BEVATRON OPERATIONAL EXPERIENCES

E. J. LOFGREN

Radiation Laboratory, University of California, Berkeley (Cal.)

Introduction

I shall report on a machine which is not in the class of most of those we have already heard about; it is obsolete in design and in a few years will not even be in the class of high energy accelerators. Now, however, it is one of a very few accelerators working in a field of extraordinary richness in nuclear physics. One of our most difficult problems is to decide, at a given moment, which of several important and interesting experiments to pursue. A consequence of this preoccupation with the physics program is that we have not studied the Bevatron as an accelerator—this may be a disappointment to those chiefly interested in the design of accelerators. We have also chosen to be rather slow in making major improvements, although there are many obvious possibilities, because we do not want to interrupt the research program.

1. History

In 1946 William M. Brobeck circulated in the Radiation Laboratory a note on a scheme for reaching Bev energies by making use of the recently enunciated principle of phase stability in a proton accelerator in which both the magnetic field and the accelerating frequency vary. The idea was formulated into a proposal to build a 10-Bev accelerator[1], which was subsequently revised to a plan to build an accelerator whose aperture would at first be very large, 4 feet by 14 feet, by could later be reduced by the addition or change of pole tips. With the large aperture, the energy would be 1.5 Bev, and with an aperture of 1 foot by 4 feet, it would be more than 6 Bev. This proposal was accepted by the Atomic Energy Commission in April 1948, and designing and site preparation started immediately. Before the magnet steel was ordered it had been decided that the largest possible aperture would be reduced to 4 feet by 10 feet.

It seemed rather probable, on the basis of theoretical studies, that the smaller aperture could be used, but the larger was chosen on the basis of no reasonable doubt at all. At that time, however, no synchrotron had ever run, although several were under construction, and no accelerator of any kind with straight sections had been completed. It seemed that a great deal of assurance could be given to the entire project, and it might be possible to start with a smaller aperture, if a test of the complete concept were made with an operating model. The decision was made in June 1948 to build a one-quarter-scale operating model. This model was put into operation [2,3] in April 1949, and was run for five months. It immediately reduced the limit of the absolutely certain aperture to 2 feet by 6 feet on the full-scale accelerator. No comprehensive study of beam dynamics was undertaken, although a comparison of a few aspects of theory and performance were made, giving confidence in the basic design principles. In addition, a lot of valuable operating and electronic-design experience was gained. The subsequent construction of the full-scale Bevatron proceeded more slowly because of the diversion of some effort to a high-intensity accelerator program. A re-evaluation of the model performance and the approaching completion of the Cosmotron resulted in a decision in December 1951 to omit the large aperture and go directly to the 1-by-4-foot size. The injector, a 10-Mev linear accelerator[4], was completed and placed in operation in June 1953. By January 1954 the Bevatron was nominally completed, including magnetic-field measurements, and ready for test operation. There were no targets, locks, windows, magnets, counting installation, shielding or any other experimental facilities; however, work on these items started immediately.

The first step in operation was to bring the injector into alignment with the inflector and both of them into alignment with the Bevatron. For this purpose the Bevatron magnet was excited with a 25-kW dc generator. The beam was located at both ends of the inflector by collector cups, which were also provided with fluorescent screens, and then by similar methods at three points around the azimuth of the magnet. We immediately proceeded to a repetition of this step with the magnet pulsed, and then turned on the accelerating power. An rf pulse of a few milliseconds was used, and the starting frequency, rf timing, and injection timing were varied in an empirical manner with the injected beam under observation on an inside collector. All this time there was a continuous battle against the numerous flaws which are inevitable in the initial trials of so complex an apparatus. An effort of sixteen hours a day would yield an average effective time of perhaps two to four hours. On February 15 the first pickup of beam by the rf was observed. The pulse was lengthened, and frequency-tracking controls were

brought into operation in the same manner, i.e., step by step--milliseconds, then tens and hundreds of milliseconds. When the beam reached an energy at which the protons penetrated the collector (100 Mev), scintillator-photo-multiplier probes were used. Scant attention was paid to the quantity of beam accelerated; the length of the acceleration period was the important thing. Finally, on April 1, 1954, a feeble pulse was obtained at a magnetic field corresponding to 6 Bev. The intensity was measured by counting the tracks in nuclear emulsion that had been inserted into the beam. The intensity was in the range of 10^4 to 10^6 protons per pulse.

During all this time there had been continuous trouble with the magnet power supply ignitrons. Faults, usually arc-throughs, occurred at a rate of one to ten or more an hour, depending on current, duty cycle, and other factors not under our control. On April 8 one of the generators developed a short circuit from a coil to the stator which resulted in a small fire and enough damage to require three months to repair. While the generator was being repaired, we installed a number of protective and monitoring devices and started a program of ignition improvement. This included the repair of several vacuum leaks in the tubes, better water-temperature regulation, and changes in the firing and grid circuits of the tubes. These changes did result in improved performance but progress was not fast, and to this day the ignitrons are a source of trouble.

When we were able to run again, we proceeded to build up the beam by a succession of improvements which, in fact, are still going on. The largest gains were made by :

1. Raising the average value of n over the width of the tank from 0.55 to 0.65.

2. Improving the output of the ion gun and the installation of a prebuncher ahead of the linear accelerator.

3. Removing various sources of noise modulation from the rf circuits.

4. Synchronizing the generators to stabilize the ripple pattern on the magnet voltage.

5. Regulating the magnet generator voltage to 0.03 %.

6. Reducing the jitter in the peaking strips which are used to time injection and rf, through use of ripple feedback techniques.

We did not undertake any period of study of the Bevatron as such, and improvement of performance was reduced to a secondary role as soon as the beam reached a usable magnitude, about 10^8 to 10^9 protons per pulse, in September 1954. The experimental program began immediately. As a result of this we still do not know as much about the machine as we would like, but the course of action was justified by the importance of the experimental program. The first effective tools of research proved to be nuclear emulsions, because of their sensitivity
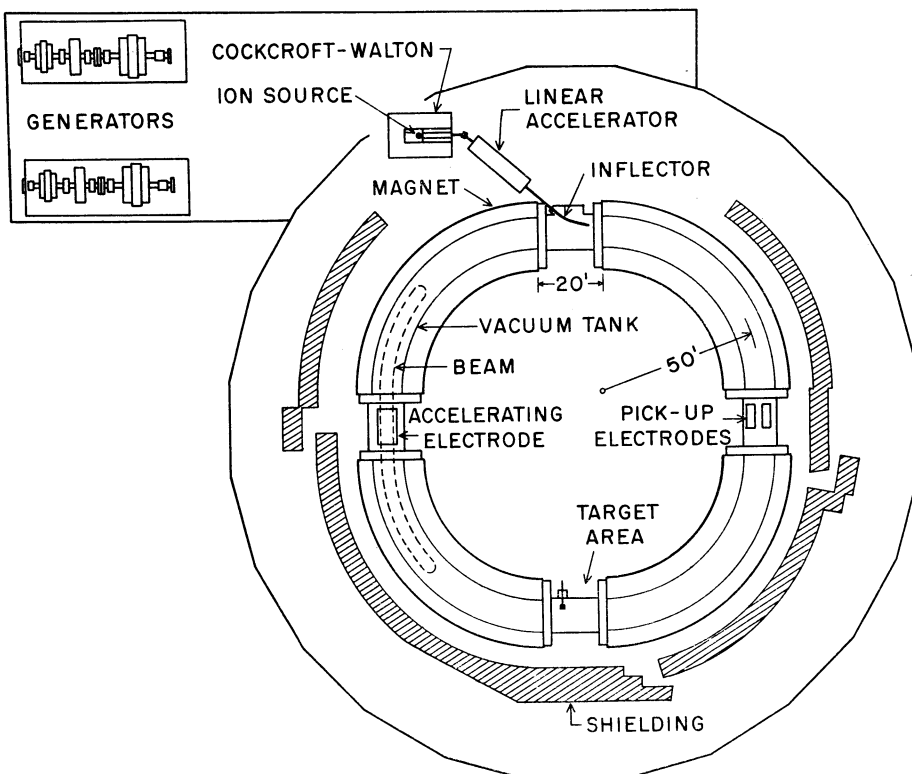

Fig. 1. Simplified plan diagram showing relationship of the major components.

and simplicity. They were soon followed by cloud chamber and counter experiments in increasing complexity.

In January 1956 a short circuit again occurred between a coil and the stator in one of the generators. It required 5 weeks to repair. There have been no other major difficulties.

2. Bevatron performance

The Bevatron is still undergoing a process of gradual improvement to increase both the magnitude of the beam and the reliability. The operating conditions for optimum adjustment at the present stage of development are summarized below.

Ion gun (480 Kev)

Total current	6-10 ma
Analyzed proton current	60%
Pulse length	1000 μsec
Beam diameter	1 cm.

Linear accelerator (9.8 Mev)

Current	200-300 μa
Pulse length	600 μsec
Beam diameter	1 cm.

Injected beam at inflector

|	
Current	150-250 μa
Acceptance time	300 μsec
Injected charge during acceptance time	$2.7\text{-}4.5 \cdot 10^{11}$ protons

Accelerated beam

Fraction of injected charge at time 4 msec after injection	20%-25%
at time 88 msec after injection (67 Mev)	~10%
at end of acceleration (6.2 Bev)	~8%

or
from 2 to $3.5 \cdot 10^{10}$ protons per pulse

Beam dimensions

At injection, horizontal	44 inches
vertical	9.5 inches
At 6.2 Bev, horizontal	4 inches
vertical	2 inches
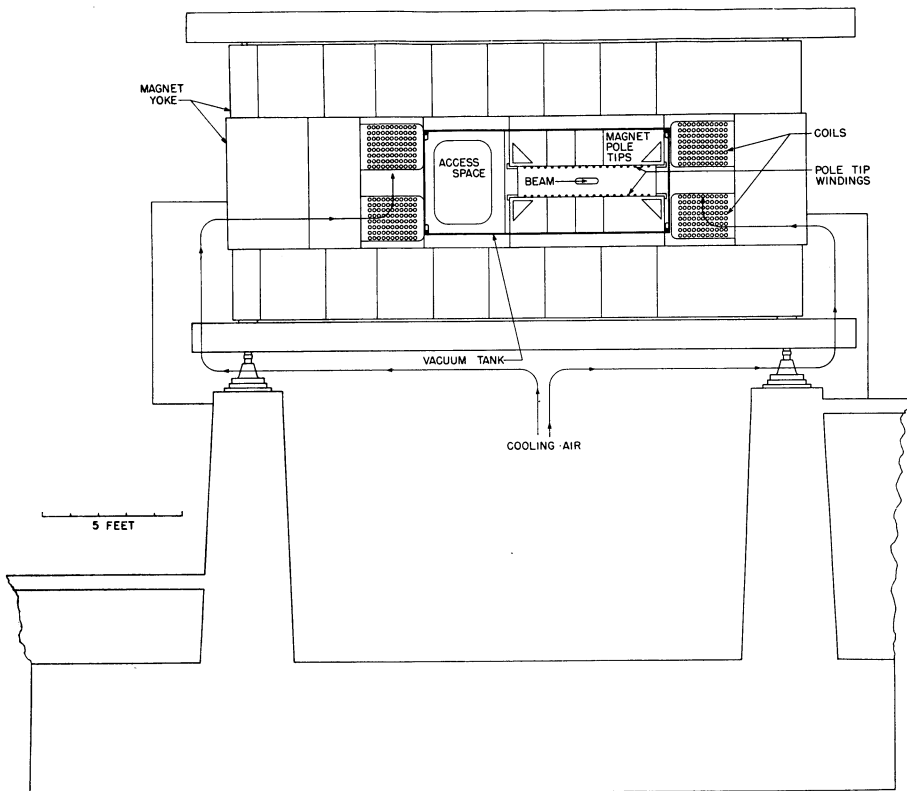
Fig. 2. Cross section through the magnet. The pole tips, which are inside the vacuum tank, are used as support members to sustain the atmospheric and magnetic forces.
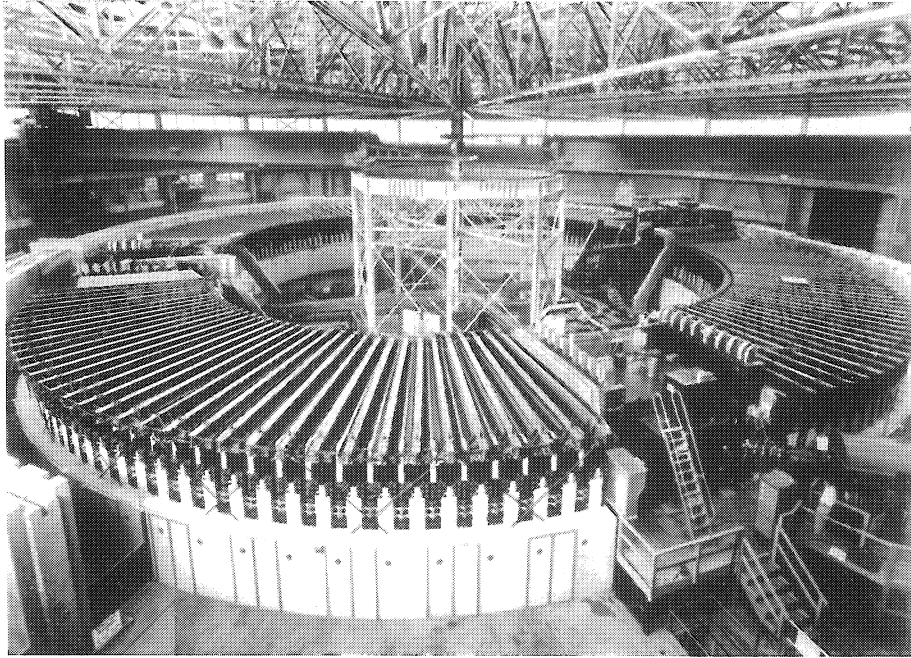
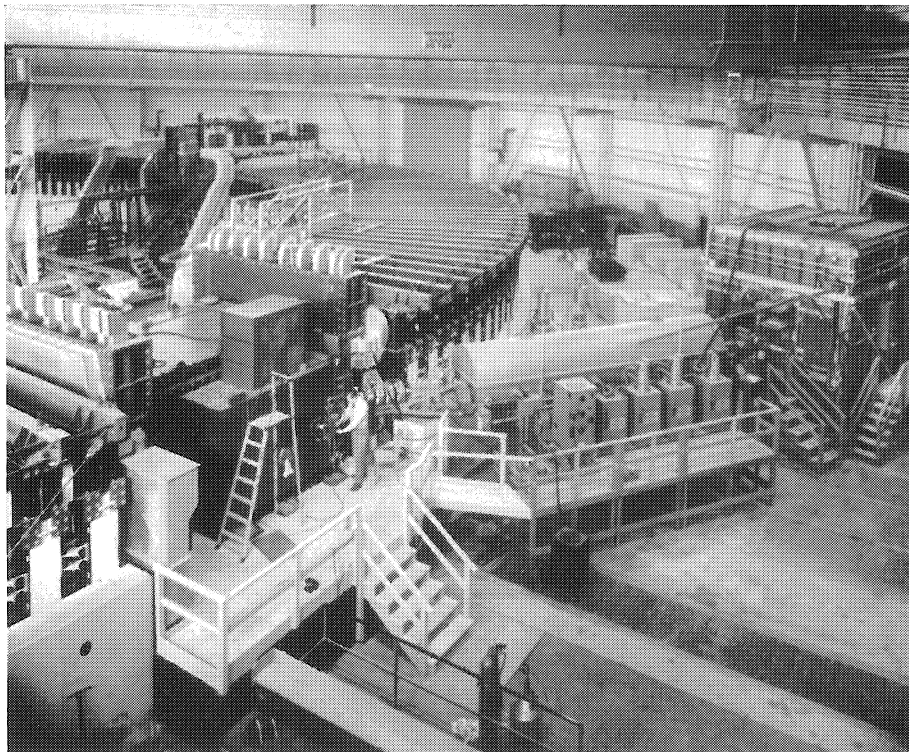Fig. 3. Panorama of the Bevatron from the injector side.

Fig. 4. The Cockcroft-Walton injector, at right, and the linear accelerator, center.

Vacuum

Pressure (measured at straight
  section with untrapped ion
  gage) 10^{-6} mm.

3. Targets and related facilities

The Bevatron magnet has a totally enclosed return yoke; therefore access to the beam—except for limited special purposes—is possible only at the straight sections. One straight section, which was entirely free of other equipment and is favorably situated in the building, was selected as the main target area, and its development proceeded first. The straight sections are 20 feet long, and in order to provide ample room for vacuum pumps, inflector, and accelerating electrode, the straight-section tanks were made very large in cross-section, about 7 feet high by 9 feet wide. For the target area, this size proved to be a disadvantage, because it is often desirable to get magnets or detecting equipment close to the target, consequently re-entrant face plates were put on the tank, both on the side toward the center and on the side away from the center (see fig. 5). These plates carry thin windows, generally aluminum 0.020 inch thick. There are also two re-entrant structures mounted on the top plate. One is a "well" open to the atmosphere and having a thin window, the other is an air lock that can be opened to the vacuum tank. Three target-insertion mechanisms, "plunging probes," are located on the inside. These mechanisms are operated by compressed air and work through locks, so that targets can be changed easily. These facilities are used to insert photographic emulsions or radiochemical targets into the beam. They are also used to generate secondary particles when one wishes to observe at approximately 90° to the primary beam. Particles emitted in the forward direction from these targets are only of very limited use because they go through the magnet yoke. Therefore, for high-momentum π^- mesons, neutrons, and scattered high-energy protons, six targets have been provided in the magnet at azimuthal positions 2.5° to 20° from the straight section (fig. 6). An additional semithin window (0.062-inch stainless steel) is built into the corner of the curved tank for use with these targets. The shielding wall opposite the main target area has a slot 50 feet long and 2 feet high. This slot is filled with small heavy concrete blocks which may be arranged to provide channels for the various beams. The arrangement is fairly flexible, but has the severe limitation that all the setups must be placed in the same area, where they seriously interfere with one another. This problem is temporarily solved by scheduling relatively long sequences of one kind of run, so that change-over time is minimized. The long-term solution, however, is to develop facilities at other areas. This work is going along on the line of establishing specialized and less flexible facilities at the other straight sections to relieve the load at the main target area, which will retain its flexible character.

One such special facility has been installed. This consists of a hole in one of the leg yokes of the magnet, and a target located so that forward-emitted K–particles of 430 Mev/c momentum are deflected 90° by the Bevatron magnetic field and emerge through the hole. It is located
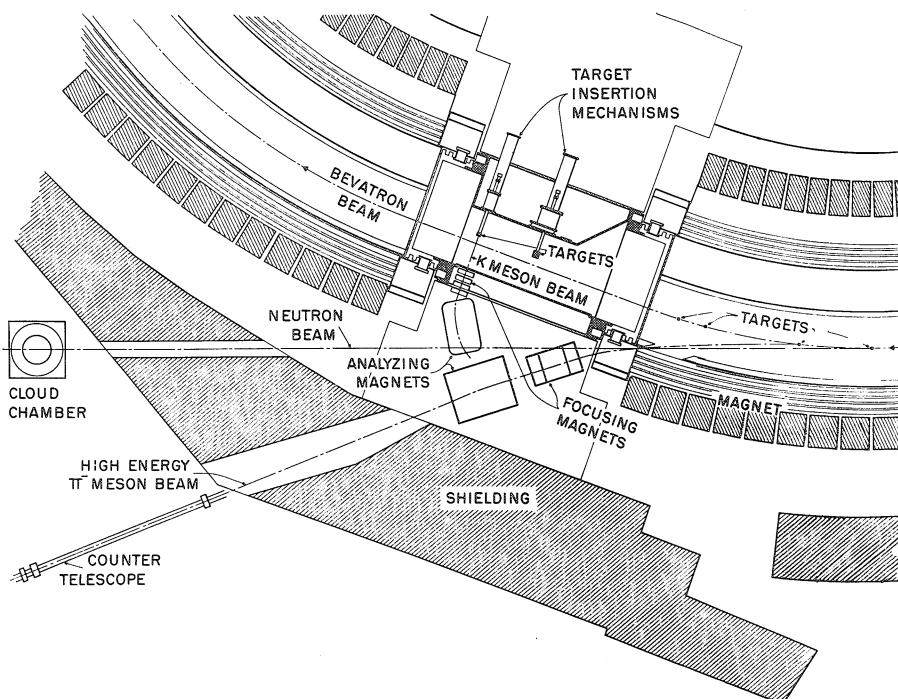

Fig. 5. Diagram of target area.

well away from the main target area so that it does not interfere. Another special facility located at the straight section containing the accelerating electrode will soon be installed to provide high-energy π⁻ mesons and neutrons.

Some of the experiments as, for example, the antiproton detection by time of flight, require a lot of space. In that experiment the last quarter of the 80-foot path extended outside the building. We are therefore adding an annular sector about 65 feet wide to the building opposite the main target area. This building will be equipped with power and water distribution, a large crane, and a heavy floor, for the largest research equipment.

A room, about 30 feet square, located next to the control room has been equipped as the main counting area. There are 37 coax cables for fast pulses connecting it to the main target area. Permanent racks lining the walls of this room provide terminations for the cables, as well as regulated power supplies and some of the counting circuitry. Some of the latter, especially the coincidence units, fast amplifiers, and prescalers, are mounted in movable racks, which are connected to the permanent installation as necessary. All of the counting equipment is fed from shielded power transformers, and a grounding system separate from the building and accelerator is provided to minimize electrical interference.

4. Auxiliary equipment

The auxiliary equipment used in setting up an experiment is extremely important and is needed on a scale commensurate with the accelerator. A tabulation of the chief items of equipment we have used (or soon will have) may be of interest. Further substantial additions to the equipment in each of the three categories will have to be made in the next year.

DC Power supplies for magnets

Three motor generators, each 180 volt, 360 kW,* 0.1 % regulation.

One motor generator, 140 volt, 41 kW, 0.1 % regulation.

Eight motor generators, each 125 volt, 20 kW, 0.1 % regulation.

Two rectifiers, each 120 volt, 24 kW.

One rectifier, 20 volt, 24 kW.

One motor generator, 415 volt, 1110 kW, 0.1 % regulation.

Six rectifiers, each 70 volt, 28 kW, 0.5 % regulation.

Two motor generators, each 180 volt, 150 kW, 0.5 % regulation.
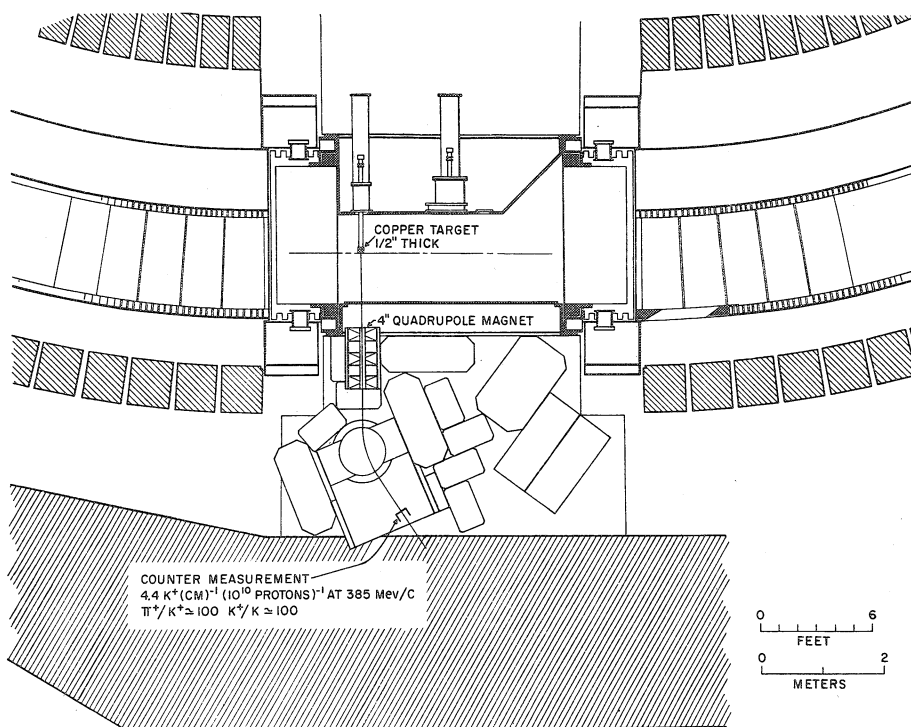

Fig. 8.   K meson spectrometer.

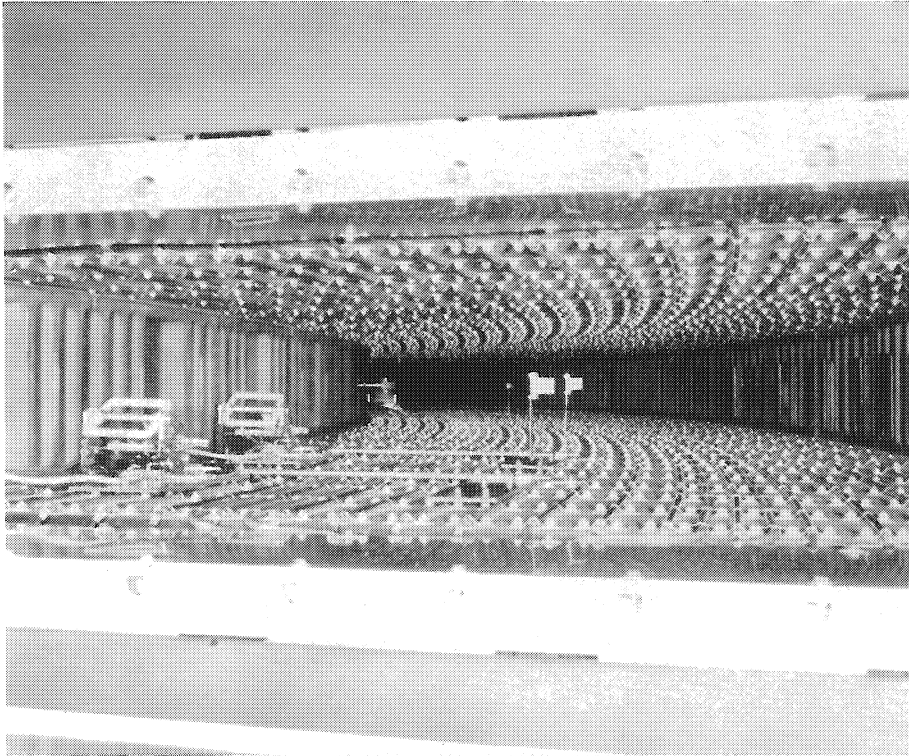* Under pulsed conditions the rating may be increased to 800 kw.

Fig. 6. View into the aperture of the magnet showing targets (center) which are flipped up by currents through rotating coil (left).
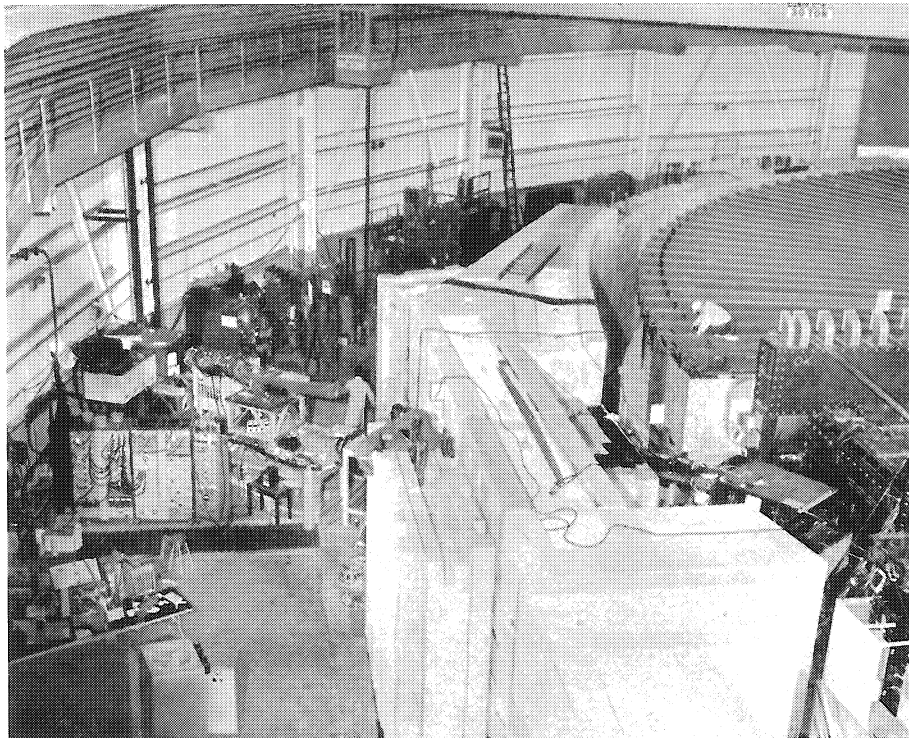

Fig. 7. Photograph of target area, shielding wall in the center, Bevatron to the right.

Analyzing magnets

Two magnets with rectangular poles, 12 inches wide, 60 inches long, maximum field 21,500 gauss, with 4-inch gap.

One magnet with trapezoidal pole, 20 inches wide and 24 inches long, maximum field 14,000 gauss, with 3.5-inch gap.

Two magnets with rectangular pole, 12 inches wide by 30 inches long, maximum field 12,000 gauss, with 4-inch gap.

One magnet with circular pole, 22 inches diameter, maximum field 12,000 gauss, with 7-inch gap.

One magnet with circular pole, 40 inches diameter, maximum field 20,000 gauss, with 8-inch gap.

Focusing magnets

Four sets of strong-focusing quadrupoles of 4-inch aperture. Each set is a triplet, the center element is 16 inches long, and the end elements are 8 inches long. The maximum field gradient is 4000 gauss/inch.

Two sets of quadrupoles, 8 inches in diameter. Each set is a triplet, the center element is 32 inches long, and the ends are 16 inches. The maximum field gradient is 14000 gauss/inch.

5. Secondary-particle flux

There are many variations in the arrangements of the target-area facilities and the auxiliary equipment to produce a usable beam. A few examples are given.

K meson at 90°

The geometrical arrangement of this beam is shown in fig. 8. The target is usually copper one-half inch thick, although it may be easily changed by the use of the vacuum lock. The particles emitted at 90° pass through an aluminum window 0.020 thick, then through a set of 4-inch-aperture focusing magnets and an analyzing magnet of the same aperture. The momentum selection may be set in the range of 200 to 400 Mev/c for either positive or negative particles. The target-to-focus distance is $13\frac{1}{2}$ feet. When the spectrometer is set for a momentum of 385 Mev/c there are 4.4 K^+ particles per centimeter for 10^{10} protons on the target. The π^+/K^+ ratio is about 100. If the field of the analyzing magnet is reversed to select negative particles, the yield is about 100 times less.

High-energy neutron beam

A high-energy neutron beam is produced by removing the interfering equipment on the outer platform so that there is a clear line of sight through the neutron-beam colli-
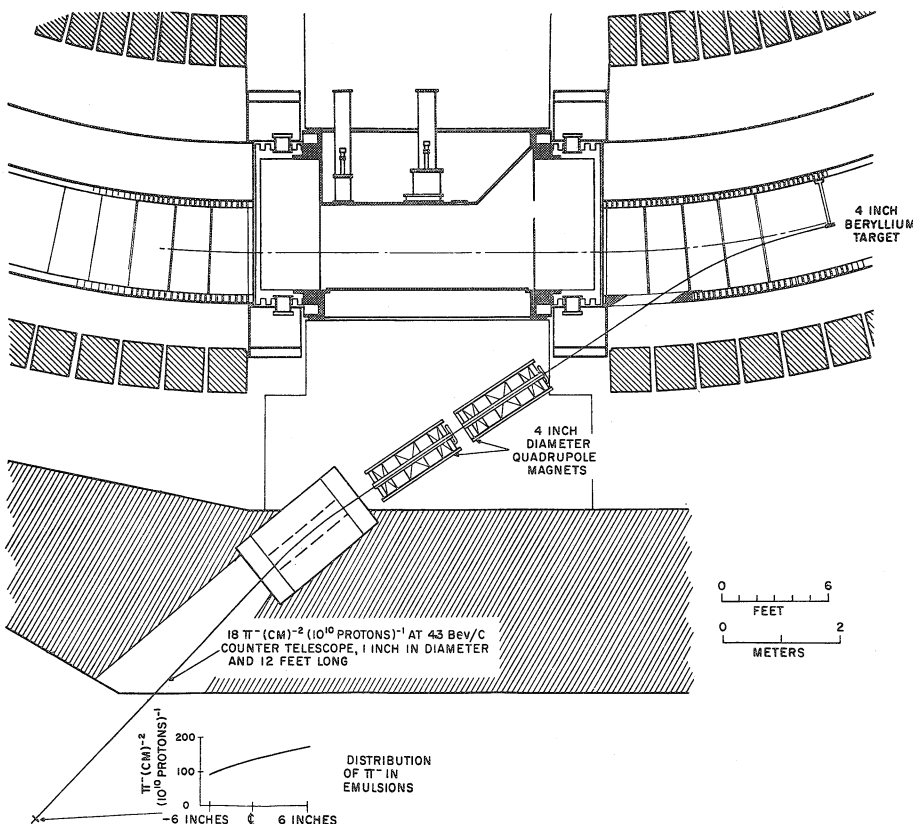

Fig. 9. π^- meson spectrometer.

mator to a target located in the Bevatron magnet 20°
from the straight section (see fig. 5). An analyzing magnet
is placed outside the shielding wall at the collimator
opening to sweep charged particles away. The distance
from the target is 60 feet, and the estimated flux is 2,000
neutrons per 10^{10} protons on the target.

π⁻ meson beam

The best arrangement for π⁻ mesons in the range of
4 to 5 Bev/c is shown in fig. 9. It requires two 4-inch-
diameter quadrupole magnets inside the shielding wall
aligned with the target at 13°, and an analyzer magnet
located in the wall. Outside the shielding wall, 60 feet
from the target, the flux is about 200 π⁻ / cm² per 10^{10} pro-
tons on the target.

Antiproton beam

This arrangement for the detection of antiprotons is new
work, now being carried out by Oreste Piccioni, Bruce
Cork, William A. Wenzel, and Glen R. Lambertson.

A set of four focusing and two analyzing magnets, ar-
ranged as shown in fig. 10, defines a beam of negative
particles emitted from the target which is located in the
Bevatron magnet 5° from a straight section. The system
of magnetic lenses, L_1, L_2, L_3, L_4, is arranged in such a
way that L_1 makes an image of the target at L_2, while L_2
makes an image of L_1 at L_3, etc. Such a system of lenses
admits particles within a large momentum band. The
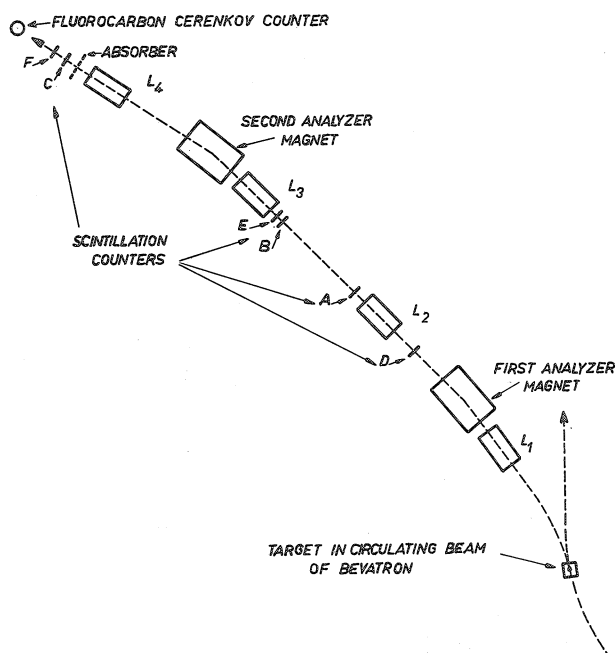momentum interval is determined only by the first analyzing

magnet. In the first trial of the arrangement, a momentum
of 1.2 Bev/c was selected, and the band width was ± 5%.

Sixfold coincidences between the Counters A, B, C,
D, E, F were obtained with cable lengths adjusted to detect,
in turn, particles of different velocities and, therefore,
different masses. The Čerenkov counter serves as a
guard counter, rejecting all particles whose velocity is
greater than β = 0.85 c. The counting rates exhibited
a definite peak, as the mass selection was varied around that
of the proton. When the selected mass is 20% below that
of the proton, the counting rate is reduced by 80%. When
the selected mass is 35% above that of the proton, the
counting rate is reduced by 90%.

At 3×10^9 protons per pulse on the target and 10 pulses
per minute, there is about one antiproton per minute.
The rate is limited by the counting system, the Bevatron
itself is capable of an order of magnitude greater beam.

6. Time structure of the Bevatron beam

A series of interesting observations of the temporal
structure of the burst of secondary particles from the Beva-
tron target under various conditions of operation have
been made by Harry G. Heard. Some slides will be shown
which illustrate a portion of that work.

In further experiments the ripple in the magnetic field
has been reduced by correction currents in pole face
windings, and the beam structure has disappeared.

7. Research programing

Programing the research on the Bevatron presents some
difficult problems because the demand for use of the
machine far exceeds the available operating time (16 hours
a day, 7 days a week). It is of course a desirable kind
of problem to have, because it demonstrates the usefulness
of the accelerator.

The scope of the problem may be indicated by listing
the chief users of the Bevatron. There are eight groups
in the Radiation Laboratory, varying in size from 6 to
20 people, whose chief research interest and activity center
around the Bevatron. These numbers include graduate
students but do not include technicians (except in a few
special cases); scanners, for example, are not included.
One of these groups specializes in cloud-chamber work,
two in emulsion work, and one in radiochemical investi-
gations, and the other four use various instruments includ-
ing bubble chambers, counters, and emulsions. In addi-
tion there are a number of smaller projects by groups or
individuals whose main interest lies elsewhere. We have
also had participants in the program from 40 or 50 different
laboratories. Most of these visitors have used emulsion
techniques, and the magnitude of the effort has varied
from a single simple exposure to continuing efforts requiring
many days of running time.

It is not possible for the individual groups to be self-
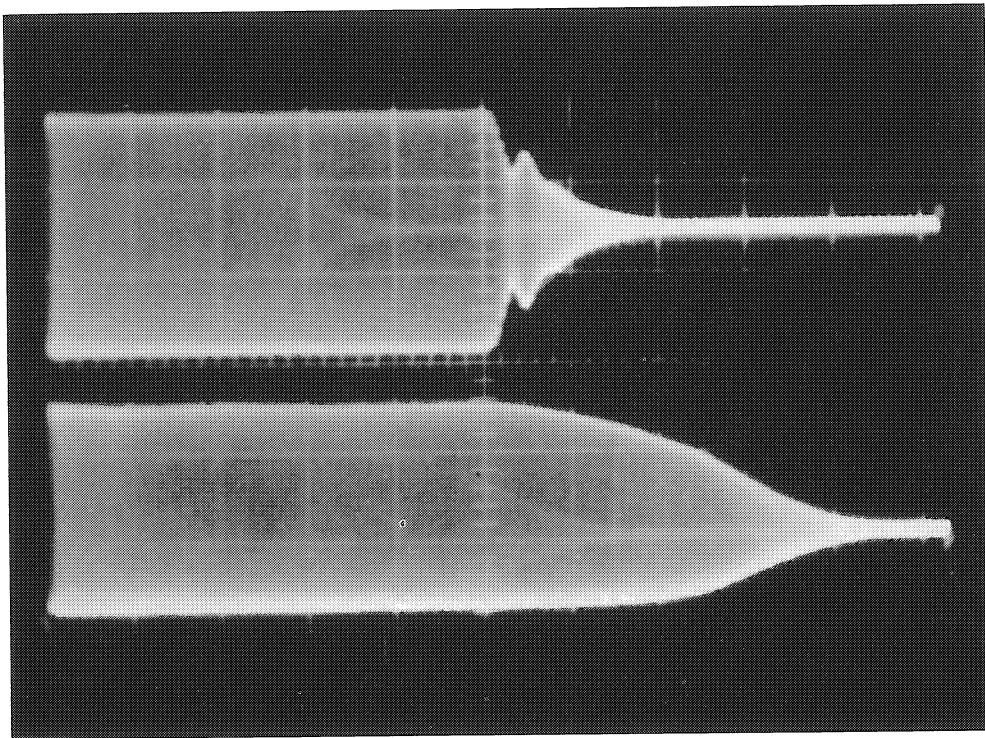sufficient in all their equipment, nor is it generally possible

Fig. 10. p̄ spectrometer.

Fig. 11. Top trace : accelerating voltage. Bottom trace: pickup electrode. Sweep speed : 200 μs/cm. The rf is turned off abruptly, and after 800 μs the rf structure of the circulating beam has disappeared so that the pickup signal vanishes.
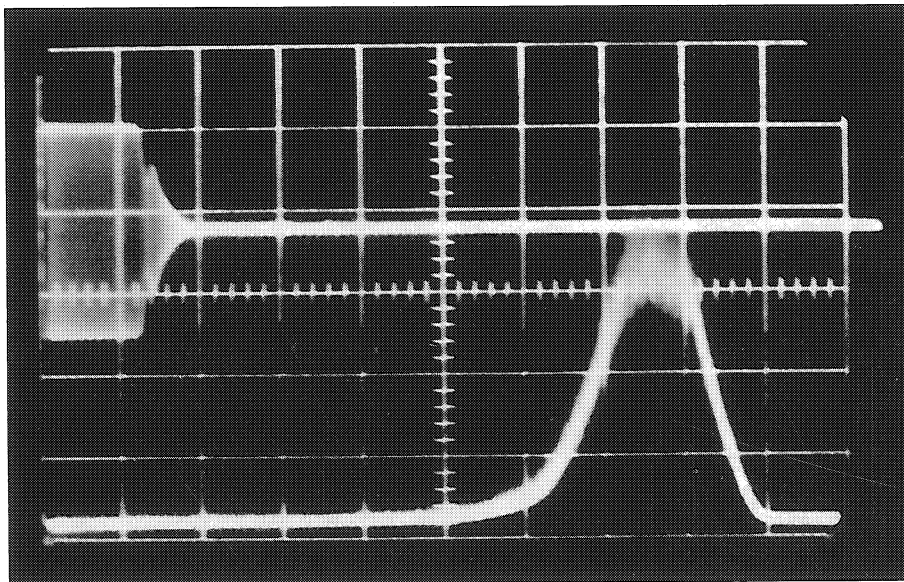

Fig. 12. Top trace : accelerating voltage. Bottom trace : integrated output from a counter telescope registering the pions from a Bevatron target. Sweep speed : 500 μs/cm. The time for the beam to spiral in is about 2 ms., and the length of the beam pulse is about 1 ms.
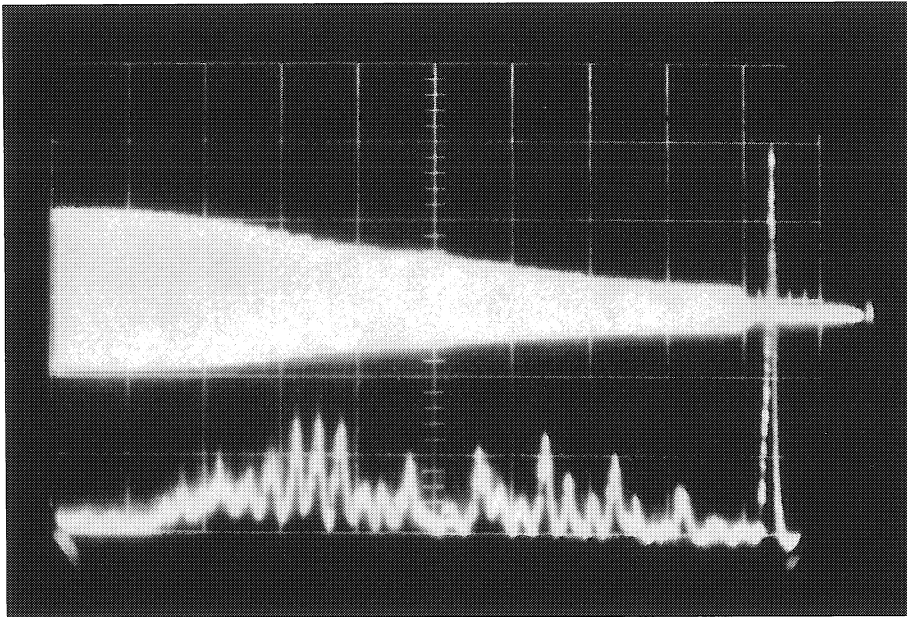
Fig. 13. Top trace : pick-up electrode signal. Bottom trace : counter telescope. Sweep speed : 10 ms/cm. The rf voltage is reduced over a period of 80 ms. The beam structure is due to synchrotron oscillations, 1380 cycles, and magnet ripple, 180 cycles.
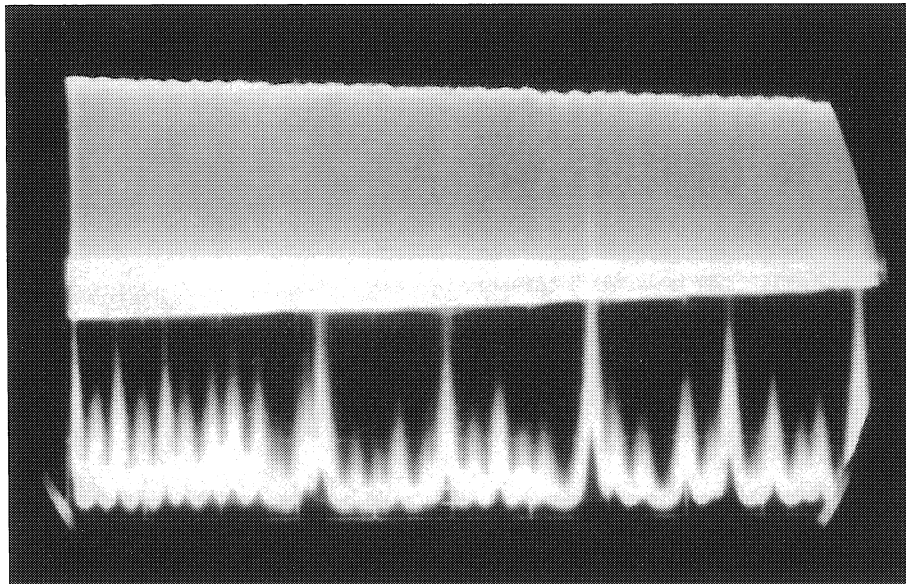

Fig. 14. The same conditions as fig. 13 except the sweep speed is increased to 2 ms/cm to more clearly resolve the small peaks due to synchrotron oscillations and the larger peaks caused by magnet ripple.
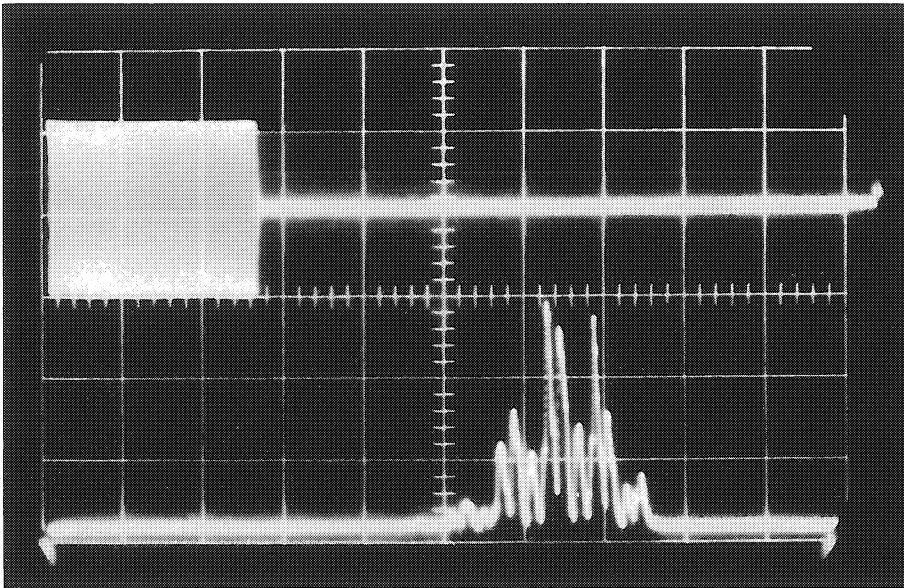
Fig. 15. Top trace : accelerating voltage. Bottom trace : counter telescope output. Sweep speed : 10 ms/cm. The rate of rise of the magnetic field has been reduced to about 1 amp/ms. The only structure remaining under these conditions is caused by magnet ripple.
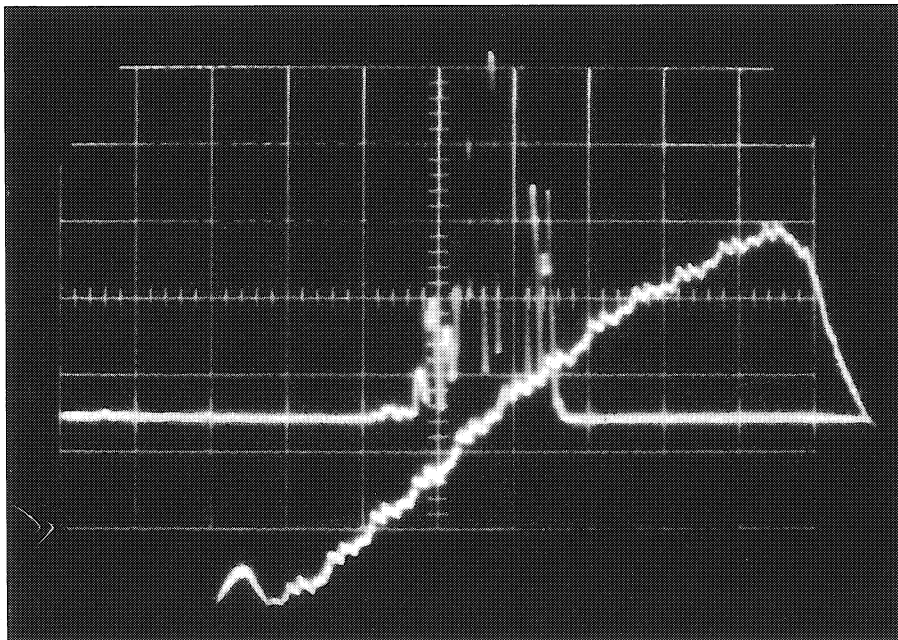

Fig. 16. Top trace : counter telescope output. Bottom trace : magnet current. Sweep speed : 10 ms/cm. The amplitude of the magnet ripple is about 2 amp. The ripple structure may be compared with the peaks in the counter output.

Fig. 17. The same as fig. 16 but at higher resolution, magnet ripple at 10 amp/cm. Sweep speed : 2 ms/cm. The coincidence between ripple and counter peaks is more easily seen.

to assign the machine exclusively to any one group for an extended period. There just is not enough equipment or running time to go around. It is clear that a high degree of cooperative effort and sharing is required. I will try to give an idea how programing works out under these conditions.

Most of the major auxiliary equipment, such as analyzing and focusing magnets, targets, and counting circuits and cables, belongs to the Bevatron and is for common use as needed by all the groups. The particle detectors, such as cloud chambers, counters, etc., generally belong to the group or individual using them, but even here there is a good deal of interchange. The various beam arrangements, such as those discussed in previous sections, are of course freely available to all the groups. Multiple running is done in nearly all cases. This may be accomplished in several different ways. In some cases a given beam may pass through a set of counters for one experimental group, then pass into another separate detecting instrument for another group. More commonly multiple operation is achieved by setting up equipment to define two different beams from the same target. Multiple operation may also be achieved by division of the pulses between two or more targets. This is done with an automatic pulse-sequence selector which can activate the targets in any selected sequence and vary the beam intensity, energy, and pulse length for each target. This method is especially useful with cloud or bubble chambers, which cannot operate at a repetition rate as high as that of the Bevatron. In still other cases it is possible to place two detectors side by side in the same beam. By one or more of these devices we nearly always have at least two experiments going and occasionally as many as five or six. There are, of course limits to multiple running. In the first place it is usually necessary that one experiment be "controlling" and the others secondary, otherwise confusion would result. It is also necessary to place a limit on complexity, otherwise

it is impossible to keep everything running at the same time, and everyone loses.

The approximate operating schedule is made up two months in advance. Written requests are submitted, briefly stating the physics of the experiment and the major equipment needed, and estimating the running time. When several requests come from the same group the experimenters are asked to indicate the relative importance of each one, and the less important ones are temporarily put aside. The important requests are then grouped according to runs that can be carried on simultaneously. These groups of run requests must next be placed in sequential order. Here the guiding principle is to arrange similar kinds of runs consecutive so as to avoid spending an excessive amount of time changing setups. As many as possible of the less important runs are then fitted in on the basis of not interfering with the important ones. This proposed schedule is then submitted for discussion at an informal meeting of the group leaders. A few changes are usually made and the schedule is then agreed to. This schedule is only approximate, however, and at the end of each week a meeting is held to discuss the details of the following week's runs. Here the adjustments are made to the schedule if there have been severe operating difficulties with the Bevatron or if there has been an unexpected turn in the progress of the experiment. This description of the research programing is of course somewhat idealized in an effort to state it simply and in general terms. Our programing is also influenced by a common desire to concentrate the necessary time and effort to do "big" experiments and to resist the natural tendency to divide the time into ever smaller fragments so as to make it go around, which would of course make some important experiments impossible.

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

LIST OF REFERENCES

1. Brobeck, W. M. Design study for a ten-Bev magnetic accelerator. Rev. sci. Instrum., *19*, p. 545-51, 1948.
2. Sewell, D. C., Brobeck, W. M., Lawrence, E. O. and Lofgren, E. J. Design of the Bevatron quarter scale operating model. Phys. Rev., *78*, p. 85, 1950.
3. Lofgren, E. J. The proton synchrotron. Science, *111*, p. 295-300, 1950.
4. Cork, B. Proton linear-accelerator injector for the Bevatron. Rev. sci. Instrum., *26*, p. 210-9, 1955.