

Dec. 25, 1962

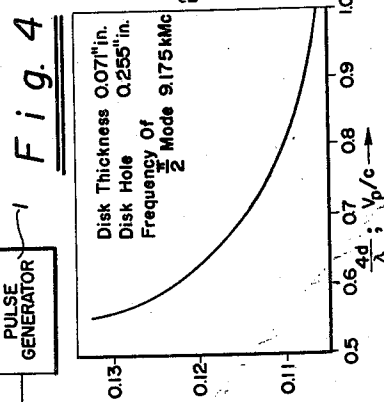
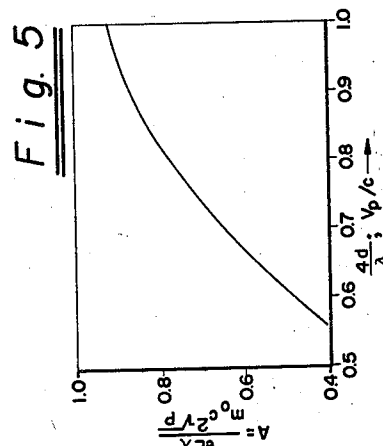
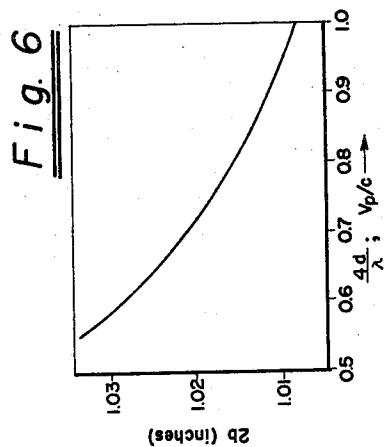
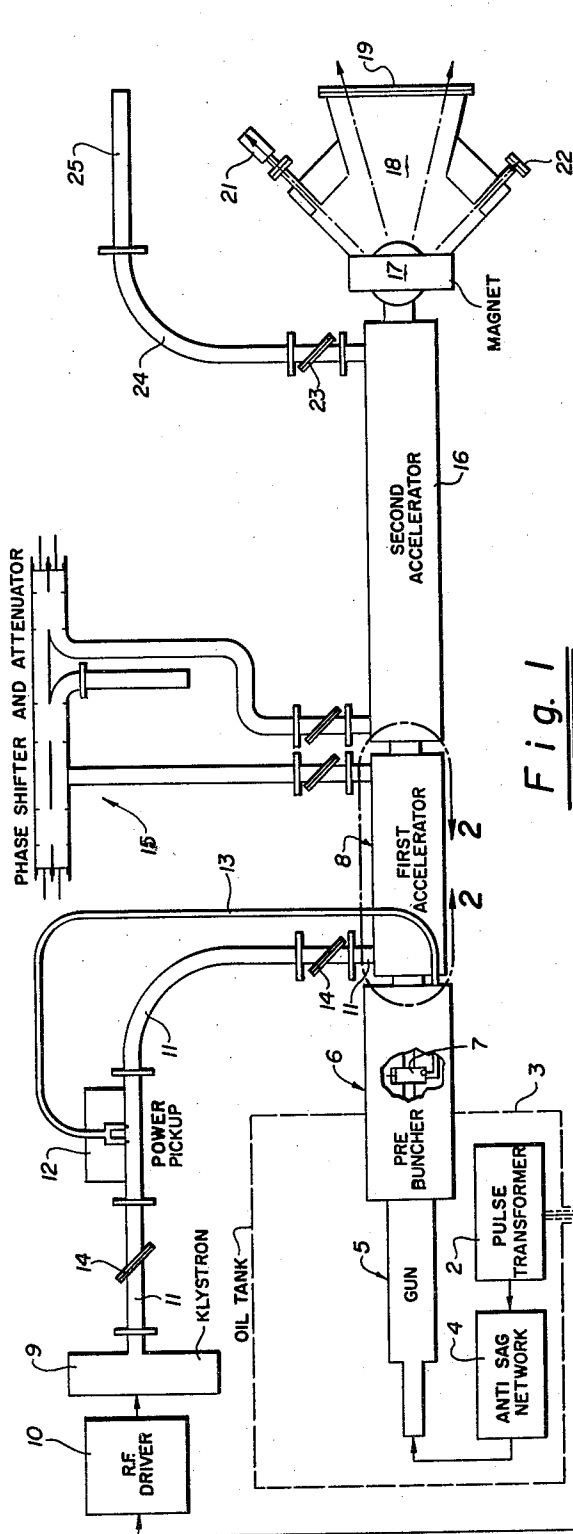
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3,070,726

PARTICLE ACCELERATOR

Filed June 5, 1959

2 Sheets-Sheet 1



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2 Sheets-Sheet 2

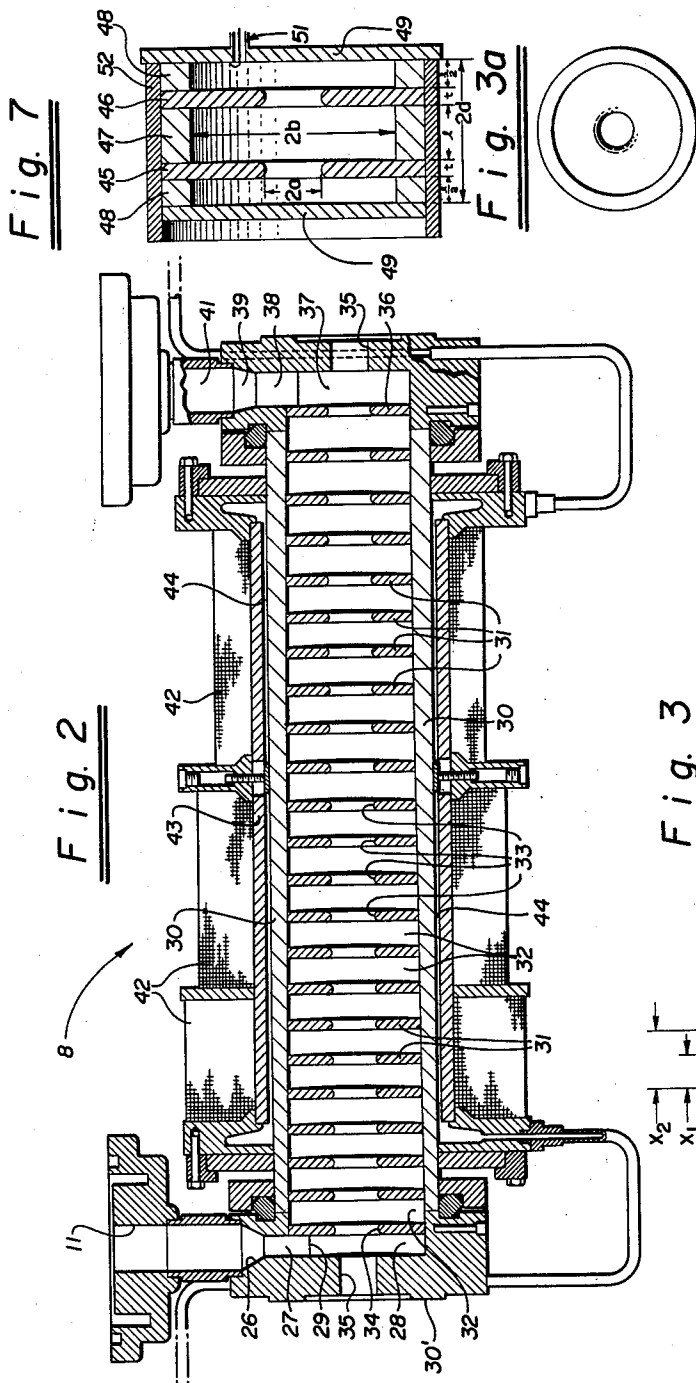


Fig. 2

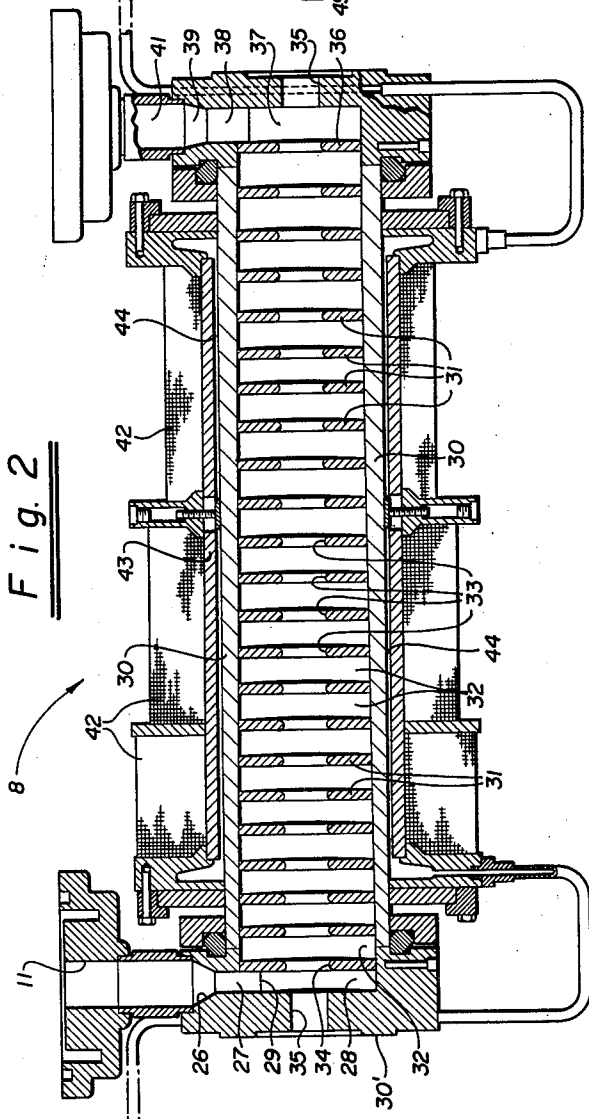
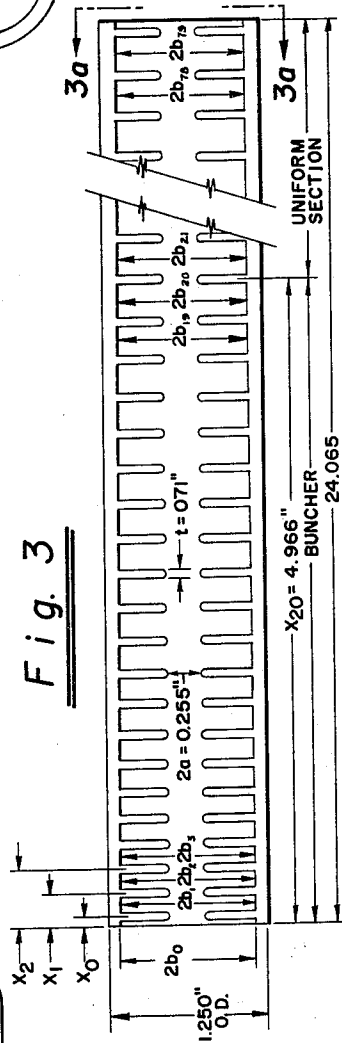


Fig. 3



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3,070,726
PARTICLE ACCELERATOR
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3 Claims. (Cl. 315-5.42)

This invention relates in general to particle accelerators and more particularly to an improved linear accelerator useful for atomic research, therapy, sterilization, polymerization and other important uses.

In the fabrication of disk loaded linear accelerators it is necessary that there be a large number of accelerator section parts, such as the loading disks, machined to very close mechanical tolerances. For most of the length of the electron accelerator, the structure and the dimensions thereof may be identical. However, in the first few feet of the disk loaded slow wave structure, termed the bunching section, the velocity of the electron beam as it travels through the bunching section increases to a large degree after entering the section. It is desirable that the field strength, E , and the phase velocity, v_p , of the wave traveling through the slow wave structure be varied as a function of position in this bunching section in a manner which will provide the optimum energy interaction between the wave and the beam and thus the best possible bunching consistent with efficient conversion of the R.F. power into electron energy. This variation is produced by changing the dimensions of successive cavities.

There are two electrical quantities E and v_p to be defined, and four cavity dimensions—beam aperture $2a$, cavity diameter $2b$, disk spacing d , and disk thickness t —to be determined. The physical realization of a particle electrical design is therefore not unique. Two arbitrary restrictions may be placed on the cavity dimensions. One of these has been to hold the disk thickness constant throughout the buncher and the remainder of the accelerator. A second restriction is to hold the disk spacing constant. A more common second restriction is to hold the phase shift per cavity a constant, generally one-quarter cycle. This condition of operation is termed the

$$\frac{\pi}{2}$$

mode. In either instance, there remain two parameters to be determined. The adjustment of the design values of E and v_p as functions of the axial distance along the accelerator, in order to produce perfect bunching, can only be accomplished by successive trials. For each choice of $E(x)$ and $v_p(x)$, the equations of motion of a relativistic electron must be integrated for several electrons entering at different phases with respect to the wave. The phases of the electrons at the output are then examined and compared with the ideal case in which either all electrons emerge from the accelerator at the same phase angle or all electrons emerge at the same energy. The former criterion is most significant for a very long accelerator, the latter is more significant for a short accelerator. It is extremely difficult to handle this problem with two variable functions. The problem is considerably simplified if one of them, generally the distribution of field strength, is fixed in advance and only the other function is considered variable. Heretofore, the above design procedure has resulted in a mechanical design in which the beam aperture, the cavity diameter and the disk spacing must all be varied. The variation in beam aperture diameter required a separate setup for machining each disk. The disks were then aligned for assembly in the slow wave structure on a mandrel which also had to be machined in steps to the

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correct diameter for each successive disk positioned on the mandrel.

It is, therefore, the principal object of the present invention to provide a novel disk loaded type linear accelerator in which the slow wave buncher section of the accelerator device comprises disks of constant thickness having beam apertures of equal diameters to eliminate a great deal of machining, the wave structure being otherwise dimensioned so as to produce a phase velocity therein which increases in variable accordance with the increase in velocity of the electrons through the section.

One feature of the present invention is the provision of a novel disk-loaded linear accelerator wherein the beam apertures in the successive disks have equal diameters, the thickness of the disks also being equal, the phase velocity of the radio frequency wave through the structure being correctly maintained by proper spacing of the successive disks one from another and the proper dimensioning of the outer diameter of the loading disks.

Another feature of the present invention is that the electric field in the buncher is comparable to the electric field in the uniform guide, with the result that the electrons gain energy rapidly and efficiently while bunching.

These and other features and advantages of the present invention will be more apparent after a perusal of the following specification taken in connection with the accompanying drawings wherein,

FIG. 1 is a schematic diagram of a linear accelerator in which the present invention may be utilized,

FIG. 2 is a longitudinal cross section view of the first accelerator portion or buncher of the linear accelerator of FIG. 1 in which the novel slow wave structure of the present invention is utilized,

FIG. 3 is a longitudinal cross section view of a typical buncher section utilizing the present invention in which the various dimensions are illustrated,

FIG. 3A is an end view of the buncher section shown in FIG. 3,

FIG. 4 is a plot of normalized attenuation of power α (nepers per free-space wavelength) as a function of the normalized disk spacing

$$\frac{4d}{\lambda}$$

in a test cavity operating in the $\pi/2$ mode. The normalized disk spacing is equal to the normalized phase velocity:

$$\frac{4d}{\lambda} = \frac{v_p}{c}$$

FIG. 5 is a plot of the normalized field strength A (energy gain per wavelength at one megawatt power flux in units of the electron rest energy) as a function of normalized disk spacing and phase velocity in a cavity operating in the $\pi/2$ mode,

FIG. 6 is a plot of the cavity diameter $2b$ required to provide that the cavity operate in the $\pi/2$ mode, as a function of normalized disk spacing and phase velocity, and

FIG. 7 is a cross-sectional view of a typical test cavity. Referring now to FIG. 1 of the drawings there is shown in block diagram form a linear accelerator system in which the present invention may be utilized. A linear accelerator system of this type is more fully shown and described in U.S. patent application Serial No. 744,608 filed June 25, 1958, in the names of L. E. Brown and C. S. Nunan and assigned to the assignee of the present application. The linear accelerator system will first be described briefly followed by a more complete description of the novel improvement of this invention.

The specific linear accelerator described herein is especially designed for accelerating electrons. However, the present invention is equally applicable to devices for accelerating other particles such as, for example, protons.

A pulse generator 1 delivers a relatively low voltage square pulse as of, for example, 13 kv. to a pulse transformer 2 which steps up the voltage of the pulse to approximately 150 kv. The pulse generator 1 contains means therein for varying the width of the pulses up to a maximum width of 6 microseconds. In addition means are provided within the pulse generator 1 for varying the pulse repetition rate from 0 up to 360 pulses per second. The desired pulse width and repetition rate is selected according to the research or process being conducted. An antisag network 4 is connected to the secondary of the pulse transformer 2 and serves to square the high voltage pulse. The squared high voltage pulse is applied to the electrodes within an electron gun assembly 5 and serves to trigger the emission of an electron beam. The pulse transformer 2, antisag network 4, electron gun assembly 5 and a portion of the pre-buncher 6 are submerged in an oil tank 3 to prevent arcing over of these components and to provide cooling thereof in use.

The beam of electrons is fed to a pre-buncher 6 which contains therewithin a pre-bunching cavity 7 disposed in the beam path and through which the electron beam passes. As the beam passes through the pre-bunching cavity 7 the beam is velocity modulated such that the beam will form into bunches of electrons as it passes into the first accelerating section 8.

A high power, high frequency source 9 such as, for example, a klystron amplifier serves to provide peak R.F. beam acceleration power in the order of 5 megawatts at a certain high frequency as of, for example, 2,800 megacycles via waveguide 11 to the first accelerating section 8. The high frequency source 9 is pulsed on in synchronism with the pulses derived from the pulse generator 1 and its R.F. input power is derived from a synchronously pulsed R.F. driver 10. A portion of the high frequency energy propagating through waveguide 11 to the first accelerating section 8 is picked up via a power pickup 12 and fed via a coaxial line 13 to the pre-bunching cavity 7. The power pickup 12 includes means for varying both the magnitude and phase of the power applied to the pre-bunching cavity 7. Since the same high frequency source 9 supplies the R.F. to the first accelerating section 8 and to the pre-bunching cavity 7 and since the power applied to the pre-bunching cavity may be varied in phase and amplitude, as desired, with respect to the power applied to the first accelerating section 8, the bunches of electrons within the beam arriving at the first accelerating section 8 are controlled to arrive substantially at a desired phase-stable position on the traveling sine wave of the electromagnetic waves propagating through the slow wave structure therewithin as, for example, 30° ahead of the crest. In this manner optimum utilization of the beam is obtained; i.e., a large fraction of the injected electrons are accelerated, a large fraction of the input R.F. power is converted to electron beam power and the accepted electrons are bunched to a small phase spread with small energy spread.

Two gas tight wave permeable windows 14 are provided in the waveguide 11 on both sides of the power pickup 12 for vacuum sealing the high frequency source 9 from the remaining linear accelerator apparatus as leaks in the vacuum system of the remaining portion of the linear accelerator would contaminate the high frequency source 9. The section of waveguide 11 between the wave permeable windows 14 is pressurized with a gas having substantial dielectric strength for cooling the windows 14 and further to prevent voltage breakdowns in the waveguide 11 in the vicinity of the power pickup 12.

As the accelerated electron beam emerges from the first accelerating section 8 the particles making up the beam will have attained energies of approximately 3-4 million electron volts. The remaining R.F. energy that has not been transformed into beam energy is propagated outwardly of the first accelerator section 8 to a phase shifter and power attenuator 15 wherein the phase and

magnitude of the power applied to the second accelerator section 16 may be adjusted, as desired, in order to further accelerate or decelerate the particles to any pre-selected energy to within the range of from 2 to 12 mev.

The beam output of the second accelerator section 16 is fed through the gap of a beam deflecting magnet 17 and thence through a scanner head 18 closed off at its flared end by an electron permeable window 19, and onto a suitable target, not shown. The beam of electrons may be swept across the electron permeable window 19 by varying the magnetic field within the gap of the magnet 17. In addition, by selecting a certain magnetic field strength, the beam may be deflected approximately 45 degrees through an energy selecting slit and into a collector 21 wherein the beam current and beam energy may be measured, as desired. By reversing the direction of this certain magnetic field strength the beam may be diverted an equal amount on the other side of the center line of the scanner and through a second electron permeable gas tight window 22 for irradiating certain samples, as desired.

The remaining R.F. energy that was not converted into beam energy in the second accelerating section 16 is coupled outwardly thereof through a vacuum tight window 23 and waveguide 24 to a dummy load 25 wherein the energy is dissipated and prevented from reflecting back through the accelerating sections and waveguide plumbing to the high power source 9. Such undesired reflected energy sets up standing waves which may produce arcs within the guides or cracking of the vacuum tight wave permeable windows due to excessive heat being generated therein.

Evacuation of the accelerator apparatus is obtained by a plurality of pump-out tubes connected at intervals to the accelerator and thence to a vacuum manifold which is pumped via a high vacuum pump. The evacuating system is not shown. In addition, portions of the accelerator are cooled via coolant jackets and pipes affixed to the linear accelerator apparatus and carrying there-within a circulating coolant. The entire cooling system is not shown.

The first beam accelerating section 8, in which the present invention is utilized, is shown in FIG. 2. More specifically, the R.F. driving energy derived from the high power source 9 is fed to the first accelerating section 8 via rectangular waveguide 11. The R.F. energy passes through rectangular waveguide 11 and thence through a short tapered transition waveguide section 26, thence through a short section of lower impedance rectangular guide 27 which intersects with a hollow cylindrical chamber 28 at a coupling iris 29.

The structure of the accelerating section 8 includes a disk loaded waveguide forming a slow wave structure. More specifically, a hollow cylindrical conductor 30 carries therewithin a plurality of centrally apertured conductive disk members 31 forming a plurality of cavity resonators 32 capacitively coupled together through the central apertures 33.

The phase velocity of the slow wave structure is designed such that it is approximately equal to the average velocity of the electrons at any given point within the structure. This requires that the phase velocity must increase from the beginning of the slow wave structure to the end thereof in variable accordance with the increase in velocity of the electrons. The phase velocity of the slow wave structure is a function of the disk spacing, i.e., the distance between the center lines of adjoining disks 31, the diameter of the coupling holes 33, the outside diameter of the disks 31 and the thickness of the disks 31 and the shape of the disk at the perimeter of the hole 33. In previous linear accelerator sections of this type the disk coupling hole diameter and other parameters were varied from cavity to cavity within the accelerator section to provide the necessary changes in phase velocity.

In the present accelerator section the disk thickness and coupling hole diameter have been held constant throughout the accelerator structure 8 and the disk spacing has been progressively increased and disk outside diameters, have been progressively decreased down the accelerator section to maintain the increasing phase velocity. Thus the present accelerator section utilizing a constant coupling hole diameter and disk thickness presents an accelerator section which is considerably easier to build, as one of the variable parameters has been eliminated. This particular feature is discussed in more detail below with relation to FIG. 3.

The R.F. driving energy is coupled into the accelerating section 8 via a centrally disposed coupling hole 34 communicating between the first resonant section 32 of the slow wave structure and the hollow cylindrical chamber 28. The end closing wall 30' of the hollow cylindrical chamber 28 is centrally bored at 35 to allow the passage of the beam of electrons therethrough. However, the end wall 30' is made relatively thick such that the bore 35 forms a cylindrical waveguide section having a cutoff frequency substantially higher than the operating frequency of the slow wave propagating structure such that negligible R.F. energy is coupled outwardly of the cylindrical chamber 28 via the bore 35.

The unused driving R.F. energy after passing through the slow wave accelerating section 8 is coupled outwardly thereof via a centrally apertured disk 36 into a hollow cylindrical chamber 37. The energy is coupled out of chamber 37 via coupling hole 38 and rectangular waveguide tapered transition section 39 through the rectangular waveguide 41 to the phase shifter and attenuator 15.

Three beam confining solenoids 42 circumscribe the hollow cylindrical slow wave structure. The solenoids 42 are carried upon a hollow cylindrical sleeve 43 which is carried coaxially of and slightly spaced apart from the hollow cylindrical conductor 30, thereby forming an annular chamber 44 therebetween for the circulation of a cooling fluid.

Referring now to FIGS. 3 and 3A there is shown a typical X-band accelerator section utilizing the features of the present invention. This section is so designed that the thickness of each of the disks, t , and also the diameters of the beam apertures, $2a$ in each of the disks are maintained constant, and the requirement of operation in the $\pi/2$ mode (one quarter-wave phase shift per cavity) is used. The particular design depends on the properties of the accelerator system with which the buncher is to be used, which determines the operating wavelength, the available R.F. input power and the velocity of the electron beam as it enters the buncher. The disk thickness, t , and beam aperture, $2a$ are chosen to be the same as in the uniform section of the accelerator. The design procedure is in three parts: (1) determination of cavity parameters, (2) determination of the proper variation of phase velocity, and (3) determination of the mechanical configuration of the buncher waveguide.

First, a demountable test cavity is constructed in which two disks 45 and 46 with standard thickness, t , and central aperture, $2a$, are sandwiched between three spacer rings 47, 48, the entire assembly clamped between flat end-plates 49, one of which is apertured for a coupling loop 51 for making R.F. test measurements, and aligned by an outside aligning sleeve 52 (see FIG. 7). The thickness, $l/2$, of each of the two end spacer rings 48 is half of the thickness, l , of the central spacer ring 47 such that the thickness l is equal to a desired disk spacing, d , less the disk thickness, t . Initially, the diameter $2b$ is chosen equal to the diameter of the cavities in the uniform section of the accelerator and the disk spacing, d , is chosen a small amount shorter than that in the uniform section. The three resonant wavelengths of this cavity are measured, and the phase and group velocity of the wave in the cavity are calculated therefrom in a manner described in chapter 8 of "Microwave Elec-

tronics," by J. C. Slater, Van Nosstrand, 1950. The wavelength at which the cavity operates in the $\pi/2$ mode will be shorter than the desired operating wavelength of the accelerator. The diameter, $2b$, of the spacer disks is then enlarged in proportion to the desired wavelength change and the new resonant wavelength measured. A second trial may be required before the correct diameter, $2b$, is found at which the cavity will operate in the $\pi/2$ mode at the operating wavelength of the rest of the accelerator. The thickness of the spacer rings 47, 48 is then reduced slightly in a manner to provide a shorter disk spacing, d , and the process repeated. In such a manner may be obtained a graph of the cavity diameter $2b$ required for operation in the $\pi/2$ mode versus the disk spacing. Such an experimentally determined graph is presented in FIG. 6.

A second required property of the cavities is the attenuation α which may be determined from the formula

$$\alpha = \frac{2\pi c}{Qv_g}$$

in nepers per wavelength where group velocity v_g was determined from the measurements in the test cavities and Q is known to be proportional to

$$\frac{2b}{1+b/l}$$

where $l=d-t$. The attenuation of any cavity with disk spacing, d , may therefore be computed from the above formula and knowledge of the Q or the attenuation in the uniform portion of the accelerator; α for a particular accelerator is plotted in FIG. 4.

Finally, the relationship between the field strength in the cavity and the power flux must be determined. This may be done experimentally for each of a series of cavities by frequency perturbation techniques as described in chapter 10 of "Microwave Measurements" by E. L. Ginzton, McGraw-Hill, 1957. It is a feature of this invention, however, that in all cavities the electric field distribution in the portion of the cavity outside the beam aperture is virtually identical and that therefore the energy storage in the fields is proportional only to the length, $d-t$, of the cavity and the axial field strength, E_1 , at the edge of the aperture. This allows the accelerating field on the axis of the cavity to be computed in a manner considerably simpler than in the case of a variable-aperture buncher. The energy storage per unit length, E_s , is equal to P/v_g when P is the power flux through the cavity and v_g the group velocity. It is also equal to

$$E_1^2 \frac{d-t}{d} F$$

where E_1 is the axial field strength at the aperture radius, and F is a form factor which depends only on the beam aperture. In the constant aperture buncher, the factor F is thus a constant. The field strength on the axis, E , may be determined by a formula derived in pages 72-73 of "Traveling Wave Tubes" by J. R. Pierce, Van Nostrand, 1950.

$$\frac{E}{E_1} = \sin \frac{c\pi}{v_p \lambda} (d-t) \left\{ \frac{c\pi}{v_p \lambda} I_0 \left(\frac{2\pi a}{\lambda} \sqrt{\frac{c^2}{v_p^2} - 1} \right) \right\}^{-1}$$

where I_0 is the modified Bessel function $I_0(x) = J_0(ix)$. The above equations may be rewritten in the form

$$A^2 = \frac{E^2}{P} = \left(\frac{E}{E_1} \right)^2 \frac{dl}{d-tv_g F}$$

where

$$\left(\frac{E}{E_1} \right)^2$$

is computed from the above formula and F is then determined by comparison with the value of

$$\frac{E}{E_1}$$

in the uniform section; A for a typical accelerator is shown plotted in FIG. 5.

Methods for measurement of the properties of the uniform section are well-known and are discussed in all the above cited references.

The second phase of the design is the determination of the required variation of v_p . This is accomplished by numerical integration of the equations of motion and of power flow in the accelerator.

$$\frac{d\gamma_n}{d\xi} = A\sqrt{P} \cos \theta_n$$

$$\frac{d\theta_n}{d\xi} = k_w - k_n$$

$$\frac{dP}{d\xi} = -\alpha$$

$$k_w = \frac{2c}{v_p}$$

$$\frac{4\pi^2}{k_n^2} + \frac{1}{\gamma_n^2} = 1$$

where γ_n is electron energy in units of electron rest energy, ξ is distance measured in free-space wavelengths along the buncher axis, A^2 is

$$\frac{E_2}{P}$$

normalized to units of energy gain in mass units per wavelength, P is power flowing at point ξ , θ_n is the phase angle between the klystron and the wave crest, k_w is the propagation constant of the wave, k_n is a propagation constant for the electron, and α is the power attenuation in nepers per free-space wavelength. The input power and initial energy are the same for all electrons. The equations are integrated for several electrons with initial phase $\theta_n = -n$, $0 < n < 2\pi$. An excellent first approximation is obtained by choosing the wave propagation constant k_w during the first integration for an electron one radian ahead of the wave crest. The propagation constant k_w is chosen such that the electron remains one radian ahead of the crest throughout the buncher. A still better design can be achieved by slowing the wave somewhat so that more electrons are trapped by the wave. This, however, can be done only by successive trials: a graph of the electron orbits γ_n vs. θ_n is prepared for each trial function k_w , and the process of bunching in each graph is compared to determine the best function k_w .

Once the desired function

$$k_w = 2\pi \frac{c}{v_p}$$

has been chosen there remains only the third phase of the design: the translation of the electrical design into the actual structure. This requires only choosing disk spacings, d_n , for successive cavities such that for each cavity

$$\frac{4d}{\gamma}$$

is equal to the value of

$$\frac{v_p}{c}$$

specified for the center of that cavity. That is,

$$\frac{4d_n}{\lambda} = \frac{v_p}{c}$$

as determined for the point

$$\xi_n = \frac{X_n}{\lambda} = \frac{\sum_{m=0}^{n-1} d_m + \frac{d_n}{2}}{\lambda}$$

Since $2a$ and t are constant and $2b$ is determined by d , the mechanical design is complete.

This design offers several advantages over the design of a buncher with variable aperture. Some of the disadvantages of the variable-aperture buncher are as follows: The simple formula for Q used in computing attenuation and the assumption of a constant form factor F used in computing

$$\frac{E^2}{P}$$

are not valid in the variable-aperture buncher. A double series of test cavities with varying $2a$ and varying d must be measured and the value of

$$\frac{E^2}{P}$$

must be measured experimentally by perturbation methods in a series of these cavities. Both the variation of the field-strength parameter A and the wave propagation constant k_n must be adjusted to provide best bunching in the variable aperture buncher, which will require more trials during the orbit-calculation phase of the design. And the fabrication is more difficult since the disk thickness t is the only dimension held constant.

Typical dimensions for an X-band accelerator buncher section of the type shown in FIGS. 3 and 3A, wherein the beam aperture diameter, $2a$, is .255 inch and the disk thickness, t , is .071 inch are set forth in the following Table 1.

Table 1

Cavity Number n	Distance of Centerline of Disk from Gun End x_n	Diameter of Cavity $2b_n$
0 (junction cavity)	0.089	1.0350
1	0.267	1.0350
2	0.448	1.0336
3	0.635	1.0310
4	0.832	1.0276
5	1.038	1.0248
6	1.254	1.0226
7	1.479	1.0206
8	1.712	1.0190
9	1.953	1.0177
10	2.201	1.0166
11	2.455	1.0150
12	2.715	1.0143
13	2.980	1.0140
14	3.250	1.0134
15	3.525	1.0128
16	3.804	1.0123
17	4.087	1.0119
18	4.373	1.0115
19	4.661	1.0112
20	4.956	1.0105
21	5.287	1.0080
(Remainder of cavities are uniform.)		

Typical dimensions for an S-band accelerator section of the type shown in FIG. 3, wherein the beam aperture diameter, $2a$, is .8225 inch and the disk thickness, t , is .2300 inch, are set forth in the following Table 2.

Table 2

Cavity Number n	Distance of Centerline of Disk from Gun End x_n	Diameter of Cavity $2b_n$
0 (junction cavity)	.251	3.291
1	1.126	3.271
2	2.046	3.265
3	2.999	3.261
4	3.974	3.259
5	4.992	3.258
6	5.961	3.257
7	6.964	3.256
8	7.973	3.256
9	8.955	3.255
10	10.000	3.255
11	11.018	3.255
12	12.037	3.254
13	13.058	3.254
14	14.080	3.254
15	15.101	3.254
16	16.129	3.254
17	17.154	3.254
Remainder of cavities are uniform.		

Since many changes could be made in the above con-

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

What is claimed is:

1. A particle accelerator comprising a particle emitter adapted to produce a beam of particles and a disk loaded slow wave structure aligned with said particle emitter through which said beam of particles is directed for energy interaction with a high frequency electromagnetic wave traveling through said slow wave structure, said slow wave structure comprising a waveguide having a plurality of disks positioned transversely thereof with central apertures therein through which said beam of particles passes, the thickness of successive disks and the central apertures of successive disks being equal in size, the inside diameter of the waveguide progressively decreasing and the spacing between the successive disks progressively increasing at locations progressively spaced from the emitter end thereof whereby the phase velocity of the slow wave structure varies in accordance with the increase in velocity of the beam particles through the slow wave structure.

2. A particle accelerator as claimed in claim 1 wherein said waveguide comprises a hollow cylindrical tube tapering to a smaller internal diameter at the end furthest removed from the emitter end.

3. An electron linear accelerator comprising an elec-

tron gun adapted to produce an electron beam and a disk loaded slow wave structure aligned with said electron gun through which said electron beam is directed for energy interaction with a high frequency electromagnetic wave traveling through said slow wave structure, said slow wave structure comprising a waveguide having a plurality of disks positioned transversely thereof with central apertures therein through which said beam of electrons passes, the thickness of successive disks and the central apertures of successive disks being constant, the inside diameter of the waveguide progressively decreasing and the spacing between the successive disks progressively increasing at locations progressively spaced from the electron gun end thereof whereby the phase velocity of the slow wave structure varies in accordance with the increase in velocity of the electrons through the slow wave structure.

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