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CALIBRATION OF THE BEVATRON BEAM-INDUCTION ELECTRODES

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ABSTRACT

Three sets of electric-induction electrodes are used in the Bevatron to yield measures of the quantity of charge in the bunched proton beam. This report considers a refined calibration of these electrodes.

It is shown that the quantity of charge in the beam may be obtained directly by measuring the amplitude of the first-harmonic component of the voltage pulses resulting from charge induced on the electrode by the circulating beam. Although changes in the configuration of the induced voltage pulse alter the phase and magnitude of the harmonic content, it is shown that the ratio of the first-harmonic component to the average value is essentially unaffected. Fourier analyses of typical beam-pulse wave forms indicate that it is possible to determine the beam charge to within 2% at any beam energy by measuring the amplitude of the first-harmonic component of the voltage pulse. Electronic equipment is provided that measures the beam charge to within less than ±4%

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INTRODUCTION

The voltage induced on the induction electrode in the Bevatron by the beam charge is a measure of the time-dependent charge density in the circulating beam. To determine the total beam charge, one can integrate these voltage pulses, and from their average value obtain a measure of the beam charge.[1,2] Although this method offers appealing simplicity, its accuracy is limited if the band width of the integrator is not sufficient to include the effects of many high-order harmonics.[3]

A different principle of measuring the total beam charge is used at the Bevatron.[4] The voltage pulses from the induction electrode are amplified and passed through a narrow-band filter to extract the first-harmonic component. The charge in the beam is inferred from the amplitude of this signal and a ratio between the amplitude of this first-harmonic component and the average value of the pulse. The system calibration is obtained from photographs of wave shapes of the beam-induction-electrode signal. A harmonic analysis of this wave form yields the desired ratio, hereinafter referred to as the calibration factor. Note that the calibration of the system is virtually independent of harmonic distortion, as all the significant harmonics are present in the wave form used to derive the calibration factor.

Prior to the numerical computations of this report, the configuration of the induction-electrode signal had been assumed to be that of a series of half-sine-wave pulses.[5] The new calibration factor discussed in this report was derived from a detailed harmonic analysis of observed beam-pulse configurations.

The theory of operation and design of the induction electrodes has been described previously and is not treated here.[4]

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[1] Van der Roay Riddiford and R. F. Coe, Some Proton-Synchrotron Beam Studies with the Induction Electrode, Department of Physics, University of Birmingham (Internal Report).

[2] Clifford Swartz, (BNL, Cosmotron Department), private communication.

[3] R. Sternheimer, Brookhaven National Laboratory Internal Report RS-47, September 23, 1954.

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

[5] William A. Wenzel, Calibration of the Bevatron Internal Beam, University of California Radiation Laboratory Internal Report Bev-174, October 15, 1956.

WAVE-FORM CHARACTERISTICS

The calibration factor for a train of periodic, positive pulses of arbitrary configuration clearly depends upon the shape and duty cycle of the pulse. Although both these effects must be considered in assessing the errors that result from the choice of a fixed value for the calibration factor, the utility of this method of beam-charge measurement depends upon the analytical as well as experimentally observable fact that the pulse wave form has only a second-order effect upon the ratio of the first-harmonic component to the average value of the pulse.

Table I summarizes the calibration ratios obtained for several models that approximate the usual beam-pulse shape shown in Fig. 1. It will be noted that even in the extreme case of the delta function, the error in this method of calibration is only on the order of 20%.

FACTORS AFFECTING BEAM-PULSE SHAPE

Random phase errors in the radio-frequency tracking equipment excite coherent phase oscillation within the bunched proton beam. Whenever groups of particles execute phase-stable oscillations within the bunch, a corresponding variation in the time-dependent density of the bunch appears and the induced-voltage pulse exhibits fine structure. The duty cycle of the bunched beam varies during the acceleration cycle, and, at a given energy, varies with the drift-tube voltage. As the amplitude of the drift-tube voltage increases above the threshold value for stable phase oscillations, the angular range of stable phase oscillations increases, and the duty factor may and usually does increase.[6] Considering these factors, the error in beam measurement may be minimized if the calibration factor is determined for a fixed drift-tube voltage and a fixed point in the acceleration cycle. A drift-tube voltage of 10 kv and an energy of 6.25 Bev have been chosen for the determination of the calibration factor.

APPARATUS

The voltage pulse induced in the induction electrode was transformed in impedance level by an emitter follower and transmitted over approximately 175 feet of transradio C-3T 197-ohm pulse cable. A Hewlett-Packard 460-A amplifier served as the termination of the pulse cable and as an amplifier for the voltage pulse before it was displayed on a Tektronix 517 oscilloscope. The electrical length of the pulse cable was 165 mμsec. Figure 1 shows that the cable termination was adequate to preclude the appearance of a measurable reflected pulse at 330 mμsec.

The frequency response of the pulse-monitoring system was limited at both ends of the frequency spectrum by the transistor characteristics. The upper half-power point was 15 Mc/sec and was limited by the α-cutoff of the transistor. The lower half-power point was 9.5 kc and was limited by the finite imput impedance of the transistor and the 240-μμf shunt capacity of the induction electrode. Thus the high-frequency bandpass of the pulse-monitoring

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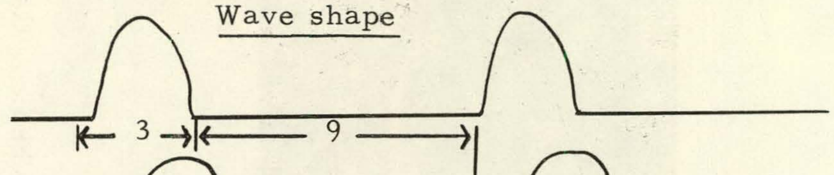
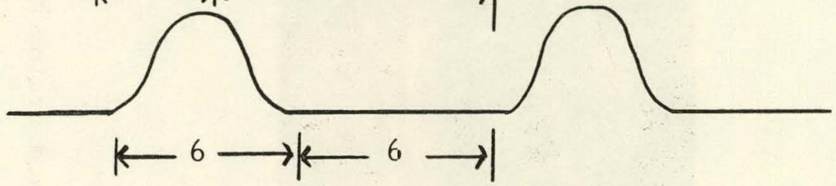
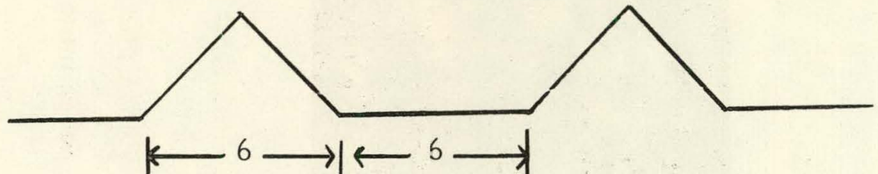
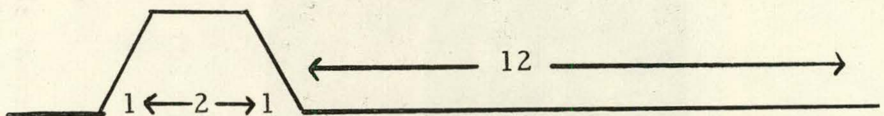
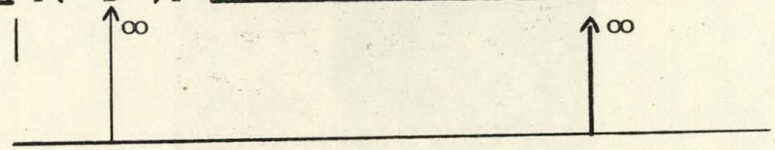
[6] N. M. Blachman and E. D. Courant, Rev. Sci. Instr. 20, 596 (1949).

Table I

Effect of wave form on calibration factor

Pulsed wave form	Wave shape	Calibration factor
Half sine wave		1.86
Full sine wave		1.66
Isosceles-triangle wave		1.62
Symmetrical trapezoid wave		1.53
Delta function		2.00
Beam pulse at 6.25 Bev for 10 kv drift-tube voltage		1.61 ± .02

(See Fig. 1)

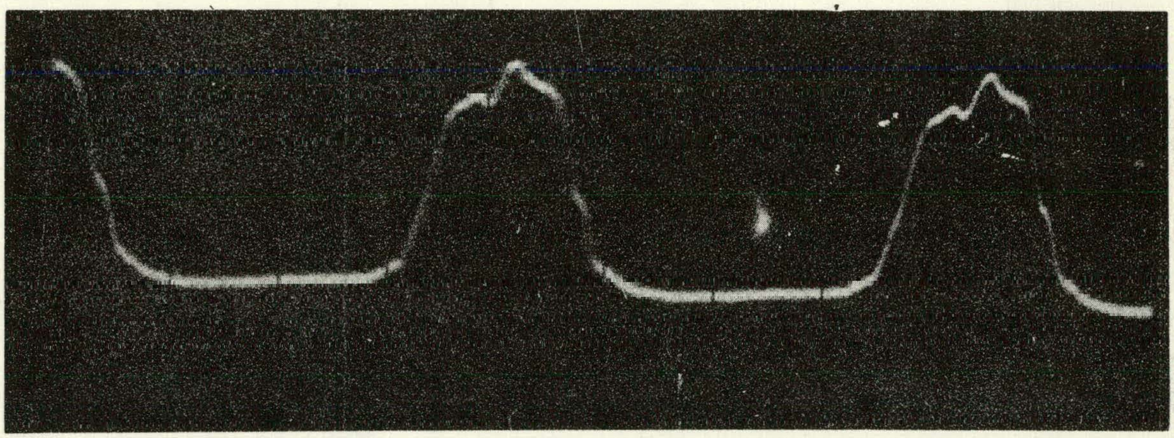


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Fig. 1. Normal shape of bunched proton beam. Calibration factor: 1.61.

system was sufficient to transmit the first six harmonics of the induction-electrode signal. The low-frequency response was adequate to reduce the droop in the top of the pulse to a negligible value.

The beam-pulse profile was obtained by photographing an oscilloscope trace. The sweep was initiated on successive magnet pulses, by a trigger corresponding to a beam energy of 6.25 Bev. The sweep speed was set at 100 mμsec/cm so that at least two consecutive samples of the beam profile were obtained on each photograph for each magnet pulse. The resultant photographic images were subsequently enlarged and subjected to a harmonic analysis.

MEASUREMENTS AND RESULTS

The duty cycle of the induced-voltage pulse was measured as a function of drift-tube voltage by measuring the pulse width of the signal. The pulse duration, which corresponds to the angular range of stable synchrotron oscillations, was found to vary 150 to 230 mμsec as the drift-tube voltage was varied from 5.5 to 16 kv; see Fig. 2. The effect of increasing pulse width is to lower the calibration ratio. The calibration data were obtained for the nominal operating voltage of the radio-frequency equipment; that is 10 kv.

As mentioned earlier, the presence of random-phase noise in the ratio-frequency equipment leads to phase oscillations that cause the configuration of the beam pulse to vary. To minimize these effects on the calibration factor, the calibration data were obtained for a fixed point in the acceleration cycle, namely 6.25 Bev. A total of 90 consecutive beam pulses were photographed and from these a representative sample of wave forms was obtained. Twelve photographs were subjected to a 24-ordinate harmonic analysis. The result of these analyses showed sufficiently small scatter that additional sampling and computation did not seem warranted. Table II summarizes the results.

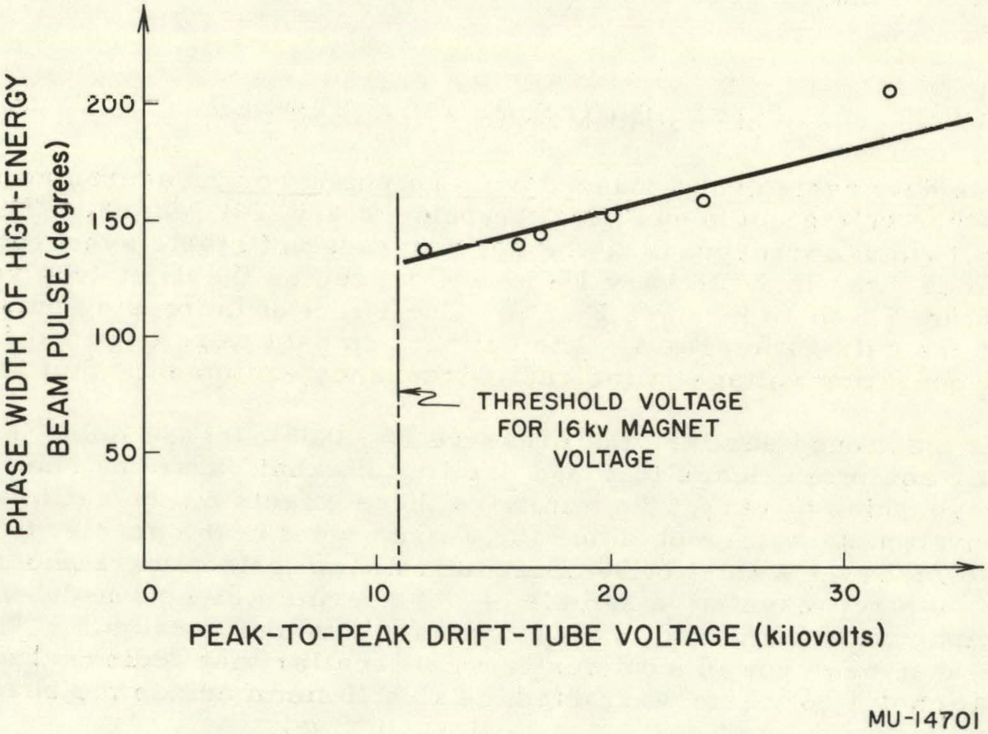

Fig. 2. Variation of phase width of high-energy proton-beam bunch with drift-tube voltage.

Table II

Calibration factor for beam pulses

Energy: 6.25 Bev; drift-tube voltage: 10 kv

Calibration factor	Number of cases analyzed	Number of cases of similar wave form in 90 pulses
1.51	1	↑
1.56	1	3
1.57	1	↓
1.59	1	↑
1.60	2	83
1.61	4	
1.62	1	↓
1.64	1	↑4↓

Figures 3 and 4 represent the extreme variations observed in the profile of the pulse. These photographs correspond respectively to the first and last entries in Table II. The maximum observed deviation of the calibration factor from the mode of 1.61 are only -6.2% and +1.9% respectively. Nine of the twelve cases analyzed fell within ± 2% of the mode. Eighty-three of the 90 wave forms photographed were similar to those having a calibration factor within ± 2% of the mode. Clearly the deviations in the calibration factor are statistical and will average out over any reasonable time interval.

SUMMARY

Fourier analyses of typical beam-pulse wave forms indicate that the ratio of the first-harmonic component to the average value of the pulse is 1.61. The average value of the circulating beam may be obtained to within ± 2% by measuring the amplitude of the first-harmonic component of the induction electrode signal. To achieve the maximum accuracy, calibration data must be derived for a fixed drift-tube voltage and a fixed point in the acceleration cycle.

Heretofore a calibration factor of 1.86 has been used in reporting the Bevatron beam intensities.[5] The change of the calibration factor from 1.86 to 1.61 will raise the indicated beam intensity by approximately 16%.

ACKNOWLEDGMENTS

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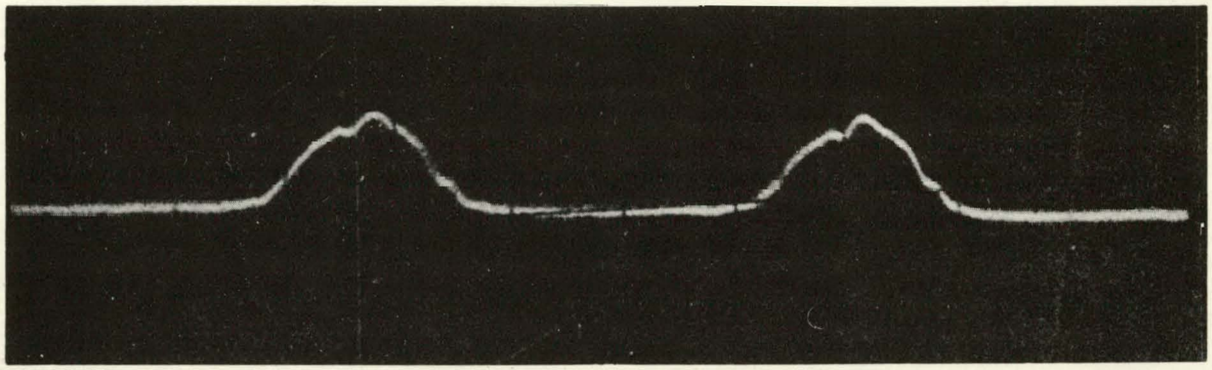

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Fig. 3. Bunched beam with calibration factor of 1.51.

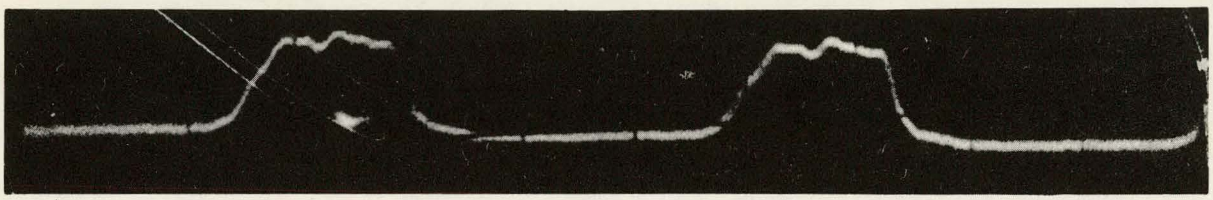

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Fig. 4. Bunched beam with calibration factor of 1.64.