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Author
Heard, Harry G.

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Harry G. Heard

Lawrence Radiation Laboratory
University of California
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ABSTRACT

This paper describes the use of p-n junction voltage-sensitive capacitors to modify the basic radio-frequency tracking program of the Bevatron. It is shown that adequate dynamic range exists to position the proton beam anywhere within the useful aperture of the accelerator at any energy during the acceleration or deceleration cycle.

The advantages of electrostatic as contrasted with the former magnetic-tracking correction are discussed. A completely transistorized relay-operated function generator is described that synthesizes the tracking-error-correction signal during the acceleration and deceleration cycles.

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INTRODUCTION

The period of the radio-frequency voltage generated by the low-level tracking oscillator of the Bevatron is controlled, to first order, by a signal derived from either the Bevatron magnetic field or the magnet current. The basic period of the oscillator is determined by the inductance of a saturable reactor.[1] As the Bevatron magnetic field or current varies, the oscillator and its associated equipment generate the function

$$\omega = f_1 (B) \qquad \text{or} \qquad \omega = f_2 (I)$$

where ω = rf angular frequency, I = magnet current, B = magnetic induction, and f_1 and f_2 are the transfer functions of the individual saturable reactors. Transfer functions of the oscillator are obtained by choosing the ferrite-core-reactor parameters to yield an inductance variation of the form

$$L = K_1 \left(1 + \frac{K_2}{B^2}\right), \qquad \text{or} \qquad L = K_3 \left(1 + \frac{K_4}{I^2}\right),$$

where L = the total inductance of the oscillator reactor, and K_i (i = 1, 2, 3, 4) are the system constants. The frequency range of the Bevatron rf equipment is only 7:1, a range easily obtained with a single saturable-reactor-controlled oscillator. The generation of a prescribed open-loop transfer function with a current-programmed oscillator requires a suitable combination of fixed and current-programmed inductors.

In the past the transfer function for the tracking oscillator has been obtained with two saturable reactors, one fixed reactor, and two shunt capacitors.[2] One variable reactor supplied the low-frequency portion of the transfer function. A second reactor supplied the desired functional relationship at high frequencies.[3] The transfer function was further refined

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[1] A. J. Pressman and J. P. Blewett, 39, 74 (1951).

[2] Winningstad, Paxson, Anderson, Kerns, and Riedel, Bevatron rf System, UCRL-1750, April 1952.

[3] C. Norman Winningstad, The rf System of the Bevatron, UCRL-2593, June 1954.

by apparatus that supplied a flexible synthetic correction signal. Two methods have been used to generate this correction signal. At first a 30-point curve-correction generator was used.[4] This was later replaced by an analog computer.[5]

A different approach to generating f_1 and f_2 is to use a single current-programmed inductor to obtain the transfer function to within 5%. The desired frequency is then produced at any magnet current or magnetic field by suitable voltage modulation of biased p-n junction diodes. This paper considers this method of frequency modulation, the characteristics of the new Bevatron frequency-control system, and the associated apparatus design to employ the principle of electrostatic beam tracking in the Bevatron.

THE CAPACITOR MODULATOR

A block diagram of the new frequency-control system of the Bevatron is shown in Fig. 1. The magnetic field is shown as the basic program source here for two reasons. First, the illustrated system compensates, to first order, for any changes in the rate of change of the magnetic field. Such changes result from the pulsing of auxiliary windings in the magnet aperture for extended charge acceptance.[6,7] Second, the magnetic field is fundamentally related to the frequency of the circulating beam. Obviously, the magnet current may be used to supply the saturating current to the reactor for simple tracking.

The capacitor modulator consists of an rf by-passed voltage divider that supplies a dc bias current to a set of 20 silicon p-n junction capacitors. The modulator is driven from the midpoint of the capacitors by way of a dc-coupled input. The capacitors have a voltage-sensitive characteristic given by the relation[8]

$$C \sim C_o V^{-\frac{1}{n}}, \text{ for } 1 < n < 4,$$

where C = capacity of the junction diode, Co = constant, V = reverse bias voltage, and n is a numerical value depending upon the characteristics of the p-n junction. As the dynamic range of the modulator decreases rapidly with increasing bias, a sufficient number of diodes is selected to give the desired dynamic range with minimum bias. The modulator, shown in Fig. 2, has a modulation index of approximately 1% of the instantaneous

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[4] Harry G. Heard, Bevatron Operation and Development. VI, UCRL-3212, Nov. 1955, p. 19.

[5] Harry G. Heard, Analog Tracking of the Bevatron Beam During Acceleration and Deceleration, UCRL-8296, July 1958.

[6] Harry G. Heard, The Effect of Rate of Rise of Magnetic Field on the Acceptance Time of the Bevatron, UCRL-3682, Feb. 1957.

[7] Harry G. Heard, A New Method for Controlling the Magnetic Field in the Aperture of Synchrotrons, UCRL-3427, May 1956.

[8] W. Shockley, The Theory of the p-n Junction in Semiconductors and p-n Junction Transistors, Bell System Tech. J. 28, p. 435 (1949).

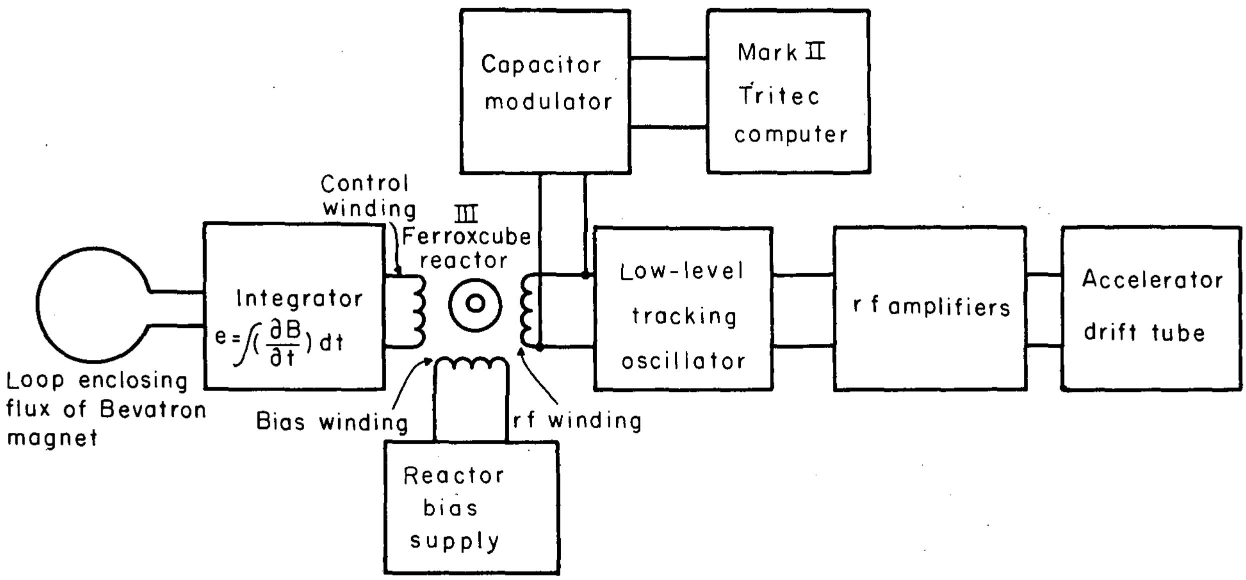

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Fig. 1. Block diagram of the electrostatic beam-position control system of the Bevatron.

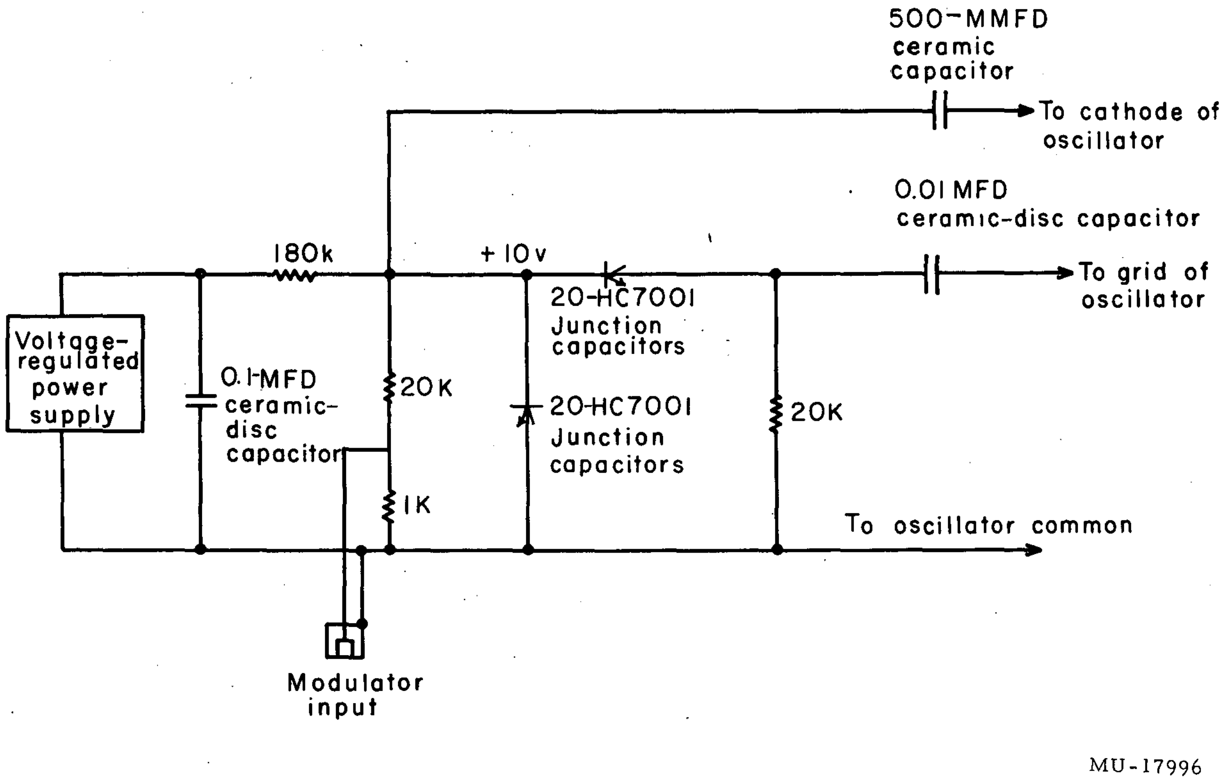

Fig. 2. Schematic diagram of the capacitor modulator.

frequency per volt of modulating signal. The dynamic range of the system (see Fig. 3) is more than 20% of the instantaneous frequency, over the Bevatron frequency range. This dynamic range is sufficient to track the proton beam anywhere within the useful aperture during the entire acceleration cycle. As this range is also greater than that developed by the second saturating reactor and associated equipment in the former tracking system,[2, 3] a considerable system simplification has been effected.

The stability of the tracking oscillator depends upon the characteristics of the ferrite core and the junction capacitors. The characteristics of the ferrite core are treated elsewhere and are not discussed here.[9] The junction capacitors are subject to a drift of approximately 200 ppm/°C. This characteristic results in a frequency drift of less than 0.01% /°C: an entirely negligible effect compared with the frequency drift caused by the ferrite core itself.

The response of the capacitor modulator to external signals, as shown in Fig. 4, is independent of frequency from dc to 10 kc. The frequency response is not limited by the junction capacitors. The parameters of the high-impedance bias network were chosen to place an upper limit on the system response to external signals. The oscillator response with the junction capacitors is faster than the former system (which used saturable-reactor modulation) by nearly an order of magnitude.

Another desirable characteristic of the junction capacitors is their relative freedom from hysteresis effects. In the former frequency control system, the beam tracking at the high-frequency portion of the acceleration cycle was markedly affected by any variations in the amplitude or duration of a modulating signal. These hysteresis effects reduce the general utility of the accelerator, as they place an upper limit on the number of experiments that may be accommodated during a given beam pulse. As no interaction or memory effects occur when the beam is controlled by the capacitor modulator, the flexibility of the accelerator is limited only by the quantity of beam available and by target interference.

DESCRIPTION OF THE MARK II TRITEC COMPUTER

The Mark I TRITEC analog computer,[10] which has proved reliable and effective in beam tracking, has been used as a basis for the design of the Mark II TRITEC computer. The system design criteria already outlined for the Mark I TRITEC[5] were extended to include printed-circuit plug-in modules. Thus provision has been made for quick replacement of circuit modules for servicing and maintenance.

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[9] Blewett, Blewett, and Plotkin, Properties of Ferrites, Rev. Sci. Instr. 24, 800 (1953).

[10] The name TRITEC was derived from the first letters of the complete title "Transistorized Rectification-Inversion Tracking-Error Corrector."

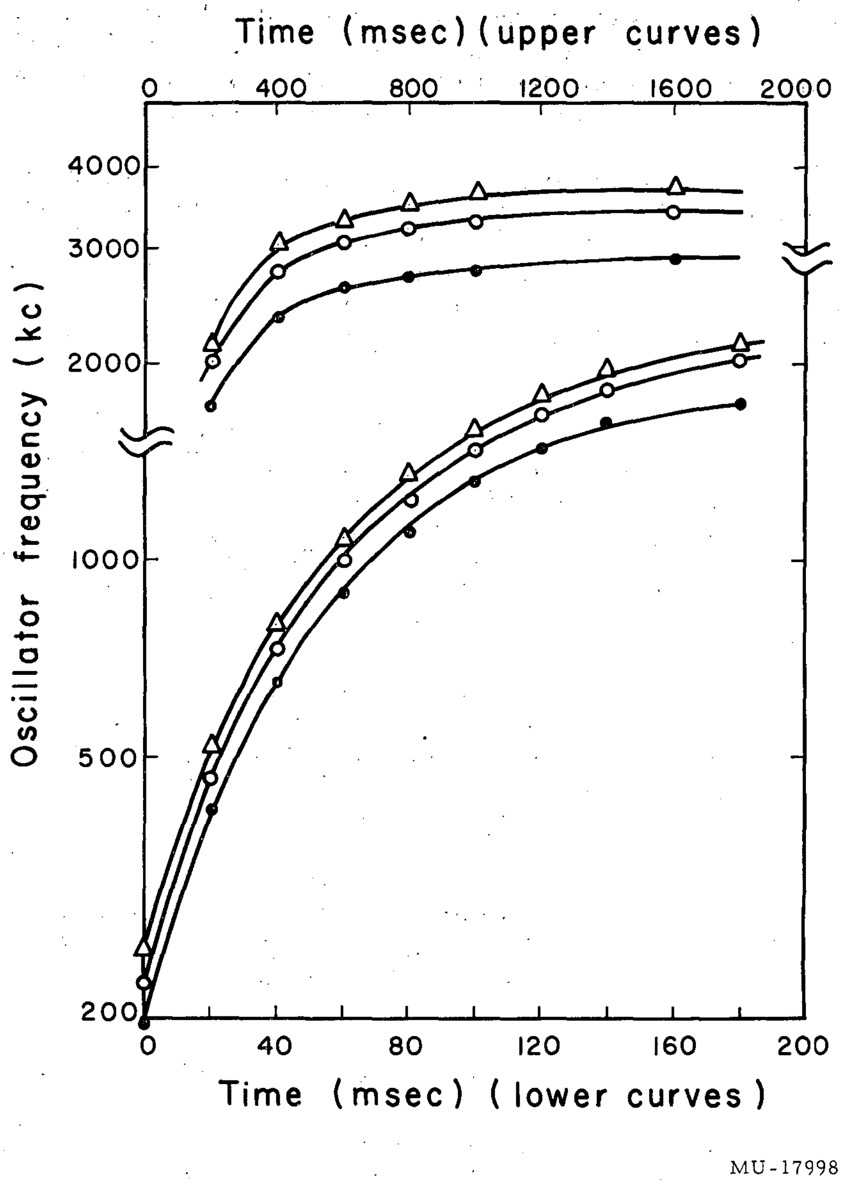

Fig. 3. Dynamic range of oscillator as varied by capacitor modulator
Oscillator frequencies: O without capacitor modulator control
△ with +10 v bias on modulator
● with -10 v bias on modulator
Reference bias on two sets of 12 HC7001 diodes = +10 v.

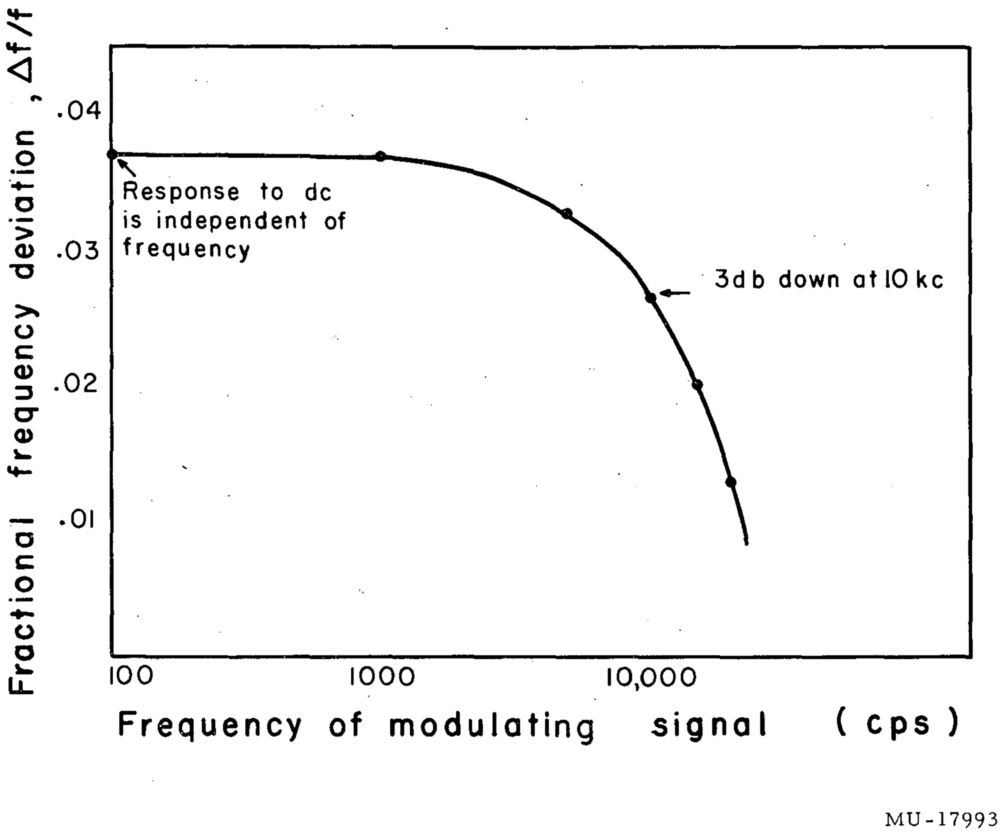

Fig. 4. Frequency response of capacitor modulator.

The task of the Mark II TRITEC is to generate the basic tracking-error-correction signal for the capacitor modulator. The computer, as illustrated in Fig. 5, consists of three chassis, one of which is a low-voltage regulated power supply. The other two units include the remote-control unit and the computer proper. Only the computer proper is discussed in this paper. The remote-control unit and power supply are the same units used in Mark I.

An operating cycle of the computer is initiated upon receipt of a trigger. This trigger is normally provided by a peaking strip located in the stray field of the Bevatron magnet. The time-dependent voltage output of the function-generating circuits is transformed in impedance level by a dc-coupled line driver before it is transmitted over a coaxial cable to the capacitor modulator.

Although provision is made for remote control of the computer, local control may be obtained by interlocked-plug substitution at the rear of the computer. This facility provides for local testing during maintenance. In addition, a desired program for operation may be stored indefinitely by locking the shafts of the local controls.

The operating cycle of the computer may be visualized with the aid of Figs. 6 and 7, which show the function-generating networks and the output signal. Function generation is accomplished by charge transfer. The complete tracking curve for acceleration and deceleration is divided into five major elements. Provision is made to vary the duration, amplitude, and shape of each portion of the curve. Timing control is obtained with the relay-driving monostable multivibrators. Amplitude control is obtained by setting the peak voltage to which the capacitors are charged. Shape control is obtained by varying the charging or discharging rate of the capacitors with resistor networks. Over-all function continuity is obtained by storing charge on memory capacitors. Although the time, amplitude, and shape controls interact somewhat, their range of control is design-limited so that improper function generation is difficult.

FUNCTION GENERATION

The interaction of the various passive elements in function generation is best visualized by reference to the simplified diagrams in Figs. 6 and 7.

The following conventions will be adopted in describing the sequence of operation:

(a) All relays are shown in their de-energized position.

(b) Subscripts 1 through 6 indicate portions of the curve shown in Fig. 7.

(c) Subscripts greater than 10 denote a subdivision of portions of the curve of Fig. 7.

(d) Capital letters, T, H, and S refer respectively to time, amplitude, and shape controls.

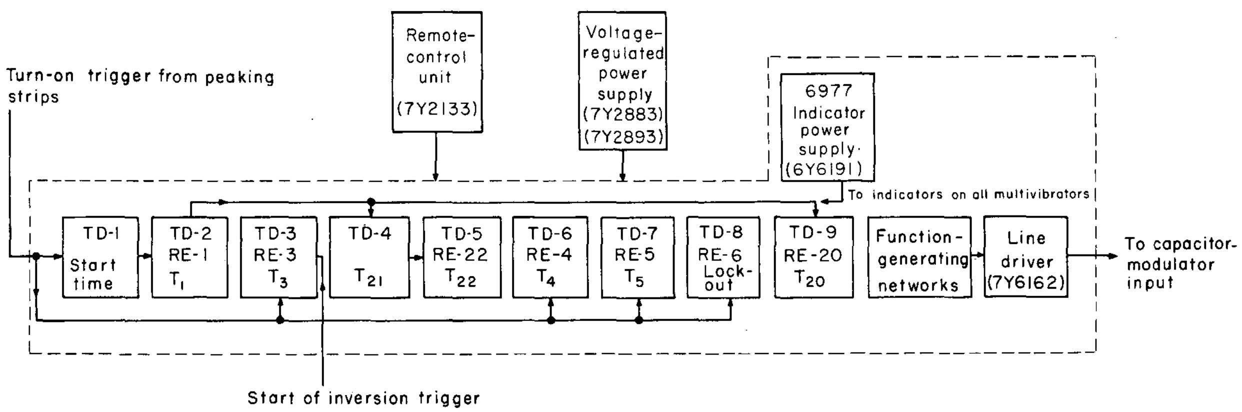

Fig. 5. Simplified block diagram of Mark II TRITEC computer.

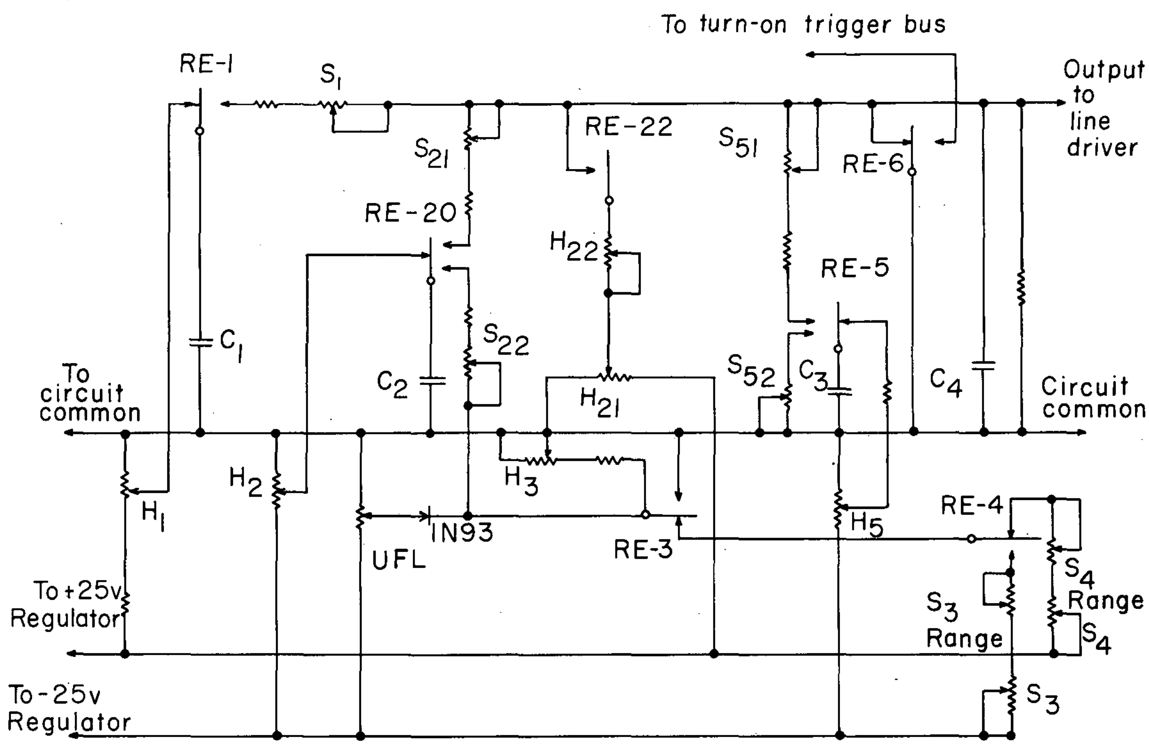

Fig. 6. Simplified diagram of function-generating networks.

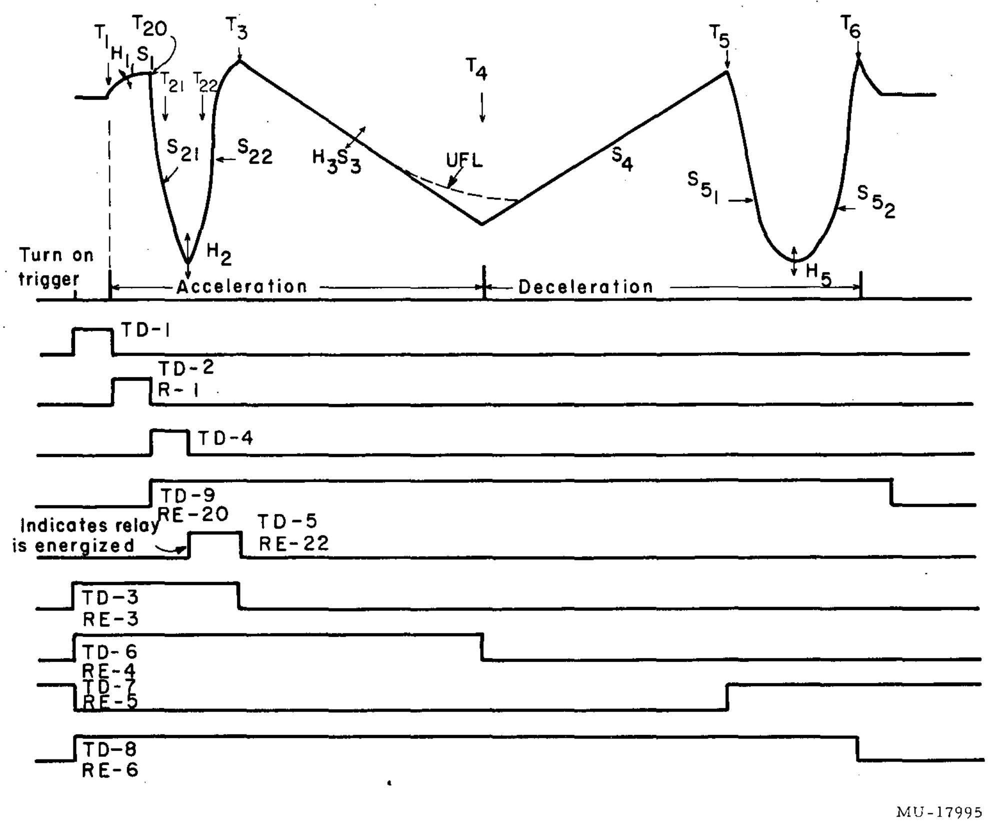

Fig. 7. Output signal and relay sequence of the Mark II TRITEC.

Upon receipt of a trigger, five of the nine monostable multivibrators, TD-1, 3, 6, 7, and 8, transfer to their quasi-stable states and thereby energize RE-3, 4, and 6 and de-energize RE-5. When RE-6 picks up, a short is removed from the output and applied to the input trigger to preclude false triggering for the duration of the acceleration cycle. The time between the initiating trigger and the start of function generation is controlled by TD-1. When TD-1 returns to its stable state, it triggers TD-2 to energize RE-1, which in turn generates the first portion of the tracking curve. When TD-2 returns to its stable state it triggers TD-4 and TD-9. RE-20 energizes and starts the second portion of the tracking cycle. Meanwhile TD-4 times out and triggers TD-5. RE-22 now energizes and modifies the output voltage until TD-3 times out to release RE-3, thereby resetting TD-5 and releasing RE-22. At this instant all the monostable multivibrators have been triggered once to their quasi-stable states. Function generation now proceeds as TD-6, 7, and 8 time out. The sequence ends as TD-8 times out and releases RE-6 to permit another trigger to initiate function generation.

Before an initiating trigger arrives, RE-5 in TD-7 is energized. The voltages to which capacitors C_1, C_2, and C_3 are charged are determined by the controls H_1, H_2, and H_5, respectively. As soon as an initiating trigger is received, RE-5 is de-energized and C_3 charges through H_5 for use during beam deceleration. RE-6 energizes to lock out the input and remove the short from the output bus. RE-3 and 4 energize to activate circuits to be used later during the acceleration cycle. When TD-1 transfers to its quasi-stable state, the cycle is started. When TD-1 times out, TD-2 is triggered and RE-1 is energized. The positive charge on C_1, as determined by H_1, is transferred to C_4 via S_1 and the output voltage rises. After TD-2 times out, TD-9 is triggered. RE-1 is de-energized and RE-20 is energized. The negative charge on C_2, as determined by H_2, is transferred to C_4, via S_{21}, and to circuit common via S_{22} and RE-3. The output voltage now swings to a negative value, and reverses direction again, and were it not for TD-4, TD-5 and RE-22 would approach zero. Actually, TD-4 is triggered at the same time as TD-9. When TD-4 times out it triggers TD-5 and energizes RE-22. C_4 now charges toward a positive voltage via H_{21} and H_{22}. Shortly after the output voltage becomes positive TD-3 times out, releasing RE-3 and resetting TD-5 to release RE-22. This connects C_2 and C_4 through the contacts of RE-3 and RE-4, thence via S_3 to a negative voltage. S_3 and H_3 now supply current to charge C_2 and C_4 negative. If the magnetic field is arrested during the acceleration cycle for a few hundred milliseconds, the Upper Frequency Limit Control (UFL) can be used to suitably limit the negative swing of the output voltage until the inversion cycle of the magnet-power supply starts. A trigger derived from the start of the inversion cycle resets TD-6 and releases RE-4. C_2 and C_4 are now charged toward a positive voltage through S_4 and H_3 and the output voltage rises again. By the time the output voltage becomes a few volts positive, TD-7 times out and energizes RE-5. The negative charge on C_3 is now transferred to C_2 and C_4, and the output voltage once more goes negative. S_{51} and S_{52} dissipate the energy stored in C_2, C_3, and C_4. The output voltage would return to zero were it not for the charge supplied to C_2 and C_4 from the positive supply via S_4, RE-4, RE-3, H_3, S_{21}, and S_{22}. Next, TD-8 times out and RE-6 de-energizes to short the output. Finally, TD-9 times out, RE-2 is de-energized, and the cycle is completed.

CONSTRUCTION FEATURES OF THE MARK II TRITEC

The Computer circuits are contained in a special cabinet shown in Fig. 8. This cabinet provides fourteen 22-pin plugs suitable for an equal number of 5X10-inch printed-circuit boards. With the exception of the indicator-power supply and line driver, all printed-circuit boards are of identical construction. Boards are fabricated from 1/8-inch epoxy glass to prevent warping. The printed wiring is 1-oz.-copper clad. A thin gold wash is provided to prevent corrosion. The wiring circuit is silk-screened on the component side of the board to assist in construction and maintenance.

Function-generation controls and resistor-network parameters are localized to the lower half of the cabinet. The mercury-contact relays are accessible from the rear of the lower chassis. The fixed resistor-network parameters are mounted on lugs inside the inner door of the lower half of the cabinet. The fixed capacitors, which must be changed if the accelerator magnet is pulsed with one generator instead of two generators, are mounted on a plug-in printed-circuit board. The changes in the timing networks for the multivibrators are obtained with an auxiliary set of plug-in boards designated for one-generator operation. Local controls are provided as shaft-lock potentiometers on the inner door. The outer door of the cabinet contains nine 6977 indicator triodes to present the state of all the multivibrators. Access to the printed-circuit cards is attained from the front of the cabinet. The rear of the cabinet also has a door. This door contains power, control, and signal cables as well as a running-time meter and ac power control circuitry. Behind the rear door one obtains access to the printed-circuit connectors. A special adapter board serves as a plug-in extension through which the printed-circuit board can be operated while removed from the cabinet for servicing.

CIRCUITRY

The specific circuit designs are not discussed in this paper. For these details the reader is referred to UCRL prints 7Y2133, 7Y2883, 7Y2893, 7Y6162, 6Y6191, 7Y6802, 7Y6585 and 7Y6592.

CONCLUSIONS

It has been demonstrated that p-n junction capacitors may be used instead of saturable reactors for obtaining the required correction program of a simple saturable-reactor-controlled oscillator. The use of voltage-sensitive capacitors results in considerable gains in circuit simplicity, reliability, frequency response, and stability. The flexibility of the accelerator is increased by the use of these capacitors, as they exhibit little if any hysteresis or memory effects.

A completely transistorized, relay-operated computer is described that synthesizes the necessary time-dependent voltage for tracking-error corrections. The Mark II TRITEC will track the Bevatron beam at all energies during the acceleration and deceleration cycle.

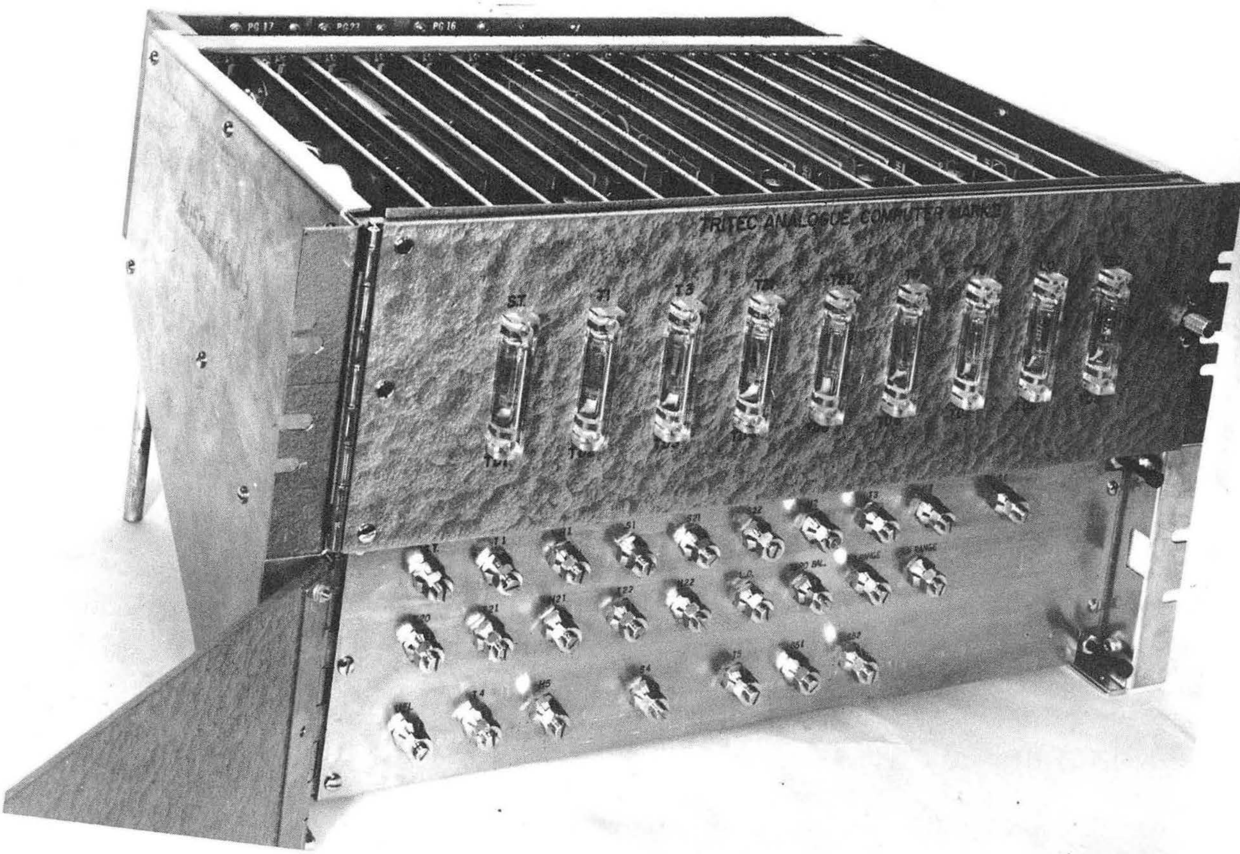

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Fig. 8. Photograph of the Mark II TRITEC showing construction details.

ACKNOWLEDGMENTS

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