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BEVATRON INDUCTION-ELECTRODE BEAM-MONITORING SYSTEMS

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ABSTRACT

A system is described that uses the east induction electrode in the Bevatron to provide beam-amplitude signals for specialized monitoring and for primary calibration of other beam-monitoring equipment.

A system is also described that uses the south induction electrodes to provide beam-position signals for tracking, and beam-amplitude signals for intensity control and general distribution to experimenters associated with the Bevatron and (by means of the telemetering radio link) to those in other areas.

A brief description is given, for each system, of induction-electrode signals, signal-amplifying, -detecting, and -isolating equipment, calibration equipment, signal distribution, control features, a meter circuit reading directly in protons per pulse, and various recording facilities.

The systems described are stable and self-calibrating, and are intended to provide the facilities indicated with a minimum of maintenance and operational difficulty.
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INTRODUCTION

Protons in the aperture of the Bevatron magnet are accelerated to an energy of 6.2 Bev in a period of approximately 2 seconds. At the end of this period the magnetic field has increased to 15,550 gauss and the radio-frequency has increased from approximately 354 kc to 2.5 Mc.

The Bevatron magnet is divided into quadrants with straight sections interposed—for acceleration (north straight section), injection (east straight section), monitoring (south and east straight sections), and experimentation (west straight section).

Investigation of various beam-detection devices has been carried out and the electric induction electrode has been chosen as the most satisfactory method of obtaining signals.\(^1\) These signals can be amplified, detected, and distributed in a form useful for tracking or "steering" in the beam in the aperture, for determination of relative beam amplitude or intensity, and recording of information on absolute magnitude of intensity.

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\(^1\) Harry G. Heard, Bevatron Beam Induction Electrodes, UCRL-3609, Feb. 1957, p. 4.
Fig. 1. The Bevatron.
EAST INDUCTION ELECTRODE SYSTEM

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 characteristics of the Bevatron induction electrodes have been tabulated and the calculated sensitivity of the east induction electrode has been shown to be $4.61 \times 10^{-12}$ 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). 2

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 the fact that 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.

Accurate use of instrumentation that operates on only the fundamental frequency of the beam signal depends on a known ratio between the amplitude of the average voltage and the amplitude of the fundamental component. This ratio had been determined in earlier work to be $1.85$. 3 A more recent analysis (not yet complete) based upon photographs of the beam signal has indicated that the ratio may be somewhat smaller. Doubling the 1.85 figure to arrive at a peak-to-peak (pk–pk) value and multiplying by the $4.61 \times 10^{-12}$ calculated sensitivity yields about $17 \times 10^{-12}$ volt per proton which, when divided down 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 ($1 \times 10^6$ protons) to 12 volts ($10 \times 10^{11}$ protons).

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 ampli-

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ifier 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 doubly shielded transmission line to a doubly 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 pk-pk, 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 ten-to-one 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 peak-detected in such a manner that an input from 120 mV to 1.2 volts pk-pk 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 amplifier, i.e., a portion of the output signal of a pentode amplifier is applied to its screen, thus minimizing the curvature of the transfer characteristic.

Automatic Calibration Equipment

The role of the band-pass amplifier and peak detector unit 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 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 which is used for the equipment. The power-supply reference is a gaseous voltage-reference tube which is essentially a long-term 0.1% device. 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, owing to aging of any of the amplifiers in the system, 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 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.
Fig. 2. Bevatron east induction-electrode system (block diagram).
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.
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.
Fig. 5. Bevatron east induction-electrode system--band-pass amplifier and peak detector.
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 automatic calibration. 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 calibration signal and also holds the system in calibration irrespective of operational triggers associated with automatic calibration.

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 main-control-room recording equipment 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.

Recording Equipment

The dc signal from one of the channels in the four-channel cathode follower is used exclusively for main-control-room recording equipment. A transfer panel containing a low-leakage dc-operated relay holds a small capacitor to the signal line until triggered 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 affect 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 10-mv 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 total beam level 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.

**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. 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 remoted to 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 remoted to 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 with the "full scale" mode useful for calibration of the system described and also for primary calibration of the south induction-electrode system (which is described later).

**SOUTH INDUCTION-ELECTRODE SYSTEM**

**Induction-Electrode Signals**

In the south straight section of the Bevatron is located the south sum electrode which is similar to the east electrode but physically smaller. The south straight section also contains another induction electrode, which is divided on a vertical plane so that the outer and inner halves can be used as sources of signals indicating when the beam is radially outside or inside the aperture centerline. The induced charge on the sum electrode and on each of the pair of radial position electrodes is transferred to 200-ohm coaxial transmission lines by means of emitter followers mounted at the electrodes. The voltage on the sum line was determined to be approximately 35 mv pk-pk across 200 ohms for a beam of $1 \times 10^{10}$ protons. The radial-position electrodes each produce approximately one-half as much signal for a given beam intensity as the sum electrode. In the case of the sum signal then, the usable amplitude range is from 35 μv ($1 \times 10^7$ protons) to something approaching 3.5 volts ($10 \times 10^{11}$ protons). The limiting factor in monitoring higher beam intensity is the restricted dynamic range of the emitter-follower.
Amplifiers for Induction-Electrode Signals

The amplitude range indicated above lends itself to five steps of amplification, each constituting a relative voltage gain of 20 db. Two H-P 460A wide-band amplifiers and a 20 db attenuator provide the first two steps, 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 of the line-driving amplifier. The switching is accomplished with low-leakage transfer relays. There are three such channels of amplification. Bandwidth 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 pk-pk for the amplified sum signal, and 0.05 volt to 0.5 volt pk-pk for each of the amplified radial-position signals. The five gain steps are referred to in terms of the system capability of monitoring beam intensity, i.e., Step 1 monitors beam intensities in the range of $1 \times 10^7$ to $10 \times 10^7$ protons, Step 2 monitors beam between $1 \times 10^8$ and $10 \times 10^8$, and so on, to Step 5, which extends to $10 \times 10^{11}$. 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 doubly shielded enclosure for the three channels of amplifiers is shown in Fig. 7.

Isolation of Amplified Electrode Signals

The amplified south sum electrode signal is of general utility. It is used to drive the beam-regulating equipment, which provides a preset level of beam, it is used for a scope 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 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 µf. The low capacitance, of less than 5 µf per follower, is obtained by "bootstrapping" the plate from the cathode so that the grid-plate 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 totem poles as a guard ring, strapped to the tube cathode. Frequency-response-tested pulse transformers provide ground-circuit isolation for all outputs. The output amplitude is generally in the range from 0.05 volt to 0.5 volt pk-pk across 125 ohms.
Fig. 6. Bevatron south induction-electrode system (block diagram).
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.
The general utility signals described above are not useful for absolute-magnitude measurements of beam intensity (for reasons discussed earlier under East Induction-Electrode System—Induction-Electrode Signal) unless a remote 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. 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 a VTVM 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 "x 10^7," "x 10^8," "x 10^9," "x 10^{10}," and "x 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.

Calibration-Signal Generator

A signal generator is located near the south straight section which delivers a 2.3-Mc signal, amplitude-stabilized within 0.1%. 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.
CONCLUSIONS

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 been held to 0.1% for the most part in order that the over-all system accuracy can be 1%.

The South Induction-Electrode System is capable of internal calibration to the extent of operator adjustments of meter/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 that is on the order of 3 to 5%. 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, to regulate beam intensity, to provide beam information to experimenters, and to drive the telemetering radio link.

The two systems have been shown to be capable of providing the facilities indicated with a minimum of maintenance and operational difficulty.

It should be noted that problems associated with the development of the instrumentation, their analysis, and the design principles involved in the final analysis are not included here; they will comprise the bulk of a later report.

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