

POSITRON BEAMS

These particles are now made with an intensity and energy approaching those of primary electron beams; their applications include scattering experiments, colliding-beam experiments and annihilation photon production.

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POSITIVE ELECTRONS, which offer interesting comparisons with negative electrons and can be a useful source of photons, may be made by pair production in a target placed in the electron path of a linear accelerator. Greater intensity can be achieved by acceleration, by a coaxial solenoid, with magnetic quadrupoles or by a solenoid-quadrupole combination. One important application of these positron beams is the production of "tertiary" beams of annihilation photons that can provide a partially monochromatic photon beam. Other applications include positron-proton and electron-proton scattering comparisons and colliding-beam experiments in which electrons are injected at high energies into storage rings.

Collision and pair production

Electron-atom collisions produce positrons in a two-stage process. An energetic electron that collides with an atom in a lump of heavy metal (the "converter") is decelerated by the electric field of the atomic nucleus or one of the atomic electrons. As a result of

this deceleration, the electron emits a photon with energy that may be as high as the initial electron energy or as low as a few electron volts. In the second stage, those photons that have sufficient energy (greater than 1.022 MeV, the combined rest mass of an electron and a positron) interact with other atoms in the same converter to create secondary electrons and positrons in equal numbers by pair production. If the initial electron energy is well above this threshold, a cascade occurs in which successive generations of positrons and electrons radiate additional photons that in turn produce positrons and electrons (figure 1). Several other processes contribute to the cascade including "pair annihilation," in which a positron and an atomic electron annihilate into two photons, and "Compton scattering," in which a photon knocks an initially bound electron out of an atom. For incident electrons of 5 GeV, the resulting shower may contain as many as 30 low-energy positrons at "shower maximum." Thus the positron intensity at injection is quite high. Final intensity

is determined by the fraction of these positrons that is captured and accelerated.

Figure 2 shows production of posi-



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trons in a traveling-wave linear accelerator with the converter about two thirds of the way down the beam path. (See Richard Neal's detailed description of the Stanford linear accelerator¹). Because positrons and electrons have opposite charge, the crests of the "electron" sine wave decelerate positrons while the valleys accelerate them. Positron acceleration can therefore be achieved by changing the phase of the traveling wave by 180 deg with respect to the positron bunches. If positrons can be produced and injected into a linear electron accelerator with the proper phase, they can be accelerated just as efficiently, and can reach just as high an energy, as electrons injected at the same point with the same initial energy and direction.

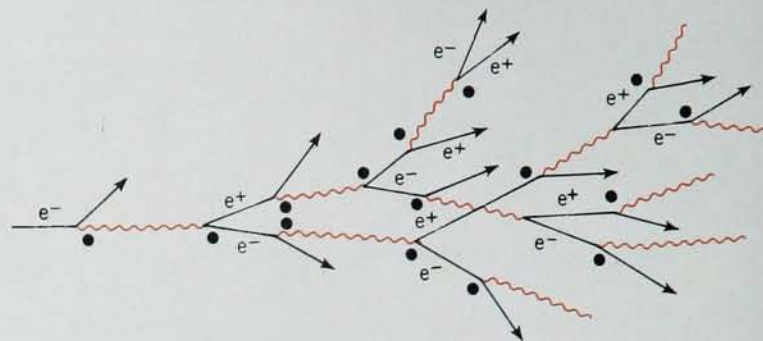
Positron beams produced in linear accelerators differ from other secondary beams in that a major fraction of the accelerator is used to increase their energy; so they normally have a higher energy than the primary electrons at the converter. Also their intensity may be higher than the initial electron intensity because of cascading.

Converter materials

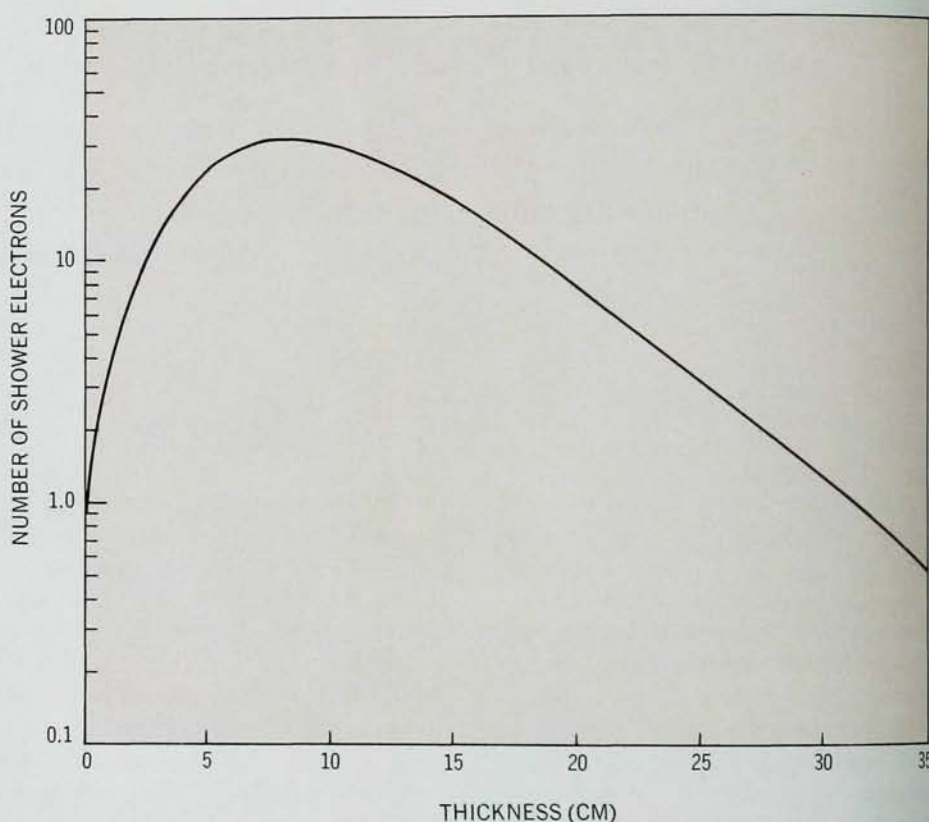
Any material can, in principle, be used for the converter because photon radiation and pair production occur whenever a beam of high-energy electrons or positrons is incident on an array of atoms. The most efficient materials are those of high density near the bottom of the periodic table—lead, tantalum, tungsten, gold and platinum—but other elements may be more resistant to heat, corrosion and radiation damage, or they might be cheaper or more easily machined. Heat conductivity and the longevity of the residual-radiation hazard are other important considerations. Thus, although all of the elements listed above have been used, others such as copper might in some cases provide a more attractive compromise.

Similarly, the optimum converter thickness is generally such that the number of positrons in the shower is a maximum. Nevertheless, thinner converters may be more efficient if relatively high-energy positrons are required for injection or if the scattering of particles in the shower leads to positron angles too large for a satisfactory capture efficiency.

A "typical" positron converter could be a water-cooled tungsten cylinder 1 cm in diameter and a centimeter or so in length. Other, more exotic, con-



CASCADE SHOWER DEVELOPMENT. Above, an electron, e^- , incident on the left radiates a photon (wavy line) in the electric field of an atom (solid dot). The photon then produces a positron, e^+ , and an electron by pair production. The multiplication process continues until the photons no longer have sufficient energy to produce positron-electron pairs. Low-energy positrons and electrons are continually absorbed by ionization. Below, the number of electrons with energy greater than 1.5 MeV in a typical shower is plotted against the depth of penetration into a copper positron converter. The primary electron energy is 6 GeV. At shower maximum there are more than 30 electrons and about the same number of positrons. —FIG. 1

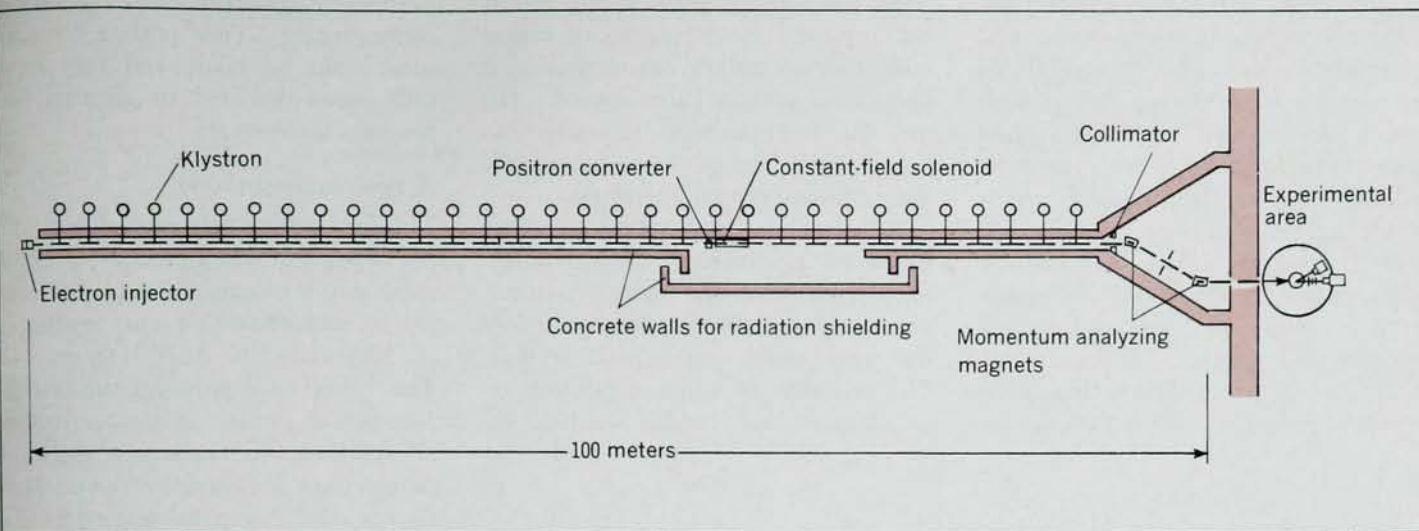


verters have been proposed and sometimes used. Thus the 200 kW power rating of the 5-GeV electron beam that strikes a positron converter at the 20-GeV Stanford Linear Accelerator Center (SLAC) has inspired physicists to consider "wands" that dip into the electron beam only on occasional pulses, "wheels" that rotate through the electron beam to dissipate the beam power within a larger volume, "brushes" with tungsten-wire bristles projecting radially from the peripheries of rotating wheels, and even liquids such as mercury or molten indium that

flow through the electron beam and into a suitable heat exchanger.

Accelerating the positron

The number of positrons that reach the end of the accelerator can be enhanced in several ways (figure 3). The most important method is the acceleration process itself. During acceleration, the component of positron momentum perpendicular to the accelerator axis (transverse momentum) remains constant, while the component along the axis (longitudinal momentum) increases linearly with the distance trav-



STANFORD MARK III ACCELERATOR beam facility. Electrons injected at left are accelerated to 600 MeV and strike a position converter two-thirds of the way along the machine. Accelerated to 300 MeV by last third of beam path, positrons are collimated and momentum analyzed to produce a well defined beam.
—FIG. 2

eled. As a result, the trajectories become more and more parallel to the accelerator axis. By the time the positrons reach the end of the accelerator, the divergent angle has been reduced by perhaps a factor of a hundred, and the number of positrons that remain sufficiently near the accelerator axis to avoid hitting the walls has been enhanced by a factor of ten thousand or more by acceleration alone. Even so, the probability of capturing a given positron in a long pipe 2.5 cm in diameter remains quite small.

Coaxial solenoid

The capture efficiency for positrons can also be enhanced by surrounding a portion of the accelerator tube with a coaxial solenoid that produces a uniform magnetic field parallel to the accelerator axis and thus parallel to the accelerating electric field. Positrons in such an electromagnetic field move along a helix of constant radius (determined by the initial transverse momentum) and of increasing pitch (determined by the increasing longitudinal momentum). For optimal effectiveness, the solenoid should be installed immediately after the converter where the angle between the positron direction and the accelerator axis is largest. Although positron solenoids have been installed over the full length of certain linear accelerators, the cost for a long (high-energy) machine is not justified by the slow increase in solenoid effectiveness with solenoid length. Typically the solenoid is terminated after

3–10 meters where the angle made by the positrons with the accelerator axis has been substantially reduced by acceleration. Ideally, positrons leave the solenoid near the accelerator axis; the reduced angle between their track and the axis then ensures an enhanced capture efficiency, usually ten or a hundred times better than without a solenoid.

Quadrupole focusing

Instead of a long solenoid, magnetic quadrupoles spaced at carefully chosen intervals along the linear accelerator can supplement a short solenoid installed near the positron converter. Used in pairs or in triplets, these quadrupoles serve as magnetic lenses to refocus the diverging positrons back toward the accelerator axis. Quadrupole focusing depends rather more critically upon the positron energy distribution than does the helical “focusing” of the solenoid. Thus quadrupoles are not very effective near the converter where fractional energy differences are large, and they are normally located farther downstream where the energy gained by acceleration is a significant fraction of the total. Quadrupoles have also been used effectively just upstream of the positron converter to focus primary electrons. This position ensures that the positrons originate in a small volume quite near the accelerator axis. For high-energy accelerators, quadrupoles and a short solenoid provide a reasonable compromise between a short solenoid used

separately and a longer solenoid installed along the entire length of the machine.

First experiment

The first positron beam produced by the Stanford Mark III Accelerator was developed by John Poirier, David Bernstein and Jerome Pine around 1958.² The positrons were generated by 350-MeV electrons incident on a thin copper converter near the midpoint of the accelerator, and no acceleration was used beyond this point. Because the converter was thin, the shower did not progress beyond one or two stages on the average, and a few positrons produced with a substantial fraction of the incident electron energy reached the end of the accelerator. These positrons were collimated and momentum analyzed to yield a well defined beam of 200-MeV positrons in the experimental area. The relatively low maximal intensity of several hundred positrons per accelerator pulse was well suited to the requirements of a cloud-chamber experiment in which the scattering of positrons by atomic electrons in a beryllium plate was measured.

An additional parameter

During 1959 extensive work was done by Jerome Pine and myself in an effort to increase the positron intensity to the point where positron experiments could be carried out with magnetic spectrometers and counters—the instruments normally used at Mark III to de-

test electrons. Positron acceleration and solenoidal focusing—both discussed by Poirier in his doctoral thesis—were first tried during this period, and various target materials, thicknesses and locations were systematically studied for the first time. As a result the positron-beam intensity increased some five orders of magnitude from several hundred to 3×10^7 positrons per pulse, 60 pulses per second (an average current of 0.3 nanoamps).³ This intensity was still more than three orders of magnitude lower than the in-

tense Mark-III electron beam, but it far surpassed the intensities of meson and other secondary beams produced elsewhere without acceleration. In fact the positron-beam intensity was beginning to compare favorably with some primary proton intensities.

In effect the new beam provided physicists at Stanford with an additional parameter—the charge, positive or negative, of the incident particle—that they could vary almost at will. The existence of either a positron or an electron beam under identical ex-

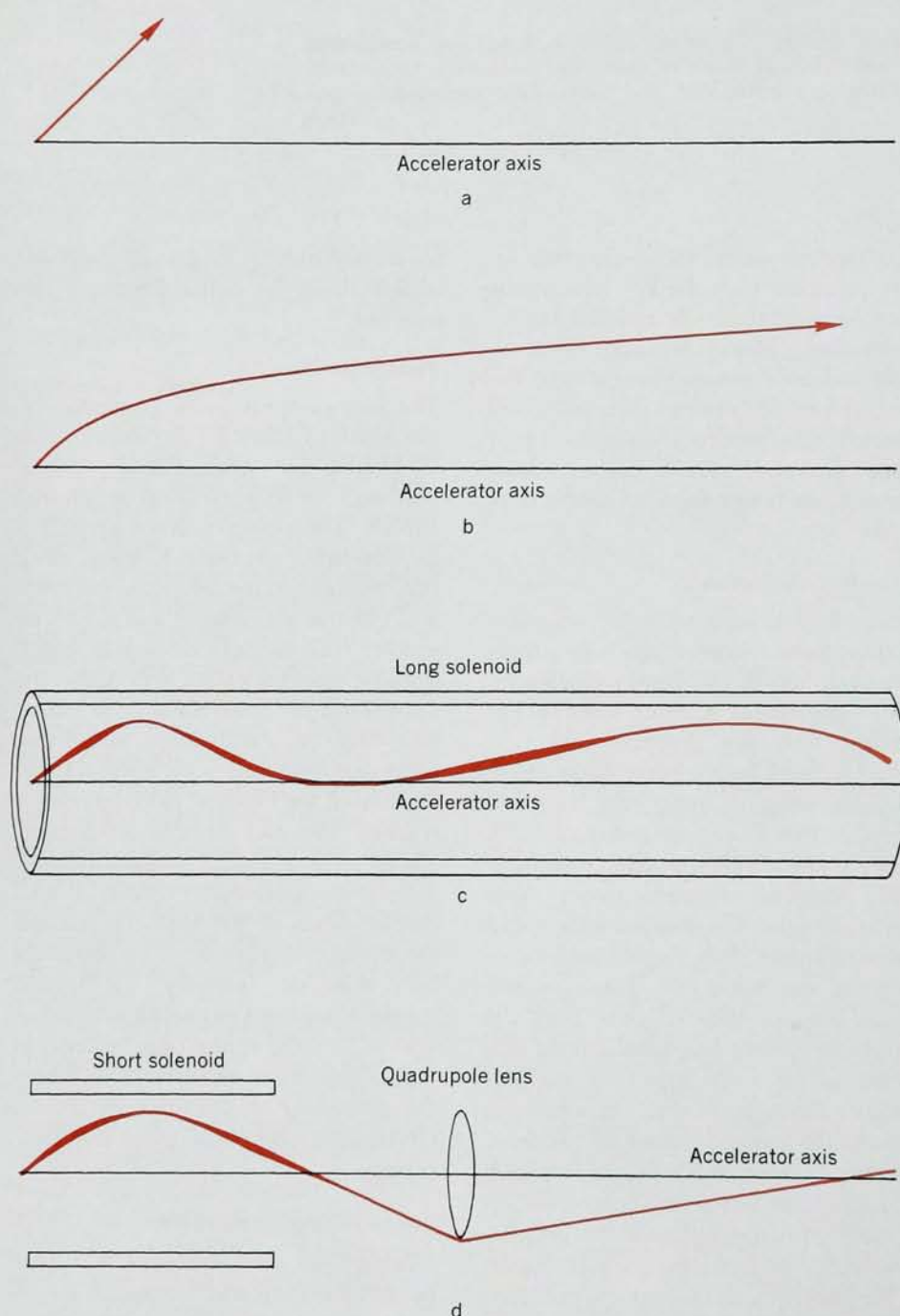
perimental conditions had one further consequence: Very precise comparisons could be made and very small differences detected in electron and positron interactions.

A two-photon process

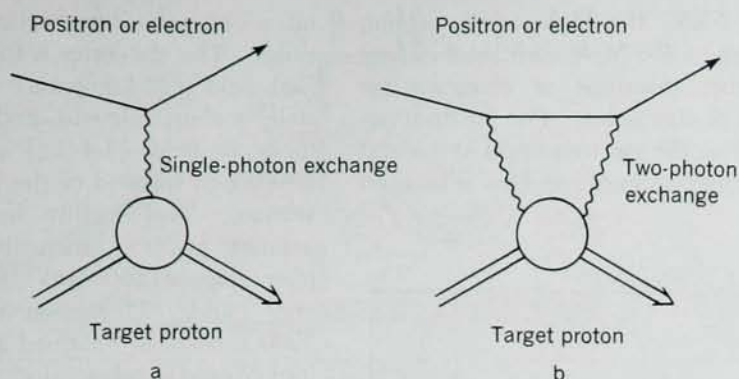
The first experiment carried out with the new beam was a precise (to 1% at some points) comparison of positron-proton and electron-proton scattering at 200 and 300 MeV (figure 4).⁴ This experiment provided the first direct test of certain assumptions made in analyzing the extensive electron-proton data obtained by Robert Hofstadter and his collaborators in the same laboratory. More explicitly the electron-proton interaction was assumed to proceed by means of the exchange of a single photon, and the exchange of two or more photons was neglected. The differences in positron-proton and electron-proton scattering provide a direct measure of the two-photon contributions. These were estimated to be of order $Z\alpha$ where $Z = 1$ is the charge of the proton in units of the electron charge and $\alpha = 1/137$ is the "fine-structure constant;" however, deformation of the proton (polarization) by the interaction of one photon can in some models enhance the interaction of the second photon in the two-photon process. The Hofstadter experiments, in which electrons were used in a systematic study of internal proton structure, were of such fundamental importance that Hofstadter himself was awarded the 1961 Nobel prize for physics.

The positron-proton work was subsequently extended to 850 MeV at Stanford⁵ and recently to energies above 1 GeV by physicists at Cornell University,⁶ at the Cambridge Electron Accelerator (CEA),⁷ and at the Deutsches Elektronen-Synchrotron (DESY) in Hamburg.⁸ The last three groups used circular accelerators and produced positron beams conventionally, that is, without positron acceleration. The experiment has also recently been done at scattering angles of 180 deg (backward scattering) by physicists at Orsay.⁹ During the last year, the positron-proton experiment has been extended to 8 GeV at SLAC.¹⁰ Within the few percent sensitivity of these experiments, positron-proton and electron-proton scattering from 200 MeV to 8 GeV showed no unexpected differences.

An experiment that yielded quite large differences in positron and elec-



POSITRON ENHANCEMENT. Situation *a*, with no enhancement, is compared with *b* where acceleration causes positron trajectory to be nearly parallel with axis. Addition of a long solenoid at *c* causes positrons to take helical path of constant radius and increasing pitch. At *d* magnetic quadrupoles supplement the solenoid. —FIG. 3

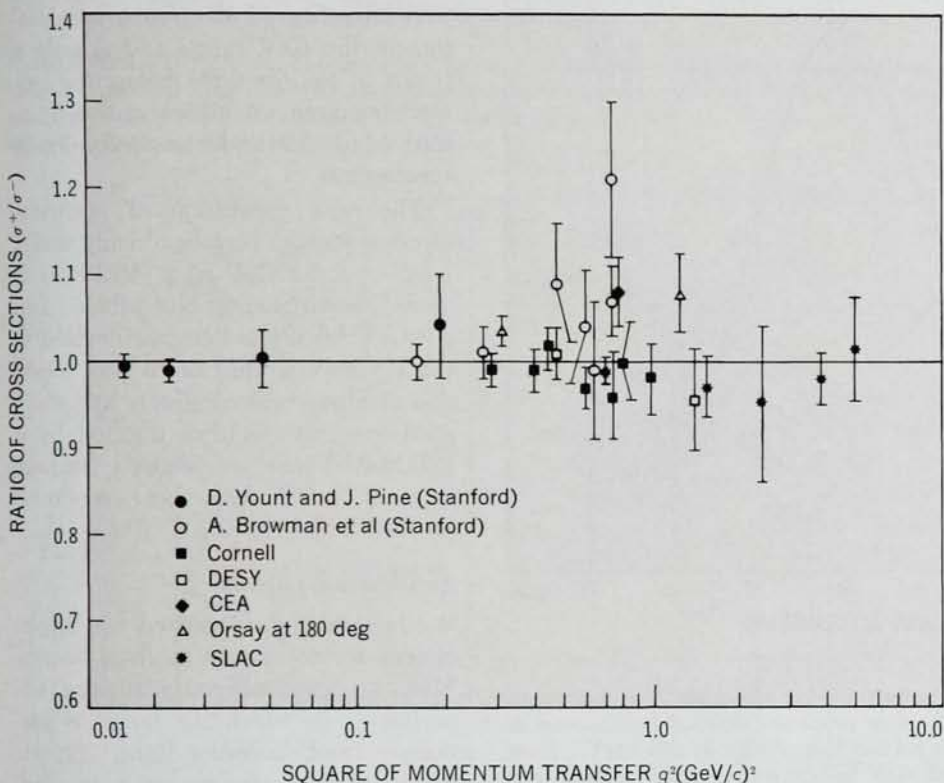


may ultimately be of greater importance. Specifically, positrons as well as electrons are now being injected at high energies into storage rings. For relativistic reasons, the available energy in such a collision is higher than can be achieved even when positrons of far greater energy interact with electrons in a stationary target. This technique not only permits an extension of the positron-electron scattering experiments to very high effective energies, but it allows the more important study, at these energies of a variety of annihilation reactions. There is a reasonable probability that instead of annihilating into the usual pair of photons, the colliding positron and electron will produce pairs of mesons or baryons. The intermediate state is a virtual photon—a “ball” of pure energy—which can then decay into any particle-antiparticle pair with rest-mass energy up to the combined energy of the two beams.

For the clashing-beam experiment (figure 6) now in progress at Orsay,¹⁴ the 1.3-GeV linear accelerator is divided into two units, each with its own electron gun. The first, consisting of four 250-MeV sectors, is used to produce positrons: Electrons at 750 MeV strike a tungsten radiator at the end of the third sector, and positrons from the radiator are accelerated to 250 MeV by the fourth sector. The fifth and final sector is used to produce a beam of 250-MeV electrons. After injection, positrons and electrons at 250 MeV are accelerated in the storage ring to 550 MeV, somewhat above the thresholds for producing muon, pion and kaon pairs. Processes involving a single intermediate meson of higher rest energy, such as the rho, omega and phi are also being studied.

The 700-MeV positron-electron storage ring (VEPP-2)¹⁴ now operating at Novosibirsk in the Soviet Union and the 550-MeV ring at Orsay have recently yielded measurements of the rho-meson production rate. These results for the rho-meson are believed by many physicists to be the best so far obtained by any procedure. They agree with previous results except that they yield a significantly narrower resonance width than has been seen previously (the resonance width is inversely proportional to the particle lifetime).

The positron-beam facility¹⁵ developed for the 1.5-GeV storage ring (ADONE)¹⁴ at Frascati is noteworthy in several respects. The linear ac-



POSITRON AND ELECTRON scattering off protons compared. “Feynman diagrams” describe the scattering of a positron or an electron on a target proton for a single-photon exchange at *a* and for a two-photon exchange at *b*. At *c* data from the seven listed sources on the ratio of the positron and electron processes is plotted against the square of the momentum transfer to the target proton. —FIG. 4

tron scattering was carried out at Stanford immediately after the first positron-proton experiment.¹¹ In this case 300-MeV positrons and electrons were scattered off cobalt ($Z = 27$) and bismuth ($Z = 83$), which are “high- Z ” elements with complicated nuclei consisting of many protons and neutrons. The two-photon effects were again expected to be of order $Z\alpha$, that is, of the order 27/137 and 83/137 respectively; thus they provide a readily measurable and rather sensitive probe of nuclear structure (figure 5). Although not as fundamental as the studies of internal proton structure, this work on nuclear—as distinguished from elementary-particle—physics has stimulated similar positron programs

at Orsay¹² and Saclay, at Saskatoon, Saskatchewan, at Frascati and at laboratories in the US.

The original positron-electron scattering experiment was repeated at Orsay¹³ in 1965 with counters, a magnetic spectrometer and a positron beam developed by Louis Burnod. The high intensity available by that time permitted an absolute measurement to 1%, an order of magnitude improvement in precision over the earlier cloud-chamber results at Stanford.²

Storage rings

Although the initial development of intense positron beams was motivated by these scattering experiments, a second and very recent application

celerator was built commercially by Varian Associates specifically for electron and positron acceleration and injection into the storage ring. The accelerator has two sections: The high-intensity section accelerates electrons

to 65 MeV; the high-energy section adds up to 350 MeV additional energy to either positrons or electrons injected at this point. For positron acceleration the electron beam at the end of the high-intensity section is focused

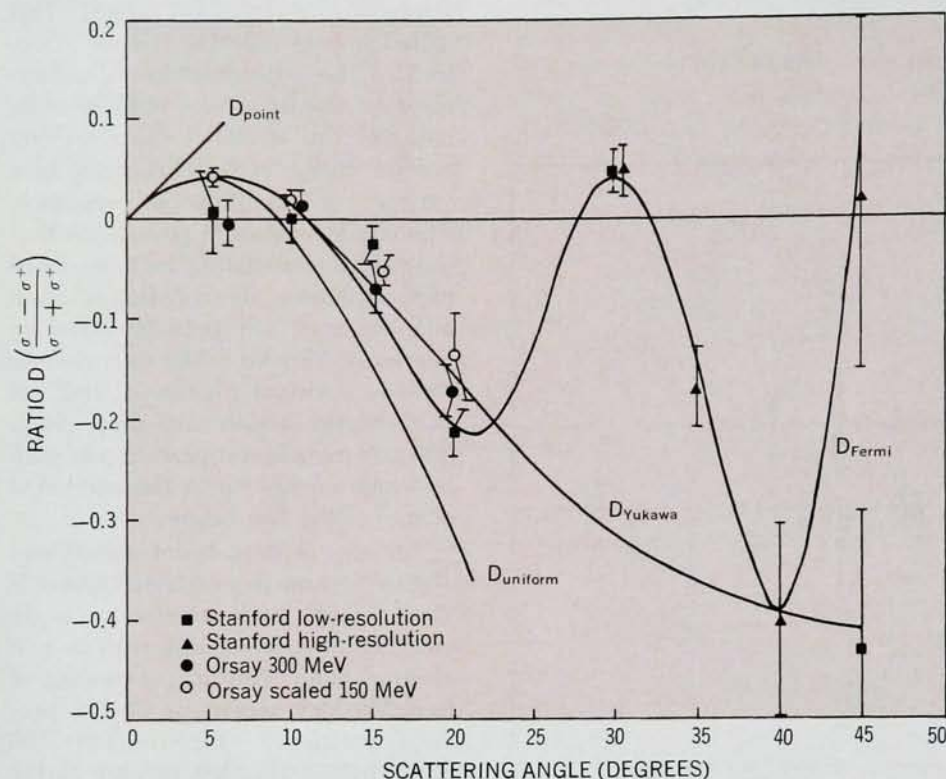
on a converter by magnetic quadrupoles. The converter is followed by a high-field (15-kilogauss) lens—essentially a short solenoid—and by a long, moderate-field (2.4 kg) solenoid extending to the end of the high-energy section. This facility has achieved average positron intensities above 1 microamp at 360 MeV in a 1% energy band. This intensity is about 3000 times that obtained at the Stanford Mark-III accelerator. It exceeds the primary proton and primary electron intensities of all circular accelerators in the GeV range and is only a factor of two or three below the primary electron intensities at the Stanford Mark III and the Orsay linear accelerators.

The next generation of positron-electron storage rings is already under way.¹⁴ A 3.5-GeV ring (VEPP-3) is under construction at Novosibirsk, and a 3-GeV facility is being assembled in the US by adapting the 6-GeV CEA; this machine will accelerate and store positrons and electrons injected by a 130-MeV linear accelerator. Storage rings of 3 GeV have been proposed for DESY and for SLAC.

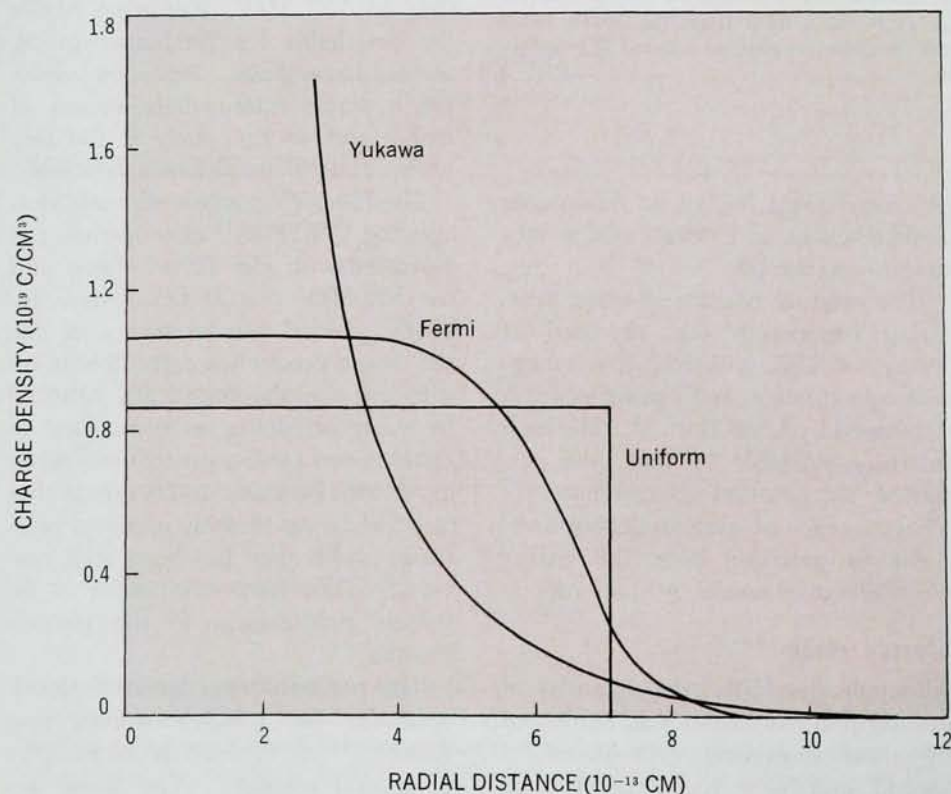
Annihilation photons

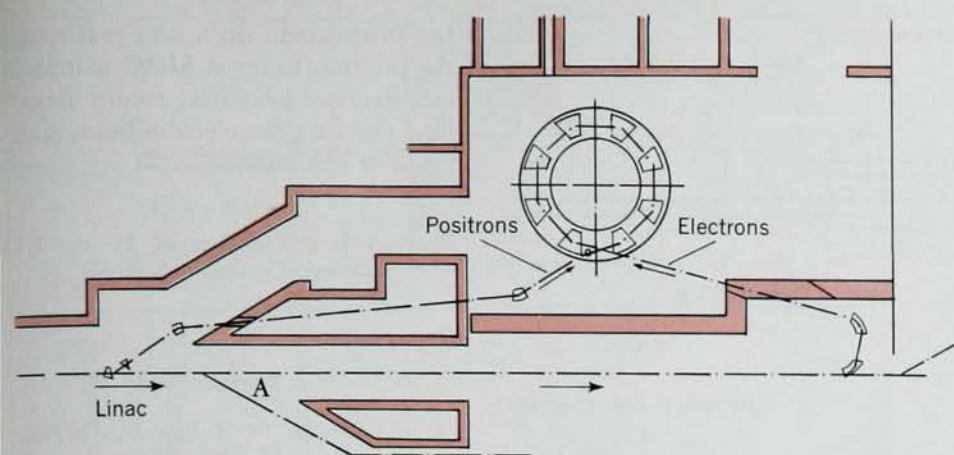
We have already discussed two applications for secondary positron beams. They are conventional scattering experiments in which the target is stationary and colliding-beam experiments in which the target is an electron moving in the opposite direction with the same velocity and energy. In a third application, of particular interest at SLAC, positrons are now being used to produce "tertiary" beams of annihilation photons.

In this third application, the positron beam is momentum analyzed and strikes a target or "radiator" at the end of the accelerator, analogous to the converter in which the positrons were initially produced. Two main processes can then occur. First, the positrons can radiate photons by deceleration in the electric fields of the target nuclei and electrons—the first step in the production of a new cascade shower. Second, unlike the electrons incident on the converter, the positrons hitting the final radiator can annihilate with atomic electrons to produce pairs of photons, each of which has a well defined energy for a given angle with respect to the incident positron direction. Annihilation is enhanced relative to radiation by using a radiator material near the

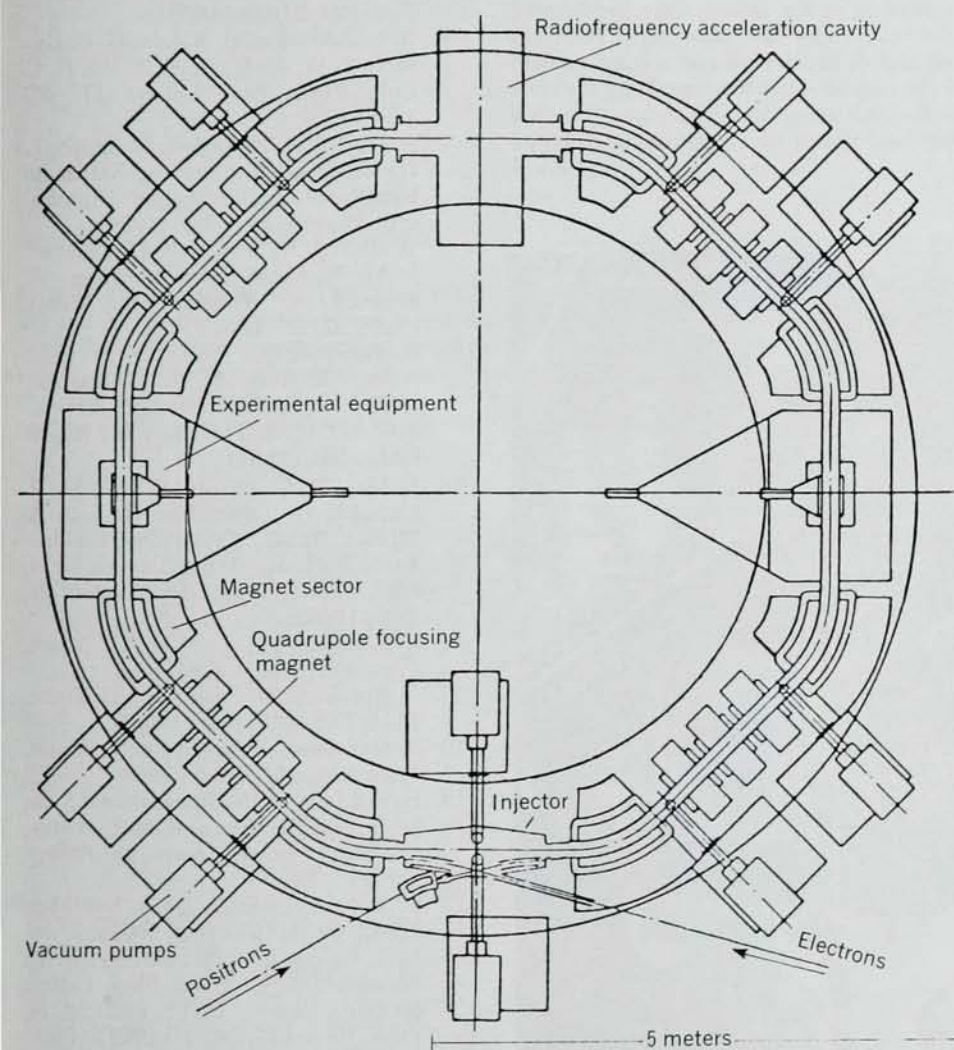


SCATTERING FROM BISMUTH NUCLEI compared for electrons and positrons. The difference between the cross sections of the two processes divided by the sum is plotted (above) against the scattering angle for an incident energy of 300 MeV. Four points taken at 150 MeV were scaled up to 300 MeV to test a theoretical scaling law. The models in this comparison, obtained from electron scattering experiments, are shown (below) for a root-mean-square bismuth radius of 5.52×10^{-13} cm. —FIG. 5





INJECTION SYSTEM for the 500-MeV Orsay storage ring, above, and the ring itself, below. The first four 250-MeV sectors of the linear accelerator (not shown) are used in the production of positrons, and the last sector produces electrons when a removeable electron injector is installed at A. —FIG. 6



top of the periodic table, for example, liquid hydrogen, lithium or beryllium.

Annihilation photons are quite distinct from radiation photons, which can have any energy up to the incident energy of the radiating positron or electron. Furthermore, annihilation photons are distributed over a broader angular region. At a particular angle the complete photon spectrum consists of a sharp spike at the annihilation-

photon energy characteristic of that angle, superimposed on a diffuse background of radiation photons. The underlying background is identical to the ordinary radiation spectrum produced by electrons for the same experimental conditions.

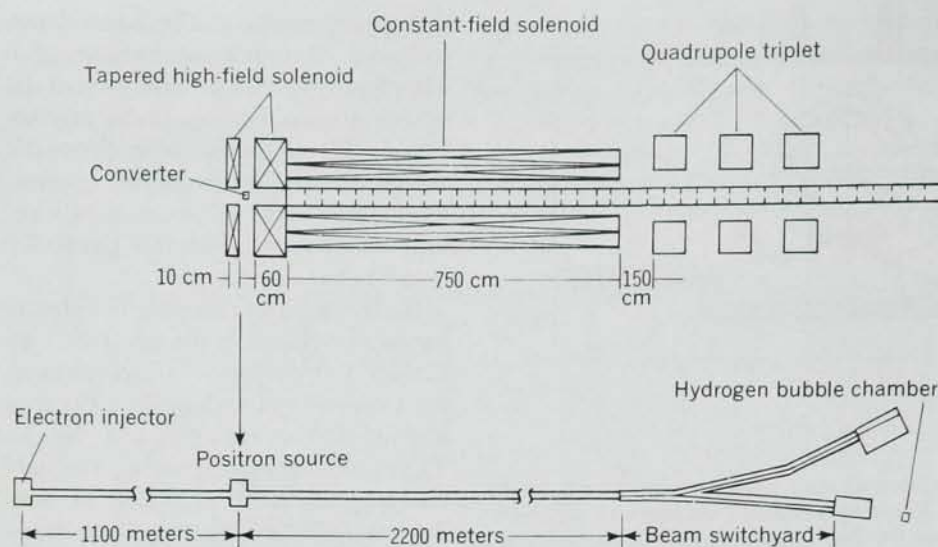
Annihilation photons provide physicists with a partially monochromatic beam, that is, a beam in which a substantial fraction of the photons have

the same energy. The annihilation technique is important because photons have no charge and cannot be energy analyzed by magnetic or electric fields. Partially monochromatic beams can also be produced by scattering laser light off a beam of electrons or positrons, but this possibility is still being developed.¹⁷

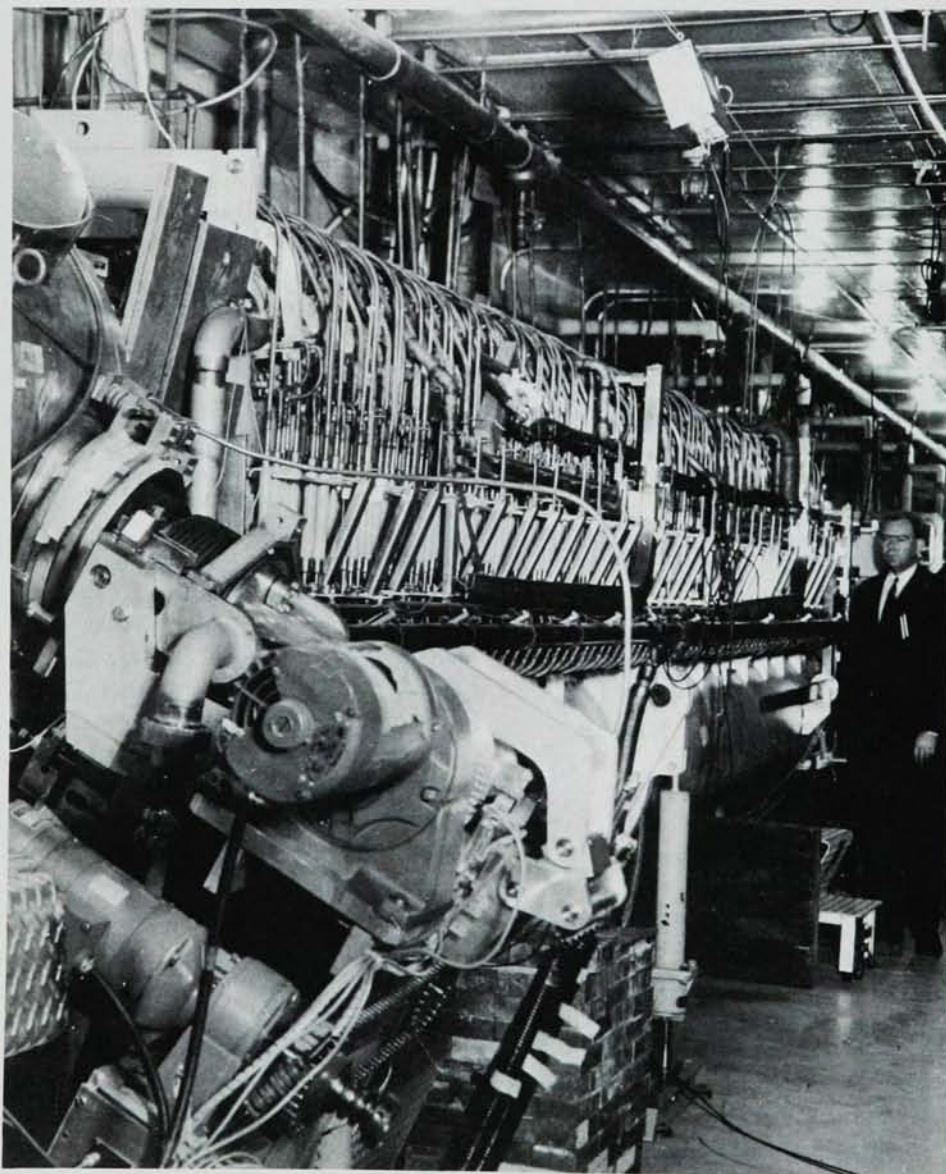
In the earliest annihilation-photon beams, developed in the late 1950's by Stanley Fultz and his collaborators at the University of California, Lawrence Radiation Laboratory¹⁶ and by C. Tzara and his colleagues at Saclay,¹⁸ the photons were produced at zero degrees to the incident positron direction, thereby enhancing the photon yield near the incident positron energy. These early annihilation beams were used to study photonuclear reactions at energies below 50 MeV—an area of research that is complimentary to electron or positron scattering from nuclei and is also active today. The Stanford and Lawrence Radiation Laboratory groups, working some 40 miles apart, evolved the positron acceleration technique independently. They used their positron beams in two rather different applications (scattering and the production of annihilation photons) simultaneously and for a considerable period before either group became aware of the other.

The positron beam developed at SLAC¹⁹ (figures 7 and 8) by Herbert DeStaebler, Jerome Pine and others—with 15 times the energy and nearly the same intensity as the electron beam at Stanford Mark III—produces a beam of annihilation photons for photoproduction experiments such as those being carried out in the one-meter hydrogen bubble chamber. The annihilation beam (figure 9) has been developed by Joseph Ballam, George Chadwick, Zaven Guiragossian, David Leith, Rudy Larsen and Stephen Williams.²⁰ Because the magnitude of the annihilation spike, relative to the radiation background, decreases with increasing energy, at high energies one must take advantage of the relatively broad annihilation angular distribution and enhance the signal-to-noise ratio by selecting photons produced at some angle to the positron-beam direction. For 12-GeV positrons and an angle of 7.15 mrad, the annihilation spike occurs at 7.5 GeV (figure 10).

A positron beam that produces a specialized beam of high-energy photons is perhaps the best measure of the extent to which the positron technique



SLAC POSITRON FACILITY. Electrons originating at the injector are accelerated to 5 GeV and strike a converter a third of the way along the 3-km path. Positrons produced in the converter pass through a tapered high-field solenoid and a constant-field solenoid of moderate strength; the positrons are then accelerated the remaining distance to the beam switchyard. Quadrupole triplets located along the accelerator provide additional focusing. The hydrogen bubble chamber, which uses positron-annihilation photons, is located beyond the switchyard. —FIG. 7



POSITRON CONVERTER at the SLAC 20-GeV accelerator. Foreground shows the wheel-target drive mechanism with uniform-field solenoid in background. —FIG. 8

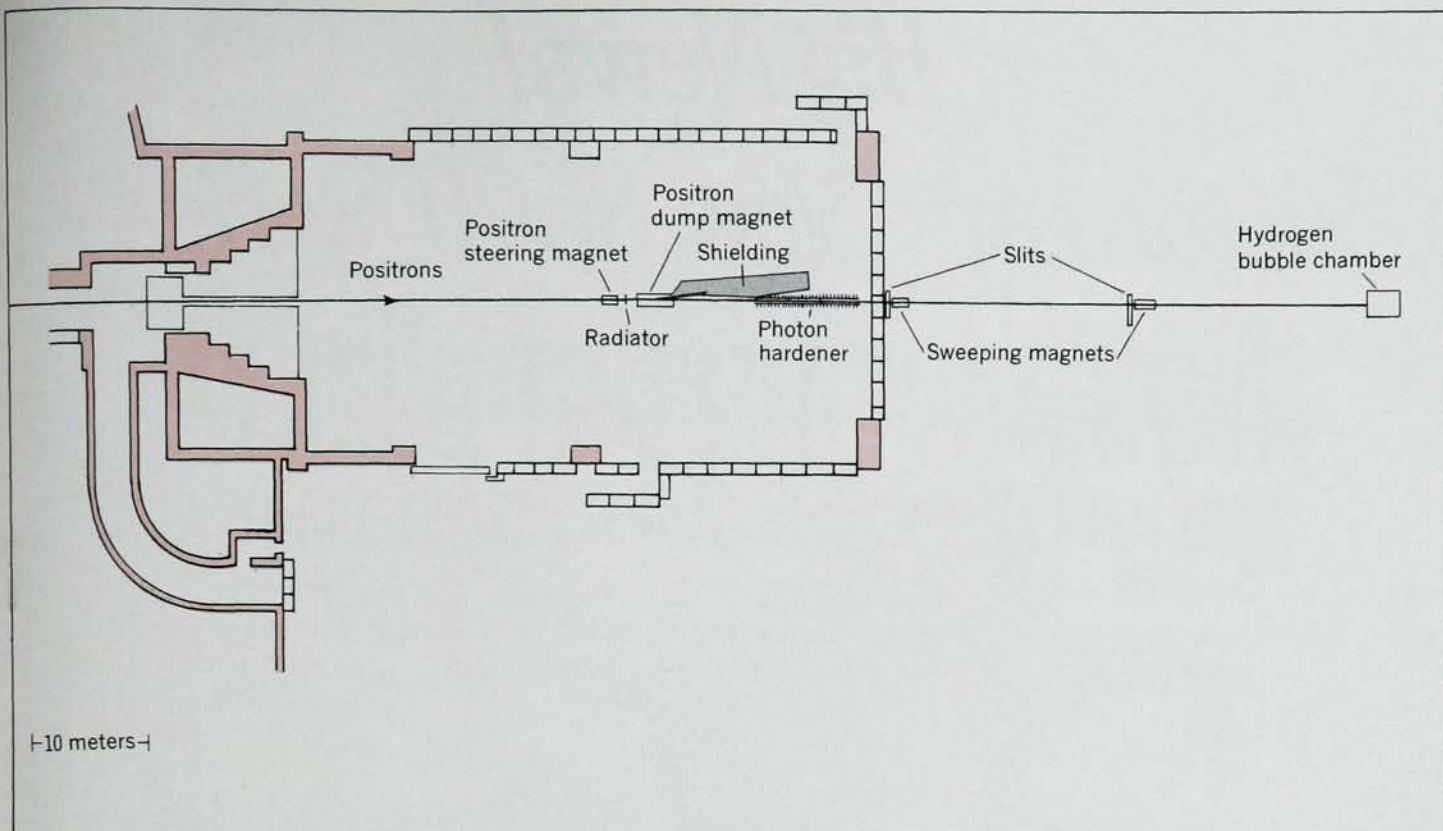
has progressed. In a very real sense, the positron beam at SLAC is treated as a standard laboratory facility almost on a par with the electron beam in its range of applications.

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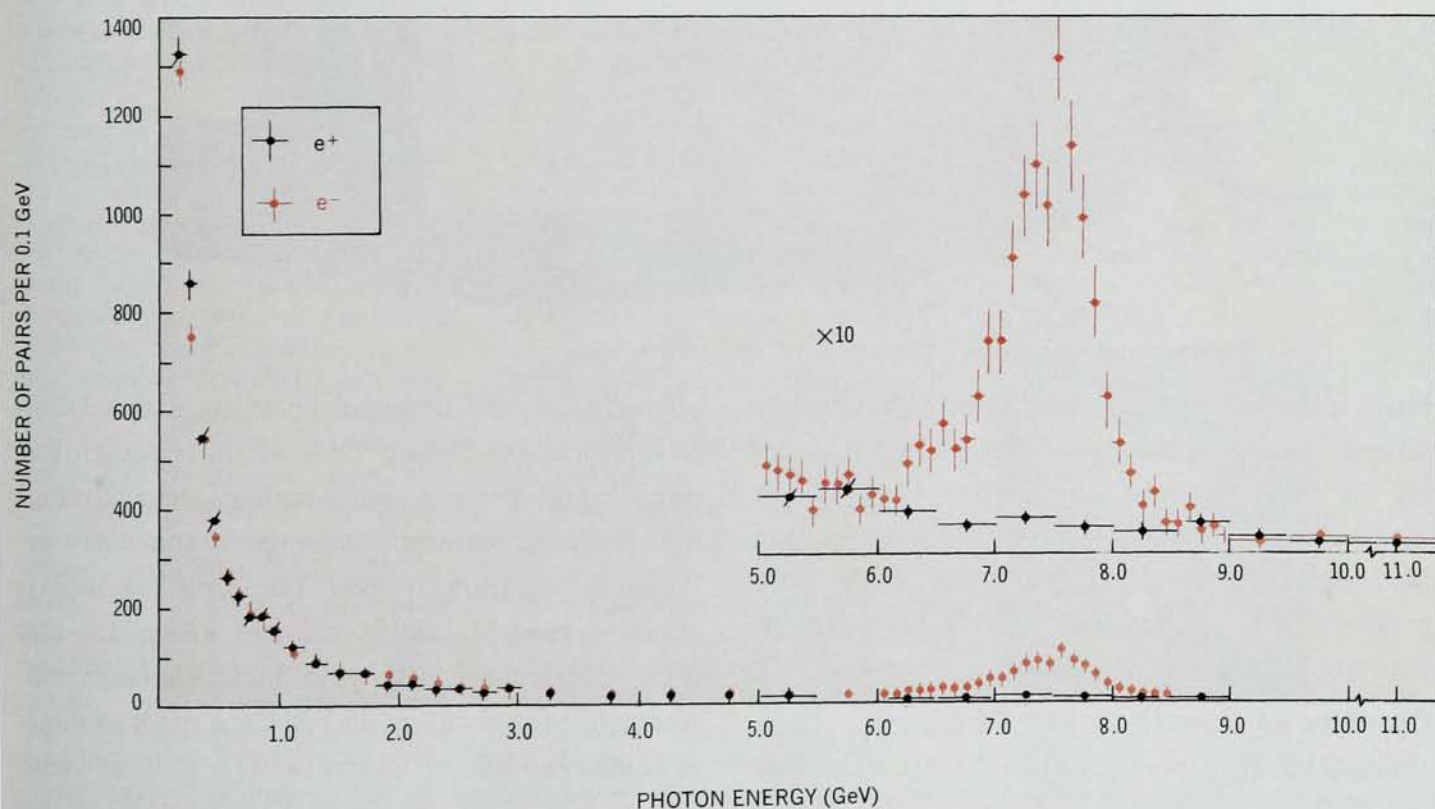
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LIQUID-HYDROGEN RADIATOR. Well collimated and momentum-analyzed positrons enter from the left and strike the radiator where annihilation produces photons. The positrons are deflected into a beam dump by the magnet located just beyond the target. The photons continue on to the one-meter-long hydrogen bubble chamber. A liquid-hydrogen photon hardener is used to absorb very low-energy photons, and slit collimators define the proper annihilation angle. Sweeping magnets eliminate positrons and electrons produced by photon showers in the collimators.

—FIG. 9



ANNIHILATION PHOTON SPECTRUM. This experimental data (colored dots) was obtained by J. Ballam et al for 12-GeV incident positrons. The complete spectrum, produced at an angle of 7.15 mrad with respect to the positron direction, shows an annihilation spike at 7.5 GeV. A background bremsstrahlung spectrum, obtained with electrons, is shown in black. The annihilation-spike region from 5.0 to 9.0 GeV is repeated at $10\times$ expanded scale.

—FIG. 10