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GIANT [USA] ACCELERATORS PLANNED TO GENERATE 10-BEV PARTICLES

K. Andreyev

[The following is a compilation of material from articles in current periodicals, principally non-Russian, on the particle accelerators projected at Berkeley and Brookhaven.]

1. Introduction

The generation of extremely high energy particles with the aid of special devices (accelerators) is one of the central problems of modern physics. At the present time cyclical resonance accelerators have had the greatest development. (Note: For the acceleration of electrons, continued use is being made of betatrons as well as resonance accelerators. Cf. UFN, 26, 181, 1944; UFN, 27, 31, 1945; UFN, 30, 119, 1946. The method of betatron acceleration is also used in the primary stage of operation in cyclic resonance electron accelerators, called synchrotrons.) In these devices the particles, revolving in a magnetic field, complete the same or very nearly the same cycles, receiving energy from a high-frequency electric field when they pass the accelerating gaps. The circular frequency ω of a particle rotating with total energy E in a magnetic field H equals:

$$\omega = \frac{ceH}{E} . \qquad (1)$$

From (1) it follows that the radius of the orbit equals

$$R = \frac{E\beta}{eH}, \qquad (2)$$

where $\beta = \frac{v}{c}$ (v is the velocity of the particle, and c is the velocity of light).

For resonance the frequency of an alternating, accelerating electric field ω_λ must equal (or be an integral multiple of) the circular frequency (i.e. angular velocity) the particle:

$$\omega_\lambda = q\dot{\theta} \qquad (3)$$

where q is a multiple of resonance (usually q = 1).

Since the energy of a particle in the process of acceleration must increase, then in order for condition (1) to be fulfilled either parameter H or parameter ω_λ or both must vary in a suitable manner.

This is one of the differences between resonance accelerators and cyclotrons, in which the parameters remain constant. Therefore the operation of a cyclotron is disrupted as soon as the relativistic effect of the increase of mass of the ions being accelerated begins to be felt. For this reason, as is well known, the cyclotron is not suitable for accelerating electrons. In modern resonance accelerators which employ the principle of "automatic phasing" the relativistic mass increase does not impede the operation of the accelerator.

Accelerators with a magnetic field H which varies over a period of time and with an accelerating field ω_λ of constant frequency are called synchrotrons. Synchrotrons are used for the acceleration of electrons. (Cf., for example, the description of an 80-Mev synchrotron in UFN, 37, 501, 1949, and the description of the first model of an 8-Mev synchrotron in UFN, 31, 584, 1947).

Accelerators with a magnetic field which is constant over a period of time and an accelerating electric field with a changing (decreasing) frequency have received the name phasotron. Phasotrons are employed for accelerating heavy particles (protons, deuterons, and α-particles). (Cf. the description of the 184-inch Berkeley phasotron, which produces 400-Mev α-particles and 200-Mev deuterons in UFN, 32, 396, 1947.)

Finally, if in a resonance accelerator both the magnetic field and the frequency of the accelerating electric field vary simultaneously, then such an accelerator is called a synchrophasotron. Here the rule for varying H and ω_A is so chosen that the radius of the orbit will remain constant. The projected synchrophasotrons have been calculated in most cases for the acceleration of heavy particles.

Modern resonance accelerators, which were first proposed by V. I. Veksler [1] in 1944, are based on the property of "automatic phasing" or "phase stability."

In the theory of accelerators it has become customary to designate as the phase of the particle φ the phase of the alternating electrical voltage $V = V_0 \cos \omega_A t$ at the moment when the particles pass the accelerating gap. The successful operation of an accelerator requires that on the average over many revolutions the phase of the particle should equal the phase corresponding to sufficiently high accelerating voltage.

The property of automatic phasing means that for a definite interval under initial conditions the phase of a particle during acceleration executes damping oscillations around a certain stationary phase (phase point) φ_0, corresponding to the accelerating resonance voltage $V_R = V \cos\varphi_0$. The motion of a particle in resonance with the accelerating voltage is called equilibrium motion, and the corresponding parameters (energy, radius, orbit, etc.) are equilibrium parameters. Coupled with the oscillations of the phase (and this also means the energy) of a particle are the oscillations of the radius of the orbit (2) about the equilibrium position (these are called radial-phase oscillations). These oscillations have a frequency considerably lower than the circular frequency of the revolving particle; in other words, radial-phase oscillations take place slowly in comparison with the particles' period of revolution. Superimposed on these slow oscillations of the radius are the much more rapid "free" radial and vertical oscillations which are well known from the theory of the betatron. (Note: See, for example, Ya. P. Terletskiy, Journ Phys USSR, 9, 159, 1945, and also UFN, 27, 31, 1945). The frequencies ω_r and ω_z of these oscillations are of the same order as the circular frequency $\dot{\theta}$ and are equal, respectively, to:

$$\omega_r = \dot{\theta}\sqrt{1-n}, \quad \omega_z = \dot{\theta}\sqrt{n},$$

where the quantity

$$n = -\frac{\partial \ln H_z}{\partial \ln R},$$

the index of diminution of the magnetic field, characterizes the configuration of the magnetic field. For statble motion the quantity n must satisfy the inequality $0 < n < 1$.

Phase oscillations for given initial conditions take place between the values φ_1 and φ_2 (see Figure 1), which are disposed, generally speaking, unsymmetrically relative to φ_0. The boundary values φ_1 and φ_2, at which an oscillating system for the phase is still generally possible, are equal respectively to φ_0 and φ_3 (the latter value is determined from a certain transcendental equation and also depends on φ_0).

Automatic phasing takes place for a sufficiently slow ("adiabatic") variation of the accelerator's parameters - namely, potential of the magnetic field H, frequency of the accelerating field ω_1, etc.

As the theory shows [2], the phase behavior of particles in resonance accelerators is described by an equation which conforms with the equation for a physical pendulum with an external moment and adiabatically varying coefficients

$$\frac{d}{dt}(a\dot{\varphi}) + b\cos\varphi = c, \tag{4}$$

where a, b, and c are slowly varying functions of time. Phase behavior can be conveniently investigated on the phase plane within the coordinates $(\varphi, \dot{\varphi})$. An illustrative drawing on the phase plane for equation (4) is shown in Figure 2 (the characteristics are the same as for Figure 1). The closed oval orbits surrounding the point φ_0 correspond to the periodic phase variations about φ_0. Such is the phase behavior for particles which are caught up in the acceleration regime and, on the average, accelerated by the resonance method.

The limit curve (separatrix) separates the closed periodic orbits from the unclosed phase trajectories. The latter correspond to such particles as are not captured in the acceleration regime, fall subsequently into completely different phases (corresponding to the lag among them), and are unable to reach high values of energy. Obviously the "phase region of capture" lies within the limits $(-\varphi_0, \varphi_3)$.

An exposition of the theory of the motion of a particle in a resonance accelerator is beyond the scope of this review, which is specially devoted to the plans for giant accelerators designed to produce protons with energies equal to 10,000 Mev.

However, since we contemplate a further exposition, it is necessary to make a few more remarks. In agreement with (1), (2), and (3) the radius of the equilibrium orbit in a synchrotron increases in proportion to the velocity of the particle (and stops increasing only in the relativistic region for $\beta \to 1$):

$$R(t) = \frac{cq}{\omega_\lambda}\beta(t). \quad (5)$$

In the phasotron the equilibrium radius increases considerably more rapidly because of the decrease of the frequency $\omega_\lambda(t)$ (and continues growing also in the relativistic region):

$$R = cq\frac{\beta(t)}{\omega_\lambda(t)}. \quad (5a)$$

In order to keep the equilibrium radius constant during acceleration ($R = R_0 =$ const.), as this takes place in the synchrotron, the frequency $\omega_\lambda(t)$ must be increased with time in proportion to the velocity $\beta(t)$:

$$\omega_\lambda = \frac{cq}{R_0}\beta(t) = \frac{cq}{R_0}\sqrt{1 - \left(\frac{E_0}{E(t)}\right)^2}, \quad (6)$$

where E_0 is the potential energy of the particles. In other words, the frequency of the electric field ω_λ must vary in the same way as the frequency of a particle, which moves in a betatron along an equilibrium orbit with the same radius and the same magnetic field as in a synchrophasotron.

On the other hand, for resonance the magnetic field must increase in proportion to $\omega_\lambda(t)E(t)$. Besides, from the point of view of the constancy of the equilibrium radius no limits are imposed on the variation of the quantity H.

Consequently, when the magnetic field is varied simultaneously, the conditions may be attained where the radius of the equilibrium orbit will remain constant and where, in addition, resonance acceleration will take place. With an arbitrary (but sufficiently slow) increase of the intensity of the magnetic field the frequency of the accelerating electric field must vary with time according to a completely fixed rule depending upon the of H(t). This rule can be obtained at once by combining (1), (3), and (6):

$$\omega_\lambda(t) = \frac{c}{\left[1 + \left(\frac{E_0}{eR_0 H(t)}\right)^2\right]^{1/2}} . \qquad (7)$$

The total variation of frequency which is necessary in the process of acceleration is determined from the initial E_i and final E_f energies of the particle. A large variation of the frequency ω_λ during acceleration presents considerable technical difficulties. For a given value of the final energy the ratio between the final $\omega_{\lambda f}$ and initial $\omega_{\lambda i}$ frequencies depends only on the initial energy and equals

$$k = \frac{\omega_{\lambda f}}{\omega_{\lambda i}} = \frac{\sqrt{1 - \left(\frac{E_0}{E_f}\right)^2}}{\sqrt{1 - \left(\frac{E_0}{E_i}\right)^2}} . \qquad (8)$$

Thus, the higher the input energy (injection energy) E_i of particles, the less necessary it is to modulate the frequency ω_λ in a synchrophasotron. As is evident from (8), in the relativistic case ($E_f \gg E_0$) the quantity k in general practice does not depend on the final energy E_f, but is determined entirely by the initial energy.

2. Bevatrons

In the last few years there has been an intensive construction of modern accelerators of various types, a number of which are already operating successfully. Together with the construction of accelerators which are calculated to produce particles with energy of the order of hundreds of Mev, there have appeared projects for the creation of much more powerful devices, in which particles will be accelerated to energies of the order of several billion electron volts. Accelerators calculated to produce particles in this energy range have received in American literature the title bevatron (from 10^9 ev = 1 Bev = 1 billion electron volts). In 1947 there was described in the literature a proton accelerator of $1.3 \cdot 10^9$ ev planned at Birmingham University. Here will be described two 10-Bev bevatrons which are being planned in the USA at the Brookhaven National Laboratory under the leadership of Livingston and at Berkeley University [sic] under the leadership of Brobeck.

The energy 10 Bev, as Livingston [4] pointed out, was chosen because it exceeded the threshold for the formation of nucleon pairs, namely 5.6 Bev. [5]. This value is located in the same energy range as a definite segment of primary cosmic rays. In the case of electrons, according to many authors radiation losses set a limit of the order of 1-2 Bev for the maximum attainable energy of electrons in cyclical accelerators. (Note: On radiation by electrons see UFN, 33, 277, 1947; UFN, 34, 398, 1948.) For protons the radiation losses, which are inversely proportional to the fourth power of the potential energy of the particle, are negligibly small for energies of several tens of Bev. Therefore, in the case of heavy particles the maximum attainable energy, if we refer to the methods now used for the acceleration of particles, is limited only by technical feasibility and by economic considerations.

Of the four principal practical types of accelerators--the phasotron, betatron, synchrophasotron, and linear accelerator--the synchrophasotron is the most advantageous at energies of this order. The phasotron requires a solid magnet of huge radius with a magnetic field whose magnitude and configuration must satisfy sufficiently rigid requirements. The betatron requires a large quantity of iron for the creation of the powerful central flux which is required in order to fulfill the condition of a 2:1 ratio. The linear accelerator for protons up to such energies must have a colossal length, while in addition the difficulties of focusing the beam of particles and synchronizing the system over its whole length must be overcome [6]. The synchrophasotron with its ring magnet is, it would seem, the most suitable and practicable for generating 10-Bev protons.

Furthermore, it is necessary to choose the type of magnet--with or without an iron core. The advantages of a magnet without iron lie in the fact that the maximum field intensity is not limited by saturation as in the case of iron and in the saving of a large quantity of iron. However, this type of magnet leads to intolerably high values of reactive power and creates very great difficulties of mechanical design and reliability, as well as in the sense of obtaining the necessary distribution of currents for creation of a magnetic field of the appropriate configuration. It is not by chance, therefore, that both projects referred to propose to employ accelerators of the synchrophoasotron type having magnets with iron cores. Of course, the known advantages of the synchrophasotron do not imply that in the design and construction of these colossal devices there are not a whole series of serious difficulties connected with problems of cyclotron, synchrotron, and betatron technology which must be overcome. Here dimensions unheard of up to this time must be encountered (suffice it to say that 10 Bev exceeds by 25 times the maximum energy obtained in accelerators up to this time).

The amount of data published on the problems of designing and building the bevatrons is not as yet great. On the project of the Brookhaven Laboratory there are only a few short remarks relating to individual constructional problems [4, 7, 8, 9]. Described in more detail is the Berkeley

University project, and to this the leader of the project, Brobeck, devoted an article [10] which appeared after a series of preliminary reports. However, even in the latter case the data cited provide only an orientation on the subject, and the majority of problems are only posed, not solved. We will consider these two projects separately.

3. The Brookhaven Laboratory Bevatron Project

The ring magnet of the accelerator will probably contain rectilinear sections, i.e., will be of the "racetrack" type (see Figure 3). (This type of magnet received the name "racetrack" from its oval form.) The rectilinear sections, in which the particle moves in the absence of a magnetic field, are inserted to facilitate the assembling and servicing of the device, to accomodate the bulky accelerating system, to provide an input and output for the beam of particles from the accelerator, etc.) The magnet is made up of plates each 1.25 cm thick. The maximum magnetic field near the orbit is 15,000 gauss. Accordingly the radius of the equilibrium orbit is $R_0 = 24.4$m. During the operation of the accelerator an energy of $5 \cdot 10^7$ joules is to be stored in its magnetic circuit. The cross section of the magnet is C-shaped and has the air gap on the outer side, the air gap being 120 X 30 cm in cross section. The properties of this type of magnet are being investigated with a 1/4-scale model in the form of a 6° arc. The injection energy is $W_1 = 4$ Mev. The frequency of the accelerating electric field varies from 0.18 Mc to 2 Mc, i.e., an eleven-fold variation. For this reason the utilization of resonators like those which are used in electron accelerators [11] meets with great difficulties in the case under consideration. The resonator would have to be very large; to tune one to the specified wide frequency range is extraordinarily difficult, and currents of the order of one thousand amperes are required in operations with an untuned resonator. Therefore it is proposed to use an accelerating system of the "transformer" type, i.e., to utilize an induction method of acceleration, not, however, for the whole revolution, as in the betatron, but in the narrow accelerating gap. One of the rectilinear sections of the chamber is surrounded by a ring of laminated or powdered ferromagnetic material whose weight reaches several tons. The winding of this ring core is primary, and the ion beam itself serves as a turn of the secondary winding. The ion beam is accelerated by the whirling electric field which is created in the chamber inside the ring-shaped magnet. It is considerably easier to vary the frequency of the electric field over a wide range in such a system. The increment of energy per revolution must amount to $\Delta W = 5.5$ Kev. The time of acceleration of protons is about 1 second. It is proposed first to test the methods, necessary for synchronizing the electric field and the directing magnetic field, on an electron model 1 meter in diameter.

According to certain reports [12] Brookhaven Laboratory is also planning a bevatron for acceleration of 3-Bev protons. On this project only the following data have been published:

$R_0 = 915$ cm, $W_i = 3$ Mev, $\Delta W = 1.15$ Kev, $A = 8$ cm,

where A is half the height of the vacuum chamber.

4. The Berkeley University Bevatron Project

The problems which are being analysed in this project not only relate in considerable measure to the given device, but also are common to all large installations calculated to produce particles with energies in the hundreds and thousands of Mev.

One of the chief difficulties encountered in the design of a bevatron (or the synchrophasotron type) is the necessity of modulating the frequency of the accelerating electrical field many times to correspond with the variation in velocity of the proton (see 7). In agreement with (8), therefore it is desirable to start the synchrophasotron regime at the greatest possible initial velocity. In estimating the energy value from which the synchrophasotron regime must begin, the author of the project proceeds from the point that at the present time a two-fold modulation of frequency has been achieved in the phasotron, and soon a three-fold modulation must be reached [13]. Therefore it is proposed to accelerate protons initially in a betatron regime to a velocity equal to one third of the speed of light and then to conduct the acceleration up to the final energy in the synchrophasotron regime. Moreover, as will be made clear below, this circumstance (the presence of an initial betatron regime) requires no supplementary increase of the quantity of iron due to the cross section chosen for the ring magnet (see Figure 5).

For the input of particles at the start of the [illegible] regime it is also necessary, in so far as possible, to utilize high voltage injection so as to decrease the losses resulting from the scattering of particles and the divergence of the beam due to coulomb repulsion, and also so as to avoid the effect of azimuthal asymmetry of the magnetic field. By azimuthal asymmetry is meant the declination of the configuration of the directing magnetic field H_z from axial symmetry, i.e., H_z depends on the azimuth of θ. If $H_z(\theta)$ is expressed as a Fourier series:

$$H = H(R)\left[1 + \sum_{\ell=1}^{\infty} h_{\ell} \cos(\ell\theta + \alpha_{\ell})\right], \qquad (9)$$

then, in agreement with Bohm and Foldy [2], the correction δR to the radius of the instantaneous orbit R_1 which is introduced by the azimuthal asymmetry δH is:

$$\delta R = R_{\ell} \sum_{\ell=1}^{\infty} \frac{h_{\ell}}{\ell^2 + n - 1} \cos (\ell\theta + \alpha_{\ell}), \tag{10}$$

where n is the index of diminution of the magnetic field:

$$n = \frac{\partial \ln H_z}{\partial \ln R} . \tag{11}$$

As is evident from (10), the circular orbit is distorted; whereupon the lower harmonics (small values of ℓ) have the largest values. Therefore, we can consider approximately that

$$\frac{\delta R}{R_0} \approx \frac{1}{n} \cdot \frac{\delta H}{H} . \tag{12}$$

There is a danger of azimuthal asymmetry in the given case due to the comparatively small value of $\frac{\Delta R}{R_0}$ (the ratio of the width of the working region to the radius of the equilibrium orbit), which, in agreement with (12), imposes rather rigid requirements on the magnitude of the azimuthal variation of the magnetic field $\frac{\delta H}{H}$. It is proposed that the injection be done with the help of a 4-Mev Van de Graaff generator, which corresponds to a sufficiently large initial magnetic field intensity of 120 gauss near the orbit. The successive steps of the acceleration process are shown in Table I.

In order to conduct the proton beam from the Van de Graaff generator tangentially to the orbit, it is proposed to use an electrical deflector made of deflecting disks of 4.5 m radius. Here the electrical field between the disks must equal 18 kv/cm. The effective width of the "injector", which introduces the danger of loss of particles by collision, is determined in this case by the thickness of the internal deflecting disks. At the end of the accelerating cycle the proton beam must be deflected on to an external or internal target, either by upsetting the resonance relationship between the frequency of the accelerating field and the intensity of the magnetic field, or by superimposing a pulsating deflecting electric field. The beam obtained from the target as a result must be utilised further for various investigations.

The general schematic diagram of the accelerator is given in Figure 4. As is evident, this is a "racetrack" type accelerator consisting of four curved sections which are connected by short rectilinear gaps. The radius of the equilibrium orbit R_0 is determined from the final energy E_m and the maximum attainable value of the magnetic field intensity H_m, in agreement with the formula $E = HR$ (in electron volts), and is equal to 24.4 m. The length of each of the rectilinear sections [illegible] m. In accordance with the "racetrack" theory [14], when the value n [illegible] 0.7 is chosen for the index of diminution of the magnetic field, the rectilinear gaps disturb the stable motion of the particles only very little. Injection must take place in two of the rectilinear gaps. The use of two injectors (Van de Graaff generators) would increase the intensity of the beam of accelerated protons and guarantee the dependability of operation. In the third rectilinear gap is placed the accelerating apparatus. Finally, the fourth and last is designed to facilitate the output of these products obtained from the collision of the accelerated proton beam with the target. Moreover, a vacuum pump is connected to each rectilinear gap (see Figure 4). The weight of iron required for the magnet is equal to 1[illegible],000 tons.

The cross section of the magnet is shown in Figure 5. Most important here are the cross sectional dimensions (height and width) of the air gaps. These dimensions to a significant degree determine the value of the whole apparatus as a unit, since the operating volume, in which the necessary magnetic field must be created, depends on them.

Selection of the height of the gap is determined by the following factors: a) angular dispersion of the input beam, b) distortion of the magnetic field's plane of symmetry, c) thickness of the chamber walls and size of the permissible gap between walls and magnet, and d) scattering of ions in the residual gas.

The input beam can be so focused that the maximum amplitude of the vertical oscillations will not exceed 7.5 cm. 5 cm is sufficient for the chamber walls and the clearance. Vertical distortion of the average plane can be corrected with the aid of auxiliary coils in the rectilinear sections. The essential factor influencing the choice of height for the chamber is obviously the scattering of ions in the residual gas. When the pressure is 10^{-5} mm/Hg, the height of the chamber available for the motion of protons is 15 cm, and the energy increment per [illegible] = [illegible]300 ev, then about 10% of the particles introduced reach the maximum energy (if factors other than scattering are not taken into account). The height selected for the air gap from the cited considerations is 20 cm.

In the general case that fraction of the number of ions introduced which reach maximum energy (if only scattering is considered) is approximately proportional to the quantity

$$\exp\left[-\frac{KR_0NZ^2}{A^2\Delta W W_1}\right] \qquad (13)$$

where W_1 is the kinetic energy of injection,

Z and N are the atomic number and number of atoms per unit volume of the residual gas,

ΔW is the energy increment of an ion per revolution,

R_0 is the radius,

K is a constant, and

2A is the vertical dimension of the vacuum chamber; this dimension is supposed to be much smaller than the horizontal dimension. (Concerning the effect of particles' scattering on the residual gas in the chamber of a synchrophasotron, see the detailed work of Blackman and Courant [12].) As a result of the exponential factor a two-fold change in pressure can increase particle losses five times which indicates the sensitivity of output current to chamber pressure. We notice, moreover, that the energy losses resulting from incomplete vacuum are extremely small; thus at 10^{-5} mm/Hg the energy losses of a 4-Mev proton are 25 ev per revolution, and the losses of a 10-Bev proton fall to less than 1 ev per revolution.

The selection of the radial dimension (the width of the operating region) is a more difficult task than the selection of the vertical dimension and it is determined by a large number of factors. These factors are: a) angular divergence of the input beam, b) radial oscillations and compressed orbits, which are determined by the "transparency" of the injector (i.e., the chance for the ions to elude the injector in the process of acceleration), c) distortion of the orbit caused by upsetting of the 2:1 ratio in the course of betatron acceleration, d) radial-phase oscillations in the course of the synchrophasotron regime, and particularly during the transitional regime (in the transition from betatron acceleration), e) azimuthal asymmetry of the magnetic field, f) inaccuracy in attaining the resonance relation (7) between the frequency of the accelerating field and the intensity of the magnetic field during the synchrophasotron regime, g) spatial non-uniformities of the magnet, and h) scattering in the residual gas in the vacuum chamber.

The change in the radius of the orbit resulting from a relative error in the 2:1 betatron condition is equal to [15]

$$\frac{\alpha}{1-n}\left\{1-\frac{H_1}{H}\right\}R_0 ,$$

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where H_i is the magnetic field during injection, n = 0.7 is the index of diminution of the magnetic field. For α = 0.1% this change of radius in the period of betatron acceleration can reach 6.25 cm.

The change of radius resulting from an inaccuracy f in fulfilling the synchrophasotron condition (7) equals

$$\frac{f}{n + \beta^2(1 - n)} R_0 .$$

For f = 0.1% this change can reach a maximum of 3.5 cm.

The change of radius due to radial-phase oscillations is equal to [2]

$$[illegible]$$

where W is the kinetic energy of an ion, $\Delta\varphi$ is the amplitude of the phase oscillations, φ_0 is the value of the steady phase (phase point), and q is the number of periods of the accelerating field in the time of one revolution of a particle (the resonance multiplier). The presence of the factor $q^{-1/2}$ is characteristic for this formula. The appearance of this factor is tied in with the fact that in this accelerator the frequency of the alternating accelerating electric field exceeds the circular frequency of revolution by q times (q = 6). At the beginning of synchrophasotron acceleration $\Delta\varphi$ can reach 1 radian. When ΔW = 6300 ev and q = 6 this has a value of 7.5 cm for the maximum deviation of the radius from R_0. Azimuthal asymmetry, if it reaches any noticeable value for the selected value of injection energy, can be corrected by shimming or properly adjusting the magnet current separately in the quadrants of the "racetrack". Since the width of the gap is several times greater than its height, losses from scattering in this case (through collision with the vertical walls) are small.

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An important and complex problem is that of the "transparency" of the injector during acceleration, i.e., the problem of how the particles can elude the injector in the process of acceleration. As Wideroe and Toushen have shown, the "transparency" of the injector depends on the velocity with which the ionic orbit shrinks during injection. The amount by which the radius of the orbit decreases in one revolution is equal to $\frac{\Delta W}{2W_1} X$. Even for $X = 1$ meter the amount of shrinkage equals only 0.075 cm. With such a small shrinkage the portion of ions captured in the system is estimated at 1% The capture efficiency can be increased, however, if we vary in an appropriate manner the value of the ratio $\frac{\bar{H}}{H}$ where $\bar{H}$ is the average value of the magnetic field inside of the orbit, and H is the value of the magnetic field near the orbit. For example, if the quantity $\bar{H}$ is kept constant in the injection period, then the radius of the orbit in one revolution will be reduced by 2.5 cm.

From all the above enumerated factors the value for the radial dimension of the operating region is chosen as 120 cm, which is about 5% of the equilibrium radius. We note that in order to guarantee the necessary value $n = 0.7$ the height of the gap must vary only by 0.7 cm over the 120 cm distance

For larger values of magnetic field intensity the width of the operating region can be made smaller. This is due to the fact that the amplitude of free oscillations tapers off as $H^{-1/2}$, while the amplitude of phase oscillations decreased during acceleration in proportion to $W^{-1/2} - W^{-3/4}$, where W is the kinetic energy (the values cited are suitable for relativistic and non-relativistic cases).

Accordingly it is proposed that for larger values of magnetic field intensity the volume inside of which the magnetic field is generated (because of saturation of the special sharp edges of the tips of the poles) be decreased (see Figure 5). In this manner a considerable decrease in the magnetic energy required can be achieved. The stored magnetic energy can be calculated from the formula $M = \frac{10}{4\pi} 10^{-8}$ [illegible], where H_m is the maximum field in the gap, ℓ is the length of the gap, Φ is the magnetic flux through the windings, eta is that part of the total number of ampere-turns which generates the field in the gap. Taking the intensity to be 17,000 gauss in the iron and as 15,000 gauss in the gap and eta = 0.8, we obtain the value 48 megajoules for M. The most important parameter in the problem of supplying the magnet with power is the time lag during which the magnetic field grows from zero to its maximum. As this time lag is increased the cost of the energizing apparatus decreases. However, a large increase of the acceleration time is limited by the following factors: a) loss of energy in the residual gas, b) scattering in the residual gas, c) divergence of the ion beam due to space charge, and d) the necessity for the ions to elude the injector. These factors have been discussed above, except for the effect of a space charge. The maximum current in a beam as a result of the space charge is of the order of 10^{-8} amperes, i.e., much higher than could be expected from the other considerations. Therefore the effect of the space charge is unimportant.

The period of acceleration, or what is the same thing the time for the growth of the magnetic field, was selected as 1 second.

Another important question in the energizing of the magnet is the means to create a huge store of energy. Generally speaking, this energy can be stored in condensers, accumulators, or revolving flywheels. The first two means seem unsuitable in this particular case due to the immense size and complexity of the equipment. It is proposed to employ three-phase, 60-cycle alternating-current generators which are hooked up to the magnet through ignitrons serving as rectifier-inverters. In order to reach an energy of $48 \cdot 10^6$ joules in 1 second in the magnetic circuit, 60,000-kilowatt generators are necessary. To decrease the reaction force on the foundation, it is desirable to employ two 30,000 kw machines which rotate in opposite directions.

With the aid of the rectifier-inverter, 60-cycle alternating current is converted into direct current which rises to a maximum in 1 second and falls to zero in the same time. While the current is rising the energy enters the magnetic circuit from the generators. After the maximum value of current has been passed the process begins to move in the opposite direction, and the energy starts to return to the generators. The latter now operate as electric motors, turning heavy flywheels. Suitable for rectifier-inverter action is the pentode ignitron GL 506, which operates at a maximum current of 900 amperes for a return voltage of 20,000 volts. For a potential of 20,000 volts in the magnetic circuit the current amplitude must reach 4,800 amperes, for which 36 ignitrons in a three-phase, full-wave rectifier are necessary. With the method described for energizing the magnetic circuit the current in it will rise and fall linearly with time.

When the rotational velocity of the rotor in a generator is 1800 rpm, a flywheel 4.5 m in diameter and 4.5 m in length and weighing 30 tons is required to maintain the velocity within limits of 10% of this value.

Since the magnet requires 300,000 ampere-turns and the amplitude of the current is 4800 amperes, then the number of turns in the basic winding must be 62. Taking the current density in the conductor as 160 amp/sq cm, we arrive at a cross sectional area of 1.7 sq cm for the conductor when the effective current is $\frac{1}{\sqrt{3}}$ 4800 = 2760 amperes. The copper in the windings weighs 325 tons, while the I^2R operating losses for continuous operation reach 1360 kilowatts. The motor power required can be estimated from: operating losses in the winding, losses in the iron, and generator losses. The requirement imposed on the losses in the iron is that they should not exceed 1% of the energy stored in a cycle, or 480,000 joules every two seconds, i.e., 240 kw. Losses in the generators should amount to about 3% of their reactive power, i.e., 1800 kw. Therefore the motor must develop [illegible] kw or [illegible] hp. The motor must be asynchronous with lagging rotation of the rotor (i. e. large relative slippage) so as to develop approximately constant power when the rotational velocity varies within the limits of 10%

The power requirement can be lowered in operation with a lower pulse frequency. For example, if we take three pulses per minute instead of thirty, then the power required for motors and generators can be decreased by 10 times. However, this economy obviously will not be worth while, since the cost of equipment for supplying power makes up only a small portion of the total cost of the apparatus, and in order to benefit from operation at a low pulse frequency the generators must be constructed with a capacity to withstand large momentary overloads.

The variation of the central magnetic flux, which is necessary for realization of the betatron regime, is achieved with the aid of a supplementary winding around the internal or external vertical yokes (see Figure 5). The central flux can most conveniently be controlled by maintaining the appropriate ratio between the voltages of the basic and auxiliary (betatron) windings. This can be accomplished by energizing the auxiliary winding from a rectifier hooked up to the main generator through a variable voltage transformer (variak).

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The cross sectional area of the inner yoke comprises 4.5% of the area circumscribed by the orbit. Therefore, while the field on the orbit varies from 120 to 450 gauss (this corresponds to acceleration in the betatron regime: see Table I), the average magnetic field intensity (density of the magnetic flux) necessary in the inner vertical yoke in order to conform to the 2:1 betatron condition must vary by the following amount:

$$\frac{2(450-120)}{0.045} = 14,000 \text{ gauss}$$

The magnetic flux density during injection is taken equal to 7000 gauss in the direction opposite from that of the magnetic flux in the air gap. During the betatron regime the flux in the inner yoke reverses its direction and again reaches a density of 7000 gauss, so that the change of flux density is equal to the required value of 14,000 gauss (see Figure 6). Corresponding to this quantity there is a change of 500 gauss in the magnetic flux at the pole tips and a change of 330 gauss in the field intensity inside the air gap.

To generate a magnetic field density of 7000 gauss in the inner yoke, 2400 ampere turns or 600 amperes in 4 turns are required. The duration of the betatron regime is

$$\frac{450 - 120}{15,000} = 0.022 \text{ sec.},$$

which corresponds to a frequency of 25 cycles/sec. At this frequency losses by Foucault currents in the transformer iron (plates 0.15 cm thick) reach 0.45 watt/kg; or 4800 kw in continuous operation. During one half cycle these losses are

$$\frac{4800}{50} = 96 \text{ kilojoules.}$$

When the potential in the auxiliary winding is 20,000 volts, the amplitude of the current required to make up for these losses is 480 amperes. Thus, the total current across the auxiliary winding must equal 600 + 480 = 1100 amperes.

At the beginning of the synchrophasotron regime the flux through the inner yoke again starts to fall off, and at the end of the acceleration it reaches a maximum in the opposite direction, when the magnetic flux density equals - 15,000 gauss (see Figure 6). For this a potential of the order of 500 volts must be applied to the auxiliary winding in the opposite direction from that which is applied in the betatron regime. In the following half cycle (idle in the sense of acceleration) a potential of the order of 200 volts must be applied to the auxiliary winding in order to bring the value of the magnetic flux up to -7000 gauss, which is the starting condition for the next cycle (see Figure 6). Obviously, the decrease of magnetic flux density in the inner yoke from +7000 to -15,000 gauss (during the synchrophasotron regime) will seem to be a reverse betatron action; i.e., it will generate a certain damping field. However, this effect is weak because of the slowness of diminution of the magnetic flux density and can be easily compensated for by increasing the amplitude of the accelerating synchrophasotron voltage by several percent.

The accelerating system is placed in one of the rectilinear gaps, as is shown in Figure 7, and can be described as a resonator 3.66 meters long stretched longitudinally across the gap. The frequency of the electrical field in the resonator is modulated by varying the capacitance with the aid of rotating condensers, also shown in Figure 7. When the ratio between the maximum and minimum capacitance of the rotating condensers is 16, the frequency can be varied from 3 to 12 megacycles. Since during acceleration the time for a revolution of the ions changes from 1.8 μsec, the frequency range used in operation at the sixth harmonic ($q = 6$) will be from 3.3 to 10 megacycles.

The value of the required increment of energy per turn can be found from the expression

$$\Delta W = e 2\pi R_0^2 \frac{dH}{dt} 10^{-8}, \qquad (14)$$

where $\frac{dH}{dt} = 15{,}000$ gauss per second. This yields the value $\Delta W = 6300$ ev.

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The equilibrium phase φ_0 is chosen approximately equal to 60°, or, in other words, the amplitude of the voltage is taken as 12,000 volts. This approximates the well-known conditions for the operation of an efficient phasotron, where the power required of the generator may be estimated as being of the order of 100 kw. The relation (7) between ω_λ and H, which must be realised with an accuracy of 0.1%, can be automatically maintained in the following manner. To the rotating condenser is attached a "collar" which activates a rheostat or some other device permitting one to obtain a voltage proportional to the required magnetic field. This voltage is compensated for by a voltage taken off a coil which rotates in the magnetic field. The potential difference is fed into the control device in order that a corresponding small variation of the resonator frequency may take place. It is proposed that the plates of the rotating condenser be shaped in such a manner that the frequency will vary according to a rule as closely approaching (7) as possible, so that the frequency correction required in operation will not be great.

The vacuum chamber is composed of porcelain sections each 30 cm wide and 120 X 20 cm in cross section, and with wall thickness of 1.875 cm (3/4 of an inch).

The joints between the individual sections are sealed with rubber gaskets which are sheathed with thin metal plates. A pair of vacuum pumps is located at each rectilinear section (see Figure 4). Two plastic rings with diameters of the order of the diameter of the orbit are attached to the sharp edges of the pole tips and close off the space around the vacuum chamber (these rings in cross section are visible in Figure 5). The volume bounded by the rings and the pole tips is evacuated in order to decrease the pressure on the vacuum chamber. This space must contain hydrogen or helium at low pressure. Thus if any gas penetrates into the chamber it will have a small atomic number, as a result of which losses from scattering will be decreased.

The expected current of accelerated ions at the output of the accelerator can be estimated approximately by the following means. The time interval Δt, in which the instantaneous orbits during injection are within the boundaries of the operating region, is determined by the formula [17]:

$$\Delta t = (1 - n) \frac{H_i}{\dot{H}_i} \frac{\Delta R}{R_0}, \tag{15}$$

where H_i is the value of the magnetic field in the period of injection and ΔR is the width of the operating region. In this case

$$H_i = 120 \text{ gauss}, \quad \frac{\Delta R}{R_0} = 5\%, \quad \dot{H}_i = 15{,}000 \text{ gauss/sec}, \quad n = 0.7.$$

From this the maximum time for capture of ions by the accelerator is $\Delta t = 120\ \mu$ sec. Assuming that each of the two Van de Graaff generators produce a current of 50 microamperes and considering that capture takes place in each two seconds, whereupon for various reasons only 2% of the maximum possible value is captured during injection, we obtain $1.2 \cdot 10^{-10}$ amperes as the average value of the current captured as a result of injection. Moreover, if we take into consideration that only 10% of this amount reaches the end of acceleration because of scattering, then we receive 10^{-11} amperes as the average current at the output. This current is sufficient for experimental purposes, particularly if we take into consideration the fact that it consists of individual pulses with much greater instantaneous values of current.

Also cited in the project are certain data on the expenditures connected with construction of a bevatron, and these may elicit considerable interest. The cost of the magnet is estimated at 10 million dollars, and cost of the apparatus which supplies the magnet with power is estimated at 1 million dollars. The over-all cost of the device is estimated at 15-20 million dollars.

In conclusion we present a table containing the values of the basic parameters of the projected synchrotron for the generation of 10,000-Mev protons (Table II).

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TABLE I

Successive Stages in the Acceleration Process

	At Injection	At the Beginning of the Synchro-phasotron Regime	At Maximum Energy
Energy of Ion	4 Mev	55 Mev	10,000 Mev
Magnetic Field	120 gauss	450 gauss	15,000 gauss
Velocity of Ion	0.0092·C	0.333·C	0.996·C

Table II

Values of Basic Parameters of Berkeley Synchrophasotron

Radius of Orbit	24.4 m
Length of Rectilinear Section	6.1 m
Height of Air Gap of Magnet	20 cm
Width of Operating Region at Low Energies	120 cm
Index of Diminution of Magnetic Field	0.7
Weight of Iron in Magnet	13,000 tons
Weight of Copper in Magnet	400 tons
Energy Stored in Magnet	$48\cdot10^6$ joules
Period of Acceleration	1 second
Frequency of Pulses of Accelerated Ions at Output	30 per minute
Power of Generator (Total)	60,000 kw
Power of Motor (Total)	5,000 hp
Amplitude of Voltage at Accelerating Gap	12,000 volts
Energy Increment of Ion per Revolution	6.3 Kev
Frequency Range of Generator	0.3 to 10 Mc
Number of Periods of Accelerating Field in One Revolution of the Ion (Multiplier q)	6

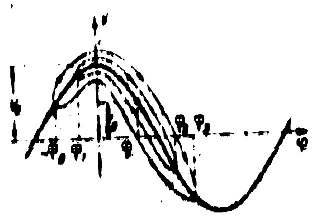

Figure 1. Alternating electric accelerating voltage and the phase be-
havior of a particle in a resonance accelerator.

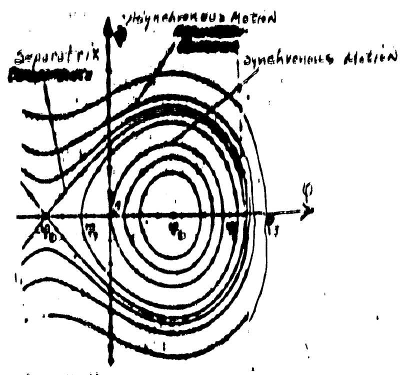

Figure 2. Picture on the phase plane for the phase of a particle in a resonance accelerator.

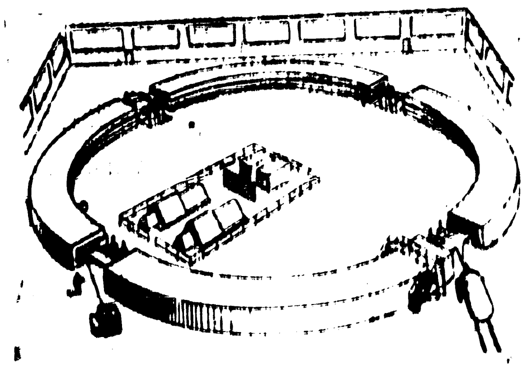

Figure 3. Schematic diagram of a bevatron—that is a projected proton accelerator of the synchrophasotron type for 10 Bev. In the right corner is shown the Van de Graaff generator used for a high voltage proton input. The beam of high energy particles goes out near the figure of the man on the left who is shown for comparison of the size of the apparatus.

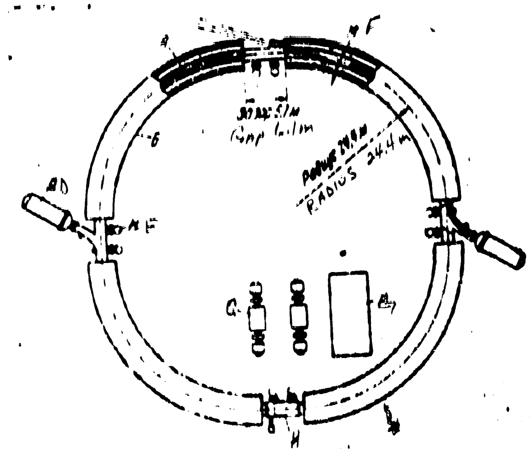

Figure 4. Diagram of the projected bevatron at the University of California: A- chamber; B- magnet; C- motor-generators; D- Van de Graaff generator; E- target; F- vacuum pumps; G- control apparatus, transformers, and rectifiers; H- accelerator section.

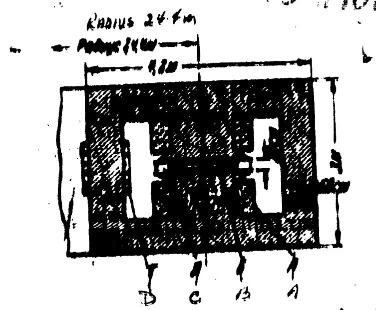

Figure 5. Cross section view of the ring magnet of the bevatron: A- basic winding; B- vacuum chamber; C- region of partical vacuum; D- suppleme tary (betatron) windings.

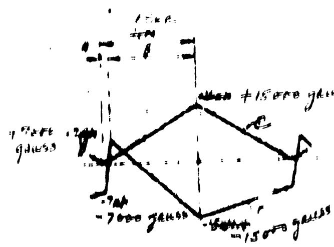

Figure 6. Graph of the variation of magnetic field intensity in the air gap and of magnetic flux density in the inner vertical yoke of the bevatron magnet: A- betatron regime 0.02 seconds, B- synchro-phasotron regime; C- magnetic field intensity in the air gap; D- magnetic flux density in the inner yoke.

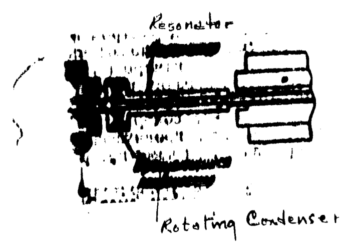

Figure 7. Diagram of the accelerating system of the bevatron which is placed in one of the rectilinear gaps.

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