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SLOW AND FAST STRUCTURE OF SECONDARY - PARTICLE BEAMS OF THE BEVATRON

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July 5, 1956

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ABSTRACT

This report summarizes the results of a coordinated investigation of the structure of the secondary-particle beams of the Bevatron. The debunching and spiral in time of the primary beam have been determined for typical experimental conditions. Two of the methods of secondary-beam production, which are discussed here, have been used extensively in cloud-chamber and counter-type experiments. Three new methods of secondary-beam production have been studied in some detail. The radiofrequency structure, synchrotron oscillation structure, magnet-ripple structure, and duration of the secondary-beam pulse are reported for each of these methods.
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INTRODUCTION

Secondary beams of particles may be produced in the Bevatron by at least five methods. The time-dependent structure and duration of a secondary-beam pulse depend upon a number of parameters over which limited control can be exercised. All the secondary beams discussed herein have been produced by causing the primary proton beam to impinge upon inner-radius targets. Depending upon the type of structure desired, the primary beam was either tracked into the target with the accelerating voltage on or was caused to strike the target by increasing the magnetic field after the particles had lost phase stability. Experiments in progress at the Bevatron require secondary beams having one of four characteristics:

1. In most scintillation-counter-type experiments it is desirable to have high primary-beam intensity, but allow the secondary beam to persist at low intensity for 50 to 100 milliseconds. The duration of the secondary beam is usually determined by the maximum allowable energy spread in a given experiment. For such measurements an ideal secondary beam should have no structure.

2. Time-of-flight experiments require very well bunched secondary beam pulses.

3. Good cloud-chamber and bubble-chamber operation require single beam pulses whose duration is of the order of one millisecond.

4. In more precise experiments, wherein the excitation function varies rapidly with the energy of the bombarding particle, or where the production cross section is low even at the peak energy of the Bevatron, it is desirable to make a long secondary beam pulse with a minimum energy spread. All these requirements have been satisfied to some degree by the techniques discussed below.
TECHNIQUE

Except in the thin-foil experiment, a tantalum target was used in all the measurements. The slow structure was obtained by integrating the output of a counter telescope that was pointed at the target. This signal was displayed on a dual-beam oscilloscope and photographed. The second beam of the oscilloscope was used for a coincident display of a reference signal, such as the beam induction-electrode signal, magnet current, or accelerating-electrode voltage.

The rf or fast structure of secondary beam was determined by observing the number of coincident counts from a counter telescope that occur during a time interval small in comparison with the period of an rf cycle. This sampling interval remained in a fixed reference with respect to the accelerating voltage during the whole secondary-beam pulse, but was changed from pulse to pulse to allow the whole rf cycle to be scanned. The ratio of the maximum to the minimum number of counts during the accumulated scanning interval of one rf cycle was taken as a measure of the rf structure of the beam.

DEBUNCHING TIME OF THE PRIMARY BEAM

The primary (circulating) beam of the Bevatron is compacted by radial, vertical, and azimuthal damping forces into a nebulous bunch whose approximate dimensions at full energy are:

- Vertical half width, 2 cm;
- Radial half width, 5 cm;
- Length, 15 meters (90° in rf phase).

If the accelerating voltage is turned off abruptly, some of the bunching forces are removed, and the momentum spread of particles within the beam causes the bunch to spread out in azimuth. After a sufficiently long time the azimuthal distribution of particles becomes uniform, and the beam degenerates into a torus. Debunching of the primary beam has been observed directly with the beam induction electrodes. Let the debunching time be defined as the interval between the removal of accelerating voltage and the time corresponding to a reduction of the beam induction signal to 10% of its original value; this time, which would be expected to be on the order of the period of a synchrotron oscillation, is shown in Fig. 1 to be approximately 800 μsec.

At the peak energy of the Bevatron the orbit contracts at a rate of $2 \times 10^{-4}$ inches/turn or $2 \times 10^{-3}$ sec/inch. Therefore, to obtain a secondary beam with minimum of rf structure, the tracking of the primary beam must be such that at the moment of rf turn-off the radius of the equilibrium orbit is large enough so that the beam will not begin to strike the target for at least one millisecond. Because of the finite radial width of the primary beam and the finite width of aperture between $n = 1/2$ and $n = 3/4$, the radial position of the equilibrium orbit cannot be made arbitrarily large. The Bevatron has been designed to have sufficient aperture so that the primary beam can circulate within the aperture for a few milliseconds before striking the target.

* $n = \text{logarithmic field index}$
Fig. 1. Sweep trigger I-24 + 89 msec. Sweep spread 200 μsec/cm.
Top trace: accelerating electrode voltage; abrupt rf turnoff. Bottom trace: south sum induction electrode signal of circulating bunched beam.

Circulating bunched beam takes about 800 μsec to debunch. This corresponds to about 2000 turns.
DURATION OF SECONDARY-BEAM PULSE
WITH ABRUPT RF TURNOFF

If the dc voltages on the final amplifier tube are turned off abruptly, the amplitude of the rf voltage on the accelerating electrode decays to 10% in about 100 μsec. The primary beam debunches, and the beam spirals into an inner-radius target within a few milliseconds; the actual time depends on the radial width of the beam, the radial position of the target, and the equilibrium orbit of the beam at rf turnoff. The approximate energy spread of the primary beam during the time that it is striking the target can be computed from the relation

$$\Delta E = \beta^2 (1 - n) \frac{\Delta r}{r} E \approx 6.6 \times 10^{-4} \Delta r E,$$

where $\Delta r$ corresponds to the half amplitude of the betatron oscillations after the primary beam has been accelerated to an average energy $E$. The duration of the secondary-beam pulse has been measured directly with a counter telescope and found to be approximately 1 millisecond (see Fig. 2). This is approximately the value obtained from the calculated radial width of the beam and the rate of contraction of the equilibrium orbit. A jitter is observed in the arrival time of the secondary-beam pulse on the target. Also, the duration of the pulse exhibits fluctuations. These uncertainties are due to the magnetic-field ripple, which modulates the rate of contraction of the equilibrium orbit. Except for a slow drift induced by the change in resistance of the Bevatron magnet winding (due to heating), the magnetic-field ripple is reproducible from pulse to pulse. Therefore, by careful selection of the turn-off time of the accelerating voltage, it is possible to minimize the time jitter and secondary-beam pulse-width fluctuation to within approximately 200 μsec.

STRUCTURE OF SECONDARY BEAMS PRODUCED BY CAUSING SYNCHROTRON OSCILLATION AMPLITUDES TO INCREASE

If the amplitudes of the energy oscillations are allowed to increase, by a gradual reduction of drift-tube voltage or by phase modulation of the tracking frequency at or near the synchrotron oscillation frequency, some of the particles soon become phase-unstable and spiral into an inner-radius target. These two methods of producing a secondary-beam pulse are essentially indistinguishable. Both methods produce beam pulses of at least 50 milliseconds duration and have been used extensively, individually and in combination, in counter experiments.

The slow structure of these beams is shown in Figs. 3, 4, and 5 with comparable time resolution. It will be noted that both techniques produce a secondary-beam pulse, which exhibits both synchrotron oscillation and magnet ripple structure. In both methods the rate of contraction of the equilibrium orbit is modulated by the magnetic-field ripple. The synchrotron oscillation structure is not the same in the two cases. If the drift-tube voltage is reduced to cause the particles to spiral in, the frequency of the synchrotron oscillations is that of the natural undamped oscillations. If, instead, the synchrotron oscillations are driven, the secondary beam has synchrotron oscillation structure of the driving oscillator. The difference is easily seen in Figs. 4 and 5.
Fig. 2. Sweep trigger I-24 + 80 msec. Sweep speed 500 μsec/cm. Top trace: accelerating electrode voltage; abrupt rf turnoff. Bottom trace: integrated output from a counter that measures the pion flux at 90° from a Ta target 1 by 1.5 by 0.5 inch.

Beam spirals into target in approximately 2 msec. Spiral in time depends upon the duration of relative phase of the magnetic-field ripple during the time the beam begins to strike the target. The energy of the circulating beam at the moment of targeting can be controlled with sufficient accuracy so that the energy spread of the beam striking the target is essentially determined by the betatron oscillations. There is no synchrotron oscillation structure and no rf structure in this ejected beam.
Fig. 3. Sweep trigger I-24. Sweep speed 10 msec/cm. Top trace: south sum induction electrode signal. Bottom trace: integrated output from counter at 90° to Ta target.

Beam ejection period is usually terminated by a burst of beam of many times the amplitude of the beam during the counting period. There is a 10:1 peak-to-valley ratio of counts on an rf-cycle basis. A 1380-cycle synchrotron oscillation structure is quite noticeable during the 50-to-100-msec beam ejection period. Both 180-cycle magnet ripple and 120-cycle weldtronics ripple modulate the counting rate to approximately 100%.
Fig. 4. Sweep trigger 1-24 + 50 msec. Sweep speed 2 msec/cm. Top trace: south sum induction electrode signal. Bottom trace: integrated output from counter at 90° to Ta target.

At greater resolution the synchrotron oscillations are easily identified, as are the spikes due to magnet ripple.
Fig. 5. Sweep trigger \( I-24 + 50 \) msec. Sweep speed \( 2 \) msec/cm. Top trace: voltage proportional to frequency of driving oscillator; frequency deviation at 830 cycles of 0.06\%.

Bottom trace: slow structure of pion flux detected at 90° to Ta target.

Pion flux has 10:1 peak-to-valley ratio of counts on an rf-cycle basis. Synchrotron oscillation structure at 830 cycles can be detected in the pion beam. Beam ejection time can be made as long as desired. Magnet ripple (~200 cps) modulates the counting rate more significantly than does the phase-modulating source.
Secondary beams produced by causing the synchrotron oscillations to grow exhibit rf structure because the accelerating voltage remains on while particles from the primary beam strike the target. This structure has been measured by observing the time dependence of the flux of secondary particles. The ratio of the maximum to the minimum number of counts was approximately 10:1 for both cases.

STRUCTURE OF THE TOROIDAL BEAM PRODUCED BY A STEP IN MAGNET CURRENT

The energy spread of the secondary beam can be kept small if the accelerating voltage is turned off abruptly. For the normal rate of rise of magnetic field this method produces a beam pulse of approximately 1 millisecond duration. If the accelerating voltage is turned off abruptly and, shortly thereafter, the rate of rise of magnetic field is greatly reduced, the equilibrium orbit contracts more slowly, and a long beam pulse of small energy spread is produced. By a careful change in the electronic phasing of the ignitron supply, it has been found possible to introduce a step of approximately 86 milliseconds' duration at the peak in magnet current. The rate of rise of current during this step can be as little as 1/10 to 1/100 of that occurring during the normal current rise. Figures 7 and 8 reveal the essential characteristics of secondary beams produced by this technique. Figure 6 shows that the accelerating voltage is turned off approximately 23 milliseconds before the primary beam begins to strike the target. Therefore, before the circulating beam strikes the target, sufficient time has elapsed so that the beam has completely degenerated into a torus with no rf or synchrotron oscillation structure. Figure 7 shows that the secondary beam pulse lasts for approximately 50 milliseconds, during which time the magnet current increases 22 amperes. Note that the structure of the secondary-beam pulse is coherent with the ripple in magnet current. Whenever the magnet current increases, some of the circulating beam strikes the target. The smallest increment in magnet current that causes an observable change in the flux of the secondary beam is 0.5 amp. At the present time, the usefulness of this technique is limited by the magnitude of the current ripple, so that the effective counting time for a 50-millisecond pulse is only about 10 milliseconds. A careful study of the magnitude of the ripple structure indicates that approximately 1000 watts of peak power at the ripple frequency could eliminate the ripple from the magnetic field and extend the counting time by a factor of 5 or more. This ripple-bucking field could easily be excited by driving the pole-face winding in the magnet aperture. Preliminary tests have already demonstrated the practicability of this technique.
Fig. 6. Sweep trigger I-24. Sweep speed 10 msec/cm. Top trace: accelerating electrode voltage. Bottom trace: integrated counting rate of counter at 90° to Ta target.

Beam begins to strike target 23 milliseconds after rf turnoff. Duration of beam ejection depends upon the rate of rise of current during the step.
Fig. 7. Sweep trigger I-24. Sweep speed 10 msec/cm. Top trace: integrated counting rate of counter at 90° to Ta target. Bottom trace: magnet current at high resolution during step; current in magnet at start of step 2500 amp; current rise during step is 50 amp; change in magnet current to eject entire beam pulse = 22 amp; magnet ripple during step = 2 amp.

The pion beam from this target has no synchrotron structure and no rf structure. There is magnet ripple structure. It is approximately twice as large as is observed during the normal rectification interval.
Fig. 8. Sweep trigger 1-24. Sweep speed 20 msec/cm. Top trace: south sum induction electrode signal. Bottom trace: integrated counting rate from the pion beam produced by a thin target.

A 0.0001-by-9-by-12-inch rubber hydrochloride film is used as a target. The energy loss in this film due to ionization is approximately 500 ev. As this energy loss is less than the energy gain per turn of synchronous particle, the recirculation factor is large. Protons become phase-unstable in passing through the film if they produce a nuclear event or lose energy via an electron-proton knock-on collision. The duration of the beam pulse is of the order of 50 msec. This corresponds to a recirculation factor of the order of $10^5$. A maximum rf structure can be produced with this target.
STRUCTURE OF SECONDARY BEAMS
PRODUCED BY TRACKING THE CIRCULATING BEAM INTO A TARGET

In many experiments it is necessary to have well-bunched secondary-beam pulses that recur in synchronism with the rf accelerating voltage. A thin-film target technique has been investigated and found to produce a rf structure ratio as large as 500:1; the secondary-beam pulses were found to have a half width of 150 μsec or approximately 135° of rf phase. The target consists of a 0.0001-inch-thick film of rubber hydrochloride attached as a sheet to a 9-by-12-inch C-shaped aluminum frame. For production of a secondary-beam pulse the tracking is adjusted to make the primary beam pass through the target. As the energy loss of a particle traversing the film is small compared with the energy that a particle can gain during its transit through the accelerating gap, a given particle recirculates through the film until it is lost owing to a nuclear event or it falls out of synchronism owing to the energy losses of multiple knock-on collisions with electrons in the foil. Figure 8 shows the duration of the beam pulse obtained by this method to be approximately 50 milliseconds.

The slow structure of this secondary beam exhibits magnet-ripple structure, as well as phase-oscillation structure. The rf structure ratio depends upon the use and location of the east clipper electrode. If the projected position of the east clipper electrode is within 0.5 inch of the front edge of the foil target, the rf structure ratio is of the order of 500:1. If the east clipper is not used, this ratio deteriorates to approximately 10:1, a result which is explained by the mechanism of energy loss in the thin target. Particles that become phase-unstable continue to recirculate through the foil unless they are removed by the clipper. Verification of this mechanism was obtained from a radioautograph of the activity distribution in the foil, as shown in Fig. 9. The intense activity at the front edge of the foil is believed to be due to the frequent recirculation of the phase-synchronous particles, which produce the large rf structure ratio. Except for striations, which may be due to variations in the thickness of the foil, the remaining activity is almost uniformly distributed along the foil. The latter activity is believed to be due to the phase-unstable particles which continue to recirculate through the foil as they spiral inward. The ratio of activity in these two areas of the foil is a measure of the number of times a particle refluxes through the target in synchronism with the accelerating voltage.

A comparison was made of the slow and fast structure of the secondary-beam pulses obtained when the beam was tracked into a thick target. This target was made of tantalum and was 1.25 inches thick in the beam direction. The observed rf structure ratio was approximately 25:1. Both magnet-ripple and synchrotron-oscillation structure were observed during the 50 milliseconds of the secondary beam.

* The clipper electrode consists of a 2 by 8 by 12 in. copper block which has 1 by 4 by 8 in. copper slabs bolted to its leading edge. This electrode causes a large contraction in the radius of any particles which passes traverses the copper.
Fig. 9. Radioautograph of the activity distribution in the 0.0001-inch foil. Intense activity located on front 0.5 inch of target, where beam recirculation per unit area is a maximum. Vertical amplitudes of oscillation do not increase appreciably as the phase-unstable particles spiral into the inner radius of the machine, as the region of n ~ 0.6 is quite large at 3.0 Bev. If the projected location of the east clipper is within 1 inch of the front edge of this target, the peak-to-valley ratio of counts during an rf cycle is on the order of 500:1 to 800:1. When the clipper is not plunged, this ratio deteriorates to 10:1. The difference in fast structure is believed to be due to the mechanism of the thin target. When the peak-to-valley ratio is 500:1, the half width of the bunching relative to an rf cycle is 135°. The pion flux from the thin target has a slow structure due to magnet ripple, and, depending upon the projected location of the east clipper, there is some synchrotron oscillation structure.
CONCLUSIONS

By use of the techniques described, secondary beams can be produced in the Bevatron which are useful for cloud chambers, bubble chambers, ordinary counter experiments, and time-of-flight counter experiments.

As a result of these measurements, several general observations with respect to secondary-beam structure are pertinent:

1. If the duration of a secondary-beam pulse is greater than the period of the ripple current in the magnet, the beam shows magnet-ripple structure.

2. If the accelerating voltage remains on during the secondary-beam pulse, both rf and synchrotron oscillation structure are present.

3. If the accelerating voltage has been off for a few milliseconds before the primary beam strikes a target, there is essentially no rf or synchrotron oscillation structure in the secondary beam.

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