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A sprawling group of buildings on an impressive campus site in the Berkeley hills provides the home of the Radiation Laboratory of the University of California. A succession of large accelerators has been built there, the latest of which is the Bevatron. It is the largest and highest-energy accelerator in operation at the present time. It was built and is operated under contract with the United States Atomic Energy Commission. It is of the type known as a proton synchrotron, of which there are two others in operation, one at the University of Birmingham, England, whose energy is 1 Bev (billion electron volts), and another at the Brookhaven National Laboratory, known as the Cosmotron, which operates at 3 Bev. The Bevatron accelerates protons (stripped nuclei of hydrogen atoms) to an energy of 6.2 Bev.

The design was started in 1947 under the direction of Professor E. O. Lawrence, and although it was the product of collaboration of a large group of physicists and engineers, the original conception was due to William Brobeck who also contributed more than any other individual. A working quarter-scale model was built and operated in 1948 and 1949 to verify the correctness of the design concept. Construction of the full-scale machine was completed in five years, and operation began in the spring of 1954. A period of adjustment and tuning up followed, and since September 1954 it has been the center of a most active and profitable program in high-energy physics. One new particle has been discovered, and an abundance of previously rare and poorly understood particles (heavy mesons and hyperons) has been provided for study. The program has had participants from laboratories all over the United States and from a half dozen other countries, in addition to the staff at the University of California.

This article first describes the Bevatron and its operation, and then discusses a portion of the research program. The principles of the machine and its early history were given in "The Bevatron," by Lloyd Smith, Scientific American, February 1951.

Note: It is impossible to give adequate credit to the large numbers of people whose efforts make up the Bevatron research program. There are highly skilled crews who operate and maintain the Bevatron, making it possible for some dozens of research groups to carry out experiments. Some of these groups are large, and there are strong interdependences between the groups. The research papers are being published chiefly in the current issues of the <u>Physical Review</u> with proper references.

Description and Operation

The main component of the Bevatron is a large ring-shaped magnet, made of four quarter circles of 50-foot radius separated from each other by a distance of 20 feet, resulting in a huge doughnut with four slightly flattened sides. Its weight is a little less than 10,000 tons, and its sole function is to guide the protons which are to be accelerated in a closed circular orbit. Inside the four sections of the magnet and extending across the space between them is the vacuum tank in which the beam travels. The clear space inside the tank is 1 foot high by 4 feet wide, but it extends to a considerably larger cross section, where vacuum pumps and other components are attached in the space between the magnet sectors. The general arrangement is diagramed in Figure 1. The magnet is cycled so that the field rises from zero to 15,500 gauss in about two seconds. The protons are injected into the Bevatron at an energy of 10 Mev at the time when the magnetic field passes through a value of 300 gauss. The protons originate in a hydrogen discharge at the high-voltage end of a 1/2-Mev Cockcroft-Walton accelerator. They then pass into a linear accelerator which increases their energy to 10 Mev (million electron volts). The linear accelerator is of the drift-tube type which has been described in "The Linear Accelerator" by Wolfgang Panofsky, Scientific American, October 1954. They then pass through an electric "inflector," which directs the beam tangent to the Bevatron orbit inside the tank. The injected beam is 1/5000 of an ampere and it lasts for 1/3000 of a second. This corresponds to about $4 \cdot 10^{11}$ protons. The protons circulate around the ring at a rate of 360,000 revolutions per second, oscillating both horizontally and vertically, but constrained to a path near the centerline by the magnetic field. In one of the straight sections there is an open-ended boxlike electrode which is threaded by the circulating beam. A radiofrequency voltage matching the frequency of the particle rotation is applied to this electrode, and that fraction of particles whose position in the orbit happens to have the correct phase relation with respect to the voltage is accelerated. The remaining particles are lost to the walls of the tank, while the accepted particles are compressed in the circumferential direction to a bunch. The frequency of the accelerating voltage must accurately match the rotational frequency of a particle, which increases as the magnetic field increases and as the particle gains energy. This frequency increases from 360,000 to 2,400,000 cycles per second, while the energy increases from 10 Mev to 6.2 Bev, in a little less than 2 seconds. During this time the protons make about 4,000,000 revolutions, gaining an average of 1500 electron volts per turn and traveling about 300,000 miles. At the start of acceleration the beam fills nearly all the cross-sectional area of the tank; as the acceleration process proceeds, the beam area shrinks to about 1 inch high by 4 inches wide. There are losses due to imperfect injection, flaws in the magnetic field, and in the control of the accelerating power, amounting to 90% of the accepted particles. When the highest energy has been reached, the beam pulse amounts to about $3 \cdot 10^{10}$ protons. A target is then moved in the tank to a position just inside the beam orbit. This target insertion is accomplished in about 1/10 second by pneumatic or magnetic devices. The accelerating power is then cut off, but the magnetic field continues to increase. This causes the orbit to shrink, and the protons are peeled off by the target.

Any of the several target arrangements may be chosen, depending upon the experiment. In the simplest case, the target inserted into the beam is the direct object of interest. Metal foils of various elements are bombarded in this manner for subsequent radiochemical analysis in studies of transmutation reactions. The target may also be a block or stack made up of layers of photographic emulsion in which, after development and under microscopic examination, the tracks of the individual protons appear as rows of silver grains. When an interaction occurs that results in a nuclear explosion, a "star" appears, each prong of which is the track of a charged fragment. The identity and energy of the fragment can be deduced from the length, density, and other characteristics of the prong. This can give extremely detailed knowledge of single nuclear events.

In most experiments the interest centers upon the secondary particles which are created when the primary beam strikes a target. In these cases a target, usually a few cubic centimeters of metal, is located with respect to openings in the Bevatron structure so that the secondary particles of choice will not be obstructed. High-energy neutrons leave the target in a forward direction and are not deflected by the Bevatron magnetic field, hence, to produce a neutron beam, a target is located so that there is an unobstructed tangential path from the target, and a collimating hole is opened in the proper direction in the concrete-block shielding wall. In a similar manner, a π-meson beam may be provided, but in this case the bending of the path of the particles in the Bevatron must be taken into account in locating the target. An analyzing magnet may provide a further deflection outside the Bevatron. This results in a relatively pure beam of a selected momentum (mass of particle times velocity), because the angle of deflection in a given field is inversely proportional to the momentum. A variety of detecting instruments, including cloud chambers, bubble chambers, counters and photographic emulsions, may be used in either case, both to study the properties of the neutrons or π mesons in this new high-energy range and to create other particles. In another important arrangement, the target is placed in one of the straight-section tanks where there is no magnetic field, and particles leaving the target at approximately right angles to the Bevatron beam are concentrated by a system of focusing magnets, and are then passed through an analyzing magnet for momentum selection. These particles are predominantly π mesons, but the interest is in heavy mesons, which are present to an extent of about 1%. This arrangement was designed for exposure of emulsion stacks to heavy mesons by Leroy T. Kerth and Donald H. Stork and has had such extraordinary success that many dozens of stacks have been exposed and are being examined in laboratories over most of the world. It has also been very successfully used with scintillation counters as the detectors. Some of the many beam arrangements are shown in the diagram of the target area.

Nuclear Physics Program

High-energy particles were first used as probes to feel out the structure of atoms by Rutherford 45 years ago, when he deduced the existence of the nucleus from the results of a classic experiment on the scattering of alpha particles passing through a foil. This method, simple in principle, of studying the nucleus by bombarding it with particles and examining the fragments is still the most fruitful method in nuclear physics. Natural alpha particles have been superseded in the last 25 years by artificially accelerated particles of increasing energies produced by a variety of accelerators. At energies of a few million electron volts, the collision between the bombarding particle and the target nucleus involves the nucleus as a whole. Energy is given to the entire ensemble, and in some cases, particularly with the lighter elements, a fragment of the nucleus may split off, leaving a nucleus of a different element, which is frequently radioactive. As the bombarding energy is raised to some tens of millions of electron volts, the collisions are energetic enough to transmute any element, and the changes may be greater. The reactions are, however, still of the same kind; not more than a few nucleons (a general name for either neutrons or protons) are added or subtracted from the nucleus, or a unit of electric charge is transferred, resulting in the emission of an electron or positron. When, however, particles of several hundreds of million electron volts, such as are produced by the large synchrocyclotrons, are used, the organizational forces of the nucleus as a whole are less important, and the nucleons act as nearly free particles when squarely struck by a bombarding particle. A new kind of phenomenon may then take place. Some of the kinetic energy of the incident particle may be transformed by a process not yet well understood and appear in the form of a particle. These particles are highly unstable on an everyday time scale, but in every sense they are real particles: they have mass and charge and are endowed with magnetic and rotational properties. They are called pi mesons or pions (see "The Multiplicity of Particles" by Robert E. Marshak, Scientific American, January 1952). The amount of energy transformed is related to the mass of the new particle by the now familiar relation of Einstein, $E = mc^2$. Not all of the kinetic energy of the bombarding particle is available for transformation because the colliding particles and the newly formed meson share a forward motion after the collision. Thus, for the production of π mesons, whose mass is 273 electron units, 139-Mev energy is required, but to get this much energy in a collision between protons, the incident particle must have an energy of about 290 Mev.

The special importance of the Bevatron in this field of physics is due to its very high energy. When a proton of 6.2 Bev strikes a traget nucleon, 2 Bev of energy is available for possible transformation; this is equivalent in mass to more than two nucleons, hence energy is available for the creation of any particles up to a pair of protons or neutrons. Whether a particle may be created--and the circumstances of its creation--is another matter to be settled largely by experiment. As early as 1947 it appeared from cosmic-ray studies that there were rare particles heavier than pi mesons and different from nucleons. It was expected then, even as the Bevatron was being built, that an important field of research would be opened up if these particles, which were later called heavy mesons and hyperons, could be produced by the Bevatron. This expectation has been amply fulfilled by both the Bevatron and the Cosmotron. In addition, the Dirac theory of particles suggests the possibility of creation of pairs of protons with complementary properties, and one of the factors in setting the size of the Bevatron was the provision of enough energy to test this prediction. These particles, called antiprotons, have indeed been produced by the Bevatron. These two projects--production and study of heavy mesons and discovery and study of antiprotons are the most important parts but by no means all of the Bevatron research program. Some of the aspects of research on heavy mesons will be given here, while the antiproton is the subject of a separate article by Emilio Segrè and Clyde Wiegand.

The table lists the particles of physics as they are presently known. The group in the middle with masses about half that of a proton are the heavy mesons. They were all discovered in cosmic-ray investigations, using either cloud chambers or photographic emulsions, and are distinguished from one another chiefly by differing decay schemes. Each unique decay scheme is tentatively assigned to a separate particle; however, it is by no means certain that two or more schemes may not be alternate decay modes of a single particle.

To determine that, accurate measurements of the other properties of the particles, such as mass and half life, are required. Such detailed knowledge of these particles has developed rather slowly and, up to a year ago, only as a result of very large-scale efforts on the part of dozens of cosmic-ray research groups. The trouble is not only that the problem is very complex, but the difficulty is compounded by the scarcity of the particles and by the severe experimental conditions encountered in using cosmic rays as a source of particles. A total of no more than several hundred individual events had been observed prior to the production of these particles by the Bevatron and the Cosmotron. The Bevatron K-particle facility, briefly described in the previous section, can provide that many heavy mesons per hour and in a directionally defined and momentum-analyzed beam. For the first time, it has become possible to do precise experiments under laboratory conditions and to have enough observations so that good statistical accuracy could be achieved.

One important project is the systematic measurement of the masses of the different K mesons, using photographic emulsion techniques. The mass of the particles may be deduced from the range, or depth of penetration into matter, of particles of a known momentum. The momentum is fixed by an accurately defined path through the analyzing magnet, and the range is determined by direct measurement of the length of the track in the emulsion. In addition, it is possible to deduce the mass of a particle if a decay is observed under such conditions that the energy of each particle can be measured, since the mass of the original particle equals the sum of the masses of the decay particles plus the energy of those particles expressed in mass units according to the Einstein relation. The work is not yet completed, but mass values for τ, $K_{\mu 2}$, $K_{\pi 2}$, $K_{\mu 3}$, and K_e have been determined to accuracies of a few tenths of a percent, and they seem to be consistent with a single value of about 966 electron mass units. This work is being carried out by two groups: one headed by Walter H. Barkas and Harry H. Heckman, the other by Robert W. Birge and Donald H. Stork. A comparison of the masses of the negative K mesons with the positive has also been made using similar methods and yielding the result that they are the same within two-tenths of a percent. This work was done principally by W. Chupp, G. Goldhaber, and S. Goldhaber.

The "K-beam" has made it possible for the first time to successfully carry out experiments with K mesons using counters as the detectors. The importance of this is due to the excellence of counters as instruments to measure small intervals of time; also, to the possibility of setting up highly selective schemes so that only certain defined particles are registered out of a large background of other particles. In making a general comparison, one can say that emulsions give a wonderfully detailed picture of the geometry of an event, but very little information as to timing, and do require a laborious effort to analyze each individual event. Scintillation counters, on the other hand, can give only a crude picture of the geometry of an event because of their large size, but they can give timing information to one-billionth of a second, and it is possible to set up counter arrays which can handle many thousands of particles, rejecting the unwanted ones and sorting out the desired ones according to some predetermined scheme. (See "Scintillation Counters" by George B. Collins, Scientific American, November 1953.) The first K-meson counting was done by Luis W. Alvarez, Frank Crawford, Myron L. Good, and M. Lynn Stevenson, and their preliminary results give no evidence for differing half lives of the τ, $K_{\mu 2}$ or $K_{\pi 2}$ mesons. Both this evidence and the mass values suggest, then, that when information is complete there may be fewer than the eight listed entries in the heavy-meson group.

A number of other important properties of these particles are being studied, such as the variation of production rate at different energies, the details of the decay processes, and their interactions with matter. As an example of the latter, it has been found that the positively charged K mesons interact with matter only one-third as strongly as do negative K mesons, and when they do interact, they usually suffer only a change of direction. The negative K mesons, on the other hand, may be absorbed by a nucleus, resulting in the creation of a hyperon, one of the last group in the particle table. Observations of this type can give important evidence as to the correctness of proposed theoretical treatments of the particles. The observations have so far been consistent with a classification scheme proposed by Murray Gell-Mann and A. Pais in which a certain value of a quantity called "Strangeness" is assigned to each particle, and the requirement is made that in an interaction, the total of this quantity must remain unchanged. This work is being carried out by Warren W. Chupp, Gerson Goldhaber, Sulamith Goldhaber, R. Stephan White, and associates at this laboratory, as well as groups from other laboratories.

Finally, one of the most promising tools for research with Bevatron-produced particles, including K mesons, should be mentioned. A liquid hydrogen bubble chamber (see "The Bubble Chamber", by Donald A. Glaser, Scientific American, February 1955) ten inches in diameter has just been brought into operation by a group of people headed by Luis W. Alvarez and James D. Gow. This instrument combines some of the best features of both cloud chamber and emulsion techniques and adds a unique one of its own. The chamber, in which the tracks of particles appear as rows of minute bubbles, contains only pure liquid hydrogen, so that all interactions are between pairs of protons, eliminating some of the difficulties of interpretation that are introduced by interactions with more complex nuclei.

We can confidently expect that within a year a number of the present uncertainties in the table of particles will be removed. We cannot, however, be sure that the number of unanswered questions will be any less, for in the course of physics it has frequently occurred that when one question is answered, at least one new one is raised.

FIGURE CAPTIONS

Fig. 1. The Bevatron is in the circular building in the center. The generators which supply the magnet with power are in the wing extending to the left. The 184-inch cyclotron is in the domed building in the upper left.

Fig. 2. The important components of the Bevatron are indicated in this diagram.

Fig. 3. The Bevatron magnet is built in four quadrants separated by straight sections. The over-all diameter is 140 feet, and the weight is 9,500 tons. The linear accelerator of the injection system, which is a complete 10-Mev accelerator in itself, appears at the right. Two overhead cranes are used to service the machine and to move experimental equipment.

Fig. 4. The magnet cycle is plotted in the upper diagram. While the magnet current is increasing, 100,000 kilowatts of power are required from the generators. Large flywheels are connected to the generators to provide this energy. During the current decay about 80% of the energy flows from the magnet back to the generators and into the flywheels. The 20% energy loss is made up by continuously operating motors. The entire pulse is repeated 10 times per second. minute,

The acceleration cycle is shown in the lower part of the diagram on the same time scale. Three one-hundredths of a second after the start of the magnet pulse the field has reached 300 gauss, the injector is triggered, and 10-Mev protons are injected. Their velocity is 15% the velocity of light. The accelerating electrode supplies an average of 1500 electron volts per turn for about 4,000,000 turns until at the end of 1.8 seconds the peak energy of 6.2 Bev has been reached, when the beam is intercepted by a target.

Fig. 5. This is the target area of the Bevatron, showing a few of the possible beam arrangements. Of course, not all of these facilities can be set up at the same time.

Fig. 6. The particles of physics as they are presently known. The word "elementary" particles is sometimes used, but it is not clear what "elementary" means because of the transformations between particles and from energy to particle. The light mesons are produced by the large synchrocyclotrons. Heavy mesons have been produced in comparative abundance by the Bevatron, and a good start has been made towards accumulating the information necessary for understanding the role these particles play in nature. The most spectacular product of the Bevatron has been the antiproton, whose existence had been predicted by Dirac. Hyperons are also produced by the Bevatron and are under study.

Fig. 7. This photograph was obtained during a trial run with a ten-inch-diameter liquid hydrogen bubble chamber. About a dozen 1.5-Bev π^- mesons enter the chamber (from above in the photograph), resulting in five nuclear interactions. They are designated by the capital letters A to E. The last event, E, is especially interesting because it is very unusual to get so many steps in a single picture. The incoming π^- meson (1) interacts with a proton, at E, producing a K^- meson (3). The proton leaves track (2). A θ^0 meson [illegible]

Fig. 1

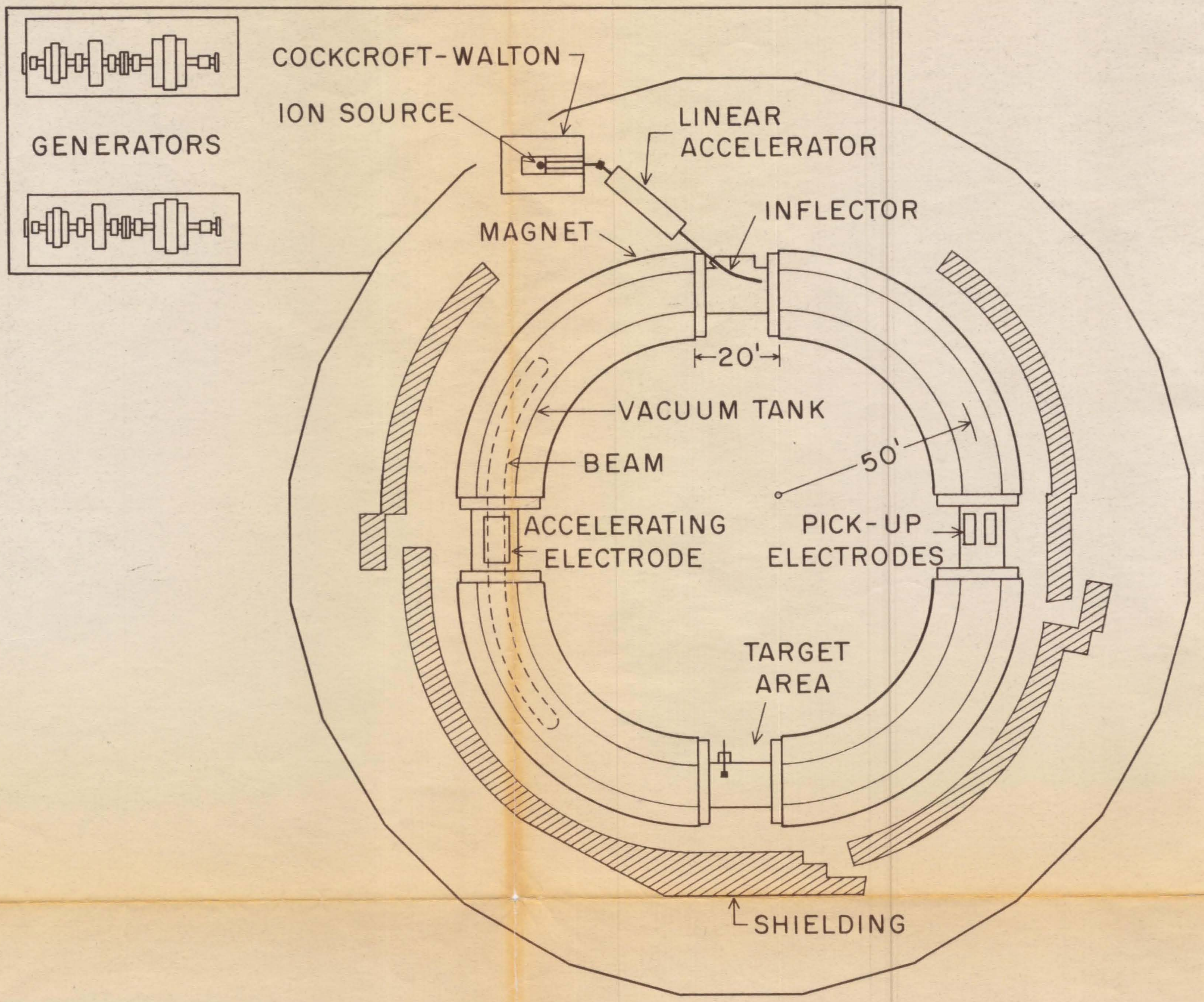
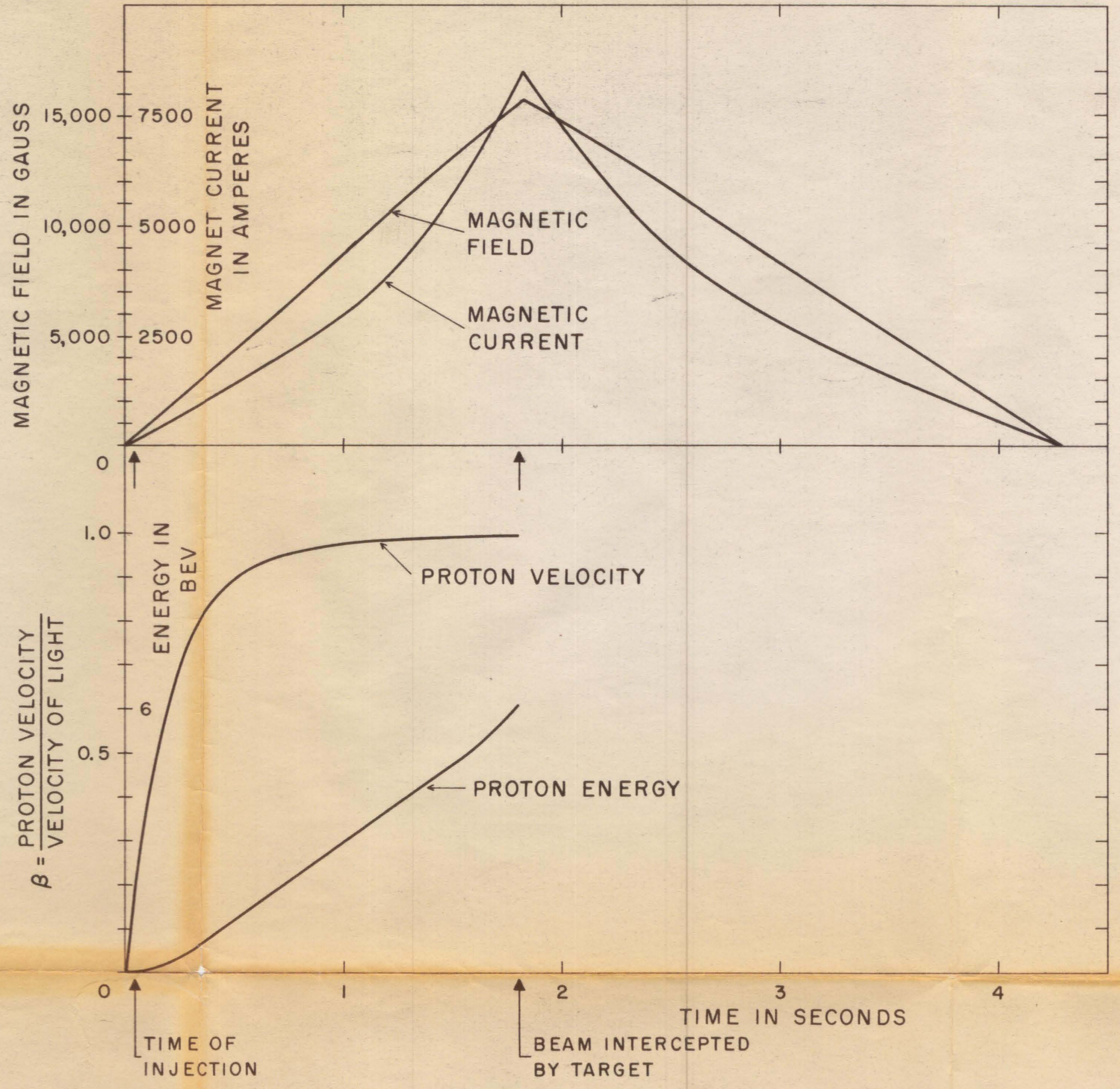
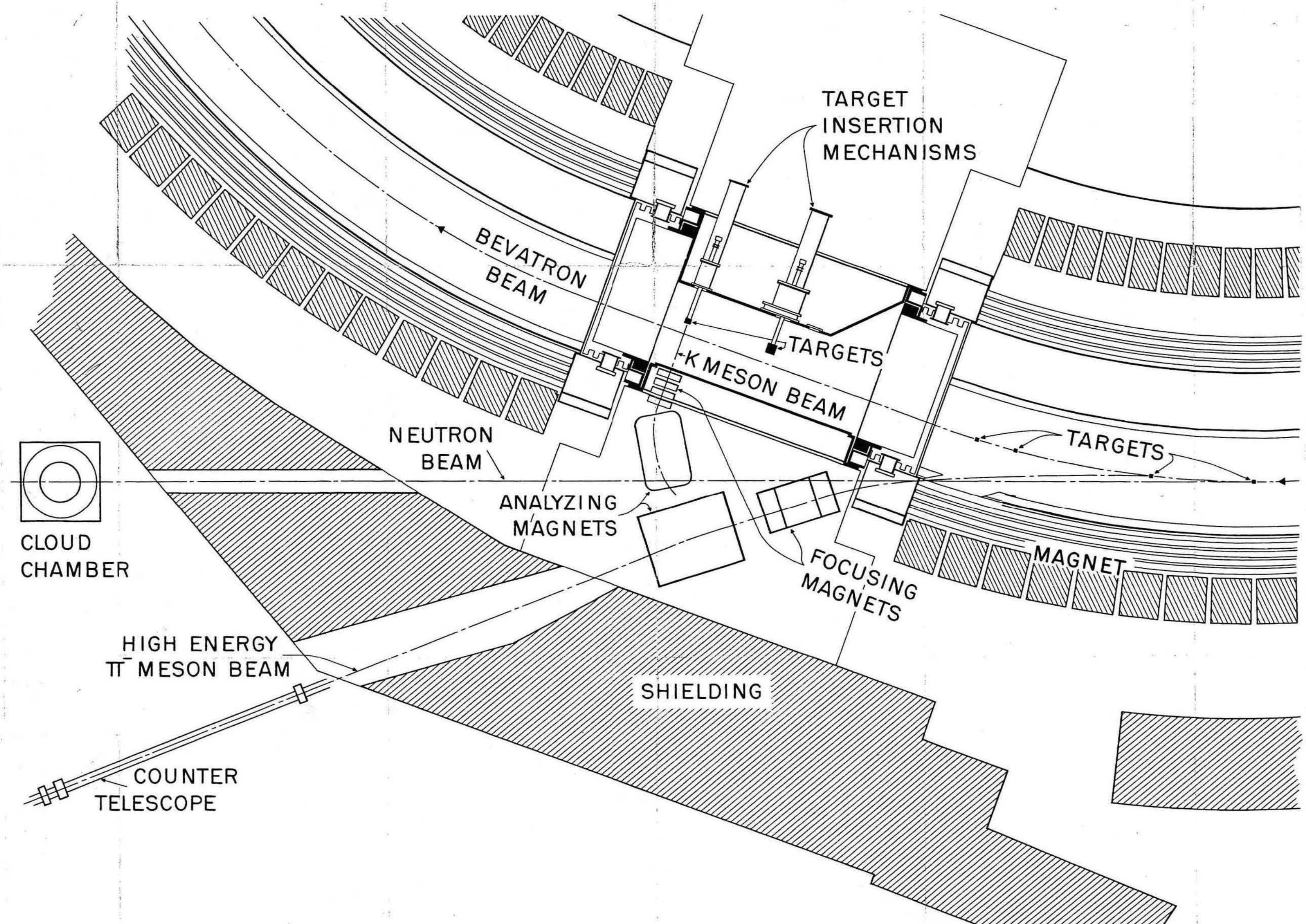

GENERATORS
COCKCROFT-WALTON
ION SOURCE
LINEAR ACCELERATOR
INFLECTOR
MAGNET
20'
VACUUM TANK
BEAM
50'
ACCELERATING ELECTRODE
PICK-UP ELECTRODES
TARGET AREA
SHIELDING

Fig. 3


MAGNETIC FIELD IN GAUSS
15,000
10,000
5,000
MAGNET CURRENT IN AMPERES
7500
5000
2500
MAGNETIC FIELD
MAGNETIC CURRENT
0
$\beta = \frac{\text{PROTON VELOCITY}}{\text{VELOCITY OF LIGHT}}$
1.0
0.5
0
ENERGY IN BEV
6
PROTON VELOCITY
PROTON ENERGY
1
2
3
4
TIME IN SECONDS
TIME OF INJECTION
BEAM INTERCEPTED BY TARGET

25171-3

Fig 7


TARGET
INSERTION
MECHANISMS
BEVATRON
BEAM
TARGETS
K MESON BEAM
NEUTRON
BEAM
TARGETS
CLOUD
CHAMBER
ANALYZING
MAGNETS
FOCUSING
MAGNETS
MAGNET
HIGH ENERGY
π^- MESON BEAM
SHIELDING
COUNTER
TELESCOPE

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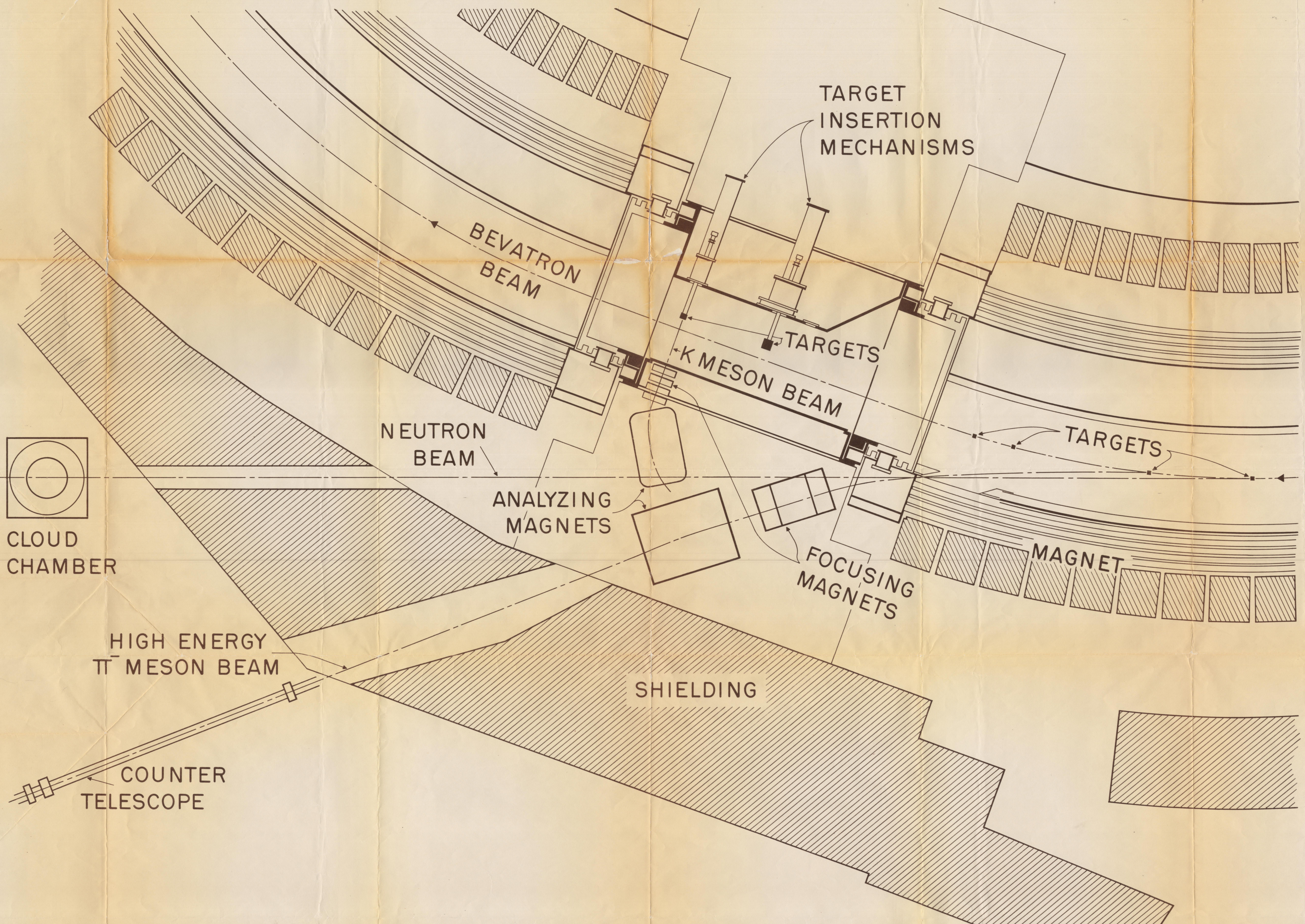
TARGET
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TELESCOPE

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