SLAC-PUB-378
September 1968
(EXPI)

POSITRON BEAMS*

by

D. Yount

Stanford Linear Accelerator Center
Stanford University, Stanford, California

ABSTRACT

The secondary positron beams produced by linear electron accelerators are used in scattering experiments with stationary targets, in electron-positron colliding beam experiments, and in the production of annihilation photon beams: they now approach primary electron beams in their energy, intensity, and range of application.

(To be published in Physics Today)

*Work supported by the U.S. Atomic Energy Commission.

The study of elementary subatomic particles is made possible in large measure by the development in recent years of high-energy electron and high-energy proton accelerators. Progress in the field of "accelerator physics" is usually reckoned in terms of the maximum "primary" beam energies and intensities that the most advanced accelerators are able to produce. More recently, as higher primary energies and intensities have been achieved, the production of high-energy "secondary" beams of mesons, photons, anti-protons, neutrons and antineutrons, positrons (anti-electrons) and even neutrinos and hyperons has assumed considerable importance.

Secondary beams are produced when an accelerated beam of primary electrons or protons strikes a suitable target. The photon (x-ray) beams produced in x-ray tubes (Fig. 1) provide a familiar example: electrons emitted from the negative cathode are accelerated by the electric field toward the positive anode where they emit x-rays with a wide range of energy and direction. Usually, secondary beams are collimated to yield "pencil" beams traveling in a well-defined direction. Unlike photon beams, charged particle beams can also be momentum-analyzed by bending the beams through a magnetic field. This results in a beam of specific momentum and momentum interval. Techniques are also available for distinguishing or for separating out particles of a particular type. The resulting secondary beams, though still very useful, necessarily have lower energies and much lower intensities than the primary beams that generate them.

The positron beams produced internally by linear accelerators (Fig. 2) differ from other secondary beams in that their energies normally exceed the energies of the primary electrons incident on the positron target or "converter." Furthermore, positron intensities can, in principle, exceed primary electron intensities. The high energy is achieved by using a major fraction of the linear accelerator to accelerate positrons. The high intensity results from a cascade production process in which a "shower" of low-energy positrons and electrons is produced in the converter by a single high-energy electron.

In linear accelerators the particles are accelerated along a straight tube by an electric field confined within that tube. There are two basic types: first, the standing-wave machine, in which the tube consists of many segments and the accelerating field exists across the gaps between segments; and, second, the traveling-wave machine, in which the electric field moves down the tube with the particles. In the traveling-wave design (Fig. 3), which is better suited to the acceleration of electrons, the wave can be visualized as a sine curve with crests indicating the maximum accelerating force and valleys indicating the maximum decelerating force. As the wave moves down the pipe, it tends to push the electrons ahead of it, gathering them into bunches near the accelerating crests. The velocity of the traveling-wave is controlled by a series of ridges within the pipe and is synchronized so that the electrons remain bunched near the crests of the waves. After the first few feet of acceleration, the electrons have gained 10 MeV and are traveling at nearly the speed of light. From this point on, the electrons travel at almost constant speed through the pipe, and the subsequent energy and momentum gain appear primarily as an increase in the electron mass.

Because positrons and electrons have opposite charge, the crests of the electron sine wave tend to decelerate positrons while the valleys tend to accelerate them. Positron acceleration can therefore be achieved by shifting the traveling wave one half cycle 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.

Two basic processes are involved in the production of positrons by an incident electron. In the first step, the electron "hits" an atom in the converter and is decelerated by the electric field of the atomic nucleus or of one of the atomic electrons. As a result of this deceleration, the electron emits a photon whose energy may be as high as the initial electron energy or lower than the photon energy in ordinary light. This same process also occurs in the anode of an x-ray tube. In the second step, those photons which have sufficient energy (greater than 1.022 MeV, the combined mass-energy of an electron plus 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, which in turn produce additional positrons and electrons (Fig. 4). 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 electron of 5 BeV, the resulting shower may contain as many as thirty low-energy positrons at "shower maximum." Thus the positron intensity at injection is quite high. The final intensity is determined by the fraction of these positrons which is captured and accelerated.

There are several means available by which the number of positrons reaching the end of a linear accelerator can be enhanced (Fig. 5). The most important of these is the acceleration process itself. During acceleration, the component of the positron momentum perpendicular to the accelerator axis (tranverse momentum) remains constant while the component along the axis (longitudinal momentum) increases linearly with the distance traveled. 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 two orders of magnitude, and the number of positrons remaining 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 one inch in diameter remains quite small.

The capture efficiency for positrons can also be enhanced by surrounding a portion of the accelerator tube with a coaxial solenoid which produces a uniform magnetic field parallel to the accelerator axis and thus parallel to the accelerating electric field. The motion of the positrons in such an electro-magnetic field is a helix of constant radius (determined by the initial transverse momentum) and of increasing pitch (determined by the increasing longitudinal momentum). For optimum effectiveness, the solenoid should be installed immediately after the radiator where the angle between the positron direction and the accelerator axis is largest. While 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 10-30 feet, by which point 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; their reduced angle then ensures an enhanced capture efficiency, usually one or two orders of magnitude better than the no-solenoid case.

In place of a long solenoid, magnetic quadrupoles spaced at carefully chosen intervals along the linear accelerator can be used to 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 insures 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 over the entire length of the machine.

A number of technical details must be worked out before a positron beam becomes a practical laboratory facility. In most cases, a wide range of solutions is available, and the particular choice represents a compromise of several competing factors. For example, photon radiation and pair production occur whenever a beam of high-energy electrons or positrons is incident on an array of atoms: any converter material can, in principle, be used. The most efficient materials are those of high density near the botton of the periodic table--lead, tantalum, tungsten, gold, and platinun--but other elements may be more resistent to heat, corrosion, and radiation damage or may be cheaper or more easily machined. Heat conductivity and the longevity of the residual radiation hazard are other important considerations. Thus, while all of the elements listed above have been used, others such as copper may in some cases provide a more attractive compromise.

Similarly, the optimum converter thickness is generally that thickness for which the number of positrons in the shower is maximum. Nevertheless, thinner converters may actually 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.

Finally, while a "typical" positron converter may be visualized as a water-cooled tungsten cylinder one-half inch in diameter extending some fraction of an inch along the accelerator axis, a number of more exotic converters have been proposed and sometimes used. Thus the 200-kilowatt power rating of the 5-BeV electron beam which strikes a positron converter at the 20-BeV Stanford Linear Accelerator Center has inspired physicists to consider "wands" which dip into the electron beam only on occasional pulses, "wheels" which 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 which flow through the electron beam and into a suitable heat exchanger (Fig. 6).

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 were collimated and momentum-analyzed to yield a well-defined beam of 200-MeV positrons in the experimental area. The relatively low maximum 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.

During 1959, extensive work was done by Jerome Pine and the author 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 detect 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 a second (an average current of 0.3 nanoamps).[3] This was still more than three orders of magnitude lower than the intense Mark III electron beam, but it far surpassed the intensities of meson and other secondary beams produced elsewhere without acceleration. In fact, it 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--which they could vary almost at will. The existence of either a positron or an electron beam under identical experimental conditions had one further consequence: very precise comparisons could be made and very small differences detected in electron and positron interactions.

The first experiment carried out with the new positron beam was a precise (to 1% at some points) comparison of positron-proton and electron-proton scattering at 200 to 300 MeV (Fig. 7).[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 via 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 Stanford[5] and recently to energies above 1 BeV by physicists at Cornell University,[6] at the Cambridge Electron Accelerator,[7] and at the Deutsches Elektronen-Synchrotron in Hamburg, Germany.[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° (backward scattering) by physicists at Orsay, France.[9] During the last year, the positron-proton experiment has been extended to 8 BeV at the Stanford Linear Accelerator Center.[10] Within the few percent sensitivity of these experiments, no unexpected differences have been found in positron-proton and electron-proton scattering from 200 MeV to 8 BeV.

An experiment in which quite large differences in positron and electron scattering were observed was carried out at Stanford immediately after the first positron-proton experiment.[11] In this case, 300-MeV positrons and electrons were scattered off of cobalt (Z=27) and bismuth (Z=83) - "high-Z" elements having complicated nuclei consisting of many protons and neutrons. The two-photon effects were again expected to be of order $Z\alpha$, i.e., of order 27/137 and 83/137 respectively; thus they provide a readily measurable and rather sensitive probe of nuclear structure (Fig. 8). While not so fundamental as the studies of internal proton structure, this work on nuclear – as distinguished from elementary particle – physics has stimulated similar positron programs at Orsay[12] and Saclay, France, at Saskatoon, Saskatchewan, at Frascati, Italy, and at other laboratories in this country.

The original positron-electron scattering experiment was repeated at Orsay[13] using counters, a magnetic spectrometer, and a positron beam developed by Louis Burnod. The high intensity available by this time (1965) permitted an absolute measurement to 1%, which represented an order of magnitude improvement in precision over the earlier cloud chamber results at Stanford.[2]

While the initial development of intense positron beams was motivated by scattering experiments such as those just described, a second and very recent application 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. Not only does this permit an extension of the positron-electron scattering experiments to very high effective energies, but more importantly, it allows physicists to study at these energies a variety of annihilation reactions. There is, in fact, 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 (ACO) (Fig. 9) now in progress at Orsay,[14] the 1.3-BeV 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 μ, π, and K meson pairs. Processes involving a single intermediate meson of higher rest energy, such as the ρ, the ω, and the ϕ are also being studied.

The 700-MeV positron-electron storage ring (VEPP-2)[14] now operating at Novosibirsk in the Soviet Union has recently yielded a measurement of the ρ-meson production rate. The Soviet results for the ρ-meson are believed by many physicists to be the best obtained to date by any procedure. They agree with previous results except that they yield a significantly narrower resonance width than has been seen before (the resonance width is inversely proportional to the particle lifetime).

The positron beam facility[15] developed for the 1.5-BeV storage ring (ADONE)[14] at Frascati, Italy, is noteworthy in several respects. The linear accelerator in question was built commercially by Varian Associates, USA, specifically for electron and positron acceleration and injection into the storage ring. The accelerator is composed of two sections: the high-intensity section accelerates electrons to an energy of 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-kilogauss) 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 is about three thousand times the positron intensity obtained at the Stanford Mark III accelerator: it exceeds the primary proton and primary electron intensities of all circular accelerators in the BeV 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-BeV ring (VEPP-3) is under construction at Novosibirsk, and a 3-BeV facility is being assembled in this country by adapting the 6-BeV Cambridge Electron Accelerator to accelerate and store positrons and electrons injected by a 130-MeV linear accelerator. Storage rings of 3 BeV have been proposed for the Deutsches Elektronen-Synchrotron and for the Stanford Linear Accelerator Center.

We have already discussed two applications for secondary positron beams, namely 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. A third application is of particular interest at the Stanford Linear Accelerator Center where 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, which is 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 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 of a beam of electrons or positrons, but this possibility is still being developed.

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 Laboratory[16] and by C. Tzara and his colleagues at Saclay, France,[17] the photons were produced at 0° with respect 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 that is also active today. It is interesting to note that the Stanford and Lawrence Radiation Laboratory groups, working some 40 miles apart, evolved the positron acceleration technique independently and used 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 the Stanford Linear Accelerator Center[18] (Figs. 10, 11) by Herbert DeStaebler, Jerome Pine and others – with fifteen times the energy and nearly the same intensity as the electron beam at Stanford Mark III--is now being used to produce a beam of annihilation photons for use in photoproduction experiments such as those being carried out in the one-meter hydrogen bubble chamber. The annihilation beam (Fig. 12) has been developed by Joseph Ballam, George Chadwick, Zaven Guiragossián, David Leith, Rudy Larsen, and Stephen Williams.[20] Because the magnitude of the annihilation spike, relative to the radiation background, decreases with increasing energy, it is necessary at high energies to take advantage of the relatively broad annihilation angular distribution and to enhance the signal-to-noise by selecting photons produced at some angle with respect to the positron beam direction. For 15-BeV positrons and an angle of half a degree, the annihilation spike occurs at 7.27 BeV (Fig. 13).

The use of a positron beam to produce a specialized beam of high-energy photons is perhaps the best measure of the extent to which the positron technique has progressed. In a very real sense, the positron beam at the Stanford Linear Accelerator Center is treated as a standard laboratory facility almost on a par with the electron beam in its range of applications.

REFERENCES

1. R. B. Neal, SLAC: The Accelerator, Physics Today, April, 1967.
2. J. A. Poirier, D. M. Bernstein, and J. Pine, Phys. Rev. 117, 557 (1960).
3. D. Yount and J. Pine, Nucl. Instr. and Methods 15, 45 (1962).
4. D. Yount and J. Pine, Phys. Rev. 128, 1842 (1962).
5. A. Browman, F. Liu, and C. Schaerf, Phys. Rev. 139, B1079 (1965).
6. R. L. Anderson, B. Borgia, G. L. Cassiday, J. W. De Wire, A. S. Ito, and E. C. Loh, Phys. Rev. Letters 17, 407 (1966).
7. A. DeHollan, E. Engels, B. Knapp, and L. Hand, Paper 6 a.9., Proceedings of the XIIIth International Conference on High-Energy Physics, Berkeley (1966).
8. W. Bartel, B. Dudelzak, H. Krehbiel, J. M. McElroy, R. J. Morrison, W. Schmidt, V. Walther, and G. Weber, DESY 67/22 (1967).
9. B. Bouquet, D. Benaksas, B. Grossetête, B. Jean-Marie, G. Parrour, J. P. Poux, R. Tchapoutian, Laboratoire de l'Accélérateur Linéaire Report LAL 1183 (1967).
10. J. Mar, B. C. Barish, J. Pine, D. H. Coward, H. DeStaebler, J. Litt, A. Minten, R. E. Taylor, and M. Breidenbach, "Comparison of Elastic Electron-Proton and Positron-Proton Scattering at Momentum Transfers up to 5.0 $(GeV/c)^2$, (Abstract for the Washington Meeting of the American Physical Society, April 1968). A fuller account of this work was reported by J. Pine in the Proceedings of the International Symposium on Electron and Photon Interactions at High Energies.
11. J. Goldemberg, J. Pine, and D. Yount, Phys. Rev. 132, 406 (1963).
12. A. Browman, B. Grossetête, and D. Yount, Phys. Rev. 143, 899 (1966).
13. A. Browman, B. Grossetête, and D. Yount, Phys. Rev. 151, 1094 (1966).

14. ACO, ADONE, and VEPP-2 are among the storage rings discussed in the the Proceedings of the International Symposium on Electron and Positron Storage Rings, Saclay, France, September 26-30, 1966.

15. C. S. Nunan, "A Positron Linear Accelerator Design," IEEE Trans. Nucl. Sci. NS-12, No. 3 (June 1965); p. 465.

16. J. T. Caldwell, R. R. Harvey, R. L. Bramblett, and S. C. Fultz, Phys. Letters 6, 213 (1963). See also S. C. Fultz et al., Phys. Rev. 127, 1273 (1962) and Phys. Rev. 128, 2345 (1962).

17. "A Photon Monochromater by Annihilation in Flight of Positrons," by J. Miller, C. Schuhl, G. Tamas, and C. Tzara in: Contributions to the Karlsruhe Photonuclear Conference at Karlsruhe, Germany, August 18 through August 22, 1960, Paper G-1.

18. H. Brechna, K. E. Breymayer, K. G. Garney, H. DeStaebler, R. H. Helm, and C. T. Hoard, "The Positron Source," Chapter 16 of "The Stanford Two-Mile Accelerator," R. B. Neal, Editor, W. A. Benjamin, Inc., New York 1968.

19. J. Ballam, SLAC: The Program, Physics Today, April, 1967.

20. J. Ballam. G. Chadwick, Z. Guiragossián, D. Leith, R. R. Larsen, and S. Williams, "The SLAC Monochromatic Photon Beam," to be published.

FIGURE CAPTIONS

1. An x-ray tube. Electrons emitted from the negative cathode are accelerated toward the positive anode where they produce x-rays with a wide range of direction and energy. The intensity of the electron and x-ray beams can be controlled by adjusting the filament current. The maximum energy of the x-rays is essentially the energy gained by the electrons during acceleration. The x-rays can be collimated to yield a well-defined beam traveling in a particular direction.

2. An early positron beam facility developed at the Stanford Mark III Accelerator. Electrons injected at the left are accelerated to 600 MeV and strike a positron converter two-thirds of the way along the machine. Positrons from the converter are accelerated to 300 MeV by the last third of the accelerator and are collimated and momentum-analyzed to produce a well-defined beam in the experimental area.

3. Acceleration of electrons or positrons by a traveling-wave linear accelerator. A high-frequency radio wave generated by klystrons flows down an electrical waveguide (a). Negatively charged electrons are repelled by the negative wave crests and attracted by the positive wavecrests to cause motion to the right (b). Positively charged positrons can be accelerated by the same wave if they are displaced one-half cycle with respect to the electrons. The process is not unlike the horizontal acceleration of a surf-board rider on ocean beach waves (c). Discs or ridges within a waveguide control the velocity of the traveling wave so that the "surfboard-riding" electrons or positrons remain in step with the wave crests (d).

4. The development of a cascade shower. In (a) 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 enough energy to produce positron-electron pairs. Low energy positrons and electrons are continually being absorbed by ionization. In (b) the number of electrons in a typical shower is plotted versus the depth of penetration into a copper positron converter. The primary electron energy is 6 BeV. At shower maximum there are more than thirty electrons and about the same number of positrons.

5. Methods by which the number of positrons reaching the end of a linear accelerator can be enhanced. In (a) there is no enhancement. In (b) acceleration causes the positron trajectory to become more nearly parallel with the accelerator axis. The addition of a long solenoid (c) causes the accelerated positrons to follow a helical path of constant radius and of increasing pitch. In (d) a magnetic quadrupole lens supplements a short solenoid.

6. Diagram of the copper wheel target or converter and associated mechanism used as a positron source at the Stanford Linear Accelerator Center. When installed in the 5-BeV, 200-kilowatt electron beam, the water-cooled wheel executes a circular motion about the beam to dissipate the intense heat through a larger volume. The wand, which dips into the beam only on occasional pulses, is shown to the left of the beam centerline.

7. Summary of the experimental results comparing positron-proton and electron-proton scattering. The "Feynman diagrams" describing the scattering of a positron or an electron on a target proton are shown in (a) for a single-photon exchange and in (b) for a two-photon exchange. In (c) the ratio of the positron

an electron processes is plotted versus the square of the momentum transfer to the target proton, a quantity which increases with the incident energy and the scattering angle. Within the few-percent sensitivity of this series of experiments, no unexpected differences in positron-proton and electron-proton scattering have been found.

8. Summary of the experimental results comparing electron and positron scattering from bismuth nuclei. The difference in the two processes divided by the sum is plotted in (a) versus 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. Qualitatively, differences in electron and positron scattering increase with the number of protons in the nucleus. Thus these data provide a sensitive test of various models of the distribution of charge within the 83-proton bismuth nucleus. The models used in (a) were obtained from electron-scattering experiments and are plotted in (b) for a root-mean-square bismuth radius of 5.52×10^{-13} cm.

9. The injection system for the 500-MeV Orsay storage ring (a) and a larger drawing of the ring itself (b). The first four 250-MeV sectors of the linear accelerator (not shown) are used to produce positrons while the last sector produces electrons when a removable electron injector is installed at the point denoted A. The main components of the Orsay storage ring are labeled as follows: a--magnet sector; b--quadrupole focusing magnet; c--injector; c_1--pulsed inflector for positrons; c_2--pulsed inflector for electrons; d--radio frequency acceleration cavity; e--experimental equipment; f--vacuum pumps.

10. Schematic drawing of the positron facility at the Stanford Linear Accelerator Center. Electrons originating at the injector are accelerated to 5 BeV and strike a converter one-third of the way along the two-mile accelerator. Positrons

produced in the converter pass through a tapered high-field solenoid and a constant-field solenoid of moderate strength and are then accelerated the remaining distance to the Beam Switchyard. Quadrupole triplets located along the accelerator provide additional focusing. The location of the one-meter hydrogen bubble chamber, which uses positron-annihilation photons, is also shown.

11. Photograph of the positron converter area at the Stanford Linear Accelerator Center. The view is in the direction of the beam, which enters from the left.

12. Facility for producing a partially monochromatic photon beam at the Stanford Linear Accelerator Center. Well-collimated and momentum-analyzed positrons enter from the left and strike a liquid hydrogen radiator where a fraction annihilates to produce two photons. Unlike radiation photons, annihilation photons have a well-defined energy at a given production angle with respect to the positron beam direction. The positrons are deflected into a beam dump by a magnet (H2) just after the target, while the uncharged 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 are used after each collimator to eliminate positrons and electrons produced by photon showers in these collimators.

13. Idealized annihilation photon spectrum for incident positrons of 15 BeV. The complete spectrum at 0.5 degrees with respect to the positron direction shows an annihilation spike at 7.27 BeV superimposed on background spectra from direct photon radiation and from indirect photon radiation. Direct radiation occurs at the proper annihilation angle; indirect radiation occurs at zero degrees after the positron has scattered into the proper annihilation angle.

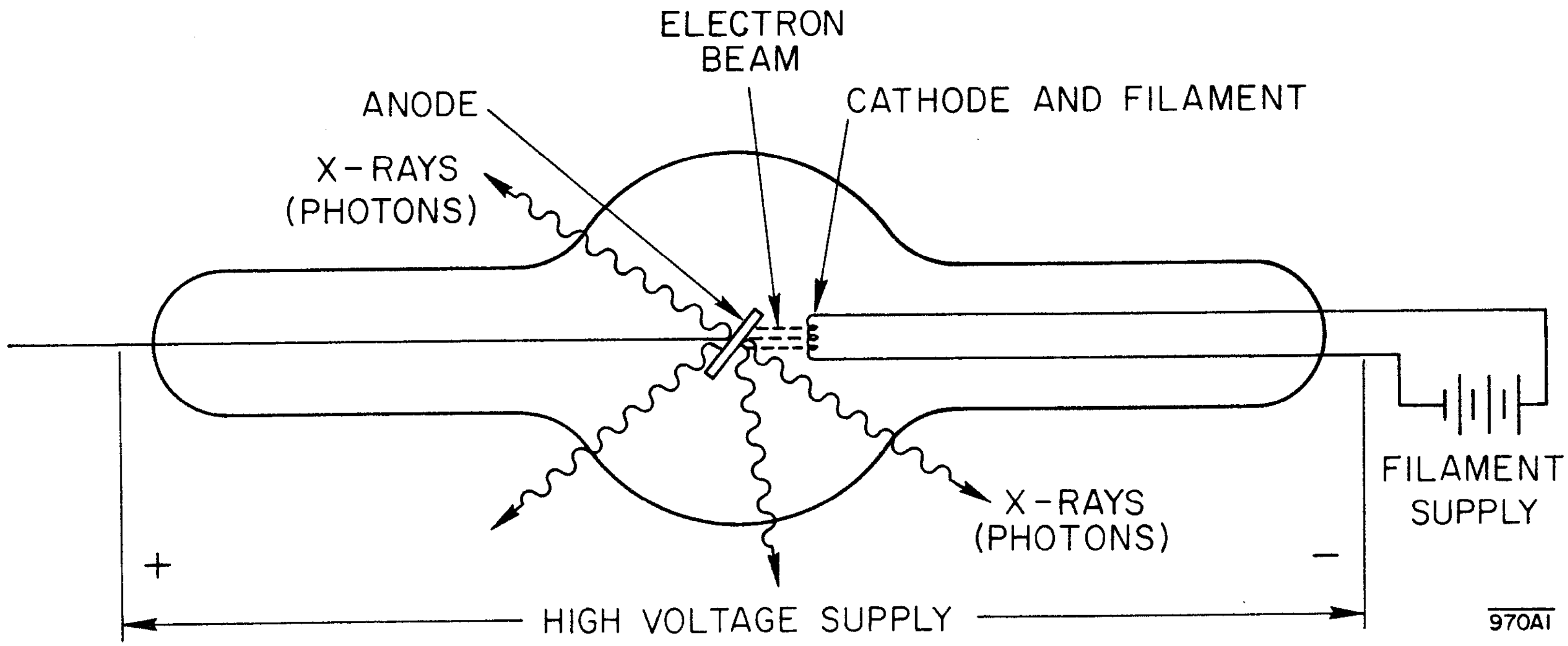

ELECTRON
BEAM
ANODE
CATHODE AND FILAMENT
X-RAYS
(PHOTONS)
X-RAYS
(PHOTONS)
FILAMENT
SUPPLY
+
−
HIGH VOLTAGE SUPPLY
970A1

Fig. 1

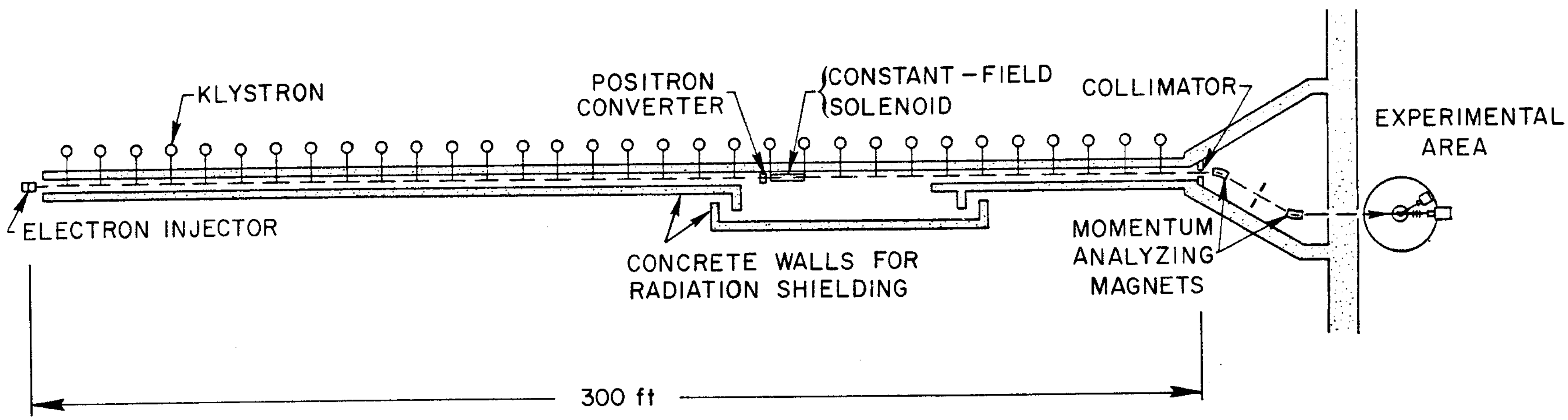

KLYSTRON
ELECTRON INJECTOR
POSITRON CONVERTER
CONSTANT-FIELD SOLENOID
CONCRETE WALLS FOR RADIATION SHIELDING
COLLIMATOR
MOMENTUM ANALYZING MAGNETS
EXPERIMENTAL AREA
300 ft

Fig. 2

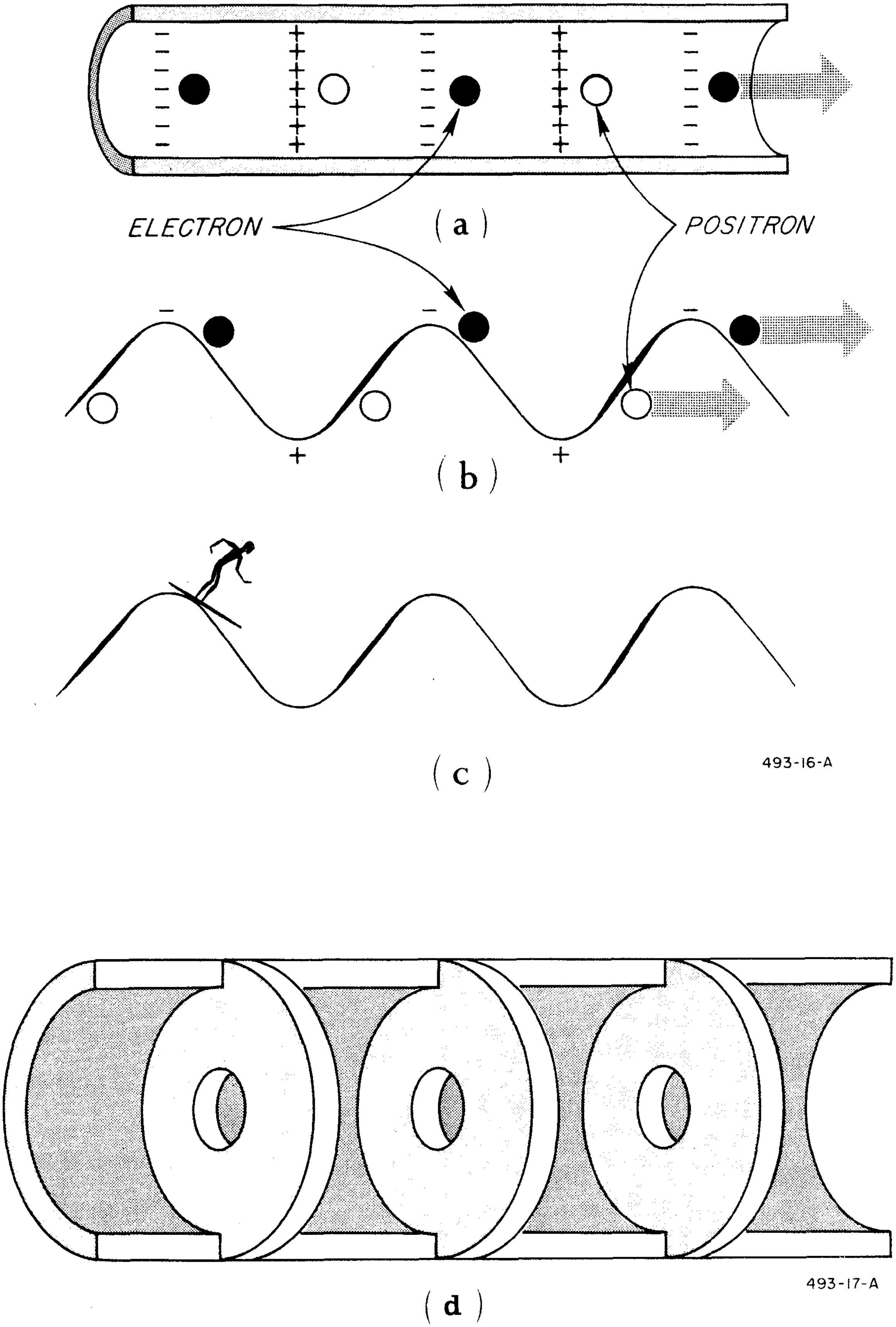
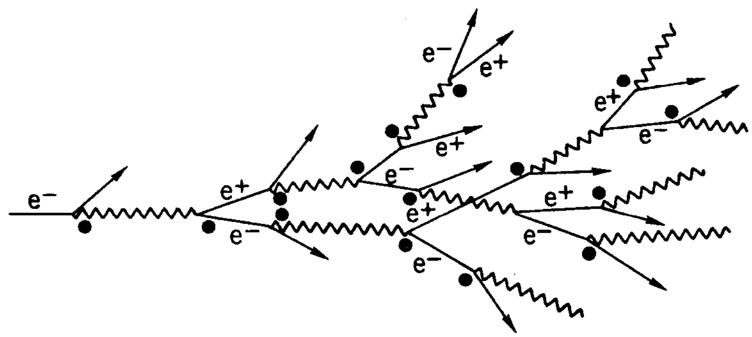
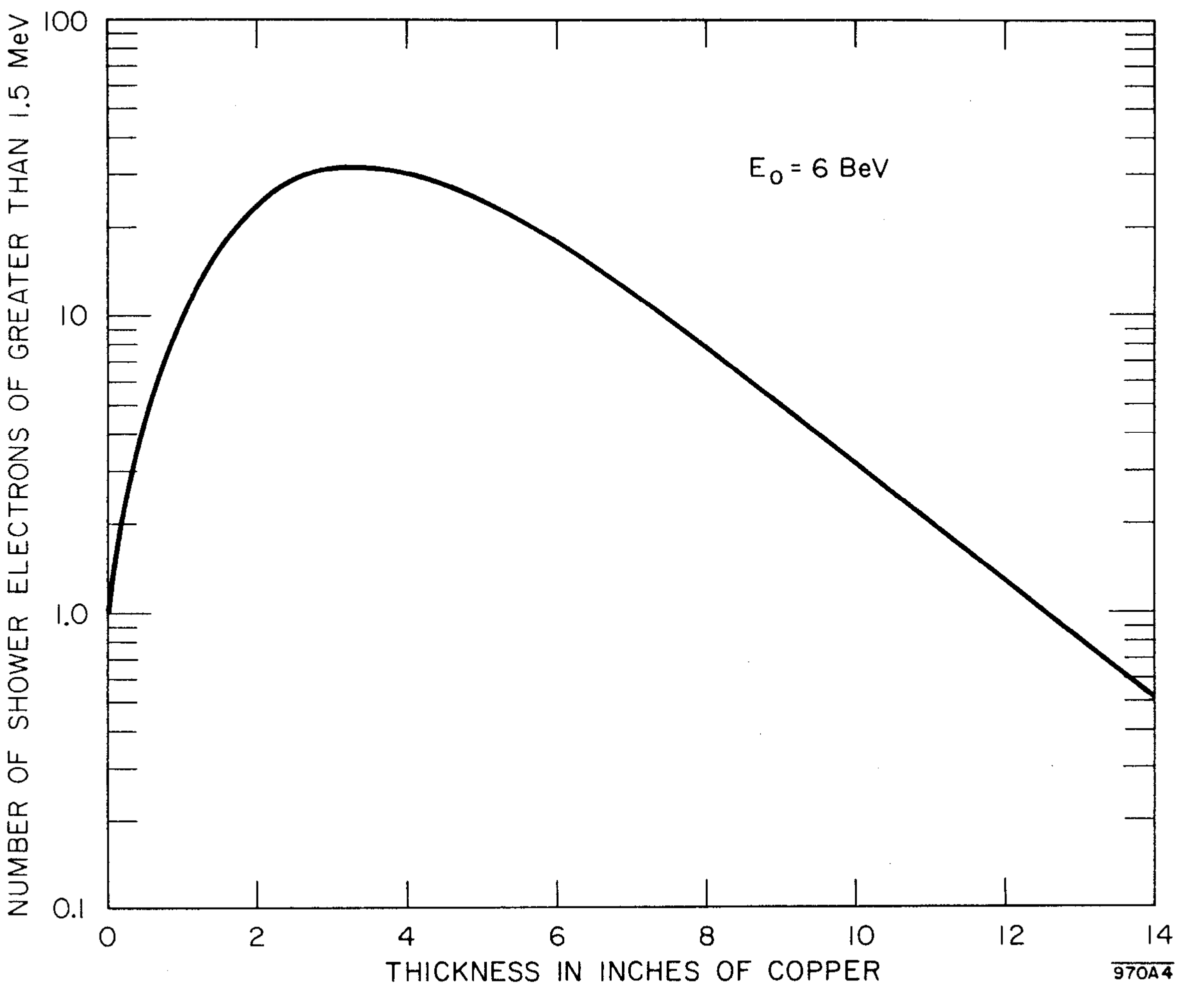


Fig. 3



e⁻
e⁺

(a)



NUMBER OF SHOWER ELECTRONS OF GREATER THAN 1.5 MeV
100
10
1.0
0.1
0
2
4
6
8
10
12
14
E_0 = 6 BeV
THICKNESS IN INCHES OF COPPER
970A4

(b)

Fig. 4

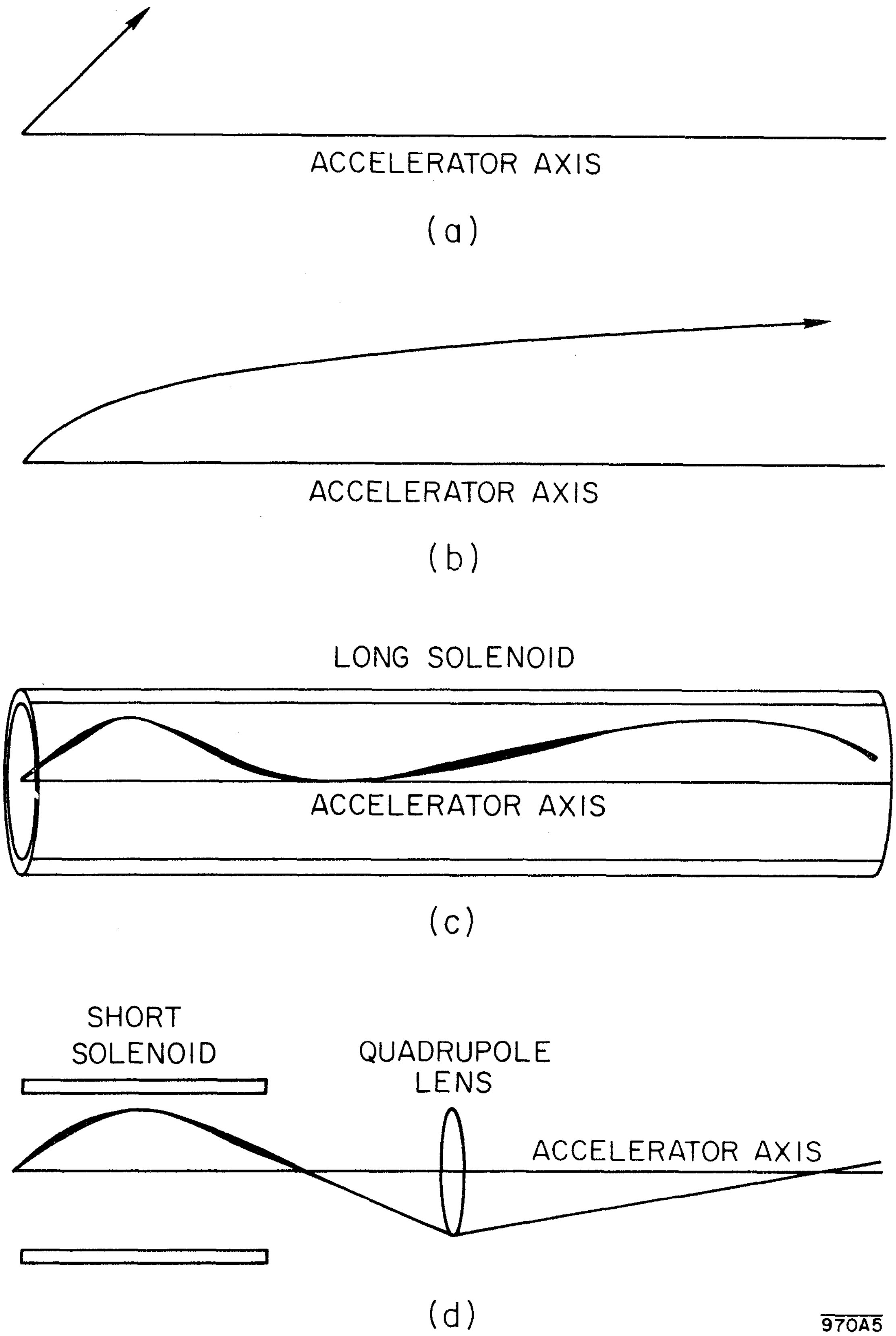

ACCELERATOR AXIS
(a)
ACCELERATOR AXIS
(b)
LONG SOLENOID
ACCELERATOR AXIS
(c)
SHORT
SOLENOID
QUADRUPOLE
LENS
ACCELERATOR AXIS
(d)
970A5

Fig. 5

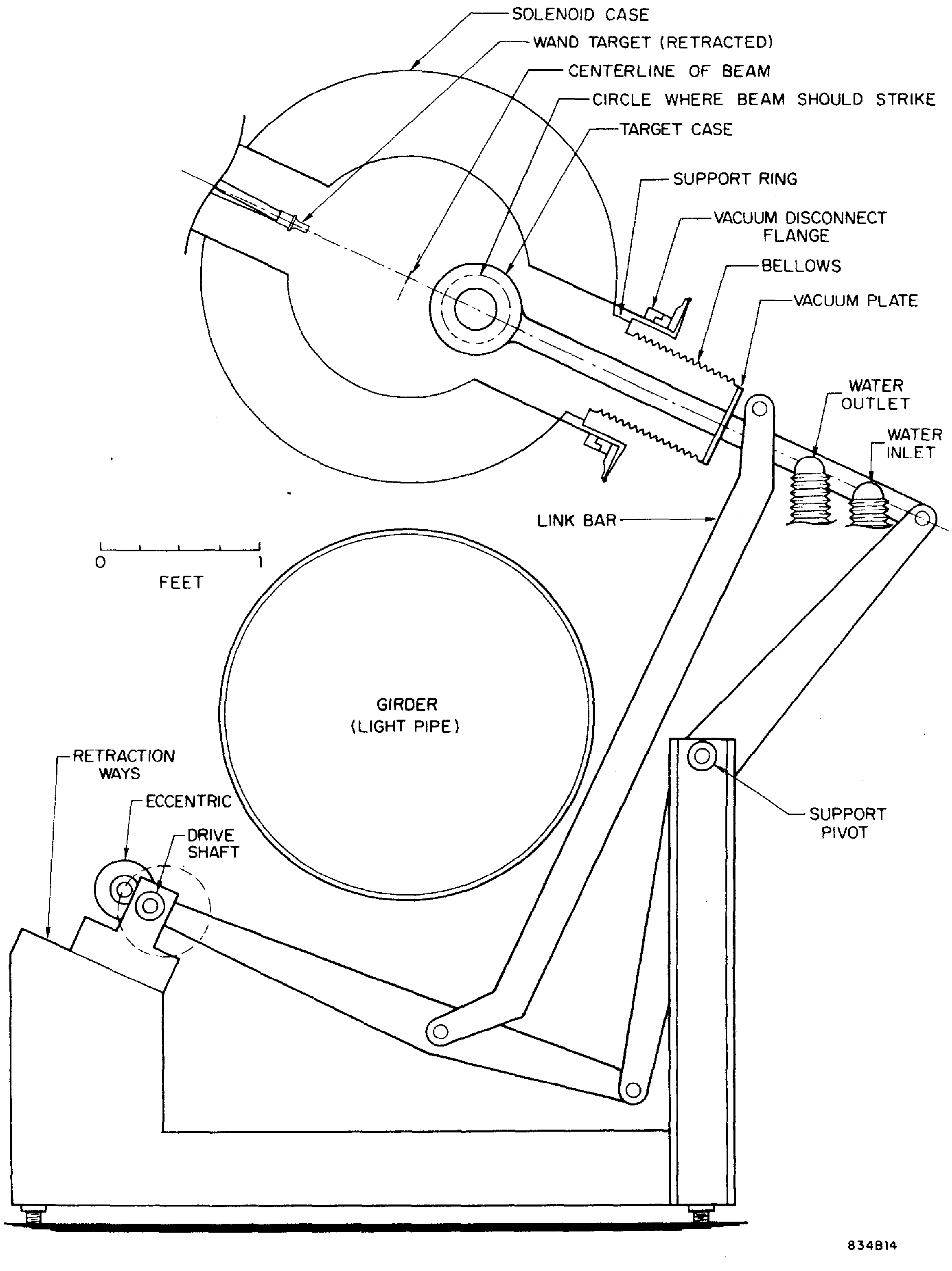

SOLENOID CASE
WAND TARGET (RETRACTED)
CENTERLINE OF BEAM
CIRCLE WHERE BEAM SHOULD STRIKE
TARGET CASE
SUPPORT RING
VACUUM DISCONNECT FLANGE
BELLOWS
VACUUM PLATE
WATER OUTLET
WATER INLET
LINK BAR
0
1
FEET
GIRDER (LIGHT PIPE)
RETRACTION WAYS
ECCENTRIC
DRIVE SHAFT
SUPPORT PIVOT
834B14

Fig. 6

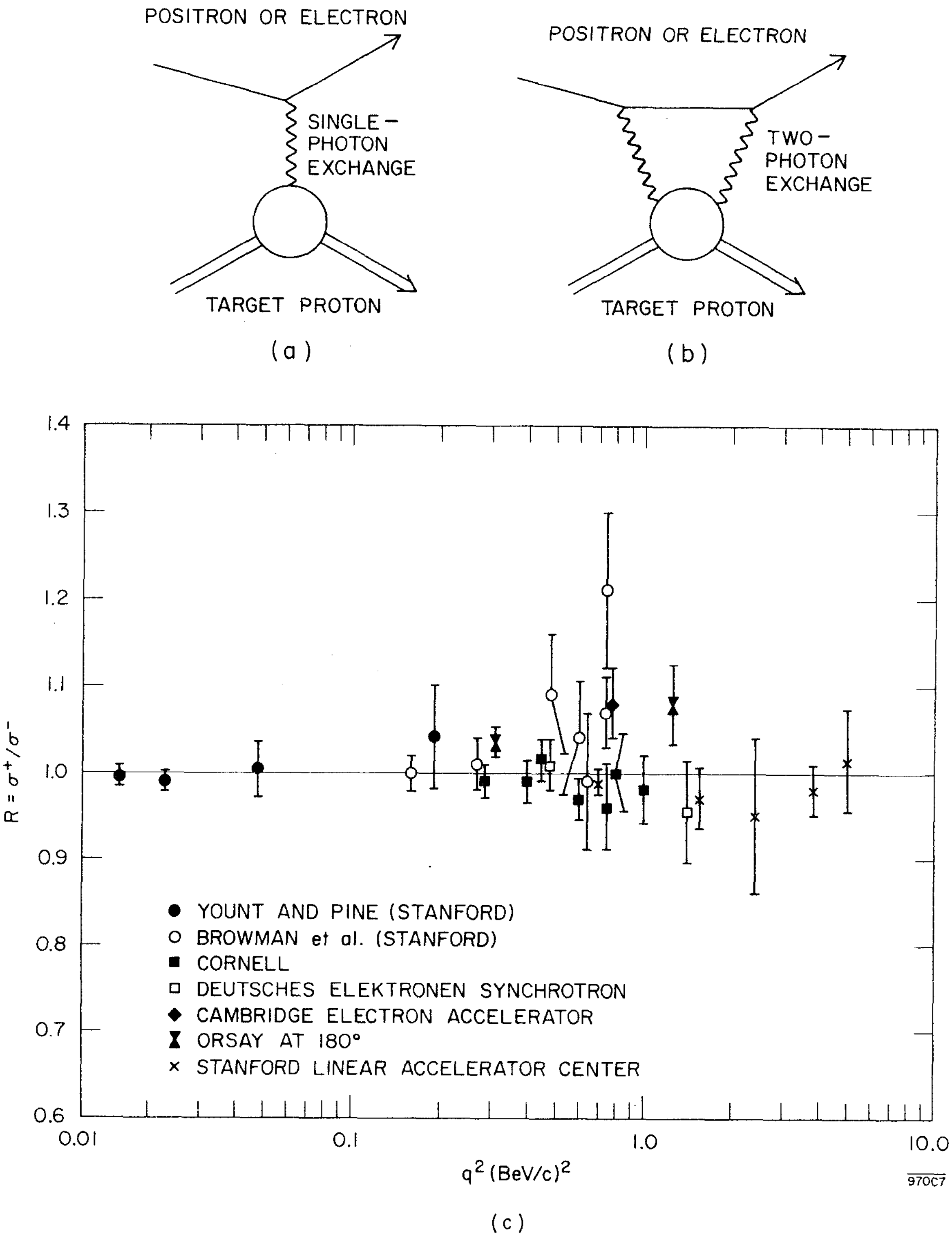
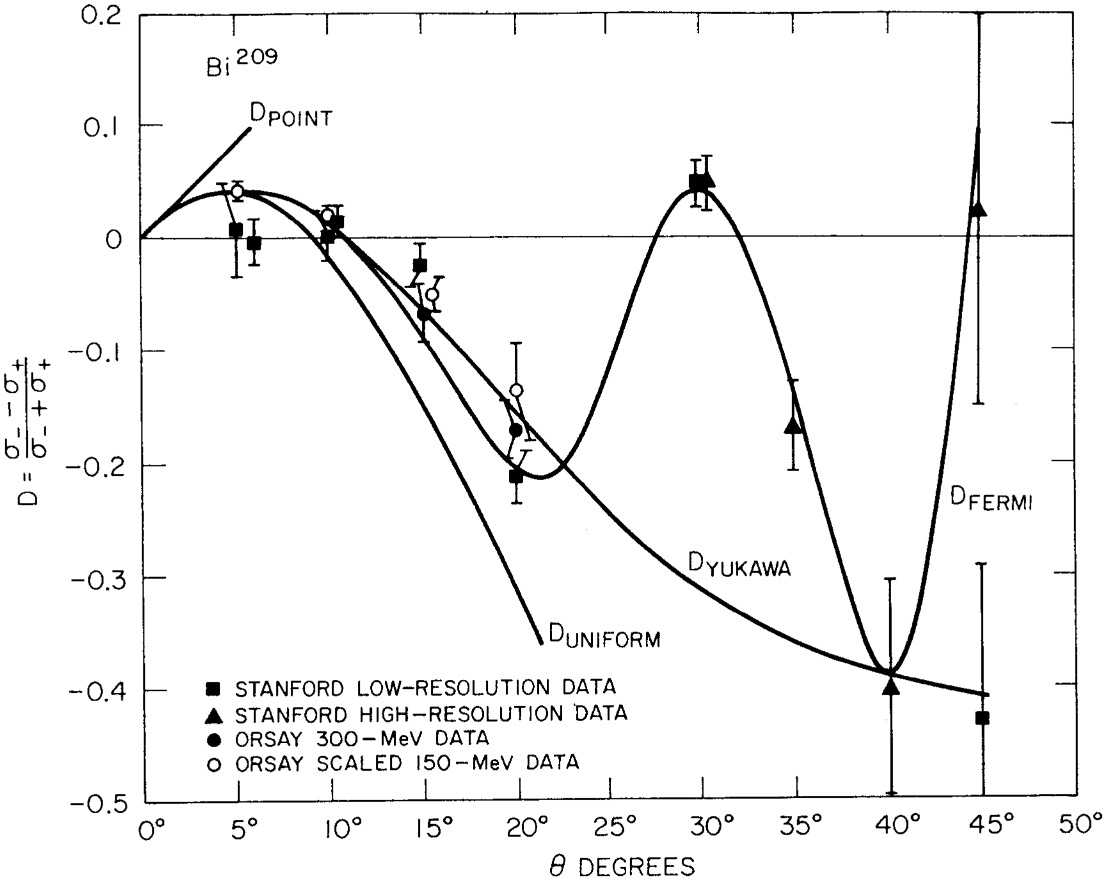
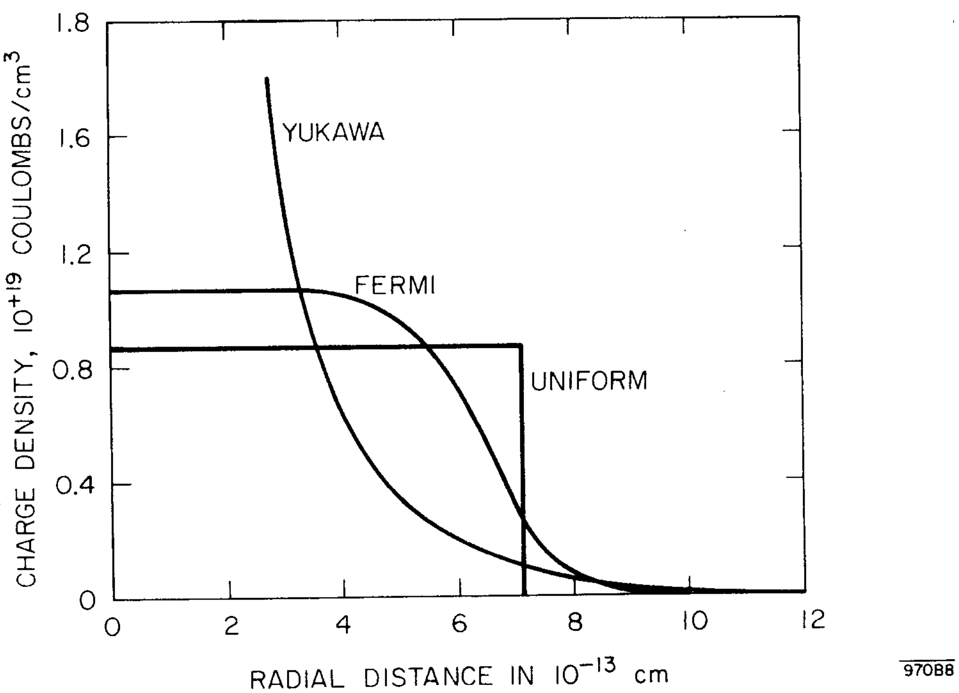

POSITRON OR ELECTRON
SINGLE-PHOTON EXCHANGE
TARGET PROTON
(a)
POSITRON OR ELECTRON
TWO-PHOTON EXCHANGE
TARGET PROTON
(b)
$R = \sigma^+/\sigma^-$
q^2 (BeV/c)^2
YOUNT AND PINE (STANFORD)
BROWMAN et al. (STANFORD)
CORNELL
DEUTSCHES ELEKTRONEN SYNCHROTRON
CAMBRIDGE ELECTRON ACCELERATOR
ORSAY AT 180°
STANFORD LINEAR ACCELERATOR CENTER
970C7
(c)

Fig. 7



Bi209
DPOINT
DFERMI
DYUKAWA
DUNIFORM
STANFORD LOW-RESOLUTION DATA
STANFORD HIGH-RESOLUTION DATA
ORSAY 300-MeV DATA
ORSAY SCALED 150-MeV DATA
$D=\frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+}$
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0° 5° 10° 15° 20° 25° 30° 35° 40° 45° 50°
θ DEGREES

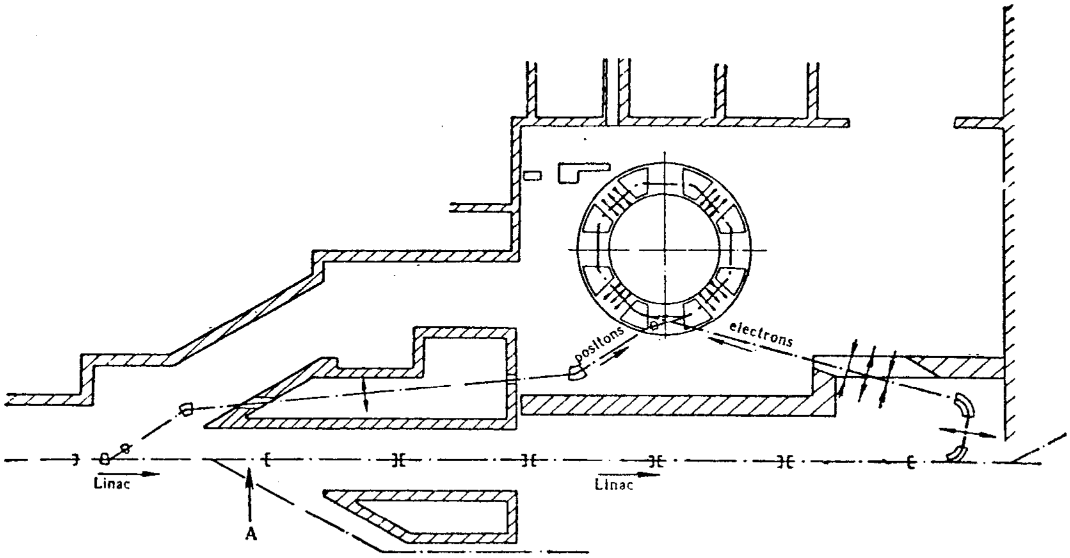
(a)



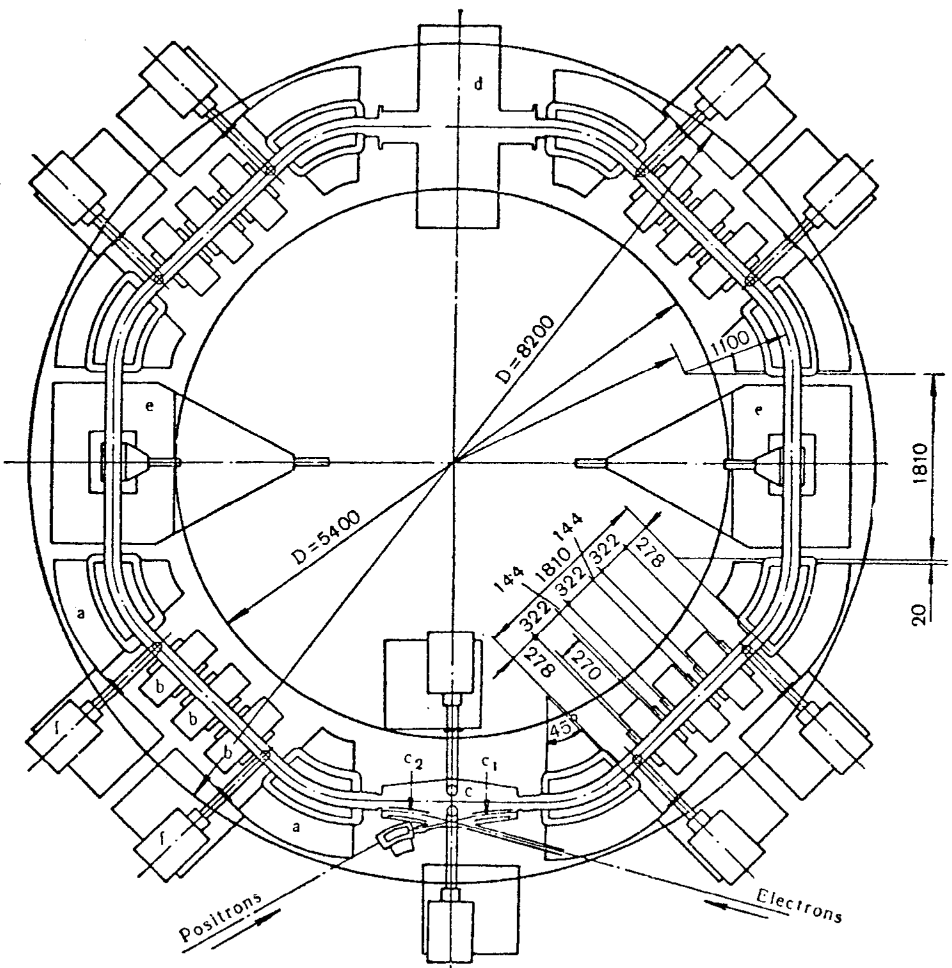
YUKAWA
FERMI
UNIFORM
CHARGE DENSITY, 10^{+19} COULOMBS/cm^3
1.8
1.6
1.2
0.8
0.4
0
0 2 4 6 8 10 12
RADIAL DISTANCE IN 10^{-13} cm
970B8

(b)

Fig. 8



(a)



(b)

970A9

Fig. 9

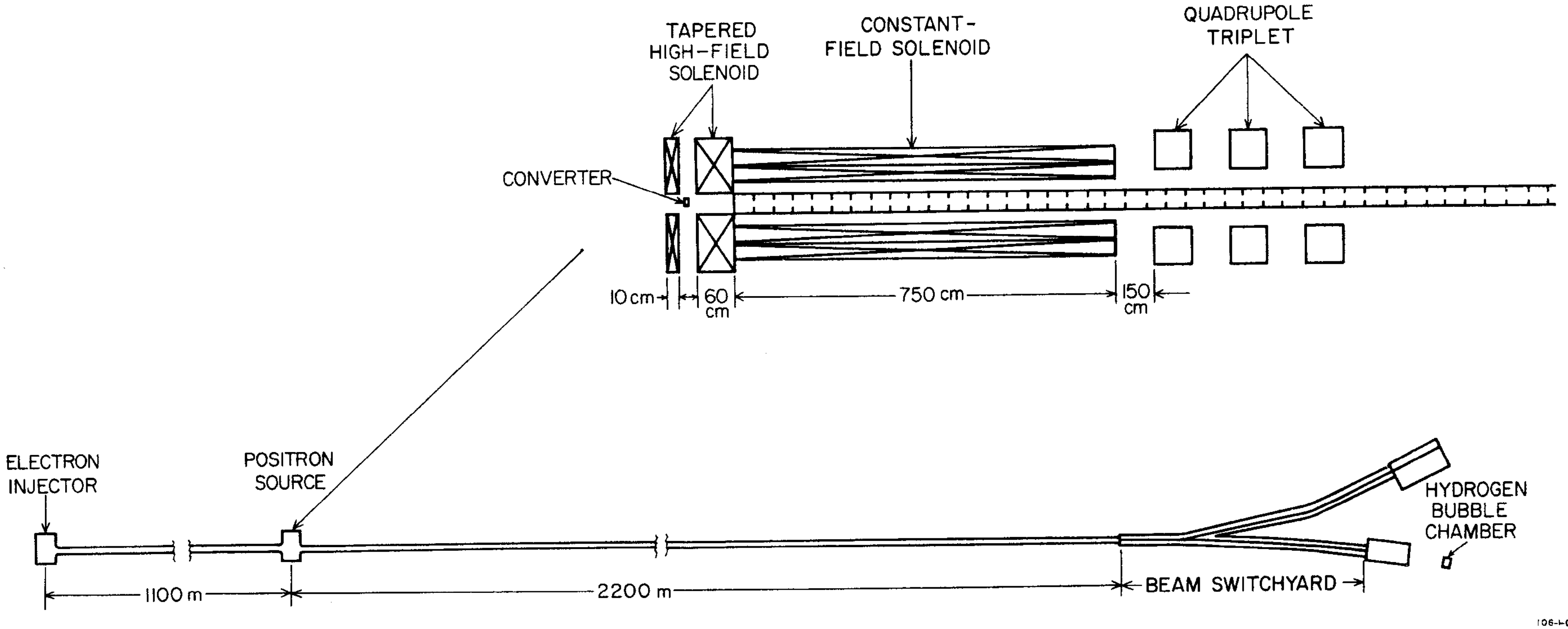

TAPERED HIGH-FIELD SOLENOID
CONSTANT-FIELD SOLENOID
QUADRUPOLE TRIPLET
CONVERTER
10 cm
60 cm
750 cm
150 cm
ELECTRON INJECTOR
POSITRON SOURCE
HYDROGEN BUBBLE CHAMBER
1100 m
2200 m
BEAM SWITCHYARD
106-1-C

Fig. 10

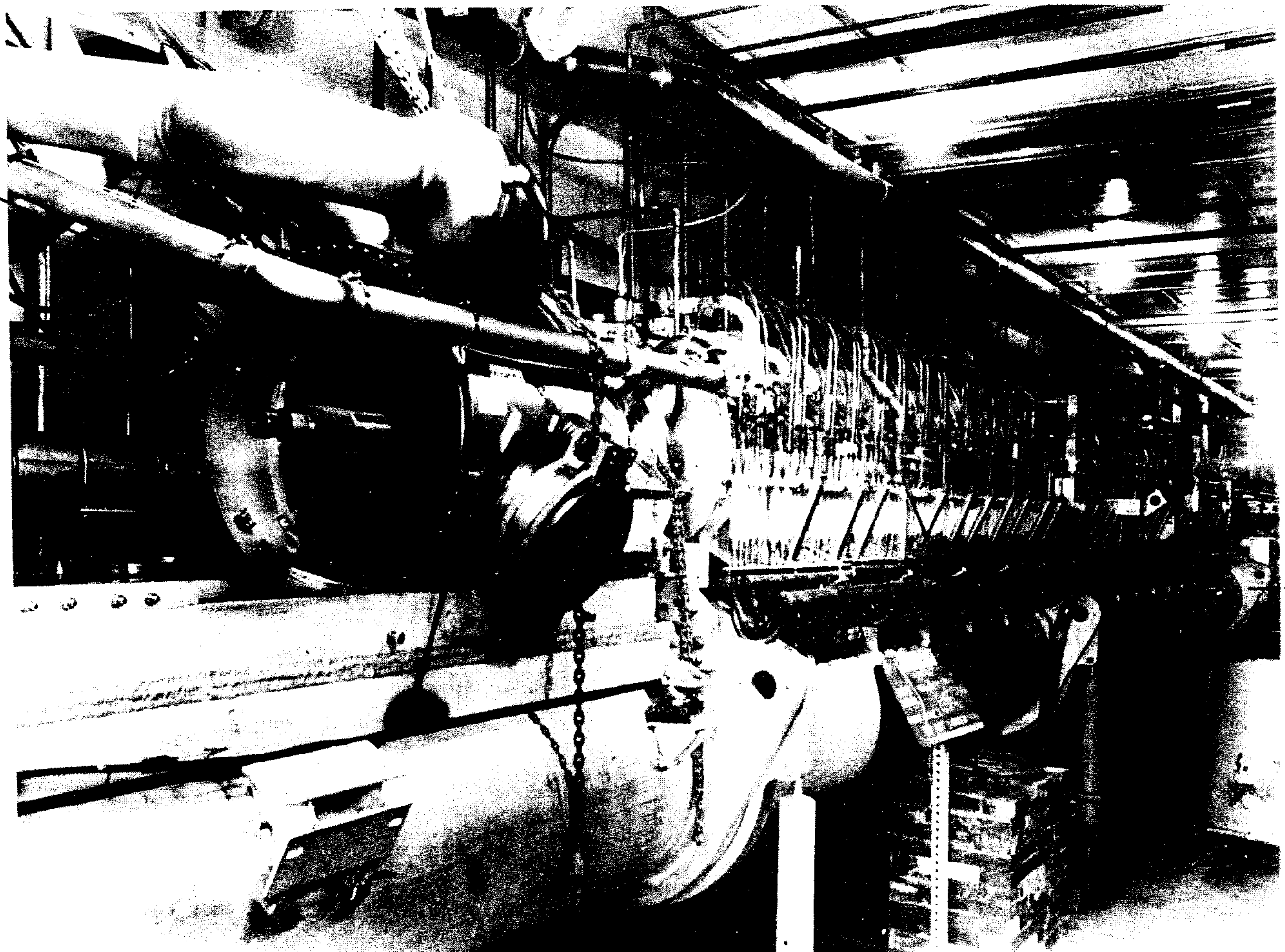
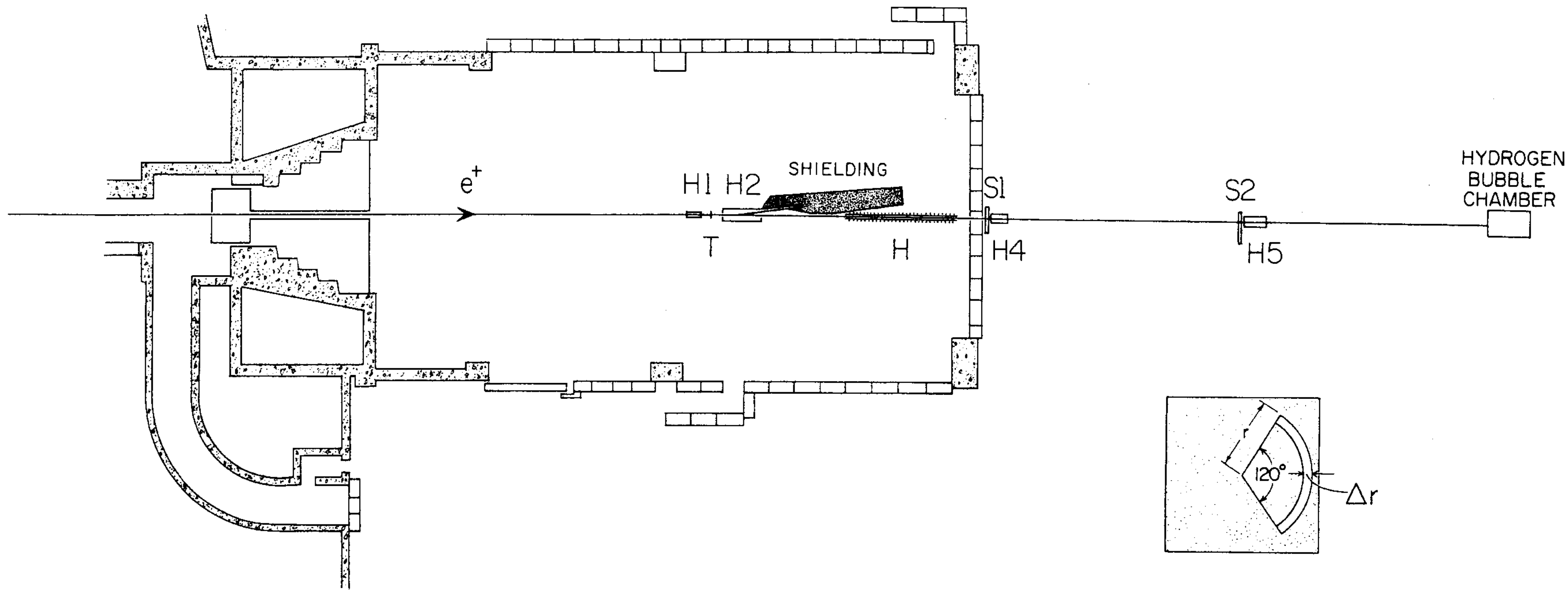

UNIFORM FIELD SOLENOID
COOLING WATER PIPES FOR TAPERED FIELD SOLENOID
WAND RADIATOR MECHANISM
COIL 0 HOUSING WITH ONE EDGE-DOUBLE PANCAKE INSTALLED
END OF SPECIAL POSITRON GIRDER
834A17
FLANGE FOR SLUG OR WHEEL RADIATOR

Fig. 11



0 1.0 5.0 10 meter

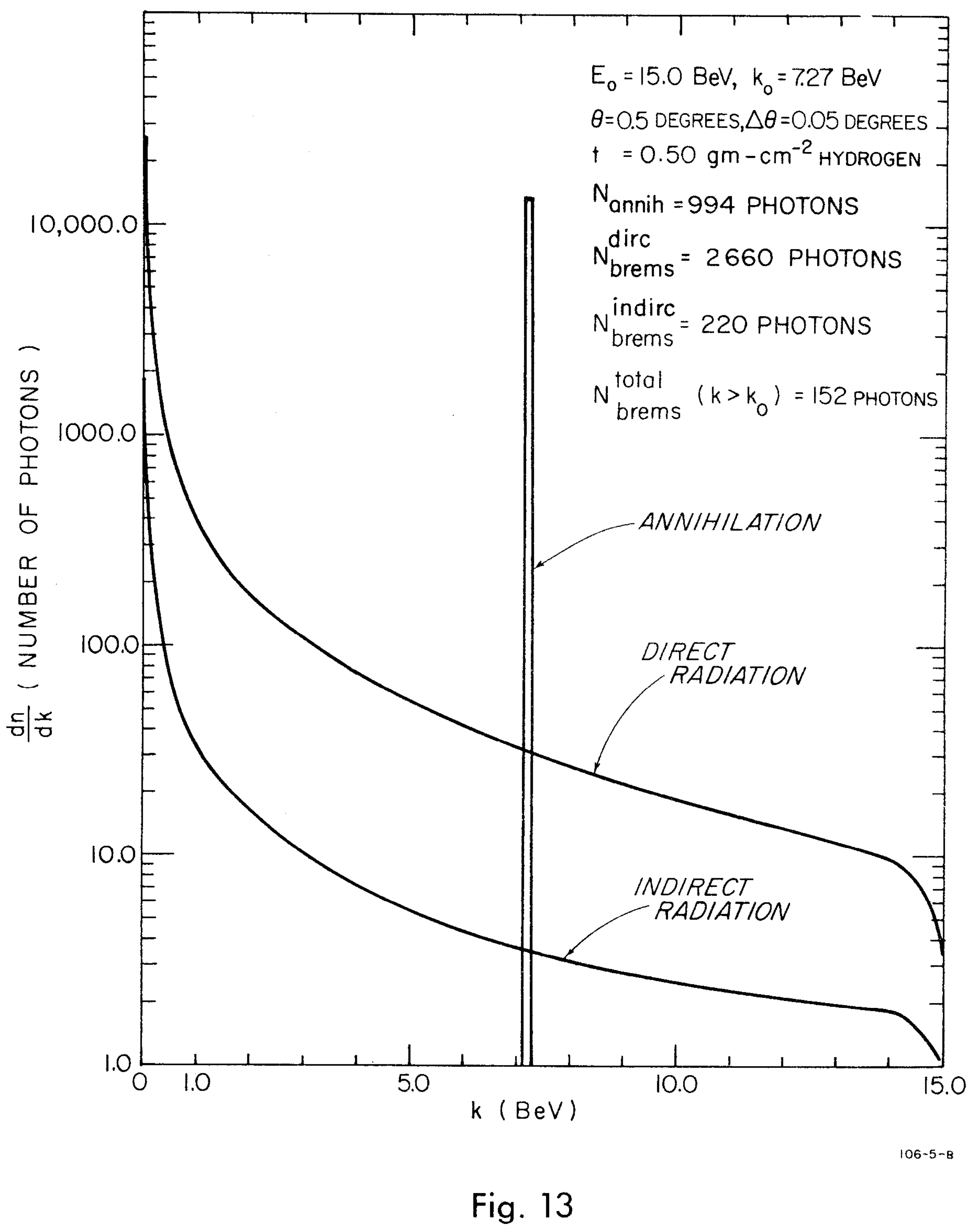
PARTIALLY MONOCHROMATIC PHOTON BEAM

T: LH_2 RADIATOR, 0.5 gm − cm^{-2}
H1 : e^+ STEERING MAGNET
H2 : e^+ DUMP MAGNET
H : 10 r.l. LH_2 PHOTON HARDENER
(LH_2 = LIQUID HYDROGEN)

S1: SLIT, $r = 17.4$ cm $\Delta r = 0.2$ cm
S2: SLIT, $r = 34.9$ cm $\Delta r = 0.4$ cm
H4, H5 : SWEEPING MAGNETS
HBC : 1m. HYDROGEN BUBBLE CHAMBER, Be THIN WINDOW, 70 X 25 cm

106-2-C

Fig. 12



E_o = 15.0 BeV, k_o = 7.27 BeV
θ=0.5 DEGREES, $\Delta\theta$=0.05 DEGREES
t = 0.50 gm-cm^{-2} HYDROGEN
N_{annih} = 994 PHOTONS
N_{brems}^{dirc} = 2660 PHOTONS
N_{brems}^{indirc} = 220 PHOTONS
N_{brems}^{total} ($k > k_o$) = 152 PHOTONS
ANNIHILATION
DIRECT RADIATION
INDIRECT RADIATION
$\frac{dn}{dk}$ (NUMBER OF PHOTONS)
10,000.0
1000.0
100.0
10.0
1.0
0
1.0
5.0
10.0
15.0
k (BeV)
106-5-8

Fig. 13