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Author
Lothrop, Fred H.G.

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Abstract

Redesign and relocation of the primary-standard induction electrode for monitoring the beam intensity of the Bevatron has been undertaken as a part of the Bevatron major improvements program. A radius-indicating electrode structure was also built. Electronics was devised so that the induced signals on the electrodes could be brought through the vacuum wall of the Bevatron with minimum loss of information. The electrode assemblies were calibrated in terms of volts induced per circulating proton. The radial sensitivity of the radius electrode structure was calculated from the geometry of the electrode and measured with a thin search wire. The average induced voltage on the standard electrode is 109 mV per 10^{11} protons. The radius-indicating structure has a sensitivity of 7.4% of full signal change per inch of radius change.

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A major improvement program at the Bevatron presently in progress has required the relocation of several major components in the straight sections of the machine. One of the components involved was the internal circulating-beam monitor, an induction electrode. This electrode was the primary standard for the measurement of the number of protons accelerated during each acceleration cycle. The principles of operation and the design of the electrode have been treated in a previous paper.[1] The original electrode, about 4 ft wide and 6 ft long, was located in the East straight section of the Bevatron. It was designed for beam intensities so low as 10^6 protons per pulse.

Additional induction electrodes were designed and installed in the transition sections of the south straight section to provide auxiliary monitoring of beam intensity and beam radial position throughout the acceleration cycle. The success of these electrodes, plus the anticipated lack of space in the vacuum tank, plus the anticipated beam intensity at the completion of the improvement program led us to design a new primary standard electrode of the same general geometry as those electrodes in the transition sections of the south straight section. Further efforts at consolidation of the internal-beam monitoring system were directed toward having only two electrode assemblies in the machine to perform all the functions previously performed by twice that number.

The two units would be (a) a sum electrode and (b) a pair of radial position electrodes. The sum electrode must provide a stable output that can be calibrated and another output capable of supplying undistorted information of beam bunch shape and phase. The radial-position electrode must provide output signals linearly indicative of beam radius over the central two feet of the Bevatron aperture. Transmission of the beam information from the electrode location to other parts of the building would be by 125-Ω coaxial cable.

Induction electrodes are high-impedance devices -- capacitors essentially, across which induced voltages are measured. Therefore, some sort of impedance transformer is necessary to match the electrode impedance to the 125-Ω transmission line impedance. The only practical transformer in this case is a cathode follower. Two cathode followers were designed, one for the sum electrode and one for the radial electrodes.

Sum Electrode Design

The voltage pulses induced on the electrodes are of a very short, almost triangular waveform. At high energy these pulses have a half-width of 60 nsec and a pulse rate of 1 pulse every 400 nsec. Such pulses are fully capable of causing the excitation of any resonant circuit associated with the induction electrode. Inasmuch as the electrode has capacitance, any inductance associated with the circuit will form (with the capacitance) an excitable resonant circuit. Thus, one of the major objectives in obtaining an undistorted pulse was to minimize any inductance associated with the signal circuit. With this requirement in mind, we designed the output connector to be a short, stubby plug which would mate with a socket mounted on the vacuum-air interface of the Bevatron. The cathode follower unit mounts on the air side of the interface. The plug is in a cylindrical shield which carries the ground connection from the electrode to the cathode follower. A second shielded connection between the electrode and the cathode follower unit carries a calibrating signal to the electrode from an external generator.

Man access to the aperture of the magnet is required for maintenance and installation of various devices. Since the electrode is essentially an extension of the aperture, it was designed to support the weight of a man crawling through without deformation of the electrode structure. Heavy aluminum plate was used for the bottom and side portions of the electrode. High-quality ceramic standoff insulators support the electrode and serve as spacers between the electrode and its shield box.

Mechanical fastening of the electrode is such that the electrode is electrically insulated from its surroundings. Phosphor-bronze springs mounted on epoxy-glass plates on the top of the electrode bear against the upper tangential brace in the transition section. Adjustable jackscrews with epoxy-glass feet bear against the lower tangential brace. These screws serve to tension the springs and to control the level of the electrode. A further clamping and indexing device attached to the lower tangential brace provides positive repositioning if the electrode is removed for one reason or another. Figure 1 shows the general mechanical features of the sum electrode. At the extreme right is a temporary frame supporting the re-entrant box that contains the cathode follower assembly. The interior of the re-entrant box is shown in Fig. 2. Figure 3 is a sketch showing the connections from electrode to box.

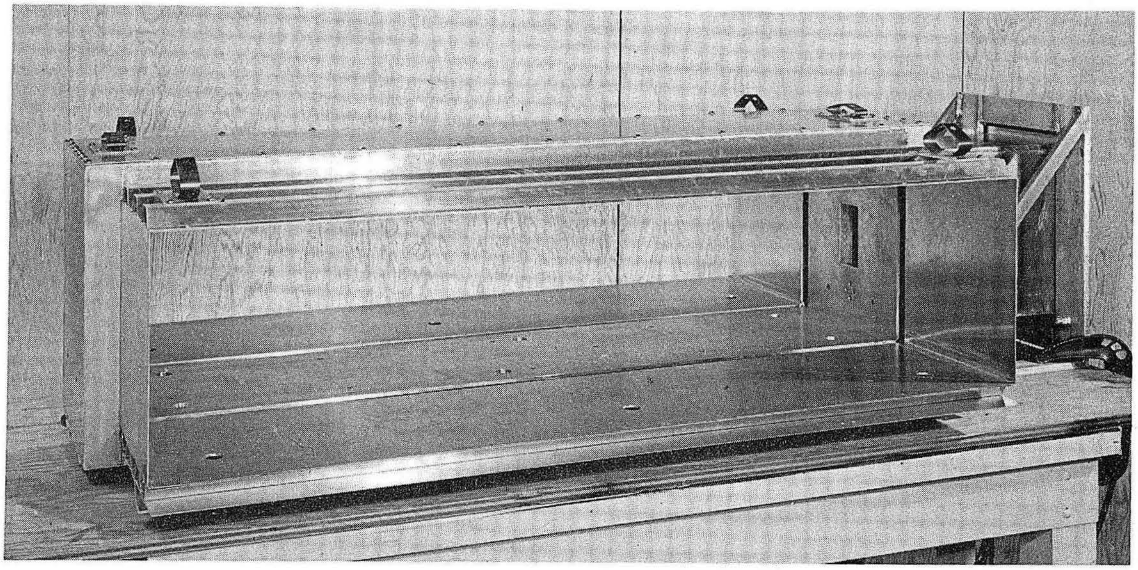

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Fig. 1. Sum induction electrode. Output coupling box is in a temporary jig at the extreme right of the electrode.

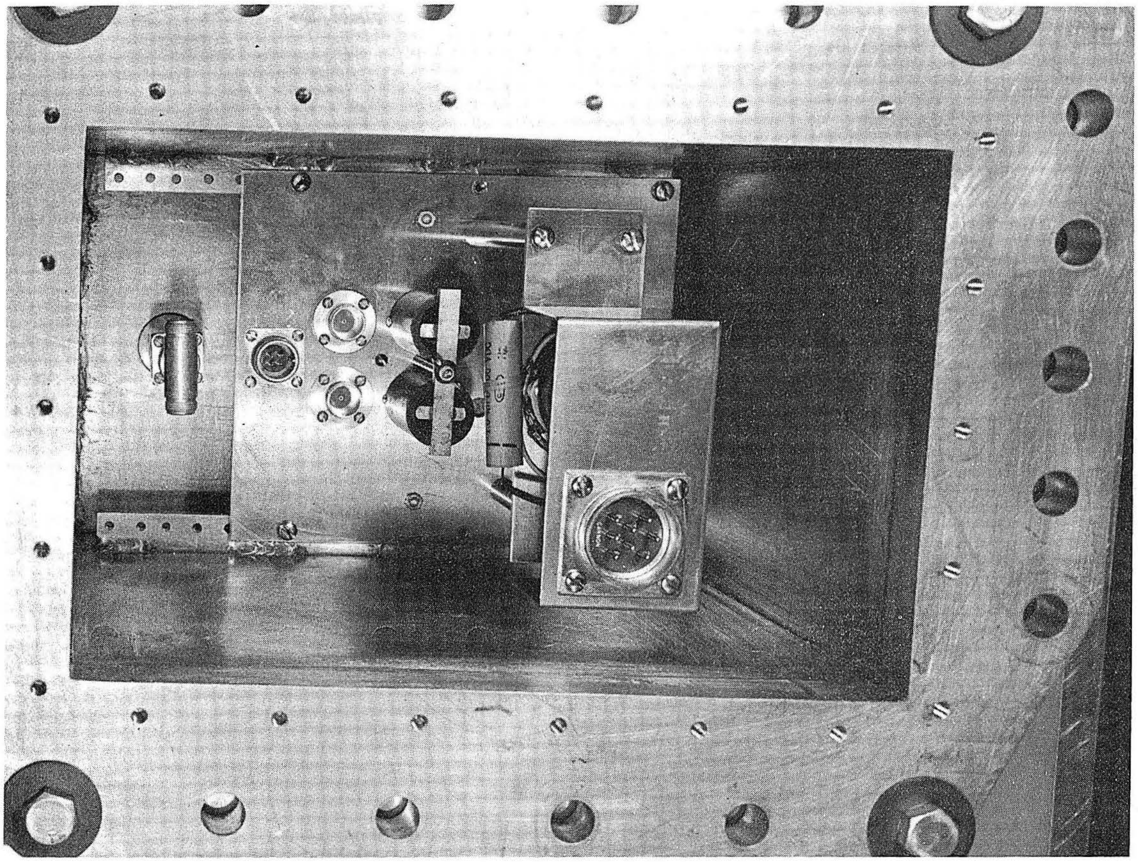

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Fig. 2. Output coupling box with cathode followers in place. At top is rotary relay for driving the attenuator. Cathode-follower tubes are in the cylindrical magnetic shields. Output and power connectors are just below and the calibration input connector is at the bottom.

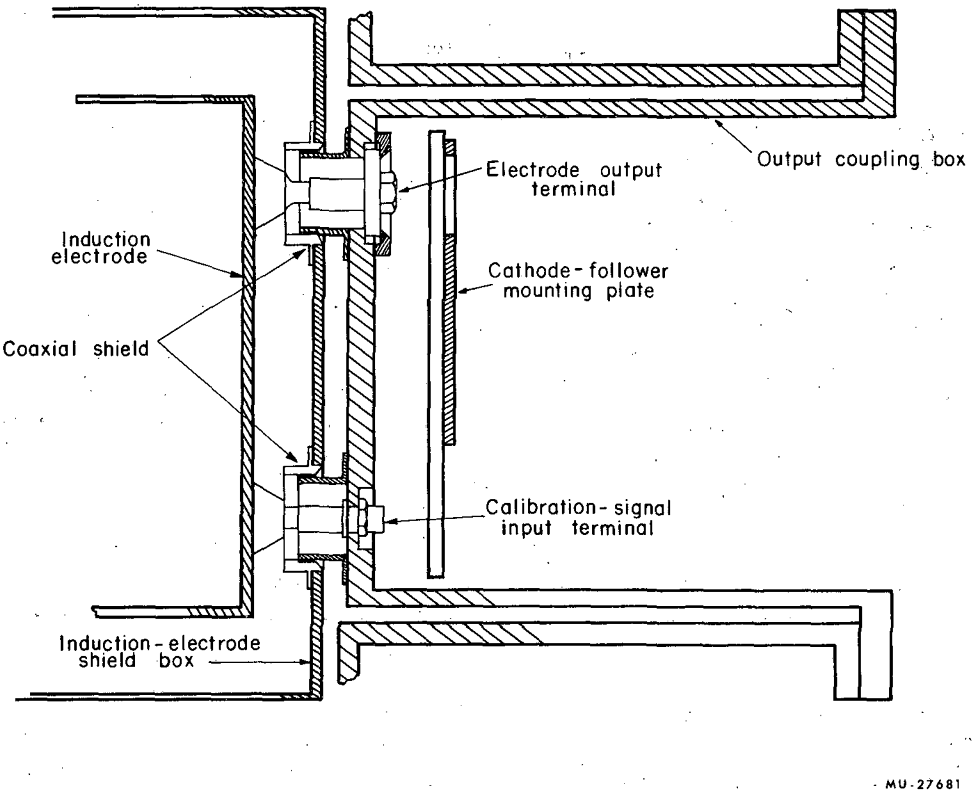

Fig. 3. Cross section looking upstream, showing the method of coupling the sum electrode to the outside world.

Calibration

The average induced voltage on the electrode is given by

$$V_{av} = \frac{ne\ell}{LC} ,$$

where n = number of protons,
e = proton charge in coulombs,
ℓ = effective length of electrode in inches,
L = one-turn path length of protons in inches,
and C = capacitance of electrode in farads.

The length of the electrode physically is different from the effective electrical length because of end effects between the electrode plates and their surroundings. We assumed that, for this electrode -- 12 in. long, with a uniform gap on each end -- the effective length would be 12 in. plus one gap length. The measured gap length was 0.88 in. Thus the assumed effective length of the electrode is 12.88 in.

Capacitance of the electrode was measured by comparing the electrode capacitance to a General Radio 722-N Standard variable capacitor which had been calibrated by the National Bureau of Standards Laboratory at Boulder, Colorado. Measured capacitance of the electrode is 400 ± 2 μμF.

The path length of the protons in the Bevatron is taken as the circumference of a circle of 600 in. radius, plus the length of four straight sections. An actual proton path may have a different radius, but at most it will be in the range between 605 in. and 595 in. This amounts to less than 1% error in path length.

Using the measured parameters of the electrode, we calculated the expected average voltage for 10^{11} protons to be 109 mV. To transform this average induced voltage into something useful for strip-chart recorders and other monitoring devices, we have elected to extract the first harmonic component of the pulse and relate the extracted harmonic to the average value of the pulse.[2] A Fourier analysis of typical beam pulses shown in Fig. 4 has given a shape factor of 1.83. (We define shape factor as the ratio of first harmonic amplitude to the average value of a pulse train.) This is in good agreement with earlier analyses of the proton bunch shape factor reported by Wenzel as 1.85. Harry Heard analyzed a pulse series and obtained a shape factor of 1.6.[3] However, the bunch shape was markedly different from the present shape.

The readout electronics designed for the old sum electrode has been retained in its entirety. Matching networks were added at the input to the system so that the net loss in sensitivity of the electrode would be regained so far as the recorders were concerned.

Basic calibration of the electrode by measuring the base-line shift and shape factor from photographs has been done twice, once at the first installation and again about three months later. The calibrations agree with each other to within ± 3.0%. We believe that the strip-chart recorders and total beam integrator are accurate to within ± 5%.

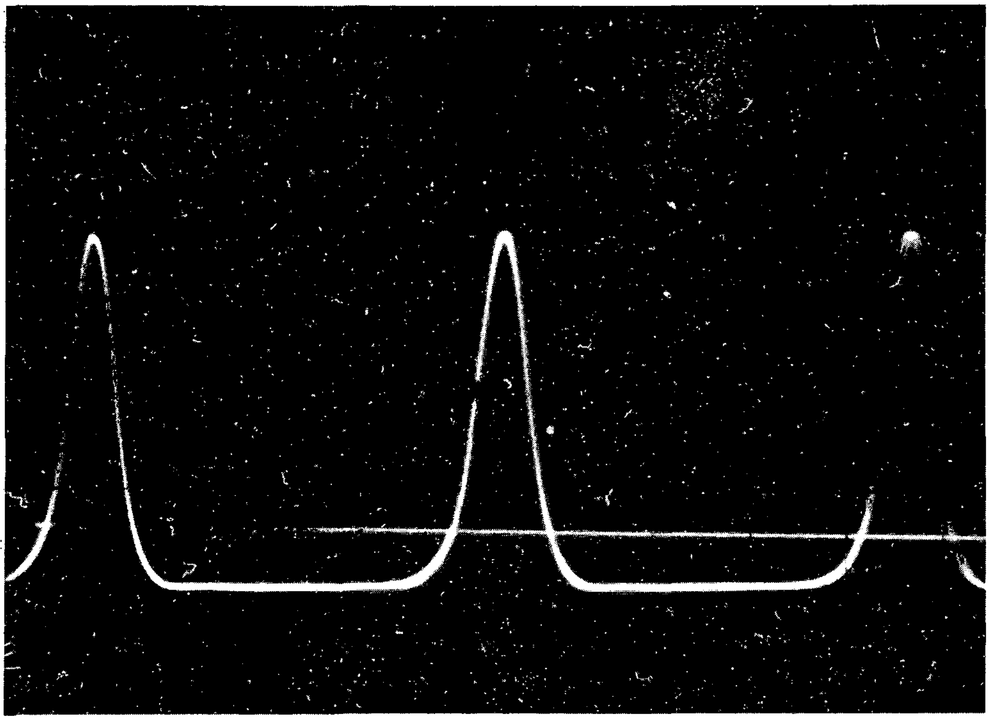

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Fig. 4. Oscilloscope photograph of proton beam pulses used for determining the shape factor of the Bevatron beam.

The gain of the entire sum electrode system (including electronics) is routinely calibrated by feeding a calibration signal directly to the electrode. A 10-$\mu\mu$F capacitor couples the calibration signal onto the electrode without introducing appreciable loading of the electrode by the signal source.

Radial-Electrode Design

Mechanical considerations for the radial electrode were the same as for the sum electrode and the design is essentially the same. The radial electrode also must support the weight of a man and therefore was made of heavy aluminum plate. Support for the radial electrode box that is located immediately downstream from the sum electrode is provided by a frame attached to the lower tangential brace and the straight section floor. Indexing is provided so that the electrode, if removed, may be accurately replaced. Insulated jackscrews are provided for leveling adjustments.

The electrical design departs considerably from that of the sum electrode. No port was conveniently available for bringing signals from the electrode to the outside world. Hence, some sort of transmission-line scheme had to be devised. We had to prevent resonant circuits from being excited and still preserve the "high-fidelity" character of the signal. The technique adopted is illustrated in Fig. 5. A 200-Ω coaxial cable is connected to the electrode through a series resistor which has a value equal to the characteristic impedance of the cable. The other end of the cable connects to the input of a cathode-follower line driver. Although the cable is not matched it is effectively back-terminated by the 200-Ω resistor. For a pulse reflected from the cathode-follower input, the impedance offered by the electrode capacity is very low and the effective impedance seen by the reflected pulse is only that of the terminating resistor. The reflected pulse is therefore completely absorbed in the series resistor. The incident pulse is that which is generated by the electrode, but very slightly decreased in amplitude. (A voltage divider is formed by the series resistor and the input impedance of the cathode follower.) A reasonably short run of C3-T cable carries the electrode signals to the side wall of the straight section. Vacuum feedthrough connectors carry the signal to cathode followers mounted on the exterior face of the side wall.

Radial induction-electrode geometry determines the type of information which may be obtained from the electrode. In the past, the Bevatron has been equipped with a radial-electrode assembly giving very high radial discrimination about the center of the aperture. Oscilloscope display of the signals gave dramatic indications of the behavior of the beam about 2 inches on either side of centerline. But beyond this limit radial information was lost. The most interesting and informative part of the Bevatron aperture extends about a foot on either side of centerline. Therefore we designed the new radial-electrode assembly to give information for this distance. The simplest geometry is employed. The electrode is split linearly, with the split extending from 1 ft inside the beam centerline at the downstream edge to 1 ft outside the beam centerline at the upstream edge of the electrode. With such a configuration one may observe the signals directly on an oscilloscope and also use the signals to obtain an amplitude-independent low-frequency signal showing radial deviation of the proton beam from an arbitrary datum line -- in our case the geometrical centerline of the Bevatron aperture.

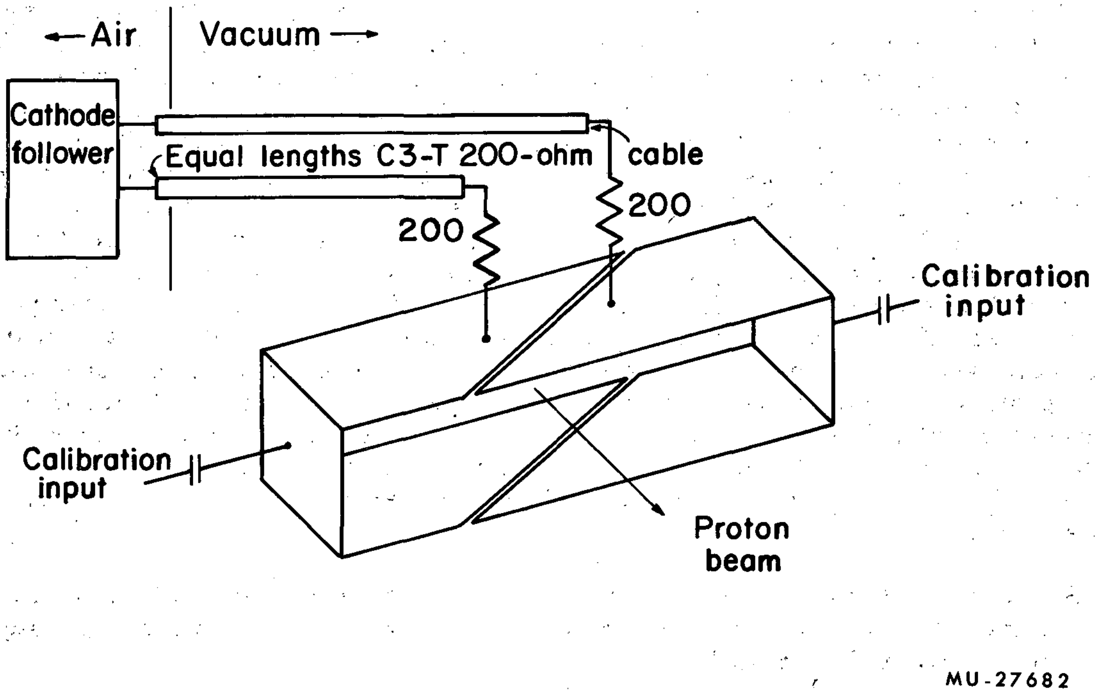

Fig. 5. Schematic diagram of the method used to bring the radial electrode signals outside the vacuum system.

Calibration

The capacitance of each end plate to its surroundings was measured. The result was 171 ± 2 μμF. The effective electrical length was determined to be 12-3/4 in.

A search wire, 0.064 in. in diameter, placed in the plane midway between the upper and lower faces of the electrode, was excited by a 2.5-Mc generator to produce the discrimination curves shown in Figs. 6 and 7. Figure 6 shows the individual curves for each plate. Figure 7 is a graph of the difference between the output voltages of the two plates. The search wire was placed at various points on either side of the geometrical centerline and the voltage induced on each plate was measured. Capacitive coupling from the wire to the end sections of the electrode is evident in Fig. 6. Electrode geometry dictates that the induced voltage become constant at radial extremes. However, the induced voltage is still rising at the extremes of Fig. 6. Figure 7 demonstrates the linearity obtained by the search-wire technique. The expected slope of the discrimination curve is also plotted on the same graph. This slope was calculated from the measurement of plate-to-shield and plate-to-plate capacities of the radial electrode structure and from the geometry of the structure. No correction was made for wire proximity effects at the extremes of the measured curves in Figs. 6 and 7.

System calibration for the radial electrode is accomplished in the same manner as for the sum electrode. A 2.5-Mc signal source is coupled to each plate through a 5-μμF capacitor.

Electronics

The averaged induced voltage on the sum electrode is 109 mV per 10^{11} protons. The peak-to-average ratio is in the vicinity of 6 to 1, so that some 600 mV will be developed on the electrode for 10^{11} protons. The expected yield of the Bevatron in the near future is 10^{13} protons. Such a yield will induce about a 60-v peak on the electrode. The initial number of bunched protons may be as high as 10^{14}. Therefore the electrode was designed to handle voltages up to 600 V. Unfortunately, cathode-follower circuits are susceptible to breakdown at such voltages. Preclusion of breakdown required us to build in an attenuator at the output of the electrode. The attenuator is a capacitive-ladder type having three sections. The attenuator feeds two wide-band cathode followers of identical design and construction. High-transconductance pentodes, Amperex type 7788 (E810F), were used in a highly stabilized circuit. The effective output impedance of the tubes is about 20 Ω. The cathode followers are matched to a 125-Ω transmission line which is direct-coupled to the tubes. The terminating resistances at the far end of the line serve as part of the cathode resistances. Direct currents carried on the transmission lines are disadvantageous, but the ease of obtaining high performance and good impedance matching far outweighs the inconvenience of such currents. We found no measurable degradation of performance at frequencies as high as 50 Mc. The gain of each cathode follower was measured as 0.42.

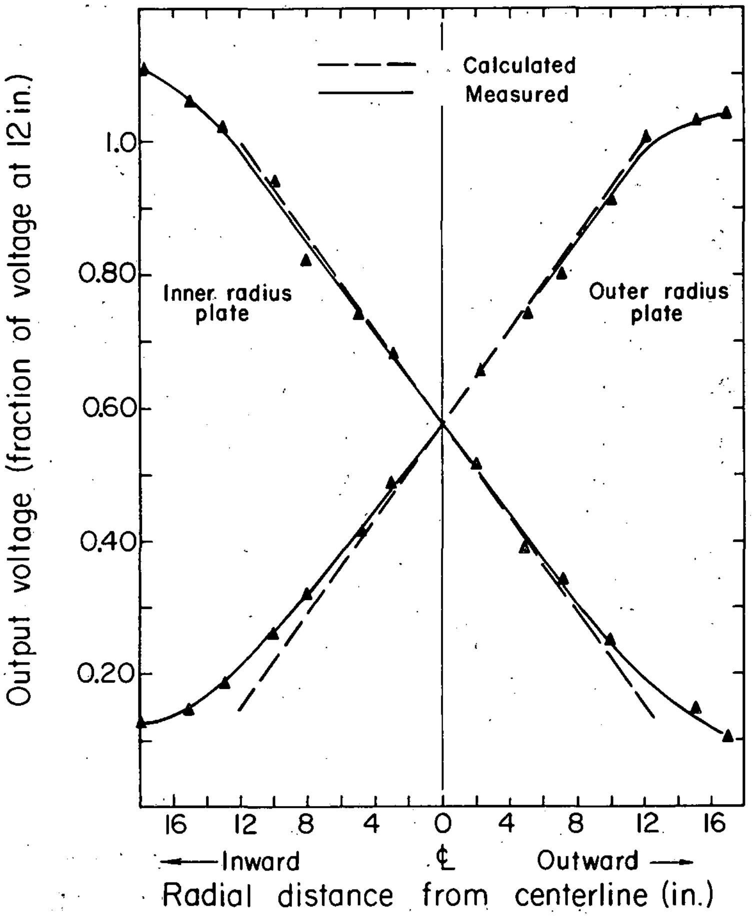

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Fig. 6. Output voltage of radial induction electrode plates as determined by the search-wire method and calculation.

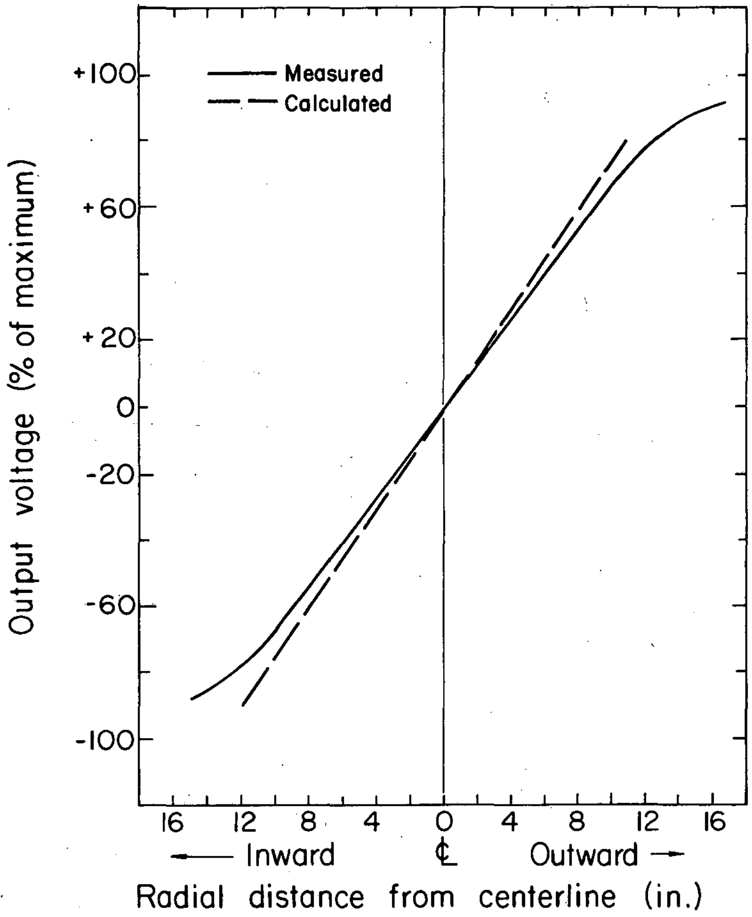

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Fig. 7. Difference voltage of the radial electrode plates obtained by subtraction of inside plate voltage from outside plate voltage of Fig. 6.

Cathode followers for the radial electrode are of more standard design. Each plate of the radial electrode delivers a signal to two cathode followers, so that there may be some independent distribution of the radial information. These cathode followers employ 12BY7 pentodes in a stabilized circuit. Range switching was not included in this system, since it is not presently needed. The entire radial system electronics is being redesigned and range switching will be incorporated in the new design.

Conclusion

The sum electrode and radial electrode installation in the south straight section of the Bevatron is pictured in Fig. 8. The foremost electrode is the radial electrode. It is mounted on its own support structure which extends out from the lower tangential brace. Two signal output leads leave the top center of the unit and end at the side-wall feedthrough connectors. Two other cables, one to each end of the electrode, carry calibration signals to each plate. Behind the radial electrode and sitting on the tangential brace is the sum electrode.

These electrodes will be capable of providing measurements of the intensity of the circulating proton beam from as low as 10^7 protons per pulse up to the maximum expected operating value of 10^{13} protons per pulse. The lower limit is set by the expected noise level of the electronics.

High-quality calibrated sum signals are now being provided to the operating staff and to a servo-feedback system for phase stabilization of the proton beam. Radial-electrode signals having good linearity over the central 2 feet of aperture are being used by the operating staff for indication of beam position. They are also supplying information to a servo-feedback loop designed to control radial excursions of the proton beam.

A summary of electrode characteristics is compiled as Table I.

Table I. Summary of the most important characteristics of the Bevatron induction electrodes.

	Length (in.)	Capacitance (μμF)	Sensivitity (mV average per 10^{11} protons)	Sensitivity (% change per in.)
Sum electrode	12.88	400	109	----
Radial electrode	12.7	156 per plate	≈ 100 per plate	7.4

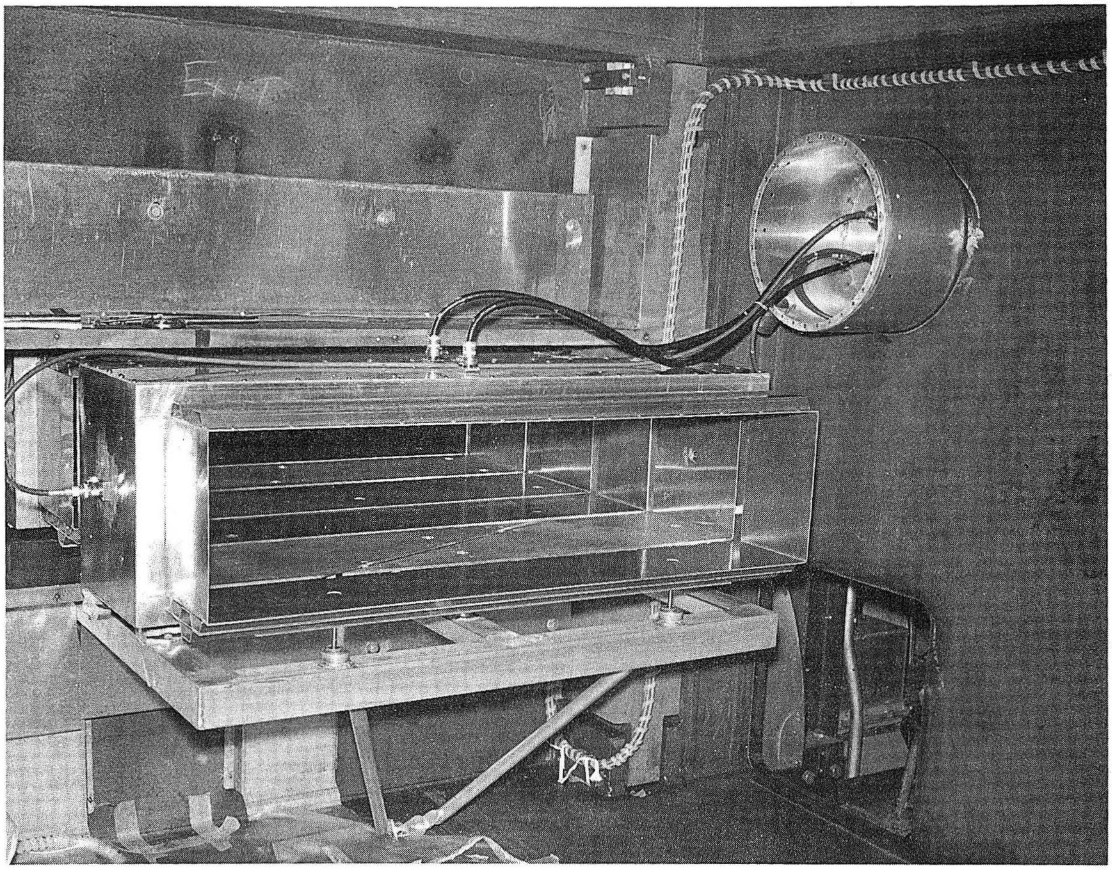

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Fig. 8. The induction electrodes installed in the south straight section of the Bevatron. The radial electrode is in the foreground. The sum electrode is in the background, on the tangential brace.

Acknowledgments

The author is grateful to Glen R. Lambertson for guidance and inspiration in this project. Dr. Wolfgang Schnell, visiting from CERN, was instrumental in the calculations and technique of measurements. He also designed the sum electrode cathode follower. Detailed mechanical engineering work was done by John Shively and Ted Lauritzen. Assistance in the assembly, installation, and testing was rendered by Perry Arana.

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2. William A. Wenzel, Calibration of Bevatron Internal Beam, Bev-174, Oct. 1956 (unpublished).

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