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# THE USE OF FILAMENTARY TARGETS TO PRODUCE PROLONGED SECONDARY-PARTICLE BEAMS IN THE BEVATRON

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## Abstract

The foil technique for producing secondary-particle beams in a proton synchrotron is extended in this work. Filamentary targets are described that are shown to produce secondary-particle beams having almost arbitrary time duration and uniform intensity. The physical limitations imposed by available materials are discussed.

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## II. Introduction

In many scintillation-counter experiments at high energy, it is possible to utilize a moderately high flux of secondary particles having considerable energy spread. In such cases, the full beam intensity of the Bevatron (2 to $3 \times 10^{11}$ protons per pulse) may be utilized if suitable means can be devised to distribute the total number of particles uniformly over a relatively long period of time. Several techniques for producing uniform secondary long period of time. Several techniques for producing uniform secondary beam pulses have already been investigated.[1,2] Three of these methods have been used with varying degrees of success. These include (a) allowing the phase-oscillation amplitude of some of the bunched particles to grow to instability by reducing the peak rf voltage on accelerating electrode, (b) driving the phase-oscillation amplitudes of some of the particles beyond the stability limit by phase-modulating the frequency-tracking oscillator, and (c) placing a foil of low atomic number on the outer radius of the synchrotron aperture, thus creating a selective energy-loss mechanism that would remove an ever increasing fraction of the particles from the primary beam. This last method has proven rather successful in producing beam pulses in the 1 to 500-millisecond range. The main disadvantage of this third approach is that appreciable scattering can take place in foils whose thickness is sufficient to yield adequate mechanical strength. Considerable improvement in secondary-beam quality has been achieved by extending the foil technique by the methods outlined below.

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1 Harry G. Heard, Slow and Fast Structure of Secondary-Particle Beams of the Bevatron, UCRL-3428, July 1956.

2 Harry G. Heard, Production of Prolonged Secondary-Particle Beams in the Bevatron, UCRL-3428, July 1956.

## II. Description of the Method

The essence of the thin-foil mechanism for producing prolonged secondary beam pulses is straightforward (see Appendix). The energy-loss foil is inserted on the outer radius of the aperture at the moment it is desired to produce a secondary beam. The frequency of the tracking oscillator is then slowly perturbed so as to cause the equilibrium orbit of the primary beam to expand onto the foil. As a function of time more and more particles from the primary beam strike the foil and lose energy. If sufficient energy loss occurs before appreciable scattering results, the particles fall out of phase synchronism and spiral onto an inner-radius target. As the asynchronous particles circulate within the aperture for several milliseconds before the increasing magnetic field intensity shrinks their orbit radius and causes them to strike an inner-radius target, the rf structure associated with the synchrotron oscillations is completely lost.

A number of phenomena must be considered if one is to gain a complete understanding of the production of a prolonged beam pulse of suitable quality. The most important of these include the probability of a particle's striking the target on successive turns, as determined by the precession of the orbit of radial between oscillations in a nonlinear magnetic field gradient; the energy loss sustained by the particle in traversing the foil; the amount of energy regained by a particle between successive traversals of the target; the amount of energy loss a particle can sustain before falling out of phase with the radio-frequency drift-tube voltage; the root-mean-square angular scattering that results from target traversal; the amount of time, measured in phase-oscillation periods, through which the phase-unstable particle circulates within the aperture before striking the target; the effect of magnet ripple on modulating the radial position of the phase-unstable particles, etc. Consideration of all of these factors indicated that the most suitable foil is a pseudo-foil or filamentary target, constructed of spaced filaments of a material of low atomic number, and placed wholly within the beam of the synchrotron.

## III. Experimental Results

Several experiments were performed with filamentary targets made of very fine aluminum wire. Considerable difficulty was experienced in these experiments as wires of sufficiently small equivalent thickness (diameter) had very little mechanical strength. Finally, nylon fibres of various diameters from 10 to 100 microns were tried with considerable success. It was found, interestingly enough, that a single fibre could be made so small that it could be suspended in the beam all during the acceleration cycle without causing appreciable beam loss. A radioautograph of one of these fibres that produced a secondary beam with an energy spread from 10 to 6300 Mev is shown in Fig. 1. A 10-inch array of 20 vertical fibres of 10-micron diameter was constructed and plunged into the center of the primary beam during the latter half of the acceleration cycle.

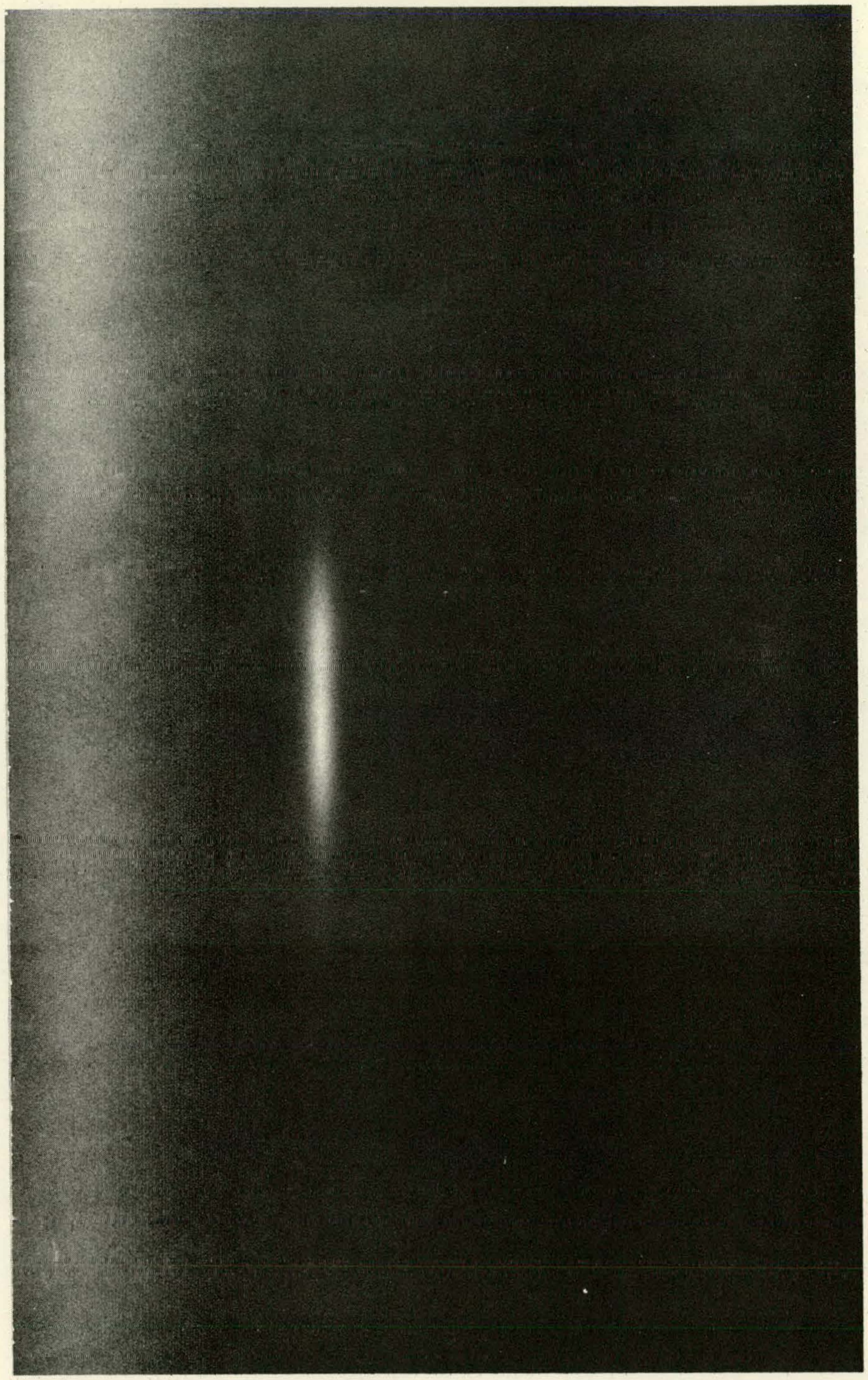

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**Fig. 1. Radioautograph of an activated 10-micron nylon fibre that was used to produce 1875-millisecond secondary-particle beam with an energy spread from 10 to 6300 Mev. The fibre was placed at a radius of 600 inches in the accelerator aperture.**

Figure 2a and 2 b show that such an array produces a nearly uniform beam loss for more than 750 milliseconds. Longer beam pulses could obviously be produced if the array were placed in the beam at lower energies. Figure 3 shows a radioautograph of the 10-micron fibres after approximately 20 minutes. It is clear from this picture that the array was immersed in the high-energy beam for an appreciable portion of the acceleration cycle.

Although this technique produces a nearly ideal secondary beam, it has a serious limitation, namely, the 10-micron nylon fibres are soon destroyed by radiation damage from the beam and by mechanical stresses caused by the target-actuating mechanism. This limitation is almost completely eliminated if the diameter of the fibre is increased to 100 microns and a stranded-fibre construction is used. Figure 4 shows the nearly uniform attenuation of the primary beam resulting from the final configuration. The fibres in this filamentary target must be replaced after an integrated incident flux of about $2 \times 10^{15}$ protons. If the Bevatron is operated at maximum intensity, this total flux is accumulated in approximately 24 hours, so that daily maintenance is required.

## IV. Conclusions

The foil technique of producing prolonged beam pulses has been extended markedly by using a vertical filamentary array of nylon fibres that reduces the effective foil thickness. The rate of secondary-beam production may be controlled by this method so as to produce beams of greatly improved quality.

This work was done under the auspices of the U. S. Atomic Energy Commission.

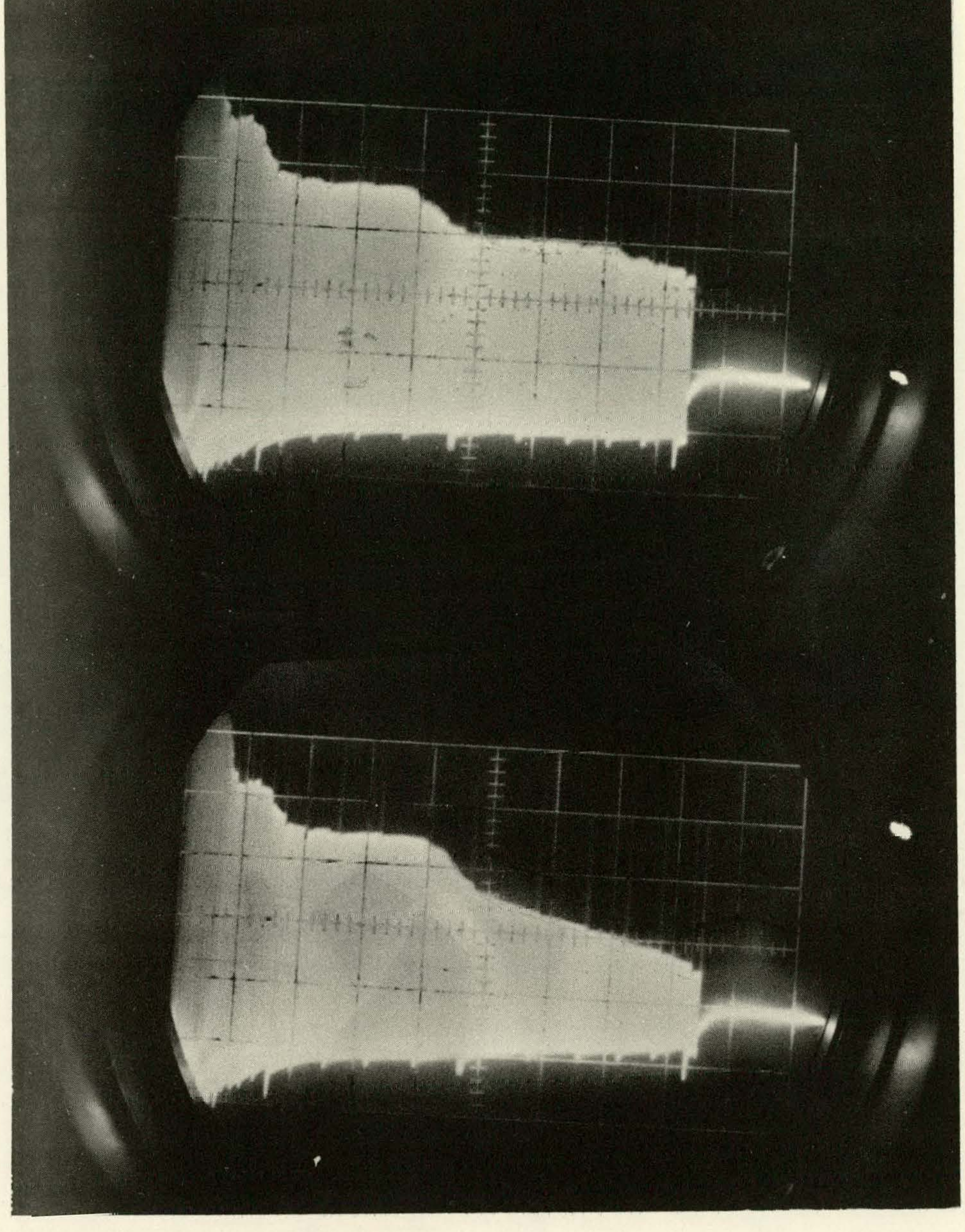

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Fig. 2. (a) Top Frame. Bevatron beam intensity versus time as seen by the south sum induction electrodes; $10^{10}$ protons per cm vertical, 200 msec per cm horizontal, filamentary target removed.

(b) Bottom Frame. Linear reduction of primary beam intensity produced by an array of twenty 10-micron fibres placed in the primary beam after 1 second. The leading edge of the vertical array was placed at a radius of 601 inches in the accelerator aperture. The monitored secondary-beam amplitude, obtained from suitably placed scintillation counters, showed a corresponding secondary-beam uniformity. (Same calibration as top frame).

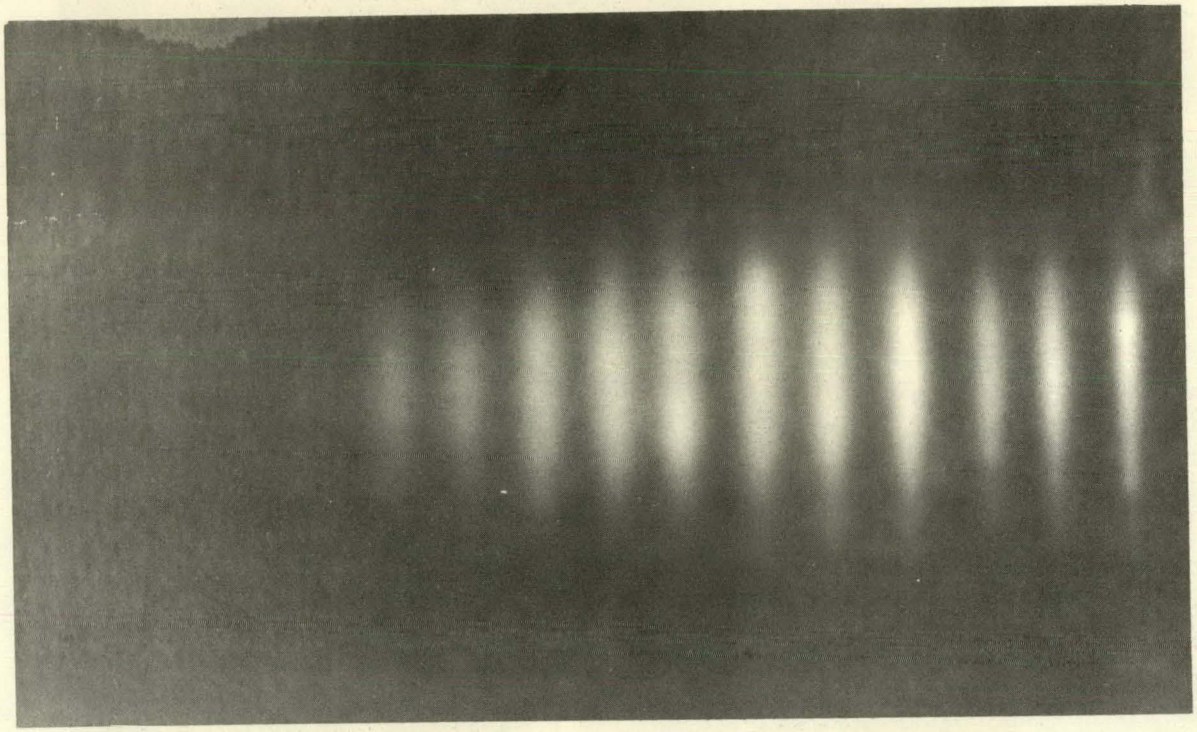

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Fig. 3. Radioautograph of a 10-inch array of 20 vertical 10-micron nylon fibres that were placed in the primary beam. Very little activity appears on fibres beyond the 11th. The right-hand fibre in the photograph corresponds to a radius of 601 inches, or 1 inch outside the geometric center of the aperture. At high energies the beam is wholly outside the 601-inch radius. Note that the maximum activity appears near the center of the array, corresponding to the location of the equilibrium orbit of the Bevatron at high energies. From this radioautograph and the known characteristics of the accelerator it is concluded that the array was immersed in the primary beam for the latter half of the acceleration cycle.

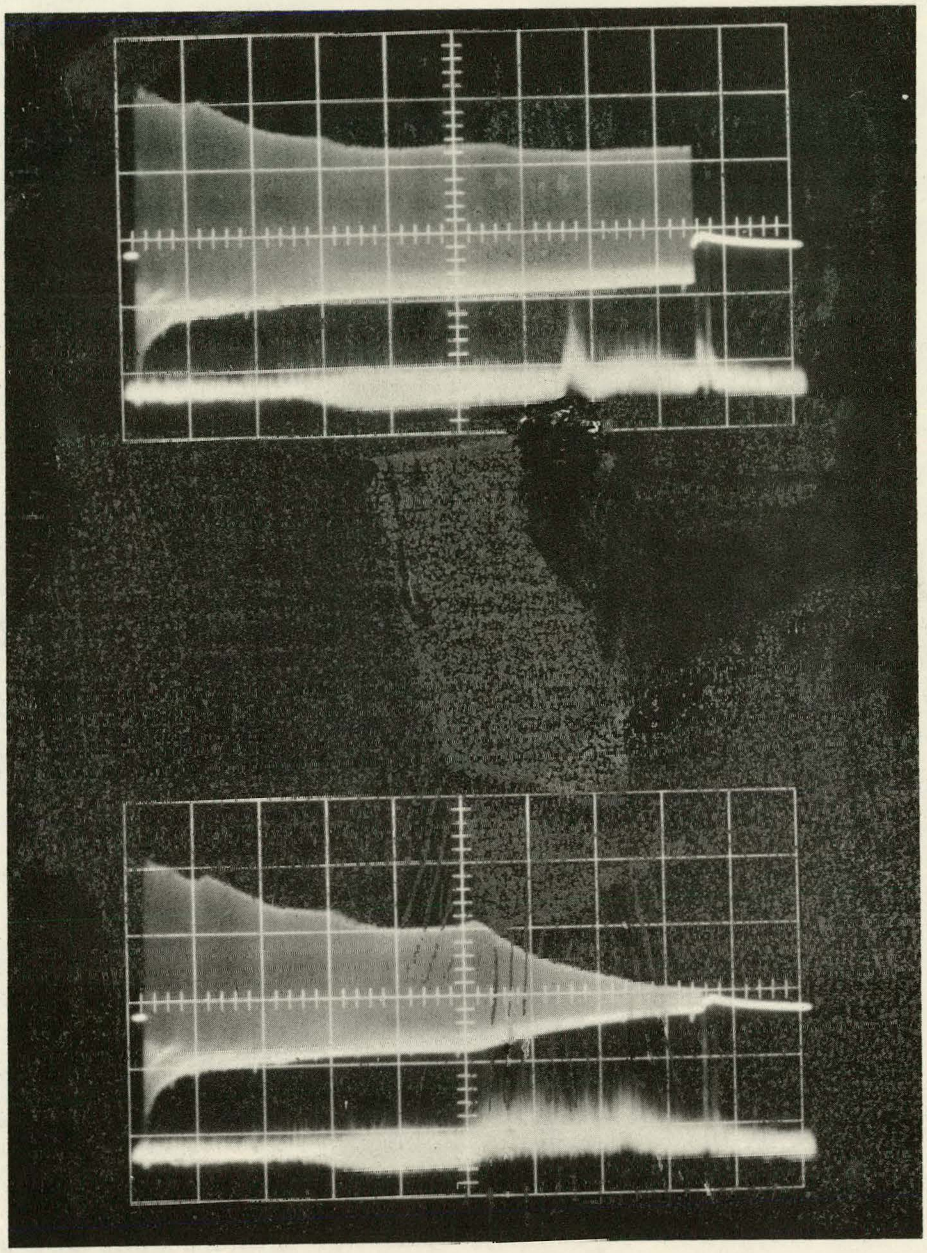

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**Fig. 4.** (a) Top Frame, Top Trace: Bevatron primary-beam intensity versus time as seen by the south sum induction electrode; $10^{10}$ protons per cm, vertical, 200 milliseconds per cm horizontal 100-micron filamentary target removed. Bottom Trace: Ungated scintillation-counter output.

(b) Bottom Frame, Top Trace: Bevatron primary-beam intensity reduction caused by the insertion of an array of 100-micron fibres. Bottom Trace: Nearly uniform counting rate produced by the filamentary target.

## Appendix

Consider the simplest case of treatment of phase oscillations wherein the energy difference $\Delta E$ between a particle at phase angle $\phi$ and that of a synchronous particle at energy $E_s$ at a phase angle $\phi_s$ is given by

$$\frac{\Delta E}{\sqrt{\frac{eVE_s}{\pi}}} = \sqrt{\phi \sin \phi_s + \cos \phi + \cos \phi_s - (\pi - \phi_s) \sin \phi_s}, \tag{1}$$

where eV represents the energy increment of a synchronous particle per turn. All other details, which have little bearing upon the discussion, have been neglected.

Now the right side of Eq. (1) is of the order of unity, so that we have

$$\Delta E \approx \sqrt{\frac{eVE_s}{\pi}} . \tag{2}$$

For a particle having an energy 6.25 Bev(lab) in an accelerator wherein the energy gain per turn corresponds to approximately 2 kev, $\Delta E$ becomes

$$\Delta E \approx 2 \text{ Mev}; \tag{3}$$

that is, the energy associated with phase oscillations is of the order of 2 Mev.

Now suppose, for simplicity again, that we consider only particles in synchronism with the radio-frequency drift-tube voltage. Then the energy that must be abstracted from the synchronous particle to cause it to become phase-unstable is of the order of 2 Mev. If we place an energy-loss target in the beam, particles lose energy at a rate of about 1 Mev per gram per $cm^2$.

Consider a nylon fibre as a target material. If the fibre is 10 microns in diameter, the equivalent thickness is

$$\rho t \approx (2)(10^{-3}) = 2 \times 10^{-3} \text{ g/cm}^2 .$$

A particle loses an average energy of the order of

$$\frac{\delta E}{\delta N} \approx (1 \text{ Mev/g/cm}^2)(2 \times 10^{-3} \text{ g/cm}^2) \approx 2 \text{ Kev/turn}. \tag{4}$$

Now, if in the worst case the particle always traverses the target on each revolution, and if there is no energy gain in transit through the drift tube, and further, if the energy losses are summed directly, the number of target traversals required to cause the particle to be removed from synchronism is at least

$$N = \frac{\Delta E}{\delta E} = \frac{(2 \times 10^6)}{(2 \times 10^3)} \approx 1000 \text{ traversals.} \tag{5}$$

Actually the number of traversals is greater, because (a) the radial precession of the betatron orbit moves the particle away from the fibre on successive transits, and (b) as long as the particle remains synchronous, it regains some energy every time it passes through the accelerating gap.

Consider first the precession of the radial betatron oscillations. The precession frequency $f_p$ for the simplest case may be written as

$$f_p = f_0 \left(1 - \sqrt{1-n}\right), \tag{6}$$

where $f_0$ is the rotational frequency of the particle in a magnetic field with a gradient of n = 0.6. Solving for the precession period, $T_p = \frac{1}{f_p}$ in (6), we find

$$T_p \approx 2\text{-}1/2 \text{ revolutions.} \tag{7}$$

Now the restoring force seen by the particle on each revolution through the drift tube is approximately $eV \sin \phi \approx 2/\text{kev}$. Therefore the particle has a few revolutions in which to regain energy before it traverses the target again.

One other consideration of importance relates to the root-mean-square scattering amplitude induced by the target. Let a be the amplitude of the radial oscillations induced by multiple Coulomb scattering through an angle $\langle \overline{\theta^2} \rangle^{1/2}$ in an accelerator of radius R with a magnetic field gradient of $n = \frac{\partial B}{B} / \frac{\partial R}{R}$. It may be shown that

$$a = R\sqrt{1-n} \left\langle \overline{\theta^2} \right\rangle^{1/2}, \tag{8}$$

wherein the rms scattering angle is expressed in terms of an equivalent radiation thickness t/tr and 1β as

$$\left\langle \overline{\theta^2} \right\rangle^{1/2} = \frac{15}{p\beta} \sqrt{\frac{t}{t_r}}\,. \tag{9}$$

For the Bevatron constants Eq. (8) reduces to

$$a = 1.13 \sqrt{\frac{t}{t_r}} \quad \text{(inches).} \tag{10}$$

Assuming a 10-micron nylon fibre ($t_r \approx 50\ g/cm^2$) with an equivalent thickness of $2 \times 10^{-3}\ g/cm^2$, we find the induced radial-oscillation amplitude

$$a = 1.13 \sqrt{\frac{2 \times 10^{-3}}{50}} \approx 6 \times 10^{-3} \text{ inch.} \tag{11}$$

Suppose further that the radial amplitude sum linearly for the thousand-odd traversals required to take the particle out of phase synchronism. Then the over-all amplitude of induced radial betatron oscillations is of the order of 6 inches.

It is clear that many approximations are involved in the greatly simplified arguments outlined above. However, it is clear even from the presentation that:

(a) It is possible to choose an "equivalent foil" made up of vertical filamentary fibres that will cause the primary beam of a synchrotron to fall out of synchronism in a controlled manner so as to produce a prolonged secondary beam.

(b) The atomic number and equivalent thickness of the foil material must be kept as low as possible so that no appreciable radial oscillation amplitudes will be induced. This latter point relates directly to the available radial width of magnetic field within which the particles remain focused.