

July 18, 1961

R. F. POST

2,993,141

PRODUCING BUNCHED ELECTRON BEAMS

Filed Feb. 10, 1958

3 Sheets-Sheet 1

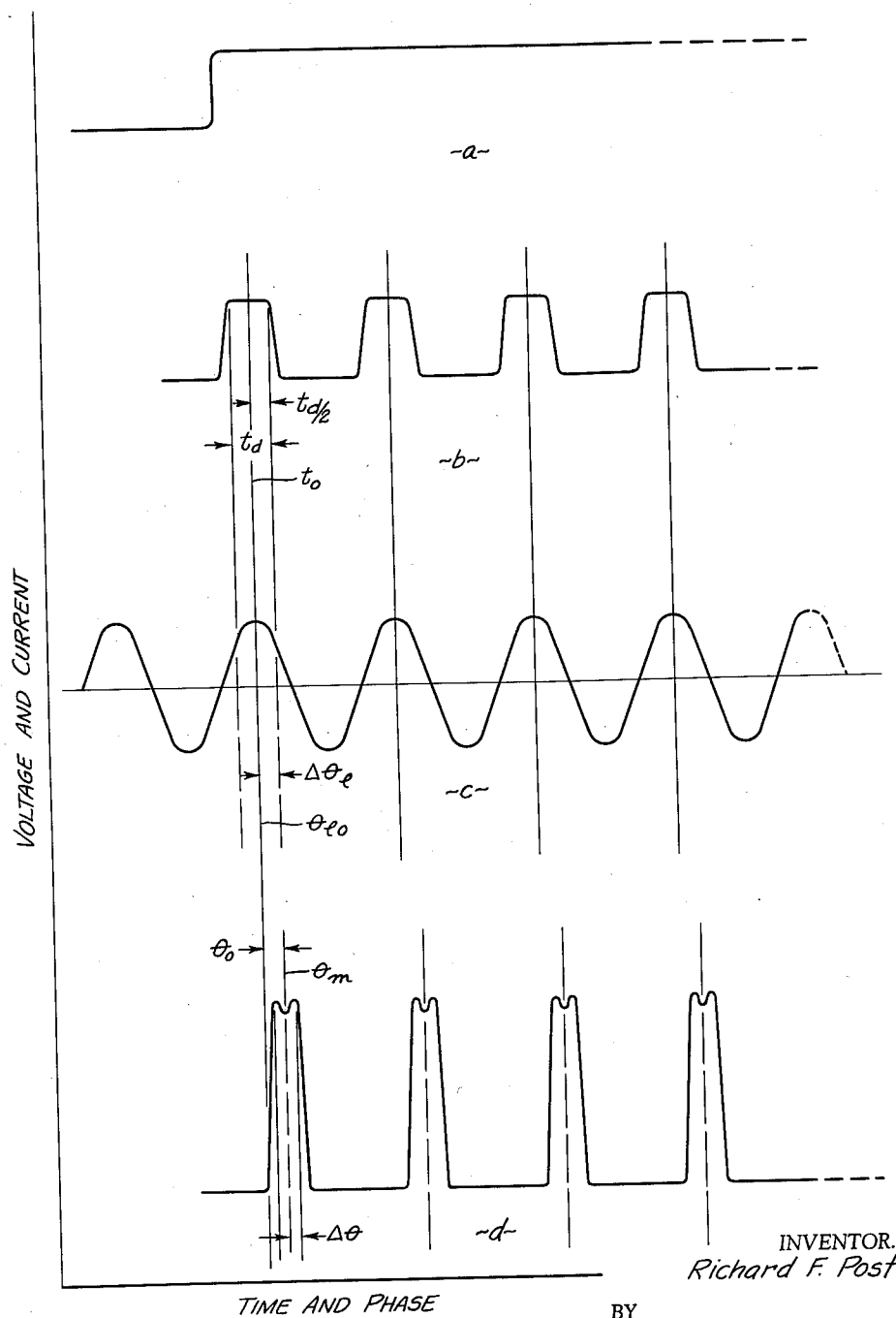


FIG. 1 -

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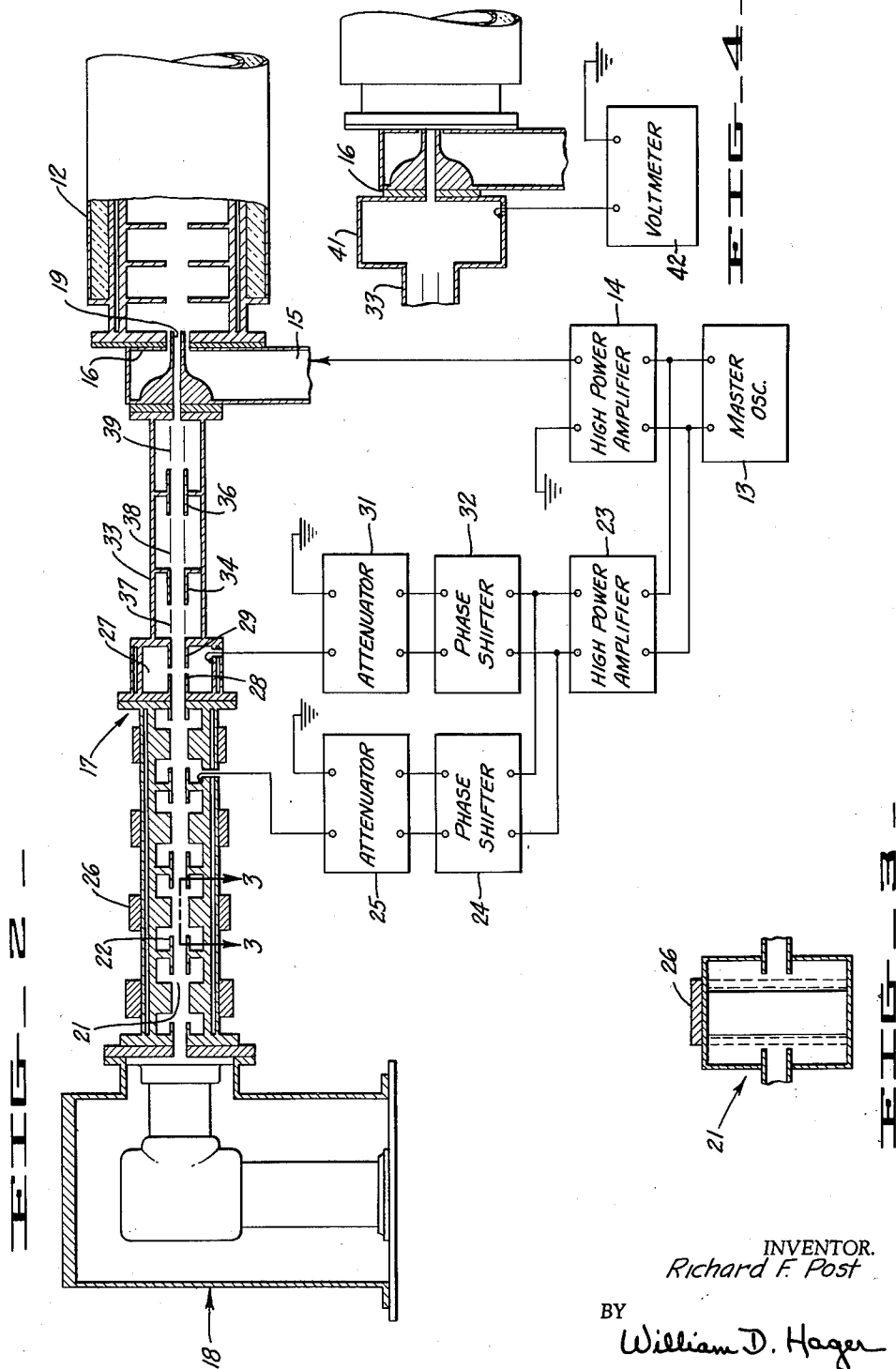
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3 Sheets-Sheet 2



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3 Sheets-Sheet 3

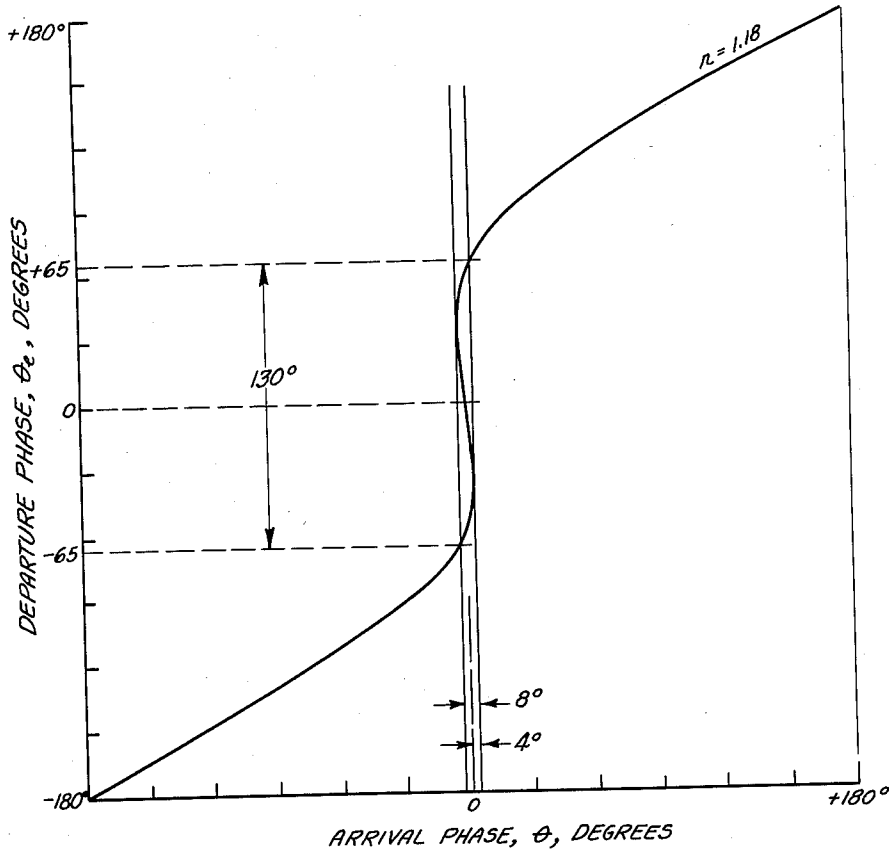


FIG. 5.

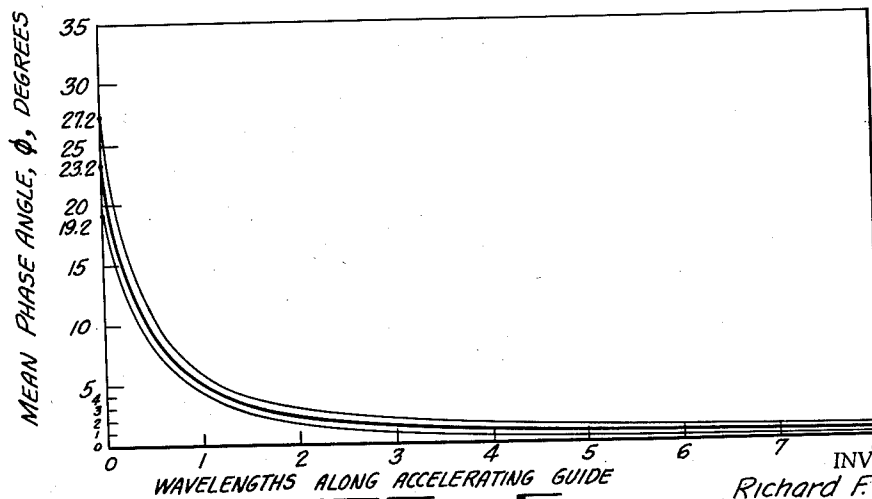


FIG. 6.

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PRODUCING BUNCHED ELECTRON BEAMS

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9 Claims. (Cl. 315-5.42)

The present invention relates generally to bunched electron beams, and more particularly, to a method and apparatus for producing such beams wherein the electrons in each bunch have a predetermined number versus phase relationship relative to a predetermined mean phase.

In the process of accelerating electrons to high energies in linear accelerators and the like, the electrons are generally injected into a periodically loaded waveguide as a bunched beam, i.e., a density modulated beam. Energy in the form of electromagnetic waves is also coupled into the waveguide in such a manner as to propagate there-through in the same direction as the electrons. Those electrons entering the waveguide in proper phase relative to the electromagnetic waves thus tend to be carried along by the waves as they propagate through the waveguide. In this connection, the amount of acceleration obtained by an electron depends upon the position at which it will ride the wave relative to the crests (positive peaks) thereof. More particularly, the electrons are accelerated to energies which are decreasing for increasing phase angle deviations from the positive peaks. Thus since an electron bunch is formed of electrons that are variously dispersed in phase, bunched electrons are accelerated in the waveguide to a variety of energies which are proportional to the phase angle deviations of the individual electrons from the crest of the wave. It is accordingly advantageous that bunched electrons injected into the waveguide be as narrowly dispersed in phase as possible whereby a minimum of energy dispersion is produced in the output beam. For example, bunched electrons that are narrowly dispersed in phase about a mean phase angle which is adjusted equal to the optimum waveguide injection angle for maximum energy will ride the accelerating wave at positions which are correspondingly narrowly dispersed about the crests. The electrons would then be accelerated to substantially the same energies which approach the maximum achievable. Similarly where the mean phase angle of a narrowly dispersed electron bunch is equal to an optimum injection angle for producing a predetermined lesser amount of acceleration, the bunched electrons would be accelerated at phase positions of the wave which are closely grouped about a corresponding mean phase position displaced from the crest of the wave. The electrons would then all be accelerated to substantially the same energy less than the maximum achievable by an amount which is dependent upon the particular injection angle employed. In addition, injection of narrowly dispersed electron bunches is effective in minimizing spurious beam loading effects in the accelerating waveguide. Such effects are characterized by harmful heating and the like due to the dissipation of energy of electrons entering the waveguide in a decelerating phase as opposed to an accelerating phase.

The present invention accomplishes the foregoing advantages by providing a method and apparatus for producing precisely controlled electron bunches having an extremely narrow phase dispersion about a mean phase angle that can be advantageously adjusted equal to the optimum injection angle for substantially any desired acceleration in the accelerating waveguide. Bunched electrons in accordance with the present invention are accordingly accelerated in the waveguide at positions with respect to the accelerating wave which are closely grouped about the optimum positions thereof. Substan-

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tially all electrons thus receive very nearly the same amounts of acceleration equal or nearly equal to the desired acceleration. Moreover, in the event the optimum injection angle is for maximum beam energy output, the phase spread of an injected bunch tends to converge as the electrons are accelerated through the waveguide. All electrons consequently gain very nearly the theoretical maximum energy attainable in a given waveguide thus resulting in waveguide performance very close to the maximum possible. No matter what mean injection angle is employed, the output electron beam produced in accordance with the present invention is essentially single valued in energy and accordingly may thereafter be controlled with relatively great precision as to the output energy, beam diameter, and the like.

It is therefore an object of the present invention to provide a method and apparatus for producing precisely formed electron bunches having a predetermined number of electrons versus phase relationship relative to a predetermined mean phase.

It is another object of the present invention to provide precisely bunched electrons at the proper predetermined injection phase relative to an accelerating wave established in an accelerating waveguide of an electron linear accelerator or other electronic apparatus such as very high frequency tubes and the like.

It is still another object of the present invention to provide a method and apparatus for producing the maximum possible beam current within the optimum acceptance phase of an electron linear accelerator.

Still another object of the invention is the provision of a method and apparatus for chopping and bunching an electron beam to form precise electron bunches having relatively little phase dispersion.

Yet another object of the invention is to minimize spurious beam loading effects in an electron linear accelerator.

An important object of the invention is to provide a method and apparatus for producing an extremely precisely bunched electron beam for injection into an accelerating waveguide to facilitate precisely controllable accelerator performance.

Another important object of the present invention is to provide a method and apparatus for attaining optimum acceleration of electrons.

A further object of this invention is to provide a high energy electron beam with a minimum of dispersion in the energies of the individual electrons.

Additional objects and advantages of the invention will become apparent upon consideration of the following description taken in conjunction with the accompanying drawing, of which:

FIGURE 1 is a graphical illustration of various voltage and current waveshapes in accordance with the present invention,

FIGURE 2 is a side cross sectional view partially in schematic of a preferred embodiment of a chopper-buncher system of the present invention as employed in an electron linear accelerator,

FIGURE 3 is a sectional view of a chopper cavity of this embodiment taken along the line 3-3 of FIGURE 2,

FIGURE 4 is a cross sectional view of a monitoring cavity which may be advantageously employed in the embodiment of FIGURE 2,

FIGURE 5 is a bunching curve illustrating graphically the arrival phase of electrons with respect to the departure phase thereof in accordance with a specific example of the present invention, and

FIGURE 6 is a graphical illustration of the variation of the phase angle of electrons as a function of number of wavelengths along the accelerating wave-

guide of a linear accelerator in accordance with the specific example.

In understanding the present invention, it will be of assistance at the outset to first consider various theoretical aspects of velocity modulation bunching as pertains to the salient aspects of the invention. More particularly, ignoring a small relativistic correction, the theory of small-signal velocity modulation bunching sets forth the arrival phase of a "bunched" electron (which has passed through a drift space), relative to its departure phase at the source of velocity modulation (e.g., a buncher cavity) as the following expression:

$$(1) (\theta - \theta_0) = \theta_1 - r \sin \theta_1,$$

where $(\theta - \theta_0)$ = arrival phase

θ_0 = net phase rotation of electron in passing through a drift space

θ_1 = starting phase of electron with respect to the bunching (velocity modulating) voltage

$$r = \text{bunching parameter} = \frac{\omega \alpha}{2u_0}$$

s = drift space length

ω = bunching frequency

u_0 = mean electron velocity

α = ratio of peak bunching voltage to beam voltage

From the foregoing expression (Equation 1) it will be apparent that the arrival phase of an electron at the end of the drift space depends upon its starting phase relative to the bunching voltage and therefore electrons introduced to the bunching voltage at a variety of positions with respect to the electric field in the bunching cavity, emerge at the end of the drift space at different corresponding arrival phases. Moreover, the electrons tend to arrive in bunches composed of electrons which depart from zero phase relative to the positive peak of the bunching voltage by varying amounts. The maximum departure, $\Delta\theta$, of any electron in a bunch from the mean phase thereof is accordingly determined by the maximum phase spread, $\Delta\theta_1$, in the starting phase, θ_1 , of the electrons relative to zero phase of the bunching voltage (i.e., the positive peak of the bunching voltage). Thus, from Equation 1, the following expression for the maximum arrival phase departure $\Delta\theta$ of bunched electrons symmetrically dispersed about a mean arrival phase angle and corresponding to a starting phase spread of $\pm\Delta\theta_1$ relative to the positive peak or zero phase of the bunching voltage is obtained. That is:

$$(2) \quad \Delta\theta = \Delta\theta_1 - r \sin (\Delta\theta_1)$$

In addition, maximum current may be obtained in electron bunches having any desired predetermined phase dispersion within the limits of $\pm\Delta\theta$ by appropriate adjustment of the various parameters of Equation 2. The necessary parameters may be determined by first deriving the maxima of the expression of Equation 2 by differentiating same and equating the derivative of the arrival phase dispersion to zero. From the foregoing, the maxima of the arrival phase dispersion departure occur when the following condition is satisfied:

$$(3) \quad r \cos \Delta\theta_1 = 1$$

Therefore, upon rearranging terms,

$$(4) \quad \Delta\theta_1 = \cos^{-1} \left(\frac{1}{r} \right)$$

$$(5) \quad \cos \Delta\theta_1 = \frac{1}{r}$$

Thus, from the trigonometric identity

$$(\sin_2 \Delta\theta_1 + \cos_2 \Delta\theta_1 = 1)$$

$$(6) \quad \sin \Delta\theta_1 = \frac{\sqrt{r^2 - 1}}{r}$$

Substituting Equations 4 and 6 into Equation 2, the expression for any desired predetermined maximum phase departure, $\Delta\theta$, in a maximum current electron bunch in terms of the required bunching parameter, r , is the following:

$$(7) \quad \Delta\theta = \cos^{-1} \left(\frac{1}{r} \right) - \sqrt{r^2 - 1}$$

Then, with r chosen to satisfy the above Equation 7 for a desired maximum phase departure, $\Delta\theta$, in the resulting maximum current electron bunches, the corresponding necessary maximum starting phase departure, $\Delta\theta_1$, must be selected to satisfy equation

$$(2) \quad \Delta\theta = \Delta\theta_1 - r \sin (\Delta\theta_1)$$

with the foregoing value for the bunching parameter, r , substituted therein.

From the foregoing mathematical analysis of velocity modulation bunching, it is accordingly to be noted that maximum current electron bunches having any desired maximum phase dispersion of $\pm\Delta\theta$ may be theoretically obtained by controlling the starting phase of the electrons relative to the peak of a bunching voltage to limits of $\pm\Delta\theta_1$, where $\Delta\theta_1$ satisfies the expression:

$$\Delta\theta = \Delta\theta_1 - r \sin (\Delta\theta_1)$$

while the bunching parameter, r , employed in turn satisfies the expression:

$$\Delta\theta = \cos^{-1} \left(\frac{1}{r} \right) - \sqrt{r^2 - 1}$$

It will be further noted that the predetermined maximum phase dispersion limits, $\pm\Delta\theta$, of the maximum current electron bunches may be advantageously selected to be grouped about the desired optimum injection phase angle of an accelerating waveguide of a linear accelerator or other electronic device. In this connection, the electron bunches may be injected into the waveguide at the optimum injection angle for maximum beam energy output and substantially all electrons of a bunch will be accelerated to the same energy which is extremely close to the maximum possible for the particular waveguide employed.

Considering now the present invention in some detail relative to the foregoing theoretical considerations and with regard to the preferred method thereof, while referring to FIGURE 1 of the drawing, it is contemplated that electrons will be provided in the initial steps of the method as a continuous electron stream, or more preferably, as electron pulses of relatively long duration as depicted in portion (a) of FIGURE 1 to facilitate the provision of electrons of relatively high energies. The electrons may be generated in the conventional manner as by means of a suitable pulsed electron gun or other equivalent electron source is capable of producing copious quantities of electrons.

The electron pulses (or streams) are next periodically interrupted at a fixed repetition rate (i.e., chopped) to form a plurality of gated electron beam pulses as illustrated in portion (b) of FIGURE 1. The duration, t_d , of each pulse is selected, in accordance with the salient aspects of the invention, to satisfy the following expression:

$$\Delta\theta = \pi f_c t_d - r_m \sin (\pi f_c t_d)$$

where $\Delta\theta$ is the predetermined phase dispersion limit of the electrons forming a maximum current electron bunch which is to be produced in accordance with the present invention, and which preferably lies within the optimum acceptance phase of an accelerating waveguide as is subsequently described. Additionally, f_c , is the fre-

quency of interruption (e.g., chopping frequency) and r_m is a constant that satisfies the expression:

$$\Delta\theta = \cos^{-1} \left(\frac{1}{r_m} \right) - \sqrt{r_m^2 - 1}$$

The foregoing gated beam pulses are best provided by introducing the electron pulses, as produced for example by an electron gun, to a cavity type dual-deflection chopper which is operative at the frequency, f_c , due to an applied sinusoidal deflection voltage as generally shown in portion (c) of FIGURE 1 oscillating at such frequency and having a phase as subsequently described. The deflection voltage is effective in periodically sweeping the electron pulses past the exit aperture of the chopper activity. Thus, during a small portion of each deflection cycle, corresponding to the time duration t_d as determined by the foregoing equation, the pulse electrons are transmitted through the exit aperture while being collected upon the cavity walls the remainder of the time. The instant in time that the electrons pass the aperture to form a pulse may be variously controlled by the establishment of a suitable continuous bias deflection field in the cavity and appropriate variation of the phase of the alternating deflection voltage. In this connection the electrons may be made to pass the aperture, for example, coincident with the positive peak of the deflection voltage (as shown in the figure) in which case the leading and trailing edges of the resulting gated pulses of duration, t_d , are symmetrically spaced in time on either side of the time, t_0 , corresponding to the positive peak of the sinusoidal voltage. Thus the leading edge of each pulse occurs at a time $(t_0 - t_d/2)$ while the trailing edge occurs at a time $(t_0 + t_d/2)$ as shown in the figure. At the deflection voltage frequency, f_c , the above times correspond to phase angles of $\pm \pi f_c t_d$ relative to the phase θ_{10} of the deflection voltage which is hereinafter considered as zero phase.

The gated pulses are next bunched (i.e., density modulated) as by velocity modulating the pulses and then permitting the pulses to pass through a field-free drift space. To facilitate the foregoing, the gated beam pulses are preferably first introduced to a radio frequency bunching voltage having a frequency equal to the frequency, f_c , of the chopping voltage or harmonically related thereto and in proper phase therewith. The bunching voltage is thus of substantially the same configuration as the chopper deflection voltage depicted in portion (c) of FIGURE 1. Such voltage is best established in an appropriately energized buncher cavity in axial alignment with the chopper. The bunching voltage is suitably phased relative to the chopper deflection voltage to compensate electron drift time therebetween. The output of the chopper may be accordingly made to effectively coincide with the input to the buncher, whereby the chopper deflection voltage and bunching voltage are in the same phase relative to the electrons of the gated beam pulses. The gated beam pulses are thus introduced to the bunching voltage with starting phases which lie within limits of $\pm \pi f_c t_d$ from the positive peaks thereof, which limits correspond to the leading and trailing edges of the pulses. In the terminology of the hereinbefore adduced mathematical considerations, the phase dispersion limits, $\pm \pi f_c t_d$, of the individual electrons thus correspond to the starting phase dispersion limits, $\pm \Delta\theta_1$. The previous equation in accordance with which the time duration, t_d , of the gated pulses was selected

$$(i.e., \Delta\theta = \pi f_c t_d - r_m \sin(f_c t_d))$$

may thus be additionally expressed in terms of the bunching starting phase as:

$$\Delta\theta = \Delta\theta_1 - r_m \sin(\Delta\theta_1)$$

which equation, with r_m a constant selected as described above, corresponds to one of the requisite conditions of

the mathematical consideration for obtaining electron bunches at maximum current within the predetermined phase dispersion limits, $\pm \Delta\theta$.

The velocity modulated pulses produced by the bunching voltage are next introduced to a field free drift space, as may be provided for example by a drift tube following the buncher cavity, to allow formation of bunches as indicated in portion (d), of FIGURE 1. It should be noted that the electrons forming each bunch are dispersed in phase about a mean phase angle, θ_m , which is separated from the center of the corresponding gated beam pulse, θ_{10} , and therefore the peak of the chopper deflection voltage, by a phase angle, θ_0 , due to the phase rotation of the velocity modulated electrons in passing through the drift space.

The bunching parameter, r , employed in bunching the electrons of the gated beam pulses in the method of the present invention is selected to equal the constant, r_m , of previous mention (i.e., r_m satisfies the equation

$$\Delta\theta = \cos^{-1} \left(\frac{1}{r_m} \right) - \sqrt{r_m^2 - 1}$$

The bunching parameter is accordingly selected to satisfy Equation 7 of the previously discussed theoretical considerations whereby maximum current electron bunches having the predetermined maximum phase dispersion $\pm \Delta\theta$ are produced. The required value, r_m , of bunching parameter may be obtained by appropriate adjustment of the drift space length, s , or the ratio of peak bunching voltage to beam voltage, α , relative to the bunching frequency, ω , and mean electron velocity, u_0 , in accordance with the previously set for the equation:

$$r = \frac{s\omega\alpha}{2u_0}$$

Since the length, s , of the drift space is generally fixed, adjustment of the bunching parameter is most easily facilitated by variation of the magnitude of the bunching voltage.

In practice, the predetermined maximum phase dispersion, $\pm \Delta\theta$, of the maximum current electron bunches produced by the method of the instant invention may be made substantially as narrow as desired, e.g., of the order of $\pm 4^\circ$. Dispersion limits within the optimum acceptance phase limits of various accelerating waveguides are easily attained and accordingly, the method is advantageously employed to accomplish electron injection in various linear accelerators or other electronic devices and in this connection it is to be appreciated that the injected electron bunches must be introduced to the waveguide proper phase relationship to the electromagnetic accelerating waves energizing same, in order for the electrons to attain a predetermined output energy. For example the electron bunches may be injected at an optimum injection angle for maximum output beam energy in which case the electrons will ride at substantially the crest of the waves, which is the condition requisite to maximum electron acceleration. More specifically, there is an asymptotic phase angle, ϕ_a , at which an accelerated electron will ride with respect to the crest of the accelerating wave and such asymptotic phase angle depends upon the injection phase angle ϕ_0 of an electron relative to the phase of the accelerating wave by a function which is dependent upon the characteristics of the particular waveguide employed. Thus, with the end of the previously mentioned drift space coinciding with the beam injection hole of an accelerating waveguide, the phase of the electron bunches entering the waveguide may be adjusted to the proper injection phase angle relative to the accelerating wave to cause the electrons to ride the wave within the bunch dispersion limits, $\pm \Delta\theta$, from substantially any desired phase position relative to zero asymptotic phase angle, i.e., the crest of the wave. The foregoing is best accomplished in the method of the present invention by maintaining the chopping voltage and bunching voltage at the proper phase angle rela-

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tive to the accelerating waveguide driving excitation, preferably by means of suitable phase shifters and the like. More particularly, the bunching voltage and chopping voltage are displaced in phase relative to the accelerating voltage by an angle determined by the injection angle, ϕ_0 , and the drift space rotation angle, θ_0 . The mean phase of the injected electron bunches consequently is made to correspond to a predetermined injection angle which produces the desired output energy in the accelerated beam. When the mean phase of the bunches is equal to the optimum injection angle for maximum output energy, for example, substantially all electrons of a bunch are accelerated at positions of the accelerating wave that are within the narrow dispersion limits, $\Delta\theta$, from the peak of the wave, and therefore receive essentially full acceleration. Similarly, when the mean phase angle of a bunch is adjusted equal to an injection angle which is displaced from the above optimum injection angle by a predetermined amount, the electrons of a bunch are accelerated at positions of the wave that are substantially within the narrow dispersion limits, $\Delta\theta$, from an angle that is correspondingly displaced from the peak of the wave. The narrowly dispersed electrons receive substantially the same amounts of acceleration, but the amount of acceleration is diminished in value according to the angle by which each bunch is displaced from the peak of the wave. The energy of the output beam from the waveguide may be accordingly varied to substantially any desired value by adjusting the mean phase angle of a bunch at injection to the proper injection angle relative to the peak of the accelerating wave.

There is consequently produced by the above method a precisely bunched electron beam wherein the electrons forming each bunch are within extremely narrow predetermined limits of phase dispersion. The bunched electron beam may be advantageously injected into accelerating waveguides by the method previously described to produce a high current electron beam having substantially zero spread in the energies of the individual electrons. Various structural arrangements may be employed to carry out the described method and in this connection there is illustrated in FIGURE 2 of the drawing a preferred embodiment of a chopper-buncher system of the present invention as employed in an electron linear accelerator to facilitate improved injection into the accelerating waveguide thereof. As shown in the drawing there is provided an electron linear accelerator 11 including a periodically loaded waveguide 12 of generally conventional construction and energized by a source of radio frequency energy, preferably a master oscillator 13 connected to a high power amplifier 14 which is in turn coupled to the accelerating waveguide as by means of a driving waveguide 15 and radio frequency coupler 16. The particular design employed in the construction of waveguide 12 may be selected to produce either a standing wave accelerating field or traveling wave accelerating field upon energization by the radio frequency source, either type of field being operable with the present invention.

A chopper-buncher system 17 in accordance with the present invention is coupled at its input end to a suitable electron source such as the usual pulsed electron gun 18 of the accelerator. The output end of chopper-buncher system 17 is in turn coupled as by means of radio frequency coupler 16 to the beam injector hole 19 of waveguide 12. The chopper-buncher system includes a suitable beam chopper which is best provided as at least one dual-deflection re-entrant chopper cavity 21 of generally rectangular cross section, as shown in FIGURE 3, colinear with and immediately following the electron gun 18. To facilitate passage of electrons from electron gun 18 into the first one of chopper cavities 21, as well as between successive cavities, axially aligned metallic drift tubes 22 are inserted in pressure sealed relationship centrally through the re-entrant walls of each cavity 21 to extend

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partially into the enclosed cavity volume. More particularly, drift tubes 22 extend a sufficient distance into the cavities to shield electrons passing axially therethrough from the magnetic field which normally exists near the sides of such a cavity.

A suitable alternating deflection field is established within each chopper cavity 21 transversely across the axis thereof to cyclically deflect the electron beam at right angles thereto. To facilitate the foregoing, each cavity 21 is dimensioned to resonate in the TE₀₁₀ mode at a predetermined frequency which may be advantageously selected as the frequency of the driving excitation applied to waveguide 12 from master oscillator 13 and amplifier 14. The indicated deflection field is then established by exciting the cavities 21 at resonance by means of a suitable radio frequency energy source which is preferably controlled in phase and frequency by master oscillator 13. More particularly, for purposes which are subsequently described, the master oscillator is preferably coupled to a high power amplifier 23 the output of which is coupled through a suitable phase shifter 24 and attenuator 25 to the cavities 21. The cavities 21 are appropriately designed such that the attenuation and phase between successive ones thereof substantially exactly compensates the electron transit time through the preceding cavity. Accordingly electrons enter each successive cavity 21 in substantially the same phase relative to the radio frequency deflection field established therein as the phase in which they entered the preceding cavity. Moreover, inasmuch as the cavities 21 each resonate in the TE₀₁₀ mode, the electrons pass through each cavity perpendicular to the alternating electric field component established therein at the point of maximum electric field.

In addition to the electric field component there is an attendant magnetic field component established in each cavity 21 as previously mentioned which has maximum values in the terminal regions thereof. The magnetic field component in combination with the electric field component would normally tend to deflect electrons passing axially through the cavity in such a manner as to produce a net deflection of zero. In the present invention, however, the drift tubes 22 enclose the axis of the cavities in the terminal regions of high magnetic field. Thus electrons passing axially through cavities 21 are shielded by the drift tubes from the magnetic field component and accordingly are only subjected to the transverse electric component of the radio frequency field.

In the preferred embodiment of the present invention herein disclosed, there is additionally provided a transverse D.C. bias deflection field of a magnitude and polarity relative to the radio frequency electric field component to produce a resultant deflection field within each cavity 21 which approaches zero during the positive excursions of such radio frequency field. The bias field may be electrostatic, or more preferably magnetostatic. In the latter case, the field may be established as by means of a C-shaped magnet 26 secured about the central region of each cavity 21 with the pole faces thereof oppositely disposed transversely across the cavity axis. Magnetic flux passes through the cavity 21 between the pole faces of magnet 26 and is effective in establishing a constant magnetic field of a magnitude and direction to deflect electrons by a substantially equal and opposite amount to that produced by the positive excursion of the radio frequency electric field. A beam of electrons entering the first cavity 21 from electron gun 18 is accordingly alternately deflected away from its output drift tube 22 and then aligned with same during a portion of the positive excursion of the radio frequency electric field. During the period of alignment, a gated beam pulse of electrons is transmitted through the drift tube into the next cavity. Similarly, the electrons are transmitted through each successive cavity 21 of the chopper only during a portion of the positive excursion of radio frequency field estab-

lished therein. The gated beam pulses consequently are produced at a repetition rate commensurate with the frequency of master oscillator 13 and therefore with that of the accelerating wave established in waveguide 12. While one chopper cavity 21 may be satisfactorily employed to chop the electron beam, the use of a plurality of cavities 21 results in minimization of angular dispersion effects of the chopping.

The magnitudes of the radio frequency field and bias field are adjusted relative to the distance between the electron beam deflection point and receiving drift tube 22 as well as the drift tube bore diameter such that the time interval within the period of each positive excursion of radio frequency field during which electrons are transmitted from a chopper cavity 21 is equal to the time, t_d , hereinbefore described with respect to the method of the invention. The time interval accordingly extends between positions in the radio frequency cycle that are symmetrically separated from the positive peak of the cycle by time increments

$$\frac{t_d}{2}$$

Moreover, as was previously described, the time interval, t_d , is selected in value relative to the predetermined optimum acceptance phase, $\Delta\theta$, of waveguide 12 to satisfy the equation:

$$\Delta\theta = \pi f_c t_d - r_m \sin(\pi f_c t_d)$$

where r_m is a constant that satisfies the equation:

$$\Delta\theta = \cos^{-1} \left(\frac{1}{r_m} \right) - \sqrt{r_m^2 - 1}$$

Accordingly, in terms of the phase angle of the radio frequency field established in the last one of cavities 21, the gated beam pulses emerging therefrom extend between phase limits of $\pm\Delta\theta_1$ (i.e., $\Delta\theta_1 = \pi f_c t_d$) from each positive peak of such radio frequency field.

The present invention is not limited to the specific chopper structure just described inasmuch as numerous modifications thereof as well as additional structures for producing discrete groups of electrons will be apparent to one skilled in the electronics art. For example, the bias field established within the chopper cavities 21 by magnets 26 may be dispensed with. The electron beam is then deflected symmetrically on either side of the axis of cavity 18 and therefore the electrons are transmitted from the cavities through the corresponding drift tubes 22 twice each cycle of the applied radio frequency chopper operating voltage coincident with the zero voltage points of the cycle. The frequency of the chopper operating voltage is consequently advantageously controlled in phase and frequency by master oscillator 13 such that one gated beam pulse is transmitted from the chopper for each cycle of master oscillator energy applied to waveguide 12. For example, the chopper cavities 21 may be operated at half the frequency of the radio frequency energy applied to waveguide 12 whereby one gated beam pulse is produced per each cycle of waveguide excitation.

As another alternative dispensing with magnets 26, the axis of the chopper cavity system may be mechanically adjusted so as not to coincide with the axis of waveguide 12. The radio frequency deflection may then be adjusted to sweep the electron beam entering the chopper cavities to the axis of the accelerating waveguide at the peak of a cycle and transmit a gated beam pulse along the waveguide axis.

Continuing now with the description of the chopper-buncher system 17, it is to be noted that such system further includes at least one buncher cavity 27 coupled in coaxial communication with the output drift tube 22 of the last one of chopper cavities 21 to receive the gated

beam pulses transmitted therefrom. More particularly, buncher cavity 27 is preferably provided as a hollow cylindrical re-entrant cavity having appropriate dimensions or otherwise tuned to the fundamental frequency of waveguide 12. Cavity 27 includes axially aligned, longitudinally gapped drift tubes 28, 29 to facilitate the establishment of a velocity modulating electric field across the gap upon appropriate excitation of the cavity. The first drift tube 28 is coaxially aligned with the output drift tube 22 of the last chopper cavity 21 to facilitate passage of the gated electron beam pulses therefrom through buncher cavity 27.

Buncher cavity 27 is energized by a suitable source of radio frequency excitation as is preferably provided by coupling the cavity through an attenuator 31 and phase shifter 32 to the output of high power amplifier 23. The phase of the buncher cavity excitation is appropriately controlled relative to that of the operating voltage applied to chopper cavities 21 by the relative settings of phase shifters 24 and 32 to compensate for the electron drift time between the last chopper cavity 21 and buncher cavity 27. The gated electron pulses emerging from the last chopper cavity accordingly enter the buncher cavity in the same phase relative to the peak of the buncher excitation as their phase relative to the peak of the chopper deflection voltage. Moreover, buncher cavity 27 is dimensioned to operate in the TM₀₁₀ mode, i.e., a radio frequency velocity modulating electric field is established longitudinally across the gap between drift tubes 28, 29 and is accordingly alternately an accelerating or decelerating field for the electrons passing through the cavity. The electrons are velocity modulated in cavity 27 in much the same manner that the electrons in a klystron amplifier tube are modulated. Moreover inasmuch as the buncher cavity excitation is in the same phase relative to the gated electron pulses as their phase relative to the chopper cavity excitation, all of the electrons of each gated beam pulse emerging from the chopper are introduced to the velocity modulating field in the buncher with a phase spread of $\pm\Delta\theta_1$ with respect to the positive peak of such modulating field. That is, the starting phase of all electrons introduced to the velocity modulating field within buncher cavity 27 is within limits of $\pm\Delta\theta_1$.

Following buncher cavity 27 there is provided a drift tube 33 in axial communication with buncher cavity drift tube 29. Drift tube 33 in turn is coupled to waveguide 12 through coupler 16 such that the beam injection hole 19 of the waveguide coincides with the end of the drift space enclosed by the drift tube 33. The electrons modulated in buncher cavity 27 accordingly tend to be grouped into narrow bunches upon passing through drift tube 33 and arriving at waveguide injection hole 19.

In accordance with the present invention, as was previously discussed with respect to the method thereof, the length, s , of drift tube 33 and the ratio, α , of the amplitude of the modulating voltage, applied to cavity 27 from attenuator 31, to the beam voltage are adjusted relative to the angular frequency, ω , of the modulating voltage and mean electron velocity, u_0 , so as to yield a bunching parameter, r ,

$$\left(\text{where } r = \frac{s\omega\alpha}{2u_0} \right)$$

which is equal to the constant r_m . More particularly, with a given length of drift tube 33, the amplitude of the modulating voltage is adjusted by means of attenuator 31 to produce a bunching parameter r_m , which satisfies the equation:

$$\Delta\theta = \cos^{-1} \left(\frac{1}{r_m} \right) - \sqrt{r_m^2 - 1}$$

As regards the purpose of phase shifters 24, 32, it is to be appreciated that same are provided to alter the phase of the chopper deflection voltage and velocity modulating (or bunching) voltage relative to the accelerating

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wave established in waveguide 12 by the proper amounts to effect injection of the bunched electrons into the waveguide at the proper injection angle relative to the crest of the accelerating wave to produce the desired amount of acceleration. Phase shifter 32 is therefore adjusted to alter the phase of the modulating voltage by an amount that is equal to the desired injection angle, ϕ , into waveguide 12 plus the phase rotation, θ_0 , of electrons in passing through drift tube 33. Phase shifter 32 is thus adjusted to produce a phase shift of $\phi + \theta_0$. Phase shifter 24 is accordingly adjusted to produce a phase shift of the above phase angle plus an additional phase angle θ_0^1 equal and opposite to the phase rotation of electrons in passing through the drift distance between the last chopper cavity 21 and buncher cavity 27 (i.e., an overall phase angle of $\phi + \theta_0 + \theta_0^1$). The electrons consequently enter beam injection hole 19 of waveguide 12 as discrete bunches wherein the electrons are dispersed in phase within limits of $\pm \Delta\theta$ from the injection angle ϕ .

In order to optimize the rise time of the electron bunches injected into accelerating waveguide beam injection hole 19, additional gating structure may be advantageously disposed within drift tube 33 to remove fringing portions of electron bunches as they are formed in passage through the drift tube. To facilitate the foregoing a pair of axially spaced collimating orifices are preferably provided as coaxially spaced drift tubes 34, 36 mounted within drift tube 33. In addition, pairs of transversely spaced electrostatic deflection plates, 37, 38, 39, energized by sources of specially shaped voltage pulses (not shown), are respectively disposed in axial alignment between buncher cavity 27 and drift tube 34, between drift tubes 34, 36, and between drift tube 36 and coupler 16. Thus the velocity modulated electrons are swept by the electric fields established between the pairs of deflection plates across the orifices through drift tubes 34, 36 to be collimated in passage therethrough and redirected back to the axis of waveguide 12. The electron bunches entering injection hole 19 accordingly have extremely fast rise times by virtue of the focusing action of the deflection plates 37, 38, 39 and collimating drift tubes 34, 36.

Considering now novel detector means for indicating proper adjustment of chopper-buncher system 17 in accordance with the present invention, there is provided a monitoring cavity 41 which may be advantageously interposed in axial communication between the end of drift tube 33 and coupler 16 as shown in FIGURE 4. The monitoring cavity 41 consequently receives the electron bunches formed at the end of drift tube 33 and transmits same through coupler 16 to beam injection hole 19. Moreover, cavity 41 is tuned to a frequency which is predetermined as subsequently described such that when the harmonic content of the electron bunches includes a component having the predetermined frequency, a resonant standing wave electric field is established in the monitoring cavity. More particularly, it can be shown that the harmonic content of a bunched electron beam can be expressed in terms of the bunching parameter, r , employed in forming the bunches by an infinite series of n harmonics of current. That is:

$$I = I_0 \{ 1 + 2J_1(r) \sin(\omega t - 2\pi N) + 2J_2(2r) \sin 2(\omega t - 2\pi N) + \dots 2J_n[n(r)] \sin n(\omega t - 2\pi N) \}$$

where: $J_n[n(r)]$ are Bessel functions of the first kind and of order n , and, ω , is the angular frequency of the velocity modulation voltage. Accordingly, cavity 41 may be tuned to the harmonic frequency corresponding to a particular order Bessel function having a first maximum occurring for a bunching parameter of value r_m in accordance with the present invention. For example, with r_m determined to be 1.2 in order to produce electron bunches having a desired phase dispersion of $\pm \Delta\theta$, monitoring cavity 41 is tuned to the sixth harmonic of

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the modulating voltage applied to buncher cavity 27, i.e., a frequency of $6f$, or 6ω . It can be shown that the sixth order Bessel function of $6r$, i.e., $J_6(6r)$, corresponding to the sixth harmonic frequency term, has a first maximum where $6r$ is equal to 7.2, i.e., for $r=1.2$. Thus, the amplitude of the modulating voltage applied to buncher cavity 27 may be adjusted by means of attenuator 31 until maximum signal is detected in monitoring cavity 41 as by means of a suitable detector and associated indicator, e.g., a voltmeter 42, coupled thereto. The bunching parameter of the buncher cavity and associated drift tube 33 is then equal to the desired value, 1.2.

It will be appreciated that since various orders of the foregoing Bessel functions have roots (zero values) which correspond to substantially any particular value of the required bunching parameter, r_m , employed in the present invention, monitoring cavity 41 may be alternatively tuned to a harmonic having a corresponding order of Bessel function whose first root is indicative of r_m . In this case occurrence of the necessary bunching parameter, r_m , is determined by zero signal in cavity 41 as could be advantageously indicated by conventional null detecting means coupled thereto.

The operation of the chopper-buncher system 17 of the present invention generally follows from the method thereof hereinbefore described and will be best understood by consideration of the following illustrative example. Consider the case where waveguide 12 is designed to a phase velocity, $v_p = C$, i.e., $\beta_p = 1$, and has a peak acceleration, α , per wavelength in units of the electron rest energy of 6 while having a permissible injection phase angle spread, $\Delta\theta$, of $\pm 4^\circ$ at an injection energy of 250 kev. From the theory of injection into such a waveguide it can be shown that the asymptotic phase angle, ϕ_a , at which an accelerated electron will ride with respect to the crest of the accelerating wave is related to the injection phase angle, ϕ , by the expression:

$$\sin \phi_a = \sin \phi - \frac{2\pi}{\alpha} \sqrt{\frac{1 - \beta_{eo}}{1 + \beta_{eo}}}$$

where:

β_{eo} = initial electron velocity in units of the velocity of light and at the injection energy of 250 kev. is equal to 0.75.

Therefore with $\phi_a = 0$ (electron at crest of wave) in the above expression, and with the specified design parameters of waveguide 12 substituted in the expression, the corresponding injection angle, ϕ_0 , for maximum acceleration is found to be $+23.2^\circ$. In the interests of simplicity and clarity, it is herein assumed that the phase rotation of electrons in passing from the last chopper cavity 21 to buncher cavity 27, is zero whereas the net phase rotation in passing through drift tube 33 is 10° . Therefore phase shifters 24, 32 are each adjusted to $+33.2^\circ$. The velocity modulating voltage applied from power amplifier 24 to buncher cavity 27 through phase shifter 32 and attenuator 31 thus leads the driving voltage applied to accelerating waveguide 12 from power amplifier 14 by 33.2° . Similarly, the operating voltage applied from power amplifier 24 to the chopper cavities 21 through phase shifter 24 and attenuator 25 leads the drive voltage by 33.2° and is therefore in phase with the velocity modulating voltage.

It is further assumed in the present example that waveguide 12 is designed to operate at a fundamental frequency of 1300 mc., and therefore that the master oscillator frequency is similarly 1300 mc. Moreover, for the permissible acceptance phase spread of $\pm 4^\circ$ (i.e., ± 0.07 radians), the value of the constant, r_m , which in accordance with the present invention satisfies the equation:

$$\Delta\theta = .07 = \cos^{-1} \left(\frac{1}{r_m} \right) - \sqrt{r_m^2 - 1}, \text{ is: } r_m = 1.18$$

Therefore, for the above noted frequency and phase spread, chopper cavities 21 are adjusted as previously described to produce gated beam pulses having time durations, t_d , of 2.78×10^{-10} seconds, which time is determined from the equation:

$$\Delta\phi = \pi f_c t_d - r_m \sin(\pi f_c t_d)$$

Thus, electron gun 18 produces relatively long duration pulses of electrons having the requisite injection energy relative to waveguide 12 of 250 kev. Such electron pulses enter the chopper comprising the series of chopper cavities 21 and are interrupted therein as previously described to produce a series of gated beam pulses of relatively short time duration. More particularly, the chopper is effective in producing 2.78×10^{-10} second duration pulses of electrons at a repetition rate of 1300×10^6 per second for introduction to buncher cavity 27. Such time duration corresponds to an electrical angle of 130° relative to the velocity modulating voltage applied to buncher cavity 27 of like frequency 1300 mc. Inasmuch as the gated beam pulses are centered with respect to the positive peaks of the chopper operating voltage applied to the last one of cavities 21, the electrons are dispersed in phase within limits of $\pm 65^\circ$ from the positive peaks. Moreover, since the velocity modulating voltage applied to buncher cavity 27 is in phase with the chopper operating voltage applied to the last chopper cavity 21, the maximum phase spread in the starting phase of electrons relative to positive peaks of the buncher modulating voltage, is similarly $\pm 65^\circ$.

The gated beam pulses upon entering buncher cavity 27, are velocity modulated and, upon passing through drift tube 33, form discrete bunches of electrons at beam injection hole 19 of waveguide 12. In accordance with the present invention, the amplitude of the velocity modulating voltage applied to buncher cavity 27 is adjusted, by means of attenuator 31, relative to the length of drift tube 33 and the various parameters of the electron beam passing therethrough to produce a resultant bunching parameter, r , which is equal to the constant, $r_m = 1.18$. Proper adjustment is readily indicated by means of the monitoring cavity 41 and voltmeter 42 illustrated in FIGURE 4 and previously described. With cavity 41 designed to resonate at the sixth harmonic of the bunching frequency, i.e., 7800 mc., the amplitude of the modulating voltage may be adjusted by varying attenuator 31 until maximum signal is detected in the monitoring cavity by means of voltmeter 42. As was hereinbefore disclosed, maximum signal at the sixth harmonic is indicative of a bunching parameter of 1.2 which is a close approximation of the desired value of 1.18.

With the above noted bunching parameter of 1.18 employed, electron bunches are produced at beam injector hole 19 of waveguide 12 with the electrons in each bunch having arrival phases relative to their starting phases at buncher cavity 27 in accordance with the bunching curve illustrated in FIGURE 5. It is to be noted from the curve that electrons introduced to buncher cavity 27 with the phase spread of $\pm 65^\circ$ in starting phase imposed by chopper cavities 21, arrive at beam injector hole 19 of waveguide 12 as discretely formed bunches having a maximum phase dispersion of $\pm 4^\circ$ from a phase angle of 10° lagging the positive peaks of the velocity modulating voltage due to the 10° phase rotation imposed by drift tube 33. Moreover, since phase shifter 32 advances the phase of the modulating voltage by 33.2° relative to the crests of the accelerating voltage applied to waveguide 12, the phase spread of each electron bunch formed at injection hole 19 is within $\pm 4^\circ$ of the optimum injection angle, $+23.2^\circ$, for maximum acceleration in waveguide 12.

Upon entering waveguide 12, the bunched electrons are accelerated by the accelerating field established therein with the amount of initial acceleration received by the electrons depending upon their injection angles

relative to the peak of the accelerating field. At injection, electrons having the optimum injection phase, $+23.2^\circ$, are accelerated by a field strength, $\cos \phi_0$, or 0.92 of the peak field. Electrons leading the optimum injection phase angle by the maximum bunch dispersion angle, 4° , and thereby having an injection angle of 27.2° , are accelerated by a lesser field strength, 0.89 of the peak field. Similarly, electrons lagging the optimum injection angle by the maximum dispersion angle, 4° , and thereby having an injection angle of 19.2° , are accelerated by a greater field strength, 0.945 of the peak field. As the bunched electrons move along waveguide 12, they progressively approach the crest of the accelerating field and the phase spread in the electrons of each bunch tend to decrease slightly by virtue of the lagging electrons receiving greater acceleration than the leading electrons. The foregoing is illustrated graphically in FIGURE 6 wherein the variation of the asymptotic phase angle of electrons is plotted as a function of number of wavelengths along the guide. From the figure it can be seen that after only one wavelength, all of the electrons of a bunch are very close to the crest of the accelerating wave, i.e., zero asymptotic phase angle. Accordingly, thereafter essentially full acceleration of the bunched electrons is attained with very little energy dispersion in the resulting output electron beam.

While the present invention has been described with respect to a single embodiment and in terms of particular steps in the method, it will be apparent that numerous modifications and variations are possible within the spirit and scope of the invention and thus it is not intended to limit the invention except by the terms of the following claims.

What is claimed is:

1. An injector for an electron linear accelerator having a periodically loaded waveguide energized by a radio frequency energy source comprising an electron gun, an electronic chopper coupled in receiving relationship to said electron gun for producing gated electron pulses with mean electron velocity, v_0 and voltage, V_0 , at a frequency f_c equal to the frequency of said radio frequency energy source and having time durations, t_d , which satisfy the equation:

$$\Delta\theta = \pi f_c t_d - r_m \sin(\pi f_c t_d)$$

where $\Delta\theta$ is a predetermined phase angle dispersion within the optimum acceptance phase of said waveguide and r_m is a constant that satisfies the equation:

$$\Delta\theta = \cos^{-1} \left(\frac{1}{r_m} \right) - \sqrt{r_m^2 - 1}$$

a buncher cavity coupled to said chopper and receiving said gated electron pulses, a buncher drift tube having a length s coaxially coupling said buncher cavity to the beam injection hole of said waveguide, a velocity modulating voltage source coupled in energizing relationship to said buncher cavity and producing modulating voltage at the frequency, f_c , of said gated pulses and in proper phase therewith, to compensate electron drift time between the chopper and buncher cavity, the amplitude, V , of said modulating voltage adjusted to produce a bunching parameter, r , in said buncher cavity and drift tube equal to said constant, r_m , where

$$r = \frac{\pi s f_c V}{u_0 V_0}$$

and phase shift means for shifting the phase of said velocity modulating voltage relative to that of said radio frequency energy source by a phase angle of $\phi + \theta_0$, where ϕ is the optimum injection angle of said waveguide and θ_0 is the net phase rotation of an electron in passing through said drift tube.

2. An injector as defined by claim 1, further defined by said electronic chopper comprising a series of re-entrant chopper cavities, a plurality of axially aligned drift tubes

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communicably connecting said cavities and extending through the re-entrant walls thereof to project axially into the cavities in the terminal regions thereof, the first one of said drift tubes co-linearly coupled to said electron gun, the last one of said drift tubes coaxially coupled to said buncher cavity, deflection magnets respectively centrally disposed with reference to said chopper cavities with pole faces oppositely disposed transversely across the cavity axis, radio frequency energy source means coupled to each one of said cavities for exciting same in the TE010 mode at a frequency equal to that of the waveguide energizing source and with an amplitude to deflect electrons through said drift tubes once each cycle of excitation for an increment of time equal to said duration, t_d , and phase shift means connected to said radio frequency energy source means for shifting the phase of the excitation energy applied to said chopper cavities, by a phase angle of $\phi + \theta_0 + \theta_0'$, relative to that of said radio frequency energy source, where θ_0' is the phase rotation of electrons in passing from the last one of said chopper cavities to said buncher cavity.

3. An injector as defined in claim 1 but wherein a pair of coaxially spaced collimating drift tubes are disposed within said bunching drift tube and pairs of transversely spaced electrostatic deflection plates are disposed in axial alignment between said pair of collimating drift tubes and between said buncher cavity and the first collimating drift tube as well as between the last collimating drift tube and said waveguide.

4. An injector as defined in claim 1 further comprising a monitoring cavity communicably connected between said buncher drift tube and said waveguide, said cavity tuned to a harmonic of the velocity modulating frequency for which the corresponding order Bessel function has a first maximum occurring for a value which is equal to the constant, r_m , times the order of the Bessel function, and detector and indicating means coupled to said monitoring cavity for detecting maximum signal therein whereby the amplitude of said velocity modulating voltage may be adjusted until said detector and indicating means indicates resonance in said monitoring cavity at which time the bunching parameter of said buncher cavity and bunching drift tube is equal to said constant, r_m .

5. In a chopper-buncher system for producing a bunched electron beam wherein the phase dispersion of the bunches is at most $\pm\Delta\theta$ from a mean phase θ_m , the combination comprising a pulsed electron gun, at least one re-entrant chopper cavity having axially aligned drift tubes extending through the re-entrant walls thereof and projecting into the cavity interior in the terminal regions thereof, one of said drift tubes co-linearly coupled in receiving relationship to said electron gun, a C-shaped deflection magnet disposed centrally about said chopper cavity with the pole faces thereof oppositely disposed transversely across the cavity axis, a radio frequency energy source coupled to said chopper cavity to excite same in the TE010 mode at a frequency, f_c , and with an amplitude to deflect electrons through the output one of said drift tubes once each cycle of the excitation energy for an increment of time, t_d , which satisfies the equation:

$$\Delta\theta = \pi f_c t_d - r_m \sin(\pi f_c t_d)$$

where r_m is a constant that in turn satisfies the equation:

$$\Delta\theta = \cos^{-1} \left(\frac{1}{r_m} \right) - \sqrt{r_m^2 - 1}$$

and with a mean electron velocity, u_0 , and voltage, V_0 , a buncher cavity having axially spaced re-entrant drift tubes, the input one of said buncher drift tubes coaxially connected to the output one of said chopper cavity drift tubes, a bunching drift tube having a length, s , connected in axial communication with the output one of said buncher cavity drift tubes, a pair of axially spaced collimating drift tubes disposed within said bunching drift tube in coaxial relationship therewith, pairs of transversely spaced

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electrostatic deflection plates disposed in axial alignment respectively between said pair of collimating drift tubes and preceding and following same for establishing transverse electrostatic deflection fields which are alternately of opposite polarity, and means coupling said radio frequency energy source to said buncher cavity for exciting same in the TM010 mode and with an amplitude, V , to produce a bunching parameter r in said buncher cavity and bunching drift tube which is equal to said constant, r_m , where

$$r = \frac{\pi s f_c V}{u_0 V_0}$$

6. An electron linear accelerator comprising a periodically loaded waveguide, a master oscillator for producing radio frequency energy at a frequency, f_c , a high power amplifier coupler to said master oscillator, a driving waveguide coupling the output of said amplifier to the input end of said loaded waveguide for establishing an electron accelerating wave therein, a buncher cavity having axially spaced re-entrant input and exit drift tubes therein, a bunching drift tube coaxially coupling the exit drift tube of said buncher cavity to the input end of said waveguide, a second high power amplifier coupled to said master oscillator, a phase shifter coupled to the output of said second amplifier and adjusted to produce a phase shift of $\phi + \theta_0$ where ϕ is a predetermined injection angle into said loaded waveguide and θ_0 is the phase rotation of an electron passing through said bunching drift tube, an attenuator coupled between said phase shifter and said buncher cavity to excite same in the TM010 mode, said attenuator adjusted to produce a bunching parameter, r_m , in said buncher cavity and bunching drift tube that satisfies the equation:

$$\Delta\theta = \cos^{-1} \left(\frac{1}{r_m} \right) - \sqrt{r_m^2 - 1}$$

where $\Delta\theta$ is a predetermined phase angle dispersion limit and the bunching parameter is defined by the expression:

$$r_m = \frac{\pi s f_c \alpha}{u_0}$$

s being the length of said bunching drift tube, α being the ratio of bunching voltage applied to said buncher cavity from said attenuator to the voltage of an electron beam transmitted through the buncher cavity, and u_0 being the mean electron velocity of electron velocity of electrons transmitted through the buncher cavity, at least one re-entrant chopper cavity having axially aligned inlet and exit drift tubes extending through the re-entrant walls thereof and projecting interiorly of the cavity in the terminal regions thereof, said chopper cavity exit drift tube coaxially coupled to the input drift tube of said buncher cavity, magnetic field generating means disposed centrally of said chopper cavity for establishing a continuous magnetic deflection field transversely across the central region thereof, a second phase shifter coupled to the output of said second amplifier and adjusted to produce a phase shift of $\phi + \theta_0 + \theta_0'$ where θ_0' is the phase rotation of an electron in passing between said chopper cavity and said buncher cavity, a second attenuator coupling said second phase shifter to said chopper cavity and exciting same in the TM010 mode, said attenuator adjusted to deflect electrons through the exit drift tube of said chopper cavity for increments of time, t_d , that satisfy the equation:

$$\Delta\theta = \pi f_c t_d - r_m \sin(\pi f_c t_d)$$

and an electron gun coaxially coupled to the inlet drift tube of said chopper cavity for injecting electrons thereinto.

7. A linear accelerator as defined by claim 6, further defined by a monitoring cavity coaxially interposed between said bunching drift tube and said periodically

loaded waveguide, said cavity tuned to a harmonic of the fundamental frequency, f_c , of said master oscillator for which the corresponding order Bessel function has a first maximum occurring for a value which is equal to the bunching parameter value, r_m , times the order of the Bessel function, and a voltmeter coupled to said monitoring cavity whereby said first attenuator may be adjusted to vary the amplitude of the buncher cavity excitation until maximum signal is detected in said monitoring cavity by said voltmeter at which time the bunching parameter of said buncher cavity and bunching drift tube is equal to r_m .

8. Apparatus for producing a bunched electron beam having bunch phase dispersion limits of $\pm\Delta\theta$ comprising a source of electrons, at least one dual deflection re-entrant chopper cavity, an input drift tube coaxially coupling said source to said cavity and extending axially into said cavity in a terminal region thereof, radio frequency field generating means coupled to said cavity for producing an alternating electric deflection field transverse to the cavity axis to cyclicly deflect electrons transverse thereto at a repetition rate, f_c , an output drift tube extending coaxially into said cavity in the terminal region thereof opposite from said input drift tube, said output drift tube having a bore diameter commensurate with a cyclic alignment of the deflected electrons with the output drift tube bore for a time duration, t_d , to thereby produce at the outlet end thereof gated electron pulses at the repetition rate, f_c , and with time durations, t_d , said repetition rate, f_c , and time duration, t_d , selected to satisfy the equation:

$$\Delta\theta = \pi f_c t_d - r_m \sin(\pi f_c t_d)$$

where, r_m , is a constant that satisfies the equation:

$$\Delta\theta = \cos^{-1} \left(\frac{1}{r_m} \right) - \sqrt{r_m^2 - 1}$$

and velocity modulation bunching means coaxially cou-

pled to said output drift tube in receiving relation to the gated electron pulses therefrom, said bunching means operative at frequency commensurate with said repetition rate, f_c , and in phase with said electron pulses while being adjusted to a bunching parameter equal to said constant, r_m .

9. Apparatus for producing a bunched electron beam having bunch phase dispersion limits of $\pm\Delta\theta$ comprising means for producing gated electron pulses at a repetition rate, f_c , and having time durations, t_d , which satisfy the equation:

$$\Delta\theta = \pi f_c t_d - r_m \sin(\pi f_c t_d)$$

where r_m is a constant that satisfies the equation:

$$\Delta\theta = \cos^{-1} \left(\frac{1}{r_m} \right) - \sqrt{r_m^2 - 1}$$

a re-entrant buncher cavity disposed in receiving relation to said last named means, a radio frequency energy source coupled to said cavity for establishing an electron velocity modulating electric field therein at a frequency commensurate with the repetition rate, f_c , of said pulses and in phase therewith, and a drift tube connected in coaxial communication with said buncher cavity to form electron bunches from velocity modulated electrons in passage through the drift tube, the length of said drift tube and amplitude of said velocity modulating electric field adjusted to produce a bunching parameter equal to r_m .

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