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METHOD AND APPARATUS FOR PHASING A LINEAR ACCELERATOR

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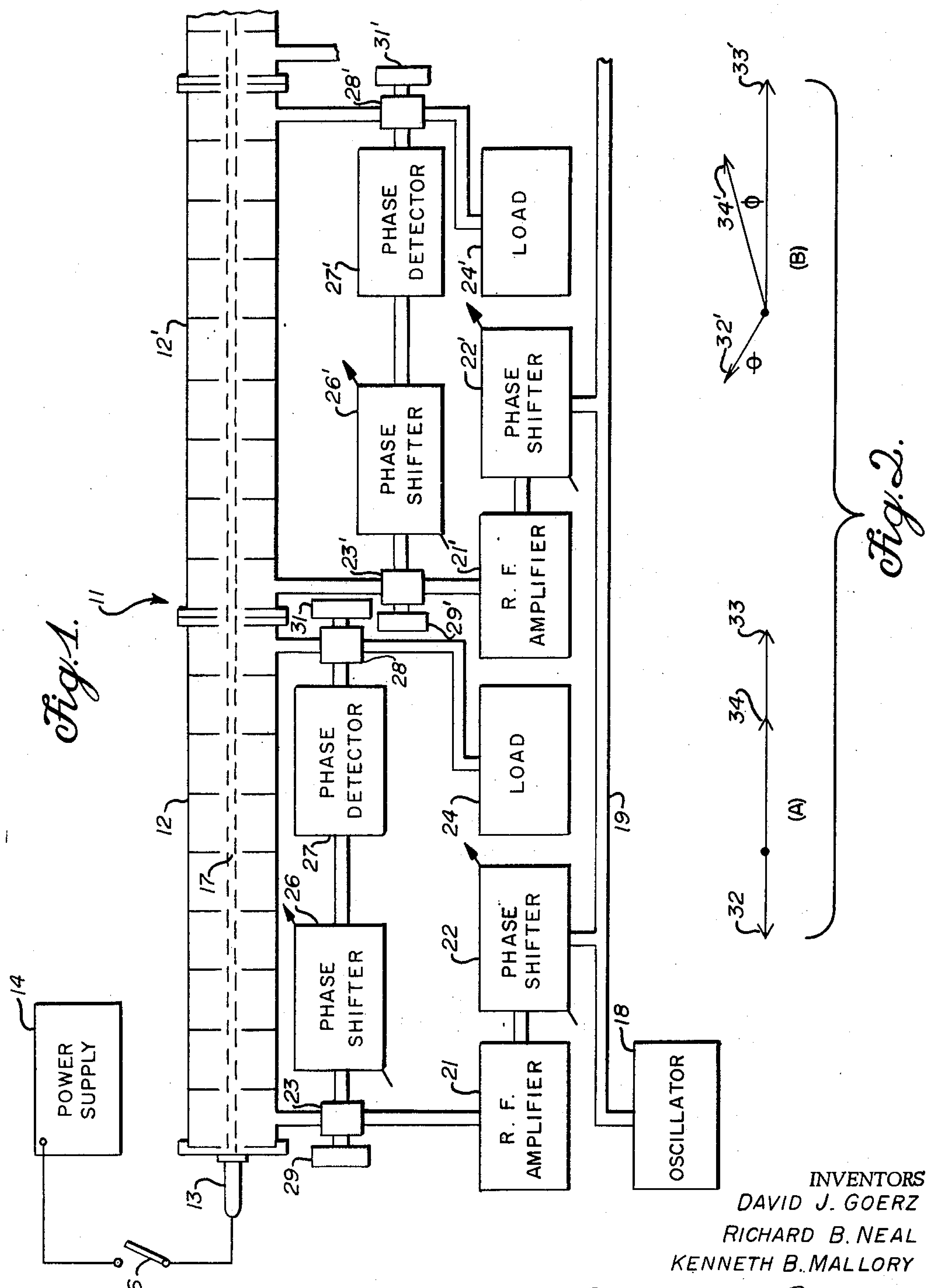

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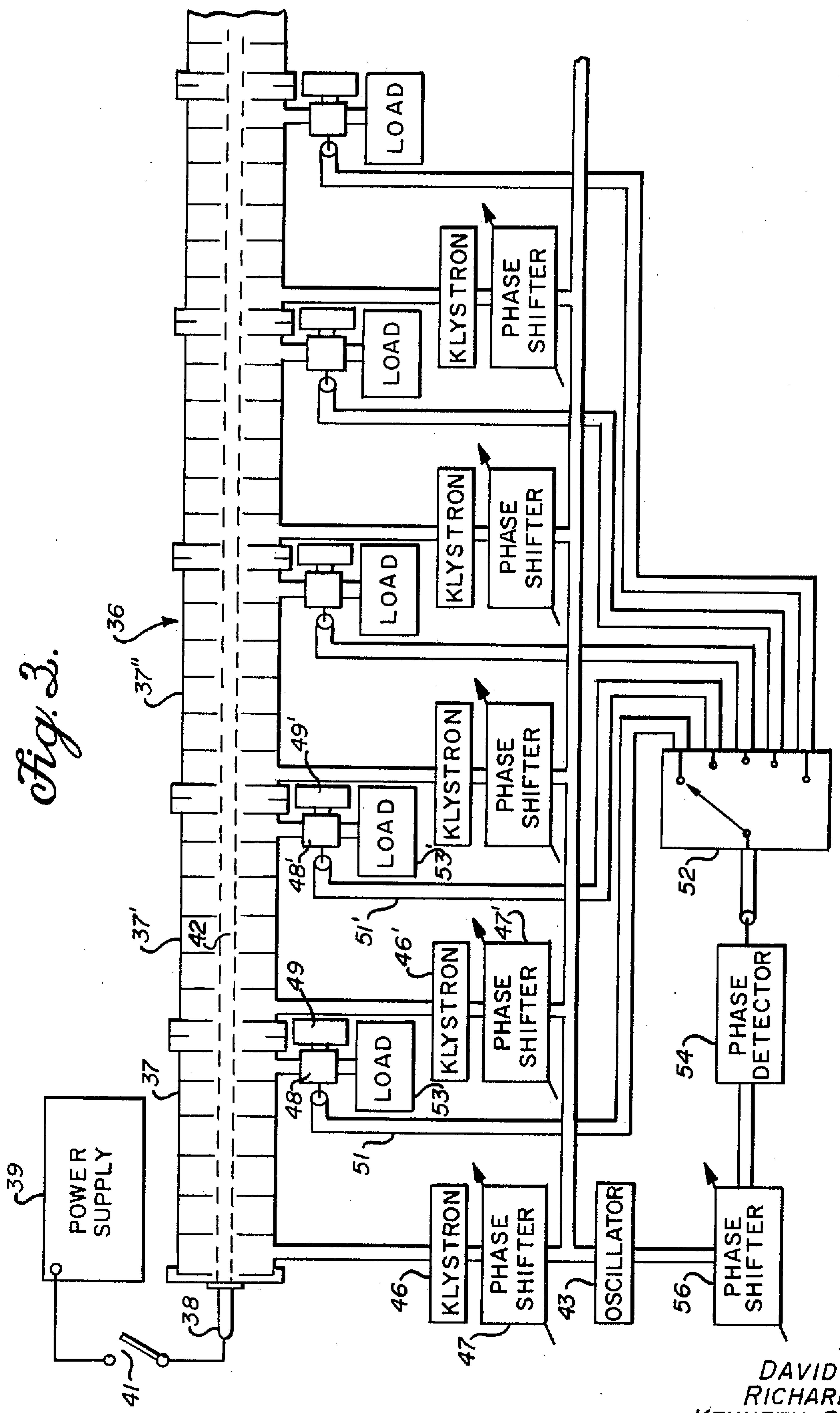

Fig. 3.

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METHOD AND APPARATUS FOR PHASING A LINEAR ACCELERATOR

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The present invention relates generally to a method and apparatus for phasing a linear accelerator. In particular, the invention relates to a linear accelerator which uses a traveling electromagnetic wave to accelerate a beam of electrons wherein the phasing operation is accomplished by using phase comparison techniques to optimize the phase relationship between the beam and the traveling wave.

In general, a traveling wave linear electron accelerator is composed of a plurality of separate loaded waveguide sections disposed end to end along the longitudinal axis of the accelerator. Each section is coupled to a source of microwave power whereby a traveling electromagnetic wave is created in each section. The accelerator structure is designed to have the phase velocity of this wave travel at about the velocity of light so that a beam of electrons injected into the accelerator can be made to "ride" along with the traveling wave. In this manner a very high energy electron beam can be created. Such high energy beams have widespread utility in the field of nuclear research as well as an increasing use for internal medical treatment on human beings. As the theory and design of linear accelerators are well known to those skilled in the art, little mention is made hereinafter regarding the details of construction or principles of operation of a linear accelerator.

A beam of charged particles moving with a traveling electromagnetic wave receives maximum power from the wave when the "bunches" of electrons which comprise the beam are positioned coincident in space with the crest of the traveling wave. As the electron beam travels through the successive sections it receives energy from the traveling wave of each section. Now, in order for the beam to obtain a maximum energy upon reaching the output end of the accelerator the beam must be in optimum phase relationship with the traveling wave of each individual section.

More specifically, the power input to each section must be phased to create a peak magnitude at the point where an electron bunch enters into the section at the particular instant when the bunch enters into the section. If these conditions are met then the beam travels through the section positioned at the crest of the traveling wave. When the phase of the input power is incorrect the electron bunch does not ride the wave crest and hence receives less than maximum energy. Therefore, the problem at hand is to couple radiofrequency power into all the accelerator sections with the proper phase relationships to achieve maximum energy transfer to the electron beam.

Present methods being used to phase existing linear traveling wave accelerators comprise, in general, varying the phase of each of the separate power inputs while observing the output energy of the electron beam. More particularly, the electron beam is turned on and microwave power is coupled into the first accelerator section only. The phase of the input to the first section is adjusted until a maximum beam energy is observed at the terminal end of the accelerator. It may be noted that beam energy is generally measured by magnetic deflection techniques. The second section is then energized and the same adjusting procedure is repeated. This process is continued until each section is tuned thereby giving a substantially maximum electron beam energy. It should be noted that throughout the specification the term "first section" referred to is meant to be the first section which must be phased, i.e., if a buncher is not used with the electron gun, the first section in line after the gun acts as a buncher and it is actually the second section in line which is the first section to be phased.

The relatively simple conventional phasing methods of the foregoing type have been found to be adequate for existing accelerators. However, the problem of phasing a very long accelerator, for example, one two miles long having 1000 individual power inputs, is more complicated than that of phasing a relatively short accelerator, e.g., the 220 foot long Stanford Mark III accelerator having only twenty-one power inputs described in the Review of Scientific Instruments, vol. 26, No. 2, February 1955, pp. 134–204.

The conventional phasing method of maximizing the beam energy by separately adjusting each power input is not adaptable to a very long accelerator because of two prime deficiencies. First, when the initial sections are being adjusted, the electron beam does not receive enough energy to be transmitted to the end of the accelerator. This shortcoming could conceivably be solved by trial and error means of just getting a beam started through the accelerator and maximizing the energy afterwards. Such a scheme, however, is very time consuming and especially difficult with a long accelerator. The most serious drawback, however, of the conventional method is caused by the large number of power inputs necessary for a very long accelerator. It is extremely difficult to perceive any variation of beam energy at the accelerator output while varying the phase of one power input when a great many other sections are also energized. Because in this situation beam energy variations are extremely small, the conventionad method has a very low sensitivity when applied to a long accelerator and hence the phasing operation would be a tedious and time consuming job.

The present invention is a particularly useful scheme for phasing very long accelerators, but nevertheless its nature is such that it can be readily used with advantages to phase an accelerator of any length. Rather than employ beam energy observations, the invention utilizes the phase relation of the electromagnetic energy at different points in each accelerator section. Whereas minute beam energy variations are difficult to measure, there do exist phase comparison means which can quite accurately determine the relative phase of wave energy throughout the accelerator.

Briefly, the principle of the invention is to observe a phase shift of the resultant traveling wave in an accelerator section when the electron beam is turned on, as compared to the traveling wave in the section with the beam off. This phase shift occurs only when the electron beam is not optimally phased with the traveling wave, hence the degree of phase shift is used as a measure of the degree to which the beam and traveling wave are out of phase.

In addition to its particular usefulness with a long accelerator, the present invention has the advantage of exhibiting a higher sensitivity than conventional methods used with relatively short accelerators. This allows the phasing operation to be performed to within virtually any degree of accuracy which may be practically required.

One very important improvement of the invention over conventional phasing schemes is the short time in which the phasing operation may be completed. For example, when using a conventional phasing method it takes about eight hours to properly tune the Stanford Mark III accelerator which is 220 feet long. Using the present invention it would take only 25 minutes to correctly phase an accelerator which is two miles long.

Another advantage of the present invention is that it does not detract from the useful length of the accelerator. Rather than insert beam energy measuring means between accelerator sections it is necessary only to insert a phase shifting and detecting circuit between the input and output coupling circuits of each section externally thereto.

Accordingly, it is the main object of the present invention to provide a method and apparatus for optimumly phasing the power inputs to the sections of a linear traveling wave accelerator.

Another object of the invention is to provide a phasing method and apparatus which are particularly suitable for very long linear accelerators.

It is a further object of the present invention to provide a phasing means and method having a high sensitivity characteristic affording extremely accurate maximizing of the electron beam energy.

A still further object is to provide a phasing apparatus and method which does not detract from the useful length of a linear accelerator.

An even further object is to provide a method and apparatus which very quickly completes the operation of phasing a linear accelerator.

The invention, both as to its apparatus and method, together with further objects and advantages thereof will be better understood by reference to the following specification taken in conjunction with the accompanying drawing, of which:

FIGURE 1 is a schematic diagram depicting generally an arrangement of apparatus as employed in a multi-section traveling wave accelerator to phase same in accordance with the present invention;

FIGURE 2 depicts various vector representations of the electromagnetic fields present in a linear accelerator at various phase relationships relative to each other, portion (*a*) being indicative of an optimum phase relation between the electron bunch and traveling wave, and portion (*b*) being indicative of an out of phase relationship between the bunch and wave; and

FIGURE 3 is a schematic diagram of a preferred embodiment of the apparatus of the invention having particular application with a very long accelerator.

Referring now to the drawings, there is shown a traveling wave linear accelerator **11** of generally conventional construction. Accelerator **11** comprises a plurality of loaded waveguide structures referred to as accelerator sections, several of such sections being depicted as **12** and **12'**. The plurality of accelerator sections are disposed coaxially end to end along the longitudinal axis of accelerator **11**. An electron gun **13** is coaxially mounted to section **12** at the front end of accelerator **11**. A power supply **14** activates gun **13** through a switch **16**. Electron gun **13** injects into the accelerator a pulsed beam of electrons designated by dashed lines **17**. The electron beam **17** travels from gun **13** through section **12** into section **12'** and so on down through the plurality of sections to the target end of the accelerator.

An oscillator **18** such as a klystron is provided in the usual manner to supply the radiofrequency power for driving the accelerator. Oscillator **18** couples into a distribution waveguide **19** which extends the length of the accelerator. A radiofrequency amplifier **21**, e.g., a pulsed klystron, couples power out from waveguide **19** through a phase shifter **22**. The microwave power output of amplifier **21** is in turn coupled through a directional coupler **23** into the first section **12** at a portion thereof nearest the electron gun **13**. The output end of section **12** is coupled to a load **24**.

In accordance with the present invention, a portion of the microwave power from amplifier **21** is diverted into a phase shifter **26**, and a phase detector **27** is coupled between phase shifter **26** and the output end of the section **12** whereby a phase comparison can be made between the power extracted from the terminal end of section **12** and the power coupled into the initial portion of section **12**. To facilitate diversion of the power in this manner, directional coupler **23** is employed in the connection of amplifier **21** to the input end of the section, one arm of the coupler feeding the phase shifter **26**. Similarly a directional coupler **28** connects the output end of the section to load **24** whereby coupling to the phase detector **27** is simultaneously facilitated through another arm of the coupler. Both couplers **23** and **28** are terminated in their remaining arms respectively by matched loads **29** and **31**.

A similar arrangement of components to those coupled into section **12** is coupled into section **12'** and the like components are designated by primed numerals. Similar arrangements are also coupled into each of the sections which comprise the length of the accelerator.

As regards the individual components of the arrangement, it should be noted that the phase detector **27** must be independent of the power level of signals fed into its inputs. This requirement is apparent upon considering the difference of wave energy between the front and terminal portions of an accelerator section. In addition, the detector should be of the type that provides a null reading when the inputs from shifter **26** and coupler **28** have exactly the same phase. When the two inputs to detector **27** are not in phase, it is preferable that the degree to which these inputs are out of phase be directly indicated as by means of a meter.

The phase shifter **26** as well as the input power phase shifter **22** may, for example, be of the slotted waveguide type illustrated in "Microwave Transmission Circuits," Ragan, vol. 9, Radiation Laboratories Series, McGraw-Hill, 1948, p. 513, or they may be of the dielectric type illustrated in the same work at p. 514. In practice, a phase shifter of the dielectric type has been proven most advantageous.

Considering now the method of the invention as facilitated with the arrangement of components described hereinbefore to phase the sections of the accelerator, microwave power from the oscillator **18** is first coupled into the distribution waveguide **19**. The amplifier **21** is then pulsed on to introduce a traveling electromagnetic wave into the first section **12**. The phase of the energy coupled into the front portion of the section, viz., the starting phase of the wave, is compared to the phase of the wave at the output end of the section and this is accomplished by observing the indication of phase departure at phase detector **27**. Such phase relationship is indicated at the detector inasmuch as the coupler **23** diverts a portion of the input energy through phase shifter **26** to one input of the detector whereas the coupler **28** diverts a portion of the output load energy to the other input of the detector.

The phase angle indicated at the detector is the phase shift of the unloaded wave in propagating through the section **12** and is employed herein as a reference phase angle. Although the reference phase angle per se may be utilized for subsequent comparison purposes, it is more convenient that departures from the reference phase angle be indicated at the phase detector as departures from zero. Accordingly, as the next step of the method a null reading is established at the phase detector by adjusting the phase shifter **26** compensatory to the reference phase angle. In other words, the reference phase angle between the unloaded wave at input and output of the section is established as a null reading of the phase detector.

After the reference phase angle is established, the electron gun **13** is turned on by switch **16** and a beam of electron bunches is injected axially into section **12** and transmitted therethrough. The electromagnetic field in section **12** now has two components. One is that of the driving electromagnetic wave introduced from the radiofrequency amplifier **21** and the other is that caused by the presence of the electron beam designated by line **17**. These two electromagnetic waves co-act to create a resultant loaded traveling wave in the section.

When the electron bunch is positioned in space exactly coincident with the negative peak of the driving wave, the phase of the resultant loaded wave remains the same as that of the unloaded wave, viz., the wave before the beam was turned on. However, when the electron beam is not positioned exactly coincident with the crest of the driving wave, a shift in the phase of the resultant loaded wave takes place throughout the length of the section. The foregoing will be more fully understood upon reference to the vector diagrams of FIGURE 2. FIGURE 2*a* vectorially represents the orientation of fields in an accelerator section when the electron bunch is in phase with the driving electromagnetic wave. Vector **32** represents the wave induced by the presence of the electron beam and the driving wave in the section is shown by vector **33**. Vector **34** represents the resultant wave created by adding the vectors **32** and **33**. It is seen that the resultant wave retains exactly the same phase as the driving wave.

Now consider the situation which exists when the electron bunch is out of phase with the driving wave by an angle θ, as shown in FIGURE 2*b*. Vector **32'** represents the electromagnetic field induced by the electron bunch, vector **33'** represents the field caused by the driving traveling wave, and vector **34'** represents the field of the resultant traveling wave. It is seen that for this out-of-phase situation the phase of the resultant traveling wave is shifted from that of the unloaded driving wave by an angle ϕ.

From the foregoing description, it is seen that the angle phase shift ϕ between the loaded wave and unloaded or reference wave is a measure of departure from the optimum phase relation between the electron beam bunches and driving electromagnetic wave wherein the beam bunches are in phase with the negative peaks of the wave. In accordance with the latter steps of the method of the invention, the phase shift ϕ is determined and the phase of the driving energy applied to the input end of the section varied to compensate the shift. When the shift is reduced to zero, viz., when $\phi=0$, the electron bunches are in phase with the negative peaks of the driving wave and the section **12** is hence optimumly phased. The foregoing steps are accomplished merely by observing the phase detector **27** and adjusting phase shifter **22** until the detector indicates a null.

Successive sections of the accelerator are phased in similar fashion to that detailed hereinbefore relative to the first section **12**. More specifically, to achieve phasing of the whole accelerator length the following procedure is advantageously followed. Before turning on the electron gun, a reference phase angle is established for each of the accelerator sections in the manner described hereinbefore. That is, power is coupled into each of the sections from their associated sources of driving energy including radiofrequency amplifiers **21** and a null reading on each of the phase detectors **27** is obtained by varying the respective phase shifters **26**. After reference phase angles have been established, switch **16** is used to turn the electron gun on. Now, the phase shifter **22** is adjusted until the detector **27** exhibits a null reading indicating that section **12** is properly tuned. Shifter **22'** is then adjusted to tune section **12'**. This procedure is repeated in succession down the accelerator until each section is correctly phased.

It is particularly important to note the extreme sensitivity attainable in phasing the sections of an accelerator in accordance with the invention. More specifically, the sensitivity of the phasing method is determined by the relationship, derived hereinafter, between the measured angle ϕ (phase shift between unloaded and loaded wave) and the phase angle θ between the electron bunches and negative peaks of the wave. From the law of cosines, it is seen that

$$E_R^2=E_e^2+E_W^2-2E_eE_W\cos\theta \quad (1)$$

where E_e and E_W are the magnitudes of the electromagnetic field components due to electron bunches and driving wave present in the accelerator section, and E_R is the resultant field. Now, from the law of sines,

$$\frac{\sin\phi}{E_e}=\frac{\sin\theta}{E_R} \quad (2)$$

By substituting E_R from Equation 1 into Equation 2,

$$\sin\phi=\frac{\sin\theta}{\left[1+\left(\frac{E_w}{E_e}\right)^2-\frac{E_w}{E_e}\cos\theta\right]^{1/2}} \quad (3)$$

Taking the differential of Equation 3 yields the relation,

$$\frac{d\phi}{d\theta}=\frac{A^{1/2}\cos\theta-\frac{E_w}{E_e}A^{-1/2}\sin^2\theta}{A\cos\theta} \quad (4)$$

where

$$A=1+\left(\frac{E_w}{E_e}\right)^2-2\frac{E_w}{E_e}\cos\theta \quad (5)$$

Considering now the limit of $d\phi/d\theta$ as θ approaches zero the following expression relating ϕ and θ obtained,

$$\lim_{\theta\to 0}\left|\frac{d\phi}{d\theta}\right|=\left|\frac{1}{\frac{E_w}{E_e}-1}\right| \quad (6)$$

Equation 6 thus shows the variation of the measured angle ϕ with respect to the actual phase angle, θ, between the electron bunches and driving wave. Hence Equation 6 is a measure of the sensitivity of the instant phasing method. Equation 6 can also be used to directly give the angle θ when the angle ϕ is known.

To illustrate the extreme sensitivity of the method, the sensitivity factor of Equation 6 is hereinafter evaluated relative to the parameters of a section of an actual accelerator, namely, the Mark IV accelerator constructed at the Hansen Microwave Laboratory of Stanford University. The ratio E_W/E_e appearing in Equation 6 may be readily expanded into terms of the operating parameters of an accelerator from the equations:

$$E_e=ir\,(1-e^{-IL}) \quad (7)$$

$$E_W=E_0\,e^{-IL} \quad (8)$$

where

I=voltage attenuation in nepers/cm.;
L=length of accelerator section in cm.;
i=peak beam current in amps;
r=shunt impedance per unit length in ohms/cm.

From Equations 7 and 8 it can be shown that:

$$\frac{E_w}{E_e}=\sqrt{\frac{P_0}{i^2Lr}}\,\frac{\sqrt{2IL}}{(e^{IL}-1)} \quad (9)$$

For the Mark IV accelerator

P_o=15 megawatts
$i=5\times10^{-2}$ amps
L=305 cm.
$r=0.47\times10^6$ ohms/cm.
IL=0.9 neper

Upon substituting these parameters into Equation 9,

$$\frac{E_w}{E_e}=5.9 \quad (10)$$

Therefore substituting this value into Equation 6, the sensitivity is seen to be:

$$\frac{d\phi}{d\theta}=0.2 \quad (11)$$

From Equation 9 it is seen that for a given accelerator structure, the sensitivity of the instant method and apparatus increases with a decrease of the input power P_o or with an increase of the electron current i. This characteristic lends itself quite beneficially to the operation of phasing an accelerator. Note, for example, that if P_0 in the above actual example was 1.5 megawatts instead of 15 megawatts, then the sensitivity as given by Equation 6 would be 1.15 instead of 0.2. Consequently, during the phasing of the accelerator the driving power P_0 can be reduced as much as is necessary to accurately complete the phasing operation. Then, after phasing is achieved, the driving power can be increased to whatever level is desired for the acceleration of the electron beam. For sake of comparison it is noted that a sensitivity between 0.1 and 0.2 is accepted as adequate for satisfactorily phasing an accelerator. Hence, as the invention is capable of a sensitivity more than five times better than that required for adequate phasing, it is seen that phasing can be achieved to within any practical requirement of accuracy.

It will be appreciated that in the case of a very long accelerator economic considerations prohibit the use of separate detector circuitry with each accelerator section. Hence an alternative embodiment of the phasing apparatus comprising a single detector circuit coupled through a switching circuit to a plurality of accelerator sections is preferably employed with a very long accelerator, and such embodiment is provided as illustrated in FIGURE 3. As shown therein, a linear accelerator **36** comprised of a plurality of substantially identical sections **37, 37′, 37″,** etc., is provided. An electron gun **38** is mounted coaxially to section **37** and is actuated by a power supply **39** through a switch **41.** An electron beam as designated by dashed lines **42** is injected axially into accelerator **36** by gun **38.** A microwave oscillator **43** feeds into a distribution waveguide **44.** Power is coupled out from waveguide **44** into a radiofrequency amplifier **46** through a phase shifter **47.** The output from amplifier **46** is coupled into a front portion of section **37.** Power is coupled from waveguide **44** into a front portion of section **37′** through a phase shifter **47′** and radiofrequency amplifier **46′.** Power is similarly coupled into the front portion of each identical section in a manner substantially the same as that for sections **37** and **37′.**

Power is coupled out of section **37** at a terminal portion thereof through a directional coupler **48** into a load **49.** Coupler **48** diverts part of the output power through a transmission line **51** into a coaxial switch **52.** A similar output coupling circuit to that of section **37** is also connected to a terminal portion of section **37′** as is shown by load **49′**, directional coupler **48′**, and transmission line **51′**, with line **51′** coupling into coaxial switch **52.** The remaining arm of coupler **48** is terminated in a matched impedance **53** as is coupler **48′** by impedance **53′** and similarly for each other section. Switch **52** is designed to couple power from one of its transmission line inputs at a time into an input of a phase detector **54.** Detector **54** has another input coupled thereto from oscillator **43** through a phase shifter **56.**

In conducting the method of the invention with the instant embodiment, the phase of the output from oscillator **43** is designated as the reference phase. Section **37** is phased by first turning on amplifier **46** and coupling power out of section **37** into detector **54** through switch **52.** Shifter **56** is then adjusted to indicate the reference phase angle between the reference phase and the output phase of section **37** as a null reading on detector **54.** Electron gun **36** is now turned on by switch **41** and shifter **47** is adjusted to give a null reading on the detector. Section **37** is now correctly phased. The electron gun is turned off by switch **41** and switch **52** is changed to couple power from section **37′** through line **51′** into the detector. Amplifier **46′** is turned on and shifter **56** is adjusted to give a null reading. Switch **41** is used to initiate the electron beam again and shifter **47′** is adjusted to give a null reading whereby section **37′** is now correctly phased. This procedure is repeated successively down through each of the sections which are connected to switch **52.**

Consider now the instant embodiment as applied to a very long accelerator having, for example 1000 sections. A compromise between the excessive cost of a large number of detectors and the complexity of long transmission line circuitry dictates that each switch **52** and detector **54** can most advantageously handle about 25 accelerator sections. Such a group of sections is designated as a sector. This means that 40 detectors and 40 coaxial switches are used with the 40 sectors. For reasons other than phasing procedures, a very long accelerator can be used to best advantage by having an electron gun optionally mountable with each sector, e.g., in this manner various different lengths of accelerator can be used for different experiments and requirements. By using this plurality of electron guns, the 40 sectors can be individually phased at the same time. Then, in the manner of the invention, the whole accelerator length can be phased by using only one electron gun and considering each sector analogous to a single section. The foregoing procedure is exceptionally rapid and the job phasing a 1000 section accelerator can be completed in about 25 minutes.

While the present invention has been hereinbefore described in terms of specific steps in the method and with respect to but several embodiments, 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. In an apparatus for phasing a linear accelerator waveguide section, the combination comprising a variable phase microwave power source coupled into said section at the front portion thereof, phase varying means associated with said power source to provide a constant phase radiofrequency reference signal, a phase shifter, a phase detector serially connected at one end thereof to said phase shifter and at the other end thereof to the terminal portion of said section, said phase shifter adapted to receive said reference signal at the free end thereof.

2. In an apparatus for phasing a linear accelerator having at least one loaded waveguide section, the combination comprising a phase shifter, a phase detector, said shifter and detector connected serially between the front and terminal portions of said section, and a variable phase microwave power source coupled into each section at said front portion thereof.

3. In an apparatus for phasing a linear accelerator having at least one loaded waveguide section, the combination comprising means for introducing variable phase microwave power to said section, means for measuring the relative phase angle between the phase of a traveling electromagnetic wave in each loaded waveguide section of a linear accelerator at a front portion of each section and the phase of said wave at a terminal portion thereof, means for introducing an electron beam into each section, and means for varying the phase of the traveling wave in each section while the beam is passing therethrough to maintain the phase thereof equal to the measured relative phase angle.

4. In an apparatus for phasing a linear accelerator, the combination comprising at least one loaded waveguide section, a variable phase microwave power source coupled through a first directional coupler into a front portion of each section, a radiofrequency load coupled through a second directional coupler into a terminal portion of each section, and a phase detector coupled between the first and second directional couplers of each section.

5. In an apparatus for phasing a linear accelerator having at least one loaded waveguide section, the combination comprising a variable phase microwave power source coupled through a first directional coupler into a front portion of each waveguide section of a linear accelerator, a phase shifter connected to said first directional

coupler, a null reading phase detector connected to said phase shifter, a second directional coupler connected to said detector, and a radiofrequency load coupled through said second directional coupler to a terminal portion of said section.

6. In an apparatus for phasing a linear accelerator having a plurality of loaded waveguide sections, the combination comprising a plurality of radiofrequency amplifiers respectively coupled into the waveguide sections at the front portions thereof, a single microwave oscillator commonly connected to said amplifiers, a phase shifter connected to said oscillator, a phase detector connected to said phase shifter, a coaxial switch having a single input terminal connected into said detector and a plurality of selectable output terminals, and a plurality of

transmission lines respectively connected between the terminal portions of said sections and the output terminals of said coaxial switch.

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