UCRL-8033
Instrumentation

UNIVERSITY OF CALIFORNIA

Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

MEASUREMENT OF BEAM CURRENT IN THE BEVATRON BY INDUCED VOLTAGES

John T. Lavrischeff
(Thesis)

October 28, 1957

Printed for the U.S. Atomic Energy Commission

DISCLAIMER

Contents

MEASUREMENT OF BEAM CURRENT IN THE BEVATRON BY INDUCED VOLTAGES

John T. Lavrischeff

Radiation Laboratory
University of California
Berkeley, California

October 28, 1957

ABSTRACT

The Bevatron uses a system of electrodes through which the internal proton beam passes in order to continuously measure the magnitude and radial position of the beam. The bunched circulating beam induces a periodic voltage on the electrodes. This signal is amplified and displayed on an oscilloscope and also converted to direct current for operation of a recorder. Two types of electrode systems are used. The first is a large hollow box to provide beam magnitude signals for specialized monitoring and for primary calibration. The second system consists of two sets of smaller electrodes. One set provides beam radial-position information for tracking control, and the other provides beam magnitude information for magnitude control and for general distribution to experimenters associated with the Bevatron. A telemetering radio link is used to relay beam information to those in other areas. Problems associated with handling the beam signal are discussed, and the design principles involved in detection, amplification, and isolation of the signal are described. Calibration techniques, signal distribution facilities, and control features are also given. The systems described are stable and provide the desired information with a minimum of maintenance and operational difficulty.

I. INTRODUCTION

The Bevatron at the University of California Radiation Laboratory, is a 6 billion-electron-volt (Bev) proton synchrotron.[1] This device receives a 9.8-Mev proton beam from a linear accelerator and further accelerates a percentage of these protons, at a nominally constant radius of almost 600 inches, to a final energy greater than 6 Bev. The particles are kept at the constant radius by means of a time-varying magnetic field. For a given energy and radius, there is only one value of magnetic field that will keep the protons from spiraling inward or outward.

A 500-microsecond pulse of protons of nearly constant energy from the linear accelerator, starts to spiral into the aperture when the average field of the Bevatron magnet rises to approximately 297 gauss. The magnetic field increases at a rate of 8000 gauss per second causing the protons entering the aperture late in the injection cycle to develop radial betatron oscillations having amplitudes as large as 20 to 25 inches. In addition, vertical betatron oscillations occur owing to divergence of the injected beam, gas scattering, and vertical imperfections in magnet alignment. The net result is that by the time the acceleration cycle starts, the injected beam is quite diffuse and has an approximate cross section of 1 by 4 feet.

The increase in particle energy is obtained by successively passing the proton bunch through an 11-foot drift tube to which is applied a radio-frequency potential. The injected protons are bunched by applying the potential to the drift tube as soon as the magnetic field rises to a value such that the instantaneous orbit for 9.8-Mev protons corresponds to a radius of 599-3/8 inches, the centerline of the chamber. When the accelerating potential is first applied, 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° start the acceleration cycle and become bunched. The other (azimuthally distributed) particles are lost. Further losses occur because radial oscillations (initiated by phase shifts) cause collisions with aperture-limiting structures. The oscillations in radius, as well

[1] William Brobeck, Design Study for a 10-Bev Magnetic Accelerator, Rev. Sci. Instr., Vol. 19, No. 9, (1948) p. 545.

as some oscillations in azimuth, occur because not all the particles arrive at the drift tube with optimum phase with respect to the radio-frequency voltage. Protons arriving at different phases receive energy increments different from the value necessary to maintain their orbit centered in the aperture. Only those particles with azimuthal phase excursions within phase-stable limits continue to be accelerated. The bunched protons gain approximately 2 kilovolts of energy per revolution as they circulate through the drift tube. The protons are accelerated to their final energy in a period of approximately 2 seconds. At the end of this period the magnetic field has increased from a low value to 15,550 gauss and the radio frequency has increased from approximately 354 kc to 2.5 Mc.

The magnet structure is divided into quadrants with straight sections interposed for injection, acceleration, measurement, and experimentation. The straight sections are designated geographically (See Fig. 1). The east straight section, which is used for injection, has room for a beam-detection device, and the south straight section is used primarily for devices relating to beam detection or control. It is the beam-detection devices and the utilization of their signals with which this report is primarily concerned. Because of the sources of their signals, the systems for measurement of beam current are called, respectively, the east and south induction-electrode systems.

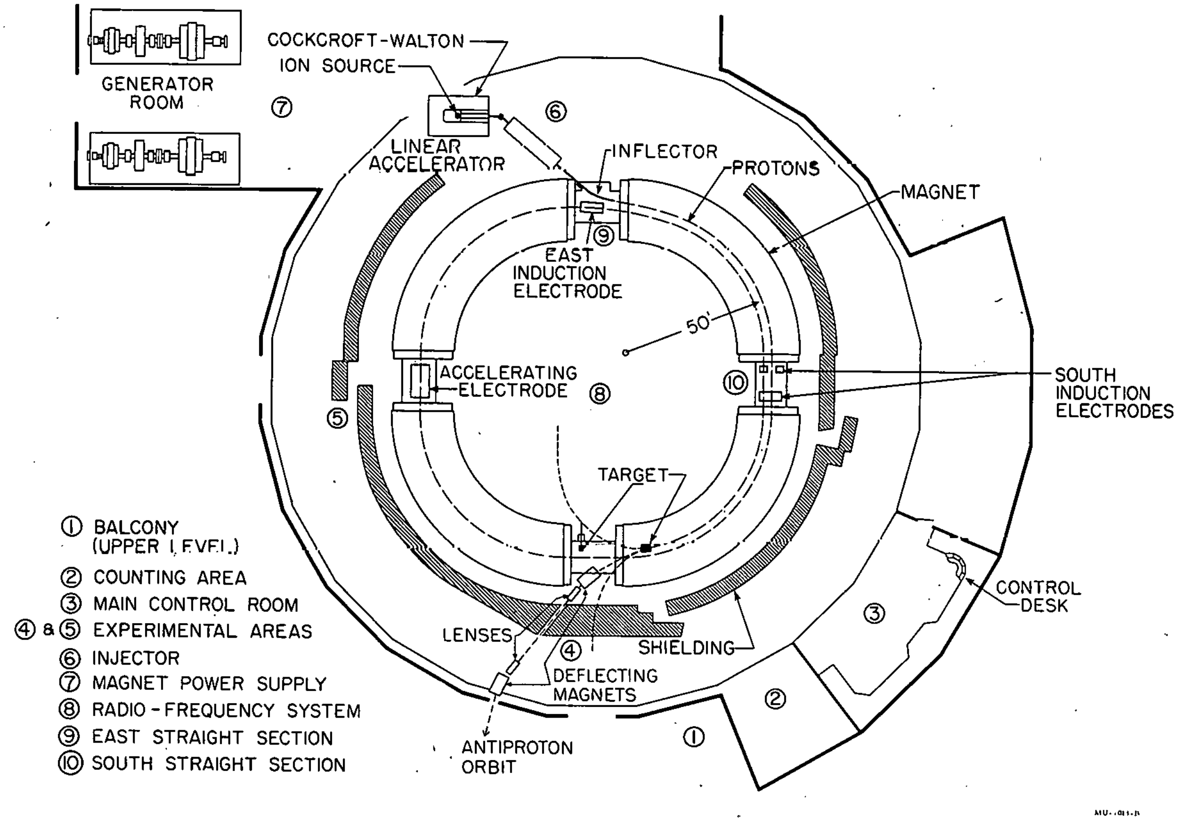


Fig. 1. The Bevatron

II. BEAM DETECTION DEVICES

There are many available methods of beam detection based upon collection or deflection techniques; however, a nondestructive method was sought. Such methods are generally based upon electromagnetic interactions with a passive device. Since the circulating beam is bunched, either magnetic or electric induction may be used to detect the presence of the charge. Electric induction was chosen in preference to magnetic induction in the Bevatron for a variety of reasons. The magnetically induced emf varies as the square of the rotational frequency of the charge. Therefore, the available signal is small in the early portion of the acceleration cycle. Furthermore, the output voltage of a pickup coil is reduced at the high-energy end of the acceleration cycle owing to the self-capacitance of the coil. Finally, a useful signal-to-noise ratio is difficult to attain because of induced transient voltages from the large pulsed magnet of the accelerator.

Electric induction also presents certain practical disadvantages. As a high-impedance device, it must be carefully shielded from stray coupling to accelerating-electrode radio frequency fields and also from induced voltages resulting from transients from the magnet power-supply ignitrons. Sensitivity to low beam current dictates large physical size (especially in length); however, for good frequency characteristics the capacitance to surroundings should be low, indicating small physical size. In addition, the electrode and connections to the electrode must be such that the beam bunches will not excite disturbing resonances in the electrode system. Despite these disadvantages, the electric-induction method of detection has been found to be quite satisfactory.[2,3] It may be used for continuous measurement of beam current during the acceleration cycle, for observation of azimuthal charge-density distribution within the bunch, for observation of phase oscillations during the cycle, and, by means of special split-electrode geometry, for observation of the radial position of the circulating beam. The latter is useful in manual or automatic beam tracking.

---

[2] William A. Wenzel, Bevatron Internal Beam Monitor, in Bevatron Targets, Beam Energy and Current Monitor, Bevatron Report No. 117, Feb. 1956, p. 12.

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

III. ELECTRIC INDUCTION ELECTRODE

A. Mathematical Analysis of Voltage Induced

The electric-induction electrode consists of an insulated structure so placed within the aperture of the Bevatron magnet that the circulating beam passes through it without obstruction. As the bunched charge passes near the electrode, a charge is induced on the electrode with respect to ground, and current flows through the input impedance of a measurement system attached between the electrode and ground. If the response of the system is adequate, the voltage developed at the system input is proportional to the instantaneous charge in that portion of the beam in the immediate vicinity of the electrode. The peak induced voltage is directly proportional to the peak density of charge in the circulating beam. The average voltage developed by the induction electrode may be expressed in terms of the distribution of the density of charge within the bunch as

$$V_{Av} = \frac{1}{2\pi} \int_0^{2\pi} V(\phi)\, d\phi \, , \tag{1}$$

where V_{Av} is the average induced voltage for a bunch and $V(\phi)$ is the voltage developed at any time when the relative phase of the bunch with respect to some arbitrary reference is ϕ. If the effective length of the electrode is ℓ and the path length of the circulating bunch around the Bevatron is L, this voltage may be expressed in terms of the charge $q(\phi)$ and the capacity C of the electrode to its surroundings as

$$V_{Av} = \int_0^{2\pi} (\ell/L)\,(q(\phi)/C)\, d\phi = \left(\frac{\ell}{L}\right) \frac{Q}{C} \, , \tag{2}$$

where Q is the total charge in the bunch. The effective path of the bunch is not exactly circular because the magnet structure consists of four quadrants with intervening straight sections. If the radius of the quadrant path is r, the length of the straight section is s, and the total charge is shown as the number of particles N multiplied by the charge on the individual particles q, the induced voltage may be expressed as

$$V_{Av} = \left[\ell / (2\pi r + 4s)\right]\left[Nq/C\right]. \qquad (3)$$

For the induction electrode located in the east straight section the constants in Eq.(3) are $\ell = 48.6$ inches, $r = 600$ inches, $s = 240$ inches, $q = 1.60 \times 10^{-19}$ coulombs, and $C = 356$ μμf. Thus we obtain

$$V_{Av} = \left[\ell q/(2\pi r + 4s)C\right] N = \left\{(48.6)(1.60 \times 10^{-19}) / \left[(1200\pi + 960)(3.56 \times 10^{-10})\right]\right\}(N)$$

$$= 4.61 \times 10^{-12} \text{ N volts},$$

or for circulating beam of 10^{10} protons an induced voltage of 46.1 mv may be expected.

B. Noise Sources

In induction electrodes, as in all devices used for measuring any quantity, there arises the problem of the signal-to-noise ratio. Noise may be defined as any phenomenon or disturbance of the system that may eventually find its way into the indicating or recording device but is not part of the signal to be measured or detected. For reliable measurement, the noise must be considerably less than the signal being measured.

Noise in the induction-electrode system may be defined as consisting of any phenomenon that causes an indication of beam to be recorded when no beam is being injected for acceleration, yet normal accelerating potentials and fields are applied. The desired signal must exceed the noise by a factor of 2 or 3 for reliable indication of beam. However, where beam current is integrated over a long period of time involving many acceleration cycles, the beam signal should be at least an order of magnitude removed from the noise in order that a reliable total measurement may be obtained.

One of the most common sources of extraneous signal in the measurement systems associated with the Bevatron is voltage induced by magnetic fields. Magnetic shielding of components susceptible to this type of interference, including the indicating and recording instruments, eliminates most of the noise due to this source in the induction-electrode systems. Further precautions involving cable runs were also necessary to remove the rest of the noise due to this source. Twisted pair cable and coaxial cable were found to be satisfactory in having minimum included area in any loop capable of having voltages induced by the magnetic field. This type of noise voltage may easily be induced in ground loops, which is one of the reasons for rigorously avoiding multiple ground paths in the induction electrode systems.

The magnet power supply constitutes a noise source in itself in that ignitron switching transients are radiated to all equipment associated with the accelerator. However, for the induction electrode systems, the radio-frequency energy radiated from the equipment producing the rf accelerating potential constitutes the greatest source of radiated noise. Electrostatic shielding procedures and careful grounding have been most useful in reducing this type of interference; however, the largest part of the remaining noise in the induction electrode systems is due to pickup of radiated rf energy. The problem is complicated by the fact that the noise in this case is within the pass band of the measuring system. In fact, at any instant in the acceleration cycle, the frequency of the induction electrode signal and the frequency of the rf pickup are the same. Single-shield techniques fail in such a situation because of the difficulty in maintaining an effective ground at all points of the shield. In coaxial cable carrying low-level signals the rf picked up along the outer conductor may be far greater than the desired signal. Double-shield techniques allow the inner shield to be a shielded common return for internal signals and this effect a great reduction of rf pickup. In this manner the pickup is largely confined to the outer shield, which is not part of the signal circuit. The induction-electrode systems use double-shielded cable and double-shielded enclosures to maintain signal transmission in the presence of high rf radiation.

Other noise sources are of internal nature. Vacuum tube amplifiers are used which have been designed to contribute very little internal noise; dc circuits have been stabilized to prevent zero drifts and other level shifts which could cause extraneous signal output. The contribution from these sources is far below that due to rf pickup, in any case.

Effective techniques for discrimination against noise in the induction electrode systems have been the use of double electrostatic shielding and of some magnetic shielding, and the exclusion of loops upon which magnet voltage could be induced. The double shield scheme was found to be most successful when the inner shield was returned to a one-point ground, preferably at the signal source, and the grounding of the outer shield was experimentally determined for minimum noise. In the east induction-electrode system, such techniques have kept the noise level at the input of the system below 12 μv peak to peak (pk-pk) across 195 ohms, measured in a band width of 100 kc to 20 Mc. The south induction-electrode system utilizes more than one signal source, and at present the inner-shield ground return is made at a point removed from the electrodes. The noise level at the system input is below 35 μv pk-pk across 195 ohms, in a band width of 100 kc to 20 Mc. This could probably be reduced further by selection of one side of one signal source as the system ground reference and attendant isolation of the other electrodes and the rest of the system.

IV. EAST INDUCTION-ELECTRODE SYSTEM

A. Induction-Electrode Signal

The east induction electrode has the form of a hollow box enclosing the beam path. The induced charge with respect to ground is transferred by means of a 200-ohm coaxial transmission line to amplifying equipment. If the line is properly terminated, its impedance becomes the lower portion of a voltage divider. The upper portion of the divider is formed by the source impedance of the electrode. The electrode is essentially a capacitive source. The calculated sensitivity of the east induction electrode was shown in III-A to be 4.61×10^{-12} average volt per proton on the basis of a high impedance generator feeding the lumped capacitance of the electrode (capacitance to guard rings and other surroundings).

The peak amplitude of the induction-electrode signal is not useful for primary calibration because the density distribution of the circulating charge varies with drift tube voltage and the peak amplitude is directly proportional to the density of charge. For this reason and because other variables can introduce distortion of the induced signal on the electrode, a band-pass amplifier is used to yield the fundamental frequency. Information for the record is not needed at the lower energies and a frequency range from 2.0 to 2.5 Mc is sufficient. This has the additional advantage of reducing the noise by about an order of magnitude.

Accurate use of instrumentation that operates on only the fundamental frequency of the beam signal depends on knowing the ratio between the amplitude of the average voltage and the amplitude of the fundamental component. This ratio has been determined (in Appendix A) to be 1.85. Doubling the 1.85 figure to arrive at a pk-pk value (for convenience in reading oscilloscope displays) and multiplying by the 4.61×10^{-12} - volt calculated sensitivity yields about 17×10^{-12} volt per proton which, when divided by the capacitance of the electrode and reduced 1% or so in the transmission line, comes out about 120 mv at the input to the amplifying equipment for 10^{10} protons. This figure represents the amount of sine wave signal (measured pk-pk) that one would apply at the input to the amplifiers in order to calibrate the system for a beam signal equivalent to that obtained when the beam intensity is 10^{10} protons per pulse. On this basis, the system was designed to handle input signals from 12 μv (10^6 protons) to 12 volts (10^{12} protons).

B. Amplifiers for Induction-Electrode Signal

The amplitude range indicated above lends itself to six steps of amplification, each constituting a relative voltage gain of 20 db. Two Hewlett-Packard (H-P) 460A wide-band amplifiers, a 20-Mc amplifier and a 20-db attenuator provide the steps required. The two highest-gain steps use all the amplifiers and the attenuator, the next two steps use the 20-Mc amplifier and the attenuator, and the two lowest-gain positions use a direct connection and the attenuator. The switching is accomplished with low-leakage transfer relays.

A block diagram of the entire system is shown in Fig. 2. The induction electrode is located in the east straight section of the Bevatron. The signals are carried by means of a double-shielded transmission line to a double-shielded enclosure located on a platform adjacent to the straight section (see Figs. 3 and 4). The enclosure contains the amplifying and calibrating equipment, including the gain-change relay panel, which determines the amplification in the system.

The signal leaving the gain-change relays is essentially normalized to be in the range of 120 mv to 1.2 volts, providing the appropriate gain step is used. In this way monitoring of the wide dynamic range of beam signals from the electrode is reduced to the use of equipment that is linear over a 10-to-1 amplitude range. Such equipment is the band-pass amplifier and peak detector, which immediately follows the gain-changing system.

The fundamental component of the beam signal is extracted in the band-pass amplifier and is peak-detected in such a manner that an input from 120 mv to 1.2 volts causes a dc output from 5 volts to 50 volts, which is then sent to the main control room for recording and distribution to remote recorders. A feature of the band-pass amplifier that boosts the signal to a level capable of linear diode detection is the application of "ultralinear" techniques to a video-type feedback amplifier, i.e., a

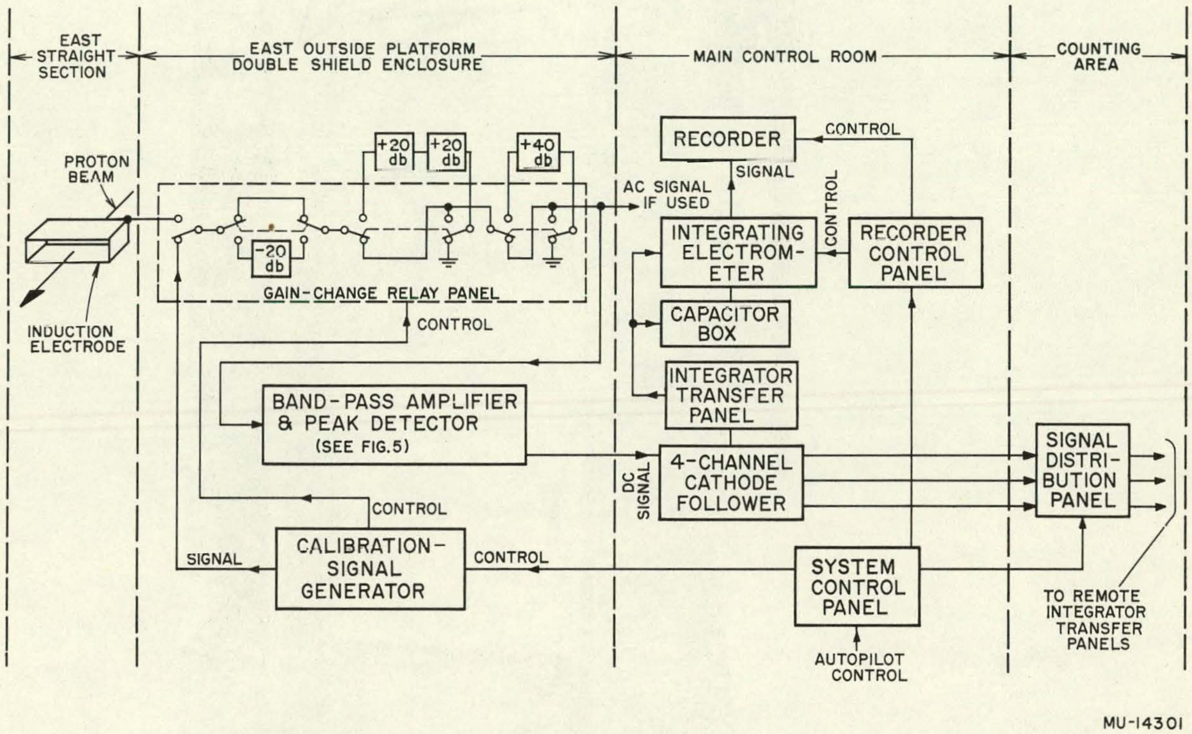
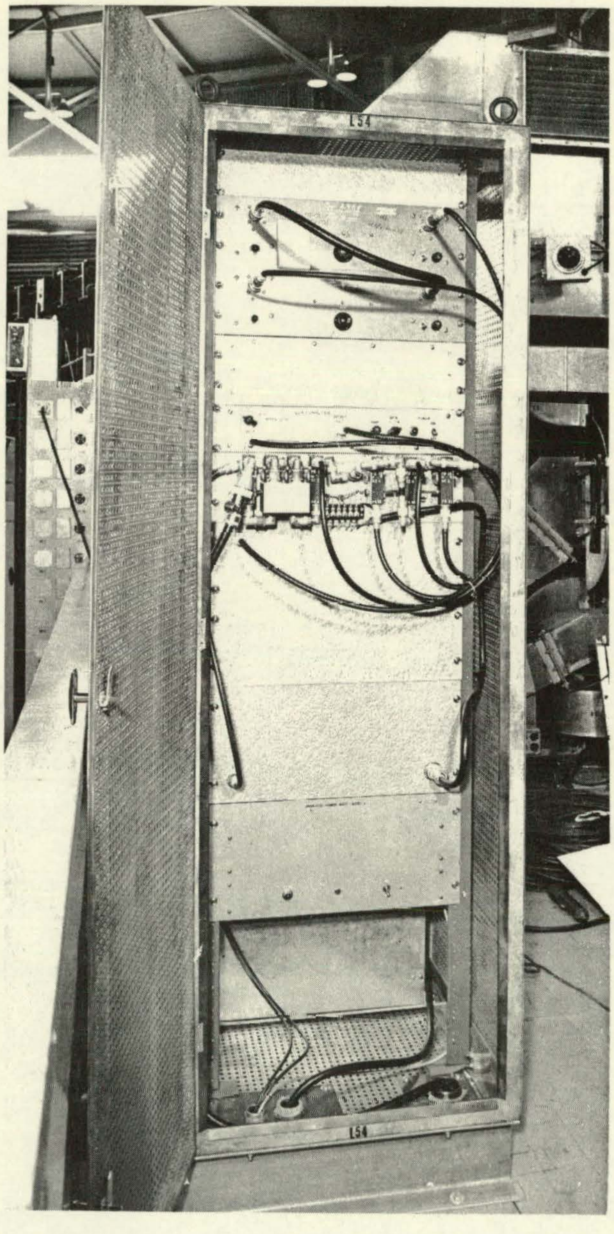
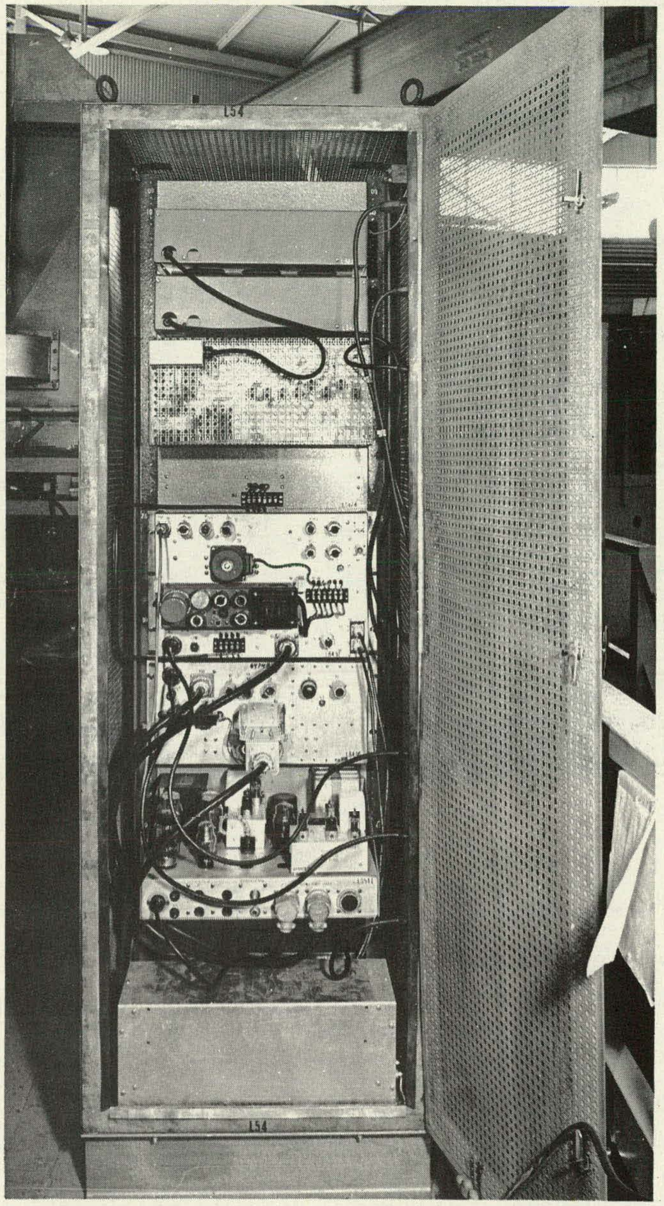


Fig. 2. Bevatron east induction-electrode system (block diagram)



ZN 1812

Fig. 3. Front view of Bevatron east induction-electrode system-double-shield amplifier enclosure. Units from bottom to top: line filter; power supply; calibration-signal generator; band-pass amplifier and peak detector; gain-change relay panel; 100 kc—20-Mc amplifier (2 panels); H-P 450A amplifier; H-P 450A amplifier.



ZN 1811

Fig. 4. Back view of Bevatron east induction-electrode system-double-shield amplifier enclosure. Units from bottom to top: line filter; power supply; calibration-signal generator; band-pass amplifier and peak detector; gain-change relay panel; 100 kc—20-Mc amplifier (2 panels); H-P 450A amplifier; H-P 450A amplifier.

portion of the output signal of a pentode amplifier is fed back to its screen, thus minimizing the curvature of the transfer characteristic.

C. Method for Continuous Calibration

The role of the unit consisting of the band-pass amplifier and the peak detector does not end with simple amplification and detection of the beam signal. This unit is shown expanded in block form in Fig. 5. At the end of the acceleration cycle, when beam signal is no longer present, a calibration signal is applied to the input of the gain-changing system. The signal is derived from a source that is amplitude-stabilized within 0.1% and has a frequency in the center of the range of the band-pass amplifier. (This signal source is described in Appendix B.) The calibration signal is of such an amplitude that on each decade range of the system the output from the detector is 50 volts. This voltage is applied to one side of the input of a continuous balance amplifier and the other side of the input is connected to a 50-volt tap on the electronically regulated power supply that is used for the equipment. The continuous-balance amplifier operates a servomotor as long as an input difference signal is present. The motor is mechanically linked to the gain-control potentiometer of the band-pass amplifier; if an input-difference signal is present the gain is brought to the point where the 50-volt signal from the detector matches the 50-volt reference, and a zero difference signal is presented to the input of the balance amplifier. Sufficient gain is included in the servo loop to insure holding the system to the reference. At the beginning of each acceleration cycle, the calibration signal is removed, the input to the balance amplifier is held shorted, the servomotor is not allowed to turn, and the band-pass amplifier and peak-detector unit functions with beam signal as previously described.

To prevent the calibration signal applied to the system between cycles from confusing the beam record, a relay is used to keep the dc signal line to the main control room discharged during the calibrating period. However, a manual calibration control is provided in the form of a button in the main control room which does allow read-out of the

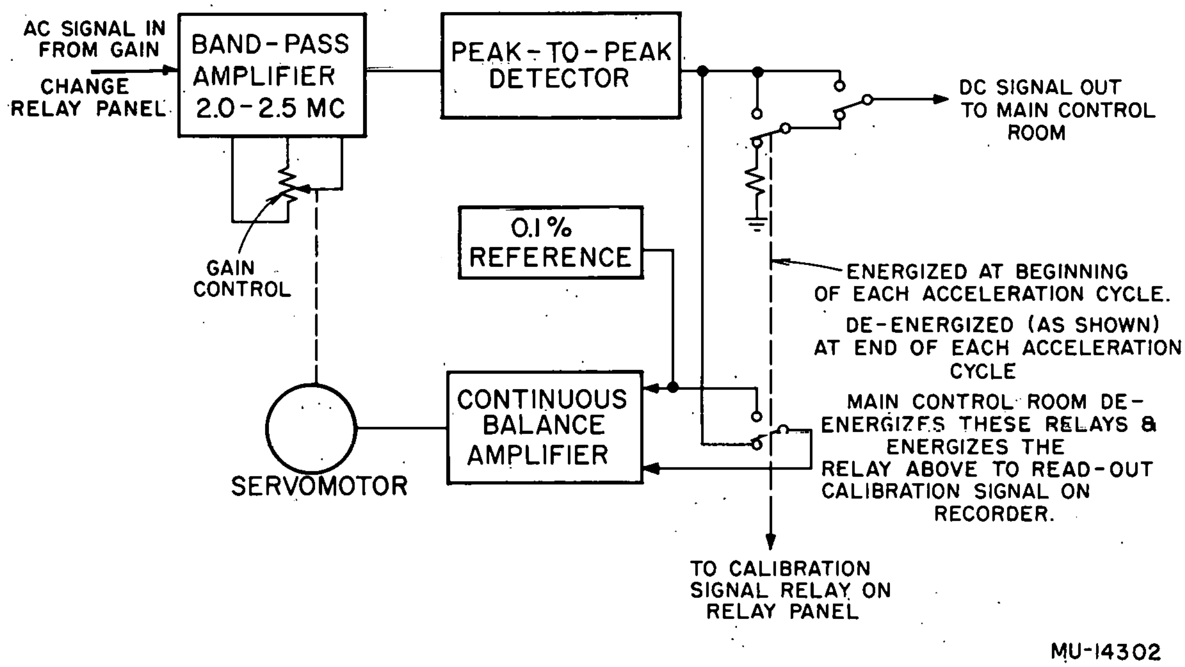


Fig. 5. Bevatron east induction-electrode system--band-pass amplifier and peak detector.

calibration signal and also holds the system in calibration irrespective of operational triggers associated with automatic calibration.

D. Signal Distribution

The dc signal to the main control room is distributed by means of a four-channel cathode follower (see Fig. 2). One channel feeds the recording equipment in the main control room and the others are used through a distribution panel in the counting equipment area to feed remote recording equipment. The four-channel cathode follower utilizes stabilized circuitry to maintain zero dc out for zero dc in within 5 mv, long term. Linearity is within 0.1% for up to 50 volts dc output, which is the normal maximum signal level. (The circuit is described in Appendix C.)

E. Recording Equipment

The dc signal from one of the channels in the four-channel cathode follower is used exclusively for recording equipment in the main control room. A transfer panel containing a low-leakage dc operated relay connects a small capacitor to the signal line until the relay circuit is triggered by a magnet-current marker to transfer the charge to the recording equipment. Triggers in the range from 0.8 Bev to full energy can be accommodated. The charge is transferred during a 1-second interval to a large capacitor which is the integrating capacitor of an integrating electrometer, then the small capacitor is returned to the signal line. Both ends of the capacitor are switched to effect ground-circuit isolation between equipment near the east straight section and equipment in the main control room. For a 50-volt signal and a 0.1-μf transfer capacitor, 500 mv dc output is obtained from the 10-μf integrating capacitor. A feedback divider having several taps and located in the electrometer unit allows use of a 0-to-10mv strip-chart recorder of the self-balancing servo-pen type, with a choice of sensitivities. The positions of this divider are labeled in terms of "Protons Full Scale - Times Decade Multiplier." The maximum-sensitivity position on the electrometer is used when the full pen travel of the recorder is desired to record the beam signal on a per-pulse or per-acceleration cycle basis. This position of the divider switch is labeled "10." In this mode the integrating capacitor is discharged between pulses. The minimum-sensitivity position is useful when it is desired to record the total integrated beam over many pulses. This position is labeled "100". In this mode a "stair-step" record is obtained, with a maximum-level signal causing a pen deflection of one-tenth full scale each pulse. When the pen has worked up to the full-scale position, the integrating capacitor is discharged and the process is repeated. At the end of a run the number of completed zero-to-full-scale sweeps can be counted to indicate the integrated beam achieved during the run. A preset counter actuated by a limit switch on the recorder can be used to turn off the Bevatron rf after the desired level of beam has been received by the experimenters.

A small pen operating on the margin of the chart indicates the decade multiplier in use by indexing one minor division for each step of gain in the system.

Similar recording equipment can be used at remote experimental areas by patching into the counting equipment area distribution panel for signals.

F. Control Features

A system control panel is located at the operating console adjacent to the controls for the south induction electrode system. Preprogramming selectors allow setup of the desired decade range of sensitivity for each channel of the three-channel sequencing autopilot (i.e., automatic control system.) The south system is useful for determination of the appropriate range to use. Decade-multiplier lights indicate at all times the sensitivity of the system in terms of protons per pulse (in the range from one to ten) times the multiplier light that is on. The decade light signals are duplicated at the distribution panel in the counting area for use with lights at remote recorders. A push-for-full-scale-signal button is located on the system control panel for reading out the calibration signal on the recorders. This button is also duplicated at the recorder control panel where the "full scale" and "integrate" modes of the recorder can be set up and calibrated. The recorder control panel also incorporates a bidirectional homing rotary relay system which operates the selsyn drive for the recorder side pen. For the "full scale" mode, a one-shot multivibrator is used to operate a relay that, at the end of each pulse, discharges the integrating capacitor. A switch on the recorder control panel connects the discharge relay to the recorder limit switch on the "integrate" mode. The "integrate" mode is considered the normal mode of operation, whereas the "full scale" mode is useful for calibration of the system described and also for primary calibration of the south induction-electrode system, which is described later.

V. SOUTH INDUCTION-ELECTRODE SYSTEM

A. Induction-Electrode Signals

In the south straight section of the Bevatron the south "sum" electrode is located. The south sum electrode is similar to the east electrode but physically smaller. The south straight section also contains a pair of induction electrodes divided on a vertical plane through the center of the aperture so that a signal is generated which indicates the radial position of the beam with respect to the aperture centerline. The sum electrode is so called because it produces a signal proportional to the beam over the entire aperture. The induced charges on the sum electrode and on each of the pair of radial position electrodes are transferred to 200-ohm coaxial transmission lines by means of emitter followers (common-collector transistor circuits) mounted at the electrodes. The voltage on the sum line was determined, by cross-calibration against the east induction-electrode system, to be approximately 35 mv across 200 ohms for a beam of 1×10^{10} protons. The radial-position electrodes each produce approximately one-half as much signal for a given beam intensity as the sum electrode. For the sum signal, then, the usable amplitude range is from 35 μv (10^7 protons) to something approaching 3.5 volts (10^{12} protons). The limiting factor in monitoring higher beam intensity is the restricted dynamic range of the emitter follower.

B. Amplifiers for Induction-Electrode Signals

The amplitude range indicated above lends itself to five steps of amplification, each constituting a relative voltage gain of 20db. Two H-P 460A wide-band amplifiers and a 20-db attenuator provide the first two setps, the next two are obtained by switching in the attenuator when only the line-driving amplifier is operative, and the last step involves switching to the - 20-db input of the line-driving amplifier. The switching is accomplished with low-leakage transfer relays. There are three such channels of amplification. Band width in the systems is limited mainly by the line-driving video amplifiers, which have a frequency response of 100 kc to 20 Mc. The result of the gain-changing system is to present a signal on the lines to the main control room which is always in the range of 0.1 volt to 1.0 volt for the amplified sum signal, and 0.05 volt for each of the amplified radial-position signals. The five gain steps are referred to in terms of the system's capability of monitoring beam intensity, i.e., step 1 monitors beam intensities in the range of 1×10^7 to 10×10^7 protons, step 2 monitors beam between 1×10^8 and 10×10^8, and so on, to step 5, which extends to 10×10^{11}. The signal-to-noise ratio is preserved by having the amplification close to the induction electrodes and having the gain change handled remotely from the main control room either by the operator or automatically in a preprogrammed sequence by the autopilot. A block diagram of the entire system is shown in Fig. 6 and the double-shielded enclosure for the three channels of amplifiers is shown in Fig. 7.

C. Isolation of Amplified Signals

The amplified south sum electrode signal is of general utility in contrast to the east induction-electrode signal, which is used for primary calibration. It is used to drive the beam-regulating equipment, which provides a preset level of beam, it is used for oscillographic display in the main control room, and it is available at several convenient locations for the experimenters. It is also used to drive the telemetering radio link by means of a special band-pass video detector which is described below under "Protons-per-Pulse Meter." In order to provide signal isolation between the various outputs so that there may be no interaction of equipment, separate cathode followers drive each distribution line as shown in Fig. 8. As there are seven output channels, the reactive loading of seven cathode followers connected in parallel to one input line might lose the 20-Mc system response. This problem is circumvented by using three low-input reactance cathode followers to drive the distribution followers. The three input followers present a total capacitance to the input line of about 15 μμf. The low capacitance, of less than 5 μμf per follower, is obtained by "bootstrapping" the plate from the cathode so that the grid-plate

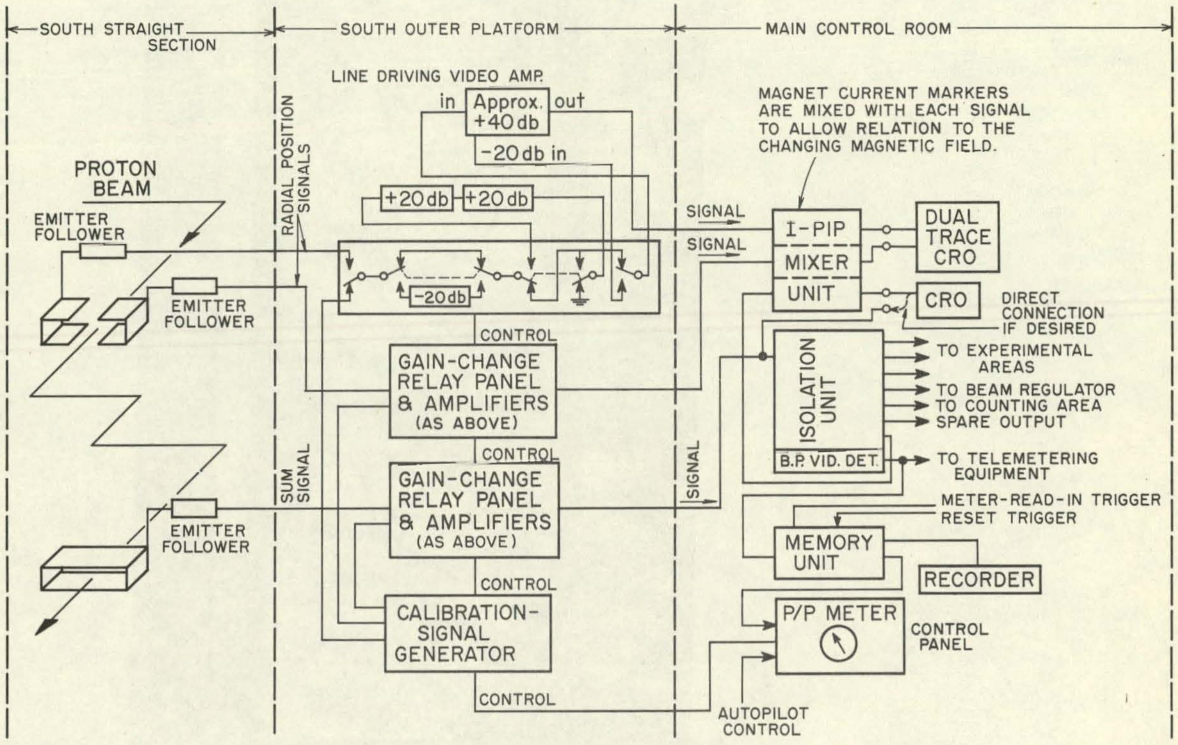
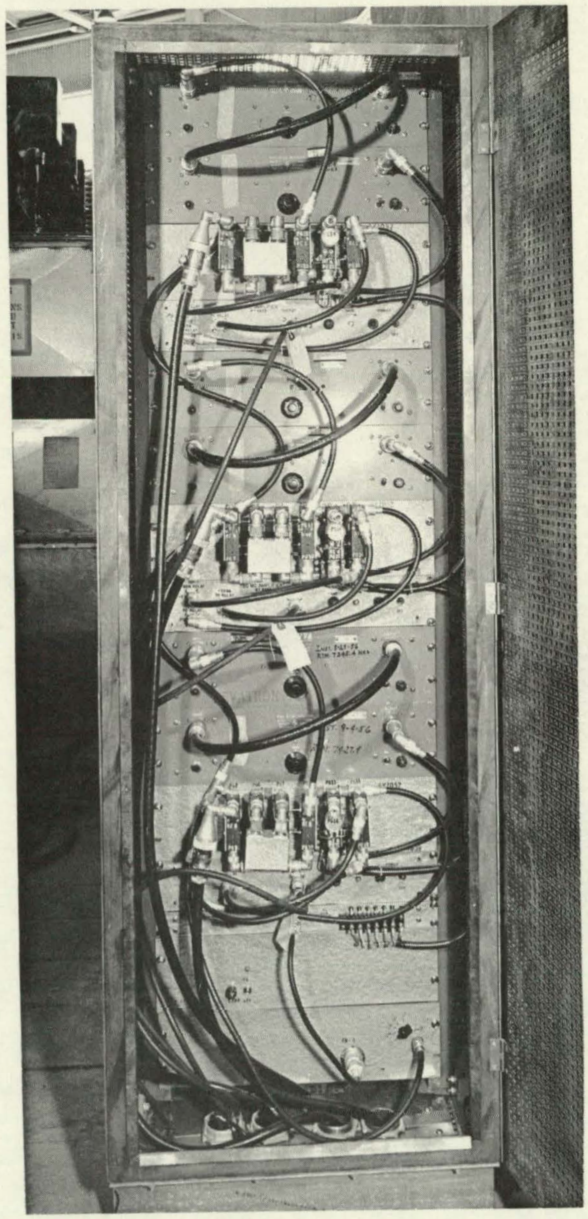


Fig. 6. Bevatron south induction-electrode system (block diagram).



ZN 1810

Fig. 7. South induction-electrode-system amplifiers. View shows an isolated rack in an enclosure of copper-plated screen. Description: Bottom seven units, calibration signal generator, power supply, and amplifiers for sum signal; top eight units, amplifiers for radial-position signals.

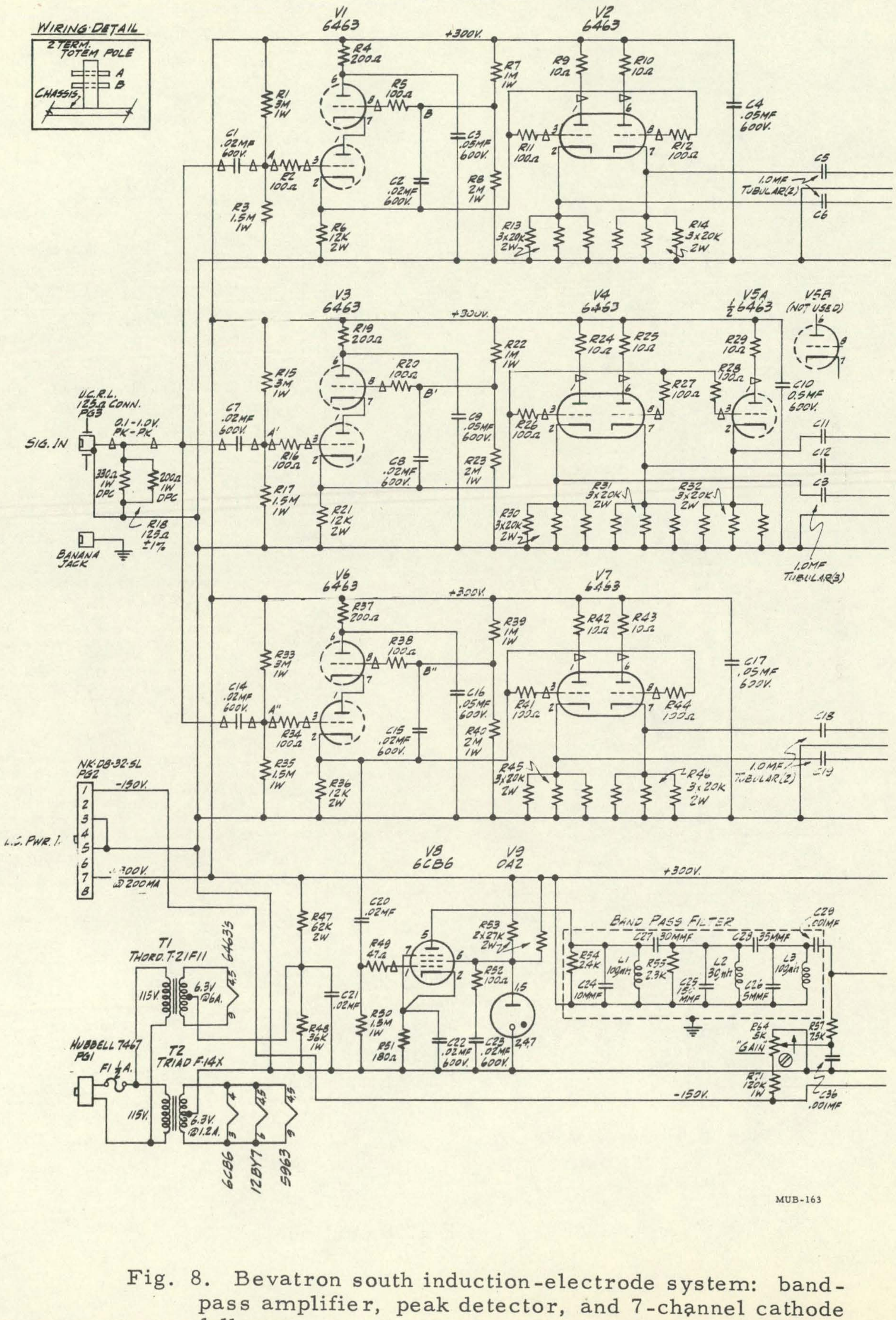


Fig. 8. Bevatron south induction-electrode system: band-pass amplifier, peak detector, and 7-channel cathode follower.

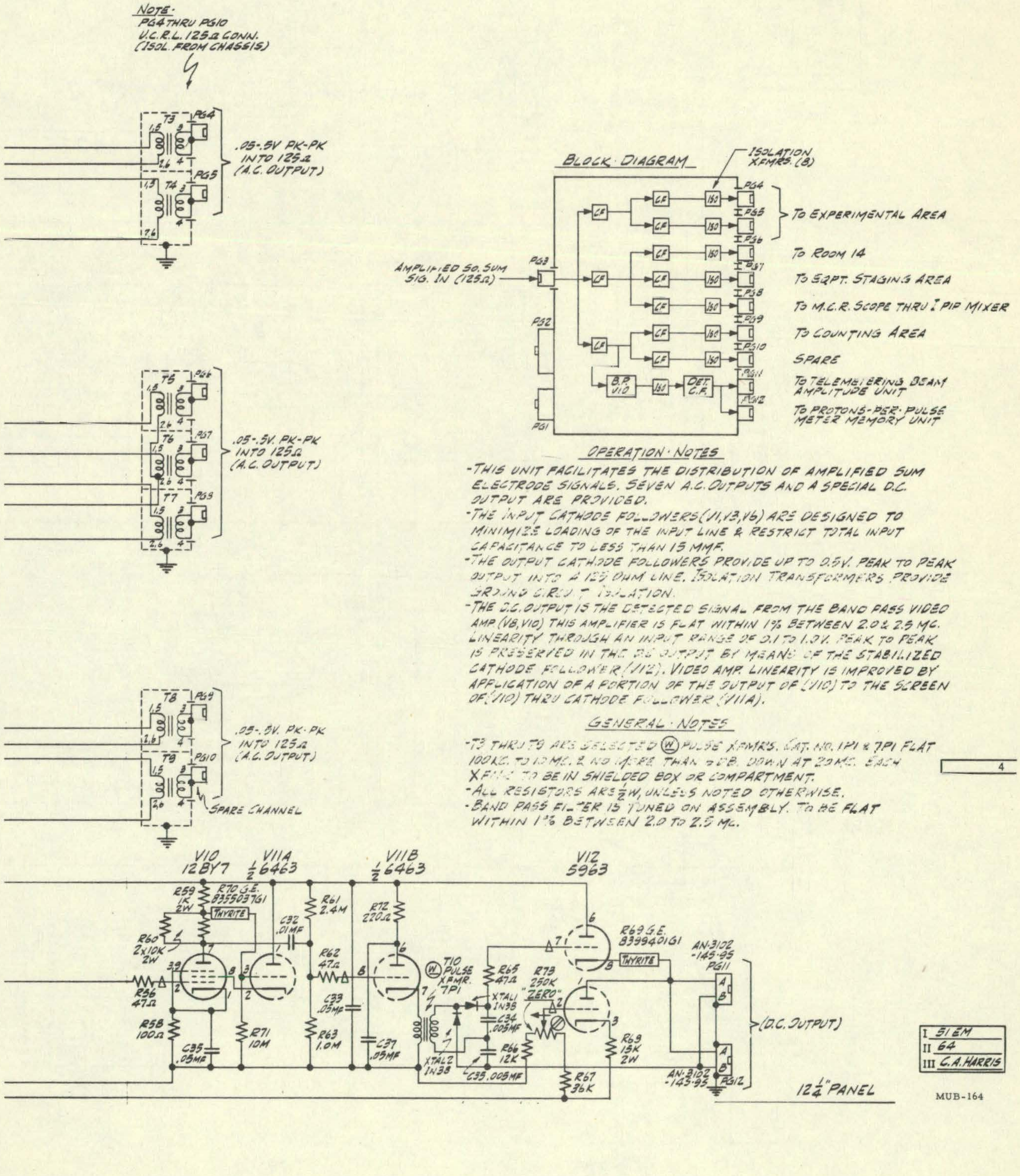


Fig. 8 continued.

capacitance of the tube is driven from the low impedance cathode rather than from the input. Wiring capacitance is minimized by driving the bottom terminals of tie-point supports as a guard ring, strapped to the tube cathode. Pulse transformers tested for frequency response provide ground-circuit isolation for all outputs. The output amplitude is generally in the range from 0.05 volt to 0.5 volt across 125 ohms.

D. Protons-per-Pulse Meter

The general utility signals described above are not useful for absolute-magnitude measurements of beam intensity (for reasons discussed earlier in IV, A unless a filter is used to extract the fundamental-frequency component of the signal. For the purpose of flexibility in absolute-magnitude monitoring in the main control room a band-pass video amplifier is used to drive a detector (see Fig. 8). The detector yields the envelope of the amplified sum electrode signal. The band-pass video amplifier receives its input signal from one of the three input isolation cathode followers. The amplitude response is within 1% from 2.0 Mc to 2.5 Mc. Thus, beam intensity may be measured from about 0.8 Bev to full energy during each pulse. A transformer is inserted in the circuit path before detection for ground isolation. Stabilized dc cathode followers drive a "memory" capacitor at a time during the pulse selected by the operator. The charge is measured by an electrometer-input vacuum tube voltmeter which operates a meter with a scale linearized to the movement and calibrated from 0 to 10 "protons-per-pulse times multiplier." The multiplier indicators are five neon lamps corresponding to the five steps of amplification that the operator or autopilot may select. They are labeled " $\times 10^7$", " $\times 10^8$," " $\times 10^9$," " $\times 10^{10}$," and " $\times 10^{11}$." Tone generators encode the decade range for modulation of the telemetering radio link. The driving signal for the protons-per-pulse meter also operates a small strip-chart recorder to provide a permanent record for the operators.

Beam-intensity information is supplied to the telemetering radio link from a separate "memory" system. Sampling occurs at a fixed time before the actual end of the acceleration cycle to avoid calibration errors that may be introduced by various "beam-spilling" techniques. A fixed attenuation of this telemetering information attempts to simulate the loss in beam intensity between the time of sampling and the end of acceleration with no beam spilling. The amplitude information is fed to a variable-frequency tone generator which modulates the transmitted carrier for the period between acceleration cycles.

E. Calibration Signal

A signal generator is located near the south straight section which delivers a 2.3-Mc signal, amplitude-stabilized within 0.1% (see Appendix II). The calibration signal is applied to the amplifiers in the two radial-position channels between acceleration cycles. The signal may be applied to the sum channel by means of a push button in the main control room. Precision attenuators in the signal generator, controlled by the same system as operates the video-amplifier gain-change relay panels, provide a signal corresponding to the maximum capabilities of the system on each of the five decade ranges of sensitivity. The operator may adjust the electrical zero and full-scale sensitivity of the protons-per-pulse meter and strip-chart recorder in the main control room to compensate for gain changes in the meter system. This adjustment presumes linearity in the system up to the full-scale signal level used for calibration.

VI. CONCLUSIONS

The primary purpose of the Bevatron is to produce a beam of high-energy protons for experimentation. The induction-electrode systems described provide information concerning the beam current, either on a per-pulse basis, or on an integrated basis for experimental runs which may last hours or days. Two other functions are provided. The induction electrode systems supply information required for maintenance of reliable operation of the accelerator, and they provide information about beam dynamics that is a necessary part of the program of continual improvement of Bevatron operation.

Information for the experimenters' record is generally required at only one point in the acceleration cycle. Furthermore, only the amplitude of the fundamental-frequency component of the induction-electrode signal (at the chosen point of measurement) is useful for permanent record. This leads to the choice of either a tuned or a band-pass amplifier. The band-pass amplifier has the clear-cut advantage over a manually tuned circuit that troublesome tuning and frequency-drift effects are avoided. The systems described use a band-pass amplifier. The band-pass circuit requires more tubes to amplify the signal to a point where good linearity results, using, say, diode rectification. In addition, a flat frequency response is required within, say, 1/2%, over a wide frequency range if a wide range of energies is to be accommodated. The critical initial adjustment of such a filter circuit becomes prohibitive if many are to be built, and in any case the harmonic rejection must remain good.

In the light of experience obtained with the band-pass circuits, some improvements are possible for future work. A frequency-tracking tuned amplifier could be used, as for the accelerating-electrode voltage. This would add some complexity, but would achieve a better signal-to-noise ratio and would continuously read out the amplitude of the fundamental-frequency component. Simple time gating would then provide one-point measurement for the experimenter.

The scheme described for storing beam-current information involves pen recorders on each system. An alternative scheme would be to digitize the recorded dc voltage and read out directly on a digital voltmeter calibrated in terms of protons. This scheme would permit easy reproduction for remote indicators, but it has the disadvantage of complicating the handling of the decade multiplier factor. Printed tape or cards could store the digitized information; however, such methods lose the graphic representation of beam fluctuations and trends that are so readily observed on pen-recorder charts.

The east induction-electrode system is an automatic calibrating system of instrumentation by means of which the absolute magnitude of the beam intensity may be recorded. Variables within the system have for the most part been held to 0.1% in order that the over-all system accuracy can be 1%. The maximum system noise is equivalent to a beam signal corresponding to 10^6 protons per pulse.

The south induction-electrode system is capable of internal calibration to the extent of operator adjustments of meter (or recorder) zero and full-scale sensitivity to a fixed signal. Actual calibration consists of cross-calibration against the east system. Over-all accuracy can be set up on the order of 3 to 5%. The maximum system noise is equivalent to a beam signal corresponding to 10^7 protons per pulse. The greatest utility of the south system has been to provide a variety of stable signals that can be used relatively to position the beam, regulate beam intensity, provide beam information to experimenters, and drive the telemetering radio link that is used to relay beam information to those in other areas.

The two systems have been shown to be capable of providing the facilities indicated, with a minimum of operational difficulty and need for maintenance. It should be stressed that absolute experimental yields are strongly dependent on target size and shape, and on the magnetic focusing properties of the Bevatron field and auxiliary fields. The accuracy of the internal beam measurements is such that, in most cases, the factors just indicated will limit the absolute experimental accuracy attainable before consideration need be given to the accuracy of the induction-electrode system.

APPENDICES

A. Ratio of Fundamental Component Amplitude to the Average Value of Induced Voltage

The induction-electrode signal consists of a train of half-sine-wave-like pulses greatly resembling the output waveform of a half-wave rectifier but with the pulse width reduced by a factor of two (see Fig. 9). A Fourier analysis of such a wave form is relatively straightforward and yields a ratio of nth term to average term of the form

$$A_n/A_0 = \pi/2 \left[\frac{\sin \pi/2\,[1 - (n/2)]}{\pi/2\,[1 - (n/2)]} + \frac{\sin \pi/2\,[1 + (n/2)]}{\pi/2\,[1 + (n/2)]} \right] . \qquad (1A)$$

For $n = 1$ the ratio of the fundamental component to the average component becomes

$$A_1/A_0 = \pi/2 \left[\frac{\sin \pi/4}{\pi/4} + \frac{\sin 3\pi/4}{3\pi/4} \right] \cong 1.85 \quad . \qquad (2A)$$

The assumption of a sine-wave-type pulse, of base width $\pi/2$ and periodicity 2π, is only one possible model of the signal. However, reference to the nth-term ratio (1A) indicates that the ratio is not very sensitive to the general shape of the wave form. Therefore the A_1/A_0 ratio shown is justified. Photographs of the induction-electrode signal have shown the duty cycle to be fairly reproducible under normal operating conditions. An important additional consideration is that all of the experimental information obtained with the Bevatron to date is based upon beam-current calibration involving the ratio given, so that if a different model and ratio were chosen they would introduce a multiplying factor between the old and new experimental data.

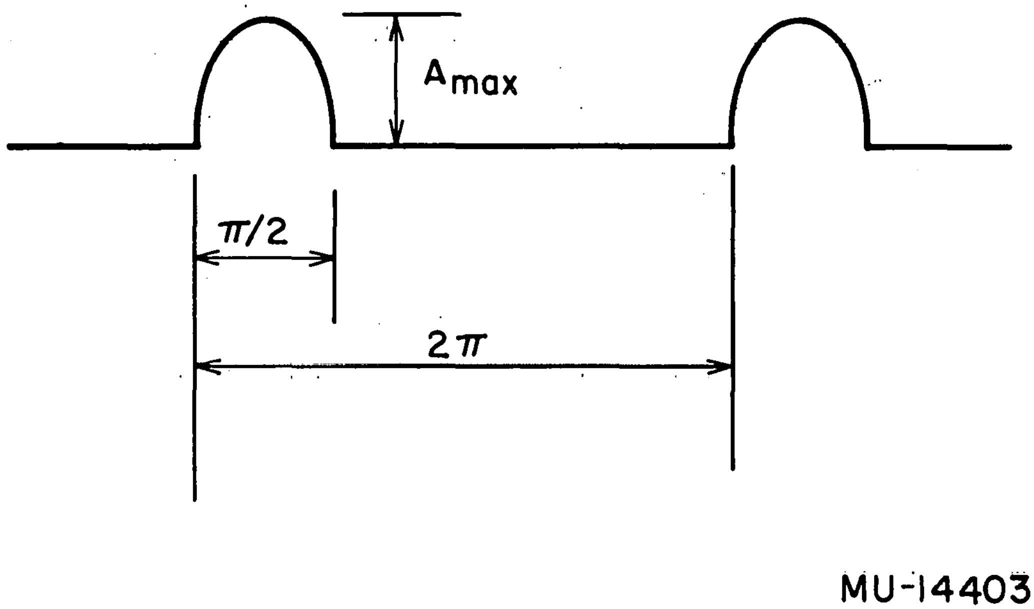


Fig. 9. Half-sine-wave pulses simulating the induction-electrode signal.

B. Calibration-Signal Source

A radio-frequency signal generator having amplitude stability better than 0.1% is used for calibration of the induction-electrode systems. The circuit is characterized by the use of a temperature-limited diode as a sensing element to develop feedback voltage, which is amplified and used to amplitude-stabilize the oscillator. Special features include maintenance of stability over long periods of time, readily available components, and good performance in strong magnetic fields.

A simplified schematic diagram is shown in Fig. 10. A beam power tube, V1, is used as the oscillator in a grounded plate Colpitts circuit. The oscillator frequency (nominally 2.3 Mc) is adjustable by means of L1. The output of the oscillator goes largely to losses in the grid circuit, which are concentrated in the resistance of the filament of regulator diode V2 by the simple expedient of tuning the reactance out of the filament and placing it in series with L1. Approximately 320 ma rms current is supplied to this filament. The signal-generator output voltage is taken from across this filament and is determined solely by the characteristics of V2. The diode is a tungsten-filament type manufactured by Thermosen, Inc., having stable emission characteristics suitable for this application. The normal voltage drop across the filament for temperature-limited operation is of the order of 5.1 volts pk-pk. An oscillator with reserve power is used so that output current in the range from zero to over 20 ma. can be supplied without loss of current through the filament.

Variations in V2 filament heating arising from variations in output load, oscillator-supply voltage, or oscillator tubes cause the plate current of the diode to vary and thus unbalance the bridge consisting of V2, R2, R3, and R4. Unbalance potentials in the bridge are applied to low-drift balanced-load differential amplifier V3. The unbalance signal is further amplified by direct-coupled stage V4A. V5 serves to hold the cathode of this stage at a high enough potential to avoid unnecessary coupling losses in transferring the signal to the grid of V4A. The amplified unbalance signal is then directly coupled to V4B, which serves as a cathode follower to supply screen voltage to the oscillator tube, V1. The signal then causes the amplitude of the oscillations to increase or decrease as necessary to maintain heating of the filament of V2 in such a way that the plate current of V2 is the value necessary to keep the bridge in balance.

C. Stable dc Cathode Follower

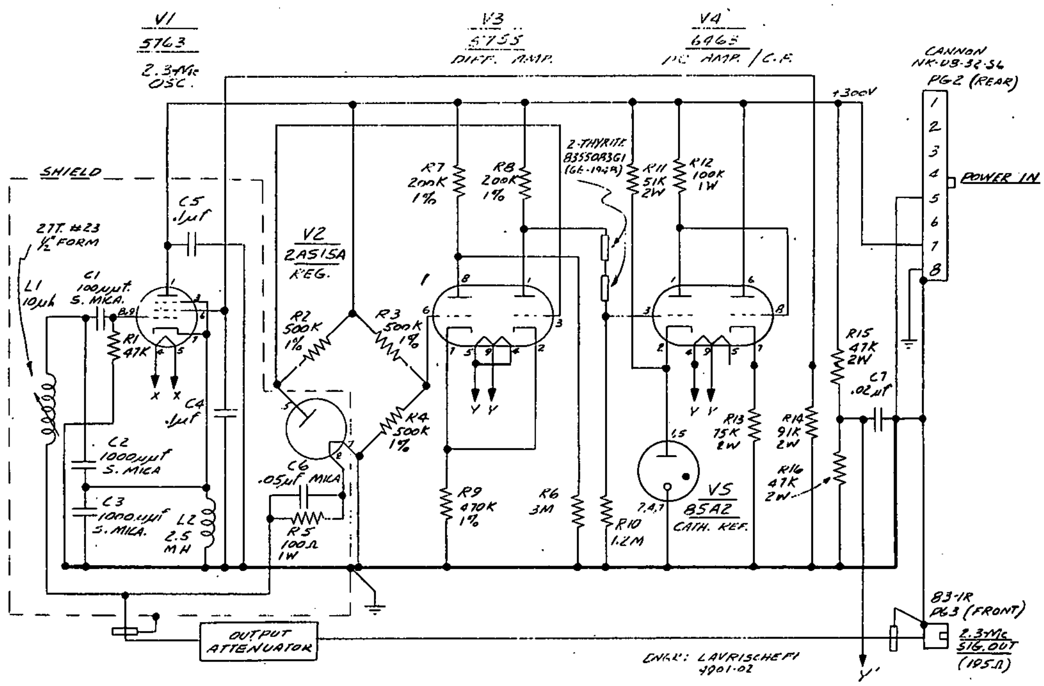
The inherent negative feedback of the cathode follower does not always afford the degree of stability and linearity desired for a particular dc application. Special techniques, such as the use of a constant-current device in place of the cathode resistor, greatly increase the linearity and, to a lesser degree, the stability.[4] Such circuitry was used in the south induction electrode system. The east induction electrode system was required to have individual circuit stability and linearity of the order of 0.1% which, in a dc cathode follower, necessitated an entirely different approach. The circuit that was developed resembles in some respects the augmented cathode follower used as a driver in high-power audio work.[5] However, the dc characteristics of the cathode follower to be described are far superior. The difference between input and output voltage remains fixed within 5 mv even on a long-term basis.

The circuit is shown in Fig. 11. Here V1 is a differential amplifier using a low-drift tube developed by Raytheon for dc amplifier service. For the circuit constants shown, and the plate currents balanced within 1 μa, the maximum grid-to-grid voltage change necessary to maintain the balance condition on a long-term basis is 5 mv, or better by a factor of 5 to 10 than the usual dual triode. The input signal voltage is connected to the grid of V1A and the amplified signal taken from the plate circuit of V1A. V1B plate is fed from constant +108 volts provided by V3.

---

[4] G. E. Valley, Jr. and H. Wallman, Vacuum Tube Amplifiers, Massachusetts Institute of Technology, Radiation Laboratory Series, Vol. 18 (McGraw-Hill, New York, 1948), pp 431-432.

[5] J. R. Macdonald, Active-Error Feedback and its Application to a Specific Driver Circuit, Proc. Inst. Radio Engrs. 43, 808 (1955).



MU-14404

Fig. 10. Calibration-signal generator.

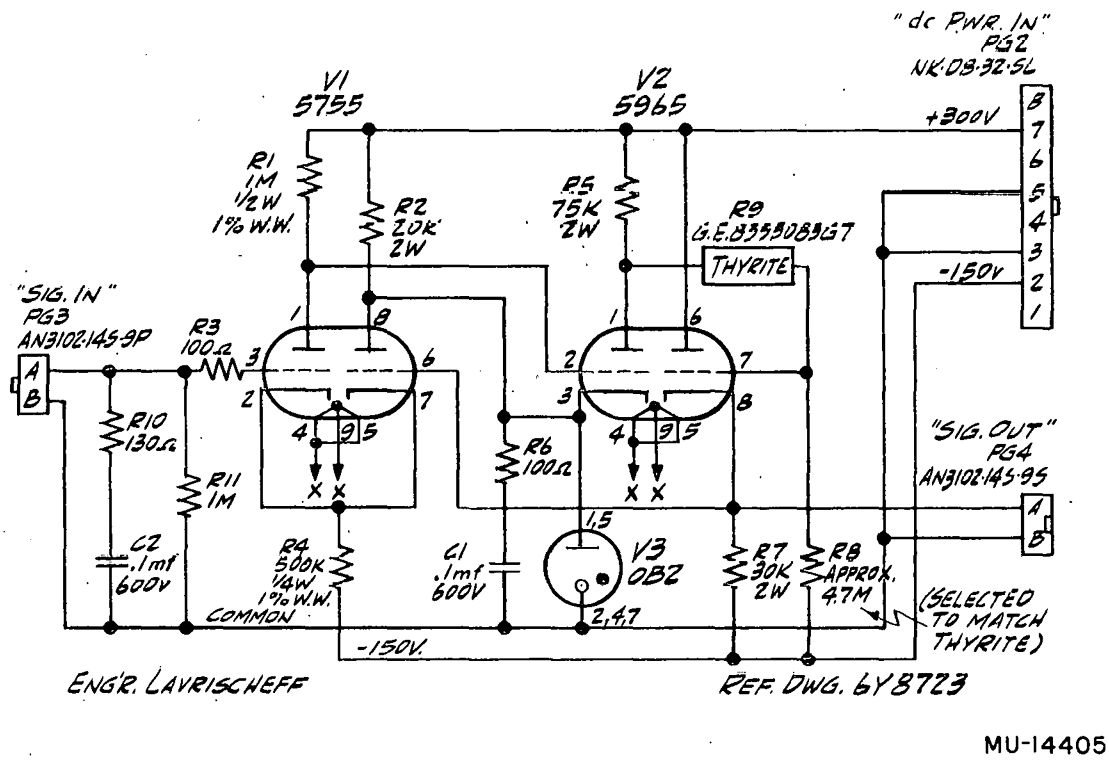


Fig. 11. Stable dc cathode follower.

The amplified signal appearing between the plate of V1A and the plate of V1B is applied between grid and cathode of V2A which further amplifies the signal for application to cathode follower V2B. The circuit output is taken from the cathode of V2B. The major feedback loop is closed by connecting the grid of V1B (the other side of the input differential amplifier) to the circuit output. If the input voltage is raised, the output also is raised, and if the output is different from the input, then the error voltage appears across the input differential stage, where it is amplified and fed back in such a manner as to compensate the difference between input and output within the limits of grid-to-grid stability of the input tube. The output impedance of the circuit is quite low, and over the normal operating range of 0 to 50 volts the linearity and stability meet the requirements of the induction electrode system easily.

Some modifications of the circuit are possible. In application, a 0.1% power supply was available that would allow replacement of the VR tube by a resistor. The thyrite R9 allows dc coupling to V2B with a 5-to-1 saving in gain compared with a resistor in the same place. Another possibility would be to use an avalanche-breakdown silicon diode of suitable voltage rating. In the breakdown region the diode would have very low ac or differential resistance, but a dc voltage drop nearly independent of current. No matter what type of coupling element is used, the upper portion of the divider must be by-passed if frequencies other than dc are to be used. With guard techniques applied to the input stage, and suitable by-passing of the coupling network discussed above, the circuit can be made to have flat frequency response to 10 Mc.

Input-terminating resistor R10 is used to terminate a long shielded twisted-pair input cable for ac. A similar cathode follower feeds the cable so that dc blocking capacitor C2 and the capacitance of the cable can be easily driven. R11 provides the dc return for V1A grid and if high input impedance is desired, R11 may be increased to the point where the 10^{-9}-amp maximum grid current of V1A becomes the limiting factor.

The transfer ratio from input to output may be made unity, or greater, by tapping down on the output cathode resistor R7 for the feedback line. The resulting negative-feedback reduction also raises the output impedance; however, useful amplifications of the order of 1 to 10 are still achieved with fairly low output impedance and with no phase inversion. This feature would make the circuit well suited for the active element in active filters and frequency-selective amplifiers. A further consequence of tapping down on the output cathode resistor is an increase in quiescent dc output level so that the circuit is no longer "zero out for zero in." This result is of no consequence, of course, if ac coupling is used throughout.

The circuit that has been described occupies a somewhat intermediate position between ordinary cathode followers and operational amplifiers. It can be made to have relatively high input impedance, an input-output transfer ratio close to unity, an input-output dc offset constant within a few millivolts over a fairly wide dynamic range, a low output impedance, and a frequency response from dc up to the megacycle region. As a dc cathode follower, the circuit described easily meets the stability and linearity requirements for use in the east induction-electrode system.

ACKNOWLEDGMENTS

The work described in this report was supervised by Professor John R. Woodyard, whose advice and encouragement are gratefully acknowledged.

I wish particularly to thank Mr. Ivan C. Lutz and Mr. Jerome A.G. Russell for their assistance, suggestions, and advice concerning the design and construction of this equipment.

I also wish to express my appreciation to Mr. Harry G. Heard and Dr. William A. Wenzel, who are to be credited with the original design and development work leading to the present electrode geometry.

Many thanks also to Dr. Edward J. Lofgren, who made this project possible.

This work was performed under the auspices of the U.S. Atomic Energy Commission.

Information Division
jm