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M. PLOTKIN ET AL

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SYNCHROTRON RADIO FREQUENCY PHASE CONTROL SYSTEM

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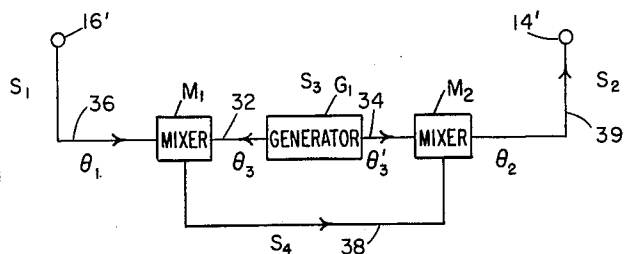


Fig. 2

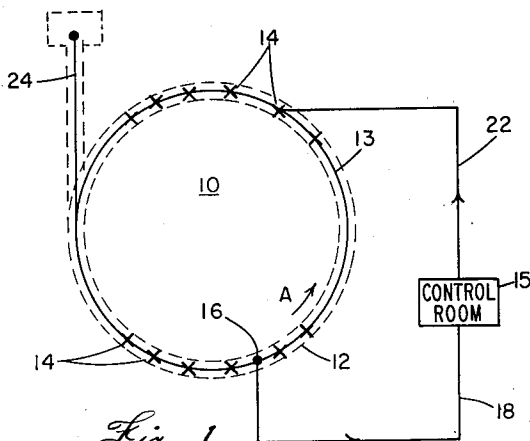


Fig. 1

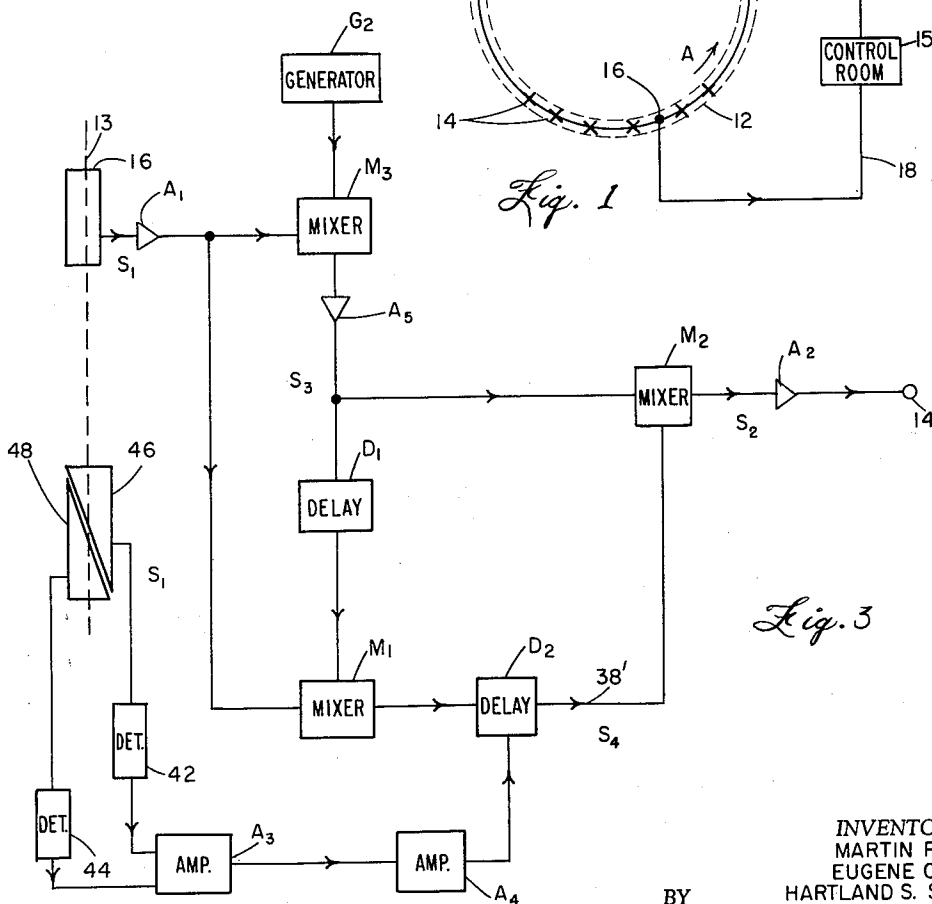


Fig. 3

INVENTORS  
 MARTIN PLOTKIN,  
 EUGENE C. RAKA,  
 HARTLAND S. SNYDER

BY

*Richard A. Goodman*  
 Attorney

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## SYNCHROTRON RADIO FREQUENCY PHASE CONTROL SYSTEM

Martin Plotkin, Massapequa Park, Eugene C. Raka, East Patchogue, and Hartland S. Snyder, Bellport, N.Y., assignors to the United States of America as represented by the United States Atomic Energy Commission  
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 6 Claims. (Cl. 328—155)

The present invention relates to a phase control system for an alternating gradient synchrotron, and more particularly, to a control system in which differential phase changes introduced by connecting cables and control equipment are cancelled.

A proton accelerator of the alternating gradient synchrotron type for producing protons with energies in the 25–30 b.e.v. region has been designed which utilizes a circular ring about one-half mile in circumference in which the protons are accelerated up to the velocities and energies required. This synchrotron utilizes 240 magnets arranged around an underground ring enclosing the evacuated orbital path of the protons. The magnetic field gradient of each successive pair of magnets is oriented to exert a net strong focusing effect which tends to hold the protons centrally on the selected orbital path. Along the circumference of the ring, there are also located twelve radio frequency accelerating stations for applying the necessary energy to accelerate the protons. As the components of the main magnet are designed for the purpose of bending and focusing the protons, all of the proton acceleration is accomplished in the twelve accelerating stations. In the accelerating stations, the frequency of the imposed accelerating signal is the twelfth harmonic of the particle rotation frequency and so the signal is in the radio frequency range varying from 1.40 to 4.46 megacycles per second over which time the acceleration of the protons is complete. In approximately a one second period, the protons are accelerated to over three times their initial velocities. In order to power the accelerating stations so the particles passing therethrough receive a "boost" or "kick" at the correct instant, it is necessary to provide some radio frequency control system. The control system designed for this synchrotron utilizes a pick-up electrode at some point in the orbit of the protons to sense electrostatically the proton groups passing this point and an arrangement for delivering a driving signal to the accelerating stations to be at the correct phase as the proton bunches are passing therethrough. As the protons sweep around their orbital path, a definite phase delay, constant over the accelerating cycle, occurs between the instant that the proton bunch passes the sensing electrode and the accelerating station. In addition, a phase factor is also introduced by the circuitry connecting the pick-up electrode to the stations wherein the acceleration takes place. Furthermore, the physical size of the synchrotron operating at the energies noted above, requires the use of lengthy cables which increase the effects of these phase factors, making them complex in nature due to the wide band of operating frequencies.

The instant invention is a simplified arrangement for compensating these various phase changes which take place and permits the accurate driving of the accelerating stations to achieve a full proton beam in the particle accelerator. Heretofore, this was accomplished by a variable-frequency oscillator which was controllable either by an arbitrary programming circuit or by a sensing circuit which responded to the changing strength of the magnetic field. Such controls have been found to be relatively inexact and require the use of an accelerating vacuum chamber of considerable size in order that the beam bunches in their

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excursions from a central orbit would not strike the chamber walls and be lost. In the alternating gradient synchrotron, however, a large chamber cannot be tolerated and more accurate means of controlling the beam is needed. By the present invention, it has been made possible to effect a close control of the frequency of the accelerating particles and maintain the phase of the RF accelerating signals to be correct as the protons pass the accelerating stations, so that closer bunching of the protons and the more accurate alignment in their path is obtained. It has also been made possible by the invention herein described to introduce in a convenient manner signals to control the phase of the accelerating signal and compensate thereby for beam path deviations due to slight inaccuracies in the magnetic guide field.

It is, thus, a first object of this invention to provide a radio frequency control system in which differential phase shift introduced by coaxial or other cables and electronic apparatus is compensated.

A further object of this invention is an arrangement for controlling the phase of a radio frequency signal.

Still another object of this invention is the provision of electrical control apparatus in an alternating gradient synchrotron for making controllable phase adjustments in the signals passing therethrough.

Other objects and advantages of this invention will hereinafter become more evident from the following discussion and description of the drawings in which:

FIGURE 1 is a highly schematized illustration of an alternating gradient synchrotron utilizing this invention;

FIGURE 2 is an electrical schematic to illustrate the mathematics involved in this invention; and,

FIGURE 3 is a basic arrangement of a control circuit designed according to the principles of this invention.

Referring to FIGURE 1, there is shown an alternating gradient synchrotron 10, consisting of a circular evacuated tube 12 in which the protons are accelerated along orbit 13 provided with a group of 240 magnets (not shown) distributed throughout the tube's length and surrounding the latter, two pair of six each RF accelerating stations 14 for accelerating the protons, and a control room 15. It is understood that there is provided at each station 14 a high power radio frequency source (not shown) which is driven by the control system hereinafter described. At some convenient point 16 is located a pick-up station which detects the presence of a proton bunch by the production of an electrical pulse due to the moving electric charge of the protons crossing the pick-up electrode (not shown) of station 16. Electrical wiring 18, consisting of appropriate cables transmits the signals to control room 15 wherein is produced the controlling signals which are passed by way of cables 22 to some particular acceleration station 14 where the high power radio frequency signals are produced by the apparatus provided at that point, as already noted. Synchrotron 10 is also provided with a linear accelerator 24 to inject the protons into tube 12, as is understood in the art.

From pick-up station 16 along orbital path 13 to some particular station 14, a proton bunch moves in the direction of arrow A and traverses an orbital distance which may be defined in phase angle of the control signal, which is the twelfth harmonic of the particle frequency. The control system is designed to give each proton bunch a "kick" at the appropriate point in time and space as it passes through each of the particular accelerating stations 14. In order for a control system to function properly to accomplish this result, it is necessary to synchronize the accelerating signal in stations 14 with the movement of the proton bunches therethrough. Thus, the control system must compensate for the phase angle introduced by lines 18 and 22, and the control system itself, as well as the

phase change introduced by the movement of the proton bunches from station 16 to station 14. In view of the large size of the alternating gradient synchrotron 10, and the resultant tremendous lengths of cable necessary to pass the various signals, as well as the wide range of frequencies superimposed thereon to complicate the phase effects even further, compensation of such effects is normally immensely complicated.

Referring to FIGURE 2 for a mathematical analysis of this invention, there is shown a source 16' of a signal  $S_1$  which is to undergo a variety of phase changes due to the existence of long leads, cables and other electrical apparatus and delivered as a signal  $S_2$  at 14' without any net changes in phase for the simplified case, although the circuit, as will be later seen, may be designed to produce any particular designed phase change, such as, for example, to compensate for the time involved in the movement of the proton bunches from pick-up electrode 16 around the orbit to radio frequency accelerating station 14. In the circuit of FIGURE 2 there is provided for accomplishing this purpose, a first mixer  $M_1$ , a second mixer  $M_2$ , and an oscillator  $G_1$ . Oscillator  $G_1$  produces a signal  $S_3$  which is delivered by leads 32 and 34 to mixers  $M_1$  and  $M_2$ , respectively. Signal  $S_3$  is always at a constant frequency difference from signal  $S_1$ . Signal  $S_1$  passes to mixer  $M_1$  on lead 36 where heterodyning takes place and the difference signal  $S_4$  at constant frequency is produced and passed by lead 38 to mixer  $M_2$ . Signals  $S_3$  and  $S_4$  are heterodyned in mixer  $M_2$  and the resultant sum signal  $S_2$  at the same frequency as signal  $S_1$  is delivered by lead 39 to output 14'. The various lead lines 36, 32, 34 and 39 introduce time effects which can be defined as phase changes  $\theta_1$ ,  $\theta_3$ ,  $\theta_3'$ , and  $\theta_2$  as indicated in FIGURE 2.

Referring to mixer  $M_1$ , the input signals defined as  $E_3 = \sin(\omega_3 t + \theta_3)$  and  $E_1 = \sin(\omega_1 t + \theta_1)$  are combined in accordance with the square law as follows (neglecting first order terms):

$$(1) \quad E_4 = [\sin(\omega_3 t + \theta_3) + \sin(\omega_1 t + \theta_1)]^2$$

$$(2) \quad E_4 = 1 - \{ \cos[(\omega_3 + \omega_1)t + (\theta_3 + \theta_1)] \cos[(\omega_3 - \omega_1)t + (\theta_3 - \theta_1)] + \cos[(\omega_3 - \omega_1)t + (\theta_3 - \theta_1)] - \cos[(\omega_3 + \omega_1)t + (\theta_3 + \theta_1)] \}$$

Only the difference frequency is passed on lead 38 by appropriate filtering (not shown) and,

$$(3) \quad \cos[(\omega_3 - \omega_1)t + (\theta_3 - \theta_1)] = \sin \left[ (\omega_3 - \omega_1)t + \left( \frac{\pi}{2} + \theta_3 - \theta_1 \right) \right]$$

Therefore, the input signals to mixer  $M_2$  are

$$\sin \left[ (\omega_3 - \omega_1)t + \left( \frac{\pi}{2} + \theta_3 - \theta_1 \right) \right] \text{ and } \sin(\omega_3 t + \theta_3')$$

Then,

$$(4) \quad E_2 = \cos \left[ (\omega_3 - \omega_3 + \omega_1)t + \left( \theta_3' - \frac{\pi}{2} - \theta_3 + \theta_1 \right) \right]$$

If,  $\theta_3' = 0$ ,

$$(5) \quad E_2 = \cos \left[ \omega_1 t + (\theta_1 - \theta_3)t - \frac{\pi}{2} \right]$$

and at 14',

$$(6) \quad E_2' = \cos \left[ \omega_1 t + \left( \theta_1 - \theta_3 + \theta_2 - \frac{\pi}{2} \right) \right]$$

If,  $\theta_3 = \theta_1 + \theta_2$

$$(7) \quad E_2' = \cos \left( \omega_1 t - \frac{\pi}{2} \right) = \sin \omega_1 t$$

If,  $\theta_3' \neq 0$  and  $\theta_3 = \theta_1 + \theta_2 + \theta_3'$

$$(8) \quad E_2' = \sin \omega_1 t$$

$E_1$ ,  $E_2$ ,  $E_3$ , and  $E_4$  are the voltages of  $S_1$ ,  $S_2$ ,  $S_3$ , and  $S_4$ , respectively,  $\omega_1$ ,  $\omega_2$ ,  $\omega_3$  and  $\omega_4$  are the frequencies of  $S_1$ ,  $S_2$ ,  $S_3$  and  $S_4$ , respectively.  $E_2'$  is the voltage on output lead 14' after suffering the phase change  $\theta_2$  on lead 39.

It is thus seen by adjusting the phase change  $\theta_3$  introduced by lead 32 it is possible to cancel out all of the other phase effects introduced between input 16' and output 14'.

An arrangement for carrying out the function of the FIGURE 2 schematic in synchrotron 10 is shown in FIGURE 3. Shown there is pick-up unit 16 for delivering the signal  $S_1$  caused by the movement of proton bunches along orbit 13 through an amplifier  $A_1$  to mixers  $M_3$  and  $M_1'$  and a constant frequency generator or oscillator  $G_2$  for delivering its signal to mixer  $M_3$ . Generator  $G_2$  and mixer  $M_3$  together constitute the variable frequency generator  $G_1$  shown in FIGURE 2. Signal  $S_3$  is the sum of the output of generator  $G_1$  and signal  $S_1$ . As such a variable frequency oscillator, mixer  $M_3$  transmits its output simultaneously through an amplifier  $A_5$  to a mixer  $M_1'$  and to a mixer  $M_2'$ . Mixer  $M_1'$  also receives the input signal  $S_1$  directly and delivers the sum output signal  $S_2$  to an amplifier  $A_2$  for use in driving the accelerating station 14. The delay which must be introduced to compensate for the other delays and phase changes occurring in the control system is accomplished by a controllable delay arrangement  $D_1$  which introduces the delay  $\theta_3$  as described in connection with FIGURE 2, and which is adjusted initially to match the delay characteristics of all of the remaining circuitry cables and lead lines put together. Delay  $D_1$  may be a conventional unit such as the "Helidel" produced by the Helipot Corporation. In line 38' may be inserted a controllable delay line  $D_2$  which introduces signals to compensate for misalignment of the proton bunches along orbit 13. Split electrodes 48 and 46 mounted along orbit 13 detect the presence of the protons and detectors 42 and 44 cancel a portion of these signals so that their difference, if any, can be measured in a difference amplifier  $A_3$  and sent to delay  $D_2$  after amplification in a D.C. amplifier  $A_4$ . Another phase shifter (not shown) may be inserted in line 38' for programming purposes.

Amplifiers  $A_1$ ,  $A_5$  and  $A_2$  must be designed to pick up the desired frequency and attenuate all others including unwanted sidebands and then follow the selected frequency as it changes rapidly during the accelerating cycle as previously described. For this purpose an amplifier such as the self-tuning amplifier utilized in the RF system of the Bevatron operating at the Radiation Laboratory of the University of California, described in the publication UCRL 2593, dated June 4, 1954, may be used. For convenience, this amplifier may be designated a self-tracking amplifier. The arrangement of FIGURE 3 may be provided with additional filters to attenuate unwanted sidebands and harmonics, if needed, such apparatus being well known in the art as described in U.S. Patent 2,758,204. It should be noted that, if desired, in controllable delay  $D_1$  other variables affecting phase may be introduced so as to make other corrections in the direction or path of the proton bunches. It should also be noted that phase changes may be necessary to compensate for the spacing of the stations 14 along the orbit but this may be done conveniently at some point after mixer  $M_2'$ .

It should be understood that the foregoing disclosure relates to only a preferred embodiment of this invention and that numerous modifications may be made therein without departing from the spirit and scope of the invention as set forth in the appended claims.

We claim:

1. A phase shifting network comprising a source of input radio frequency signal of widely variable frequency, oscillator means for producing a radio frequency signal at a frequency differing by a constant amount from said input signal, said oscillator means comprising a first mixer and a radio frequency generator producing a constant frequency signal, said first mixer heterodyning said input signal with said constant frequency signal for producing said oscillator signal, means for introducing a selected amount of phase change in said oscillator signal, second mixer means for heterodyning said phase shifted oscillator

signal and said input signal for producing a beat frequency signal of unchanging frequency, and third mixer means for heterodyning said beat frequency signal with said oscillator signal prior to said phase shifting for producing an output signal of identical frequency to said input signal but phase shifted by the aforesaid selected amount. 5

2. A control circuit for transferring a radio frequency control signal from a source to a remote load with a predetermined amount of phase change, comprising, generator means for producing a radio frequency signal at a frequency having a constant difference with respect to said control signal, means for introducing a selected amount of phase change in said generator signal to compensate for phase changes introduced by said circuit between said source and said load and accomplish said predetermined phase change at said load, first mixer means for heterodyning said phase shifted generator signal and said control signal from said source for producing a beat frequency signal of unchanging frequency, and second mixer means for heterodyning said beat frequency signal with said generator signal prior to said phase shifting for reproducing said control signal for delivering to said load at said predetermined phase change. 10

3. The control circuit of claim 2 in which further means are provided to introduce a phase change in said beat frequency signal to make adjustments in said predetermined amount of phase change. 15

4. In a synchrotron having an orbital path for particle bunches, a control circuit for transferring a radio frequency control signal produced by an electrode at one point in said path detecting the passage of a particle bunch thereby to an accelerating station at another point on said path for delivering a driving signal at the instant said particle bunch is passing through said accelerating station, comprising generator means for producing a radio frequency signal at a frequency having a constant difference with respect to said control signal, means for introducing a selected amount of phase change in said generator signal to compensate for phase changes introduced by said circuit between said electrode and said station and necessitated by the time interval covered by said particle bunch travelling from said electrode to said station, first mixer means for heterodyning said phase shifted generator signal and said control signal from said electrode for producing a beat frequency signal of unchanging frequency, and second mixer means for heterodyning said beat frequency signal with said generator signal prior to said phase shifting for reproducing said control signal for delivery to said station at the desired phase. 20

5. In a synchrotron having an orbital path for particle bunches, a control circuit for transferring a radio frequency control signal produced by an electrode at one point in said path detecting the passage of a particle bunch thereby to an accelerating station at another point on said path for delivering a driving signal at the instant said particle bunch is passing through said accelerating station, 25

6. In a synchrotron having an orbital path for particle bunches, a control circuit for transferring a radio frequency control signal produced by an electrode at one point in said path detecting the passage of a particle bunch thereby to an accelerating station at another point on said path for delivering a driving signal at the instant said particle bunch is passing through said accelerating station, comprising generator means for producing a radio frequency signal at a frequency having a constant difference with respect to said control signal, means for introducing a selected amount of phase change in said generator signal to compensate for phase changes introduced by said circuit between said electrode and said station and necessitated by the time interval covered by said particle bunch travelling from said electrode to said station, first mixer means for heterodyning said phase shifted generator signal and said control signal from said electrode for producing a beat frequency signal of unchanging frequency, second mixer means for heterodyning said beat frequency signal with said generator signal prior to said phase shifting for reproducing said control signal for delivery to said station at the desired phase, and means to detect misalignment of said particle bunch from its proper path and introduce a further phase shift in said accelerating signal to correct said misalignment. 30

6. In a synchrotron having an orbital path for particle bunches, a control circuit for transferring a radio frequency control signal produced by an electrode at one point in said path detecting the passage of a particle bunch thereby to an accelerating station at another point on said path for delivering a driving signal at the instant said particle bunch is passing through said accelerating station, comprising generator means for producing a radio frequency signal at a frequency having a constant difference with respect to said control signal, means for introducing a selected amount of phase change in said generator signal to compensate for phase changes introduced by said circuit between said electrode and said station and necessitated by the time interval covered by said particle bunch travelling from said electrode to said station, first mixer means for heterodyning said phase shifted generator signal and said control signal from said electrode for producing a beat frequency signal of unchanging frequency, and said mixer means for heterodyning said beat frequency signal with said generator signal prior to said phase shifting for reproducing said control signal for delivery to said station at the desired phase, said generator means comprising an oscillator at constant frequency and a mixer for heterodyning said control signal from said electrode with the oscillator to produce said generator signal having said constant difference in frequency from said control signal. 35

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