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Author

Lofgren, Edward J

Publication Date

1956-04-01

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UNIVERSITY OF CALIFORNIA

Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

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Edward J. Lofgren

April 5, 1956

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Radiation Laboratory
University of California
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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, but 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 smallest aperture could be used, but the largest 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 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

¹William M. Brobeck, "Design Study for a Ten-Bev Magnetic Accelerator," *Review of Scientific Instruments* 19, No. 12, 545 (1948).

²Duane C. Sewell, William M. Brobeck, Ernest O. Lawrence, Edward J. Lofgren, "Design of the Bevatron Quarter-Scale Operating Model," *Phys. Rev.* 78, No. 1, 85 (1950).

³Edward J. Lofgren, "The Proton Synchrotron," *Science* 111, 295 (1950).

⁴Bruce Cork, "Proton Linear-Accelerator Injector for the Bevatron," *Review of Scientific Instruments* 26, No. 2, 210-219 (1955).

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-photomultiplier 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. We installed a number of protective and monitoring devices and started a program of ignitron improvement, while the generator was being repaired. 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 "came on" 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, 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 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.

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 μ sec
Beam diameter	1 cm

Linear accelerator (9.8 Mev)

Current	200 - 300 μ a
Pulse length	600 μ sec
Beam diameter	1 cm

Injected beam at inflector

Current	150 - 250 μ a
Acceptance time	300 μ sec
Injected charge during acceptance time	$2.7 - 4.5 \cdot 10^{11}$ 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
vertical

44 inches
9.5 inches

At 6.2 Bev,

horizontal
vertical

4 inches
2 inches

Vacuum

Pressure (measured at
straight section)

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. 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. (See the K-meson facility in the figure.) Particles emitted in the forward direction from these targets are only of very limited use because they go through the magnet yoke. 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. 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 accompanying illustrations show the target area in some of its typical arrangements. 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 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 that of 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

These components are involved in supplying power are involved in supplying power:

Already in service:

3 motor generators	180 volt	360 kw*	0.1% regulation
1 " "	140 volt	41 kw	0.1% "
8 " "	125 volt	20 kw	0.1% "
2 rectifiers	120 volt	24 kw	-----
1 " "	20 volt	24 kw	-----

(*under pulsed conditions the rating may be increased to 800 kw)

To be in service this year:

1 motor generator	415 volt	1110 kw	0.4% regulation
6 rectifiers	70 volt	28 kw	0.5% "
2 motor generators	180 volt	150 kw	0.5% "

Analyzing Magnets

- 2 Rectangular pole 12 inches wide, 60 inches long, maximum field 21,500 gauss, with 4-inch gap.
- 1 Trapezoidal pole, 20 inches wide and 24 inches long, maximum field 14,000 gauss, with 3.5-inch gap.
- 2 Rectangular pole, 12 inches wide by 30 inches long, maximum field 12,000 gauss, with 4-inch gap.
- 1 Circular pole, 22 inches diameter, maximum field 12,000 gauss with 7-inch gap.
- 1 Circular pole, 40 inches diameter, maximum field 20,000 gauss at 8 inches gap.

Focusing Magnets

- 4 sets of strong-focusing quadrupoles of 4-inch aperture. Each set is a triplet, the center element 16 inches long, and the end elements 8 inches long. The maximum field gradient is 4000 gauss/inch.
- 2 sets of quadrupoles, 8 inches in diameter. Each a triplet, the center element 32 inches long, and the ends 16 inches. The maximum gradient is 1400 gauss/inch.

5. Secondary-Particle Flux

There are many variations in the arrangements of the target-area facilities and the auxiliary equipment to produce usable beam, of which those diagramed are typical. It might be of interest to give the flux of particles in some of the more useful setups.

K-Meson "Beam"

The geometrical arrangement of this beam is shown in the diagram. The target is usually copper, 0.5 inch thick, the focusing magnets have an aperture of 4 inches, and the target-to-focus distance is 13.5 feet. The momentum may be set in the range of 200 to 400 Mev/c for particles of either sign. The K-meson flux at the center of the distribution is 3 particles/cm² for 10¹⁰ protons on the target. A counter array 4 inches wide by 0.5 inch high, sensitive to K mesons only, registers a total of 15 particles for 10¹⁰ protons on the target. The ratio of K⁺ mesons to π⁺ mesons is between 1% and 2%.

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 collimator (see diagram) to a target located in the Bevatron magnet 20° from the straight section. 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 10¹⁰ protons on the target.

π⁻-Meson Beam

The best arrangement for π⁻ mesons in the range of 4 to 5 Bev/c is not shown. It requires two 4-inch-diameter quadrupole magnets on the platform, aligned with the target at 13°, and an analyzer magnet located in the shielding wall. Outside the shielding wall, 60 feet from the target, the flux is 200 π⁻/cm² per 10¹⁰ protons on the target.

Antiproton "Beam"

The arrangement for momentum-velocity identification of antiprotons is shown in the diagram. The most abundant particle is, of course, the π^- meson. When the magnets are set for a momentum of 1.2 Bev/c the π^- flux is 2,200 π^- in a 2.5-inch-diameter area for 10^{10} protons on the target. The ratio of antiprotons to π^- mesons is 1/44,000.

6. 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. We certainly cannot fix on a best solution to the problem, because the situation is rather fluid, changing as we learn how to use the machine and as the physics requirements change.

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 investigations, and the other four use various instruments including bubble chambers, counters, and emulsions. In addition 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.

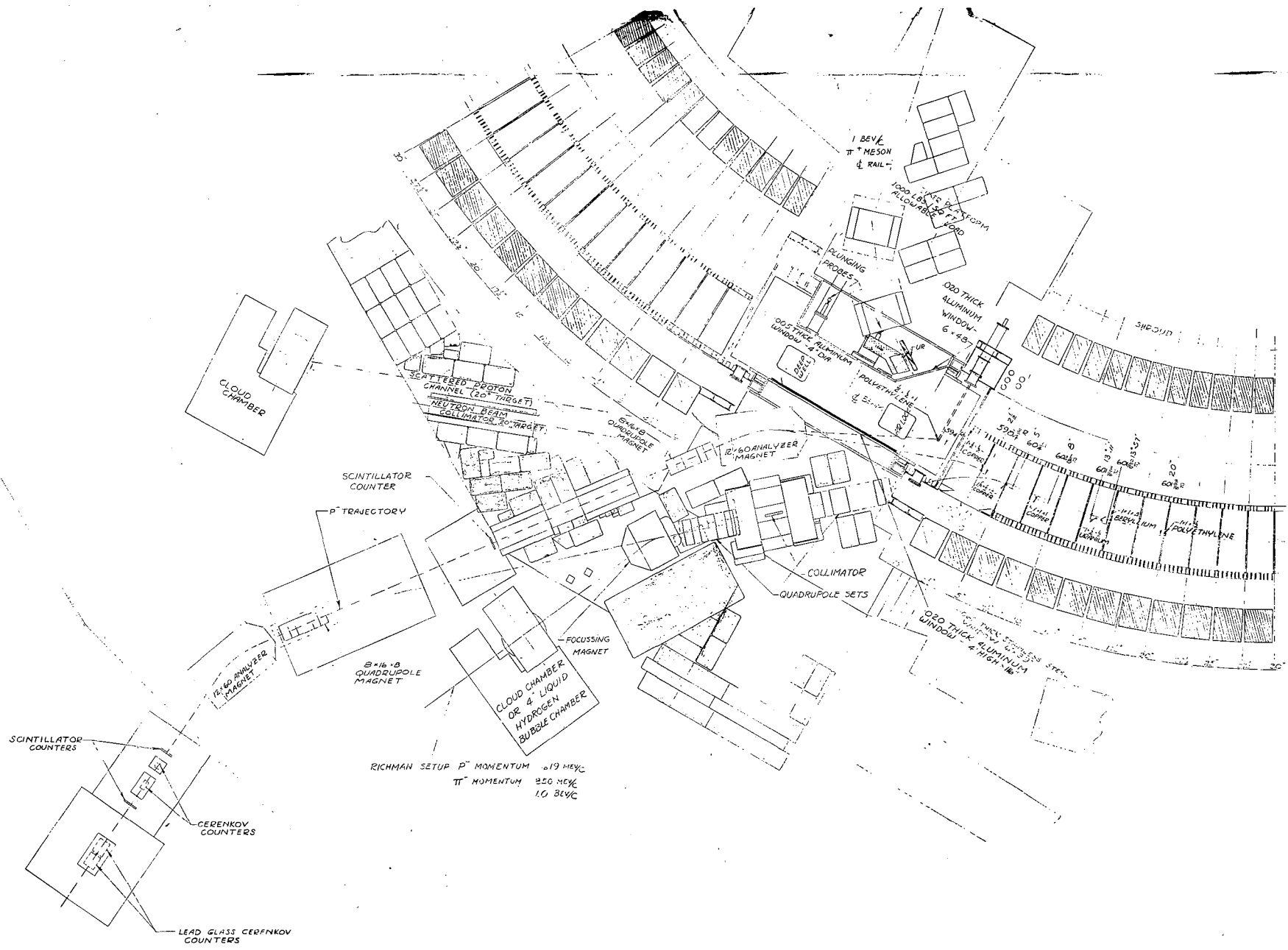
It is not possible for the individual groups to be self-sufficient in all their equipment, nor is it generally possible to assign the machine exclusively to any one groups for an extended period. There just is not enough equipment or running time to go around. It is clear that a high degree of cooperative effort and sharing is required. It 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 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 other 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 consecutively 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.



RICHMAN SETUP P^+ MOMENTUM 0.19 MEV/C
 π^+ MOMENTUM 250 MEV/C
 1.0 BEV/C

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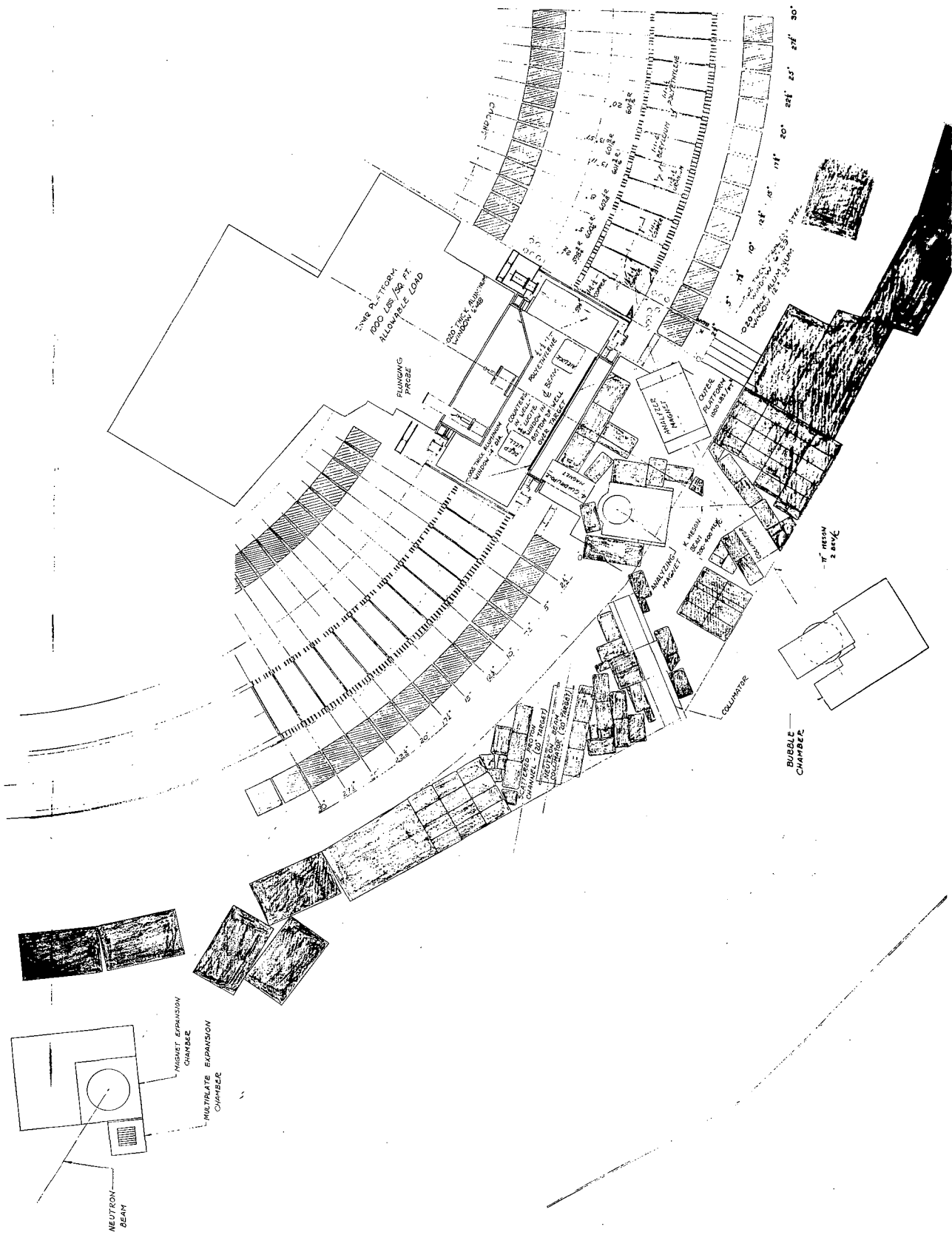


Fig. 2