

June 25, 1968

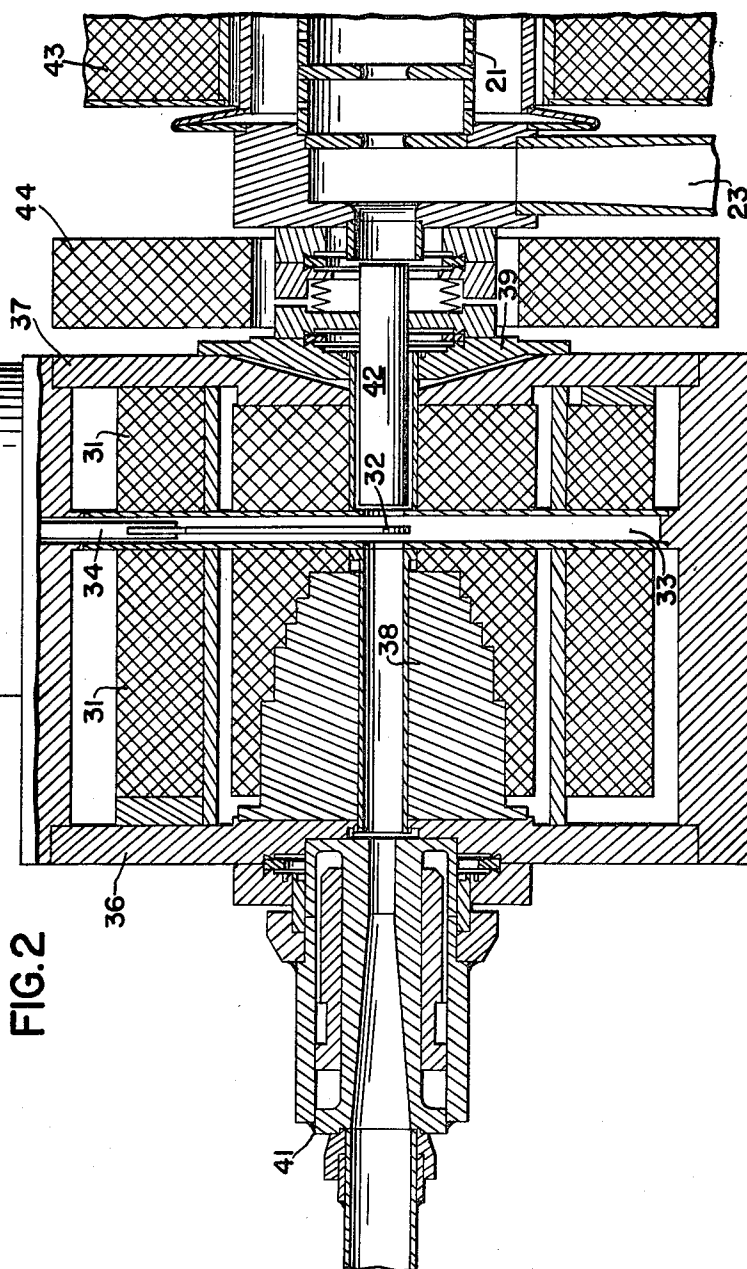
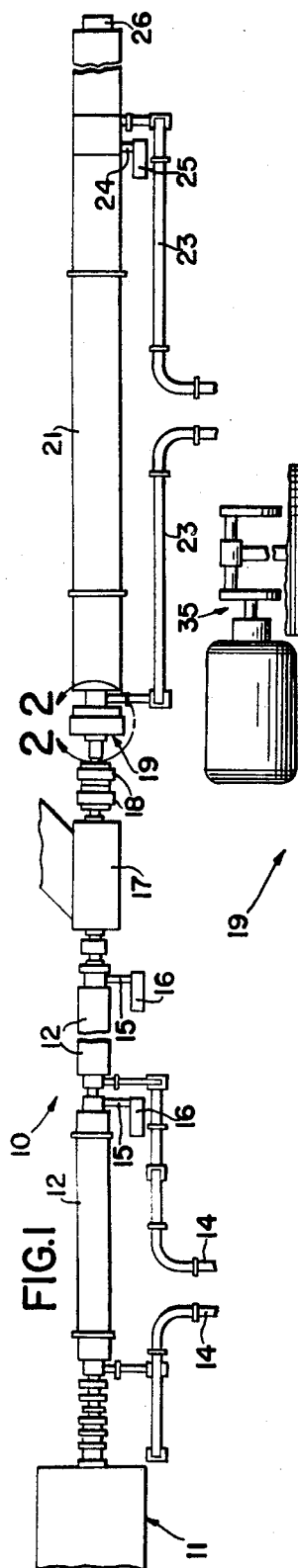
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3,390,293

HIGH ENERGY PARTICLE GENERATOR

Filed June 30, 1964

2 Sheets-Sheet 1



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FIG. 3

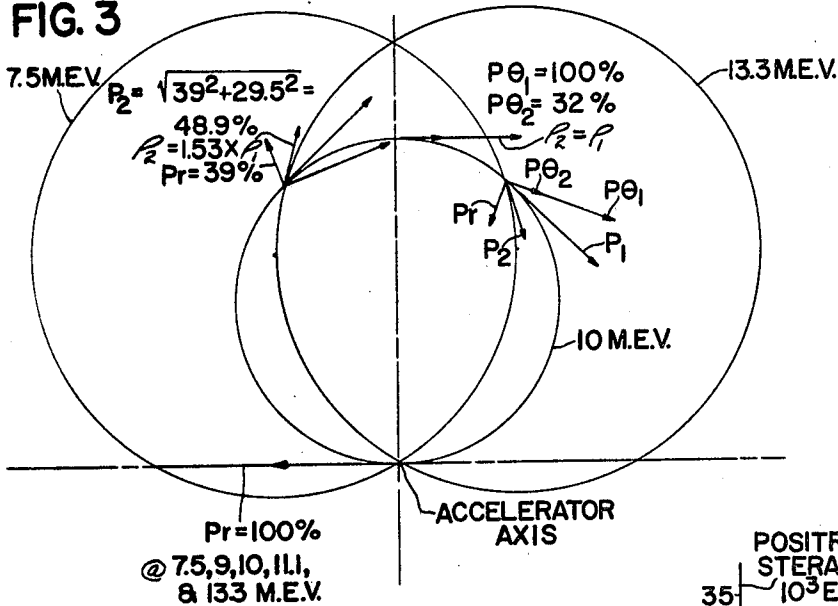


FIG. 4

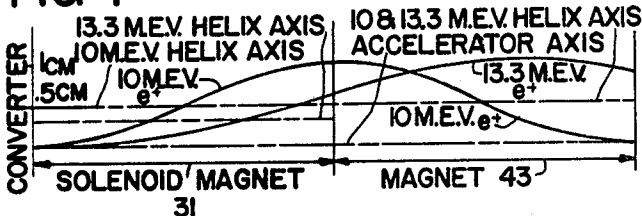


FIG. 5

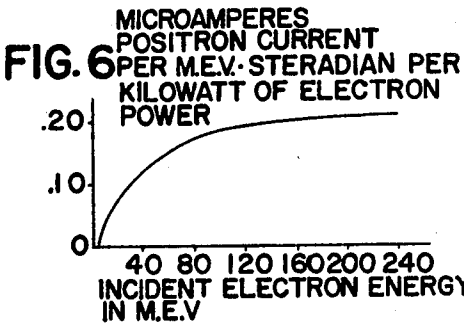
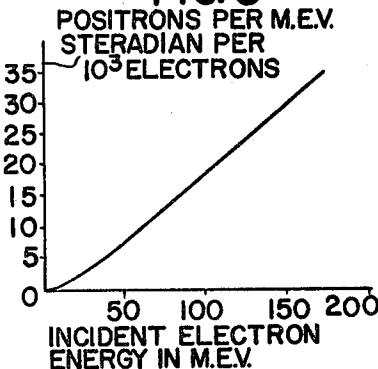
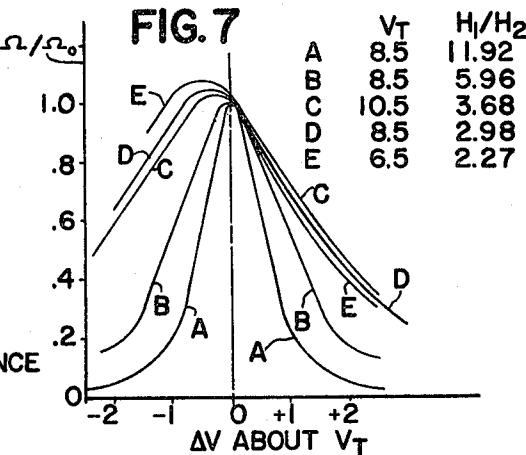


FIG. 7



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HIGH ENERGY PARTICLE GENERATOR
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The present invention relates in general to high energy particle generators and more particularly to apparatus for generating high energy positrons.

Presently, collisions of high energy particles are being utilized to perform novel nuclear and elementary particle research. For example, continuously variable energy monoenergetic photons which can be used, for example, in examining photonuclear resonance which can be created by the annihilation of a high energy electron with its positively charged anti-particle, the positron. It is conventional to produce high energy electrons by accelerating electrons in, for example, a linear accelerator. Similarly, high energy positron beams can be produced by placing a high Z (atomic number) target or converter part way down a segmented linear accelerator, bombarding the target with an electron beam from the first part of the accelerator to produce a shower of particles from the target and accelerating the positrons from the shower in the second part of the accelerator.

The shower of particles includes electrons and positrons ejected from the target with broad angular distribution and broad energy distribution. With the phase of the accelerating RF field in the second part of the accelerator properly adjusted only the positrons will be accelerated in that portion of the accelerator and the problem then becomes the selection and confinement of positrons in a desired band of energies which can be accelerated in the same accelerating structure.

With an accelerated electron bombardment high Z target of optimum thickness the positron yield per mev. steradian has a broad maximum at about $\frac{1}{2}$ the bombarding electron energy. The positron yield per kilowatt of bombarding electron beam power increases significantly with electron energy in the range from 10 to 60 mev. and remains relatively constant above 60 mev. as shown in FIG. 6.

A suggested arrangement for capturing the positrons showered from an electron bombarded target is the use of a thin magnetic lens placed after the target for focusing a particular angle of produced positrons into succeeding accelerator sections in which the positrons are contained by accelerator solenoids. In this case, the peak magnetic field H_0 from the thin lens is approximately:

$$H_0 = 0.8 \times 10^4 \sqrt{\frac{V_0(1+V_0)}{r_0 z_f}} \quad (1)$$

where V_0 is the positron energy in mev., r_0 is the radius of the accelerator aperture and z_f is the lens focal length. The distance from the converter or target to the mid-plane of the thin lens gap is set at z_f for the desired energy positron. For 0.2 steradian acceptance and 1 cm. radius aperture $z_f = 4$ cm. with electron bombarding energy of 65 mev. positron energy at optimum yield is about 8 mev., for which, in accordance with the above Equation 1, H_0 must be 32 kilogauss for positrons to leave the thin lens parallel to its axis. Positrons emitted at an angle $\theta = r_0/z_f$ at off-energy V_1 will leave the thin lens with a ratio of radial momentum P_r to axial momentum P_z as follows:

$$\frac{P_r}{P_z} = \theta \left[\frac{V_0(1+V_0)}{V_1(1+V_1)} - 1 \right]$$

from which for small ΔV ,

$$\frac{P_r}{m_0 c} \sim 4\theta \Delta V$$

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where $\Delta V = V_0 - V_1$ in mev., m_0 is the rest mass and c is the velocity of light. In such a thin lens structure for $a+1$ milliradian divergence at a positron output of 358 mev., $P_r = 0.7 m_0 c$. For 0.2 steradian acceptance

$$\theta = \frac{1}{4} \text{ and } \Delta V \sim 0.7 \text{ mev.}$$

The foregoing illustrates that the thin lens approach has limitations when used in a high energy linear accelerator because of the difficulty in obtaining a magnetic field strength high enough to focus the positrons of optimum emission energy and because of the limited energy spread accepted from the converter at large angles.

The object of the present invention is to provide a particle generating apparatus for producing maximum positron current for a given output emittance and given maximum output energy spread utilizing practical magnetic fields.

Broadly stated the present invention, to be described in greater detail below, is directed to a positron generator including means for establishing a high intensity longitudinally extending magnetic field around the target converter and generating and accelerating a beam of electrons which is directed onto the target in line with the lines of force of the high intensity magnetic field to generate forwardly directed positrons from the target. The magnetic field is selected such that positrons in a desired band of energies and which cross magnetic field lines upon leaving the target are imparted rotational momentum so as to follow a helical path and the synchronous energy particles are rotated through a mean angle of substantially 180° in the magnetic field before being introduced into a succeeding accelerating structure.

With this invention, a wide acceptance angle of substantially uniform energy positrons is possible since positrons of synchronous energy have zero radial momentum upon leaving the magnetic field and continue down the the accelerator without increase in beam cross-section. Additionally, this result is achieved with a practical magnetic field strength in a solenoid magnet which precedes the accelerating structure. Since the solenoid precedes the accelerating structure its coil diameter can be maintained at a minimum, without the necessity for the solenoid coils to be spaced from the positron beam by the radial thickness of the usual accelerating waveguide corrugations.

Another object of the present invention is the provision of a long lower intensity magnetic field immediately following the high intensity magnetic field surrounding the target so that the positrons that leave the high intensity field enter the accelerating structure and are confined within the lower intensity field. This construction permits the use of a greater solid angle of acceptance of off-energy positrons within a desired energy spread and therefore, a greater positron beam current.

Other objects, features and advantages of the present invention will become more apparent after a perusal of the following specification taken in connection with the accompanying drawings wherein:

FIG. 1 is a foreshortened schematic view of a particle generating apparatus utilizing the present invention;

FIG. 2 is an enlarged cross sectional view of a portion of the structure shown in FIG. 1 and delineated by lines 2-2;

FIG. 3 is a schematic view transverse to the axis of the converter assembly and showing the helical paths of particles of different energy flattened out in a single plane;

FIG. 4 is a schematic view of the longitudinal paths traced by particles of different energies longitudinally in the particle converter assembly;

FIG. 5 is a graph showing the positrons per mev. steradian plotted vs. electron energy incident on the target converter;

FIG. 6 is a graph of microamperes of positron cur-

rent per mev. steradian per kilowatt of electron power vs. incident electron energy;

FIG. 7 is a graph showing acceptance angle vs. positron energy; and

FIG. 8 is a graph showing total acceptance vs. long lower intensity magnetic field, H_z .

Referring now to the drawings with particular reference to FIG. 1, a particle generator 10 in accordance with the present invention, for producing high energy positrons includes a source of electrons schematically illustrated at 11 such as, for example, a cathode for producing a pulsed beam of electrons. The electron beam is accelerated to relativistic velocity in a particle accelerator such as, for example, in a plurality of linear accelerator sections 12 which can be typical disc loaded waveguides in which a radio frequency wave from an RF source, such as, for example, a klystron (not shown) coupled into the accelerator via a waveguide 14 gives up energy to the electrons for acceleration of the electrons. At the end of each accelerator section 12 residual RF power is coupled via an output waveguide 15 to a load 16. The accelerated electrons pass through a switch assembly 17 in which the electrons can be diverted for utilization in other experiments or passed directly therethrough, through a pair of focusing quadrupole magnets 18 and into the converter assembly 19 to be described in greater detail below.

In the converter assembly 19 the electrons are directed onto a high Z target to produce a shower of positrons which are then accelerated in a succeeding acceleration section 21 such as, for example, a conventional disc loaded accelerating waveguide. Energy for accelerating the positrons is directed from an RF source such as, for example, a klystron (not shown) via the input waveguide 23 to the accelerating section 21. Residual RF power not absorbed in the accelerating section 21 is coupled via the output waveguide 24 to a load 25. Typically, a plurality of accelerating sections 21 are utilized before the accelerated positrons are abstracted for use through an output window at 26.

The converter assembly 19 includes a split solenoid 31 for providing a high longitudinally extending magnetic field for capturing positrons generated at a target 32 located at the central gap 33 in the solenoid 31. In order to avoid destruction of the target 32 by the high energy electron beam, the target is in the form of a cooled moving annulus such as of, for example, tungsten one radiation length thick which is supported from an actuating arm 34 and cooled by a water cooling tube around its periphery. The actuating arm 34 is controlled through a vacuum seal by a rotating assembly generally indicated at 35 for moving the annual target 32 so that the impinging electron beam traces a circle around the target. Since the rotating assembly 35 does not form a part of the present invention it will not be described in greater detail.

The solenoid 31 is provided with the input and output field return plates 36 and 37 of, for example, iron and input and output pole pieces 38 and 39 respectively which are provided with apertures for passage of the electrons and positrons respectively and for establishing a uniform high magnetic field through the target 32 located on the axis of the solenoid 31.

The input pole piece 38 is coupled to a collimator 41 which collects the non-focused portion of the accelerated electron beam as the electron beam is focused to a minimum spot size on the target 32 by the quadrupole magnets 18. The quadrupoles 18 are rotated 90° with respect to one another for focusing the electron beam on the target 32.

The output pole piece 39 of the solenoid 31 is coupled to the accelerating section 21, and a water cooled particle absorber 42 of, for example, tungsten is located between the target 32 and the accelerating section 21 for

absorbing X-rays, electrons, and positrons emitted outside the chosen maximum solid angle.

The output pole piece 39 closely surrounds the particle absorber 42 to abruptly change the direction of the magnetic field lines of the solenoid 31 from longitudinally axially extending lines to radially extending lines for converting the azimuthal momentum of positrons at the end of the solenoid into axial momentum. An accelerating waveguide magnet 43 which provides a field of lower intensity than the field of the solenoid 31 surrounds the accelerating section 21 and extends to the input waveguide 23. An auxiliary coil 44 is positioned between the solenoid 31 and the accelerator input waveguide 23 to effectively extend the field of the accelerator magnet 43 to the pole piece 39 of the solenoid 31. The accelerating guides and apparatus defining the particle beam paths are evacuated in the conventional manner by vacuum pumps (not shown).

Referring now to FIG. 3, there is shown compressed into a flat plane transverse to the axis of the solenoid 31 the helical paths traced by different energy positrons generated at the target 32. Since the positrons emitted on the accelerator axis at an angle thereto cross lines of force of the solenoid magnetic field, rotational momentum is imparted to the positrons so that they trace helical paths longitudinally down the length of the solenoid 31 with the helix axis parallel to the accelerator axis. At position of emission, radial momentum of the positron is maximum while azimuthal momentum is zero. After the positron has traveled a cyclotron half period corresponding to rotation through 180° of the helix cycle, positrons of the desired synchronous energy, such as, for example, 10 mev. as shown in FIG. 3, will have reached their radial outermost position at which position their radial momentum is zero and their azimuthal momentum is maximum and equal to the radial momentum at emission.

The solenoid 31 is designed such that the end of its field occurs at this cyclotron half period or after the positrons of desired synchronous energy have zero radial momentum so that the positron azimuthal momentum is converted into axial momentum as these positrons pass through the radial magnetic field at the output end of the solenoid 31. Positrons of higher and lower energies but with the same initial radial momentum, such as positrons with energies of 7.5 and 13.3 mev., will have completed more or less rotation respectively. The radial momentum of these particles will be unaffected as they leave the solenoid magnetic field but their azimuthal momentum will be converted to axial momentum.

The current i_+ of positrons around 10 mev. produced in a converter of proper length is:

$$i_+ = 20 \text{ } k \Delta V \Omega P \quad (3)$$

where:

i_+ = microamperes peak positron current accepted for acceleration

k = coefficient from FIG. 5; $k \sim 1$ @ 30, 1.2 @ 40, 1.5 @ 60 mev. and up

ΔV = mev. energy spread accepted for acceleration

P = megawatts peak electron power at converter.

An acceptance solid angle of 0.2 steradians with a 1 cm. radius aperture requires a solenoid axial length of 6.2 cm. from the target for helix half cycle. The radial momentum P_r of off-energy positrons leaving a solenoid in which no acceleration occurs is:

$$P_r = \theta P_z \cos \left(\frac{\pi}{2} \frac{V_0}{V_1} \right) \sim 2\theta \Delta V \text{ in units of } m_0 c \quad (4)$$

The solid angle of acceptance Ω_0 is related to the aperture

radius r_0 , the chosen positron total energy V_T , and the solenoid magnetic field H_1 by

$$\Omega_0 = \frac{9}{4} \pi \times 10^{-6} r_0^2 H_1^2 / V_T^2 \quad (5)$$

By way of example, for $r_0=1$ cm., $V_T=8.5$ mev. and $\Omega_0=0.2$ steradian $H_1=14,300$ gauss.

Comparison of Equations 1 and 2 above with equations 4 and 5 shows that for equal solid angle and equal radial momentum, the system utilizing a short solenoid magnetic field surrounding the target converter in accordance with one aspect of this invention accepts twice the energy spread of the thin lens system described above and requires a more practicable magnetic field.

Assuming constant gradient acceleration after the solenoid and no acceleration in the solenoid, a positron leaving the solenoid with energy V_0 and radial angle θ and accelerated to final energy V_f over the length L changes its radial displacement from axis by:

$$\Delta r = \theta L_{rel.} \quad (6)$$

where the relativistic length

$$L_{rel.} = \frac{\ln \frac{V_f}{V_0}}{\frac{V_f}{V_0} - 1} L \quad (7)$$

By way of example for $L=4,000$ cm., $V_f=358$ mev., $V_0=8$ mev., $L_{rel.}=348$ cm.

For $\Delta r=2$ cm. corresponding to crossing the aperture, $\theta=.0057$ and $P_r=.0057 \times 16.5=0.095$ m_0c . This limits ΔV to 0.19 mev. for 0.2 steradian. When such an accelerator is tuned for lower energy, the transmitted radial momentum and energy spread are reduced. For example, with $V_f=100$ mev., $P_r=0.038$ m_0c and $\Delta V=0.076$ mev. for 0.2 steradian.

In accordance with another aspect of the present invention, in order to transmit a larger energy spread and to have this transmitted energy spread be independent of tuning of the accelerator over the full range of output energy, the positrons are caused to pass through the field of the accelerator magnet 43 during their acceleration after describing a half cycle of a helix in the short high intensity solenoid 31 at the target converter 32. The intensity of the field of the accelerator magnet 43 is chosen to match the usable radial momentum P_{r0} at the accelerator output 26. For this condition, the magnetic field H_2 of the lower intensity accelerator magnet 43 is:

$$H_2 = \frac{2(P_{r0}/m_0c)}{r_0(e/m_0c)} = \frac{3412}{r_0} \left(\frac{P_{r0}}{m_0c} \right) \quad (8)$$

By way of example, for aperture radius $r_0=1$ cm. and $P_{r0}=0.7$ m_0c corresponding to ± 1 milliradian divergence at 358 mev., $H_2=2400$ gauss.

Off-energy positron emitted on axis describe smaller diameter helices in the solenoid 31 high intensity field than in the magnet 43 low intensity field because they keep their radial momentum in the transition from high to low magnetic field. Thus, the accepted solid angle decreases for off-energy positrons according to the following equation:

$$\frac{\Omega}{\Omega_0} = \left(\frac{V_T/V}{\rho_2/\rho_1} \right)^2 \quad (9)$$

$$\left(\frac{\rho_2}{\rho_1} \right)^2 = \left(\frac{H_1}{H_2} \right)^2 \cos^2 \left(\frac{\pi}{2} \frac{V_T}{V} \right) + \sin^2 \left(\frac{\pi}{2} \frac{V_T}{V} \right) \quad (10)$$

Where:

V_T =chosen positron total energy (180° of helix in H_1)

V =off-energy positron total energy

H_1 =short high intensity magnetic field in solenoid 31

H_2 =long lower intensity magnetic field in magnet 43

ρ_1 =helix radius in H_1

ρ_2 =helix radius in H_2

At the end of the accelerator magnet 43 positrons generated on axis leave the magnetic field with zero azimuthal momentum and with radial momentum not exceeding that which they carried through the transition from the high field of solenoid 31 to the lower field of magnet 43 due to being off-energy. The exit radial momentum varies from maximum of P_{r0} (the radial momentum for aperture radius r_0 in units of m_0c) on axis to zero at the beam periphery r_0 and the area A_p in phase space is defined by a circle of area $\pi r_0 P_{r0}$.

Since $P_{r0}=A_p/(\pi r_0)$, from Equation 8:

$$H_2 = 1085 A_p / r_0^2 \quad (11)$$

The beam out of the accelerator must be contained within an emittance defined by the magnetic device or system into which the beam is injected. Thus, for a given output energy, the area A_p in phase space is defined. The useful maximum solid angle, Ω_0 from the converter is limited by focus aberrations, phase spread between trajectories and fall-off of positron intensity at large angles from axis. With A_p and Ω_0 specified, the choice of positron emission energy V_T and the aperture radius r_0 must be made to maximize the total acceptance $\Omega \Delta V$ of the stepped magnetic field system. Choice of r_0 determines H_2 by Equation 10; choice of r_0 and V_T determine H_1 by Equation 5. FIG. 7 shows curves of Ω vs. positron energy V as determined by Equation 9. FIG. 8 shows total acceptance $\Omega \Delta V$ in mev. steradians vs. lower intensity magnetic field H_2 .

For given maximum solid angle from converter and given acceptance in phase space at output of accelerator, FIGS. 7 and 8 show that the total acceptance in mev. steradians is approximately inversely proportional to aperture radius and is relatively independent of chosen positron energy at converter. Thus, to maximize total positron current, the aperture radius is minimized by maximizing accelerator magnetic field, as limited by economics and the solenoid field is set to provide 180° helix rotation for the positron energy at converter corresponding to maximum yield per mev. steradian.

While it is believed that the above is a full and complete description of the present invention, the following example is given of the values of an operable particle generator in accordance with the present invention:

Output emittance at 358 mev. -----	10^{-3} radian cm.
Aperture radius, r_0 -----	1 cm.
Radial momentum at axis, P_{r0} -----	0.7 m_0c maximum.
Phase space area -----	0.7 π m_0c .
Positron chosen emission energy, V_0 -	8 mev.
Solid angle of acceptance, Ω_0 -----	0.2 steradian.
Solenoid magnetic field, H_1 -----	14.3 kg.
Accelerator magnetic field, H_2 -----	2.4 kg.
Mev. steradians acceptance $\Omega \Delta V$ ----	0.4.
Electron beam on converter -----	418 milliamperes,
	65 mev.
Positrons per electron per mev. stera-	
dian -----	.01.
Peak positron current -----	1.6 milliamperes.
Average positron current at 3.2 μ sec.	
pulse length, 250 p.p.s. -----	1.3 microamperes.

While the invention has been described with respect to the production of positrons with accelerated electrons the apparatus, when properly modified, will operate on other particles too. For example, accelerated electrons or protons can be utilized to bombard a target to produce mesons which can then be accelerated to desired energy. Therefore, the terms "electrons" and "positrons" are used herein to include other particles where appropriate.

Since many changes could be made in the above construction and many apparently widely different embodiments of this invention could be made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accom-

panying drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is.

1. A positron generating and confining apparatus including means for generating a beam of electrons; means for accelerating said beam of electrons to substantially relativistic velocity; a target electrode of a material having a high atomic number; means for directing said accelerated beam of electrons onto said target for generating positrons; means defining a high intensivity short longitudinally magnetic field extending through said target and substantially aligned with the direction of incidence of said beam of electrons for confining the positrons generated in said target and imparting a rotational momentum to said positrons, said magnetic field of said field defining means of a length such that positrons in a desired band of energies rotate through a mean angle of substantially 1810°; and means for accelerating the positrons after leaving said magnetic field defining means.

2. A positron generating and confining apparatus including means for generating a beam of electrons; means for accelerating said beam of electrons to substantially relativistic velocity; a target electrode of a material having a high atomic number; means for directing said accelerated beam of electrons onto said target for generating positrons; means defining a high intensity short longitudinally extending magnetic field extending through said target and substantially aligned with the direction of incidence of said beam of electrons for capturing positrons generated in said target and imparting a rotational momentum to said positrons; and means for accelerating the positrons leaving said magnetic field defining means including an accelerating structure and means for establishing over a length of the accelerating structure a long magnetic field of lower intensity than said high intensity field, said high intensity field defining means of a length such that positrons in a desired band of energies rotate through a mean angle of substantially 80° from said target until leaving said high intensity magnetic field and entering said lower intensity magnetic field.

3. A high energy particle generator including means for generating a beam of electrons; means for accelerating said electrons along a given beam path to substantially relativistic velocity; a solenoid positioned along said beam path for establishing a high intensity magnetic field extending longitudinally of said path and with an abrupt discontinuity at the output end of said solenoid where

said magnetic field is directed substantially radially of said solenoid; a target electrode positioned within said solenoid; means for directing said accelerated beam of electrons along said beam path thereby to generate forwardly directed positrons from said target, the magnetic field of said solenoid imparting rotational momentum to positrons generated at said target and with the magnetic field of said solenoid such that positrons in a desired band of energies and crossing magnetic field lines of force in said solenoid are rotated through a mean angle of substantially 180° before reaching the radially directed field at the output end of said solenoid; and means for passing the positrons from the output end of said solenoid into a particle utilizing device.

4. A high energy particle generator including: a solenoid for establishing a high intensity longitudinally extending magnetic field with an abrupt discontinuity at the output end of said solenoid where said magnetic field is directed substantially radially of said solenoid; a target electrode positioned within said magnetic field; means for accelerating particles generated in said target including a wave-particle interacting structure for transferring energy from an electromagnetic wave to particles passing there-through and means for establishing over a length of said interacting structure a long magnetic field of lower intensity than said solenoid field thereby to constrain particles in said interaction structure; means for generating a beam of electrons; means for accelerating said beam of electrons and directing said accelerated beam of electrons onto said target in line with said solenoid magnetic field thereby to generate forwardly directed positrons from said target for subsequent acceleration by said particle accelerating means, the magnetic field of said solenoid imparting rotational momentum to positrons generated at said target and with the magnetic field of said solenoid such that positrons in a desired band of energies and crossing magnetic field lines of force in said solenoid are rotated through a mean angle of substantially 180° before reaching the radially directed field at the output end of said solenoid; and means for introducing the positrons from the output end of said solenoid into said magnetic field of lower intensity.

No references cited.

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