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Author
Heard, Harry G.

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Ernest O. Lawrence
Radiation
Laboratory

BERKELEY, CALIFORNIA

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Harry G. Heard

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Harry G. Heard

Lawrence Radiation Laboratory
University of California
Berkeley, California

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ABSTRACT

A brief description is given of the beam programming equipment of the Bevatron. The system described provides analog-computer-controlled as well as beam-controlled frequency tracking. Equipment is described that permits arbitrary adjustment and control of the radial position of the circulating beam at any energy. Beam-intensity control and the automatic reduction of phase errors in the acceleration system are provided. Included also are units that produce long and short beam pulses. Equipment that permits highly multiple operation is also discussed. The integration of these equipments for extended injection is treated.

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Harry G. Heard*

Lawrence Radiation Laboratory
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INTRODUCTION

The purpose of this paper is to describe the salient features of a beam-programming system developed for the Bevatron. The main technical objective of the design was the development of an integrated, highly reliable stable beam programming system, to facilitate a fuller utilization of the Bevatron as a basic research tool. In addition to providing highly flexible control of the circulating beam position and intensity, the system design incorporates the functions that will ultimately permit an increase in the over-all beam intensity to a value limited by the injected charge.

The basic functions of the beam-programming system may be broadly classified as follows:

1. Analog-controlled frequency tracking of the circulating beam over a 7:1 frequency range at any beam intensity.
2. Beam-controlled frequency tracking for all beam intensities above 10^8 protons. Automatic switching from beam-controlled to analog-controlled tracking after a preselected interval.
3. Automatic reduction of phase errors between the circulating proton beam and the drift-tube radio-frequency voltage.
4. Arbitrary adjustment and control of the radial position of the circulating beam at any energy.
5. Reduction of the intensity of the circulating beam to any of four preset arbitrary levels at any preselected circulating beam energies.
6. Production of high-quality beams for use in bubble chambers, emulsion exposures, and counter experiments.
7. Automatic selection of a predetermined mixture or sequence of beam programs and targets.

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*Now at Levinthal Electronic Products, Palo Alto, California.

8. Automatic control of the frequency, amplitude, and phase of the drift-tube rf voltage to permit the utilization of a depressed rate of change of magnetic field for maximum charge acceptance.

With the exception of the last category, all the above functions may be performed at any circulating beam energy during acceleration or deceleration. Before the beam programming system is discussed in greater detail, the basic characteristics of the accelerator will be reviewed.

Protons are injected into the aperture of the Bevatron magnet by means of an 18-foot radius 35-degree electrostatic analyzer, located at a radius of 621-1/2 inches. A pulse of 9.8-Mev protons, of relatively small energy spread, starts to spiral into the aperture at the instant that the average field of the 50-foot radius Bevatron rises to approximately 297 gauss. Because the magnetic field is increasing at a rate of approximately 8000 gauss per second, protons that enter the aperture late in the injection cycle execute free radial betatron oscillations having amplitude as large as 25 inches;[5] that is, approximately the radial half-aperture of the accelerator. Vertical betatron oscillations also develop during the injection period. The latter are mainly due to the divergence of the injected beam, gas scattering, and a number of aberrations resulting from slight defects in the magnet. By the time the acceleration cycle starts, the injected beam is quite diffuse and has a cross section of approximately 1 x 4 feet. At the end of the injection cycle, radio-frequency voltage is applied to the accelerating electrode or drift tube, and bunching action takes place. Energy is added to the particles in the circulating proton beam by means of an 11-foot drift tube. The radio-frequency voltage is applied to the drift tube as soon as the magnetic field rises to such a value that the instantaneous orbit for 9.8-Mev protons corresponds to a radius of approximately 600 inches; that is, the center line of the magnetic aperture. At the time when the rf drift-tube voltage is turned on, its frequency is approximately 354 kilocycles, corresponding to the period of rotation for $\beta = 0.145$ protons, having a 394-foot orbit.

When the rf is turned on, the aperture may be considered to be filled with protons having the same instantaneous orbit and all possible radial amplitudes from zero to the half-width of the chamber. Only those particles within a stable azimuthal range of approximately 180 degrees start the acceleration cycle and become bunched; others are lost. Because of radial oscillations caused by the energy contained in the phase oscillation, additional oscillations in the equilibrium orbit occur and, correspondingly, additional losses occur. The bunched protons will gain approximately two kilovolts of energy per revolution as they recirculate through the drift tube. Oscillations in azimuth and radius occur, as not all the particles arrive at precisely the optimum phase with respect to the rf drift-tube voltage. Protons arriving at different phases receive energy increments different from the value necessary to maintain their orbits centered in the aperture. Therefore, oscillations in phase occur. Only those particles whose phase excursions remain within phase-stable limits continue to be accelerated. At the end of approximately 1-3/4 seconds, the magnetic field has increased to 15,550 gauss. The radio frequency has increased to 2.5 mc, so that the 6.2 Bev protons remain nearly centered in the aperture. The acceleration and deceleration cycle for the circulating beam differ only in detail and need not be discussed here.

The Bevatron beam utilizes the full aperture during the injection cycle. Therefore all targets, foils, and clippers must be retracted. Shortly after the acceleration cycle starts, however, the radial width of the beam is considerably less than the useful radial aperture. This is because the amplitudes of the betatron oscillations damp as the inverse square root of the magnetic field intensity. As the beam remains stable for magnetic field gradients between n= 1/2 and 3/4 in a weak-focusing accelerator, the beam may be placed at any radial position within the aperture wherein the magnetic field gradients satisfy these boundary conditions. Azimuthal oscillations that develop as a result of the relative phase of a particle with respect to the drift tube voltage as it crosses the accelerating gap lead to corresponding oscillations in energy. These energy oscillations quickly become of second order as they are superimposed on the steady increase of proton energy with time. This variation in energy does, however, result in radial phase oscillations. Thus the instantaneous orbit for a given particle expands and contracts with time and is centered about an equilibrium orbit defined by the frequency of the drift-tube voltage.

The azimuthal extent of the bunched beam also decreases slightly during acceleration due to phase-damping forces. These forces are sufficient to decrease the azimuthal extent of the bunch to approximately one-half its original length. Meanwhile the increasing magnetic field and average particle energy cause the fractional radial oscillation due to phase oscillations to approach a negligible value. In the discussion that follows the radial oscillation arising from phase oscillations is neglected. The phase oscillations themselves will be considered only in regard to their phase variations with respect to the rf drift-tube voltage.

This vastly oversimplified description of the proton synchrotron is completely inadequate for the technical understanding of the detailed operation of the accelerator. It is included here only for orientation. The salient features of the beam programming system shown in Figure 1 are now discussed.

ANALOG-COMPUTER-CONTROLLED FREQUENCY TRACKING

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; see Figure 2. The saturating current for this reactor is derived from the shunted magnet current or from the magnet field by integrating the voltage induced in a loop located in the magnet aperture. The second-order corrections to the radio-frequency voltage that are necessary if the beam is to be kept within the magnet aperture are either synthesized directly with an analog computer or are derived from the radial position of the beam. Tracking-error signals are used to modulate voltage-sensitive pn-junction capacitors that shunt the saturable reactor in the low-level tracking oscillator.[1]

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

This capacitor modulator adjusts the time-dependent period of the radio-frequency drift-tube voltage. Because of saturation effects that develop in the pole tips of the magnet at high values of magnetic field intensity, the center of the useful region of the magnetic field does not remain in the center of the aperture.[2] Therefore, the average rate of change of frequency of the tracking oscillator must be reduced by an appropriate amount to compensate for the outward shift of the useful magnetic aperture at high proton energies.

The difference between the frequency generated by the tracking oscillator and that required to place the circulating beam at a desirable radial position at any point in the acceleration cycle can be obtained by modulating the capacity in the low-level tracking oscillator. An appropriate correction signal may be synthesized with a time-dependent function-generating computer and applied to the voltage-sensitive capacitors in the tracking oscillator. This method of frequency tracking is referred to herein as analog-controlled frequency tracking. Measurements on the Bevatron indicate that the required correction signal is not monotonic. It is, however, simple enough so that it may be generated within the required tolerance by a computer. The time-dependent correction signal that is generated is divided into five portions.[1] The shape of the error signal during each one of these portions is controlled by RC networks that add to or subtract from the charge stored on a memory capacitor. The time-varying voltage on this memory capacitor is then used to modulate the frequency of the tracking oscillator. The basic advantage of this method of beam control is that it is completely independent of beam intensity. Further, the use of a relay-operated computer and RC networks simplifies the problem of function generation to the extent that the position of the beam may be controlled over extensive energy ranges with a minimum number of control adjustments. This method of beam control establishes the gross frequency or radial-beam-position program necessary to keep the circulating beam within the useful portion of the aperture during acceleration and deceleration. It does not, however, provide the discreet radial-position control required for missing targets, clippers, and foils. Auxiliary-beam programming equipment, to be described below, provides this facility. The frequency-correction system used during the decelerating portion of the magnet cycle differs only in its time dependence from that required during acceleration.[3] The automatic or beam-controlled frequency tracking will be considered next.

BEAM-CONTROL FREQUENCY TRACKING

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

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

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

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

electrodes by making their response a rapidly changing function of the radial position of the beam. The voltage induced on each of these electrodes may be averaged and subtracted to yield a signal whose amplitude and polarity correspond to the deviation of the center of the proton beam from the center line of the induction electrodes.[5] The output of this radial position discriminator, when fed directly to the capacitor modulator, will adjust the frequency of the tracking oscillator to that value required to maintain the beam in the center of the induction electrodes. As mentioned earlier, in the Bevatron this is not a desirable feature as the center of the useful portion of the aperture increases in radius during the acceleration cycle.

To obtain the correct tracking-error signal a saturation program generator is required. This time-dependent signal, when added to the beam-derived signal, generates the desired frequency program. In most applications beam-controlled frequency tracking does not provide the desired flexibility in positioning the proton beam. This type of tracking is most useful in correcting the tracking frequency during the early portions of the acceleration cycle. Provision is made, as shown in the block diagram in Figure 3, for the beam programming system to switch from the beam-derived frequency-correction signal to the analog-computer-derived frequency-correction signal, when the two correction signals match. This enables one to track the circulating beam automatically over most of the low-energy portion of the tracking curve, where the rate of change of frequency is greatest, and to concentrate on analog-controlled tracking for beam-position control at high energies. The detailed control of the radial position of the beam will now be considered.

ARBITRARY CONTROL OF THE RADIAL POSITION OF THE CIRCULATING BEAM

Shortly after the acceleration cycle starts, the radial width of the beam is reduced by the adiabatic damping action of the increasing magnetic field. Therefore, the radial extent of the aperture is several inches greater than necessary to contain the beam. If the gross frequency program is adjusted so as to cause the circulating beam to move to the outer half of the aperture, target insertion may start on the inner radius and vice versa. This type of gross beam-position control is normally exercised by the analog tracking computer. At high energies, however, the useful radial width of the field shrinks to dimensions comparable to that of the beam. Despite this fact, it is frequently desirable to place a target in such an extreme radial position that the clearance between the beam and the target is of the order of a small fraction of an inch. In such cases it has been found desirable to exercise additional control of the radial position of the circulating beam. These third-order corrections to the frequency-tracking program are generated by a special-purpose computer.[6] The latter provides a more precise and detailed control of the frequency program over a limited frequency range. This computer, which has three independent channels, can generate arbitrary time-dependent signals composed of ten connected straight-line segments having arbitrary slopes. The output of this computer, when summed with that of the main computer, develops the detailed frequency program.

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[5] Harry G. Heard, The Beam-Controlled Frequency-Correction System of the Bevatron, UCRL-8828, July 1959.

[6] Harry G. Heard, Arbitrary Control of the Radial Position of the Internal Beam of the Bevatron, UCRL-9006, July 1959.

ORBIT OSCILLATORS

In the earliest particle-physics experiments on the Bevatron, beams were produced by allowing all of the circulating beam to strike one target at the termination of the acceleration cycle. As the circulating-beam intensity increased with the progressive development of the Bevatron, it became possible to consider performing more than one experiment per acceleration cycle, provided that the experiments did not require the same circulating beam energies. A method of of perturbing the rate of change of the rf was developed so that multiple targets, erected in sequence, could share portions of the circulating beam.[7] A group of 3 short-pulse and 4 long-pulse orbit oscillators was developed to permit the desired displacement of the beam.

The seven orbit oscillators are included functionally in the beam programming equipment. They cause the beam orbit to expand or contract by applying a pulsed half-sine-wave perturbation to the capacitor modulator. As long as the period of this disturbance is long compared with the period of normal phase oscillations, the equilibrium orbit of the beam is simply displaced radially. If the new equilibrium orbit brings some of the circulating beam into a target, a secondary beam of particles results. The beam not expended on the target is returned to its unperturbed position for additional acceleration. If the period of this perturbation is short compared with that of existing phase oscillations, however, phase disturbances are created that are sufficiently large to cause some of the beam to be removed from a phase-stable orbit. The resulting asynchronous beam is compressed onto a target by the increasing magnetic field. This technique has been used to produce beam pulses to as short as 2 to 4 milliseconds. The seven orbit oscillators are completely independent in both their timing and amplitude controls. They may be mixed or used in any desired sequence for highly multiple operation.

PROLONGED SECONDARY-PARTICLE BEAMS

In many experiments of the scintillation-counter type it is desirable to produce a moderately high flux of secondary particles over a counting period as long as 1/10 to 1/2 second. A method was developed to produced such a beam by causing the circulating beam to strike a thin target on the outer radius of the aperture.[8] The energy loss sustained by those particles passing through the outer-radius foil is large enough to cause them to fall out of phase synchronism. As before, the orbit of the asynchronous particles is compressed by the increasing magnetic field until the inner-radius target is struck. By making the foil effectively quite thin, (that is by using a few nylon strings) and by perturbing the tracking-oscillator frequency slowly, the rate of change of the rf may be adjusted to produce beams for several hundred milliseconds. This third-order correction of the tracking frequency is accomplished with a ramp-function generator. The output of the ramp-function generator is mixed with the basic analog frequency program to determine the actual radial position of the beam. Operating experience has indicated that one such unit will provide the desired beam-control flexibility.

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[7] Harry G. Heard, Extended-Orbit Control for Production of Short Beam Pulses, Bevatron Report 204, Dec. 1956.

[8] Harry G. Heard, Production of Prolonged Secondary-Particle Beams in the Bevatron with Thin Foils, UCRL-3608, Dec. 1956.

PRODUCTION OF EXTREMELY SHORT BEAM PULSES

None of the above frequency programming equipment will produce beam pulses of the order of 10 microseconds duration. Such pulses can be produced by abruptly changing the magnetic field intensity in a straight section of the Bevatron. The effect of this change in magnetic field intensity is to cause an abrupt change in the radial position of the beam. An appropriate frequency-error correction signal must also be generated to compensate for the radial position change if phase jumps are to be minimized. This correction signal is applied to the capacitor modulator in the tracking oscillator.

PHASE LOOP CONTROL

If beam losses in a proton synchrotron are to be minimized, the amplitude of phase oscillations must be limited. As the natural phase-damping forces are small, phase errors that develop throughout the acceleration cycle have a cumulative effect and beam losses occur. If the varying frequency of the drift-tube voltage is modulated at the frequency of the phase oscillations, but in opposite phase, the amplitude of phase oscillations may be decreased.[9] This is accomplished by modulating the frequency of the tracking oscillator with a signal derived from the beam. The error signal for this ac feedback loop is derived by comparing the phase of the radio-frequency drift-tube voltage with that of the beam-induction-electrode signal. Because of the relative physical location of the beam induction electrode with respect to the drift tube, a wide-band rf phase shifter must be added to provide an appropriate phase null. The phase difference between these two signals is derived by a non-linear multiplier. The differentiated phase-error signal is then used to frequency-modulate the capacity of the tracking oscillator so as to damp phase disturbances.

BEAM-INTENSITY CONTROL

When several experiments are being conducted during a given acceleration cycle, it frequently becomes desirable to reduce the beam intensity to a predetermined level before or after each fraction of the beam is removed. Similarly, it is frequently desirable to have the beam amplitude remain constant, even though the injected charge varies from pulse to pulse. A group of four beam regulators is provided in the beam-programming system to permit arbitrary adjustment of the beam amplitude to any value below the maximum value of the injected charge.[10] Each of the four channels of the beam regulator is independent. They may be mixed or operated in sequence as desired. These units function by generating either tracking-error signals or phase-error signals until the beam intensity is adjusted to a value corresponding to a preset reference. Signals derived by these units are fed to the capacitor modulator.

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[9] Harry G. Heard, Reduction of Phase Errors in the Bevatron Beam Acceleration System, UCRL-9007, July 1959.

[10] Harry G. Heard, Regulation of the Bevatron Beam Amplitude, UCRL-8262, July 1959.

EXTENDED INJECTION

Within limits, if the rate of rise of magnetic field is reduced, the injection period may be increased. Experiments at the Bevatron indicate that the injected charge may be increased by as much as a factor of 5, if the rate or rise in magnetic field is reduced.[11] The transition from the reduced rate of change of field to the normal rate of change of field must be accomplished in such a way as to retain the increase charge. Provision is made in the beam-programming equipment of the Bevatron to modulate the amplitude of the drift tube voltage. The phase and frequency loops must also be closed to minimize beam losses that result during this transition period. The actual reduction in the rate of change of field is accomplished by driving current through the pole-face windings in such a way as to reduce the rate of change of field during the injection period.[12]

RELAY-CONTROL SEQUENCE SELECTOR

The selection of pre-assigned targets, clippers, flip coils, basic frequency programs, auxiliary frequency programs, and beam intensities is controlled in the Bevatron by a relay-controlled sequence-selection unit.[13] This unit is capable of repeating a prearranged instruction program during each magnet pulse and mixing these programs in accord with a predetermined pulse priority schedule. Together with the 15 associated time delays, this unit can be used to program any of the frequency control functions described earlier. Its use in conjunction with eight additional time delays and appropriate selector switches permits the selection of any one of 18 targets, foil, and beam clippers for use in Bevatron experiments.

GENERAL CONSTRUCTION FEATURES

The all-solid-state circuitry of the beam-programming system of the Bevatron is of modular design. The various subassemblies comprising this system are fabricated as printed circuits. The printed circuits are mounted in specially designed printed-circuit cabinets. Insofar as possible, germanium transistors have been used throughout and adequate attention has been given to thermal design. The conservative policy observed in the electronic circuit engineering and construction practice has been reflected in the choice of high-reliability components. Despite the over-all complexity of this system, many years of maintenance-free service is expected. Provision has been made in each cabinet for addition of circuit modules and for updating equipment as required. In addition, new circuit modules which plug into the existing sockets may be fabricated if design improvements are conceived.

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

[13] Edward J. Lofgren and Harry G. Heard, Bevatron Operation and Development, UCRL-3033, Aug. 1955.

RESULTS AND CONCLUSIONS

Development of the beam-control system for the Bevatron has resulted in an over-all increase in the beam intensity. In addition, a system has been provided that has increased the flexibility of the accelerator without sacrificing stability or reliability.

As many as six independent experiments have been conducted on the Bevatron simultaneously by using this equipment. The number of simultaneous experiments now scheduled during Bevatron operation is frequently more than two.

ACKNOWLEDGMENTS

In closing, the author would like to acknowledge the assistance of Tom Innes, Donald McClure, and Fred Lothrop in the printed-circuit design and prototype testing. Recognition is also due to Charles Carr and Ivan Wood for equipment fabrication. This work was performed under the auspices of the United States Atomic Energy Commission.

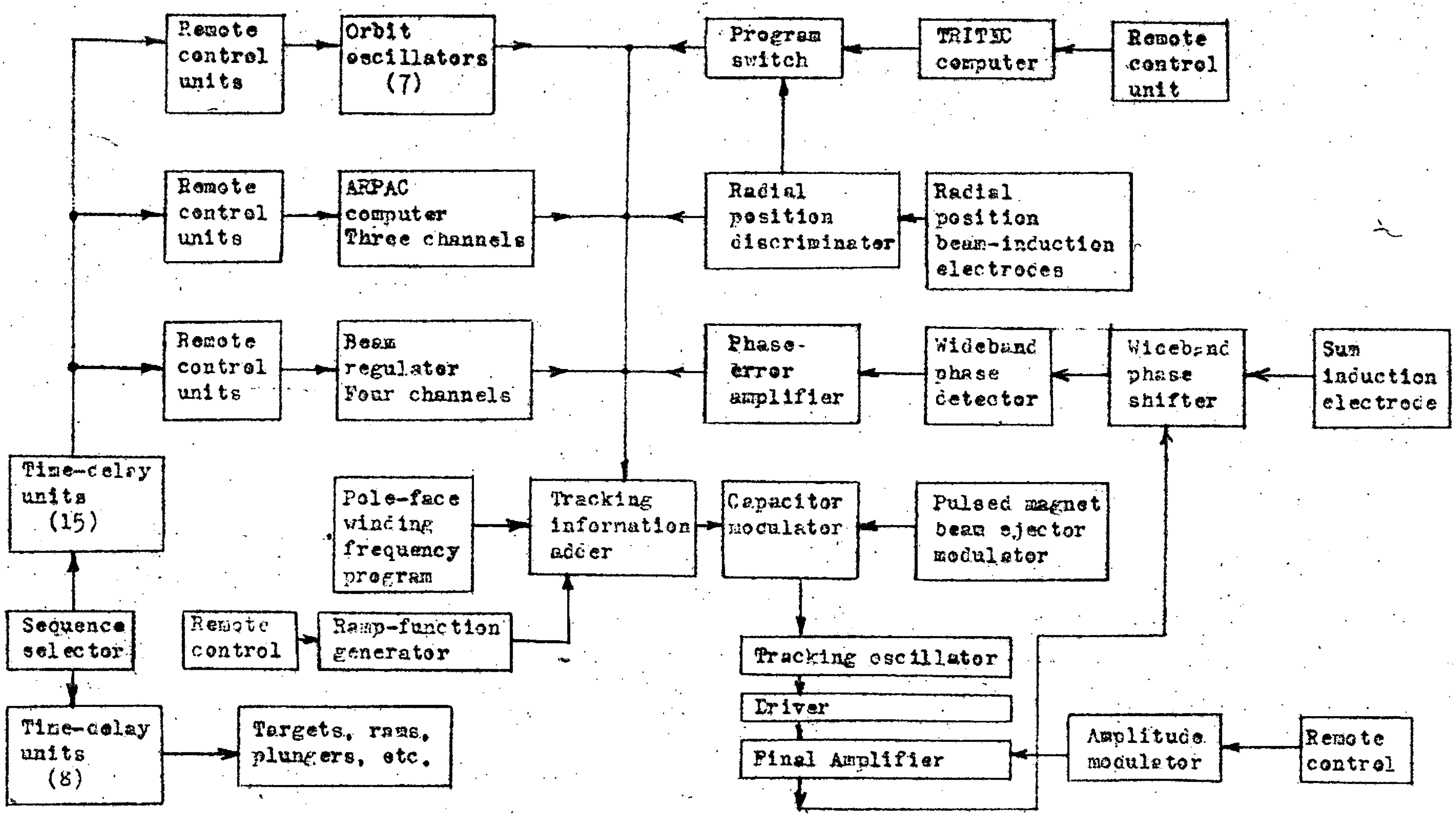

Fig. 1. Block diagram of the beam-programming system of the Bevetron.

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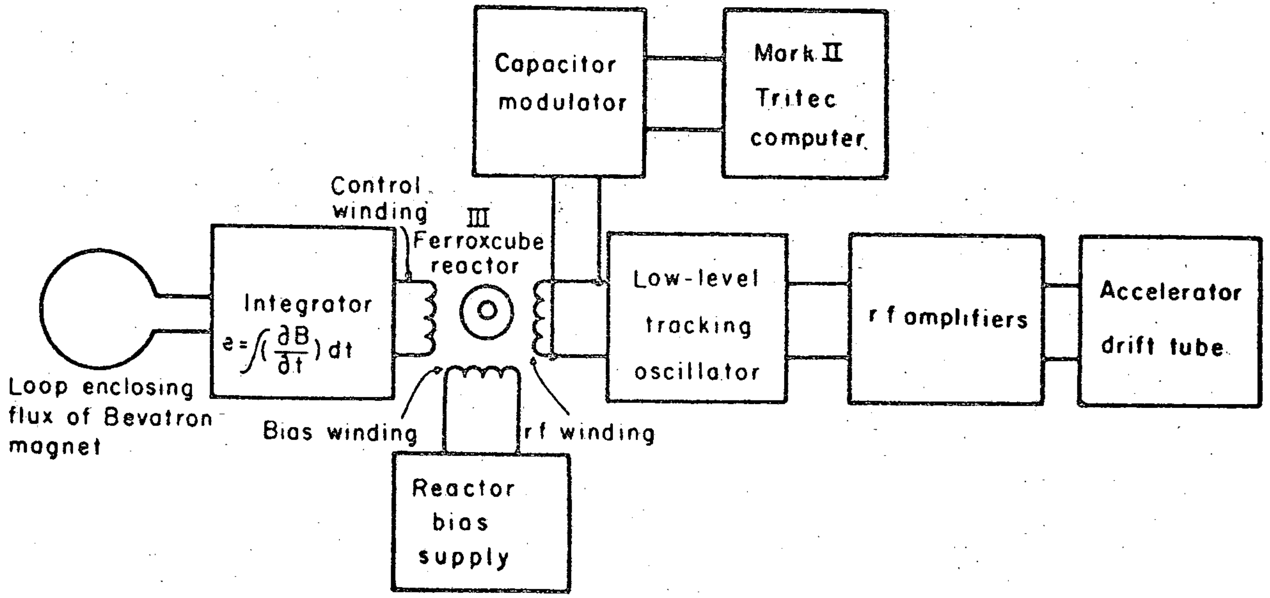

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Fig. 2. Simplified diagram of the variable-frequency oscillator that develops the basic tracking frequency program of the Bevatron.

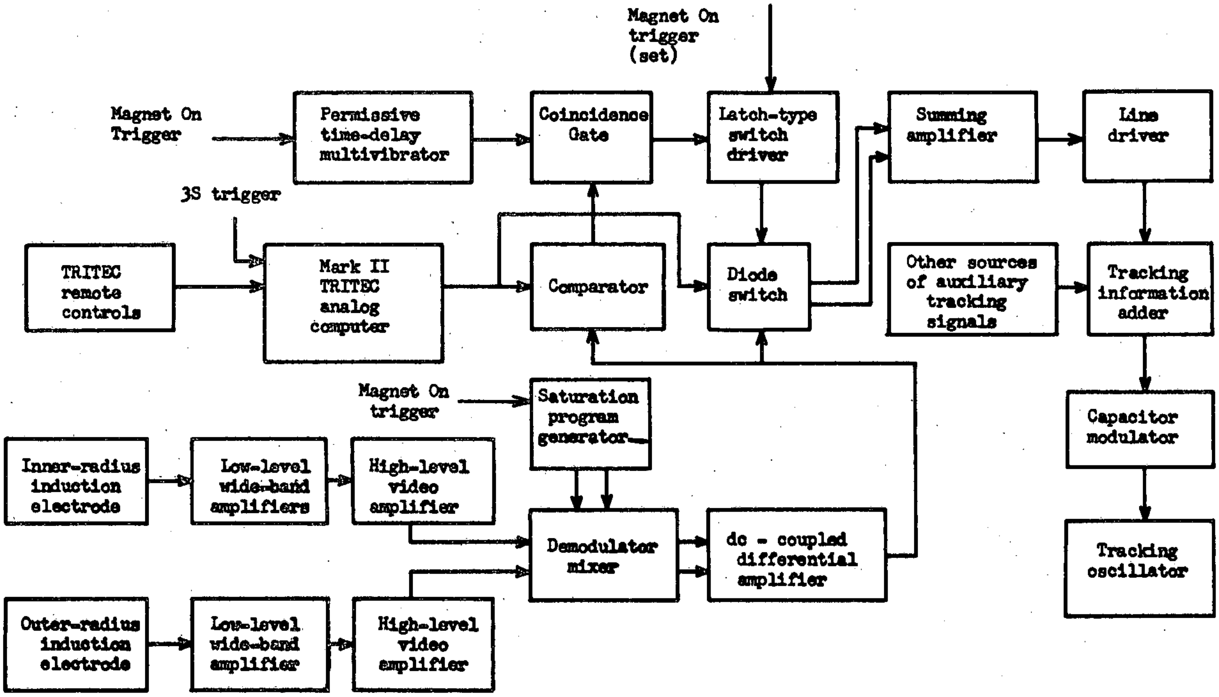

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Fig. 3. Block diagram of the Bevatron beam-controlled frequency-correction system.