Title
UCRL Accelerators -- The Bevatron

Permalink
https://escholarship.org/uc/item/2g82k0ks

Author
Lawrence Berkeley National Laboratory

Publication Date
1958-03-01

UCRL Accelerators
THE BEVATRON

THE UNIVERSITY OF CALIFORNIA
Radiation Laboratory - Berkeley

THE BEVATRON

GENERAL PRINCIPLES OF OPERATION

The Bevatron is a machine that accelerates protons to relativistic energies--that is, energies at which the velocity of the particles approaches the velocity of light. It is a member of a class of accelerators called proton synchrotrons. Its operation is analogous to the behavior of a system consisting of a baseball tied to a string and revolving about a post, and a boy striking the ball with a bat each time it passes him (see Fig.1). The important features of this analogy are:

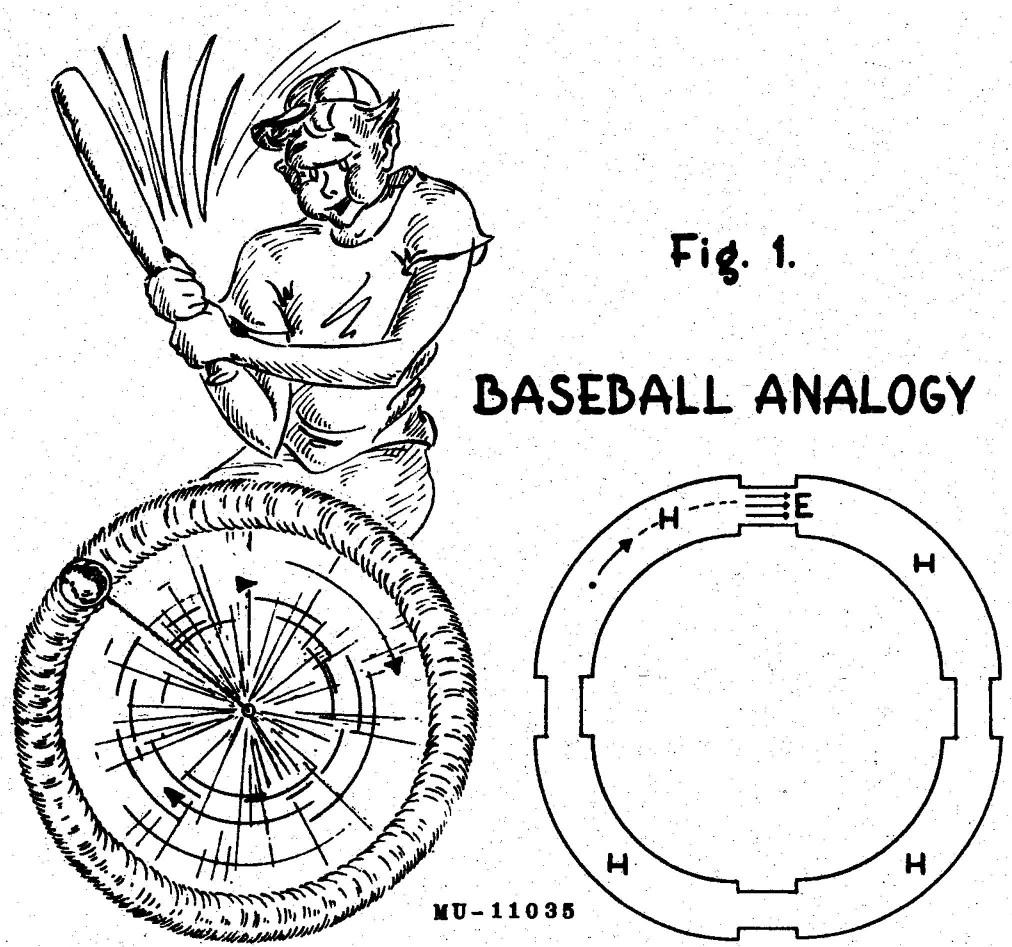


Fig. 1.

BASEBALL ANALOGY

MU-11035

baseball = proton
string = magnetic field H
boy with bat = electric field E

1. The string constrains the ball so that it moves in a circle of constant radius and continually recircles past the boy.

2. Even if the boy only hits the ball weakly, he can impart a great deal of energy to it if he hits it often enough.

3. As the ball gains energy and, therefore, velocity, the boy's "timing" changes; that is, the frequency with which he hits the ball must increase.

4. As the ball gains energy and, therefore, momentum, the force the string must exert to keep the ball revolving in a circle increases. A limit to the amount of energy that can be imparted to the ball will be reached when its momentum is so high that the string breaks.

In the Bevatron:

1. The magnetic field constrains protons to move in nearly circular orbits of constant radius so that they continually recircle through a region containing an accelerating electric field. (This "constant-radius" feature is important for economic reasons. If the protons spiraled out from the center, the whole circle would have to be covered with magnet iron. Here the magnet covers only the outer edge.)

2. The electric accelerating field imparts relatively little energy to the proton during a single traversal. High energies are obtained by having many traversals.

3. The electric accelerating field is produced by a radio-frequency oscillator. This field obviously must be in the right direction when the protons pass through it, and considerations relating to stability further require that the protons enter the field within a limited phase interval. This is the problem of "timing." As the proton gains energy and, therefore, velocity,

the time it requires to circle the Bevatron decreases. Therefore, to keep the timing correct, the frequency of the rf oscillator must increase during acceleration.

4. As the proton gains energy and, therefore, momentum, a stronger magnetic field is required to constrain it to move in the same orbit. Thus the magnetic field must increase during acceleration. There is a limit to the strength of field the Bevatron magnet can produce, and it is this which limits the energy that can be imparted to the protons.

The baseball analogy breaks down in one respect, which is discussed later.

There is a unique relation between the value of the magnetic field, the frequency of the rf oscillator, and the energy of the proton being accelerated, which must be satisfied at every instant. For this reason a proton synchrotron is not a continuous machine, but must be pulsed. A group of protons starts off together, and the energies of the protons, the value of the magnetic field, and the rf oscillator frequency all increase simultaneously, keeping in step until the end of the accelerating cycle. At that time this group of high-energy protons is available to an experimenter. Then the magnetic field and the rf oscillator frequency return to their initial values and the cycle can begin again. In the Bevatron, acceleration takes 1.8 seconds.

THE BEVATRON MAGNET

The weight and massive bulk of the Bevatron are largely associated with producing the magnetic field. The magnet iron weighs 10,000 tons, or the equivalent of a medium-sized cruiser. The motor generator, which supplies current for the magnet coil, must deliver a peak power of 100,000 kw and an average power of 7,000 kw. (A town of 30,000 population consumes about 7,000 kw.)

To achieve the rising magnetic field, the coil is pulsed with an essentially dc voltage at the beginning of the accelerating cycle. Owing to the self-inductance of the system, the current requires time to build up and the result is a gradually rising magnetic field.

It is necessary to have access to the region where the protons circulate to insert the accelerating electrode, targets, vacuum pumps, etc. Therefore, while in principle the Bevatron could have the shape of a ring, actually there must be access regions where there is no magnet yoke and, therefore, no magnetic field. In these regions the particles travel in straight lines. At the Bevatron there are four of these straight sections. The protons are injected into the Bevatron at the east straight section; they are accelerated by an electric field in the north straight section; and some of the targets are located in the west straight section.

Since for successful acceleration the frequency of the rf oscillator and the strength of the magnetic field must satisfy a certain relationship, either the frequency must be made to track the magnetic field or the strength of the field must be made to track the frequency. In the Bevatron the magnetic field rises according to the characteristics of the magnet excitation equipment and of the magnet itself; the rf oscillator has been designed so that its frequency stays precisely in step.

THE ELECTRIC FIELD

Energy can be imparted to the protons when they pass through the north straight section. In the Bevatron the protons first actually lose some energy and then gain back a greater amount. This happens as follows: In the north straight section there is a rectangular tube through which the protons pass. The rf oscillator makes the potential of this tube, with respect to the rest of the Bevatron, vary sinusoidally in time. The protons enter the tube when its potential is positive and rising (see Fig. 2). If the protons get to Position 2 at Time t_2, they will have lost energy, because they had to climb a potential hill of 14 kv. Once they get to Position 2, they can coast to Position 3, because the region inside the tube is all at the same potential, and therefore there are no fields to exert forces. The crucial point is that during the time it takes the protons to coast inside the tube from Position 2 to Position 3, the potential of the entire tube rises from 14 kv to 15.7 kv. When the protons come out of the tube, they gain 15.7 kv in going from Position 3 to Position 4. Thus, they fall down a potential hill that is 1.7 kv higher than the one they had to climb, so the net result is a gain in energy of 1.7 kev. The protons then circulate through the entire Bevatron without changing their energy until the magnetic field brings them back to the north straight section, where the process is repeated. During a cycle that accelerates the protons from 10 Mev to 6.2 Bev, there are approximately 4,000,000 revolutions, which take the protons a distance somewhat farther than from here to the moon.

In the above explanation it was assumed that the rf oscillator would make the potential of the tube both positive and rising each time the protons were ready to enter. This is the problem of timing. Correct timing requires that the period of the rf oscillator equal the time it takes the proton to circle the Bevatron. Since during acceleration the energy of the proton changes, the time required to circle the Bevatron also changes; therefore, for correct timing, the frequency of the rf oscillator must continually change. The problem is to know at each instant just what the frequency should be and to adjust the oscillator to that frequency. What is needed is a device that will determine the energy of the protons, figure out the appropriate frequency, and adjust the rf oscillator to that frequency. In effect there is such a device at the Bevatron, and it works as follows: In a constant-radius machine, there is a unique relationship between

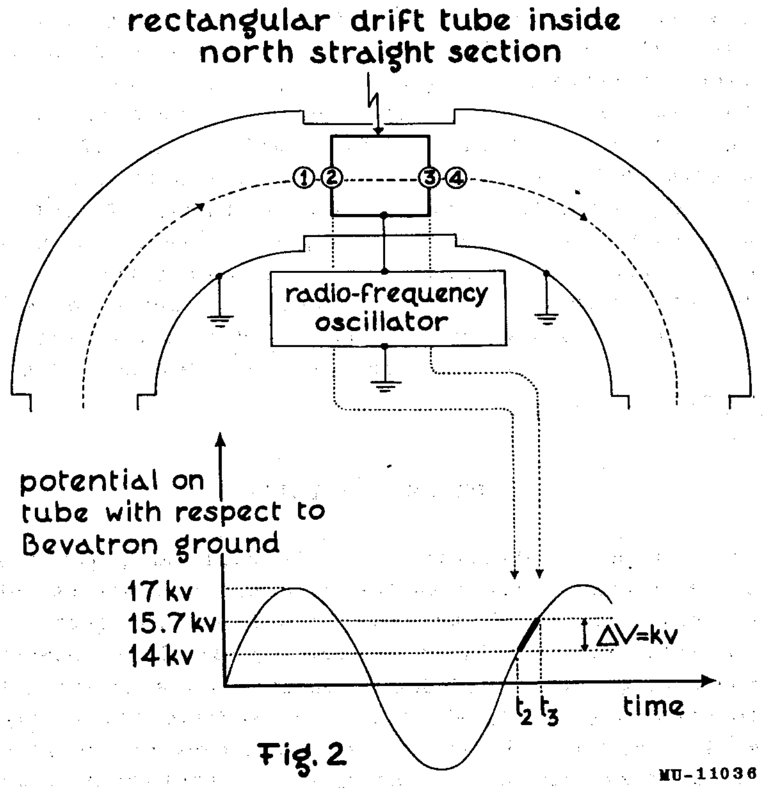


Fig. 2

MU-11036

ACCELERATING ELECTRIC FIELD

the energy of the protons and the value of the magnetic field that is guiding them. There is also a known relationship between the strength of the field and the current in the magnet coil. Therefore, a measurement of this current at any instant contains all of the information needed to determine the energy of the protons. At the Bevatron a sample of the current is shunted off and used to vary the inductance of an element whose value in turn determines the frequency of the rf oscillator. By this device, approximately correct timing is achieved. Actually the frequency must be controlled to a fraction of a percent, and additional, more sensitive devices are needed as trimmers.

PHASE STABILITY

In the baseball analogy, the ball was given additional momentum, and then the tension in the string automatically increased just the right amount to continue to constrain the ball to its circular orbit. Here, however, the analogy has broken down, because in the Bevatron the constraining force, which is the magnetic field, rises at its own natural rate and the frequency of the rf oscillator as well as the energy of the protons must keep in step. Forcing the frequency to track is clearly possible, although it may be difficult in practice. Whether or not the energy can be made to stay in step is not so obvious. The required condition is that if the particle gains too little (or too much) energy, forces come into play that make it gain more (or less) energy on succeeding revolutions. This is indeed what happens. Consider a proton that has gained too little energy. It is bent in a tighter circle and therefore comes to the north straight section slightly early. In Fig.2, it is seen that at an earlier time the slope of the curve and, therefore, ΔV, which is the energy gain, is greater. By a similar argument, particles that may have gained a little too much energy arrive late and gain less than their normal amount. Thus they get back into step. This phenomenon is referred to as phase stability.

NEED FOR AN INJECTOR

Protons are injected into a cyclotron with a kinetic energy of only a few kev. In the Bevatron, however, the protons are accelerated to 10 Mev before being injected. This pre-acceleration is needed for the following reasons:

1. Coulomb scattering. Protons are scattered by any residual gas in their path. The problem this creates can become particularly serious in the Bevatron because of the relatively long paths traversed by the protons. The higher the initial energy of the protons, the less the scattering.

2. Frequency range. As mentioned before, the period of the rf oscillator must correspond to the time required for the protons to circle the Bevatron, and therefore must change as their velocity increases. It is difficult to make an oscillator whose frequency must cover a wide range. The higher the initial energy of the protons, the less the total frequency change required.

3. Residual magnetic fields. Even with no current flowing in the magnet coil, there are residual magnetic fields in the Bevatron. Stable operation requires that during acceleration the ratio of these residual fields to the total field be small. It is hardest to keep this ratio small at the time of injection. The higher the initial energy of the protons, the larger the total field at injection (hence the smaller the ratio).

A block diagram of the injector is shown in Fig.3. The components are discussed in the next section.

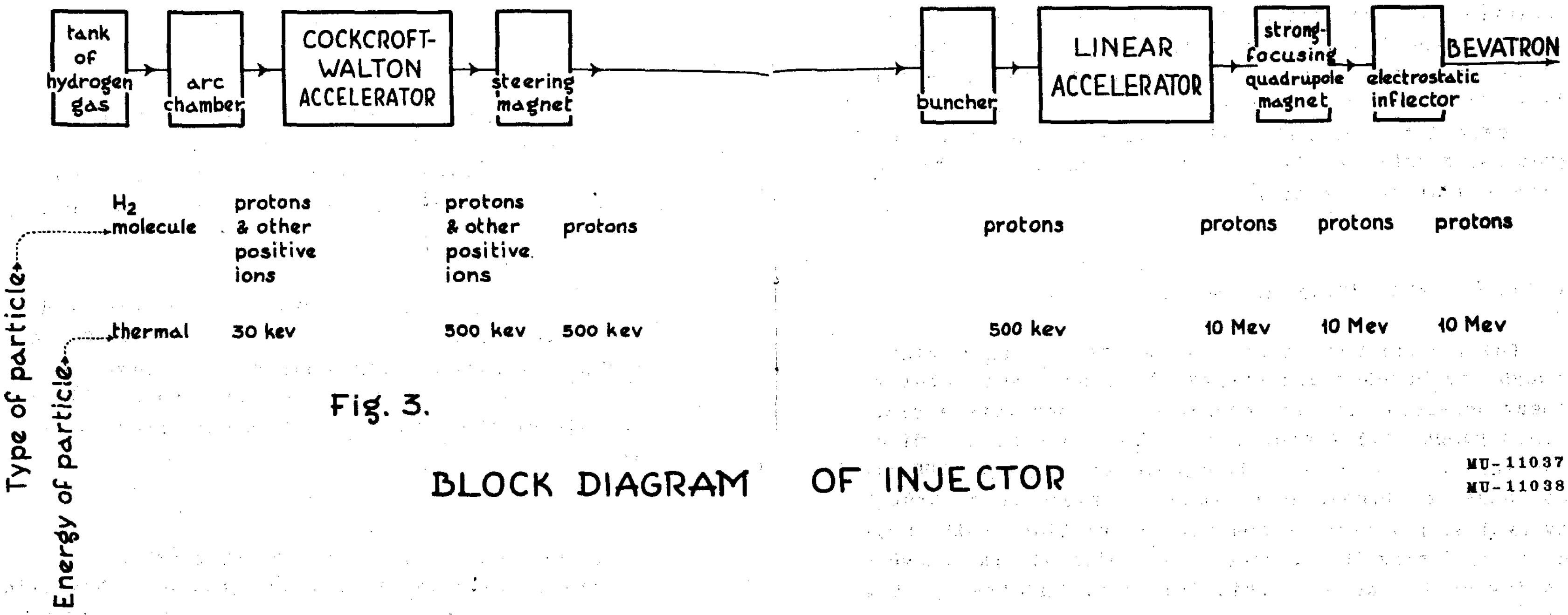


Fig. 3.

BLOCK DIAGRAM OF INJECTOR

MU-11037
MU-11038

HISTORY OF A PROTON DURING ACCELERATION

Ion Source

The protons accelerated by the Bevatron start as constituents of hydrogen gas. Hydrogen molecules diffuse into an arc chamber, where they are bombarded by electrons. The arc is struck for 700 microseconds twice per second. The protons (and other positive ions produced) are drawn by electrodes into the accelerating tube of a Cockcroft-Walton accelerator.

Cockcroft-Walton Accelerator

A Cockcroft-Walton accelerator is an electrostatic accelerator. Unlike the Bevatron it accelerates particles in one step. In essence it is a power supply that converts 20 kv, 800 cycles to + 500,000 volts dc. This potential is used to set up a field along the axis of a tube. The protons enter this tube after leaving the ion source and are accelerated by the field to an energy of 500 kev. Since the Cockcroft-Walton is nothing but a source of dc voltage, whenever protons are injected into it, it will deliver them at 500 kev. Therefore, there are 700-microsecond bunches of 500-kev protons leaving the Cockcroft-Walton twice per second.

The Steering Magnet

After the Cockcroft-Walton, the next acceleration takes place in a linear accelerator. Between the Cockcroft-Walton and the linear accelerator, however, there is a stray magnetic field from the Bevatron that is strong enough to deflect the 500-kev protons. Furthermore, the strength of this stray field varies, depending on Bevatron running conditions. Successful steering of the protons to the linear accelerator requires that the effect of this stray field be compensated. This is accomplished by having the protons pass through a magnet after they leave the Cockcroft-Walton. The strength of this magnet is adjusted so that the protons can be steered over to the linear accelerator.

The Buncher and Linear Accelerator

The proton beam passes from the steering magnet through the buncher and enters the linear accelerator. (Linear accelerators are described in a separate article in this pamphlet.) A proton must enter during a limited phase interval in order to be accelerated. During 700 microseconds the linear accelerator rf field goes through many cycles. For this reason only a fraction of the protons enter during the correct phase interval. The buncher is a device to increase this fraction. In effect, what it does is speed up protons that would arrive too late and slow down protons that would arrive too early. The buncher is a tuned cavity excited to the right frequency by coupling energy from the linear accelerator. The phase with respect to the linear accelerator is variable and is adjusted for maximum bunching action.

Strong-Focusing Quadrupole Magnet and the Electrostatic Inflector

The protons leave the linear accelerator with a kinetic energy of 10 Mev. In order to reduce the angular divergence in the beam, the protons are passed through a quadrupole magnet, which acts as a converging lens. The inflector then makes them enter the accelerating chamber of the Bevatron tangent to the orbit they should follow. The inflector consists of two curved plates with an electric field between that bends the path of the protons until they are headed in the right direction (see Fig. 4).

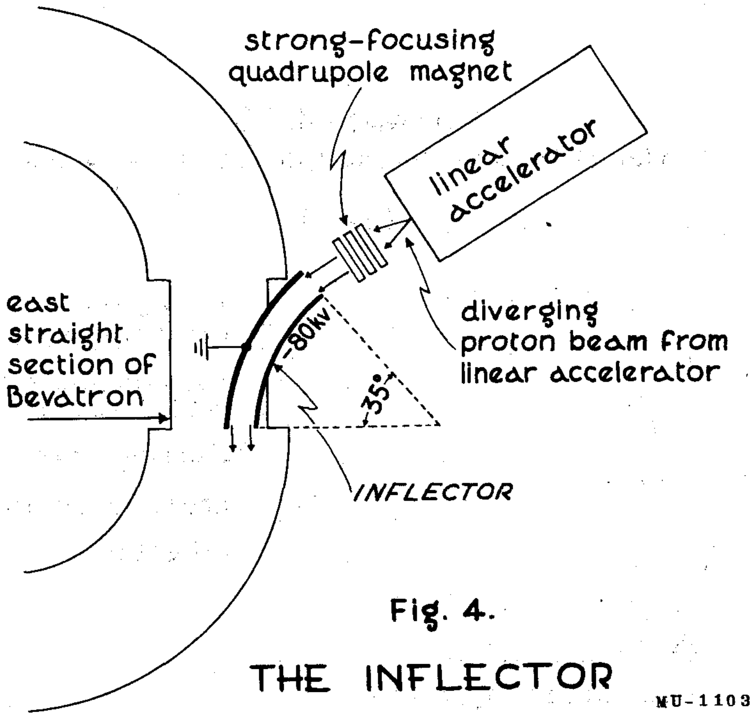


Fig. 4.

THE INFLECTOR

MU-11039

"Acceptance" by the Bevatron; Acceleration

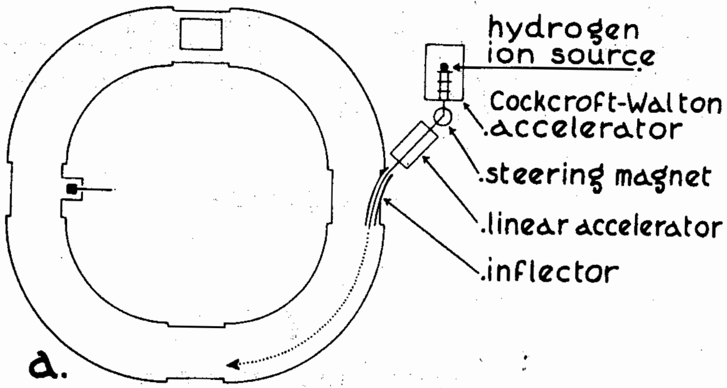
Just prior to the Bevatron's acceleration cycle there is no current in the magnet coil; there is no accelerating voltage in the north straight section; and the arc in the ion source is off. The cycle starts when a signal from a master timing device tells the motor generator to deliver current to the magnet coil. When the field has risen to the value that is just right to guide 10-Mev protons, another signal is sent to the ion source to initiate the arc. This in turn starts the sequence of events just described.

We have thus reached the following situation: The accelerating voltage is still off, the magnetic field is just right for 10-Mev protons and is rising at its natural rate. A pulse of 10-Mev protons that will last for 700 microseconds has started spraying into the Bevatron. There

"SNAPSHOTS"

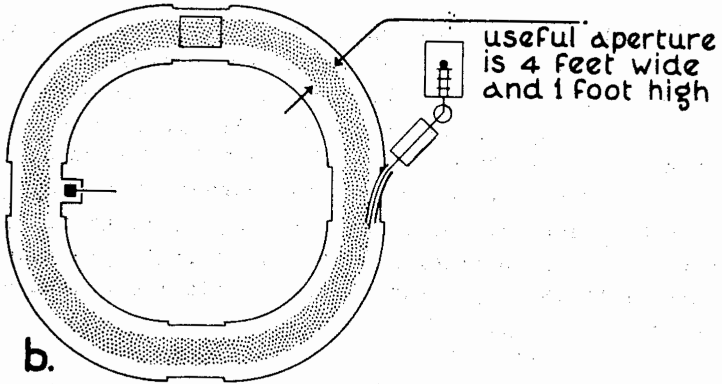
SHOWING THE INSTANTANEOUS POSITIONS OF THE PROTONS

Fig. 5.



a.

just after injection has started



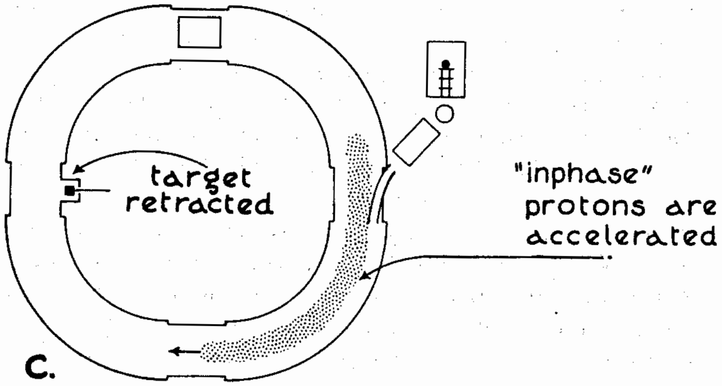
b.

just before turn-on of accelerating voltage

MU-11040

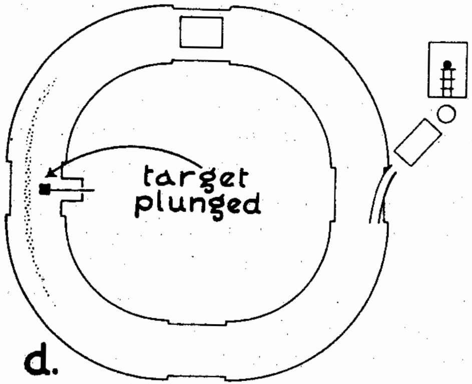
"SNAPSHOTS"

Fig. 5. *continued*



c.

a few milliseconds after turn-on of accelerating voltage



d.

just before accelerating voltage is turned off

MU-11041

is now a technical problem of making the protons miss the inflector after they come back around to their starting point. This problem will not be discussed here, except to say that the protons' orbit is not a simple circle but has radial oscillations superimposed on it. Furthermore, the previous statement that an orbit in a proton synchrotron has a unique radius is an oversimplification. Actually, the accelerating chamber in the Bevatron is 4 ft wide, so the instantaneous radius of the orbit can vary from 52 ft to 48 ft. Therefore, as the field increases, protons can gradually spiral inward away from the inflector. It is a combination of these two effects that saves the proton from an early death. During the 700 microseconds, the Bevatron fills up with protons, and the stage is set for turning on the accelerating voltage. When this is done, protons that have the right phase will be accelerated and will therefore stop spiraling inward. These protons are "accepted" by the Bevatron. They comprise about 15% of all the protons injected.
Parts a, b, and c of Fig.5 show what snapshots of the proton might look like taken

(a) at the beginning of injection,
(b) just before turn-on of the accelerating voltage,
(c) a few milliseconds after turn-on of accelerating voltage.

Note that just before turn-on of the accelerating voltage the injected protons are distributed uniformly around the Bevatron's entire circumference. Now since, to be "accepted," a proton must pass through the accelerating field during the right interval in its rf cycle, and since this interval is shorter than the time it takes a proton to circle the Bevatron, those protons that are accepted will exhibit a spatial grouping. They extend over only 1/4 to 1/2 of the circumference (compare parts b and c of Fig.5). Furthermore, they will stay in their spatial group as they are accelerated.

This group of protons then continues to circulate around the Bevatron, gradually gaining energy as described in the section on the electric field, until they have reached the energy desired by the experimenter who will use them. This energy can be anywhere from a maximum of 6.2 Bev down to 10 Mev. Most experimenters use energies near the maximum. Approximately 30% of the protons that are accepted survive to full energy.

Bringing the Protons to a Target

When the protons have been fully accelerated, the accelerating voltage is turned off. The protons then coast around the Bevatron without changing their energy; but they gradually spiral inward because the magnetic field is still rising. A snapshot of the protons taken just before the accelerating voltage is turned off would not look like a snapshot taken just after it was turned on. Compare Fig. 5b with 5c. The protons now occupy a strip only a few inches wide, compared with the 4-ft width just after injection. This is very convenient, because it allows one to insert a target into the Bevatron late in the acceleration cycle without interfering with the beam. Then when the rf is turned off, the protons can spiral inward and strike the target, which is waiting for them. Most of the facilities for plunging targets are located in the west straight section. There are plunging probes, which enter the Bevatron through air locks. The experimenter can have a probe retracted into its air lock and can put on it any target he desires. The nature of the target used--and what happens after the proton strikes it--depends on the particular experiment being performed.

TYPES OF EXPERIMENTS AT THE BEVATRON

The Bevatron provides experimenters with a supply of high-energy protons. The experimenter is interested in finding out what happens when these protons interact with other matter. The things he looks for might be roughly classified as follows:

1. The effect of the matter on the incident proton. For example, does the proton lose energy? Is it deflected? How much?, etc.

2. The effect of the proton on the matter it strikes. Do transmutations take place? What kind? How often?

3. The production of new matter as a result of the interaction. What kinds of particles can be produced? How often?, etc.

4. Properties of the "New Particles." Once new particles are produced, the experimenter is interested in studying their properties. Thus, for example, a beam of high-energy π mesons may be directed onto a second target; and the experimenter may study the effect of the target on the π mesons, the effect of the π mesons on the target, or the transformation of some of the kinetic energy of the π mesons into still other new particles.

In this sense the Bevatron makes available to the experimenter not only beams of protons, but also neutrons, mesons, and other new particles.

It might be noted at this point that the new particles are unstable. They interact or spontaneously break up after very short times. For this reason they are not found occurring naturally. To study them, one must make them; and this requires a source of high-energy particles. The higher the energy available, the greater can be the mass of the produced particle. As even higher-energy machines are made, other hitherto unknown particles of greater mass may be produced. At present the Bevatron makes available more energy for the production of these new particles than any other machine in the world. Its closest competitor is the Cosmotron at the Brookhaven National Laboratory, which accelerates protons to 3 Bev. Machines are now being built that will produce even higher-energy protons. The Russians are completing a machine like the Bevatron that goes up to 10 Bev. A 25-Bev machine is being built by the Cern Group (European Organization for Nuclear Research) in Switzerland, and another 25-Bev machine is being built at the Brookhaven National Laboratory in New York.

Nature has her own "bevatrons," which she uses to produce cosmic rays. Cosmic rays are primarily high-energy protons that reach the earth's atmosphere from somewhere in outer space. In a sense, nature is far ahead of man in that cosmic-ray protons have been observed to have energies a million times as great as the best the Bevatron can do. These cosmic rays are free for the taking, and a great deal of pioneering work in high-energy physics has been done by workers who use them. There are very important respects, however, in which a man-made machine like the Bevatron is far superior. These are intensity, purity, and convenience. The Bevatron can deliver 10^{10} protons to a one-square-inch target every six seconds. It would take many years for that many cosmic-ray protons to pass through a similar target located at the top of the earth's atmosphere. The Bevatron produces a pure beam of essentially monoenergetic protons. Cosmic-ray protons interact in the atmosphere and are therefore accompanied by secondary particles of various kinds. Even if one gets his equipment above the earth's atmosphere, the energies of the protons cover a wide range. Under these conditions many experiments that require controlled conditions are impossible.

EXPERIMENTAL EQUIPMENT USED AT THE BEVATRON

Various kinds of experimental equipment are used at the Bevatron to detect the presence of the high-energy protons and their progeny.

One class of devices might be termed visual detectors. They give the experimenter a picture showing actual paths of the charged particles being studied. These are the photographic emulsion, the bubble chamber, and the cloud chamber. The pictures are obtained while the particles traverse a solid, liquid, or gas, respectively. The photographic emulsions used in nuclear physics are basically similar to those used in photography, except that it is a charged particle passing near a grain, rather than a photon, that renders it developable. The picture that is obtained is a trail of developed grains, which lie along the track followed by the particle. The bubble chamber is filled with liquid under such conditions of temperature and pressure that it is superheated. If a charged particle passes through it, the liquid adjacent to the path of the particle "boils," i.e., bubbles form, and this trail of bubbles can be photographed. A cloud chamber contains a supersaturated gas. A charged particle passing through it forms ions along its path which serve as condensation centers. Drops form on these ions, and the trail of drops can be photographed.

All three of these devices serve as combined target and detector. An incident particle may interact in the solid, liquid, or gas; and the emulsion, bubble chamber, or cloud chamber detects the results of the interreaction in the sense that it gives a picture of the paths of all the charged particles involved. All three devices not only show where the particles have gone, but a study of the tracks (density, scattering, length, curvature) can also yield quantitative information on the mass and velocity of the particle. The photographic emulsion has particularly good spatial resolution and lends itself to precise quantitative measurements. The liquid used in the bubble chamber can be liquid hydrogen. For high-energy work this is effectively a target of pure protons in a relatively dense form, which is extremely desirable in many experiments. The cloud-chamber gas can be hydrogen under pressure, and one can insert solid plates of any material desired to act as additional targets. The bubble chamber and the cloud chamber are bulky and are placed outside the Bevatron. By means of magnets the particles to be studied can be guided from the Bevatron to the chamber. Photographic emulsions are also used in this way; but, in addition, they have been plunged into the beam and used as the internal primary target.

COUNTERS

Another way of getting information is by the use of counters. These devices produce electric signals when particles pass through them. Here the experimenter must infer the path of the particles, since he cannot see them directly. For example, if three counters in a row give signals in quick succession he will infer that a fast particle traveled along a line through the three counters. In addition to telling the experimenter when a particle has traversed a particular path, counters can also give quantitative information on the particle's mass, charge, and velocity. This kind of information is obtained by measuring the time required for a particle to go from one counter to another; by measuring the magnitude of the signals from the counters; and by measuring the effects of absorbers and magnetic fields placed between the counters.

Since the information comes in the form of electric signals, the experimenter needs electrical equipment to handle it (amplifiers, coincident circuits, scalers, etc.). There is a special counting area containing this equipment with facilities available to all experimenters who use the Bevatron. In a typical experiment the counters are placed near the Bevatron target, and the signals are sent on cables into this counting room, where the experimenter collects his data.

BEVATRON STATISTICS

GENERAL

Maximum proton energy	6.2 Bev
Number of protons per pulse	$10^{10} = 10^{-9}$ coulomb
Proton velocity	99% velocity of light = 184,000 miles per second
Project approved	February 1948
First accelerated beam	February 15, 1954
Sole purpose	High-energy research

MAGNET

Total magnet weight	10,000 tons
Steel weight (yokes and legs, 1/2" thick; pole tips, 1/4" thick), low-carbon steel	9500 tons
Steel weight of one sector (2 yoke slabs and 2 legs, 20 x 10 ft)	60 tons
Steel weight of one yoke slab of 288 slabs (20 x 2.5 x 2 ft)	22 tons
Air-cooled copper coil (stranded, 1.4-inch diameter)	350 tons - 137,000 ft
Crane capacity (2 cranes)	30 tons each
Magnetic field at injection (10 Mev)	300 gauss
Magnetic field at 6.4 Bev (design)	16,000 gauss

Radius of orbit	50 ft
Length of each of four straight sections	20 ft
Length of orbit (one turn)	394 ft
Cross section of beam aperture	1 ft axially x 4 ft radially

MAGNET POWER SUPPLY

Flywheel Motor Generators – Two Sets

Peak power input to magnet	100,000 kw, 12-phase
Generated current, total	8333 amp
Generated voltage (max at injection)	18,000 volts
Generated voltage at max current	12,000 volts
Driving motors	3600 hp each
Power dissipation in coil windings	3600 kw
Energy stored in magnetic field at peak current	80 megajoules, or 20 kilowatt-hours
Energy stored in rotating flywheels	500 megajoules, or 125 kilowatt-hours
Pulse rate (design)	10 per minute
Efficiency of energy recovery	80%
Weight of flywheels	65 tons each
Rotational speed of generators (no load)	860 rpm
Change in rotational speed of generators at full power output	7%
Power cost for one pulse	$0.10

Ignitron Rectifier and Inverter

Number of units	48
Current passed per unit	2000 amp

Coil Cooling

Cooling air	560,000 cfm (changes magnet room air once every 2 minutes)
Power required to circulate air (total of two units)	500 hp

VACUUM SYSTEM

Volume of system	11,000 ft^3
Surface area at vacuum	25,000 ft^2
Length of vacuum gaskets	1 mile
Operating pressure	4×10^{-6} mm Hg or $\frac{1}{100,000,000}$ atmosphere
High-vacuum pumps (24)	32" diffusion pumps
Mechanical pumps	1800 cfm atmospheric air
Time to pump from atmos pressure to operating pressure	48 hours
Vacuum envelope	4 steel tangent tanks 4 stainless steel curved tanks

INJECTION

Cockcroft-Walton Injector

Voltage	460,000 volts

Proton current (H_2^+ eliminated by 20° turning magnet)	3 milliamperes
Supply current (peak)	30 milliamperes
Number of cascade rectifiers	13

Linear Accelerator

Voltage (proton injection energy to Bevatron)	9.8 Mev
Proton current	150 μamp
Pulse length	500 μsec
Supply power (peak)	1 megawatt
Power to cavity (peak)	0.5 megawatt
Number of drift tubes	42
Length of cavity	18.2 ft
Acceleration frequency	202.5 megacycles
Vacuum system	two 20" mercury diffusion pumps

ACCELERATION

Starting accelerating frequency	360 kc
Final accelerating frequency	2500 kc
Average voltage gain per turn	1500 ev
Number of revolutions of protons	4,100,000
Distance traveled by protons during acceleration	305,000 miles 12 times around earth, or more than distance to moon
Time of acceleration	1.75 seconds

INCIDENTAL INFORMATION

Estimated cost	$9,000,000
Actual cost (outside contracts, materials, labor, and engineering)	$9,600,000
Engineering effort	200 man-years
Engineering drawings made	10,500
Number of vacuum tubes used	3000 - more than 1000 different types
Types of electronic chassis	200
Electronic chassis racks	1000 ft^2
Coaxial signal cable	150,000 ft
Control wiring	900,000 ft
Heaviest piece of magnet	24 tons
Crane capacity	30 tons
Building floor area	75,000 ft^2
Magnet room diameter	220 ft
Shielding effectiveness	attenuation of radiation by a factor of 400
Concrete shielding, lower and upper course	150 lb/ft^2
Concrete shielding, middle course	225 lb/ft^2
Magnet designed to withstand earthquake load of	15% gravitational acceleration

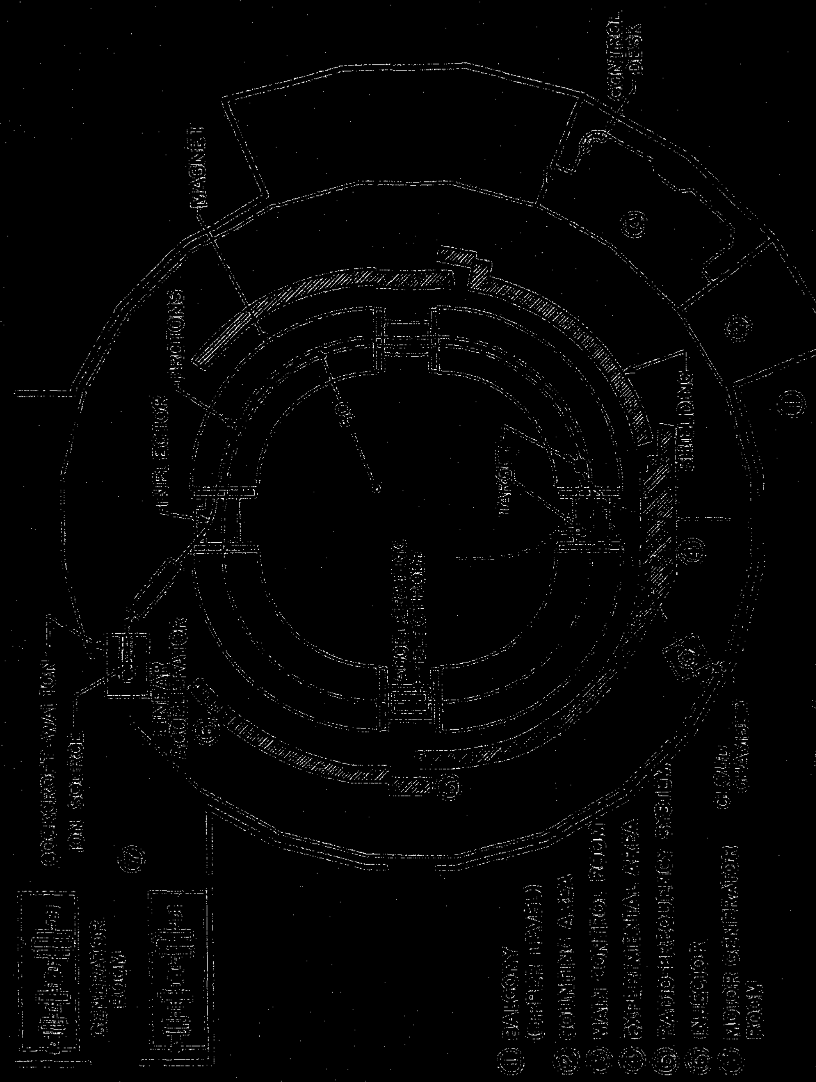


Fig. 6

.tion

0

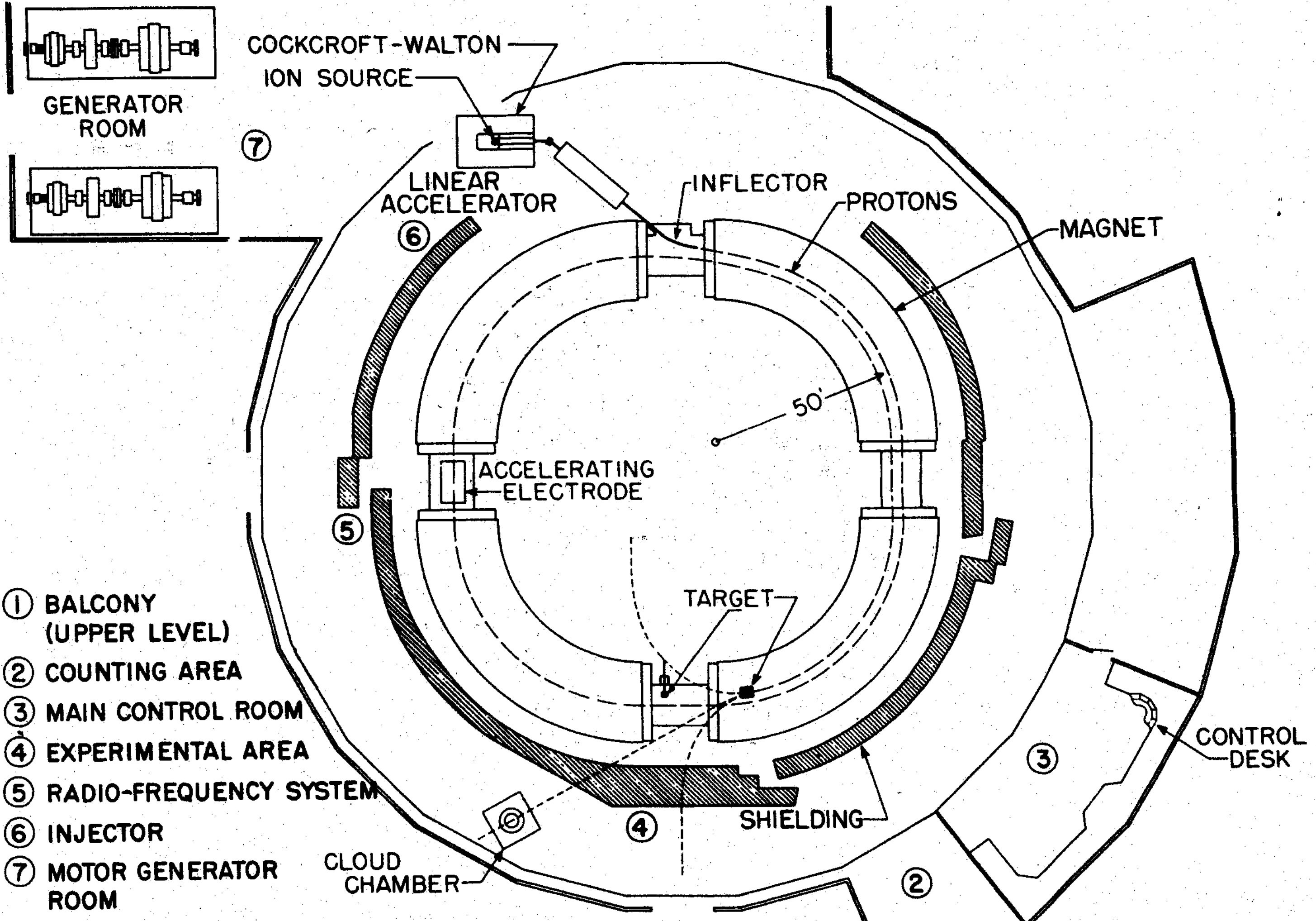
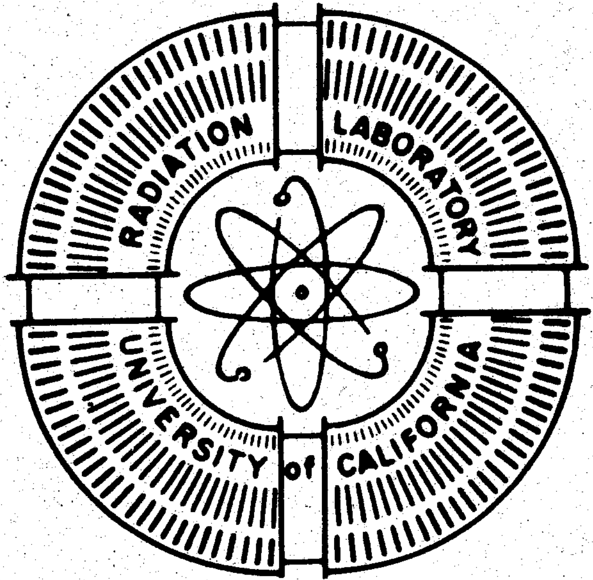


Fig. 6.

MU-7013-A



Pub. No. 2a
7M
Mar. 1958