Nov. 13, 1956 M. L. GOOD **2,770,755**

LINEAR ACCELERATOR

Filed Feb. 5, 1954

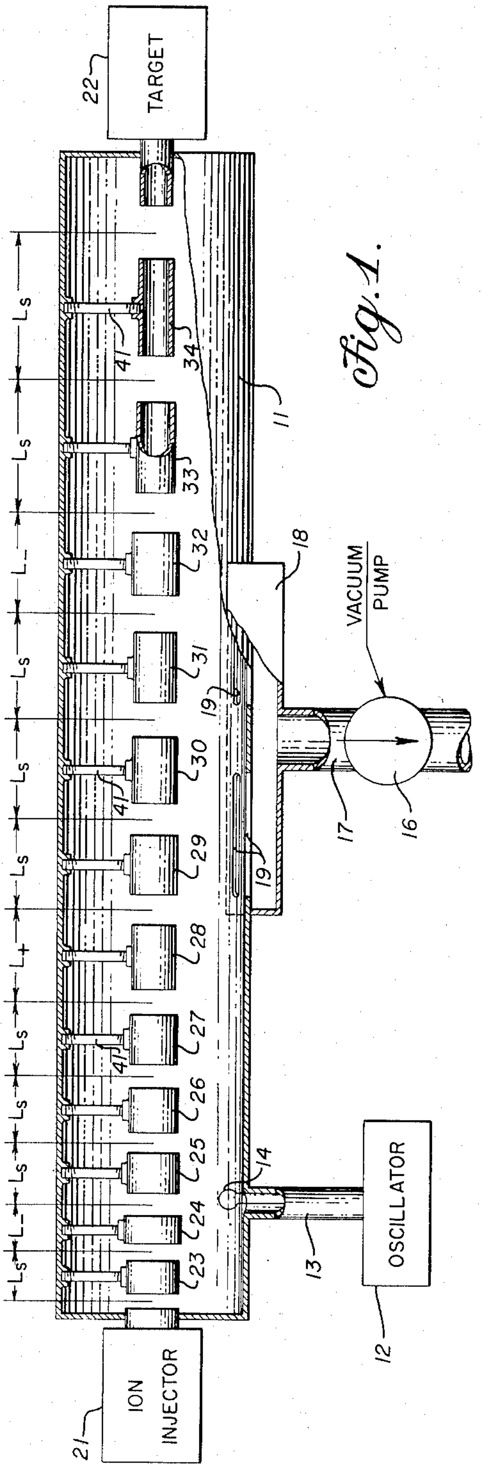

Fig. 1.

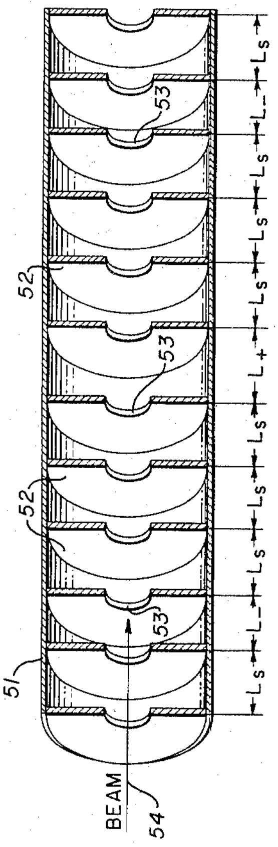

Fig. 3.

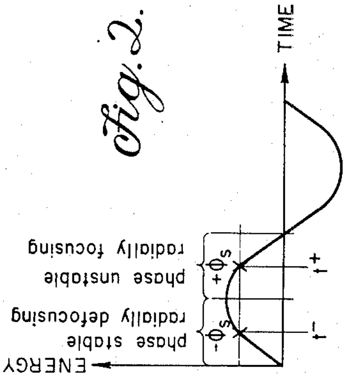

Fig. 2.

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LINEAR ACCELERATOR

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4 Claims. (Cl. 315—5)

The present invention relates to improvements in linear accelerators and more particularly to a method and apparatus for particle focusing in a linear accelerator.

It is well known that in a conventional linear ion accelerator, as disclosed in United States Patent 2,545,595, issued March 20, 1951, to L. W. Alvarez, without grids or foils disposed in the ion beam, phase stability and radial focusing cannot be achieved simultaneously. The reason for such incompatibility between phase stability and radial focusing is that a particle which crosses the center of an accelerating gap before the radio-frequency peak is phase stable (had the particle arrived later, the energy gain would have been greater so that the particle would tend to arrive earlier at the following gap), but is subject to radial defocusing because of the increasing and diverging electric field present in the latter portion of the gap. The same type of reasoning illustrates that a particle which crosses the center of an accelerating gap after the radio-frequency peak is radially focused, but phase unstable. If either phase stability or radial focusing is lacking, the output of the accelerator is limited in energy or current value, respectively.

As indicated above, and more particularly in the referenced patent, foils or grids may be disposed across the entrance opening of the drift tubes in the path of the beam to distort the electric field and achieve radial focusing during phase stable operation. It will be apparent that such expedients used to achieve radial focusing attenuate the beam of particles and also introduce mechanical difficulties due to the mounting problems and to the handling of extremely thin sheets of metal.

The present invention overcomes the aforementioned difficulties and permits the accomplishment of phase stability and radial focusing without the necessity of foils or grids by properly spacing the drift tubes so that the particle beam encounters alternate conditions of radial focusing and radial defocusing. The final result of the proper spacing of the drift tubes is to achieve an output of higher current value and higher attained energy.

It is therefore an object of the present invention to provide a new and improved linear accelerator for charged particles.

Another object of the present invention is to provide a method of achieving radial focusing in a linear accelerator.

Still another object of the present invention is to provide a linear accelerator having drift tubes spaced apart along the path of the particle beam to achieve radial focusing.

A further object of the invention is to provide a linear accelerator arranged to alternately focus and defocus accelerated particles to achieve greater and more efficient focusing.

Other objects and advantages will be apparent in the following description and claims considered together with the accompanying drawing, in which:

Figure 1 is a schematic and cross-sectional view of a linear accelerator constructed in accordance with the present invention;

Figure 2 is a diagram showing the energy gain of a particle in crossing an accelerating gap of the accelerator of Fig. 1 as a function of the time of crossing mid-gap; and

Figure 3 is a cross-sectional view of a loaded waveguide type of linear accelerator utilizing the focusing method of the present invention.

Referring to the drawing in detail, Fig. 1 in particular, there is provided an elongated cylindrical and air-tight tank **11**. A conventional high power electronic oscillator **12** is coupled to the tank **11** by a section of coaxial cable **13** and a coupling loop **14**. The dimensions of the tank **11**, the frequency of the oscillator **12**, and the mode of coupling are suitably correlated to excite the tank in the TM 010 mode of resonance. To lower the internal pressure of the tank **11** for optimum operation a vacuum pump **16** is connected by a pipe **17** to a manifold **18** which is suitably mounted about a plurality of elongated communicating slots **19** in the wall of the tank.

Disposed at one end of the tank **11** is an ion injector **21** of conventional design for introducing a beam of charged particles into the tank, substantially along the center line thereof. Conventional target apparatus **22** is mounted at the other end of the tank **11** to receive the beam of charged particles. A plurality of hollow cylindrical drift tubes **23—34** are disposed in alignment along the center line of the tank **11** in spaced-apart relation to surround the beam of charged particles during selected portions of the distance from the injector **21** to the target **22**. To maintain the drift tubes **23—34** in proper position, each is suitably mounted by an arm **41** extended from the wall of the tank **11**.

In general, according to conventional design criteria for linear accelerators, successive drift tubes decrease in diameter and increase in length from the injector **21** to the target **22** while the gaps between adjacent drift tubes remain substantially constant. Such decrease in diameter of the drift tubes is necessary to preserve the electrical characteristics of the resonant cavity formed by the tank **11**. The aforementioned gradation of drift tube lengths may be readily calculated from the formula:

$$L_s=\frac{V}{C}\lambda$$

where

L_s=distance between centers of successive gaps between adjacent drift tubes (synchronous length)
V=velocity of charged particles
C=velocity of light
λ=wavelength of the applied radio-frequency voltage

From such formula is will be noted that the distance, L_s, is directly proportional to the velocity, V, of the charged particles so that the distance, L_s, at the injector **21** end of the tank **11** will be less than that at the target **22** end.

Referring again to the conventional design criteria for a linear accelerator, it is to be noted that two synchronous phase angles $(-|\phi_s|, +|\phi_s|)$ exist for charged particles in passing an accelerating gap (see Fig. 2). By synchronous phase angle, ϕ_s, is meant the electrical degrees of the sinusoidal radio-frequency accelerating voltage between the peak value and the value necessary to accelerate a particle to arrive at the next gap exactly one radio-frequency voltage cycle later. One such phase angle, $-|\phi_s|$, occurs during the increasing positive portion of the accelerating voltage and the other, $+|\phi_s|$, at the identical value during the decreasing portion of the voltage (the times of the phase angles occurrence are labeled $t-$ and $t+$, respectively, on Fig. 2). Particles which enter an acceleration gap during the increasing portion of the applied acceleration voltage, but at other than the synchronous phase angle, are acted upon by forces tending to return the particle to the synchronous phase angle and so such portion of the voltage is phase stable. Conversely, particles which enter a gap during the decreasing portion of the voltage, but at other than the synchronous phase angle, are acted upon by forces tending to increase the out of phase condition and so such portion of the voltage is phase unstable. Now, as stated previously, phase stability and radial focusing are incompatible in the conventional linear accelerator without the addition of some type of focusing device. Thus when such an accelerator is operated in the region of phase stability, radial defocusing occurs and when operated in the phase unstable region, radial focusing occurs.

In the past linear accelerators of the type described have been operated in the phase stable region, $-|\phi_s|$, and foils or grids have been utilized in the path of the beam of particles to achieve radial focusing. In the presently described linear accelerator charged particles are injected from the injector **21** so as to cross the center of the first acceleration gap (between the injector and the first drift tube **23**) substantially at the synchronous phase angle, $+|\phi_s|$, occurring during the decreasing portion of the voltage cycle. The particles are thus accelerated with radial focusing and phase instability. The length of the first drift tube **23** is established so that the distance, L_s, between the first and second acceleration gaps conforms to the previously noted formula for synchronous length. In accordance with the present invention, it is desired to have the particles reach the third gap at the time of the other synchronous phase angle, $-|\phi_s|$, and to accomplish such result a lesser distance, L—, is provided. The distance, L—, may be readily calculated from the formula:

$$L-=L_s\left(1-\frac{|\phi_s|}{\pi}\right)$$

The length of the second drift tube **24** will be, accordingly, less than the normal synchronous length (see Fig. 1) and thus particles will be accelerated to arrive at the third gap earlier in the time of the voltage cycle.

The following three gaps again conform to the formula for synchronous length, L_s, to assure phase stability and radial defocusing. Next, it is desired to switch back to the first mode of acceleration; i. e., where the particles are accelerated with phase instability and radial focusing. To achieve such switch it is necessary to delay the time of arrival of the particles at the next gap to the time corresponding to the second synchronous phase angle, $+|\phi_s|$. A longer than normal drift tube **28** is introduced as the sixth of the drift tubes **23**—**34** and the length thereof may be readily correlated to the solution of the formula:

$$L+=L_s\left(1+\frac{|\phi_s|}{\pi}\right)$$

The following three gaps are established to conform to the synchronous length, L_s, to continue acceleration of the particles with phase instability and radial focusing. Next it is desired to switch to the opposite synchronous phase angle, $-|\phi_s|$ and, to do so, a distance less than the synchronous length is provided between the successive gaps. The length of the drift tube **32** is established accordingly. The particles are then further accelerated in the resulting condition of phase stability and radial defocusing through two gaps which are spaced-apart by the appropriate synchronous length, L_s, to the target **22**.

From the foregoing it will be noted that particles from the injector **21** are accelerated alternately from a condition of phase instability and radial focusing to one of phase stability and radial defocusing. Such acceleration results in overall phase stability and radial focusing of the beam and such fact may be readily proven mathematically in a manner analogous to that for "strong focusing" in the synchrotron type of particle accelerator.

In the conventional linear accelerator using grids or foils for radial focusing the beam oscillates about the synchronous phase angle in a periodic manner during the transit time from the injector **21** to the target **22**. For optimum beam stability in the above-described linear accelerator using phase reversal, the reversal of ϕ_s should occur at a separation equal to one-quarter of the period of phase oscillation of the beam in a comparable conventional accelerator. In practice, it has been found that a close approximation to the optimum arrangement can be achieved by spacing the reversals every few drift tubes, the number of which becomes greater as the energy of the particles increases. The illustration of Fig. 1 shows twelve (12) drift tubes **23**—**34** and it is desired to point out that the invention is not limited to such number of drift tubes because linear accelerators having more or less numbers of drift tubes are completely operable to achieve the desired acceleration.

Now consider the operation of a linear accelerator such as described above and illustrated in Fig. 1. With the pressure of the tank **11** suitably established by means of the vacuum pump **16** and a suitable electric field (TM 010) established by means of the oscillator **12**, the injector **21** is energized to introduce pulses of charged particles axially of the tank at an initial predetermined value of velocity. Such predetermined value of velocity is set so that the particles arrive at the center of the gap between the injector **21** and the first drift tube **23** substantially at the time, $t+$ (see Fig. 2), when the electric field has a value equivalent to the synchronous phase angle, $+|\phi_s|$. The drift tubes **23**—**34** provide lengths along the path of the particles which are free of electric fields and so the only influence of the fields upon the particles occurs in the gaps between the drift tubes. Thus particles are accelerated by the first gap with phase instability but with radial focusing through the first drift tube **23** to the second gap.

The particles then arrive at the second gap at substantially the same synchronous phase angle, $+|\phi_s|$, because the distance between the centers of the first and second gaps is the synchronous length, L_s. The distance between the second and third gaps is less than the synchronous length by an amount calculated to assure that the particles arrive at the third gap substantially at the time, $t-$ (see Fig. 2), corresponding to the other synchronous phase angle, $-|\phi_s|$. The successive distances to the fourth, fifth, and sixth gaps are in accordance with the synchronous lengths, L_s, so that the particles are accelerated with phase stability and radial defocusing. To switch back to acceleration with phase instability and radial focusing, the distance between the sixth and seventh gaps is increased according to the aforementioned formula for L+ and particles will arrive at the latter gap at the time, $t+$, corresponding to the first referenced synchronous phase angle, $+|\phi_s|$.

Again, the distance between the seventh, eighth, ninth, and tenth gaps is established to conform to the synchronous length, L_s, and particles are successively accelerated with phase instability and radial focusing. To further increase the overall phase stability and radial focusing which results from the phase alterations another phase reversal is arranged by the insertion of a distance less than the synchronous length, L—, between the tenth and eleventh gaps. Particles then arrive at the eleventh gap at the time, $t-$, during the waveform of the voltage across the gap when the other synchronous phase angle, $-|\phi_s|$, occurs. The net result is to accelerate the particles successively to the twelfth, thirteenth, and finally to the target **22** with optimum phase stability and radial focusing.

It has been found that the output beam energy and strength of a linear accelerator utilizing phase reversal is greater than can be achieved in a conventional type of linear accelerator with focusing grids or foils. The reasons for such improvement are the avoidance of beam attenuation attendant with focusing grids or foils and greater strength of focusing.

An electrically loaded wave guide type of linear accelerator (see Fig. 3) may be readily constructed wherein phase reversal focusing, as set forth in the foregoing, is utilized. A tank **51**, similar to the tank **11**, is suitably excited by an oscillator (not shown) in an axial-electric mode so that the distance between nodes is equal to substantially a half wave length of the frequency of the oscillator. Diaphragms **52** having centrally disposed apertures **53** are mounted transversely of the axis of the tank at the nodes in the conventional accelerator. The considerations, which have been described in the foregoing, concerning acceleration of charged particles also apply in the presently described accelerator. Thus the spacing between the second and third diaphragms is established to be less than the calculated synchronous length and the formula for L— is applicable. The spacing between the sixth and seventh diaphragms is increased over the value for the synchronous length and the formula for L+ applies. Also the spacing between the tenth and eleventh diaphragms is altered to the calculated value for L—.

With the spacing as indicated above, a beam of charged particles is introduced axially into the tank **51**, as indicated by the arrow **54**, to reach the center of the space between the first and second diaphragms at the time, $t+$ (see Fig. 2), corresponding to the synchronous phase angle, $+|\phi_s|$. The particles are then accelerated into the space between the second and third diaphragms where the voltage cycle will have reached the time, $t-$, corresponding to the other synchronous phase angle, $-|\phi_s|$. A reversal of phase angles occurs again between the sixth and seventh diaphragms and also between the tenth and eleventh diaphragms. The particles in the period of acceleration alternate between a condition of phase instability and radial focusing and a condition of phase stability and radial defocusing. The result is the same as previously stated; i. e., higher energy and higher current in the output beam.

While the salient features of the present invention have been described in detail with respect to two embodiments, it will be apparent that numerous modifications may be made within the spirit and scope of the invention, and it is therefore not desired to limit the invention to the exact details shown except insofar as they may be defined in the following claims.

What is claimed is:

1. In a linear accelerator for charged particles, the combination comprising an elongated air-tight tank, evacuating means associated with said tank, a plurality of drift tubes disposed axially in spaced apart relation in said tank, a sinusoidal radio-frequency oscillator coupled to said tank for producing an axial electric field, injector means disposed at one end of said tank for projecting ions in a beam along the axis thereof during the decreasing portion of the excitation cycle of said oscillator to provide a radially focused beam, the length of said drift tubes along the path of said ion proportional to a synchronous length which is proportional to the velocity of said ions with selected drift tubes proportionately and alternately lesser and greater than said synchronous length in such order to provide alternate radial focusing and defocusing forces upon said ions as accelerated, and a target disposed at the other end of said tank to receive said ions.

2. In a linear accelerator for charged particles, the combination comprising an elongated air-tight tank, evacuating means associated with said tank, a sinusoidal radiofrequency oscillator coupled to said tank for establishing an axial electric field, means for axially injecting charged particles into said tank, and a plurality of drift tubes having a dimension along the path of said particles proportional to a synchronous length which is proportional to the velocity of said particles and relatively spaced apart to provide exposure of said particles to said axial electric field, selected ones of said drift tubes dimensioned proportionately lesser than said synchronous length by a synchronous phase angle factor, and additional selected ones of said drift tubes dimensioned proportionately longer than said synchronous length by said synchronous phase angle factor, said selected drift tubes of lesser length alternated with said additional selected drift tubes of longer length along the path of said particles whereby alternate radial focusing and defocusing of said particles occurs during acceleration to achieve both phase stability and overall radial focusing of said particles.

3. In a linear accelerator for charged particles, the combination comprising an elongated air-tight tank, evacuating means connected to said tank, a radiofrequency oscillator coupled to said tank to provide an axially extended electric field, an ion injector mounted centrally at one end of said tank to axially project a beam of ions through said tank, a target mounted centrally at the other end of said tank to receive said beam of ions, and a series of drift tubes mounted coaxially in spaced-apart relation within said tank between said injector and said target to provide a plurality of gaps along the path of said beam, said drift tubes having a dimension along the path of said beam proportional to a synchronous length at the velocity of said beam of ions with selected drift tubes having a similar proportional dimension less than said synchronous length by a synchronous phase angle factor and other selected drift tubes having a similar proportional dimension greater than said synchronous length by said synchronous phase angle factor interspersed.

4. In a linear accelerator for charged particles, the combination comprising a wave guide, evacuating means connected to said wave guide, a radiofrequency oscillator coupled to said wave guide to provide an axial-electric mode of excitation, an ion injector mounted centrally at one end of said wave guide to axially project a beam of ions through said wave guide, a target mounted centrally at the other end of said wave guide to receive said beam of ions, and a series of centrally apertured conductive diaphragms mounted transversely within said wave guide, said diaphragms spaced apart a distance proportional to a synchronous length at the velocity of said beam of ions with selected diaphragms spaced a distance less than said synchronous length and other selected diaphragms spaced a distance greater than said synchronous length.

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