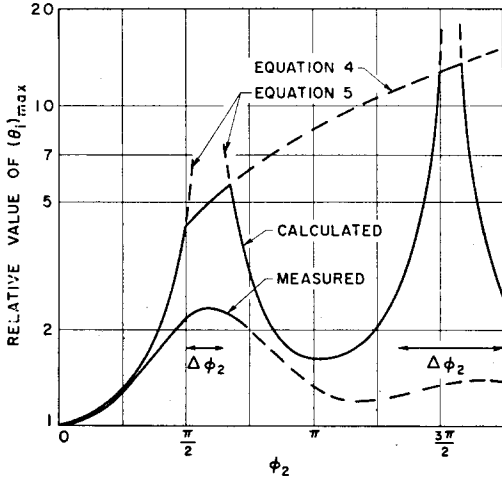


Fig. 3. Calculated and measured relative acceptance angles, $(\theta_i)_{\max}$, as a function of Φ_2 . The curves refer to tantalum radiator, eight foot solenoid, $E^- \approx 350$ MeV, $E^+ \approx 300$ MeV.

from the radiator over a finite area determined by the size of the electron beam and the radial spread of the shower. Second, the positrons have a broad energy spectrum. The $\Delta\Phi_2$ regions show on fig. 3 are for a range of E_1 from 4 to 12 MeV. Experimental results (square roots of relative intensities) are also shown in fig. 3. If r_a is assumed to be reduced by a factor ~ 2 inside the solenoid (which is a plausible way to take account of the beam size), then the height of the theoretical peaks is reduced by a factor ~ 2 and reasonable agreement is seen in the region near $\Phi_2 = \pi/2$. The value of H at the experimentally observed maximum is about 700 gauss, consistent with expectations.

It was possible to run the solenoid up to about 3000 gauss ($\Phi_2 \approx 2\pi$). At the high fields, experimental results were not very reproducible and there were indications that excessive radial steering was generated by the solenoid. In no case was an intensity comparable to that for $\Phi_2 \approx \pi/2$ observed. The dashed extension of the experimental curve in fig. 3 represents a rough average of our

observations. In view of the expected range of $\Delta\Phi_2$, it was not anticipated that higher fields would lead to significantly better intensities than that obtained at the first maximum. The measurement and correction of magnetic asymmetries of the solenoid are not convenient and hence have not been attempted for this installation. In future installations this problem will be given more attention.

It was also possible to attain $\Phi_2 = \pi/2$ with subsections of the solenoid 2 feet and 4 feet long, beginning at the radiator. The maximum intensities occurred at values of H consistent with the theory, and decreased slowly with the solenoid length, being about 20% lower for 2 feet than for 8 feet. Ideally, the short high-field case is expected to be better, but its larger chromatic aberration ($\Delta\Phi_2$) plausibly explains the observed decrease. From eq. (1a):

$$\frac{d\Phi_2}{\Phi_2} = \frac{aez_2}{(aez_2 + E_1) \ln [(aez_2 + E_1)/E_1]} \frac{dE_1}{E_1}$$

where z_2 is the solenoid length. This equation is useful in considering chromatic aberration. In the limit of an extremely short solenoid ($aez_2 \ll E_1$), $d\Phi/\Phi \approx dE_1/E_1$. For a long solenoid ($aez_2 \gg E_1$), $d\Phi/\Phi \approx [\ln(E_2/E_1)]^{-1} dE_1/E_1$ and the reduction of chromatic aberration with solenoid length is apparent. Since eventually one gains only logarithmically, the eight-foot solenoid is a reasonable choice.

6. Summary

As a result of the work discussed above it has been possible to attain a beam intensity of 7×10^6 positrons per pulse (60 pulses per second) through a $\frac{1}{2}$ in. collimator at the end of the accelerator. This is for a positron energy of 300 MeV with an energy spread of $\pm 1\%$ defined by the analyzing magnet system. A typical electron beam under these conditions is about 5×10^{10} electrons per pulse, while the electron beam incident on the positron radiator is about 1.5×10^{11} electrons per pulse. The net conversion efficiency from electrons to relatively mono-energetic positrons is thus about 5×10^{-5} , while the ratio of energy-analyzed beams is about 1.4×10^{-4} .

Acknowledgements

We are particularly indebted to J. A. Poirier for early suggestions regarding the reacceleration method⁹). L. N. Hand helped in an exploratory experiment. R. G. Gilbert, L. L. Combs and T. M. Sartain have given generous assistance in suiting the Mark III accelerator to our needs.

Note added in proof: Since the preparation of this

manuscript, the maximum intensity of the 300 MeV positron beam discussed here has risen to about 3×10^7 positrons per pulse. This is partially the result of better tuneup procedures, which have increased the gain obtained with the solenoid to a factor 8, instead of the factor 5 reported above. Furthermore, the addition of a prebuncher to the accelerator has increased the electron beam intensity at the radiator by about a factor 2.5.