June 7, 1960 R. F. POST 2,940,001

ELECTRON ACCELERATOR

Filed Feb. 8, 1955

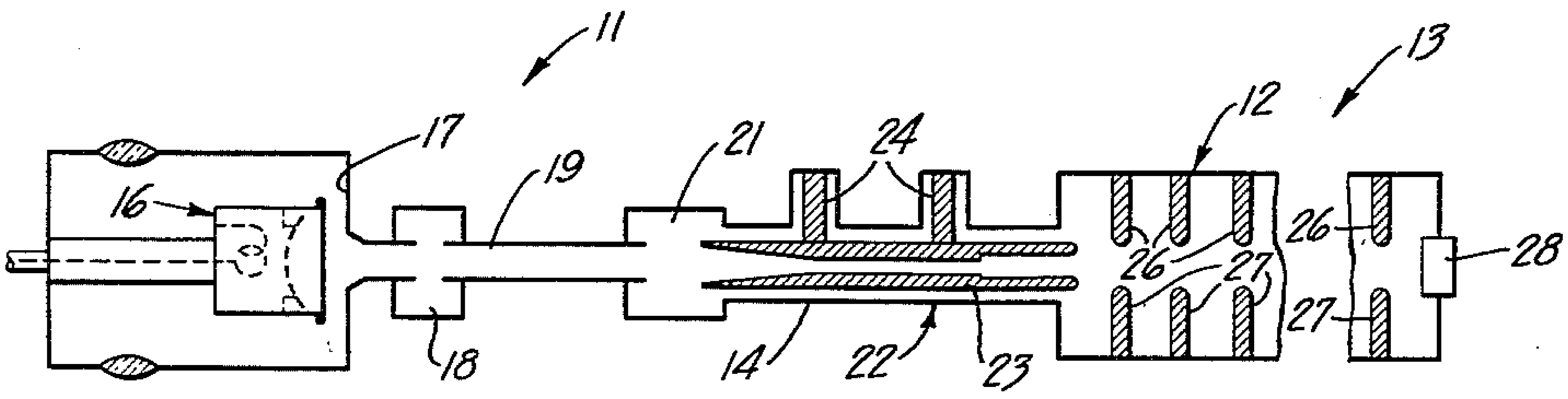

FIG_1_

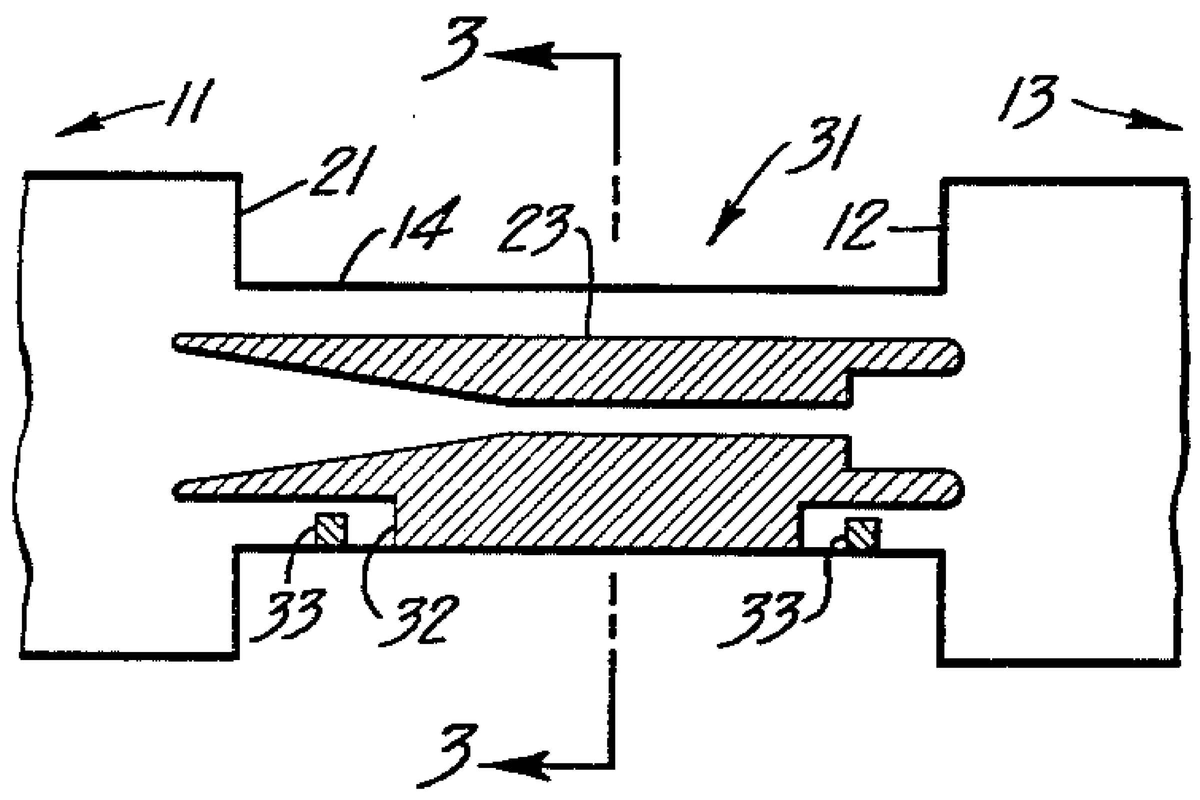

FIG_2_

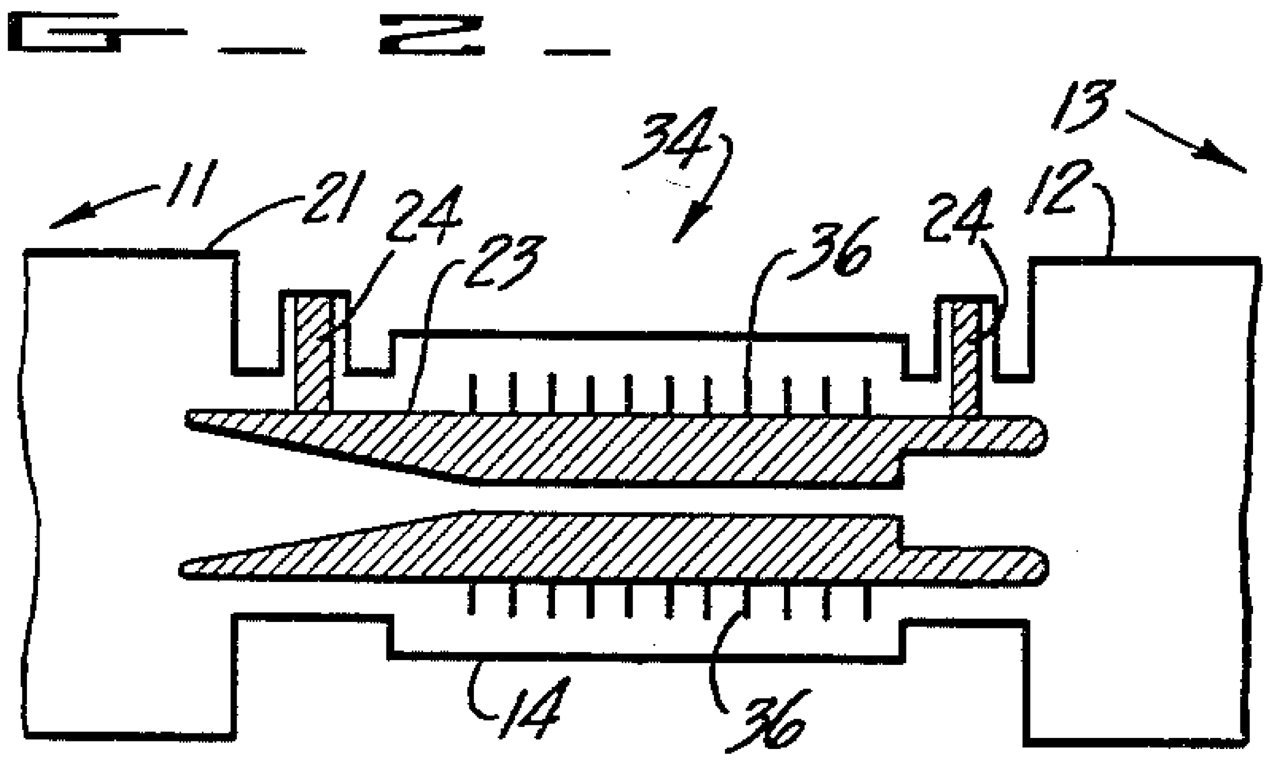

FIG_4_

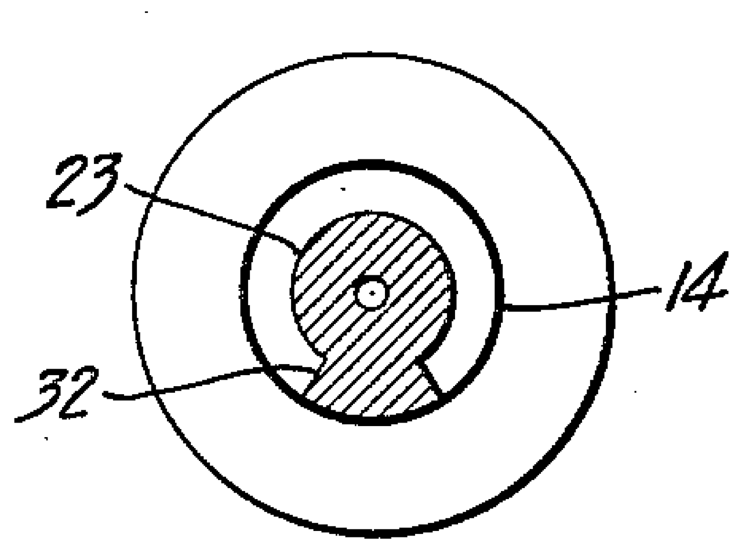

FIG_3_

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2,940,001

Patented June 7, 1960

2,940,001

ELECTRON ACCELERATOR

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Filed Feb. 8, 1955, Ser. No. 486,865

15 Claims. (Cl. 315—5.42)

The present invention relates to an improved method and means for injecting electrons into and applying accelerating energy to a traveling-wave electron accelerator.

Conventional traveling-wave electron accelerators comprising a waveguide having spaced walls defining, in effect, successive resonant cavities are normally energized by a radio-frequency vacuum tube such as a velocity-modulated electron tube coupled thereto and have associated therewith an electron gun source admitting a beam of electrons into the waveguide. The present invention provides method and means for energizing an accelerator waveguide and injecting high voltage electrons therein in a single operation. The invention contemplates the simultaneous production of radio-frequency energy and high voltage electrons with a subsequent further acceleration of said electrons by the radio-frequency energy in the form of a traveling voltage wave. One manner of carrying out this method is to couple the radio-frequency energy and electrons from a velocity-modulated electron tube into a traveling-wave linear accelerator in correct phase so that the energy excites the accelerator waveguide to further accelerate the back phase (voltage-doubled) electrons injected.

The method and means of the present invention is herein illustrated and described with respect to specific steps and structure in the interest of clarity, however, no limitations are intended or be inferred therefrom, reference made to the appended claims for a precise delineation of the scope of the invention.

The invention is illustrated in the accompanying drawing wherein:

Figure 1 is a schematic representation of a preferred embodiment of the electron accelerating means of the invention;

Figure 2 is a schematic representation of alternate collector coupler means;

Figure 3 is a section view taken at 3—3 of Figure 2; and

Figure 4 is an alternate embodiment of the collector coupler.

Considering now the invention in some detail as to the method thereof, it is contemplated that there will be produced a bunched beam of electrons. These electrons may be continuously emitted from an appropriate electron emitter such as a hot filament, for example, and the electrons are accelerated by suitable electrical fields to a relatively high potential and collimated into a beam. This beam of electrons is then velocity modulated as by time varying electrical fields to produce a bunched electron beam having periodic electron density variations. The bunched electron beam is then employed to produce electromagnetic energy as by passing same successively through one or more resonant catcher cavities whereby same are excited. There thus results a bunched electron beam and electromagnetic radiation with the latter being employed to further accelerate a small portion of the bunched beam and return energy thereto so that there is produced a resultant high voltage electron beam.

There is produced in the first portions of the above process a voltage doubling action whereby certain relatively few electrons in the bunched beam attain substantially twice the velocity or voltage of the remaining electrons, by virtue of passing through the catcher cavity 180° out of phase with the phase of driven oscillations in said cavity. These voltage-doubled electrons are herein chosen for further acceleration. Following production of the electromagnetic energy by the bunched beam, the beam is collimated or otherwise operated upon to materially reduce the beam current and as the main portion of the beam tends to defocus in the process of establishing the electromagnetic energy, collimation of beam discriminates in favor of the voltage-doubled electrons.

In addition to collimating the beam, the electromagnetic energy waves are directed along the beam path for returning energy to the beam. In order for the beam to be accelerated by the electromagnetic waves the phase of the latter is varied with respect to the voltage-doubled electron beam pulses, or vice versa, and in this respect certain alternative steps are possible. In order to obtain the proper phase relation, either the phase of the electromagnetic waves may be advanced with respect to the beam pulses or it may be retarded with respect thereto. Advancing the phase of the electromagnetic waves may be accomplished by passing both the energy waves and electron beam through a transmission line wherein the wave velocity is substantially equal to or greater than the speed of light and the electron beam velocity is much less so that in a predetermined distance a desired phase advance is achieved. Retarding of the energy wave phase may be accomplished by directing both energy waves and the beam through a slow wave structure wherein the wave velocity is reduced to less than that of the beam and wherein a predetermined distance of travel shifts the relative phase to the desired relationship. Although both of the above alternatives are feasible, a minimum length of travel of beam and wave results either from the slow wave propagation or the propagation of the wave at a velocity greater than that of light for in both cases a maximumized velocity difference between wave and beam is attained. Certain advantages will be seen to attach to the minimization of distance required to accomplish this step of the method.

Acceleration of the voltage doubled portion of the bunched beam is accomplished by establishing traveling voltage waves with the electromagnetic waves originally produced by the beam and passing the beam therethrough in proper phase to receive acceleration therefrom. As to the proper phase relation same is produced in the above-noted manner so that the voltage waves established do accelerate the voltage-doubled electrons of the beam.

There is produced by the above process a high voltage electron beam of periodically varying electron density. The original electron beam produced in the process will be seen to have actually supplied energy to a small portion of itself to drive same to a high voltage and this is accomplished by producing electromagnetic energy from the beam and then feeding same back into a selected portion thereof. Various structural arrangements may be employed to carry out the described method and referring to Figure 1 of the drawing wherein one preferred means is illustrated, there is shown a velocity-modulated electron tube **11** axially aligned with the waveguide **12** of a traveling-wave linear accelerator **13** and communicating therewith through a cylinder **14** disposed between same. The electron tube **11** may consist of a conventional electron-beam radio-frequency tube such as klystron and including an electron emitter **16** having a filament and heating means therefor to emit electrons within the tube. Electrons are accelerated from the emitter **16** by an anode **17** which may be formed as a transverse tube wall having an aperture therein for the passage of electrons. Accelerating potential may be supplied by externally energizing the emitter **16** at a negative potential with respect to the anode **17**. A continuous beam of electrons is formed by the acceleration of electrons from the emitter and this beam passes through the anode aperture and thence through a buncher cavity **18** aligned with the emitter and adapted for excitation by an externally applied time-varying voltage of a radio frequency, for example. The electron beam is velocity modulated by this voltage in the buncher cavity **18** in a conventional manner so that the electron beam in traversing a relatively field free space beyond the cavity **18** becomes bunched with periodic variations in electron density. Following the buncher cavity **18** is a second cavity **21** connected to the first by an elongated passage **19** through which the electron beam travels. The second cavity **21** is designed to resonate at the frequency of the bunched beam so that there is thus produced in a conventional manner a resonant energy exchange within the cavity **21** whereby electromagnetic energy is produced therein.

The above-described elements and operation are conventional in tubes such as a klystron, however, the electron beam is conventionally intercepted by a collector beyond the output cavity **21** with the radio-frequency energy developed in the tube being fed into other apparatus as by coupling loops or the like for use therein. The present invention removes both the electron beam and radio-frequency energy from the tube and for this purpose provides a collector-coupler **22** in axial alignment with the tube **11** communicating with the output cavity **21** thereof. This collector-coupler **22** includes the cylinder **14** and an inner member **23** shown as a cylinder or solid of revolution having an axial passage therethrough similar to a reversed venturi with a diameter decreasing with separation from the cavity **21** and having an enlarged opening at the exit thereof, as shown. The member **23** may be mounted as by a pair of quarterwave stubs **24** within the cylinder **14** to minimize insulation problems as shown in Figure 1. A small opening therethrough will be seen to intercept and collect a large portion of the electron beam from the electron tube **11**. Within the tube **11** a certain small portion of the electrons in the beam experience an additional acceleration to substantially twice the voltage of the rest of the beam electrons by virtue of their phase being such as to be accelerated in the output cavity **21** rather than decelerated. These electrons are called voltage-doubled electrons. It is these voltage-doubled electrons which are preferentially chosen in the present invention for additional acceleration, since it can be shown that an increase in injection voltage increases the efficiency of, and simplifies the design of, traveling wave accelerators.

Within the collector-coupler **22** of Figure 1 the radio-frequency energy from the tube **11** travels at the speed of light between the cylinder **14** and member **23** while even the voltage-doubled electrons traveling through the axial passage in member **23** have a much lower velocity so that the energy waves advance in phase with respect to the bunched electrons of the beam in passing through the collector-coupler. By choosing the proper length of coupling the energy waves advance in phase exactly the proper amount in relation to the bunches of voltage-doubled electrons as noted below. Within the accelerator waveguide **13** there are provided a plurality of transverse partitions **26** having openings therethrough on the waveguide axis and defining a loaded waveguide consisting of a plurality of successive cavities **27** of proper dimensions to propagate an electromagnetic wave at the correct phase velocity to accelerate the injected electrons at the frequency of the energy coupled thereto from the tube **11** by the collector-coupler **22**. There is thus established in the accelerator **12** a traveling wave receiving its energy from the tube **11** and giving up energy to electrons passing therethrough in proper phase relation thereto. As noted above, the proper choice of length of the collector-coupler **22** will place the voltage-doubled electrons in proper phase relation to the cavity excitation so that only bunches of voltage-doubled electrons are accelerated thereby. The collector-coupler **22** thus acts as a collector for the electron beam of the tube **11** while yet admitting passage of a portion of said beam therethrough and also couples the tube energy into the waveguide **13** for exciting the cavities **27** thereof.

The portion of the electron beam accelerated in the waveguide **12** may be utilized exteriorly of the apparatus by the provision of a window **28** at the closed end of the waveguide on the axis thereof. The window **28** is pervious to the accelerated electron beam and yet seals the system to maintain a vacuum therein which is advantageous in the operation thereof.

With regard to the variation in phase of the electromagnetic waves and the voltage-doubled electrons of the beam it is desired in apparatus of the type above described that the phase of the energy waves be shifted 180° (π radians) with respect to the phase of the voltage-doubled electrons. With the above described coaxial collector-coupler of Figure 1 having a length L, the following relationship is attained for 180° phase shift in same:

$$\frac{2\pi L}{\beta g \lambda_0}-\frac{2\pi L}{\beta e \lambda_0}=\pi$$

wherein:

λ_0=free space wave length at operating frequency
βe=velocity of electron beam relative to free space velocity of light (c)
βg=phase velocity of wave relative to free space velocity of light (c)

Solving this relationship for L gives:

$$L=\frac{\lambda_0}{2}\left(\frac{\beta e \beta g}{\beta g-\beta e}\right)$$

The phase velocity of the wave is substantially equal to the free space velocity of light so that $\beta g=1$ and in a typical case of 300 thousand electron volts, $\beta e=0.8$ so that substituting in the above relationship,

$$L=2\lambda_0$$

and in a typical velocity modulated electron tube, as a klystron, wherein the wave length is 10.5 centimeters, $L=21$ centimeters.

Although the above determined length of the collector-coupler is not excessive it may be reduced by alternative structure such as shown in Figures 2 and 3.

The alternative embodiment of Figures 2 and 3 illustrates a collector-coupler **31** including a cylinder **14** connected between the output cavity **21** of a tube **11** and the waveguide **12** of the accelerator **13**. Coaxially within this cylinder **14** is mounted a cylindrical member **23** similar in structure to the like numbered member of Figure 1 but shorter, as noted below. In this embodiment a fundamental coaxial mode at each end of the coupler is transformed in the central part of the coupler to a special waveguide mode. Thus at each end the coupler **31** and surrounding cylinder **14** are symmetrical so that the electric fiield of the transmitted electromagnetic waves is directed radially outward from the coupler axis and uniform about the member **23**. This coaxial mode of transmission because of its axial symmetry is particularly desirable for coupling out of the cavity **21** and into the accelerator **13**. The central portion of the coupler **31** is supported by a wall or upstanding member **32**, as shown in Figure 2 and 3, parallel to the coupler axis and below same between the cylinder **14** and member **23**. This wall **32** actually comprises a portion of the coupler **31** formed by the cylinder **14**, member **23** and wall **32**, insofar as the transmitted electromagnetic waves are concerned, for the mode of wave transmission is altered thereby to become circumferential wherein the wave velocity exceeds that of light. Small vertical posts **33** are disposed upon the cylinder **14** below the member **23** at each end of the wall **32** thereof for impedance matching between the coaxial and waveguide modes and these posts are conventionally termed matching posts. While the aforesaid matching posts serve to illustrate an embodiment of the invention, various other means for accomplishing the same results will suggest themselves to those skilled in the art.

In the embodiment of Figures 2 and 3 wherein the wave velocity in the center section coupler exceeds the speed of light the length L of the center section having the wall **32** attached thereto may be determined from the relation:

$$\frac{2\pi L}{\beta g \lambda_o}-\frac{2\pi L}{\beta e \lambda_o}=\pi$$

wherein all symbols are as above defined. Thus:

$$L=\frac{\lambda_o}{2}\left(\frac{\beta g \beta e}{\beta g-\beta e}\right)$$

as in the case of the embodiment of Figure 1, however, in this case the phase velocity of the wave in the center section is determined by the boundary conditions for the transmission mode which may be stated as:

$$\sin (K_2 p)=0 \text{ or } K_2=\frac{\pi}{p}$$

wherein: p=mean circumferential dimension of the coupler and $K_1^2+K_2^2=K^2$, where

$$K=\frac{2\pi}{\lambda_o} \text{ and } K_1=\frac{2\pi}{\beta g \lambda_o}$$

Solving this for βg gives

$$\beta g^2=\frac{1}{1-\left(\frac{\lambda_o}{2p}\right)^2}$$

and in a typical case wherein the diameter of the member **23** is 2.5 centimeters and the cylinder diameter is 3.5 centimeters, $p=7.0$ centimeters, so that with $\lambda_0=10.5$ centimeters and $\beta e=0.8$, as above, $\beta g=1.60$.

Thus, substituting in the above equation for L gives $L=0.8\lambda_0$ or 8.4 centimeters. This dimension of 8.4 will be seen to be materially less than the length of 21 centimeters calculated above for a typical structure of the embodiment of Figure 1 and even with the addition to this of the end sections of the coupler the resultant length is substantially less than that of the coupler of Figure 1.

One further embodiment of the coupler is herein illustrated in Figure 4 wherein a member **23** substantially identical to that of Figure 1 except for size is mounted as by quarter wave length stubs **24** in a cylinder **14** between the tube **11** and accelerator **13**. In this instance a periodic structure is formed within the coupler **34** formed by the above mentioned elements so as to produce a periodically loaded coaxial section to delay the phase of the wave with respect to the electrons. Such a structure is well known for its properties of slow wave propagation and in the illustrated embodiment there are provided upon the coupler a plurality of radial flanges or discs **36** spaced evenly along the coupler upon the exterior surface thereof. As the wave is propagated between the cylinder **14** and central member **23**, the discs **36** form such a periodic structure as to materially reduce the wave velocity. Within practical limits the wave velocity may be made as small as desired and, for example, a value of $\beta g=0.5$, wherein βg here again equals the phase velocity of the wave relative to the velocity of light, may be achieved with a ratio of disc to member **23** diameter of about 1.5 to 1 and a ratio of cylinder to member **23** diameter of about 1.7 to 1. The relationship noted in relation to the case of Figures 1 and 2 is here again ap-

plicable with a change in sign as βe is greater than βg so that

$$\frac{2\pi L}{\beta e \lambda_o}-\frac{2\pi L}{\beta g \lambda_o}=\pi, \text{ and } L=\frac{\lambda_o}{2}\left(\frac{\beta e \beta g}{\beta e-\beta g}\right)$$

Substituting $\beta e=0.5$ and $\beta g=0.8$ in the above relation gives $L=0.67\lambda_0$ so that with $\lambda_0=10.5$ centimeters, $L=7$ centimeters. In this case, as in that of Figure 2, L is taken as the length of the center periodic section of the coupler **34** so that an addition is to be made thereto of the unloaded end sections to determine the overall length.

There has been described above an improved method and means for electron acceleration wherein but a single source is employed to produce a pulsed electron beam and energy for accelerating same. With regard to the alternative embodiments of the coupler illustrated and described, same are presented as illustrative only and particularly the calculations herein included are to be taken only as examples and in no way limiting upon the scope of the invention which is precisely delineated in the following claims.

What is claimed is:

1. An electron accelerator comprising a velocity modulated electron tube, a waveguide disposed in axial alignment with said electron tube and having transverse partitions defining connected resonant cavities, and coupling means intermediate and interconnecting said tube and waveguide with coaxial means therein directing radio-frequency energy from said tube into said waveguide and having a small opening therein limiting electrons transmitted from said tube into said waveguide, said coupling means also including means for varying the relative phase of said radio-frequency energy and beam to provide substantially 180 degrees phase difference therebetween.

2. Improved electron accelerating means comprising a traveling-wave linear accelerator including a waveguide, a velocity modulated electron tube generating a bunched beam of electrons for producing radio-frequency energy, said electron tube and accelerator wave-guide disposed in axial alignment, and coupling means connecting said tube and waveguide for admitting to said waveguide a portion of the bunched electron beam of said tube and coupling said radio-frequency energy to said waveguide with an advance in the relative phase of said radio-frequency energy whereby said waveguide is energized to accelerate said bunched electrons therein.

3. An improved ejector for an electron accelerator comprising a velocity modulated electron tube including means producing a bunched electron beam and defining a resonant cavity traversed by said beam wherein electromagnetic waves are excited thereby, and coupling means communicating with said tube at said cavity in axial alignment with the electron beam thereof, said coupling means defining coaxial openings therethrough for passing said electromagnetic waves and a portion of said electron beam in predetermined shifted phase relationship and adapted for connection to an electron accelerator to inject therein electromagnetic waves and a bunched electron beam.

4. Improved coupling means for coupling a velocity-modulated electron tube to a traveling-wave linear electron accelerator accelerating waveguide comprising an elongated tube adapted for axially aligned communicable connection between the output cavity of said velocity-modulated tube and the input of said waveguide, and a coupling cylinder disposed coaxially within said elongated tube and having a beam collimating aperture therethrough for transmitting a collimated bunched electron beam through the aperture and electromagnetic waves through the annulus between said cylinder and elongated tube from the output cavity of the tube to the input of the waveguide.

5. Improved coupling means as claimed in claim 4 further defined by said coupling cylinder having smoothly curving convex inner walls tapering radially inward away

from the inlet end thereof for collecting the majority of electrons of an entering electron beam and passing only a small percentage thereof.

6. In an improved injector for an electron accelerator including a periodically loaded accelerating waveguide, the combination comprising a klystron having an open-ended output cavity, a cylinder connected in axial alignment with said klystron in unimpeded communication with the output cavity thereof and adapted for communicable connection to the accelerating waveguide of an electron linear accelerator, and an inner coupling cylinder disposed in said cylinder, said inner coupling cylinder having a passage therethrough tapered radially inward for collimating an electron beam from said klystron to pass only a small portion thereof and having a length sufficient to advance the relative phase of electromagnetic wave energy radiated from the klystron through the annulus between said inner coupling cylinder and outer cylinder a predetermined amount over that of the electron beam passing through said passage.

7. An electron accelerator comprising a velocity modulated electron tube producing a bunched electron beam and resonant electromagnetic energy, a traveling wave linear accelerator having a waveguide, and means coupling said tube and waveguide in alignment and providing direction communication for coupling the electromagnetic energy into said waveguide for energizing same with traveling waves, and said coupling means further providing an electron passage into said waveguide and including means varying the relative phase of coupled energy and electron beam whereby said electron beam is accelerated in said waveguide by the voltage waves therein.

8. An electron accelerator as claimed in claim 7 further defined by said coupling means having a central aperture of small diameter collimating said electron beam to intercept all but the central core thereof and having an elongated waveguide structure wherein the relative phase of the energy and electron beam varies in proportion to the length thereof for establishing such a phase relationship that said voltage waves accelerate predetermined bunches of electrons in said beam.

9. An electron accelerator comprising a velocity-modulated electron tube producing resonant electromagnetic energy with a bunched electron beam, a traveling wave electron accelerator structure axially aligned with the electron beam of said tube at the end thereof, and a coupler communicating between said tube and said accelerator structure with said coupler including a coaxial member for coupling electromagnetic energy from said tube into said accelerator structure and defining an axial aperture for collimating the electron beam from said tube to substantially original cross section prior to entry of same into said accelerator structure.

10. An electron accelerator comprising tube means establishing resonant electromagnetic energy with a bunched electron beam, coupling means communicating with said tube means in line with the electron beam of same for passage of said beam therethrough and including a periodically loaded waveguide structure coaxial section wherein said electromagnetic energy is transmitted at a low propagation velocity so that the phase of said electron beam advances over that of the transmitted energy, and a plurality of communicating resonant cavities of successively increasing volume connected to said coupling means wherein said electromagnetic energy establishes traveling voltage waves for accelerating portions of said electron beam passing therethrough.

11. An electron accelerator as claimed in claim 10 further defined by said coupler having a length sufficient to retard the phase of the electromagnetic energy one hundred and eighty degrees relative to the phase of said bunched electron beam.

12. In an injector for an electron accelerator including a plurality of communicating resonant cavities, the combination comprising means producing a bunched electron beam, means defining a cavity resonant at the frequency of said beam bunches and disposed for beam traverse therethrough whereby resonant electromagnetic energy waves are established in said cavity, and coupling means admitting a collimated portion of said electron beam into said cavities for passage therethrough, said coupling means including a coaxial section coupling said electromagnetic energy into said cavities for exciting same and including axially spaced radial disc loading said section for reducing wave propagation velocity therein whereby the relative phase of said electromagnetic waves and electron beam entering said cavities is proportional to the length of the coupling means for establishing cavity excitation of a phase to accelerate predetermined electron bunches of said beam.

13. An electron accelerator comprising a velocity modulated electron tube including means establishing an electron beam, means bunching said beam to produce spaced high density main beam bunches and intermediate secondary beam bunches of lesser density, and means defining a cavity traversed by said beam and resonant at the passage frequency of said main beam bunches for excitation thereby to produce electromagnetic energy waves accelerating secondary beam bunches; a periodic waveguide structure defining consecutive cavities resonant at the frequency of said energy waves; and a coupler-collector communicating between said electron tube and waveguide and including an elongated coaxial section coupling energy waves into said waveguide for energizing same and beam collimating means collecting divergent low energy electrons of said main electron bunches and passing high energy secondary electron bunches into said waveguide for acceleration therein.

14. An electron accelerator as claimed in claim 13 further defined by said collector-coupler including means varying the relative phase of output energy waves to substantially correspond with the phase of said secondary electron bunches.

15. An electron accelerator as claimed in claim 13 further defined by said collector-coupler having a predetermined field free length with means controlling propagation velocity of said energy waves therethrough for setting the relative phase of exciting energy waves and electron bunches.

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