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Harry G. Heard

July 1, 1959

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ABSTRACT

A transistorized tracking system is described that generates the signals necessary to control the radial position of the proton beam of the Bevatron. The source of frequency-correcting signal may be either an analog computer or a radial-position discriminator that derives signals from the beam itself. Provision is made to switch from one tracking-signal source to the other at the instant the two voltage sources have equal values. The system will track the proton beam at all levels of beam intensity and may be used in conjunction with pulsed auxiliary magnet windings to extend the injection time of the accelerator, thereby increasing the over-all intensity of the beam. The advantages of automatic beam tracking are obtained without a sacrifice in operational flexibility.

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I. Introduction

The period of the radio-frequency voltage that accelerates the proton beam of the Bevatron is controlled, to first order, by the inductance of a saturable reactor in the low-level tracking oscillator. The saturating current for this reactor is derived from the shunted magnet current or, from the magnetic field, by integrating the voltage induced in a loop located in the magnet aperture. The second-order corrections to the radio-frequency voltage, which are necessary if the beam is to be kept within the magnet aperture, are either synthesized with an analog computer[1] or derived from the radial position of the beam.[2] These tracking-error signals modulate voltage-sensitive capacitors that shunt the saturable reactor.[3]

The system described in this paper derives the radial-position tracking-error signal. In addition it integrates the functions of the analog computer and the radial-position discriminator to facilitate the use of either or both signal sources for controlling the radial position of the proton beam during the acceleration and deceleration cycles of a Bevatron magnet-current pulse.

[1,2] Harry G. Heard, Bevatron Operation and Development. VI, UCRL-3212, Nov. 1955.

[3] Harry G. Heard, Electrostatic Tracking of the Proton Beam of the Bevatron, UCRL-8808, June 1959.

II. Description of Apparatus

The Beam-Controlled Frequency-Correction System consists of six major units. These include the beam-induction electrodes, the low-level and high-level rf amplifiers, the electronic circuitry associated with deriving and controlling the disposition of the radial-position information from the beam (generally described below as the radial-position discriminator), an analog computer and its control unit, the capacitor modulator, and various power supplies. As the analog computer and capacitor modulator have been described elsewhere,[3] and the rf amplifiers and power supplies are of familiar design, the discussion in this paper will be confined to the remaining units.

III. Beam-Induction Electrodes

Two identical beam-induction electrodes, placed symmetrically about the center line of the magnet aperture, generate electrical signals that are a function of the radial position and intensity of the proton beam.[4] As the electrodes are equivalent to less than 1% of the length of the bunched proton beam, the instantaneous potential of the electrodes corresponds to the density of the bunch measured in the direction of motion. Radial-position information is obtained from these electrodes by making their response a rapidly changing function of the radial position of the beam. The voltage induced on each electrode, as indicated by rf model studies, varies by a factor of approximately 20 over the central 8 inches of the magnet aperture, (see Fig. 1).

If the radial position of the beam is determined by taking the difference, at radio frequencies, between the voltages induced on each electrode, the beam-position definition can be quite accurate. Because of practical difficulties associated with envelope recovery, the signals from each electrode are amplified to the order of tens of volts and rectified before their difference is obtained. If the gain of the wide-band amplifiers is not the same for each signal, a residual signal level will appear even though the beam is, in fact, centered in the aperture. In the closed-loop system described below, this

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[4] Harry G. Heard, Bevatron Beam-Induction Electrodes, UCRL-3609, Feb. 1957.

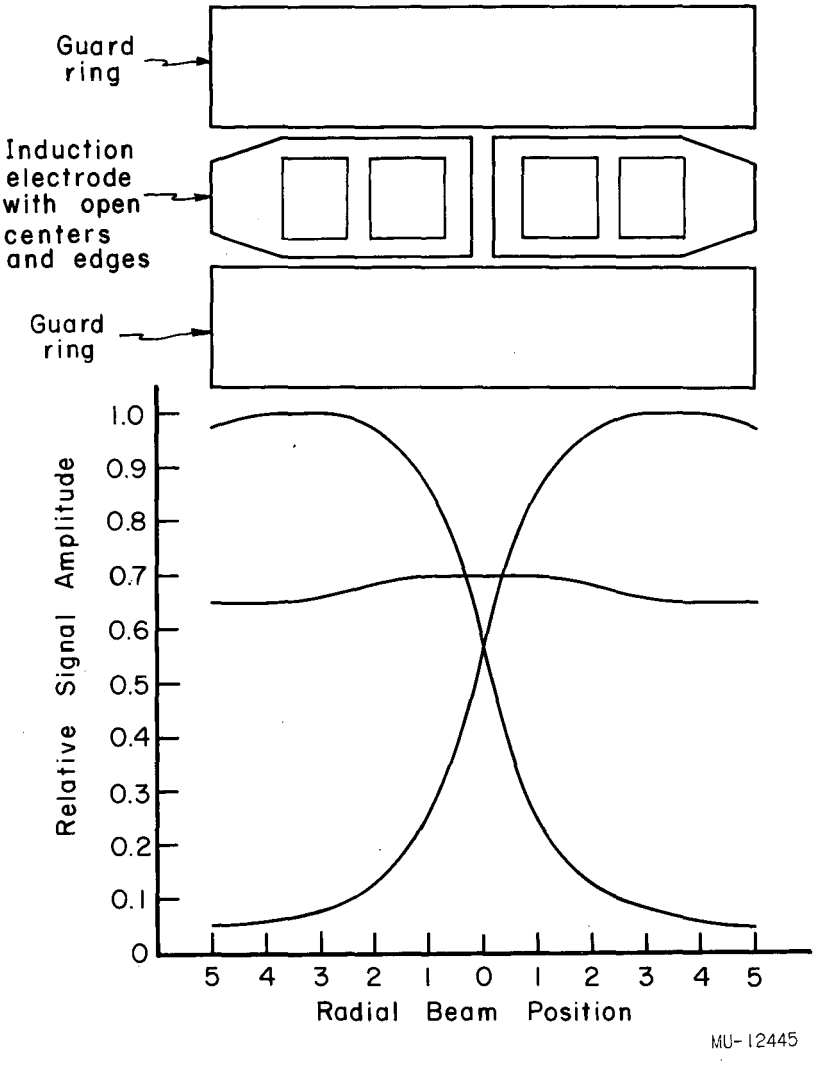


Fig. 1. Response of the radial-position and sum-induction electrodes in the south straight section of the Bevatron.

residual signal will cause a small error in radial positioning of the beam. The magnitude of this error is minimized by making the discrimination ratio of the beam-induction electrodes as large as possible. A residual signal on the order of 10% will cause a beam-position error of less than 3/4 in. when the servo position loop is closed.

If the beam is tracked with the radial-position discriminator, there is a lower limit of beam intensity below which automatic tracking is ineffective. This limit is reached when the beam intensity, as detected by the limiting sensitivity of the induction electrodes, is of the same order as the noise level of the induction-electrode amplifiers. For transistor emitter followers this limit is on the order of 10^7 protons. When it is desired to track beam below this intensity -- as, for example, for an internal emulsion exposure, or when Coulomb scattering causes large beam losses--the beam must be tracked from a synthetic source. As outlined below, the analog computer may be selected for exclusive control of tracking as these occassions arise.

IV. Beam-Control Equipment

The functioning of the various parts of the beam-control equipment is best visualized with the aid of the block diagram of Fig. 2. Signals derived from the radial-position induction electrodes are first amplified, and then fed to the demodulator-mixer. Here they are demodulated to obtain a dc voltage dependent upon the radial position and intensity of the beam. These voltages are fed to a mixer, consisting of a feedback-stabilized dc-differential amplifier, having two summing junctions. An appropriate time-dependent signal is added at these junctions to the demodulated signals from the beam. The time-dependent signal, derived from the saturation program generator, is used to reduce the frequency of the tracking oscillator by an appropriate amount to compensate for the outward shift of the useful magnetic aperture at high proton-beam energies.[5] The output voltages of the demodulator mixer are further amplified and discriminated by another feedback-stabilized dc-differential amplifier. The single-ended output of the latter unit is fed to the comparator, via the auto-manual switching-level control; it also goes to one input of the diode switch.

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[5] Harry G. Heard, Correction of the Magnetic-Field Gradient of the Bevatron with Pole-Face Windings, UCRL-3944, Sept. 1957.

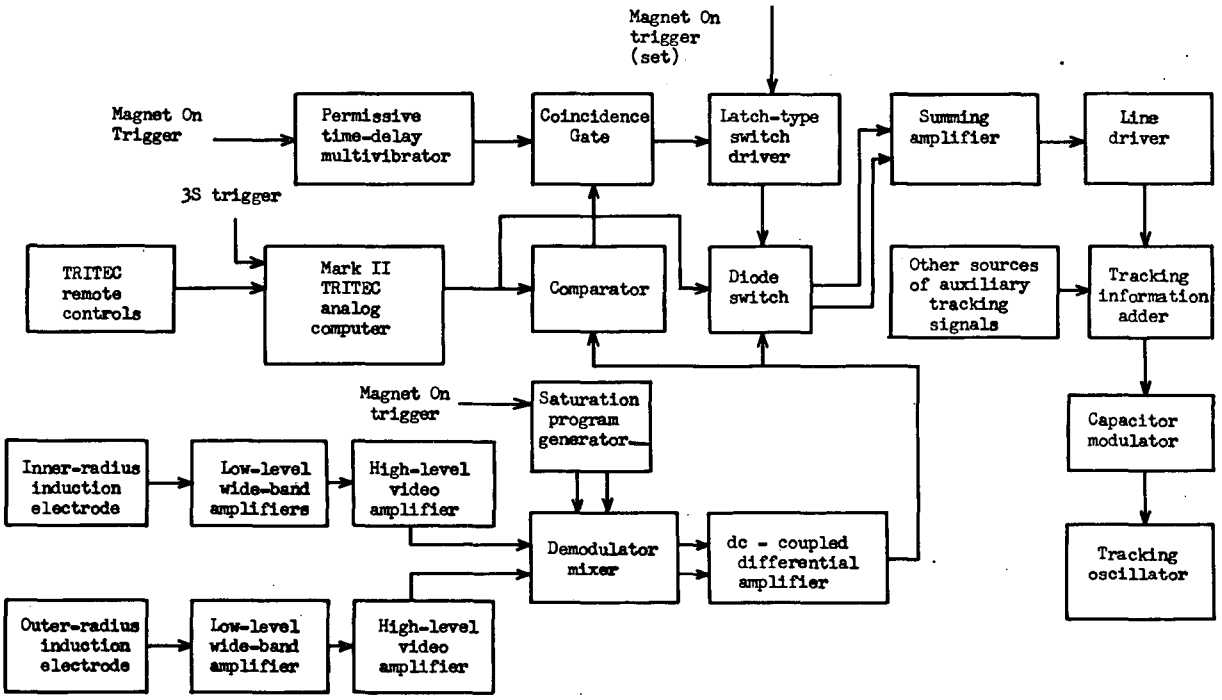


Fig. 2. Block diagram of the Bevatron-beam-controlled frequency-correction system.

The output of the Mark II TRITEC Analog Computer[3] is fed to the other input of the comparator as well as to the other input of the diode switch.

The diode switch output feeds a summing amplifier. When activated by the switch driver, the diode switch and summing amplifier perform the "EXCLUSIVE OR" function. That is, the summing-amplifier output contains either the beam-derived or the analog-computer-derived frequency-correction signal, not both. To further reduce interaction between these sources, the inactivated signal source is always shorted out by the diode switch. The summing-amplifier output is fed to the line driver, thence to the tracking-information adder, and finally to the capacitor modulator in the tracking oscillator.

The switch driver is SET by a trigger derived from the magnet excitation voltage (Magnet On). When SET, the diode switch shorts out the analog-computer output and ultimately connects the beam-derived frequency-correction signal to the tracking oscillator. The switch driver is RESET by a trigger derived from the coincidence gate. Coincidence is indicated when the permissive time-delay multivibrator, which was previously triggered by a "Magnet On" pulse, times out and, in addition, a trigger is received from the comparator. The latter unit generates triggers whenever the analog signal compares with the reference level (manual switching) or whenever the beam-derived radial-position signal compares with the analog signal (automatic switching). This switching logic permits the accelerator to start tracking from the beam itself. After a predetermined time, the beam is switched automatically to analog control so that arbitrary beam-position control may be exercised as needed for individual experiments. In those experiments in which there are no constraints on beam position, the beam may be tracked without analog control by denying the RESET for the switch driver. Whenever it becomes necessary to control the beam exclusively with the analog computer, automatic tracking can be turned off by denying the SET trigger for the switch driver and the trigger for the permissive time-delay multivibrator. This function is provided by a front-panel-mounted switch.

For the most part, the electronic circuits developed for this system will not be discussed in detail. The reader is accordingly referred to the following UCRL prints: 7Y7044, 7Y7033, 6Y6182, 7Y7012, 7Y7023, 7Y7104, 7Y6162, 6Y6162, 6Y6191, 7Y6124, 7Y7212, 7Y7223, and 7Y7233.

V. Stabilized Transistor dc Amplifiers

The importance of system stability in the direct-coupled feedback loop that controls the radial position of the internal proton beam may be understood from the following. The voltage-sensitive capacitors, which correct the frequency of the tracking oscillator, have a sensitivity on the order of 30 parts per thousand. The internal beam, for the worst case at 2.5 Mc has a position-versus-frequency sensitivity on the order of 1300 parts per million. Therefore voltage changes of the order on 20 mv result in beam displacements on the order of 1 in. For routine operation, therefore, a system stability on the order of millivolts is required.

In order to develop an over-all system stability on the order of millivolts with transistorized circuitry, special attention must be given to the thermal characteristics of the active and passive circuit elements and, in addition, the sensitivity of the circuits to variations in power-supply voltages. Drift in dc-coupled transistorized circuits is mainly caused by two phenomena: variation of the input conductance of the transistor with temperature, and variation of the collector-to-base saturation current. Changes in the value of the base spreading resistance and the current amplification factor with temperature are sufficiently small so that, for most applications, their variation may be neglected. Whether input conductance or saturation current limits the stability of the dc amplifier depends upon the ambient temperature. Both these temperature-sensitive phenomena vary at approximately the same rate.[6] Considering germanium transistors at room temperature, the input conductance increases 10% per ^{o}C. Similarly, the saturation current increases 10% per ^{o}C. For the circuits under consideration here, the variation of the input conductance limits the over-all stability. Expressed in terms of the variation of base-to-emitter voltage for a fixed collector current, germanium transistors at room temperature, exhibit an average negative shift of 2 to 3 mv/^{o}C. As the rate of shift is predominantly a function of the energy gap of the semiconductor material, being larger for silicon than for germanium, no increase in stability can be expected in the circuits described below through the use of the more expensive silicon transistors.

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[6] Shockly, Sparks, and Teal, p-n Junction Transistors, Phys. Rev. 83, 151 (1951).

To operate the input stage of the dc-coupled amplifier at constant collector current, despite changes in the base-to-emitter voltage with temperature, requires that the emitter current be held constant. Constant-emitter-current operation can be obtained without undue loss in gain if an emitter-coupled or differential-amplifier configuration is used.[7]

The emitter-coupled amplifier has several additional characteristics that are of considerable importance. Space does not permit a detailed development of the characteristic of this circuit. It will be sufficient to point out that this amplifier may have high input impedance (megohms) good gain stability (1%), high common-mode rejection (100:1), high voltage and current gain (approximately one-half that of a common emitter amplifier), low output imedance, good frequency response, and large dynamic range, as well as low drift. Further, if several common-emitter amplifiers are cascaded, using alternate n-p-n and p-n-p transistors, the over-all system can be made relatively insensitive to power-supply voltage changes. The summing amplifier (Fig. 3) is an example of the type of amplifier used in this system. This amplifier has an open-loop gain of approximately 80 db, and a rejection ratio greater than 60 db. In the closed-loop configuration it has an internal gain of 10, a long-time stability on the order of a millivolt, and a frequency response flat from dc to 150 kc. The transient output impedence is a fraction of an ohm and, with a single 2N1041 output transistor, the amplifier will deliver a 15-volt (peak-to-peak) signal to a 100-ohm resistive load. The output noise level depends upon the band width of the amplifier. For wide-band operation the rms noise level is on the order of 1 mv. If the power-supply voltages are changed independently by 1%, the output voltage shifts approximately 10 mv, indicating significant internal degeneration. Amplifiers of similar configuration are used in the demodulator-mixer, saturation program generator, and radial-position discriminator, and line driver.

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[7] D. W. Slaughter, The Emitter-Coupled Differential Amplifier, Trans. I.R.E. (Circuit Theory) March 1956, p. 51.

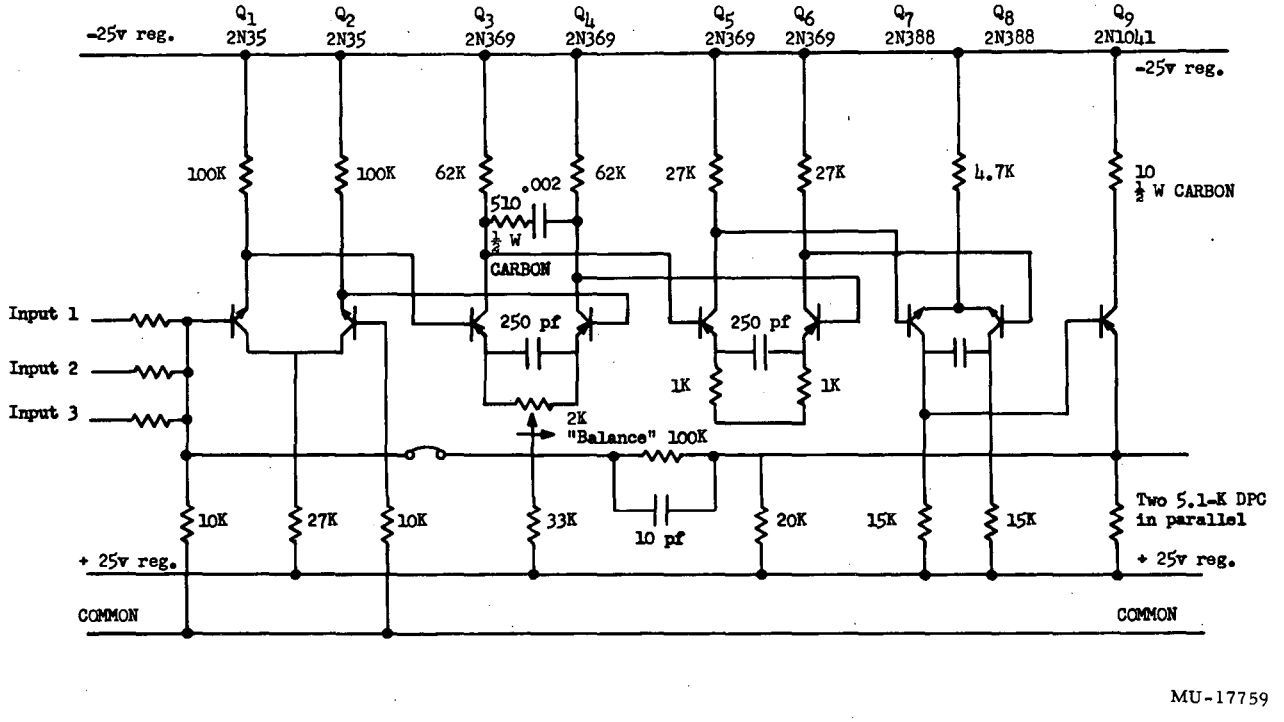


Fig. 3. Schematic diagram of the summing amplifier.

VI. Permissive Time Delay

Before the diode switch changes the tracking-error signal from the radial-position discriminator to the analog computer, it is desirable that the proton-beam energy be relatively high. This is because the tracking-error signal is relatively complex at low beam energies. At energies of more than 1.5 Bev the error signal becomes a montonic function. The permissive time-delay multivibrator, which is triggered to its quasi-stable state by a "Magnet On" trigger, provides the desired delay. It is only after this multivibrator returns to its stable state that a signal of the proper polarity is sent to the coincidence gate.

VII. Comparator

Equality between the two sources of tracking-error signal is indicated by an output pulse from the comparator. This unit consists of a pair of emitter followers that couple the signal sources to an emitter-coupled amplifier. The output of one collector of the amplifier is dc-coupled to an emitter follower that drives differentiating networks. The differentiated output signals, which correspond to the comparison of the two error signals, are amplified by two cascaded n-p-n — p-n-p Class B amplifiers. The amplified leading edge of the comparison pulse drives a biased blocking oscillator. This unit is capable of generating an output trigger of 25 volts when the two tracking-error signals compare within a millivolt.

VIII. Coincidence Gate and Switch Driver

As the comparator generates pulses every time the tracking-error signal from the radial-position discriminator equals that from the analog computer, a logical "AND" or coincidence gate is necessary to insure that the switch driver is not RESET until the proton-beam energy is in excess of 1.5 Bev. The first comparator output pulse that is generated, after the permissive time delay returns to its stable state, activates the coincidence gate. The transistor AND circuit triggers a biased blocking oscillator that RESETS the switch driver.

The switch driver consists of two latch-type bistable multivibrators and four buffer amplifiers. These multivibrators change states only on the first pulse of a unipolarity pulse train. After they have been SET or RESET they are insensitive to additional pulses of the same polarity from the same source. Pulses of the opposite polarity are precluded by diodes. The choice of this type of circuit renders the switch driver insensitive to additional pulses that occur whenever the radial-position discriminator and analog computer signals are equal. One and only one transition can be made, and this transition can occur only after receipt of a trigger from the coincidence gate. A simplified diagram of one latch-type multivibrator is shown in Fig. 4.

IX. Diode Switch

The diode switch provides a convenient means of synchronous switching between signal sources at electronic speeds. As shown in the simplified schematic, Fig. 5, a single unit of the diode switch consists of a ring of four high-back-resistance diodes driven by a pair of biased, pulse amplifiers. The current output of the switch driver unit is sufficient to drive the pulse amplifiers from cutoff to saturation. Transistor storage effects, encountered were the pulse amplifiers turned off from the saturated state, would produce undesired switching transients in the output of the diode switch. To overcome this limitation, fast germanium switching transistors were used, and, in addition, the transistor switches were clamped to within a few hundred millivolts of saturation by a diode-feedback-clamp circuit. If a silicon diode and a germanium diode are connected in a feedback loop around

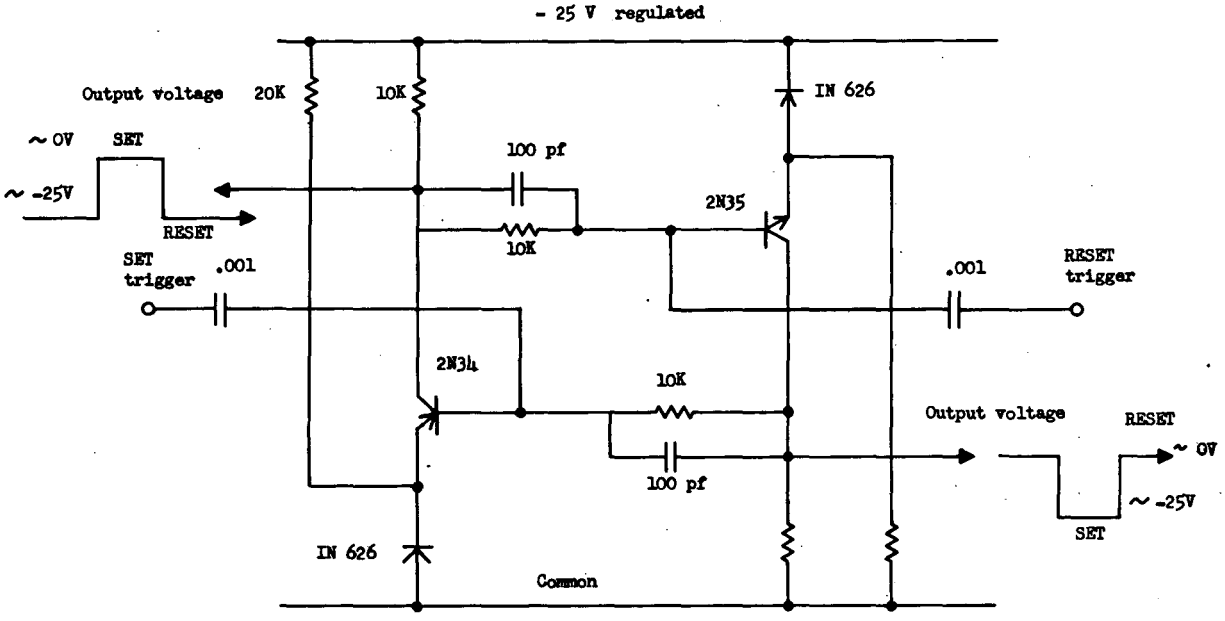


Fig. 4. Simplified schematic of the latch-type bistable multivibrator.

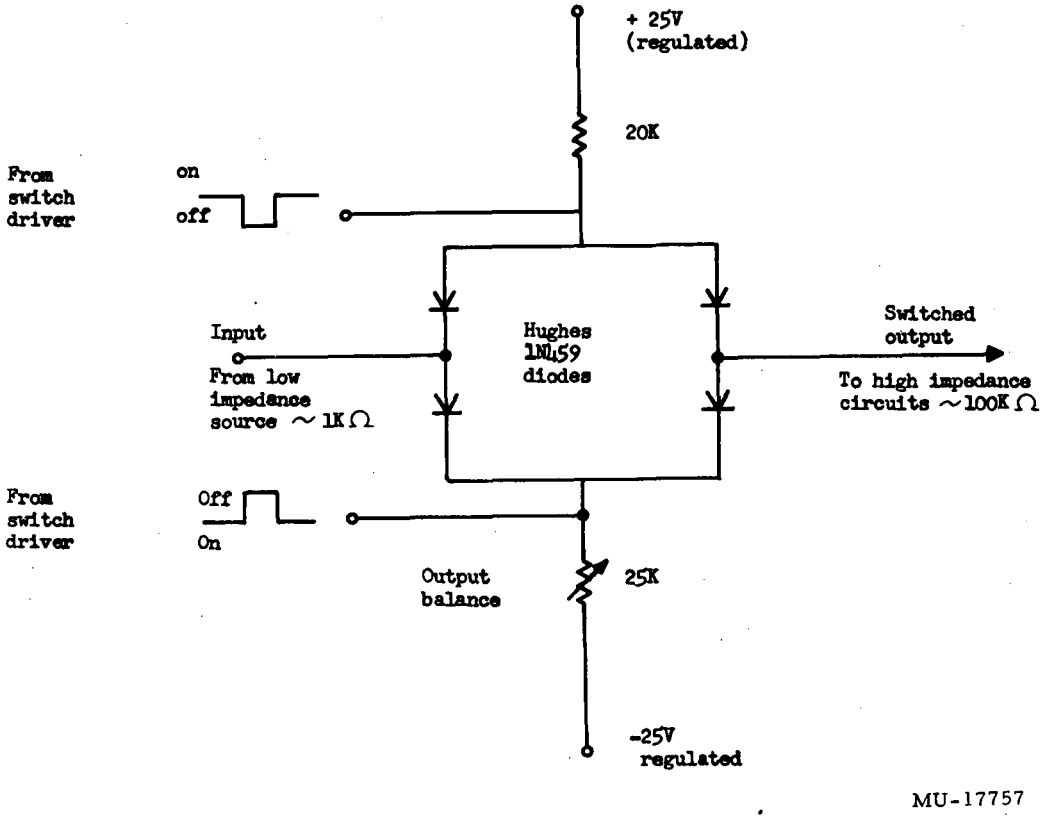


Fig. 5. Simplified schematic of the diode switch. The switch illustrated is normally closed. To obtain a normally open switch, one reverses the polarity of all diodes.

a germanium transistor, as shown in Fig. 5, clamping occurs when the collector-to-emitter voltage of the transistor equals the sum of the base-to-emitter voltage and the difference between the forward-voltage drop of the germanium and silicon diodes.[8] Another feature of this clamp is that before clamping occurs, the collector current is multiplied, β, by the common-emitter current gain. At the onset of clamping, the rate of change of collector current with respect to base drive current drops to α, the common-base current gain of the transitor. As the degeneration of the clamp circuit precludes overdriving the transistor, the recovery of the clamped transistor from the "On" state is rapid.

The diode switch itself makes the transition from Off to On in less than a microsecond. The transmission losses in the switch are negligible if the load impedance of the switch is large compared with the resistance of a forward-bias diode. The attenuation of a single diode ring is approximately 60 db. The shift in dc output level between On and Off operation can be balanced, with the potentiometer provided. The dynamic range of the switch is, in this design, limited by the diode supply voltage to 20 volts peak to peak.

X. General Construction Features

The all-solid-state circuitry of the Beam-Controlled Frequency-Correction System is of modular design. The 10 separate subassemblies comprising the demodulator-mixer, saturation program generator, radial-position discriminator, comparator, permissive time-delay multivibrator, switch driver, diode switch, summing amplifier, line driver, and indicator power supply are fabricated as printed circuits. The printed circuitry is fabricated from 1/8-in.-thick epoxy-glass-laminate boards to preclude connector failures caused by board warpage. The 1-ounce copper conductor of the printed wiring is gold-washed to insure good solder joints and retard aging. Either 5X7 or 5X10-inch boards are used in circuit layout, the board size being dictated by the over-all circuit complexity.

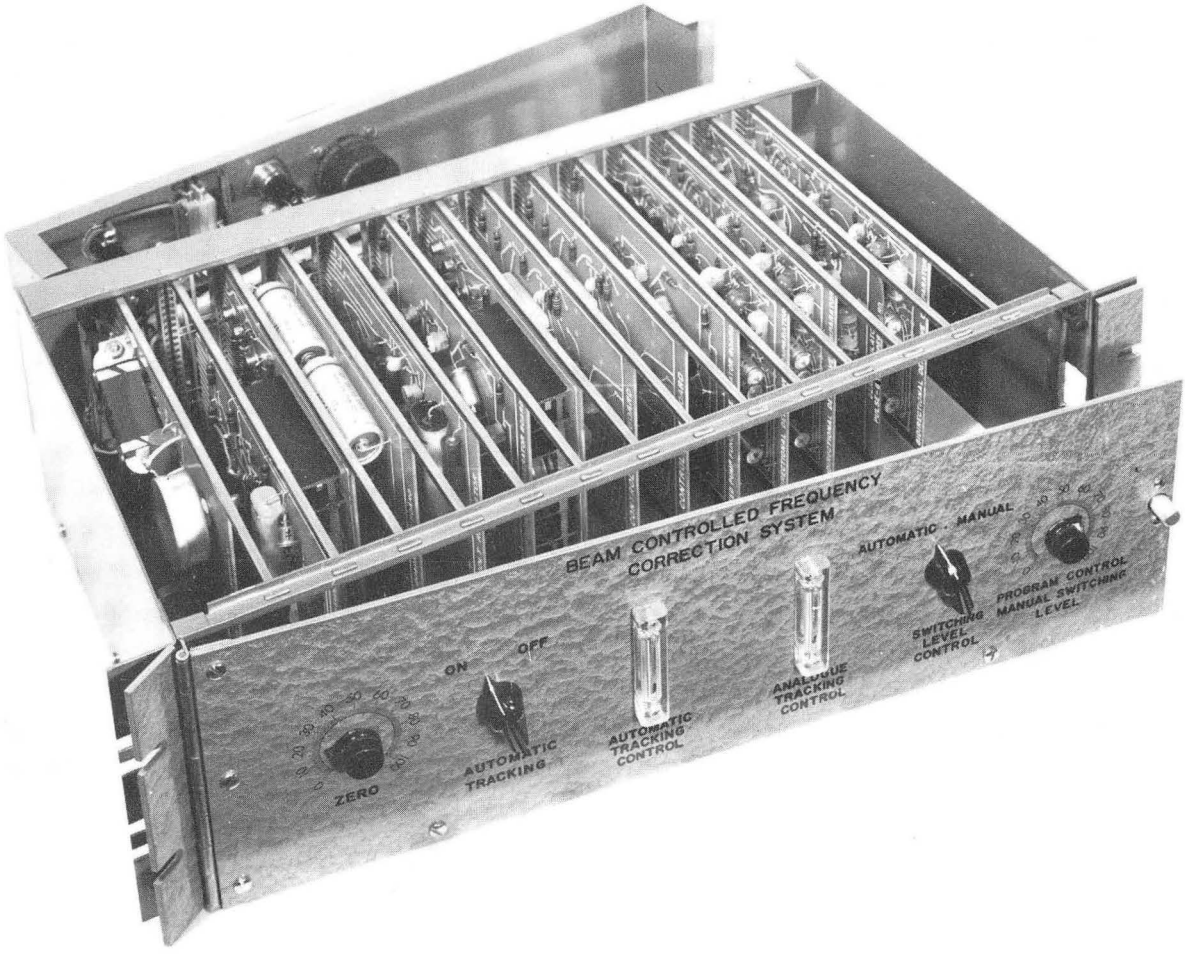
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[8] R. H. Baker, Maximum-Efficiency Switching Circuits, MIT Lincoln Lab. Report TR-110, 1956.

All components, including transistors and diodes, are soldered into the printed-circuit wiring. Single-sided circuits are employed throughout to facilitate maintenance and simplify construction. Two complete spare boards are provided for each module so that quick replacement may be effected in event of equipment malfunction. One of the spare boards is provided with sockets so that the performance of various portions of the circuit may be investigated or checked by maintenance personnel. A special board is provided that permits in-place checking of any board in the system while the module itself is removed from the main cabinet.

All the subassemblies are contained in a specially designed $5\frac{1}{4}$-inch printed-circuit cabinet, the front and rear doors of which are hinged to permit direct access to the modules and the interconnecting wiring (see Fig. 6). A conservative policy is observed in thermal design. All transistors are provided with heat sinks equivalent in thermodynamic design to 85% of an infinite heat sink. As all the printed-circuit boards are mounted vertically, all components are cooled by natural convection. Should ambient temperatures dictate forced-air cooling, there is a relatively unobstructed space on each side of each board for air circulation. All operating controls and circuit-function indicators are confined to the front panel. The rear panel contains all plugs for triggers, signals, ac and dc power, an elapsed-time indicator, an ac-power switch, fuse, and a neon ac power indicator.

The conservative design policy observed in the electronic circuit engineering and construction has been reflected in the choice of high-reliability components. Despite the over-all circuit complexity, the system should give many years of maintenance-free service. Provision has been made in the cabinet layout for the addition of up to four more circuit modules if equipment updating is required. In addition, new circuit modules, which plug into the existing sockets, may be fabricated if design improvements are conceived.



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Fig. 6. Front top view of the printed-circuit cabinet of the beam-controlled frequency-correction system.

XI. Conclusion

An all-solid-state tracking system has been provided that meets exacting stability requirements and provides automatic control of the radial position of the proton beam of the Bevatron. The precision of an automatic tracking system, when used in conjunction with the Mark II TRITEC analog computer and other auxiliary tracking equipment, can be obtained with no sacrifice in flexibility of proton-beam radial-position control. This equipment will automatically remove frequency errors that arise when the rate of rise of the magnetic field is reduced to extend the charge acceptance of the Bevatron. In addition it will virtually eliminate the need for tedious analog tracking at low proton-beam energies at all beam intensities above amplifier noise level. The electronic circuitry will track the beam automatically at all energies, transfer tracking control to the analog computer at energies above 1.5 Bev, or permit complete analog tracking as the experimental situation dictates.

The conservative philosophy employed in the engineering and construction of this equipment should result in high reliability and virtually maintenance-free operation.

XII. Acknowledgments

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