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BEVATRON TARGETS, BEAM ENERGY AND CURRENT MONITOR

Authors
Chupp, Warren W.
Murray, Joseph J.
Wenzel, William A.

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UNIVERSITY OF CALIFORNIA

Radiation Laboratory

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Chupp, Murray, Wenzel
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BEAM TARGETS

Warren W. Chupp

The 6-Bev proton beam has the following characteristics:

1. Amplitudes of vertical oscillation ~ 1".
2. Amplitudes of radial oscillation ~ 2".
3. Rate of decrease of stable orbit at full energy with rf off ~ 1/3 mil/turn.
4. The vertical and radial oscillation frequencies are not far removed from the rotational frequency. For $n = 0.63$, $\frac{\omega_{rad}}{\omega_{rot}} = 0.73$, $\frac{\omega_{vert}}{\omega_{rot}} = 0.92$.

Several facts regarding the behavior of the beam on targets follow directly from these characteristics. Because the beam moves in so slowly and the oscillations are rapid, a target, small in height and with a radial extent large compared to 1/3 mil, will intercept all the beam if it is located on the median plane and inside the orbit. Protons with large radial oscillations will be intercepted first, and the radial distance in from the tip of the target where the protons strike cannot be much more than 1/3 mil.

The targets used in the Bevatron cannot be set in a fixed position because the aperture must be clear at the time of injection, and at high energy the region of "good" field (the region of field with the proper gradient to keep the beam reasonably focused over a period of several thousand turns) is in the center of the aperture near the circulating beam.

The usable aperture at injection extends from 582" R to 622" R. At 6.1 Bev the region of "good" field extends from 597" R to 609" R.

Typical targets can be used effectively at radii between 597" and 603". The probes used at present can be plunged into the desired radial position in a minimum time of 0.2 sec and a maximum time of 1.5 sec.

In order to achieve reliable operation of targets, several design specifications have been adopted as practical measures, though they need not rigorously apply to all cases.

Normal specifications are:

1. Target-height minimum = 1/4".

   This dimension limit allows for some misalignment of the probe from a level line, some vibration at the end of the stroke, and an uncertainty as to the exact location of the median plane of ± 1/16".

2. Addition of a "lip" which extends radially outward from the tip of the target. The lip is constructed of lucite or polyethylene to minimize multiple Coulomb scattering. The nominal thickness in the beam direction is 1/8", and the amount of radial protrusion is 1/8" to 1/4". The function of such a lip is to increase the spacing between successive turns from the normal 1/3 mil to ∼ 1/8" to 1/4" so that a large fraction of the protons will penetrate the full target thickness. Without such a lip, one can expect only grazing encounters with the target. The theory of the lip target has been given by McMillan (R.S.I. 22, 117, 1951).

3. The width of the target (radial dimension) is determined by the intensity distribution of protons landing on the target after traversing the lip. This distribution, which depends on the lip geometry, proton energy, and magnetic field, has been determined experimentally during the course of the beam-deflection experiments and internal emulsion exposures. The

characteristic distribution is shown in Figure 1 and will be referred to later.

4. The target support should be as light as possible, and on the probe-mounted targets, the target should stand out a minimum of 6" from the standard brass holders.

The present method of support is to use thin-walled stainless steel tubing as a support member.

BEAM CLIPPER

The protons, after traversing the target, acquire larger radial oscillations as a result of the contraction of the radius of curvature caused by the energy loss in the target and the acquisition of radial velocities produced by Coulomb scattering in the target. The change in the radius of curvature brought about by an energy loss ΔE is given by $\Delta r \cong \frac{r}{1-n} \frac{\Delta E}{E}$ where E is the total energy of the protons and $n = \frac{-r}{H} \frac{dH}{dr} \sim 0.6$ is the magnetic field exponent.

At 6 Bev

$\Delta r \cong 0.4\, w$ $\qquad$ Δr = inches

w = target thickness in gm cm^{-2}.

The approximate amplitude induced by multiple Coulomb scattering is

$|\Delta a| \sim 2\left(\frac{w}{w_r}\right)^{1/2}$ with w = target thickness
w_r = radiation length $\qquad$ Δa = inches.

Most of the targets used produce a Δr of at least several inches. After one passage through the target, the beam will ride at smaller radius with several inches amplitude of oscillation. The protons can then "see" a relatively large radial interval in the space between the target and the inner wall of the accelerating chamber. The probe target holder and other obstructions can then act as secondary targets producing background radiation.

The clipper is a large copper block 8" high, 2" to 4" thick in the beam direction, and 12" long in radial dimension. It is mounted on a plunging probe 180° from the west target area. Protons incident on the clipper are degraded, attenuated, and scattered. Plunging this device to a radial position about 3" short of the target position reduces the background proton intensity to about 1/40 of the total beam.

The distribution of beam intensity along the radial dimension of the target has been determined experimentally for several cases which approximate general-use targets.

The studies carried out under the beam-deflection program and in internal beam exposures are in general agreement. The beam distribution along the radial dimension of the target is independent of the target for targets greater than 5 gm/cm^{-2} equipped with a standard lip and using the clipper. The general intensity pattern is shown in Figure 1.

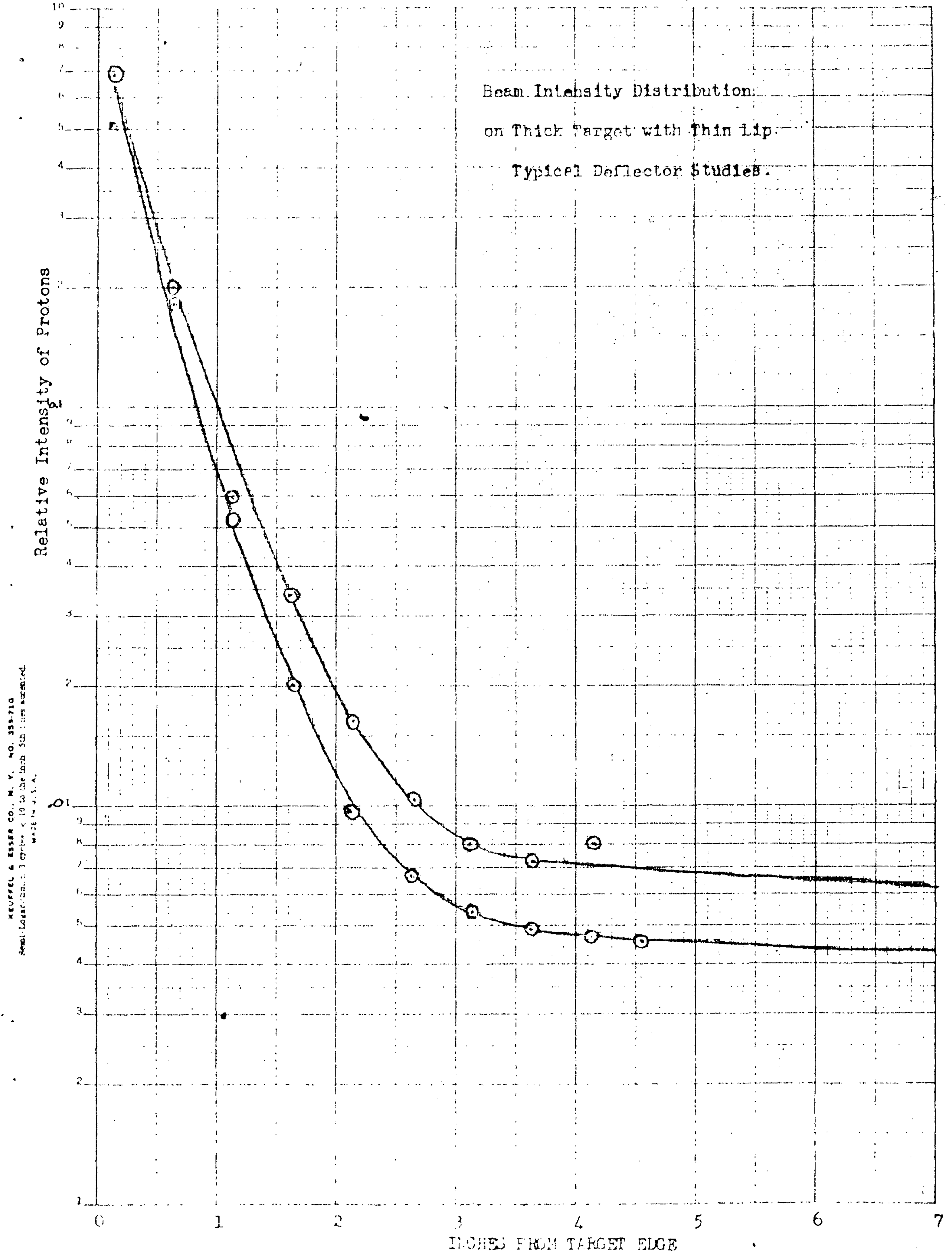
Small targets ($\ll 5$ gm/cm^{-2}) or those necessarily small in radial dimension and in the beam direction should not be used on the standard probe, but rather mounted on a "flip-up" target mounting. The "lip" may be dispensed with. It is desirable to use the clipper, however.

"FLIP-UP" TARGETS

The standard "flip-up" targets are described both as to geometry and location in the machine on a sketch prepared by W. W. Salsig after each shutdown and rearrangement. Copies may be obtained through the Bevatron office.

The maximum dimension in the beam direction that can be accommodated is 1-1/4", and the maximum target mass tolerable is 130 gm.

A new type now available can accommodate targets 4 inches thick in the beam direction.



Beam Intensity Distribution on Thick Target with Thin Lip
Typical Deflector Studies.

ACCURACY OF DETERMINATION OF PROTON ENERGY IN THE INTERNAL BEAM OF THE BEVATRON

Joseph J. Murray

In a table[1] posted in the counting area, one finds a list of current markers (I-pips) with corresponding values of proton energy, rf frequency, effective flux density, magnet current and time. The proton energy corresponds to the momentum computed from measured values of the magnetic field[2] according to the relation

$$p = \frac{1}{2\pi} \oint H dl$$

where the line integral is taken around the machine along the nominal beam centerline, which has a radius, r_o, of 599-3/8 inch in the quadrants.* It is believed that the error of the average H used in the integral was less than ± 0.3%. This is the only source of error taken into account in the uncertainty of ± 0.3% assigned to the proton energy $\left(\frac{dT}{T} \approx \frac{dp}{p} \text{ above 1 Bev}\right)$. Other possible sources of error of comparable magnitude are the following:

1. Deviation of the actual beam centerline from the nominal path.
2. Shift of the I-pips with respect to the magnet currents to which they corresponded at the time of the field measurements.

Spread of the beam energy arising from betatron and phase oscillations is relatively negligible ($\ll 0.1\%$). In what follows, the numbered items will be discussed briefly.

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[1] Windsor, Lambertson and Mack, 4383-01 EIA, Dec. 2, 1954 (Revised 1-18-55).

[2] Glen R. Lambertson, Testing the Magnetic Field of the Bevatron, University of California Radiation Laboratory Report No. UCRL-2818, November 10, 1954.

*The effective flux density listed in the table is defined by $2\pi H_{eff} r_o = \oint H dl$. The rf frequencies listed under the column subheaded "At Current Marker" were computed from the velocity corresponding to p for a path length around the machine equal to $2\pi r_o + 4L_s$ where $L_s = 20$ feet is the length of a straight section. The significance of other entries under "Frequency" is now obsolete.

A difference between the actual and nominal beam centerlines may exist for two reasons. First, by choice or necessity the beam may be tracked off the nominal centerline. Beyond flip No. 15, for example, the beam is normally tracked at a radius a few inches greater than that of the nominal centerline. If the difference between the actual and nominal radii is Δr, the corresponding energy increment is given by

$$\frac{\Delta T}{T} = \beta^2 \quad (1 - n) \quad \frac{\gamma}{\gamma - 1} \quad \frac{\Delta r}{r} \approx 0.5 \quad \frac{\Delta r}{r} \quad \text{above 1 Bev,}$$

where T is kinetic energy and n is the logarithmic field index equal to 0.6.

Secondly, however, the <u>shape</u> of the actual beam centerline may differ from the nominal shape, and, of course, knowledge of the radius of the beam at one point could not reveal that fact. In such a case the $\oint Hdl$ along the actual path of the beam may differ from the nominal value even after correction for Δr. The results of a preliminary experiment seem to indicate that energy errors, possibly as large as 0.5%, may exist because of this effect. No more definite conclusions can be drawn from the present information, and no prescription for correction can be given.

From the ratio of signals observed on the inner and outer segments of the induction electrode, one can make a crude estimate (± a few inches) of the actual beam radius. A more accurate determination (better than ± 1 inch) can be made by observing with the induction electrode the beam interference produced by a flip-up target as a function of target radius. Such a target is available at the west-inside-south transition tank station. Another even more accurate though more elaborate method, and one which provides a continuous monitor of beam position, is to measure the interval between the time of rf "off" and the time the beam centerline reaches a target at a known radius. Using the proper value of dr/dt (see Fig. 1), one then calculates the beam radius at the time of rf "off". The measurement can be made in several ways, for example, by triggering an oscilloscope with the same pulse used to trigger rf "off" and observing on the sweep this same pulse together with the signal from a scintillation counter located near the target. A typical sweep is shown in Figure 2. The fairly sharp trailing edge of the signal envelope corresponds to the time of arrival of the beam centerline at the target.

There are two sets of I-pips, referred to as the east and west sets, which are generated by two separate peaking transformers,[4] one in each of two parallel branches of the magnet-current distribution network. The magnet current flowing in one of the peaking transformers at a particular I-pip can be determined to ± 0.05% by measurement of the corresponding bias current. The total magnet currents listed in the table are actually twice the currents measured in the east peaking transformer at the time of the field measurements. At that time it was determined that the currents in the two branches of the magnet circuit were equal at I-pip No. 23, by placing the bias currents of the two peaking transformers in series and noting that the east and west pips occurred simultaneously. It was assumed that the currents were also equal at other I-pips. The short-term stability of the I-pips with respect to magnet current is of the order of ± 0.01%, although long-term drifts of the bias current do occur. For this reason, one may find the east and west pips separated in time by a millisecond or so,* and neither set may correspond exactly to the currents listed in the table. By having the current

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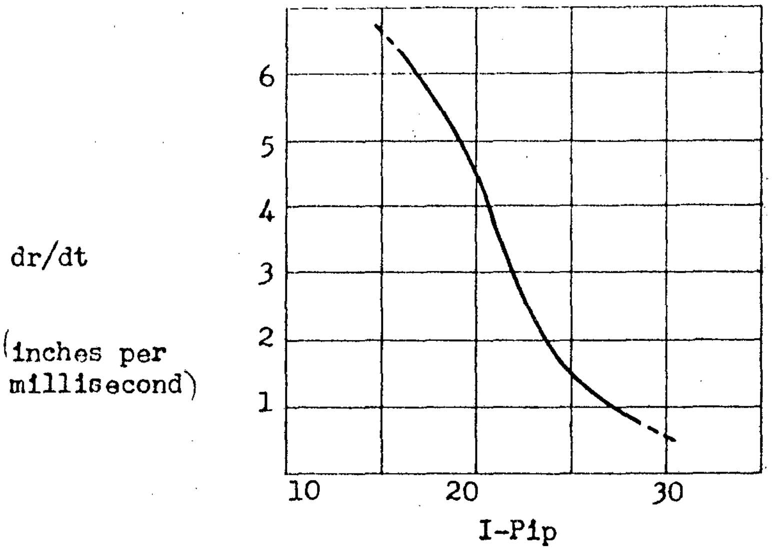
[4] Current Marker Maintenance Manual, 6Y2671.

* The west pips are normally made available to experimenters. In some instances timing difficulties may be avoided by requesting that rf "off" be triggered by a west pip, since the control room has both east and west pips available.

measured at the I-pip of interest (and in the proper peaking transformer), one can make such correction to the energy as necessary by interpolation of the table.



$$\frac{dr}{dt} = \frac{1}{1-n}\,\frac{r}{H}\,\frac{\partial H}{\partial t}$$

Fig. 1. Rate of collapse of the beam with rf "off".

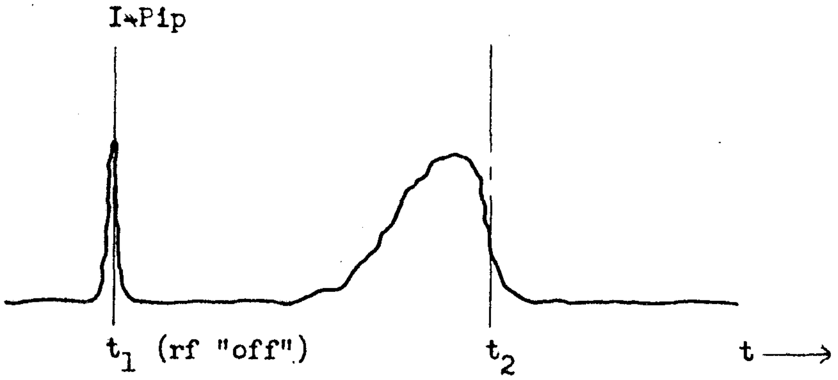


Fig. 2. Typical oscilloscope sweep on which the I-pip used to trigger rf "off" is presented together with the output of a scintillation counter located near the target; t_2 is the time of arrival of the beam centerline at the target; $(t_2 - t_1) \times \frac{dr}{dt}$ (see Fig. 1) is the difference in radii of the target and the beam centerline at the time of rf "off".

BEVATRON INTERNAL BEAM MONITOR

William A. Wenzel

Because the circulating beam of the Bevatron is bunched, the induction electrode serves as a convenient monitoring device. The circulating beam induces on the box-shaped electrode a periodic charge whose fundamental frequency is the accelerating radiofrequency. This signal is amplified and displayed on an oscilloscope or integrating recorder.

Monitoring is required for three purposes. First, continuous monitoring is usually required for maintenance of steady operation. Second, the study of the behavior of synchrotron operation is a necessary part of the program of continual improvement of Bevatron operation. Third, the experimenter often requires integrated beam information as a record of a run lasting over a period of hours or days.

Monitoring equipment in the first two cases is similar. An oscilloscope presentation following a wide-band amplifier ($\gtrsim 8.5$ mcps) is convenient for observation of the beam level from rf turn-on through the whole acceleration cycle or for observing the details of the bunched beam. The signals from the two halves of a split electrode, displayed on a dual-beam oscilloscope, give total beam magnitude and radial beam position at the same time. Sensitivity is limited partly by amplifier noise and partly by rf pick-up.

On the other hand, monitoring the beam level at a given time in the acceleration cycle for a recorded presentation imposes different limitations. There are two serious and one minor objection to the use of the wide-band system for this purpose. First, the noise level from the ignitrons is very large. Although these transients do not interfere with the scope presentation (with a slow sweep speed), efforts to rectify the output of the wide-band amplifier show that the noise duty is very large. Second, distortion of the induced signal on the induction electrodes would make integration of the beam pulse inaccurate. This could result from distortion of higher harmonics of the pulse, due to imperfect amplification or even to geometrical effects involving the leads from the electrodes themselves. Another perhaps less important consideration is that the use of a wide-band system introduces maximum amplifier noise into the integrated signal.

For these reasons, and the fact that information for the record is required at only one point in the acceleration cycle, a tuned or band-pass amplifier is to be preferred. The advantage of the band-pass over the tuned circuit is that troublesome tuning is avoided, and there is less sensitivity to frequency drift. On the other hand, more tubes are required to amplify the signal to a point where good linearity using, say, a diode rectifier results. The band width should be sufficient to accommodate a wide range of energies, say, from 1 to 6 Bev. This energy range is covered with a frequency range of 2.20 to 2.50 mcps. In any case, higher harmonics than the fundamental must be rejected.

Accurate use of a detector which operates only on the first harmonic of the beam signal depends on a known ratio between total signal and first-harmonic amplitude. With the wide-band presentation, the beam structure is observed to be as shown in Fig. 1.

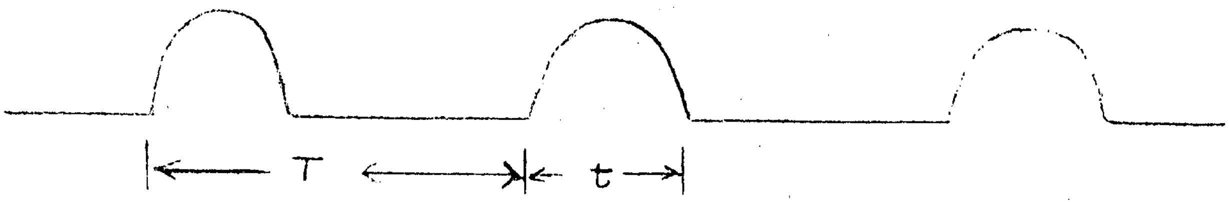


Figure 1.

The "duty cycle": $\frac{t}{T} = 100^\circ \pm 20^\circ$. If we approximate the beam pulse by a half sine wave of period 2t, we find by Fourier analysis that the amplitude of the first harmonic is related to the dc level by the relation $A_1 = (1.85 \pm .06)\, \bar{V}_{dc}$

$$V_{dc} = \frac{Ql}{C(2\pi R + 4L)}$$

where Q is the charge of the beam, l is the length and C the capacity of the induction electrode, R is the radius of the beam orbit, and L is the length of each of the four straight sections of the Bevatron.

The amplifier is calibrated with an rf signal from the master oscillator at a known level. This is a convenient method, since at a given time the master oscillator has the same frequency as the beam fundamental.

Aside from amplifier drift, especially when a high Q-tuned circuit is used, the accuracy of the method is limited only by the uncertainty of the beam "duty cycle", and the effective length-to-capacity ratio of the electrode itself. The capacity is easily measured, as is the length, if guard rings are used. This is the case for the electrode in the east tangent tank. For the electrodes in the south tangent tank, the effective length is estimated and may be in error by as much as 30%.

Absolute measurements with the east electrode are hampered by the large amount of rf pickup from signal cables unless the required amplifying and detecting system is placed near the east tangent tank.

The scheme presently used to store the information on beam magnitude is an integrating electrometer and a recorder. A capacitor charged to a voltage proportional to A_1 is dumped by relay into the integrating capacitor of the electrometer at any arbitrary predetermined time in the acceleration cycle.

An alternative scheme, similar to that used at the Cosmotron, would convert this dc voltage to a gate which permits a fixed-frequency oscillator to operate a scaler. This digital method permits easy reproduction for remote indicators, but loses the record of individual pulses.

Ultimate accuracy of the monitoring scheme used, limited only by the effective capacity to length ratio of the electrode and the reproducibility of the beam "duty cycle", should be about ± 5%. Amplifier drift and rf pickup (especially at low beam levels) has limited the accuracy to about ± 20% to 30%. The equivalent beam level due to rf pickup is, at best, 10^7 particles per pulse.

It should be stressed that absolute experimental yields, based on the internal beam monitor, are strongly dependent on target size and shape and the magnetic focusing properties of the Bevatron field. In most cases, these considerations will limit the absolute experimental accuracy attainable. For counter experiments, the monitor should measure the beam just before spillout, and any gating used on the counters should cover the entire spillout time.