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ABSTRACT

A relay-operated function generator is described that develops time-dependent program signals to establish discrete control of the radial position of the Bevatron beam. This computer has three independent channels. It may be used at any instant during the acceleration or deceleration cycle of the synchrotron. The unit is transistorized and designed for high reliability.

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I. INTRODUCTION

Protons are accelerated in the Bevatron by the electric field developed across two 3-inch gaps located at the ends of an 11-foot drift tube. The radio-frequency voltage is switched on as soon as the pulsed magnetic guide field rises to a value such that the instantaneous orbit for 9.8-Mev protons is in the center of the aperture that is, 599-3/8 inches. At the start of the acceleration cycle, the frequency of rotation of the protons corresponds to $\beta=0.145$ for protons traversing a 394-foot orbit. As the protons gain energy and β approaches unity, the frequency of the drift-tube voltage increases from 358 to 2475 kilocycles.

Even though the peak drift-tube voltage is 10 kilovolts, the protons gain only approximately 2 kv during their transit through the drift tube. This energy gain corresponds to the change of the phase of the drift-tube voltage that occurs while the protons are shielded by the drift tube. As the protons gain in energy, their velocity increases by a factor of approximately seven. The frequency of the drift-tube voltage changes in the same ratio. In general, the frequency of rotation is given (in mks units) by

$$f = \left(\frac{Bec}{2\pi + \frac{NL}{r}} \right) \left(m_o^2 c^2 + B^2 e^2 r^2 \right)^{-1/2}, \quad (1)$$

where B is the magnetic field intensity, r is the radius of curvature of the orbit, and N is the number of straight sections of length L. If a proton is to remain at constant average radius, its momentum must increase uniformly so as to track the increase in intensity of the guide field. Suppose the frequency of the drift-tube voltage differs slightly from the value given.¹ The proton arrives at a different phase with respect to the drift-tube voltage and therefore gains (or loses) momentum.

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¹ Harry G. Heard, Correction of the Magnetic Field Gradient of the Bevatron With Pole-Face Windings, UCRL-3944, Sept. 1957.

The change in orbit radius that accompanies the momentum deviation is

$$\Delta r = \frac{r \Delta f}{f} \left[\frac{(1-n)}{1 + \frac{(Ber)^2}{m_o c}} - \frac{1}{1 + \frac{NL}{2\pi r}} \right], \quad (2)$$

$$n = -(\Delta B/B)/(\Delta r/r), \quad (3)$$

where n is the magnetic field index.¹ If the frequency deviation of the drift-tube voltage is adiabatic -- that is, slow in comparison with the period of phase oscillations² -- the radial position of the beam may be changed without loss of particles provided that the equilibrium orbit remains within the stability limits of the guide field. The radio-frequency voltage that is used to track the Bevatron beam is generated by a low-level tracking oscillator.³ A close approximation to the desired proton orbit frequency is generated by varying the inductance of a ferrite-core saturable reactor.⁴ Either the magnet current or the integrated voltage induced in a loop in the magnet aperture is used to achieve the necessary transformation,

$$f = \tilde{u}_1(1) = \tilde{u}_2(B). \quad (4)$$

The approximations indicated in Eq. (4) emphasize that auxiliary equipment is needed to assure that the beam tracks at the desired radial position in the aperture. The necessary correction to the orbit frequency is established with a time-dependent function generator.^{5,6,7}

In using the Bevatron as a research tool, it is desirable to establish control over the radial position of the beam during any portion of the acceleration or deceleration cycle. To the extent that the stability limits of the guide field permit, the radial position of the beam may be controlled by a computer that introduces a deviation in the frequency of the drift-tube voltage. If it is to be flexible enough to accomodate all of the

²Lloyd Smith, Influence of Imperfections in the rf System in Phase Oscillations in the Bevatron, UCRL-3045, June 1955.

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

⁴A. J. Pressman and J. P. Blewett, Proc.I.R.E. 39, 74 (1951).

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

⁶Harry G. Heard, Electrostatic Tracking of the Proton Beam of the Bevatron, UCRL-8808, June 1959.

⁷Harry G. Heard, The Beam-Controlled Frequency-Correction System of the Bevatron, UCRL-8828, July 1959.

useful aperture available at any time during the acceleration or deceleration cycle, the computer must contain an arbitrary function generator. This unit must be capable of generating a different beam-position program for different magnet pulses, as well as generating more than one program during a given magnet pulse. The analog computer described in Section II performs these functions.

II. DESCRIPTION OF THE ARPAC COMPUTER

The solution to the problem of supplying satisfactory radial-position control of the Bevatron internal beam divides into two parts. First, the average beam position is controlled in a gross way so that tracking losses are minimized and the necessary targets and probes do not interfere with the beam prematurely. Second, the basic frequency program is altered so as to cause the beam to strike targets at the desired moments and in a prescribed order. The first function is supplied by an analog computer. This provides a voltage-modulation signal to adjust the capacity of voltage-sensitive pn-junction capacitors that shunt the current-programmed inductances in the low-level tracking oscillator.⁵ The second function is supplied by the ARPAC⁸ computer described below.

The operation of the ARPAC computer is illustrated by the functional block diagrams of Figs. 1 and 2. The computer consists of nine units, two of which are regulated power supplies. The seven remaining units include the computer proper, three dc-stabilized line drivers, a remote-control unit, a serial marker generator, and a special unit that permits rapid testing and maintenance of the computer circuits.

The functioning of the various computer elements can best be visualized by reference to Fig. 1. A trigger, derived from a suitable current marker or peaking strip, is delayed by a coarse external time-delay unit. Precise timing is controlled with an internal time-delay unit denoted "start time." As soon as the coarse delayed trigger arrives at the computer, a lockout circuit is energized which removes a short from the output bus and applies a short to the input bus to preclude additional triggering during the period of the lockout multivibrator. At the conclusion of the start-time interval, a trigger is applied to the first of ten sequentially operated time-delay multivibrators. Sequential triggering of identical units was selected so that a single control could be used to expand the time scale and increase the amplitude of the generated signal. Each of these units is triggered by a pulse derived from a previous multivibrator when the latter returns to its stable state. During the quasistable state of a given multivibrator, a mercury-contact relay is activated. Each mercury-contact relay operates to connect the armature of a potentiometer to the output bus. Each potentiometer floats between two regulated power supplies of opposite polarity. The impedance

⁸ The name ARPAC was derived from the first letters of the complete name, "Arbitrary Radial-Position Analog Computer."

MU-19032

Fig. 1. Functional block diagram of the ARPAC computer.

MU-19031

Fig. 2. Block diagrams of the monostable-multivibrator-operated relay control chain of the ARPAC computer (single channel). (Relay drop-out time exceeds pickup time; memory capacitor is low-loss type.)

of the potentiometer is sufficiently high so that it acts as a controllable constant-current source, which supplies charge of a sign and magnitude dependent upon the angular setting of the potentiometer shaft. Each of these relays sequentially operates to place charge of the chosen sign on a memory capacitor in shunt with the output bus. Approximately linear charging occurs during each interval, so that the function generator is capable of generating ten connected straight-line segments. The slope of each segment is determined by the setting of the individual potentiometers.

The duration of each charging interval depends grossly upon the size of the capacitor used in the timing circuits for each multivibrator. As all multivibrators in a given set have the same components, ten equal time intervals are generated. The duration of each of the ten time intervals can be varied simultaneously with the "magnify" control. The magnify control operates a gear chain to turn simultaneously the shafts of the ten potentiometers that adjust the periods of all the sequential multivibrators. As constant current charging occurs during each time interval the magnify control has the effect of increasing the amplitude of the output signal, as it also controls the time duration of each of the ten line segments generated by the computer.

The time interval of each of the ten multivibrators can be adjusted from approximately 1 to 20 milliseconds with one set of timing capacitors, and from approximately 10 to 200 msec by utilizing a second set of plug-in capacitors.

The output voltage of this computer appears across the memory capacitor in shunt with the output bus. A line driver, having an internal impedance of several megohms, senses the voltage across the shunt capacitor and transforms the impedance level to less than 50 ohms. The line-driver output is mixed with other signals in the mixer chassis and routed to the pn-junction capacitors in the low-level tracking oscillator.

As each monostable multivibrator operates, a trigger signal is generated that is suitably shaped by the serial marker generator and displayed on the operator's oscilloscope. The amplitudes of the output signals of this serial marker generator appear in ruler form. This presentation assists the operator in associating a given control function with a given portion of a ten-segment curve.

The number of line segments that are effective depends upon the setting of the lockout control. This control determines the duration of the quasi-stable state of the lockout multivibrator, whose function it is to short either the input or the output of the computer. As soon as the coarse timing trigger arrives, the lockout circuit is activated to remove the short from the output of the computer and short the input-trigger bus. Depending upon the time scale chosen, from one to ten line segments can be used to generate a single-valued function having arbitrary duration, magnitude, sign, and derivative.

The description given thus far refers to a single channel of the computer. Actually, there are three channels, each of which can operate independently. As usually arranged, only one of these channels is employed on a given magnet pulse; however, the flexibility of the computer is such that all three channels may be utilized at the same time or at three different times during a given magnet pulse. The computer is provided with a remote-control unit and is interconnected with the relay-controlled sequence selector of the Bevatron in such a way that an arbitrary predetermined sequence of magnet pulses can be intermixed with predetermined beam and target programs.

The remote-control unit for this computer has three channels, each of which is identified by color--red, yellow, or green. Each panel is back-lighted by a separate set of appropriately colored low-intensity lamps, which are activated only when the channel is in operation. These lamps are switched on by control circuitry that is operated by the relay-controlled sequence selector. In addition to this provision for a visual display that indicates which of three channels has been selected for a given magnet pulse, there is a separate neon bulb that lights for the duration of the period as controlled by the lockout circuit. These controls, together with the display provided by the output of the linedriver and the serial marker generator, provide the accelerator operator with complete information required to determine and control any desired combination in the radial-beam-position control program.

The control of the computer may be switched from local to remote by means of appropriate plugs. The controls are interlocked by plug substitution so that only one set of controls can affect the computer at any time.

III. CONSTRUCTION FEATURES

The function-generating circuits of the computer are contained in a special chassis, the rear view of which is shown in Fig. 3. The nine active plug-in printed-circuit boards for the three channels of the computer are contained within a special 5-1/4-inch printed-circuit cabinet. The nine inactive printed-circuit boards, which permit a 10:1 change in the time scale, are also stored in this cabinet, along with two spare units.

The printed circuit boards are 5x7-inch units with 1-ounce copper conductors. A thin gold wash retards corrosion and aids in component soldering during construction. The wiring circuit is reverse-printed on the component side of the boards to aid in circuit identification during construction and maintenance.

Function-generation controls are located on the front panel, as shown in Fig. 4. The memory capacitors and mercury-contact relays are confined to the lower portion of the chassis, as seen in Fig. 3.

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 the event of equipment malfunction. One of the spare boards is provided with sockets, so that the transistors may be removed to permit the performance of various portions of the circuit to 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. A special test set is provided that permits units to be checked in a realistic environment without interfering with the normal operation of the computer.

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 has already undergone more than 12,000 hours of continuous operation without malfunction. It should give many more years of maintenance-free service. Additional circuits may be added to this cabinet, as design improvements warrant, by addition of the appropriate plug-in sockets at the rear of the printed-circuit cabinet. The

ZN-2305

Fig. 3. Rear view of the computer chassis, showing printed-circuit racks and general construction details.

ZN-2304

Fig. 4. Front view of the local control panel.

printed-circuit modules themselves may be updated or changed, if justifiable design improvements are conceived.

IV. CIRCUITRY

The specific circuit designs are not discussed in this paper. For these details the reader is referred to UCRL prints 3Z4764, 7Y2395, 7Y2433, 7Y2404, 7Y3233, 7Y2444, 7Y2413, and 7Y2424.

V. CONCLUSIONS

A completely transistorized, relay-operated computer is described that synthesizes the necessary time-dependent voltages for perturbing the radial position of the internal beam of the Bevatron. The three channels of this computer are independent and provide the desired stability and control required in utilizing the Bevatron in highly multiple operation.

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