

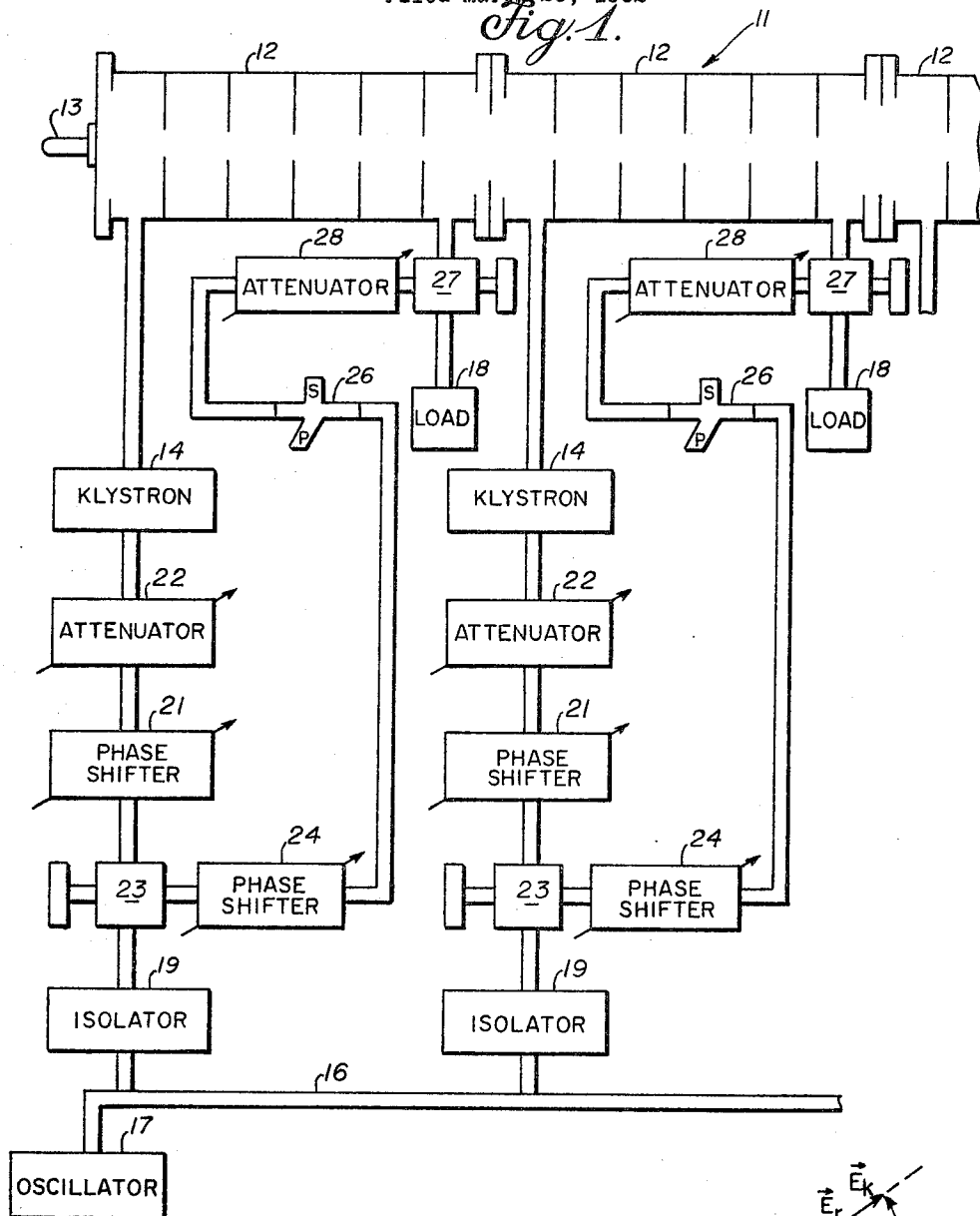
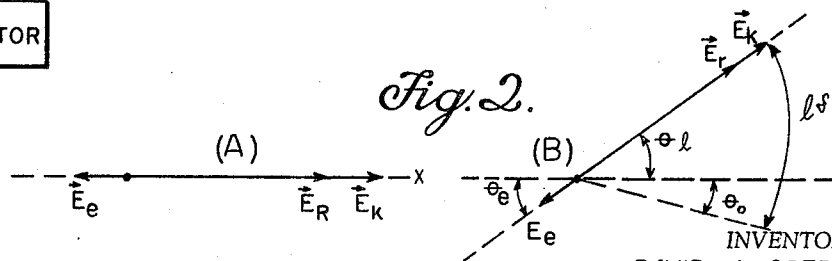
Aug. 2, 1966

D. J. GOERZ, JR., ETAL

3,264,568

ELECTRON LINEAR ACCELERATOR PHASING METHOD INVOLVING
ALTERNATELY TURNING ON AND TURNING OFF THE
ELECTROMAGNETIC DRIVER OF THE SECTION
BEING PHASED

Filed March 26, 1962



INVENTORS
DAVID J. GOERZ, JR.
RICHARD B. NEAL
KENNETH B. MALLORY
BY *Roland A. Johnson*
ATTORNEY

1

3,264,568

ELECTRON LINEAR ACCELERATOR PHASING METHOD INVOLVING ALTERNATELY TURNING ON AND TURNING OFF THE ELECTROMAGNETIC DRIVER OF THE SECTION BEING PHASED

David J. Goerz, Jr., Belmont, Richard B. Neal, Menlo Park, and Kenneth B. Mallory, Palo Alto, Calif., assignors to the United States of America as represented by the United States Atomic Energy Commission

Filed Mar. 26, 1962, Ser. No. 182,691

4 Claims. (Cl. 328-233)

The invention disclosed herein was made under, or in, the course of Contract No. AT(04-3)-363 with the United States Atomic Energy Commission.

This invention relates to the phasing of multisection electron linear accelerators for maximum transfer of energy in a narrow energy spectrum from the driving wave to the accelerated beam, and is particularly directed to a method of accomplishing such phasing with a minimum interference to the research use of the accelerator.

In electron linear accelerators comprised of a large number of waveguide sections, considerable time is required to appropriately phase the radio frequency driving sources coupled to the sections to produce accelerated electron beams of maximum energy and minimum energy spectra. More particularly, the driving source associated with each section must be phased for maximum energy transfer to the electron beam passing through that section. By virtue of the many sections and associated driving sources involved, the overall time consumed in the individual phasing of the respective sources is substantial. Where the phasing disrupts the use of the accelerator beam for research purposes, the "on" time of the accelerator for physics experiments is hence limited.

It is therefore an object of the present invention to provide a method of phasing a multi-section electron linear accelerator wherein the beam can be used for physics purposes while the phasing is proceeding.

Another object of the invention is the provision of a multi-section electron linear accelerator phasing method wherein the loss of overall beam output energy during phasing of a section is negligible.

Still another object of the invention is to provide an extremely sensitive method of phasing electron linear accelerator waveguide sections.

It is yet another object of the present invention to provide a phasing method of the class described by which more than one section may be phased simultaneously without interaction.

It is still another object of the invention to provide a method of phasing a multi-section electron linear accelerator in which the externally impressed field is removed from the section being phased, and the electron beam passing through this section induces a wave therein which serves as a phasing reference.

One other object of the invention is to provide a phasing method of the class described which is relatively simple and may be conducted with minimum auxiliary equipment requirements.

A further object of the invention is the provision of an electron accelerator phasing method which is accurate even under conditions of nonsynchronous operation, viz., when accelerator temperature or frequency deviations cause the phase-velocity of the wave to differ from the velocity of light and of the electrons.

A still further object of the invention is the provision of a phasing method of the class described which is relatively sensitive even for low beam currents.

Additional objects and advantages of the invention will become apparent from the following description and

2

claims considered together with the accompanying drawing, of which:

FIGURE 1 is a schematic diagram of one arrangement of apparatus which may be employed with an electron linear accelerator to facilitate the conduct of the phasing method of the present invention; and

FIGURE 2 is a graphical presentation of the wave vectors associated with a section of the accelerator at several conditions of phase between the beam and driving electromagnetic wave;

Portion (a) being indicative of a near optimum phase relationship between the beam bunches and wave at the output of a waveguide section under synchronous conditions, wherein the phase velocity of the driving wave is at the velocity of light and of the electrons, and

Portion (b) being indicative of a near optimum phase relationship between the beam bunches and wave at the output of a waveguide section under non-synchronous conditions, wherein temperature or frequency deviations cause the driving wave to differ from the velocity of light and of the electrons.

Referring now to FIGURE 1, there is shown a multi-section traveling wave linear electron accelerator 11 of generally conventional construction. More particularly, the accelerator includes a plurality of loaded waveguide sections 12 communicably coupled in coaxially aligned end-to-end relationship. A suitable electron source 13 is provided at the input end of the accelerator to introduce a bunched electron beam axially into the first waveguide section. Each of the sections 12 is driven at its input end by a klystron 14 or equivalent RF amplifier coupled thereto, the plurality of klystrons 14 being, in turn, driven from a pulsed drive line 16, suitably coupled thereto, and fed by a master oscillator 17. The output end of each waveguide section is coupled to a load 18. As a result, traveling electromagnetic waves are propagated through the waveguide sections, and the bunched electron beam is accelerated from the input to the output end of the accelerator by the waves propagating through the successive sections. When these waves are in proper phase relative to the beam bunches, maximum energy is transferred therebetween. Where synchronous conditions exist in a section, viz., the driving wave propagates through the section at the velocity of light and of the electrons, the electrons gain the maximum energy where the beam bunches are injected into the section in phase with the wave crests. Where non-synchronous conditions exist and the wave in a section travels somewhat faster than the velocity of light and of the electron bunches due to frequency or temperature deviations, the electrons gain the maximum possible energy where they start at an optimum injection angle, slightly ahead of a wave crest, and slip over the crest to a position slightly behind it as they travel down the waveguide section. Thus, where the klystrons 14 are suitably phased to establish driving electromagnetic waves in the respective waveguide sections 12, commensurate with the electron bunches entering such sections with a proper injection angle relative to the wave crests, maximum possible energy is transferred to the beam along the entire length of the accelerator.

It has been found that in the case of a synchronous section, proper injection occurs where the klystron wave, electron beam-induced wave, and resultant wave vectors, $\vec{E}_k$, $\vec{E}_e$, and $\vec{E}_R$, are collinear and arranged as depicted in FIGURE 2(a). As shown therein, the klystron or driving wave, $\vec{E}_k$, and resultant wave, $\vec{E}_R$, are in phase, while the beam-induced wave, $\vec{E}_e$, is in 180° phase relationship therewith, all vectors being disposed upon an arbitrary reference line, x.

In the case of a non-synchronous section, optimum injection is very closely approximated by an injection angle, θ_0 , of the wave relative to a reference at the input end of a waveguide section such that θ_1 , the corresponding angle of the wave relative to the reference at the output end of the section, is unchanged by the beam-induced wave component of the resultant wave. In other words, where θ_0 is productive of klystron wave, electron

beam-induced wave, and resultant wave vectors, $\vec{E}_k$, $\vec{E}_e$, and $\vec{E}_R$, respectively, which are collinear and at the angle θ_1 at the output end of a section, the injection angle between the beam bunches and wave crests is very close to optimum. In fact, it has been observed that the decrease in energy transferred from the wave to the beam under the foregoing circumstances is of the order of only 0.5% of that in the truly optimum case.

The vector diagram depicting the foregoing phase conditions at the output end of a waveguide section for near optimum injection in the non-synchronous case is illustrated in FIGURE 2(b). As illustrated, there exists a phase angle difference, δ , per unit of section length between the electron and RF wave propagation constants throughout the length, l , of the section. Accordingly, in passing through the section, the klystron wave vector, $\vec{E}_k$, is shifted from its initial angle, θ_0 , relative to reference, x , through an angle, $l\delta$, to angle θ_1 relative to the reference at the output end of the section, where

$$\theta_1 = \theta_0 + l\delta$$

The beam-induced wave vector, $\vec{E}_e$, is now at an angle, θ_e , relative to the reference, where $\theta_e = \theta_1 + 180^\circ$. Thus, $\vec{E}_e$ is oppositely directed from $\vec{E}_k$ and, therefore, collinear therewith. The resultant wave vector, $\vec{E}_R$, is hence collinear with both $\vec{E}_k$ and $\vec{E}_e$, and in 180° phase relation with the latter. It will thus be appreciated that for proper injection in the non-synchronous case, the vectors, $\vec{E}_k$, $\vec{E}_e$, and $\vec{E}_R$, at the output end of a section are arranged in identical phase relationship to each other as they are for proper injection in the synchronous case. The only difference is that in the non-synchronous case, the vectors are disposed along a line at the angle, θ_1 , to the arbitrary reference line, x , rather than along the reference line itself.

The phasing method of the present invention utilizes to great advantage the phase relationship, described hereinbefore, as a basis for adjustment of the phase of the driving wave in a waveguide section equal to or very close to the optimum phase productive of maximum energy transfer to the beam. In accordance with the phasing method, the phase of the beam-induced wave, $\vec{E}_e$, alone at the output end of a waveguide section 12

is observed. Now the phase of the resultant wave, $\vec{E}_R$, including both of the components, $\vec{E}_e$ and $\vec{E}_k$, is observed at the output end of the section. As noted hereinbefore, when $\vec{E}_e$ and $\vec{E}_R$ bear a collinear 180° phase relationship at the output end of a section, the section is properly phased. Accordingly, the phase of the klystron 14 driving the input end of the section is next adjusted until the

phase of the resultant wave, $\vec{E}_R$, at the output end of the section is observed to be 180° relative to the observed phase of the beam-induced wave, $\vec{E}_e$, alone. All of the wave vectors are at this time collinear, as depicted in FIGURES 2(a) and 2(b), and the section is properly phased.

Considering now the method in greater detail as to the physical steps thereof, the driving klystron 14 of a waveguide section to be phased is first turned off, and the phase of the beam-induced wave, due to the electron beam passing through the section in the absence of the driving wave, is observed at the output end of the section. The driving klystron is then turned on and the phase of the driving wave thereby generated is adjusted until the phase of the resultant wave at the output end of the section is observed to bear a 180° relationship to that determined for the beam-induced wave alone. The section is at this time properly phased. It is of importance to note that the beam was on at all times during the phasing procedure. In a very long linear accelerator made up of a large number of waveguide sections, the loss of overall beam energy due to removal of the driving power from a single section is minimal. Hence, the phasing method of the present invention may be conducted without disruption of the beam for research purposes. In addition, several waveguide sections may be independently phased at the same time.

To facilitate the conduct of the phasing method, apparatus may be provided as depicted in FIGURE 1. More particularly, each driving klystron 14 is coupled to the drive line 16, through an isolator 19, a variable phase shifter 21, and a variable attenuator 22, in series. A directional coupler 23, or the like, is employed in the connection of the isolator to the phase shifter such that a portion of the signal from the drive line may be extracted and applied through a second variable phase shifter 24 as a reference signal to one side arm of a magic T 26 or equivalent phase detector. A directional coupler 27 is similarly employed in the connection of the load 18 to the output end of the section such that a portion of the output signal may be applied through a second variable attenuator 28 to the other side arm of the magic T.

With the foregoing structural arrangement, the phasing method is conducted by first turning the klystron 14 off. The variable attenuator 28 is adjusted to approximately equate the input power levels in the side arms of the magic T. Now the phase shifter 24 is adjusted to produce a minimum in the series (s) arm of the T, as indicated by a suitable meter (not shown) or the like. The reference signal is at this time in phase with the beam-induced wave signal.

With the klystron 14 on, the attenuator 28 is readjusted to approximately equate the input power levels in the side arms of the magic T. Phase shifter 21 is adjusted to, in turn, vary the phase of the driving wave generated by the klystron until a minimum is observed in the parallel (p) arm of the T, as by means of a meter (not shown) or the like, coupled thereto. This minimum is indicative of a 180° phase relationship between the resultant wave output signal from the section and the reference signal. Inasmuch as the reference signal was previously adjusted to be in phase with the beam-induced wave signal, the latter is also in a 180° phase relationship with the resultant wave signal and the section is hence properly phased.

From the foregoing, it will be appreciated that the terms "observe" and "determine," as employed herein with respect to methods of observing or determining phase, are to be taken as including various comparison techniques, such as setting a reference equal to a predetermined phase and comparing the phase of a signal to that of the reference by null detection, in addition to direct measurement techniques. Hence, these terms are to be taken as inclusive of all techniques for making one aware of the existence of a predetermined phase relationship.

It should be noted that the sensitivity of the present phasing method represents a ratio of improvement of the order of 50 over most existing phasing methods which typically have sensitivities of the order of 0.1. More particularly, the sensitivity, σ , is given by the rate of change

of the observed angle (phase shift between the resultant and beam-induced waves) relative to the phase angle between the electron bunches and crests of the wave at the output of a section. It can be readily shown that with the present method, the sensitivity is given by:

$$\sigma = \frac{E_k/E_e}{E_k/E_e - 1}$$

With $E_k/E_e=5.9$, which is a comparable figure to that yielding the 0.1 sensitivity value mentioned above for previous phasing methods, the sensitivity is hence $\sigma=1.2$ for the present method. It will be appreciated further that at worst the sensitivity of the present method is 1.0. Thus, to adjust the phase angle between the electron bunches and driving wave at the output of a waveguide section to an accuracy of one degree, it is only necessary to determine the output phase angle of the resultant wave relative to the beam-induced wave to an accuracy of the order of one degree.

While the present invention has been hereinbefore described in terms of specific steps in the method and with respect to a single structural embodiment with which the method may be conducted, 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 a method of phasing a waveguide section of a multi-section electron linear accelerator, the steps comprising measuring the phase of a resultant traveling electromagnetic wave at the output end of said section due to an electron beam and driving electromagnetic wave passing through the section relative to the phase of the beam-induced wave at the output end of the section, and adjusting the respective phases of said resultant wave and beam-induced wave to establish a phase difference therebetween of 180 degrees.

2. A method of phasing the respective waveguide sections of a multi-section electron linear accelerator comprising the steps of measuring the phase of the beam-induced wave at the output end of one of said sections due to an electron beam passing through the section in the absence of a driving electromagnetic wave therein, measuring the phase at the output end of said one section of a resultant wave due to the electron beam passing therethrough in the presence of a driving electromagnetic wave propagating through the section, and adjusting the phase of said driving electromagnetic wave in relation to phase of said resultant wave until the resultant wave is displaced 180 degrees from the measured phase of said beam-induced wave.

3. In a method of phasing a multi-waveguide section electron linear accelerator wherein an electron beam is accelerated through successive sections by driving electromagnetic waves established by a plurality of klystrons respectively coupled to the input ends of said sections, the steps comprising:

- (a) turning off the klystron coupled to one of said sections;
- (b) measuring the phase of the beam-induced wave at the output end of said one section;
- (c) turning on the klystron coupled to said one section to produce a resultant wave at the output end of said one section including klystron-driven wave and beam-induced wave components;
- (d) phasing said klystron to establish a phase relation of 180° between the phases of said measured phase of the beam-induced wave and said resultant wave; and
- (e) repeating steps (a) through (d) inclusive relative to each of said sections of said accelerator.

4. In a method of phasing a waveguide section of a multi-section electron linear accelerator, the steps comprising extracting a beam-induced wave signal from the output end of said section established by an electron beam passing through the section in the absence of a driving electromagnetic wave propagating through the section, measuring the phase of said beam-induced wave signal in relation to the phase of a reference signal to determine the phase angle therebetween, adjusting the phase of said reference signal to null said phase angle to zero, applying microwave power to the input end of said section to create a driving electromagnetic wave which propagates from the input to the output end thereof and accelerates said beam therethrough, extracting a resultant wave signal from the output end of said section, measuring the phase of said resultant wave signal in relation to the phase of said reference signal to determine the phase angle difference therebetween, and adjusting the phase of said microwave power while retaining the phase adjustment of said reference signal until said phase angle difference is 180 degrees.

References Cited by the Examiner

UNITED STATES PATENTS

2,883,536	4/1959	Salisbury et al.	328—155
3,019,296	1/1962	Schelling	328—155 X
3,089,092	5/1963	Plotkin et al.	328—155
3,147,396	9/1964	Goerz et al.	315—5.422

HERMAN KARL SAALBACH, *Primary Examiner.*

R. D. COHN, C. R. CAMPBELL, *Assistant Examiners.*