Many technical problems, primarily relating to the high operating temperatures, must be overcome before such systems find application.

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INSTRUMENTS AND TECHNIQUES

The Cambridge Electron Accelerator

This 6-billion-volt machine will be the world's highest energy electron synchrotron.

M. Stanley Livingston and William A. Shurcliff

By the autumn of 1961, if all goes well, the family of great accelerators will be joined by a new member: the Cambridge Electron Accelerator (CEA). The newcomer differs from the mammoth *proton* accelerators at CERN and Brookhaven in that it will produce high-energy *electrons*. The electron is the lightest of all charged particles and can be accelerated to especially high velocity. In the Cambridge machine the electrons will reach a speed virtually indistinguishable from that of light itself—a speed of 0.999,999,996 *c* (*c* is the velocity of light). A more meaningful measure is the electron energy, which will be 6 billion electron volts (6 Bev)—five times higher than that available from any existing electron accelerator. Another interesting property is the electron mass, which will be increased to nearly 12,000 times the rest mass, or to a value six times greater than the mass of a proton. (*Ponderizer* might be a more descriptive name than *accelerator.*)

This machine will also produce higher intensities than other multi-Bev accelerators. Thanks to the fast cyclic repetition rate of 60 cycles per second, the number of 6-Bev electrons produced per second will be about 6×10^{12}, equivalent to an average current of 1 microampere. Since the product of current and voltage is power, the average power in the electron beam will be 6 kilowatts. With such high electron energy and beam intensity available, experimenters will be able to explore a new range of phenomena in particle physics.

The CEA is jointly sponsored by Massachusetts Institute of Technology and Harvard University and is supported by the U.S. Atomic Energy Commission. Unlike other large accelerators, built in large open areas at the national laboratories, the CEA is located in the heart of a university, in close proximity to the Harvard physics buildings and libraries (Fig. 1). Thus it will be readily available to the faculties and students. Senior staff members of the CEA hold appointments from the universities and cooperate in the research and teaching programs. As one of the major accelerator research facilities of the country, the CEA will be available for use by qualified visiting scientists from other institutions here and abroad.

The operating policies are guided by a joint M.I.T.–Harvard committee composed of administrative and scientific representatives of the two institutions. Detailed planning began in April 1956. Site excavation was started in November 1957, with a ceremony involving a twin-handled shovel jointly wielded by President Julius A. Stratton of M.I.T. and President Nathan M. Pusey of Harvard. A laboratory staff has been assembled, with representatives from many countries. A laboratory report (*1*) summarizes the basic design principles and gives the names of many of the persons who have contributed.

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Particle Physics

The field of research serviced by these giant machines is called "particle physics." It is the study of the properties of the fundamental particles—the protons, neutrons, and electrons of which matter is made—and of the laws of force and particle interaction that make these particles stable and other forms of matter unstable. The concentrated, intense beams of high-energy particles from accelerators are used as probes for studying these properties. At Bev energies the probes are extremely "sharp," capable of penetrating to within collision distances smaller than the dimensions of single particles, and thus able to disclose details of their structure.

At these energies, unstable particles are formed which represent "excited states" of matter, such as the several types of mesons (intermediate, in mass, between electrons and protons) and the several types of hyperons (greater in mass than protons or neutrons). The excess mass of these short-lived states of matter is supplied by the kinetic energy of the bombarding particles. Of great interest, also, are the "antiparticles"; it now appears that each normal particle has its antiparticle, and that matter and antimatter form a symmetrical pattern. A newly created antiparticle, after being slowed down, "annihilates" with a normal twin, and the mass energy of the two particles is transformed into the kinetic energy of the resulting photons or other secondary particles.

Why Electrons?

High-energy electrons can do many things that protons cannot do. One of the basic areas of research in particle physics has been the study of the distribution of mass, charge, and magnetic field inside single particles by scattering electrons from simple targets. In recent years such experiments have been performed with the 0.7-Bev linear accelerator at Stanford University and the 1.2-Bev synchrotrons at Cornell University and at California Institute of Technology. The much higher energy of the Cambridge machine will extend these studies and should improve the resolution; crucial experiments lie just beyond the energy limits of the existing accelerators. One specific goal is the determination of the electric form factor and the magnetic form factor of the proton and the neutron.

Electron scattering experiments are of especially great value since electrons exert—traditionally—only central forces (forces that depend solely on distance of separation and not on orientation). Protons exert central forces and also noncentral forces; the latter depend on the orientation (polarization) of the bombarding particles and the target particles. Since the dependence is complicated and not fully understood, the different, and presumably simpler, evidence from electron scattering experiments should aid significantly in the interpretation of the complex nuclear force.

A beam of 6-Bev electrons is a superlative tool for producing high-energy photons ("bremsstrahlung" x-rays) from any target. This bremsstrahlung radiation is a continuous spectrum extending up to the maximum energy of the electrons. Calculations suggest that one photon of between 5- and 6-Bev energy will be emitted for every ten electrons striking the target. The angle of projection of the photons is limited to a very narrow cone in the forward direction; the angle is so small that the spread amounts to less than one inch in a 100-foot run.

The photon beam can be used for a variety of experiments not possible with proton accelerators. An example is the photoproduction (from targets consisting, say, of hydrogen) of pairs of mesons, hyperons, and other particles. Photoproduction is theoretically simpler to analyze than proton-proton interactions (which also produce particle pairs), since it involves the known electromagnetic field interaction. The several types of short-lived particles, or excited states, will be produced in much greater abundance than is possible at lower energies. The 6-Bev energy is sufficient for production of all known particles, in the form of pairs, except the heaviest—the *X* hyperon; *X* particles can be produced singly in alternative processes. Study of photoproduction reactions will add vital new information about the interparticle forces. The secondary particles themselves will have quite high energies and hence can be studied effectively.

Specialists in the field of quantum electrodynamics are eagerly awaiting the results of one particular type of photoreaction—namely, the photo-

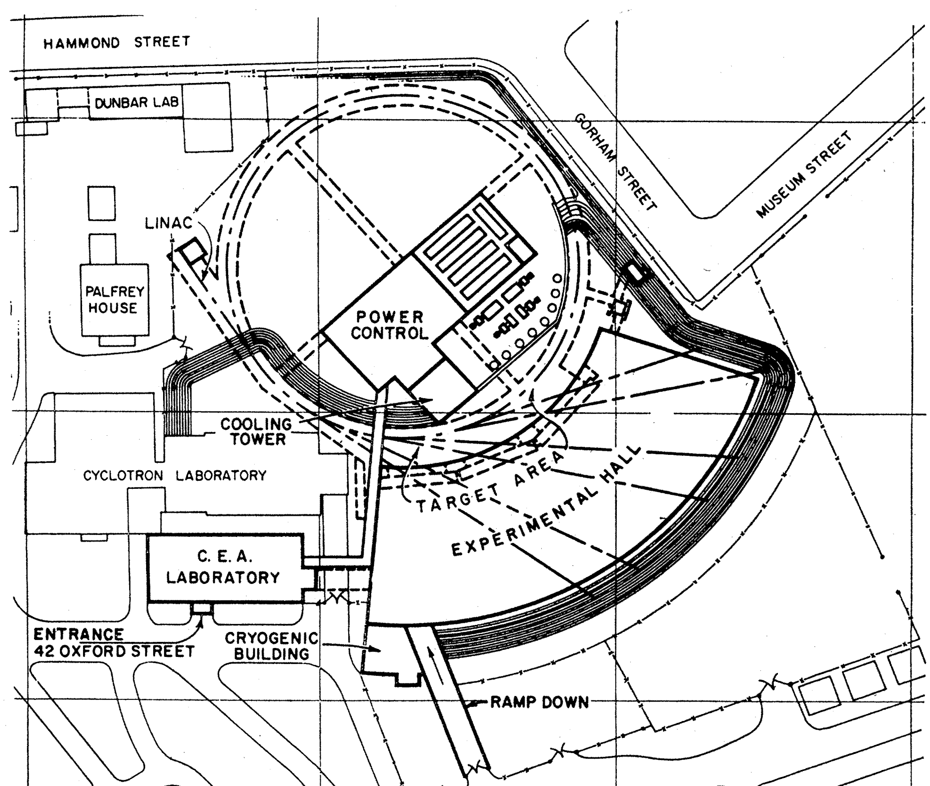

Fig. 1. The general layout of the Cambridge Electron Accelerator. The circular orbit is 236 feet in diameter and is 10 feet below ground level. The experimental hall is as large as a football field.

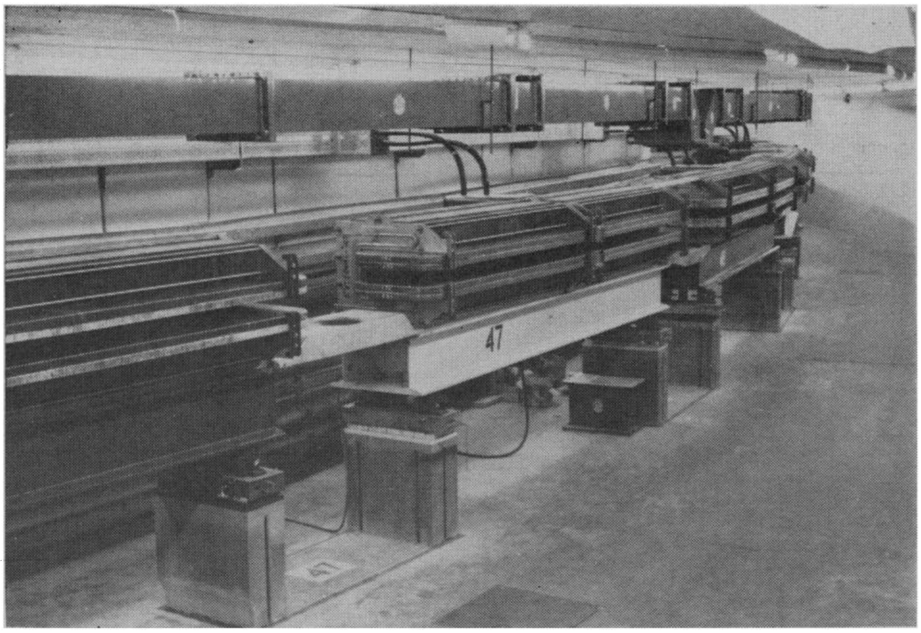

Fig. 2. A portion of the circular array of 48 magnets. Each magnet is 12 feet long and weighs 6 tons. Above the magnets are the radio-frequency waveguides.

production of pairs of positive and negative muons (μ mesons). Experiments performed with existing accelerators suggest that muons are generally similar to electrons (except as regards mass and lifetime) and obey the same quantum electrodynamical laws that electrons obey. The question is: Will this similarity persist even when multi-Bev energies are employed—that is, when the collision distances are less than 2×10^{-14} centimeter and hence are less than the diameter of the electron itself? Is there an energy at which the well-established laws of quantum electrodynamics break down?

Design Principle

The Cambridge Electron Accelerator, like other synchrotrons, operates on the principle of phase-stable synchronous acceleration at constant radius, a principle analogous to that of the synchronous electric motor. Particles follow a circular orbit in a magnetic field and gain energy in varying amounts from radio-frequency electric fields applied at accelerating gaps around the orbit. A particle crossing a gap at the ideal moment—that is, at the "synchronous phase" of the radio-frequency wave—receives the correct acceleration, hence arrives at the next gap at the ideal moment. The momentum of such a particle increases at just the right rate to match the increase in magnetic field strength; thus, the diameter of the orbit remains unchanged. Particles that fall behind the synchronous phase receive less energy and catch up with the synchronous particles; those that lead in phase get more energy and fall back. (Paradoxically, the only way a very fast electron ($v \cong c$) can catch up in phase is to slow down physically. When going more slowly it travels in an orbit of smaller diameter and hence completes one turn in shorter time.) Individual particles oscillate about the synchronous phase; the oscillations are gradually damped and the electrons become "bunched" about the correct phase.

The main components of the CEA are the preaccelerator, the ring of 48 magnets forming a circular orbit, and the radio-frequency system for acceleration. Operation is cyclic, at a frequency of 60 cycles per second. In each cycle a pulse of electrons from the preaccelerator is inflected into the orbit when the strength of the magnetic field is low. As the field strength increases, the electrons are accelerated by the radio-frequency system to higher and higher energy. When the field strength reaches its maximum value and the electrons have attained their maximum energy, they are diverted toward a target adjacent to the orbit (or are ejected for use in the experimental hall). The magnetic field strength then returns to zero, and the cycle repeats. The result is a sequence of short bursts of high-energy electrons. Each group makes about 10,000 trips around the ring in an elapsed time of 1/120 second (0.008 sec); the period of a single revolution is 0.7 microsecond.

The preaccelerator, or linac, produces pulses of electrons of 25-Mev (million electron volt) energy. It is located in a straight spur tunnel that is tangent to the circular tunnel housing the 48 magnets. It emits a pulse (of about 1 microsecond duration) in a slender, well-colliminated beam which is inflected into the orbit by an auxiliary magnet field in one of the spaces between magnets. The auxiliary field is maintained just long enough to fill one turn of the orbit with electrons and is then pulsed off very quickly (0.1 μsec) so as not to distort the orbit of electrons completing their first turn.

The 48 magnets, each 12 feet long, are arranged in a circle 236 feet in diameter (Fig. 2). Each is separated from its neighbor by a 3-foot space, or straight section. The poles of the magnets are not parallel but are slightly wedge-shaped, to provide the nonuniform fields that accomplish the alternating-gradient focusing discussed in a later paragraph.

The feature that makes an electron synchrotron simpler than a proton synchrotron is the extremely high speed of the orbiting particles. In the CEA, the electrons are injected into the orbit with an energy of 25 Mev and a speed of 0.9998 c; consequently, the speed can increase by only 0.02 percent in the subsequent acceleration. Because the speed is so nearly constant, and because the orbit radius changes so little (about 0.3 in.), the accelerator designer may employ a *fixed frequency* radio-frequency system. This permits use of tuned, high-Q radio-frequency cavities which, when excited at the resonant frequency, produce very high accelerating voltages even at relatively low power.

The magnetic field produced by the ring of 48 magnets does not change the energy of the electrons but performs the function of deflecting them into a circular path so that the radio-frequency system can act on them repeatedly, throughout many turns (about 10,000). In a typical turn, the kinetic energy of the electron increases by about 0.6 Mev. If this were the only energy requirement on the radio-frequency system, this system could be of quite modest size and power.

The actual requirement near the end of the acceleration interval is ten times higher than the average required for acceleration, due to the enormous radiation losses suffered by the electrons. It is well known that whenever a strong magnetic field acts on a very fast electron, accelerating it radially, the electron radiates energy (synchrotron radiation) consisting of a broad spectrum of visible light, ultraviolet, and soft x-rays. The energy lost by synchrotron radiation increases with the 4th power of the electron energy. A 5-Bev electron traveling in an orbit of 90-foot radius (*2*) loses about 2 Mev of energy per turn, and a 6-Bev electron loses 4.5 Mev per turn. To compensate for such losses the radio-frequency acceleration system must be driven to especially high voltages at the end of the acceleration cycle.

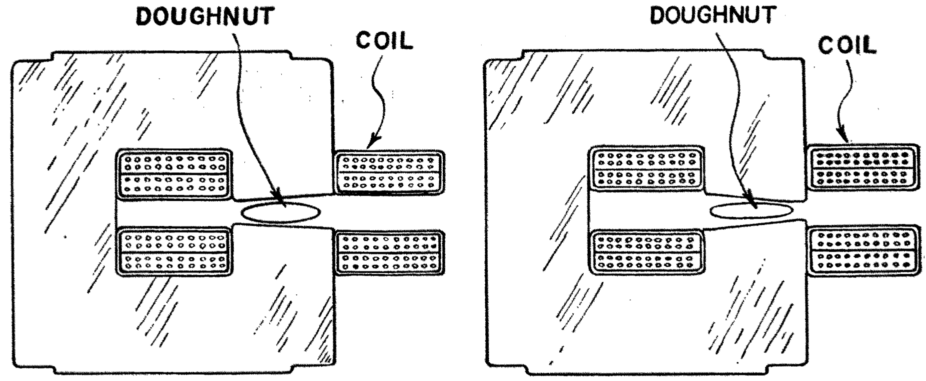

Fig. 3. Cross sections of magnets of (left) the open, vertically-focusing type and (right) the closed, horizontally-focusing type.

Synchrotron radiation is disturbing in another way: an orbiting electron suffers discrete changes in momentum on emitting photons of synchrotron radiation and begins to oscillate about the normal orbit. The oscillation grows with increasing energy and with time, so that ultimately many electrons would be thrown out of the orbit. This phenomenon sets a practical limit on the energy that can be imparted to an electron by a given synchrotron. With the 1/120-second rise time and the orbit radius chosen for the Cambridge accelerator, the practical energy limit is between 6 and 7 Bev.

Alternating Gradient Magnetic Focusing

The CEA, like the 30-Bev proton synchrotrons at CERN and Brookhaven, uses a magnet system of the alternating gradient, or strong focusing, type, which confines the beam to an orbit of very small cross section. This focusing principle permits use of magnets that are of small size and have modest power requirements. Thus, the magnets can be operated at a high cyclic rate and short acceleration interval. Because this interval is short, the energy loss by synchrotron radiation remains within reasonable limits, and the design of a 6-Bev machine becomes practical.

Of the 48 magnets, 24 have "positive" gradient and 24 have "negative" gradient (Fig. 3). The field gradient results from the wedge-shaped gap between the poles. By curving the sloping pole-face profiles slightly (so that they resemble portions of a rectangular hyperbola), the gradient can be made uniform across the pole face. In a positive-gradient magnet the gap height *decreases*—and field strength increases—with increasing distance from the accelerator center point; hence, an electron traveling at too-great radius is urged back toward the central orbit; such a magnet is said to be radially focusing. In a negative-gradient magnet the gap height *increases* with distance from the center point and the vertical flux lines are slightly curved outward, so they exert a downward force on an electron that is traveling above the ideal orbit and an upward force on an electron that is below this orbit; such a magnet is said to be vertically focusing. The two types of magnets alternate around the ring; and although each type somewhat reduces the focusing effect of the other type, the over-all effect is one of strong focusing in both vertical and radial directions.

The focusing forces cause the electrons to oscillate about the central orbit. Such "betatron" oscillations occur in both the radial and vertical directions. The number of oscillation wavelengths per turn depends on the magnetic gradient and is greater for larger gradients. An integral number of wavelengths per turn is highly undesirable, since it would lead to resonance build-up of oscillation amplitudes. Magnets are designed, and gradients chosen, so that the number of wavelengths per turn stays between integral values during the entire acceleration interval. The CEA magnets were designed so that the magnetic field increases (or decreases) by about 10 percent per inch of displacement across the pole face; this gradient leads to a figure of 6.4 for the number of betatron wavelengths per turn, for both radial and vertical oscillations.

The magnets must be precisely aligned around the circular orbit in order to minimize oscillation amplitudes. Alignment errors must be confined to about ± 0.005 inch in the vertical and ± 0.01 inch in the radial coordinate. Firm foundations are required, and also precise adjustment mechanisms and accurate surveying techniques. The magnets rest on heavy girders supported on precision jacks and traverse mechanisms; these rest on piers supported by piles driven deep into the gravel subsoil and mechanically isolated from the rest of the building.

Each magnet consists of 6 tons of die-stamped C-shaped laminations, bonded together into blocks and assembled on a girder 12 feet long. The average magnetic gap length (at the central orbit) is 2 inches, and the poles are only 6½ inches wide. The necessary magnetic uniformity (better than ± 0.5 percent) was achieved by shuffling the laminations prior to bonding and by assembling them with high precision. A typical tolerance is ± 0.001 inch.

The magnet excitation coils are of stranded copper and contain tubes in which cooling water circulates. Each magnet is equipped with "pole face winding" systems which make it possible to make minor corrections to the

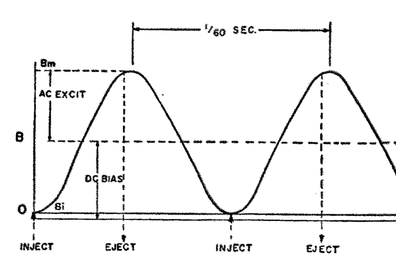

Fig. 4. Wave form of magnetic field strength resulting from the full-biased excitation current. The cycle period is 1/60 second, and nearly half the period is devoted to actual acceleration of electrons.

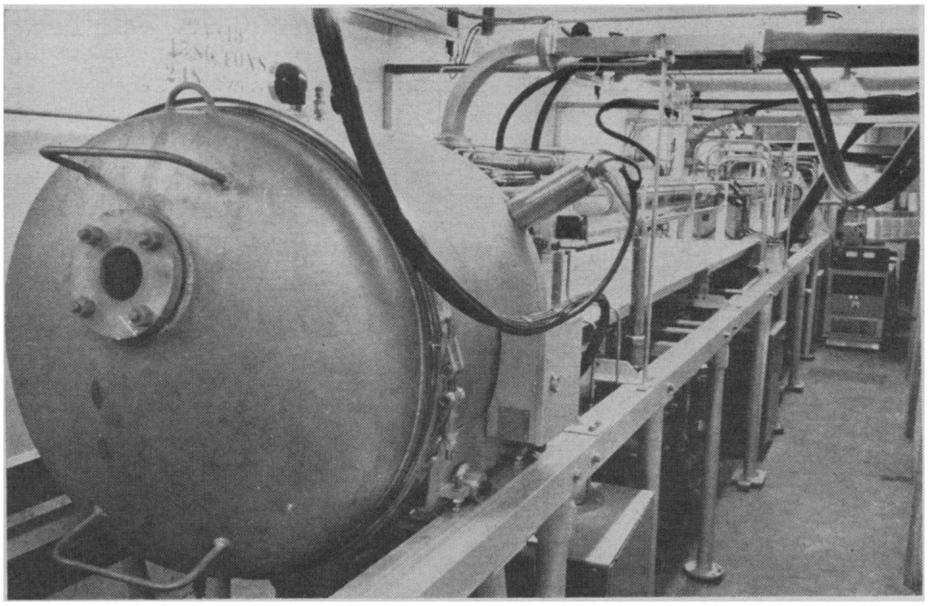

Fig. 5. The 25-Mev linear preaccelerator, which accelerates the electrons from a standing start to a speed of 0.9998 *c* in a path length of 25 feet. The electrons then enter circular orbit tangentially.

field gradient and to the field itself at the time (near injection) when the field strength is low and remanent fields are appreciable.

One of the unique engineering features of the accelerator is the magnet power supply. This consists of a massive resonant circuit driven by an electronic self-excited oscillator. The power dissipated in the circuit amounts to 1000 kilowatts, and the peak value of circulating power exceeds 100,000 kilovolt-amperes. Electrical engineers have been intrigued by this application of electronic principles to such a large alternating-current power supply.

The current in the magnet excitation coils has a full-biased sinusoidal wave form, as indicated in Fig. 4. It varies from zero to maximum and back again 60 times a second. At the time the preaccelerated electrons are injected into the ring, the excitation current and the magnetic field (then about 30 gauss) are increasing slowly. Eddy-current distortion of the field is small at this critical time, and the efficiency of acceptance of the injected electrons is high. The acceleration rate is greatest when the exciting current is half-maximum. When the current has nearly reached a maximum, the rate of increase of field is again small and the time interval for beam utilization at approximately constant energy is conveniently long.

The full-biased current can be considered as the superposition of a direct current (420 amperes) and an alternating current (300 amperes, root mean square value). The direct current is supplied by a low-voltage ignitron-rectifier system. The alternating current is supplied by pulsing a high-voltage direct-current source.

The resonant alternating-current circuit consists of the ring of 48 magnets (connected in pairs), 24 banks of capacitors, and a ring-shaped energy-storage inductor with 24 identical windings. Cabling connections form a series circuit through the magnet coils and inductor windings, with the capacitor banks connected across the inductor windings. Thus there are 24 subunits in series, each resonant at 60 cycles per second. The direct-current bias current provided by the low voltage supply is introduced at the geometrical and electrical center of one of the inductor windings and traverses all magnet coils and inductor windings in series. A key feature of the circuit is that the currents in all 48 magnets are identical, and consequently the magnets are powered with equal amplitude and phase.

The pulses providing the alternating-current power are fed to the circuit through a distributed set of primary windings around the inductor cores. The pulses are obtained by firing an ignitron in the high-voltage direct-current supply; the ignitron closes the circuit momentarily and sends a pulse of power through the primary from a storage capacitor. The timing signal for pulsing the ignitron is taken from a chosen phase of the circulating power in the main resonant circuit. The timing is such that the pulses occur when the magnet excitation current is decreasing; hence, the pulses do not disturb the smooth rise in field during the acceleration interval.

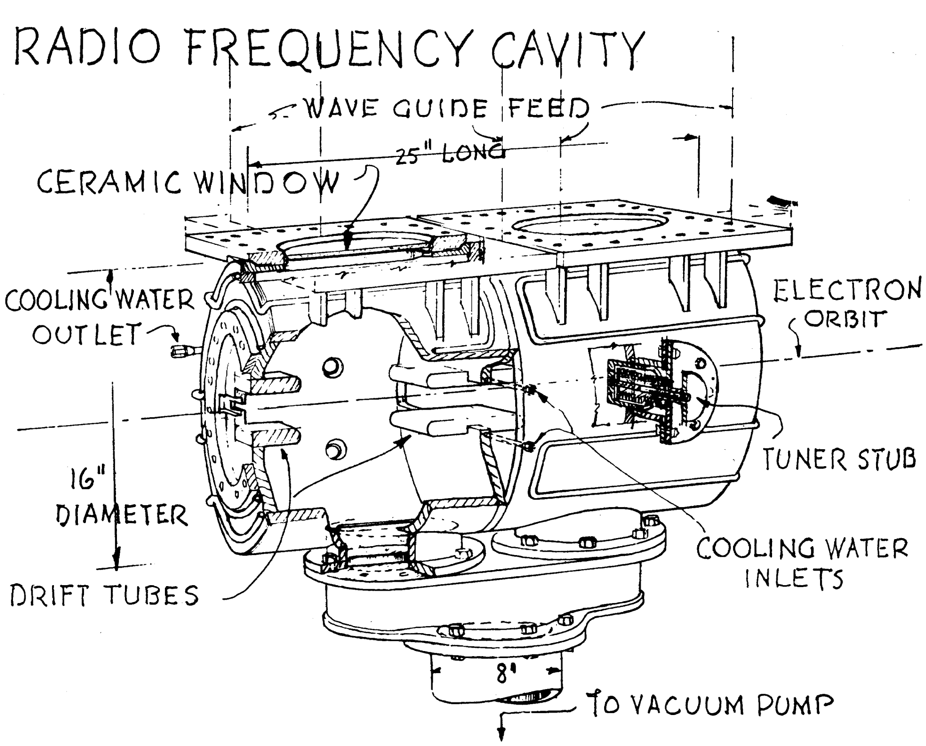

Fig. 6. One of the 16 radio-frequency cavities. The electrons travel along the horizontal axis of the cavity's two resonant chambers and are accelerated by the intense electric fields in the chambers. The fields are supplied by waveguides 18 inches wide (not shown) and air-tight ceramic windows.

Injection

The 25-Mev preaccelerator is a microwave waveguide linac of the traveling-wave type and operates at a frequency of 2855 megacycles (Fig. 5). It consists of two 10-foot sections of S-band, iris-loaded waveguide, each powered by a pulsed Klystron tube of 5-megawatt peak pulse rating. Electrons are emitted from an oxide-coated cathode and pulsed by a 200-kilovolt modulator; they traverse a pre-buncher cavity tuned to the 2855-megacycle frequency, then pass along the two waveguides. The emerging beam has a peak pulse intensity of 150 milliamperes; the beam diameter is 0.4 inch, the angular spread is 0.04 degree, and the energy spread is ± 1.5 percent.

The modulator is triggered by a signal derived from the increasing magnetic field in one of the 48 magnets; triggering occurs when the field strength reaches the value (about 30 gauss) appropriate to 25-Mev electrons. The pulse is of 1-microsecond duration, sufficient to fill the circular orbit of the synchrotron. The preaccelerated beam enters the synchrotron ring almost tangentially at one of the field-free spaces between magnets. There the beam is deflected about 3 degrees (by a weak magnetic field) so as to join the synchrotron orbit smoothly. The deflecting magnetic field is produced by a short pulse of current in a set of specially shaped windings; it is cut off just before the inflected electrons complete one turn around the orbit.

Radio-frequency System

The acceleration system consists of 16 resonant radio-frequency cavities (Figs. 6 and 7) connected by waveguide links to form a circular loop 240 feet in diameter. The cavities operate in phase synchronism, achieved by tuning them and also the waveguide links to the frequency of 475.83 megacycles. The system of resonant cavities and waveguide links constitutes a closely coupled, high-Q, series-resonant circuit which is unique in radio-frequency engineering. It is perhaps the most extended system of high-Q resonant circuit elements operating in a single mode that has ever been built.

Each cavity consists of two half-wave resonators and includes re-entrant drift-tube electrodes forming two 8-inch gaps across which the radio-frequency potential is developed. Thus, the orbiting electrons experience 32 accelerations per turn. The cavities are formed of thick plates and cylinders of high-conductivity copper, brazed to form vacuum-tight chambers. Each cavity is 16 inches in diameter and 24 inches long and is built to very close tolerances. An adjustable tuning stub is mounted in the side of each resonator unit. The radio-frequency power is fed to the cavity through two alumina ceramic vacuum windows installed on the side (upper surface) of the cavity and traverses the two half-wave resonators within the cavity. At peak power the voltage across each resonator gap is 200 kilovolts. Cooling water circulates within the heavy walls and is thermostatically controlled to maintain constant cavity dimensions and hence constant resonant frequency.

The waveguides, of standard rectangular type, 18 inches wide, are formed of welded aluminum sheet and flanges. In each link there are a thermal expansion "choke" joint and two phase-shifters for adjusting the electrical length of the link. The radio-frequency power is fed from an amplifier in the power building by way of a radial run of waveguide which joins the main loop at a T joint.

Since the radio-frequency system includes 48 tuned components (32 half-wave resonators and 16 waveguide

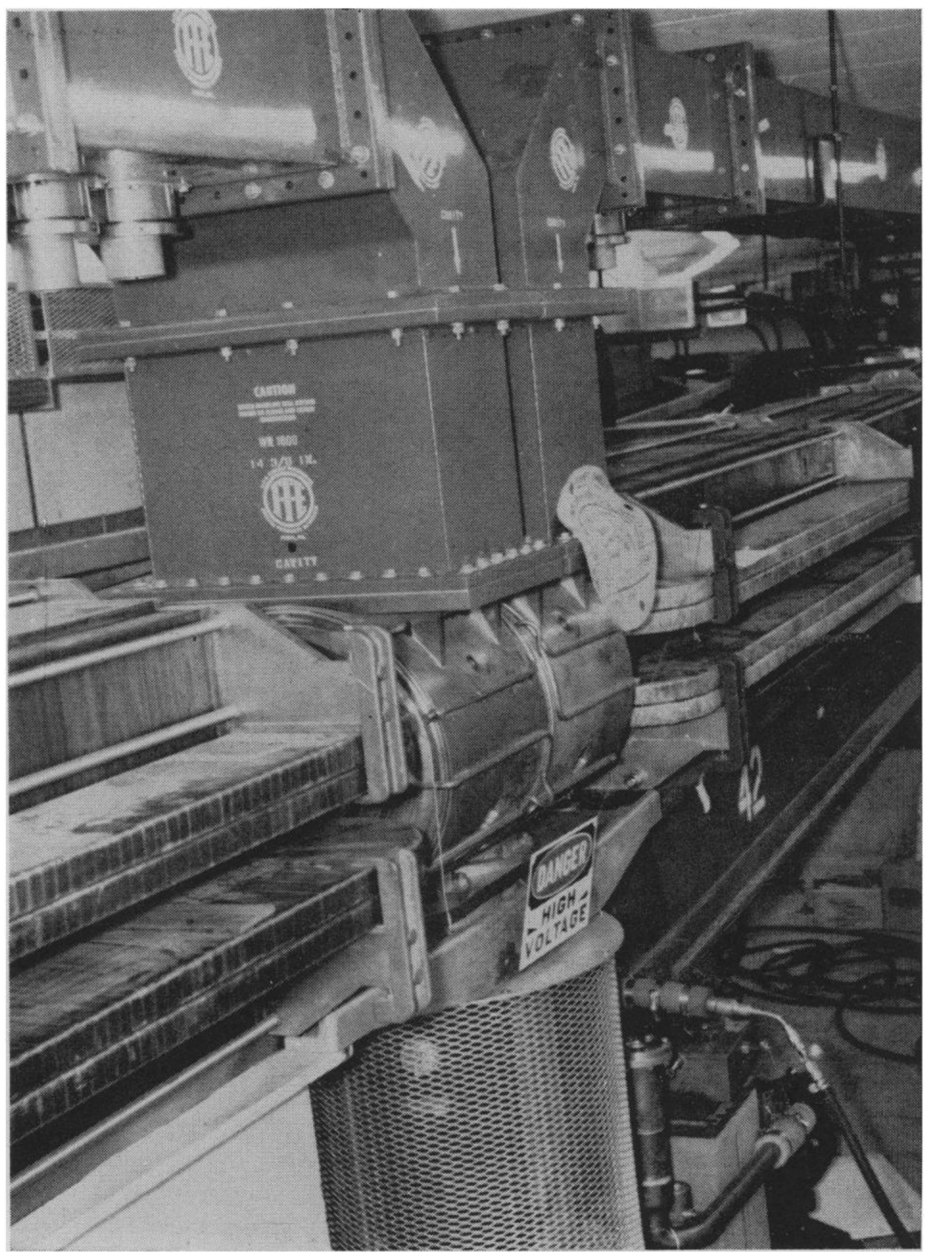

Fig. 7. A radio-frequency cavity in place between two magnets. Above the cavity are the radio-frequency waveguides. Below, suspended from the cavity, is one of the 48 high-vacuum pumps.

links), there are at least 48 possible modes of oscillation. Only one of these modes provides identical phases in all cavities, a condition essential for acceleration of electrons. This mode is spaced from its nearest neighbors (in frequency) by about ten bandwidths and can be selected by precise tuning of all components.

The 475-megacycle power supply consists of a power amplifier (transmitter) employing a high-frequency "superpower triode" as the output stage. Peak power output, occurring at the end of the acceleration interval, is 400 kilowatts; the average power for the duty cycle required in this application is 80 kilowatts. Frequency is determined by a master oscillator which provides excitation for the transmitter. The transmitter is modulated so as to provide about 20 kilovolts per resonator gap (320 kilovolts per turn) at the start of the acceleration interval and 200 kilovolts per gap (6 megavolts per turn) at the end of the cycle, the large increase being necessitated by the rapidly increasing radiation losses experienced by the orbiting electrons.

Vacuum System

The vacuum chamber inside which the beam circulates consists of 48 slender tubes which fit between the poles of the 48 magnets and connect the 16 radio-frequency cavities and 32 other vacuum manifolds occupying the spaces between magnets. Beneath each cavity and manifold is a high-vacuum pump and also a rough-vacuum pump for initial pump-down.

The vacuum chambers have an oval cross section of about 1½ by 5½ inches and are formed of nonmagnetic stainless steel tubing slotted at ½-inch intervals to minimize eddy currents that could distort the magnetic field. An external coating of Fiberglas cloth and epoxy resin seals the slots and provides a vacuum-tight coating. The slots are narrow so that the interior surface is mostly steel, which minimizes evolution of vapor and protects the resin from damage by the intense synchrotron radiation.

The high-vacuum pumps are of the recently developed high-voltage, titanium-discharge type. The discharge between titanium electrodes ionizes the residual gas, and the sputtered titanium acts as a "getter" for the ions that strike the pump walls. The pumps are electronic, without moving parts or objectionable vapors. Metal gaskets are used throughout the vacuum system, and all components are carefully cleaned and baked at elevated temperatures under vacuum. When the initial pump-down is complete, the rough-vacuum pumps are shut off and the titanium pumps continue to operate, maintaining high vacuum in the totally sealed system. The operating pressure of about 1×10^{-6} millimeters of mercury is low enough so that scattering of the orbiting electrons by residual gas in the chamber is negligible.

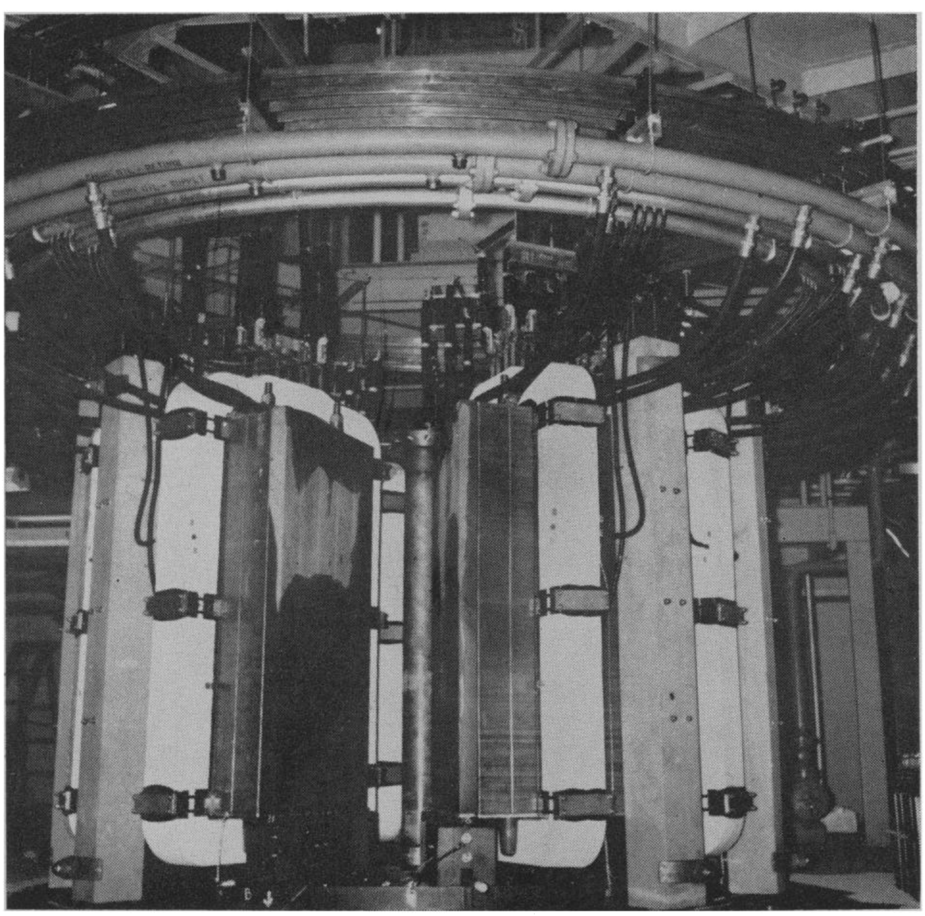

Fig. 8. The 60-ton toroidal inductor for the magnet power supply system (in this photograph one core block and one excitation coil have been removed). The peak energy storage of the inductor is 600,000 joules.

Laboratory Arrangements

The circular tunnel is located underground, with the orbit 10 feet below ground level. Concrete and earth fill (6 to 15 feet thick) over the tunnel shield the above-ground areas from high-energy secondary or scattered radiations. The main power supplies (Fig. 8) are in a central power building connected to the ring by four radial tunnels. One portion of the circular tunnel is widened to provide room for targets, magnets, and other equipment needed for producing, analyzing, and focusing emergent beams. Outside this area is a large experimental hall, separated by a thick shielding wall of iron-ore-loaded concrete blocks. Beams of electrons, photons, and secondary particles can be brought through small channels in this wall into the experimental hall for research experiments.

The experimental hall is larger than a football field and is provided with electrical power, cooling water, a 40-ton traveling crane, and other features. The apparatus used for experiments will be assembled along the trajectories of the emergent beams, from six or more alternate target locations in the ring. Several experiments can be set up and carried out, simultaneously or sequentially, while new experiments are being prepared.

The large pieces of equipment required for experiments include analyzing and focusing magnets, spectrometer mounts for studies of angular distributions, target assemblies of special types, a large hydrogen bubble chamber, and a wide variety of other items. Each experiment will require specially designed shields of dense concrete, iron, and lead. In many cases the output data from electronic counters or other apparatus will be transmitted to data-processing electronic computers in the laboratory building, for analysis and recording. A large cryogenics plant for liquefying helium is being built; a separate helium expansion engine will be mounted near the hydrogen bubble chamber, for maintaining low temperature there. Cold helium gas will be used to cool various special targets of hydrogen and deuterium.

Targets located in a straight section can be placed just outside or inside the beam orbit, and the beam can be diverted against the targets by pulsing special magnets or by turning off the radio-frequency acceleration at the peak of the cycle. High-energy photons are projected forward from such a target in a sharply defined tangential beam. Charged secondary radiations, such as mesons or hyperons produced in a target, can be focused and analyzed magnetically and can pass through other channels in the main shielding wall. Single-beam pulses can be directed at one target (for instance, in a bubble-chamber experiment) and other pulses can be directed at a target serving a different experiment.

In other experiments an emergent beam of 6-Bev electrons will be used. Special magnets located just inside the orbit at chosen straight sections can be pulsed to jolt the electrons out of the orbit into a well-defined emergent beam. This beam will traverse a vacuum pipe through the shielding wall and will be focused by magnetic lenses onto a target in the experimental hall.

A detailed discussion of the experiments planned is beyond the scope of this account. Scientists from M.I.T. and Harvard, as well as from other nearby universities, are actively engaged in designing experiments that should go far toward exploiting this new energy range in the field of particle physics. No effort is being spared to have the necessary equipment and instruments ready for use when the accelerator is completed.

Notes

1. CEA staff report No. CEA-81 (1 Aug. 1960).
2. Although the average radius of the CEA orbit is 118 feet, the radius of a path segment between the poles of a magnet is shorter—90 feet. In the field-free spaces between magnets the path is straight.

INSTRUMENTS AND TECHNIQUES

Defocusing Images To Increase Resolution

Resolution of two luminous particles is improved by defocusing the microscope or telescope.

Harold Osterberg and Luther W. Smith

Consideration of the distribution of energy density in the diffraction image of two unresolvably small, self-luminous particles led us to expect that a marked increase in the lateral resolving power of a microscope or telescope should occur in appropriately selected out-of-focus image planes. This expectation has been confirmed experimentally. In order to obtain an appreciable advantage, the instrument must be adjusted far out of focus, and thus the appearance of two neighboring concentrations of energy density in the blurred image of two self-luminous particles has, no doubt, either been ignored or considered spurious by many observers.

Particles that are viewed by means of the light that they scatter or cause to fluoresce act, in effect, as self-luminous particles. Particles in a dark-field microscope scatter light into the objective and tend to act almost as though they were self-luminous. In fact, under certain conditions of illumination, particles appearing against dark backgrounds closely imitate self-luminous particles. These conditions of illumination exist in interference microscopes, in which destructive interference between the direct and the reference beams renders the background practically dark. Conclusions with respect to the out-of-focus states of self-luminous particles apply, therefore, with minor modifications, to suitably illuminated non-self-luminous particles.

The Airy unit is used as the unit of linear measure in the following discussion. The Airy unit r_a is defined by

$$r_a = 0.61\ \lambda/\text{N.A.} \qquad (1)$$

where λ and N.A. denote wavelength and numerical aperture, respectively. Distance r_a refers to either the object space or the image space, according to whether N.A. is the numerical aperture of the object space or of the image space of the objective. The numerical aperture with respect to the object space is ordinarily $|M|$ times the numerical aperture with respect to the image space, where M denotes the magnification ratio of the objective.

According to Rayleigh's criterion, two particles are resolved when their separation equals or exceeds one Airy unit. In order that two like particles shall be separated by one Airy unit, their effective radius must not exceed one-half Airy unit. We shall see that it is possible experimentally to resolve two like particles having the separation 0.58 Airy unit. The effective radius of such particles can exceed one-fourth Airy unit only slightly. Such particles are unresolvably small from the viewpoint of diffraction theory.

The family of curves of Fig. 1 shows how the distribution of energy density $I(W)$ in the diffraction image of a single self-luminous particle varies with W for a series of out-of-focus states that are most conveniently and completely specified by the parameter ψ. The variable W is the distance in Airy units from the center of the diffraction image, and

$$\psi = \pi \rho_m^2 z/\lambda \qquad (2)$$

where z denotes the out-of-focus distance in the image space and ρ_m denotes the numerical aperture of the objective with respect to its image space. When $\psi = 2\pi$, the eyepiece has been de-

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