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Harry G. Heard

July 3, 1958

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ABSTRACT

This paper outlines the development of function generators designed to synthesize a correction function in the open-loop radio-frequency accelerating equipment of the Bevatron. A function generator is described that will control the beam position during acceleration and deceleration.

The mechanisms of phase transition and beam deceleration are delineated. Results of beam deceleration from 6.25 Bev to 300 Mev are given. Advantages of beam deceleration and analog frequency tracking are discussed.

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INTRODUCTION

The radio-frequency voltage that is used to track the Bevatron beam is generated by a low-power oscillator.¹ A close approximation to the desired proton-orbit frequency is generated by varying the inductance in a ferrite-cored saturable reactor.² Either the magnet current or the magnetic field is used to program the oscillator frequency.

In the original design of the radio-frequency tracking equipment, the deviation of the programmed frequency from that required to maintain the beam in a desired equilibrium orbit was synthesized, as a second-order approximation, by a 30-point function generator known as a curve corrector. The curve corrector was designed to generate thirty connected straight-line segments. The duration of each segment of the correction function was fixed by triggers, known as current markers, that were derived from a sample of the magnet current.

After the major difficulties in obtaining a high-intensity proton beam in the Bevatron had been solved,³ an investigation was made of the accuracy with which it was necessary to generate the correction function. It was found that if one permitted the beam to deviate in radial position from a central orbit, the necessary correction function could be synthesized as three curved-line segments. Accordingly, a relay-operated function generator, known as a curve computer, was designed. Even though this curve computer did not possess the flexibility of the curve corrector, it was much more stable and, as it required only one trigger instead of thirty, was considerably more reliable.⁴

Originally, the curve computer was designed as a substitute for the curve corrector. It was only used when critical beam control was not required. The functional simplicity of operation and ease of beam control

¹C. N. Winningstad, The Rf System of the Bevatron, UCRL-2593, June 1954.

²A. J. Pressman and J. P. Blewett, Proc. Inst. Rad. Eng., 39, 74 (1951).

³Edward J. Lofgren and Harry G. Heard, Bevatron Operation and Development, III, UCRL -2822, Feb. 1955.

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

that resulted from analog tracking soon indicated that the basic ideas of beam control needed revision. If an analog computer were used as a primary tracking device at all times and other units were built that would supply special localized beam control, the simplicity, reliability, and reproducibility of an analog tracking system could be retained and the system flexibility could be increased with auxiliary tracking equipment. This philosophy has been pursued in developing beam-control facilities in the Bevatron.

Further studies of beam tracking indicated that the same principles that were involved in accelerating the beam could be applied to decelerate the beam if the necessary advance in synchronous phase could be obtained.⁵ This report discusses the results of extension of analog tracking to the deceleration cycle of the magnet-current pulse. An analog computer is described that tracks the beam throughout the acceleration and deceleration cycles.

THEORY OF PHASE TRANSITION

If a particle is to be accelerated and decelerated in a proton synchrotron, it must retain phase stability at all times. As the phase-stable angles during acceleration and deceleration are different, a phase transition is required between the end of the acceleration and start of deceleration cycles. In the Bevatron, the drift-tube voltage is maintained at nearly twice the level required to supply the minimum energy gain to a particle per revolution. Therefore, the equilibrium phase-stable angle of a synchronous particle is approximately 150° . As the ratio of available energy gain to the threshold energy gain per revolution is increased, the phase-stable angle approaches 180° . During the decreasing magnetic-field cycle of the magnet-current pulse, for the same rate of change of magnetic field and drift-tube voltage, deceleration will occur about a synchronous-phase angle of about 210° . To change from acceleration to deceleration, the synchronous phase must, therefore, be advanced from 150° to 210° . The advance in phase must occur in an adiabatic way if beam losses are to be prevented.

Measurements on the Bevatron magnetic field show that the change in the rate of rise of magnetic field is slow enough, during the shift from the increasing to the decreasing magnetic field cycle of the magnet pulse, so that a two-step adiabatic phase advance is possible. Actually, the magnetic field increases to a peak value and dwells for approximately 20 milliseconds before it begins to decrease. During this dwell time, which is associated with switching the magnet-power-supply ignitrons from the rectification to the inversion function, a new phase-stable angle must be established. As the magnetic field begins to decrease, an additional phase advance is needed. It will be seen that if the radio-frequency voltage remains on and at the same amplitude during the entire switching period, the necessary phase advances will occur automatically.

⁵Walter D. Hartsough, Bevatron Operation and Development, VII, UCRL-3236, Dec. 1955, p. 17.

Consider the events that occur with the change in the rate of rise of magnetic field at the start of the dwell period. With the radio-frequency voltage on, the excess-to-threshold ratio becomes large and varies adiabatically as the rate of rise of magnetic field slows down at the start of the dwell time. The phase-stable angle advances from 150° to nearly 180° . The beam remains bunched even though rather large phase excursions are stable. When the magnetic field begins to decrease, the excess-to-threshold ratio reduces adiabatically to approximately 2. The phase-stable angle advances to approximately 210° and the deceleration cycle starts.

Experiments were performed on the Bevatron to test the validity of these ideas. The radiofrequency voltage was allowed to remain on during the dwell period. All the beam remained bunched. In fact, there was no evidence of beam loss even though the dwell period was extended to 86 milliseconds. Beam losses occurred, however, shortly after the start of the inversion cycle. Later experiments showed that this loss was due to improper frequency tracking. When relatively crude tracking apparatus was assembled, the beam was decelerated from 6.25 to 1 Bev. Although only about 1% of the beam survived at 1 Bev, it was apparent that most of the beam losses were again caused by inaccurate frequency tracking. Later, the TRITEC⁶ analog computer, described in this paper, was constructed and used to track the beam with the required accuracy. With this computer, it has been possible to decelerate the beam to an arbitrarily low energy without losses due to tracking.

DESCRIPTION OF THE TRITEC COMPUTER

Because of the difficulties that would arise if an attempt were made to switch between two tracking systems at the termination of the acceleration cycle, a single computer was designed for both acceleration and deceleration. Rather than attempt to modify the existing computer, which was in continuous use in the Bevatron, it was decided to construct an entirely new computer. The redundancy provided by an additional analog computer would provide an operating spare in case of a major circuit failure in either unit.

The TRITEC operation is illustrated by the functional block diagrams in Figs. 1 and 2. The computer consists of five chassis, two of which are regulated power supplies. The three remaining units include the computer proper, a remote-control unit, and a dc-stabilized cathode follower.

An operating cycle of the computer is initiated upon the receipt of a single trigger. Though this trigger is normally provided by a peaking strip located in the stray field of the Bevatron magnet, any external trigger source may be used for test and maintenance purposes. The time-dependent voltage output of the computer is generated at a relatively high impedance level. The

⁶The name TRITEC was derived from the first letters of the complete title, "Transistorized Rectification-Inversion Tracking-Error Corrector".

MU-15556

Fig. 1. Block diagram of component units in TRITEC computer.

MU-15555

Fig. 2. Block diagram of circuits in TRITEC local unit.

output voltage is transformed in impedance level by the dc-stabilized cathode follower and transmitted over a coaxial cable to programmed power supplies that frequency-modulate the low-level tracking oscillator. Either local or remote control of the computer is provided by means of appropriate plugs. The controls are interlocked by plug substitution so that only one set of controls may affect the computer at any time.

The complete tracking curve is divided into five major portions. Provision is made to vary the duration, amplitude, and shape of each of these portions at either control unit. There is a small amount of control interaction in the control of the duration of each portion of the curve. This is not a serious limitation, as the tracking curve is well within the tolerance required. Amplitude and shape controls are very nearly independent. Provision is made to reduce the rate of change of frequency at an arbitrary time during the acceleration cycle. Thus, the beam may be tracked if the magnetic field is arrested for a few hundred milliseconds.

FUNCTION OF THE TRITEC COMPUTER

Upon receipt of an initiating trigger, five of the seven monostable multivibrators--namely TD-1, 4, 5, 6, and 7-transfer to their quasi-stable states and thereby energize RE-3, 4, and 6 and de-energize RE-5 (see Fig. 2). When RE-6 picks up, a short is removed from the output and applied to the input trigger bus to lock out the circuit for the complete duration of the tracking cycle. The time between the initiating trigger and the start of the function-generation cycle 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 cycle. When TD-2 returns to its stable state, it triggers TD-3. RE-2 energizes and generates the second portion of the acceleration cycle. At this time, all the monostable multivibrators have been triggered once to their quasi-stable states. Function generation thereafter proceeds automatically until all the multivibrators return to their stable states. The third, fourth, and fifth portions of the tracking curve are generated when TD-4, TD-5, and TD-6 respectively time out.

Function generation is accomplished in the TRITEC by charge transfer. Amplitude control is obtained by controlling the peak voltage to which capacitors are charged. Time control is obtained with the multivibrator circuits. Shape control is obtained by varying the rate of energy dissipation by switching various resistive networks between capacitors for charge transfer.

The interaction of the various components in function generation is best understood with the simplified diagram of the switching circuits shown in Fig. 3 and the generated function in Fig. 4. All relays are shown in the de-energized position. The subscripts 1 through 6 indicate the portion of the curve shown in Fig. 4. Double subscripts denote a subdivision of a particular portion of the curve. Capital letters T, H, and S refer respectively to time, amplitude, and shape controls.

MU-15557

Fig. 3. Simplified diagram of relay sequence in function generation.

MU-15554

Fig. 4. Tracking-error curve and relay-sequence diagram for complete acceleration-deceleration cycle.

Before an initiating trigger arrives, relay RE-5 is energized. The voltages to which capacitors C_1 , C_2 , and C_3 are charged are determined by controls H_1 , H_2 , and H_5 . As soon as the initiating trigger is received, RE-5 de-energizes to charge C_3 through H_5 for use during the deceleration cycle. RE-6 energizes to lock out the input and remove the short on the output bus. RE-3 and RE-4 energize to activate the circuits required for function generation during the acceleration cycle. When TD-1 transfers to its quasi-stable state, the cycle is started. As soon as TD-1 times out, TD-2 is triggered and energizes RE-1. 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-3 is triggered. RE-1 is de-energized and RE-2 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, reverses direction again, and finally approaches zero. When the energy stored in C_2 and C_4 is nearly dissipated, TD-4 returns to its stable state and RE-3 is de-energized. This connects C_2 and C_4 through the contacts of RE-3 and RE-4, thence via S_3 to the minus-25-volt bus. S_3 and H_3 form a voltage divider and a constant-current source to charge C_2 and C_4 negative until TD-5 returns to its stable state. Next, RE-4 de-energizes and C_2 and C_4 charge positive through S_4 and H_3 until TD-6 returns to its stable state. RE-5 now energizes and transfers the negative charge stored in C_3 onto C_2 and C_4 . S_{51} and S_{52} dissipate the energy stored in the system until TD-7 returns to its stable state. RE-6 then de-energizes and shorts the output bus to dissipate the remaining charge on C_4 . Finally, TD-3 times out, RE-2 is de-energized, and the cycle is complete.

CIRCUITRY

As the specific circuitry of the TRITEC does not constitute a major contribution in this paper, the comments are restricted to general design parameters and the logic involved in the over-all design. For circuit details, the reader is referred to UCRL prints 7Y2095, 7Y2023, 7Y2013, 7Y2133, and 5Z6273.

System reliability was the paramount consideration in component selection and circuit design. This led to the use of mercury relays in low-voltage circuits driven by transistors. As all electronic systems have a finite failure rate, the secondary aim was to provide ease of maintenance. The circuits for each time-delay unit were made similar in circuit geometry, and practically all the components in similar parts of the circuits were made identical. Visual indication of the state of each multivibrator was provided and every major circuit junction was made a convenient test point. Wiring was color-coded and parts with similar functions, such as relays, potentiometers, timing condensers, etc., were grouped in the same areas. Panel-mounted chassis-type construction was used so that all circuit wiring was contained within the chassis. Thus, most maintenance may be performed on the units without necessitating their removal from racks. A hinged access door was provided in the front panel for convenience in changing the potentiometers and condensers in the function-generating networks.

Other design criteria include low-noise-level circuitry, low output impedance, and reproducible and stable operation. The voltage instability of generated function is well below 0.1%. The ripple output and noise output are below 5 millivolts peak. The transistor circuitry has ample dc feedback to stabilize against thermal runaway and the circuitry function is not affected by temperatures that the transistors themselves can withstand (85°C). Although circuitry was designed around 2N361 transistors, 2N461 and 2N359 transistors with a high enough punch-through voltage were also found to perform satisfactorily.

PERFORMANCE

The components in the function-generating circuits of the TRITEC were chosen to duplicate, within 0.2%, the curve generated by the analog computer. Because of the lower output impedance of the TRITEC line driver, a different correction function was found necessary. The new correction function was determined empirically when the TRITEC was used to track the beam. The dynamic range of the controls proved more than adequate to overcome this difficulty and beam was immediately tracked to 6.25 Bev. Deceleration tracking was attempted as soon as the tracking had been optimized during the acceleration cycle. Beam was decelerated without difficulty to 1 Bev (see Fig. 5). The terminal energy was determined by time-interlock circuits in the radio-frequency equipment. As soon as these circuits were modified, the beam was decelerated to an arbitrarily low energy.

There appears to be a nearly constant, but small, rate of beam loss during the deceleration cycle. Approximately one-half the beam is lost during deceleration from 6.2 Bev to 300 Mev. As the magnet-power-supply voltage ripple during inversion is much larger than during the rectification cycle, the beam losses are probably due to driver phase oscillations.

UTILIZATION

From intuitive considerations, it might appear pointless to decelerate the high-energy proton beam. There are, however, two excellent reasons for considering this mode of operation. Firstly, there is the general problem of obtaining a useful flux of particles from targets located in the outer half of the accelerator aperture. If one tracks the beam onto an outer-radius target during the acceleration cycle, the secondary-particle flux has a relatively pronounced ripple structure. This is caused by the rf phase bunching of the beam and the low-level position modulation of the equilibrium orbit as a result of finite ac ripple voltage in the power supplies of the radio-frequency accelerating system. During the deceleration cycle, however, the thin-foil method⁷ may be used to produce prolonged secondary beams with nearly ripple-free characteristics. In the deceleration phase, the foil would, of course, be located on the inner half of the aperture.

⁷Harry G. Heard, Production of Prolonged Secondary-Particle Beams in the Bevatron with Thin Foils, UCRL-3608, Dec. 1956.

Fig. 5. Signal of beam-induction-electrode during the deceleration cycle. Peak beam intensity is 5×10^{10} protons at the start of deceleration. Terminal energy is less than 1 Bev.

Secondly, whenever a given experiment cannot utilize the entire primary beam, two or more experiments may be able to share the beam on different targets. The targets need not be in the same half of the aperture. Different targets may be used. They may be located at the same radial position and may even use the same primary-beam energy. Realization of this latter objective depends upon the time lag of the order of 20 to 80 milliseconds, between the end of the rectification cycle and the start of the inversion cycle. During this brief period, targets may be introduced or removed from the active region of the aperture. Two major experiments utilizing this latter feature have been carried out successfully.

CONCLUSIONS

It has been demonstrated theoretically and experimentally that the beam in a synchrotron may be accelerated and decelerated without fundamental limitations. The additional flexibility obtained in beam programming has been found desirable.

If an analog computer is used as a basic tracking device at all beam intensities, a simple, reliable, and stable system can be achieved. Deviations from the usual beam position may be obtained as required with auxiliary tracking equipment.

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